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WORLD WEATHER WATCH

PROCEEDINGS OF THE THIRD WMO WORKSHOP ON THE IMPACT OF VARIOUS OBSERVING SYSTEMS ON NUMERICAL WEATHER PREDICTION

Alpbach, Austria, 9-12 March 2004

Edited by

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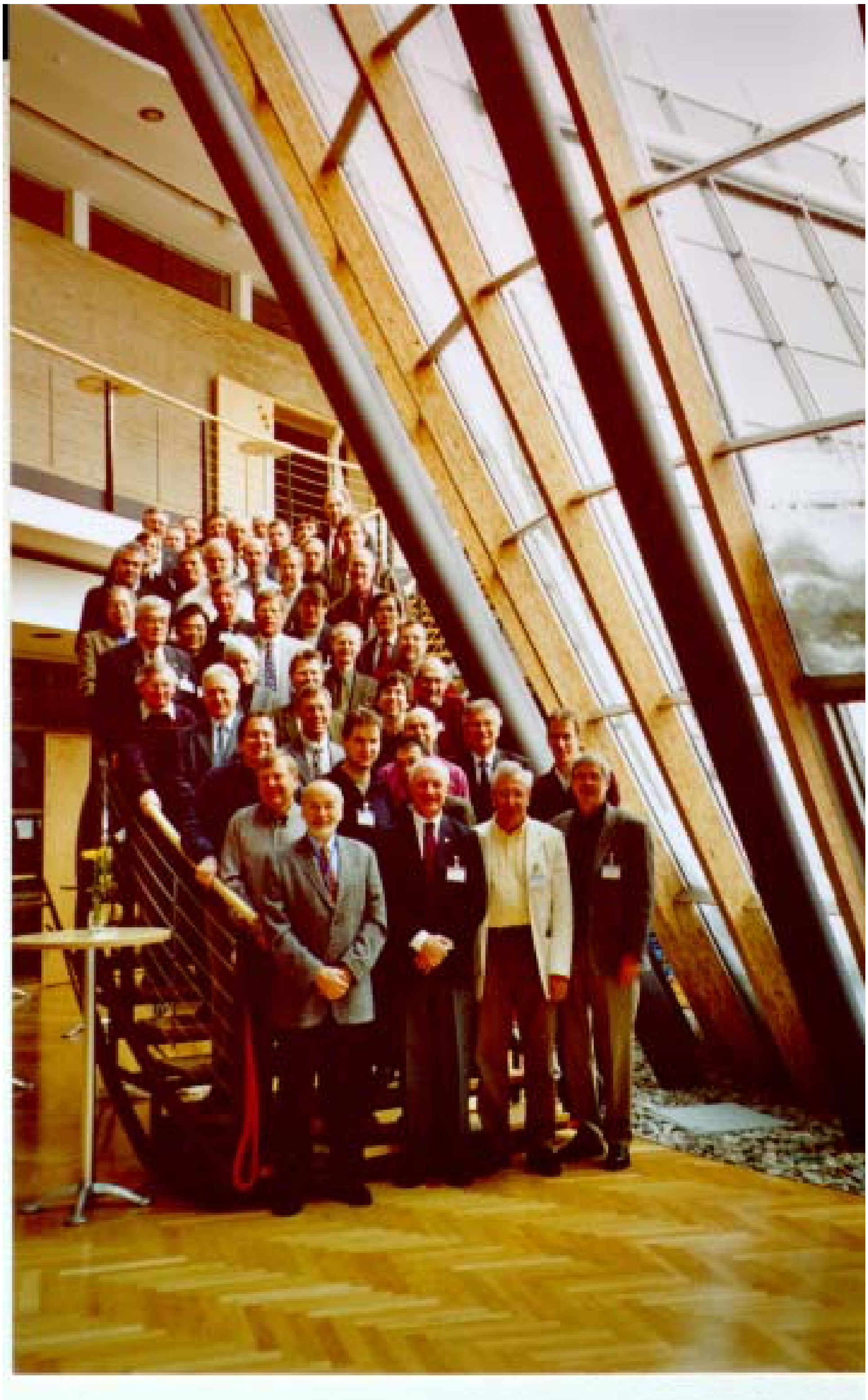

Participants of the Third Workshop on the Impact of Various Observing Systems on Numerical Weather Prediction, Alpbach, Austria, 9-12 March 2004

Alpbach, Austria
(Venue of the Third Workshop on the Impact of Various Observing Systems
on Numerical Weather Prediction, 9-12 March 2004)

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THIRD WMO WORKSHOP ON THE IMPACT OF VARIOUS OBSERVING SYSTEMS ON NUMERICAL WEATHER PREDICTION (Alpbach, Austria, 9-12 March 2004)

GENERAL SUMMARY AND CONCLUSIONS

1. Introduction

The Fourteenth Congress (Geneva, May 2003) noted with satisfaction the challenging work being continued by CBS on the redesign of the GOS, which had already resulted in updated observational requirements of all WMO Programmes and a first assessment of the evolution of the surface- and space-based components of the GOS. This complex process involves experts and decision makers in observing technology, network design, data assimilation techniques and NWP, and eventually may require new joint funding mechanisms for the deployment of observing equipment and systems in remote and/or extraterritorial areas. It should be also underlined, that Member countries have a great interest in optimising their investment in observing systems with the view that advancing scientific knowledge and technology provide opportunities for increasing the availability of observational data while reducing the costs. In the light of the above CBS had continued to accomplish, as a matter of priority, several important actions through its Open Programme Area Groups (OPAGs) and, in particular OPAG on Integrated Observing Systems, by organizing and co-sponsoring expert meetings, workshops and studies focus on the redesign of the GOS.

This WMO Workshop on the Impact of Various Observing Systems on Numerical Weather Prediction organised by the CBS Expert Team on Observational Data Requirements and Redesign of the Global Observing System is considered as another important step forward in the process of redesign of the GOS. Special thanks should be extended to the Coordination Group for COSNA (CGC) chaired by Mr M. Lystad for their decision to provide the financial resources needed for this Workshop from the COSNA Trust Fund and Dr Helmut Rott from the University of Innsbruck for the help and coordination of the local organization of the Workshop in Alpbach.

Since previous Workshops that took place in Geneva (April 1997) and in Toulouse (March 2000), certain significant changes and developments have affected both surface-based and satellite-based subsystems of the GOS. That included new onboard instruments on operational satellites and launches of more R&D satellites. Intensive data assimilation studies (including impact studies) on these new data were carried out from 2002 onward. The conventional observing systems related to radiosonde and aircraft observations are also changing as demonstrated by regional programmes like EUCOS or NAOS. Targeting strategies started to be implemented in operational activities of some NMHSs and also envisaged in major research projects like THORPEX. More and more efforts are devoted to meso-scale observing and assimilation systems.

At this Third WMO Workshop the key recent results in all these areas were presented and discussed. The Workshop's agenda covered three major sections including Global Forecast Impact Studies, Regional Aspects of Impact Studies, Observation Targeting Studies and Observation Network Design Studies, where 30 lectures were presented. Almost 50 experts representing all major NWP and other centres active in the area of observing system impact studies, as well as representatives of the CGC Management Group and the WMO Secretariat attended the Workshop. The programme of the Workshop and the list of participants are given in Annexes I and II respectively.

The full text of papers presented at the Workshop as provided by the authors are reproduced in the second part of the Proceedings.

Section 2 of this Summary contains the assessment of impacts from various observing systems. Section 3 presents specific recommendations focused on implementation of evolving user's requirements as had developed under each section of the Workshop. Section 4 lists the overall conclusions and recommendations from the Workshop.

2. Assessment of impacts from various observing systems

2.1. Global impact of some global observing systems

An up-to-date summary of the impact from different observation types and parameters over the northern and southern hemisphere extra-tropics and tropics is presented in Table 1. The value given for each observation type resulted from all recent studies, in particular those presented at this Workshop. The results are expressed in terms of gain in large-scale forecast skill at short and medium-range (unit = hour). The gain is assessed by adding the observing system to all others used routinely in the assimilation. Since the number of observing systems routinely used varies considerably from centre to centre, this marginal gain may also vary considerably from one study to the other. The table also shows those variations of gain whenever they are supported by significant studies, otherwise general comments are provided. The table also contains notes with indication of whether the overall contribution to the skill of the NWP systems has increased/decreased as compared with assessments of the Workshop-2000. More and more satellite data are used by the more advanced data assimilation systems (but not necessarily by all operational assimilation systems). This explains an increase in the contributions from satellite sub-systems of the GOS to the performance and the skill of NWP systems. As a consequence, other components of the GOS, such as the radiosondes, now have less impact. Overall, the contributions from the satellite and radiosonde data towards the performance of the NWP systems in the northern hemisphere gave similar impact as presented in the synopsis of the results from the Workshop (see Table 1).

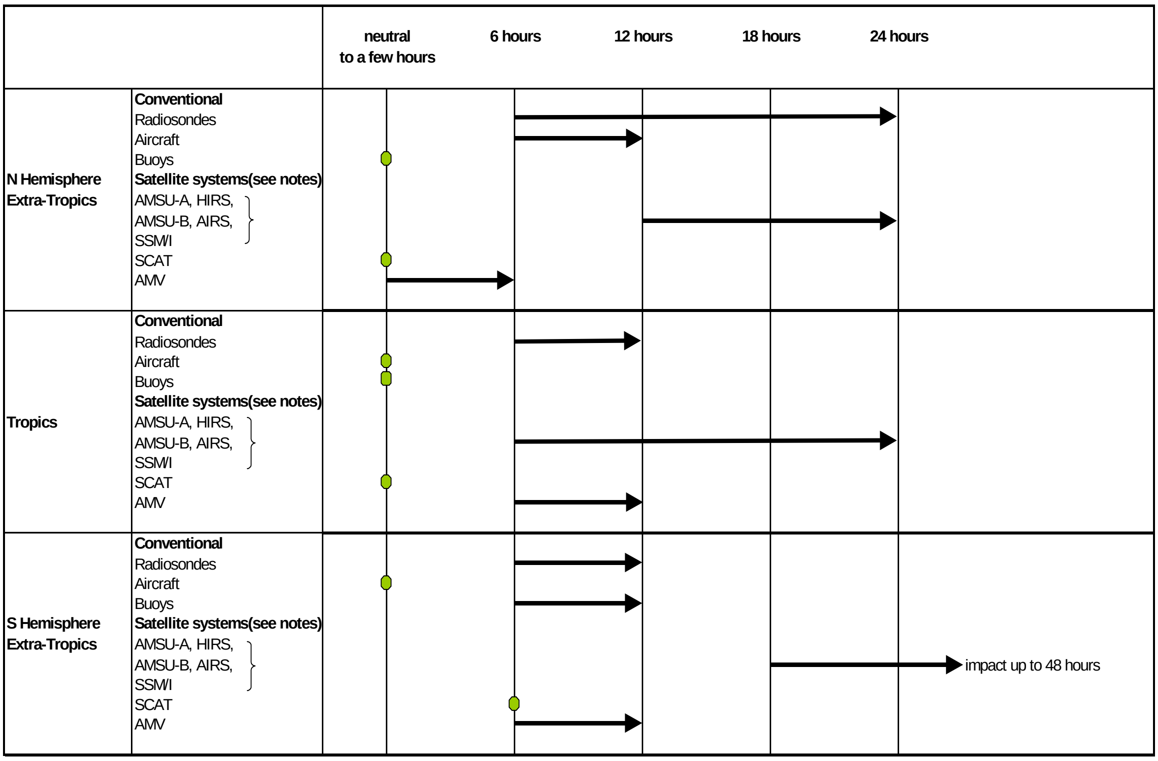
The table should be considered as a rough guide. It is implied that the magnitudes of the impact depend upon the model and assimilation scheme used, upon the impact variable and also the forecast range. The following specific remarks have also to be kept in mind when using the table.

a) Some observing systems that are rated low individually (e.g.: several grey bullets in the table which correspond to "neutral to a few hours") may have a significant impact when acting together (modest but complementary contributions). Some of them have also a large impact on the very-short range forecast (e.g.: aircraft reports), which does not appear in this table.

b) Some global observing systems (such as scatterometer data or surface wind observations in general) have an impact, which grows with the resolution: these data have a modest impact on the long waves but they are important for determining (e.g.) the exact position and characteristics of a cyclone.

c) Very local observing systems cannot be rated globally and do not appear in the table (for example MODIS winds). They are mentioned in section 2.2.

Table 1: Current contributions of some parts of the existing observing system to the large-scale forecast skill at short and medium-range



Notes:

1. SATELLITE SYSTEMS

AMSU-A...............The dominant and more largely used sub-system
HIRS.......................Less important than AMSU-A, useful complement for humidity
AMSU-B...............Not used yet in many centres: important for humidity over land
AIRS.......................Evaluation just starting (equivalent to one AMSU-A)
SSM/I.....................Important impact on humidity fields (esp. tropics and SH)

2. OBSERVATION PARAMETER TYPE

Surf. Pressure Ps.....Important to anchor model Ps. (large model biases otherwise)
Surf. Wind.............Satellites provide dense coverage over oceans but must be complemented by less dense observations of Ps
Wind profiles.........The more important information to observe, esp. in the tropics

3. EVOLUTION OF THE RELATIVE IMPACT OF VARIOUS OBSERVATION TYPES

Compared to results obtained at previous workshops
(i) ……………….The relative impact of satellite data has increased
(ii)……………….Consequently, the relative impact of radiosonde data has decreased
(iii)………………The impact of aircraft data has slightly increased

2.2. Impact of some regional observing systems

A significant number of studies presented at this Workshop deal with the impact of observations on regional and mesoscale NWP. These studies are able to evaluate the impact of systems, which are deployed only on a local basis: radars, profilers, GPS networks, etc. This was not the case in the previous Workshops. One can now try to summarise the impact of observations on regional and mesoscale NWP (then the impact is often concentrated on very short range forecasting).

- **a) High-density aircraft data** with also ascent and descent observing phases (such as the ACARs in the US) contribute to an important reduction of the RMS error in the forecast range 3 to 12h. When they are not available (during the night) profiler data are an interesting substitute, because they can report very frequently. When neither aircraft data nor profiler data is available for a region, it is important to have a dense radiosonde network reporting at least every 12h.
- **b) MODIS winds** (AMV from polar orbiting satellites) show a positive impact, very significant to the north of 60N. This is obviously related to the lack of wind observations on the polar cap in all the other observing systems.
- **c) Radiances and high-resolution winds from geostationary satellites** show also a positive impact, especially on the location and intensity of specific weather events.
- **d) Precipitation data from radars** are now assimilated in various mesoscale systems. They do improve the location and intensity of precipitation forecasts at very short range; the improvement seems larger in sophisticated data assimilation systems.
- **e) GPS observations** (Zenithal Total Delay or Precipitable Water) obtained from surface networks show occasionally some modest positive impact; this is encouraging for a system that is still in development.

3. Reports from the sessions

3.1 Session 1: Global Forecast Impact Studies (chaired by Lars Peter Riishojgaard and Jean-Noel Thepaut)

3.1.1 Overall impact of various components of the GOS

It is confirmed from all global data impact studies confirmed that satellite data, in particular ATOVS data, are the major source of information in NWP systems. The satellite data dominate in the SH, but in the NH large variability can still be found in the results depending on the NWP and data assimilation system used. There is also a large seasonal dependency. AMSU has much larger impact than HIRS (except for low level humidity fields).

The ability of global NWP systems to use satellite data has evolved remarkably over recent years, but several issues remain to be resolved, e.g. the best use of SSM/I data and the appropriate thinning of Automated Motion Vectors (AMV) data. Modeling capabilities must continue to grow and must be developed in step with the use of the data.

The approach for conducting and evaluating impact studies should be revisited. The overall impact of one component of the observing system can be established through denial studies (incremental approach) or through impact assessment by adding the observations to a baseline system.

It was noted that the overall impact on global model performance of some data types may be small but may be better reflected in individual cases and synoptic patterns. Weather parameter verification and synoptic studies are an essential part of the evaluation process.

Regarding guidelines for the evaluation of impact studies, there is a need for regional cases studies and time series verification.

3.1.2 Humidity analysis

A number of issues related to low tropospheric humidity have been identified. SSM/I provides information on horizontal distribution, but its vertical distribution is poorly defined. Adjoint studies show very large sensitivities in heat processes to errors in the humidity distributions. Analysing and modeling the low level humidity is not only an observational problem but also a modeling problem.

Stratospheric humidity fields are also important as demonstrated in bias and sensitivity studies. However, these features are poorly understood and most of the differences in assimilation systems are mainly based on differences in the model physics. Depicting the stratosphere is also both a modeling and an observation problem.

Only a few radiosondes penetrate deeply into the stratosphere. The value of these data has been established, but it remains an open issue how many of these are required for global NWP and what their global distribution should be. A problem is that NWP models assimilate humidity observations from satellites obtained only over cloud-free areas in dry air (clear skies). Under these circumstances, radiosondes provide the only measurements in cloudy systems. More effort should be made toward assimilating rain affected / cloudy radiances.

3.1.3 Tropical analyses

Lack of wind observations, in particular vertical wind profiles, hurts NWP results in the tropics. There may be a problem of predictability and additional observations may not help considerably, but if more observations would be available are to come in 10 years, or so, assimilation and models have to be ready. Thus, the workshop recommends a “small careful yes” in terms of for improving wind observations in the tropics, as long as modeling and assimilation techniques improve in parallel.

3.1.4 Observation targeting

Observation targeting is discussed in at the Workshop’s Session 3 (see section 3.3 of this summary). The targeted use of high-resolution satellite data could be of particular interest in the future. It will require the development of adequate corresponding data assimilation capabilities.

3.1.5 Timeliness

The requirements for early delivery and frequent updates of forecast guidance have evolved over recent years. NWP centres have significantly reduced their data cut-off times at the expense of available observations in their data assimilation processes. Timeliness requirements for observational data are becoming more stringent for NWP centres. HH + 20 to 90 minute data cut-off times are currently applied for many NWP short-range runs. Late data can only be assimilated in update runs with long data collection times (several hours). Within the next few years, a data processing and delivery time of approx 20 to 30 minutes is expected to be the operational requirement used in medium and short-range forecasts. Any minute gained is useful because observation arrival drives the rest of the forecast production chain. It is expected that NPOESS will be compliant, but further developments will be needed for METOP to meet these timeliness requirements.

3.1.6 Remarks concerning specific data types

3.1.6.1 AIRS

AIRS data are now assimilated either in research or operational mode at a number of centres; there is a modest impact despite poor treatment of data in clouds and a conservative data assimilation approach (we are still on the learning curve).

AIRS is a research instrument. As the distinction between research and operational instruments is fading away, the use of AIRS in an operational context is important. Research satellites are considered to be part of the GOS within the CBS; thus in this context they are really part of the NWP operational systems.

Future improvements will come from assimilating AIRS cloudy radiances. Furthermore it may be possible to infer atmospheric motions from AIRS radiances or AIRS retrieval fields; these could serve as a proxy to the MODIS wind products.

The preparation phase completed pre-launch for AIRS serves as a good example of collaboration between data producers and users.

3.1.6.2 AMSU

AMSU data are critical for successful NWP and the time spacing between satellites should be optimal (need for data from satellites in morning and afternoon orbits). NWP centres are concerned by the possible failure of NOAA-15. It is not known at this stage if SSMIS will serve as a replacement for the early morning AMSU. It was noted that the SSMIS is still an unfamiliar data set; no data have been released yet.

Interaction with NWP centres early after satellite launch and preferably during the cal/val phase is desirable. In this context, the excellent experience and interaction with NESDIS prior to the release of AIRS data was underlined cited in this context.

NWP centres are making efforts to make better use of cloud-affected radiances. Work is also underway to assimilate satellite data over land (and a better treatment of data at land-sea boundaries); this should be encouraged further (especially if the conventional network is would degraded further). The use of HIRS data over sea/ice/land boundaries is also a problem for HIRS.

3.1.6.3 AMVs

AMVs are a useful component of the GOS. NWP centres apply heavy thinning to the AMVs prior to their assimilation. The difference between the scales resolved in the data assimilation systems and those observed in the satellite data remains a problem. The QI information has been a valuable addition to the AMVs, and the CGMS efforts to unify the product have been of great help.

WMO and CGMS were very supportive in harmonizing the QI and the format for AMVs. This was acknowledged with appreciation by the workshop. However, it was noted that more interaction is still needed to achieve a better understanding of the processing and generation of these products. The International Winds Workshop (planned for June 2004) was seen as an important forum for communicating such information. The Workshop would encourage data providers were encouraged to make available more information regarding the AMVs estimates, e.g. with to attach the appropriate weighting function attached.

There still remains considerable room for improvement in the exploitation of high-resolution winds in global NWP (super-obing? adaptive sampling, accounting for AMVs representativeness, height assignment, etc.). THORPEX may provide the opportunity for investigating adaptive sampling.

3.1.6.4 MODIS winds

MODIS winds are a unique source of wind observations at high northern and southern latitudes. Mostly positive results have been reported from impact studies with global NWP systems, but occasional negative impact has been reported from using the data over the southern hemisphere. Several NWP centres expressed an interest in using the data.

MODIS winds appear to have become an important part of the space observing system (operational use at ECMWF and GMAO, positive results seen by a number of centres). Improvements are currently being made in the MODIS wind production as it is being transferred to NESDIS.

The workshop recommended that an operational follow-on to MODIS polar winds be secured (this requires a water vapour channel on the operational imagers on NPOESS and METOP). In the longer term, direct use of radiances over the poles will also merit investigation (where surface emissivity over ice, spatial resolution, need some study).

3.1.6.5 Scatterometer winds

Scatterometer data are being used operationally at ECMWF and other centres. They can be crucial for resolving synoptic features, e.g. for depicting tropical cyclones. It is important to capitalize on these research missions (ERS-2, QuikSCAT). It is also important to become familiar with other space-based surface wind observations as soon as possible; in this context, it was noted with dismay that data from the Windsat/Coriolis mission has not been made available to the NWP community to date.

3.1.6.6 Precipitation data

Satellite precipitation observations are or will be used operationally, with the precipitation radar from space (TRMM-PR) used for validation. Such an activity may help to reconcile the assimilation of observations in clear air and cloudy areas and should have high priority.

3.1.6.7 GPS radio-occultation measurements

Ongoing research in GPS radio-occultation measurements has been encouraging (from results obtained by the Met Office and GMAO). The complementary effect from the use of data from different observing methods (limb and nadir) was pointed out. This raises the question whether this type of observation reduces the need for stratospheric radiosonde observations? It was noted that specific OSEs could be carried out done to answer this question, but any conclusion would be is premature at this stage (data coverage before COSMIC will remain marginal).

3.1.6.8 Space-based Lidars

OSSEs have been completed that look realistic (they include systematic errors and have been verified against real observations) and show encouraging results. ECMWF evaluates ADM-AEOLUS data through ensemble analyses (to avoid the definition of the “truth” nature run).

3.1.6.9 Radiosondes

Radiosondes remain essential for global and regional NWP. However they are the only observations for which we do not know in detail precisely when and where the measurements are performed. There is a recommendation to include the time stamp, the sensor, and sensor sub-type information, etc. in the message (using the BUFR code). This is most important for limited area models. There is a general WMO strategy to move away from character code to binary code within eight years. The workshop reiterated the need for a timely distribution of radiosonde observations in BUFR with all significant points included in the message together with the time of observation and the position of each data point.

Impact studies have confirmed the positive contribution of the radiosondes to regional and global NWP. Further to this, studies to assess the relative value of the radiosondes for use in bias corrections in the Radiative Transfer (RT), a forward model should be considered.

3.1.6.10 Surface observations

Despite the overwhelming volume of satellite data, surface data (in particular surface pressure) over sea remain a requirement to anchor the pressure field. Surface data are important not only in global NWP, but also for regional NWP.

The impact of surface pressure and wind data was addressed in several OSEs. A large negative impact was found when surface pressure data were removed. There is no alternative equivalent source of observations available. Good quality surface pressure observations are of particular importance over the oceans. Surface pressure observations from ships only, in the presence of surface wind data, manage to recover much of the forecast skill lost when surface pressure observations are removed.

It was concluded from high-resolution (T511) experiments that surface observations over sea and land are still a very important component of the GOS. Their impact can be seen at all forecast ranges (very systematic during the first 72 hours) and in all seasons, with the largest impact in summer. Data from buoys and ships are of crucial importance synoptically.

3.1.6.11 Aircraft observations

Some new results on the impact of aircraft data were presented. It was generally acknowledged that these observations are a valuable contribution to the observing system. Observations at flight level and during ascent and descent are available at high temporal resolution. All NWP centres are now making use of the data and previously stated extensions of the data coverage into otherwise data sparse regions remain highly desirable (as reported in the Toulouse workshop 2000). It was noted that the AMDAR system is easily adaptable to observation targeting.

3.1.6.12 Ground- based GPS

The use of Integrated Water Vapour information (or Zenithal Total Delay – ZTD) obtained from ground based GPS systems is currently being tested, mainly in regional models. The data processing needs to be standardized and the correction of data biases needs to be addressed. These data will also be of interest for use in global models. Global exchange of these data was recommended.

3.1.7 General template for running OSEs

It was noted that it would be highly desirable for a list of recommendations to be drafted that provide a guide for running and evaluating OSEs (same time periods under investigation among different centres). Coordination is needed to define how to evaluate the impact of a given instrument: guidance is needed on whether to run a denial experiment from the full observing system or to add a new instrument on top of an agreed upon basic system, how many days constitute a minimum number of days to run the OSE, etc. A guidance document exists within ET-ODRRGOS that could serve as a starting point. This could be reviewed and updated by a subgroup of the workshop. It was mentioned that some degree of freedom should be left to the users because internal constraints often exist and because a large variety of impact studies allow cross-referencing of results.

3.1.8 OSSEs

The evaluation of new instruments, dropsonde capabilities, etc. could be done through OSSEs (note comments in section 3.1.6.8), but this requires a well-maintained and updated system (nature run, new real and synthetic observation types, etc.). This is also labour and computer intensive.

3.2 Session 2: Regional aspects of impact studies (chaired by Per Undén and Stan Benjamin)

3.2.1 Themes of the session

The major themes in this session were focused on the:

- need for more development work at regional scale
- regional OSEs which tend to rely more on case studies
- assimilation of data from research observing systems is growing and better understood
- need for improved regional and upstream observing systems, but also for considerable additional work on satellite data assimilation

3.2.2 Observing systems

3.2.2.1 Precipitation

Work on the assimilation of precipitation data has been undertaken at several centres:

- JMA - variational assimilation of 1h precipitation fields
- Meteo Swiss – latent heat nudging to 2 km radar reflectivity
- NCEP-Eta/EDAS – precipitation assimilation including latent heating/water vapour
- NOAA-FSL/RUC – radar reflectivity/lightning assimilation
- NCEP-GFS, ECMWF –- global assimilation systems using SSM/I, TRMM retrieved rain rate data

The overall impact is positive; it impact is seen primarily in the first several hours, with some impact out to 24 hours.

Concerns in this area are:

- Why is there no discernible impact at longer forecast projections? Projection onto dynamics – wind and temperature fields? Modeling of convective systems? Bottom line is either through precipitation observations or through improved observations of wind and temperature, there is a need for improved dynamics (wind and temperature) at the mesoscale to improve duration of accurate precipitation predictions.
- 4D-Var and 3D-Var can both add/remove precipitating systems (e.g., JMA 4D-Var, NCEP 3D-Var for global system). Nudging may help to build systems but not to forecast them; nudging does not clear out incorrectly forecast precipitating systems.
- Why is there an over-forecasting of light precipitation – is there a need for explicit physics?

The workshop recommended a continued effort to develop more advanced data assimilation methods. Research with 3D-Var and 4D-Var systems must be undertaken that can build both clear and precipitating systems from the background field. Research on developing appropriate divergent winds from precipitation assimilation must be started initiated.

- Collection of multi-station radar data sets with Quality Control (QC) applied in a timely manner, must be implemented is very important since precipitation assimilation is most important for short-range forecasts.
- This must be done in a timely manner since precipitation assimilation is most important for short-range forecasts.
- Ultimately, this will become an issue for global assimilation, to have timely sharing of global high-resolution radar data (both reflectivity and radial winds, where available).
- Improved quality and timeliness for microwave-based rain-rate data is important.

3.2.2.2 Satellite data

A summary of the major remarks on the impact is as follows:

- AMSU radiances – positive impact from all studies (HIRLAM, ALADIN, CMA-GRAPES, CIMSS)
- QuikSCAT – neutral impact (HIRLAM)
- GOES and METEOSAT AMVs – positive impact (NESDIS – EDAS/NCEP – ALADIN/Morocco)
- MSG radiances – ALADIN/France
- More impact is found from moisture channels in the warm season
- Clear positive impact from radiances/retrievals from GOES; MSG data is just becoming available

Issues raised include:

- Should there be more impact in regional / higher-resolution studies, especially from AMSU-B?
- There is a problem with bias correction for regional domains
- Can regional NWP take better advantage of high-resolution satellite data without thinning?
- One common problem with the global assimilation is the treatment of clouds
- Regional NWP tends to have larger percentage of land coverage. Therefore, slightly less emphasis on satellite data assimilation in past and more competing *in situ* data over land areas.

After discussion the following recommendations were made. More experimentation and development is needed regarding assimilation in regional NWP of (a) full resolution satellite data, (b) satellite radiances/products over land, and (c) cloudy radiances. Timeliness is important for regional assimilation. Data must be available within 30-60 min for regional NWP. Research on bias correction for regional applications is needed.

3.2.2.3 GPS ground-based precipitable water

Many groups discussed the use of GPS data (JMA, FSL/RUC, HIRLAM, MeteoSwiss) and reported positive impact in several studies. These were dependent on network and processing approach. Results with RUC show a strong positive impact. GPS Precipitable Water (PW) system is very mature in the US, with large spatial coverage; there has been a strong effort to date to improve quality, especially through identifying erroneous orbit data.

Issues that remain are:

- This is still an experimental system in some areas
- Common processing methods are needed. Processing techniques from regional centres should be leveraged (US, European, Asian/Japanese processing should be coordinated).
- Only an integrated quantity can benefit from combination with multi-channel satellite moisture assimilation (and assimilation of surface moisture observations). GPS PW can also, in turn, improve calibration of satellite moisture assimilation since GPS PW is relatively bias-free with adequate processing and also not absent in full cloud cover.
- Should there be requirement for total column PW report from radiosondes? (Since significant-level data is not always available)

Recommendations include:

- Encourage common processing between regional the processing centres concerned. Need to have improved processing to address, inter alia, the bias problem noted from European GPS ZTD (Zenithal Total Delay) data. US processing does not show bias problems.

- Encourage interaction between global NWP community and global geodetic community on common interest in gathering real-time GPS data, as positioning accuracy can be greatly increased from assimilation of accurate ground-based GPS data.
- Organize and formalize data distribution via GTS.

3.2.2.4 Aircraft

Impact Use of aircraft data (used in regional models) presented at the workshop includes assessed as follows:

  - FSL/RUC showed strong impact on short-range (3-12h) wind and temperature forecasts
  - HIRLAM showed weak positive impact
  - South Africa showed weak positive impact, but acknowledged that this is the main source of any additional data
  - Impact is clearly related to the distribution/density of the aircraft data, dependent on geographical regions, and a function of airline flight structures
- Expansion of aircraft/AMDAR observations to additional carriers (e.g. freight carriers to increase night time coverage) and other, especially data-sparse regions, (especially those that are data-sparse) will clearly aid accuracy of regional NWP.
- Stronger impact in US certainly related to higher volume in US, possibly also due to use of isentropic coordinate in RUC.

3.2.2.5 Profiler

Profiler experience has been reported from JMA, FSL/RUC, ALADIN, and HIRLAM. The major results are:

- Impact is positive but dependent on network size and vertical extent of profiler observations; OSEs need to use high-frequency assimilation (at least 3h, hourly is preferable) to take advantage of profiler observations.
- Profiler networks need monitoring. This occurs in US (manual monitoring, QC flags issued for BUFR data from US profilers). European wind profiler data has shown wind speed biases, for instance, and is not currently considered highly reliable for all stations. Bird migration contamination is a problem for profiler and radar wind data.
- In US, boundary profilers (915 MHz) are being implemented for air quality monitoring purposes.
- Advantages of wind profiler data include continuous hourly data, all weather, wind profiles, and full tropospheric profiles at 441 MHz (but these are more expensive).

Recommendations include:

- Use as fully as possible.
- Monitor quality, blacklisting desirable needed (in Europe, (already done in the US)
- Encourage implementation or expansion of profiler networks, where cost effective (i.e. more expensive than aircraft but also more continuous data and not dependent on airline operations).

3.2.2.6 *Radiosondes*

Regional radiosonde studies were reported by FSL/RUC and CIMSS/EDAS. They find that radiosondes are clearly important and even dominant for regional OSEs, especially with winds being especially important. Moisture observations are the dominant type for short-range forecasts. Radiosondes are still the most important observation tool for verification of basic tropospheric variables - mass and wind.

Recommendations, given importance of *in-situ* data for regional NWP, are to:

- Maintain at least the current network and actively counteract any further degradation, preferably with some optimization through relocating of some stations in certain areas to minimize overlap with aircraft hubs, wind profilers, etc.).
- Maintain current network of similar size, optimized with moving of current stations in some situations (minimize overlap with aircraft hubs, wind profilers).
- Recognize the need for Ensure 12-hourly radiosonde data observations over all global land areas. These data will be critical to improving regional NWP skill for these areas (including Africa – ref – Met Office and Meteo-France studies, South America, Russia).
- Consider adding full digital data for all radiosonde transmissions, including time and position. If full levels are not transmitted, need to add precipitable water.

3.2.3 *Issues*

What are key distinctions between regional and global OSEs studies?

- duration of forecast – focus on 3h to 3 days
- horizontal resolution – 2-40 km
- effect of lateral boundary conditions – more pronounced with smaller domains
- use of regional and experimental data sources
- larger area covered by land, hence more conventional observational coverage
- more resolved physics such as multi-species cloud microphysics, soon chemistry/aerosol will also be added
- regional data, often not available to global models, is used
- different priorities of observation systems
- chemistry, pollution applications, environmental monitoring
- sometimes model is non-hydrostatic for high resolution
- regional NWP will encounter various new issues a few years before the same issues will be faced by global NWP

Issues remain regarding precipitation verification and guidelines for regional OSEs and case studies.

3.2.4 Summary of recommendations / conclusions for regional observing systems

- There should be a global consolidation of GPS ground-based reporting: use of common accurate orbit data, elimination of bad erroneous orbit data

- There are several possibilities for additional profile observations over land
    - aircraft – to equip other fleets
        - major and lesser carriers, especially in Africa, South America, Asia, emphasis on high-resolution ascent/descent plus enroute at jet levels
        - capability for equipping fleets serving even more local routes – emphasis on mid and lower-tropospheric data
        - moisture sensors – WVSS-2, TAMDAR?
    - radiosondes
    - wind profilers

- *In-situ* observing systems when improved, will:
    - improve regional forecasts consistently
    - improve global forecasts intermittently

- Consideration needs to be given to what satellite data could better be used in regional scale models
    - full-density data, e.g., AMV thinning not needed
    - what are the requirements for future NWP

- Improved assimilation methods include:
  - 4D-Var
  - Ensemble methods
  - Dynamic background error covariance specification
  - Isentropic coordinate application – FSL/RUC, future NAVDAS

3.3 Session 3: Observation targeting studies and observation network design studies (chaired by S. Lord and J. Caughey)

3.3.1 *Adaptive observing*

Adaptive observing is a newly establishing concept.

- Such observations can be linked to severe weather events, as well as societally important events
- No single technique is best for computing where the sensitive areas are; this depends on the data assimilation system and other observation used
- Impact of such observations depends on data usage, background covariances, etc.

Research is ongoing

- There are positive, but not overwhelming, results
- There is a link between marginal resource expenditure and positive impacts
- There is a link to past and future field programmes (THORPEX)
- There is an opportunity to take advantage of data selection strategies from other platforms (e.g. satellite)
- Techniques involve approximations, short cuts, some lack of a strong theoretical basis
- There is a need for careful experimental design with controls
- Studies on adaptive removal of observations (removal instead of deployment) should be encouraged
- Verification should be relevant to the significant event and case studies must be accumulated (communicate to decision makers as well as scientific community).

Issues include:

- Can adaptive observations continue to provide positive impact in parallel to continually improving data assimilation systems and increasing observations (e.g. hurricane targeting)?
- Is it worth the cost?
- Is targeting with operational systems worthwhile?
- Interactive networks must address the economics of observing systems
- There is a large variety of weaknesses in all operational systems, including forecast models, assimilation techniques, forward models …
- Improved simulation systems, ongoing support, overall strategy for design, and implementation of advanced instruments are all required
- The needs for in situ and satellite observations must be integrated in a non-competitive, locally optimal way, especially in developing countries

3.3.2 Operationally Unsupported and New Observing Systems

3.3.2.1 AMDAR progress includes

- Rapid expansion increase in daily data volume
- On-going expansion to Africa, Asia, Canada, Saudi Arabia
- Planned expansion to regional carriers proceeding but has been problematic
- Desired expansion to new countries globally
- Progress in network planning and data management important in maximizing cost effectiveness
- Progress in network monitoring and feedback to airlines for remediation

- Development of a humidity sensor
  - o WVSSII sensor tested in US in 2nd quarter 2004, others possible
  - o TAMDAR beginning April 2004 on regional carriers in US, France, Australia
  - o UK laser diode system installed on research aircraft
  - o DWD planning to adapt Vaisala sensor
  - o Russian Federation actively developing new sensor
- Turbulence (EDR) reporting is proceeding
- Icing program is proceeding

Future directions include

- Emphasis on broadening coverage and regional programs
- New sensors into operations
- Training, education, outreach
- Integration into GOS

Impact tests have shown

- In the US data distribution on week-ends is half that of week-days resulting in 7% worse forecasts on week-ends
- There is a 20% skill loss with no observations
- Ascent/descent data show
  - ▪ Positive impact in analyses and 48 h forecasts and 5 days over monthly mean 500 hPa height over North America and Europe (0.4 day at day 8)
  - ▪ Some biases with radiosondes
  - ▪ Consistency of results across NWP centres
  - ▪ 2-7% improvement in RUC analysis and 2-5% in 12 h forecasts at and below flight level, equal to or greater than increasing resolution from 40 km to 20 km (NCEP results?)
  - ▪ Off-time (or asynoptic ?) data is most valuable in mid and lower troposphere
  - ▪ Larger impact than profiler data and more economical (but smaller domain covered by profilers)

Issues remain regarding

- Optimal use of data for all NWP problems
- Winter vs summer and length of studies
- Multi-use of data (nowcasting, climate, air quality, etc)
- How to optimize issues for non-technical decision-makers?

3.3.2.2 AIRS experience indicates

- It is an accurate and stable instrument with greater vertical resolution and application to other gases and clouds
- 95% of the globe is cloud covered
- NWP impact is currently small but positive
- Cloud clearing increases the number of observed profiles which can be used
- It is providing risk reduction for other advanced sounders
- Real-time data provision is essential for development and testing
- Treatment of clouds remains a big issue
  - o Cloud clearing requires research data sets, not operationally distributed one
  - o Use of cloud contaminated radiances needs research (also this requires assumptions)
- Principal component analysis offers
  - o Data compression
  - o Quality control
  - o Radiance reconstruction and noise reduction

3.3.3 Design of new networks, instruments or observing services

Issues include

- Shifting resources from well observed to poorly observed areas
  - Homogeneous coverage (space and time) desirable
  - Possible on global basis, not just regional (e.g. North Atlantic)
- Network management
  - Performance monitoring and feedback to providers
  - Encourage and plan for growth
  - Justification studies
    - OSEs
    - Pilot studies for new instruments & strategies: (e.g. AMDAR local carriers have shown feasibility of programme and willingness to participate)
- Designing a new network
  - Climate variability (from re-analysis) may be distorted by existing observational shortcomings
  - Design can be formulated as a variational problem based on reduction of natural variability
  - Russian radiosonde network provides an example
  - Local considerations and other applications may pertain
- Design of new instruments (e.g. MSG)
  - Active interaction with users for new capability and products is very desirable
  - Re-analysis of satellite data is critical to
    - Backfill products with latest algorithms
    - Re-calibrate instruments after real-time
    - Provide continuity of data across contemporaneous and successor instruments
    - Measure adequacy of pre-launch benchmarks and operational validation

4. Workshop conclusions and recommendations

During its final session, the workshop reviewed the draft recommendations for the evolution of the GOS from developed by the CBS OPAG-IOS Expert Team on Observational Data Requirements and the Redesign of the GOSlobal Observing System (ET_ODRRGOS). These recommendations together with an the first draft of implementation plan are given in Annex IV of the final report of ET on ODRRGOS Report from its the 6th session of the ET (held in Geneva, 3-7 November 2003). The recommendations from this 3rd WMO Workshop on the impact of various observing systems on NWP should be viewed considered in conjunction with the ET recommendations; the discussion focused mainly on complementary issues raised in the presentations and during the discussions.

4.1 Interaction between NWP centres, data providers and users

(i) Data assimilation and modeling capabilities have grown and are under constant development to make optimal use of current and future observing systems. NWP centres require

- early (advance) information about new data types;
- early access to test data and observations during the cal/val phase to prepare for the operational use of the data
- information on the characteristics of the data and products (e.g. AMVs which may be representative of atmospheric layers rather than just at one level).

(ii) Research satellites provide valuable data for NWP, which should be made available in a timely fashion. Research satellite data provide NWP centres with an excellent opportunity to prepare for new satellite data streams, which will become part of the operational global observing system.

(iii) Effective learning of how to make use of new data types can best be achieved through operational use of any experimental data streams.

(iv) It was recognized that NWP centres will have to do more work relevant to other environmental areas. This will require a wider data exchange and more cooperation on model developments (i.e. issues of environmental monitoring, atmospheric chemistry and transport processes will need to be addressed)

4.2 Observational data requirements

(i) It was recommended that polar wind observations be developed further and an operational follow-on to the MODIS winds be secured (this will require a water vapour channel on the operational imagers on NPOESS and METOP). Timeliness of data delivery can be addressed through direct data read-out. The number of stations with direct read-out capability should be increased. Such data should be made available directly to the processing centres.

(ii) The workshop reiterated the need for a timely distribution of radiosonde observations in BUFR with all observation points included in the message together with the time and the position of each data point; information on instrument calibration prior to launch and information on sensor type and sub-sensor type is also required.

(iii) For regional forecasting systems, a strong requirement was expressed for comprehensive and uniform coverage with at least 12-hour frequency of temperature, wind, and moisture profiles over continental areas and coastal regions. It was noted that the radiosonde network still plays an important role in meeting this requirement.

(iv) The extension of the coverage of vertical soundings into ocean areas (eg as pursued in the EUCOS programme) was supported and considered to be a valuable data source for general NWP.

(v) More T, U/V, Q profiles, but especially winds, are needed in the tropics. Rapid development of the AMDAR programme could be one solution.

(vi) Timeliness requirements for observational data are becoming more stringent for NWP centres. HH + 20 to 90-minute data cut-off times are applied at present for many NWP short-range runs. Within the next few years, a data processing and delivery time of approx 20 to 30 minutes is expected to be the an operational requirement.

(vii) Ground based GPS processing (ZTD and PW, priority for ZTD) should be standardized to provide more consistent data sets. Data should be exchanged globally. The coordination of geodetic data between the GPS processing centres is required.

(viii) There is a requirement for exchange of high-resolution radar data (both reflectivity and radial winds, where available) for use in regional models, and also in global models in future.

(ix) Workshop results on the usefulness of stratospheric observations should be consolidated and requirements for a stratospheric global observing system should be refined (need for radiosondes, radiances, wind data, humidity data, noting the availability and required density of existing data sources, including GPS sounders, MODIS winds and other satellite data).

4.3 Proposals for future studies

(i) The capability to make best use of high-resolution observations (space and time) should be developed. This includes

- assimilation experiments using hourly AMVs together with hourly radiance data
- optimal extraction of information content from AMV

- targeted use of high resolution satellite data (implies the development of corresponding assimilation capabilities).

(ii) The conduct and evaluation of impact studies should be revisited. The overall impact of one component of the observing system can be established through denial studies (incremental approach) or through impact assessment by adding the observations to a baseline system.

(iii) Guidelines for the evaluation of impact studies need to be revisited and the need for regional cases studies and time series verification should be included.

(iv) Impact studies have confirmed the positive contribution of the radiosondes to regional and global NWP. Studies to assess the relative value of the radiosondes for use in bias corrections in the RT forward model should be considered.

(v) The value of a properly tuned OSSE system was acknowledged (the huge initial investment was noted). Such a OSSE system would be a useful tool for the assessment of new observing systems in the shorter term, but less relevant for observing system to come on stream 10 to 15 years ahead. Complementary approaches e.g. use of simulated data in ensemble assimilation systems or studies of information content could be applied.

REFERENCES

Pailleux, Jean (Ed.), 1997: Impact of Various Observing Systems on Numerical Weather Prediction, Proceedings of CGC/WMO Workshop, Geneva, 7-9 April 1997, WMO Technical Report No. 18, WMO/TD No. 868

Pailleux, Jean, and Boettger, Horst (Ed.), 2000: Proceedings of Second CGC/WMO Workshop on the Impact of Various Observing Systems on Numerical Weather Prediction, Toulouse, France, 6-8 March 2000, WMO Technical Report No. 19, WMO/TD No. 1034.

ANNEX I

Third WMO Workshop on the Impact of Various Observing Systems on Numerical Weather Prediction

Alpbach, Austria
9 – 12 March 2004

PROGRAMME

TUESDAY, 9 MARCH 2004

Welcome and Opening Remarks

08.30	Welcome Jean Pailleux (Météo-France) Helmut Rott (University of Innsbruck)
08.40	Paul Menzel (NOAA/NESDIS) and Dieter Schiessl (WMO) GOS evaluations within the ET-ODRRGOS
08.50	Gerhard Steinhorst (Deutscher Wetterdienst) Opening Remarks from a CGC/COSNA perspective
09.00	Horst Boettger (ECMWF) Major conclusions from the Toulouse NWP OSE Workshop
09.10	Martin Ehrendorfer (University of Innsbruck) Atmospheric predictability and data assimilation
Session 1a:	***Global forecast impact studies (chair: Martin Ehrendorfer)***
9.30	Erick Andersson (ECMWF) Impact studies of main types of conventional and satellite humidity data
10.00	Alexander Cress (Deutscher Wetterdienst) Global and regional impact studies at Deutscher Wetterdienst
10.30	Break
11.00	Steve Lord (EMC) Observing System Experiments with NCEP's Global Forecast System
11.30	Graeme Kelly (ECMWF) OSEs of all main data types in the ECMWF operational system
12.00	Richard Dumelow (Met Office) OSEs using the Met Office operational global model
12.30	Lunch

Session1b: ***Global forecast impact studies (chair: Jim Purdom)***

02.00 Lars Peter Riishojgaard (NASA GMAO)
Data impact studies with GMAO system

02.30 Jean-Noel Thepaut (ECMWF)
Surface data impact studies

03.00 Gilles Verner (CMC)
Data impact studies in the CMC global NWP system

03.30 Break

04.00 Jean Pailleux (Météo-France)
Impact studies performed with the global ARPEGE NWP system

04.30 Steve English (Met Office)
Satellite data OSEs

05.00 Peter Steinle (BMRC)
Impact of various observing systems on the BMRC NWP systems

WEDNESDAY, 10 MARCH 2004

Session 1c: ***Global forecast impact studies (chair: Steve English)***

08.30 William Lahoz (DARC)
Impact of Research Satellite Observations in a Data Assimilation System for the Troposhere and Stratosphere

09.00 Clément Chouinard (CMC)
Recent OSE studies with the revised CMC 3D-Var system in hybrid coordinates with lid at 0.1 hPa

09.30 Ron Errico (GMAO)
Estimation of Observation Sensitivity using the NAVDAS Adjoint System

10.30 Break

Session 1d: ***Global forecast impact studies (chairs: Jean-Noel Thepaut and Lars Peter Riishojgaard)***

10.30 Summary and Discussion of Session 1

12.30 Lunch

Session 2a: Regional aspects of impact studies (chair: Johannes Schmetz)

02.00 Ko Koizumi (JMA)
Observation system experiments using JMA meso 4D-Var

02.30 Stan Benjamin (NOAA/FSL)
Data denial experiments with the Rapad Update Cycle (RUC) with Raob, aircraft, profiler, GOES, and surface data; a RUC-based OSSE for a space-based wind-finding lidar

03.00 Per Unden (SMHI/HIRLAM)
Observation impact studies with HIRLAM

03.30 Break

04.00 Jean Quiby (Meteo Swiss)
Impacts of non-conventional observing systems on regional NWP

04.30 Chen Dehui (CMA)
Use of impact of satellite and radiosonde data: some case studies performed with GRAPES_3DVAR in China

05.00 Hilarie Riphagen (SAWS, South Africa)
Impact of AMDAR data in regional Eta model forecasts over South Africa

05.30 Paul Menzel (NESDIS/CIMSS)
Four season impact study of Raob, GOES and POES data in the EDAS

THURSDAY, 11 MARCH 2004

Session 2b: Regional aspects of impact studies (chair: Ko Koizumi)

08.30 Yong Wang (ZAMG)
Impact studies performed with the LAM system ALADIN

09.00 Alexander Beck (University of Vienna)
Observation impact on data assimilation with dynamic background error formulation

Session 2c: Regional aspects of impact studies (chairs: Stan Benjamin and Per Unden)

09.30 Summary and Discussion of Session 2

10.30 Break

Session 3a: ***Observation targeting studies and Observation network design studies (chair: Herbert Pümpel)***

11.00 Richard Hodur (NRL)
Summary of past and current efforts on targeted observations

11.30 Jim Caughey (EUCOS)
Evolution of the EUCOS Operational Programme and experiences from the THORPEX Atlantic TOST

12.00 Johannes Schmetz (EUMETSAT)
Overall contribution of Meteosat and MSG satellites to observing systems at global and regional scale

12.30 Lunch

Session 3b: ***Observation targeting studies and Observation network design studies (chair: Alexander Karpov)***

02.00 Oleg Pokrovsky (MGO, Russian Federation)
Optimal design of the sonde network in Siberia

02.30 Jeff Stickland (AMDAR Panel)
The global AMDAR system

03.00 Ralph Petersen (CIMSS/EMC)
Impact of AMDAR data on Numerical Prediction Models

03.30 Break

04.00 Mitch Goldberg (NESDIS/ORA)
Increasing the NWP Impact of AIRS Data

Session 3c: ***Observation targeting studies and Observation network design studies (chairs: Steve Lord and Jim Caughey)***

04.30 Summary and Discussion of Session 3

FRIDAY, 12 MARCH 2004

Session 4: ***Workshop Conclusions (chairs: Horst Böttger and Jean Pailleux)***

08.30 Discussion and Conclusions

10.30 Break

11.00 Wrap-up

12.00 Adjourn

ANNEX II

Third WMO Workshop
on the Impact of Various Observing Systems
on Numerical Weather Prediction

Alpbach, Austria
9 – 12 March 2004

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Impact studies of main types of conventional and satellite humidity data

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1. Introduction

The new humidity analysis formulation of Hólm et al. (2002) was implemented operationally as part of the October 2003 upgrade of ECMWF's integrated forecasting system (IFS version cy26r3). At the same time humidity data from several additional satellite instruments (AIRS, AMSUB, Meteosat-5, GOES-9,10 and 12) were introduced in the assimilation system. In order to test the upgraded system and its ability to extract information from the main types of humidity data, a comprehensive set of humidity observing system experiments (OSE) was carried out. Seven one-month experiments were run, in each experiment withholding one type of humidity data. The results were compared with a standard cy26r3 control assimilation using all the available data of the pre-operational system.

The effort on humidity analysis is motivated by the increasing availability of humidity data, and by the need to improve the assimilation in cloudy and precipitating regions: The latent heat release from strong convective events can modify the jet-stream aloft and influence subsequent down-stream developments. The moisture content of the air on the warm side of a frontal zone can influence the rate of development of baroclinic systems. In the tropics, the supply of low-level humidity affects the intensity of the tropical convection, and hence the intensity of the Hadley circulation. ECMWF's current development programme for radiance assimilation in cloudy and precipitating conditions (Marécal and Mahfouf 2003; Chevallier et al 2004; Moreau et al 2004; Andersson et al. 2004) relies on an accurate assimilation procedure for humidity.

In this OSE study the assimilation impact of humidity data is evaluated in terms of analysis increments, short-range forecast performance and precipitation amounts. The experiments are defined in Section 2 and the typical data coverage for each observing system is shown. The analysis and forecast impact is shown in Sections 3 and 4, respectively. The OSE results are summarized and conclusions drawn in Section 5, and a list of additional humidity observing systems expected in the near future is given.

2. Definition of experiments

The one-month OSE was run from 1-31 July 2003, using 4D-Var (Rabier et al. 2000) with 12-hourly cycling (Bouttier 2000) at the current operational resolution, i.e. T511L60 (~40km) with analysis increments computed at T159L60 (~120 km) (Courtier et al. 1994). The 26r3 pre-operational test suite was used as control. Seven assimilations were run, withholding one main humidity observation type in each experiment as detailed in Table 1. The impact of each observing system is investigated in terms of the difference between the control assimilation and the experiment with that data type withheld. The control system uses SSMI radiance data (Bauer et al. 2002), horizontally and vertically polarized at three frequencies (19, 37 and 85 GHz) and vertically polarized at 22 GHz. These channels show a differential sensitivity to the integrated atmospheric water-vapor content and wind-induced sea-surface roughness. Radiosonde dew-point temperatures are converted to specific humidity (q), and used at all reported levels below 300 hPa, subject to the operational station blacklist. SYNOP 2-meter relative humidity (RH) is used over land, not over sea. Radiance data from the water-vapour channel of each of the five geostationary platforms (GOES-9, 10 and 12 and METEOSAT-5 and 7) are used, providing a complete and frequent coverage within 50° of the equator. Three microwave channels from AMSUB are used depending the land/sea mask and the height of the terrain. From the infrared sounding instruments (HIRS and AIRS) it is primarily the 6µm band that carries humidity information. For HIRS this corresponds to channels 11 and 12, and for AIRS it comprises channels 1290-1843. The numbers of processed and used data from each of the satellite instrument with important humidity sensitivity are listed in Table 2.

Typical data coverage of assimilated data, for each of the seven observation types, is shown in Figure 1. The satellite systems provide very good coverage over the oceans, with gaps in cloudy and precipitating regions depending of the sensitivity to clouds in the infrared (McNally and Watts 2003), and to thick clouds and rain (Bauer et al. 2002) for the microwave instruments. The geostationary data and some of the higher-peaking channels of AIRS, HIRS and AMSUB are used also over land. The conventional data (SYNOP and radiosondes) provide an uneven coverage over land.

Table 1: Definition of the seven humidity observing system experiments, and the control assimilation run for the period 1-31 July 2003, using 4D-Var at T511L60 resolution.

Experiment	Name	Description
0010	Control	Cy26r3 pre-operational test suite – all data used
efqo	NoSSMI	Removed 3*SSMI radiances, 7 channels
efqp	NoRSq	Removed radiosonde q profiles
efqq	NoSYNOPrh	Removed SYNOP RH2m data
efqr	NoGEOS	Removed clear-sky WV radiances from 3*GOES and 2*METEOSAT, 1 channel
efqv	NoAMSUB	Removed 2*AMSU-B radiances, 3 channels=3,4,5
efws	NoHIRS6µ	Removed 2*HIRS radiances in 6µm band, chan=11,12
efwt	NoAIRS6µ	Removed 1*AIRS radiances in 6µm band, chan=[1290:1843]

Table 2: List of processed and used humidity sensitive radiance satellite data in ECMWF pre-operational tests, for the date 20030701-00 UTC. The test-system became the operational system on 7 October 2003

Instrument	Spacecraft	Total number processed	Number of used data	# of channels, available and (used)	Humidity sensitivity of used data
Imager, Geostationary orbit	METEOSAT-5 METEOSAT-7 GOES-9 GOES-10 GOES-12	181,000 312,000 899,000 553,000 496,000	20,000 43,000 37,000 26,000 17,000	2 (1) Infrared	Upper troposphere
HIRS, Polar orbiting	NOAA-14 NOAA-15 NOAA-16 NOAA-17	64,000 63,000 1,684,000 1,423,000	0 0 88,000 77,000	19 (6) Infrared	Mostly upper troposphere
AMSUB, Polar orbiting	NOAA-15 NOAA-16 NOAA-17	402,000 399,000 403,000	0 34,000 33,000	5 (3) Microwave	Upper and mid troposphere
SSMI, Polar orbiting	DMSP-13 DMSP-14 DMSP-15	88,000 89,000 88,000	38,000 33,000 39,000	7 (7) Microwave	Total-column
AIRS Polar orbiting	AQUA (EOS-PM)	52,242,000	1,915,000	2378 (230) Infrared	Upper and mid troposphere

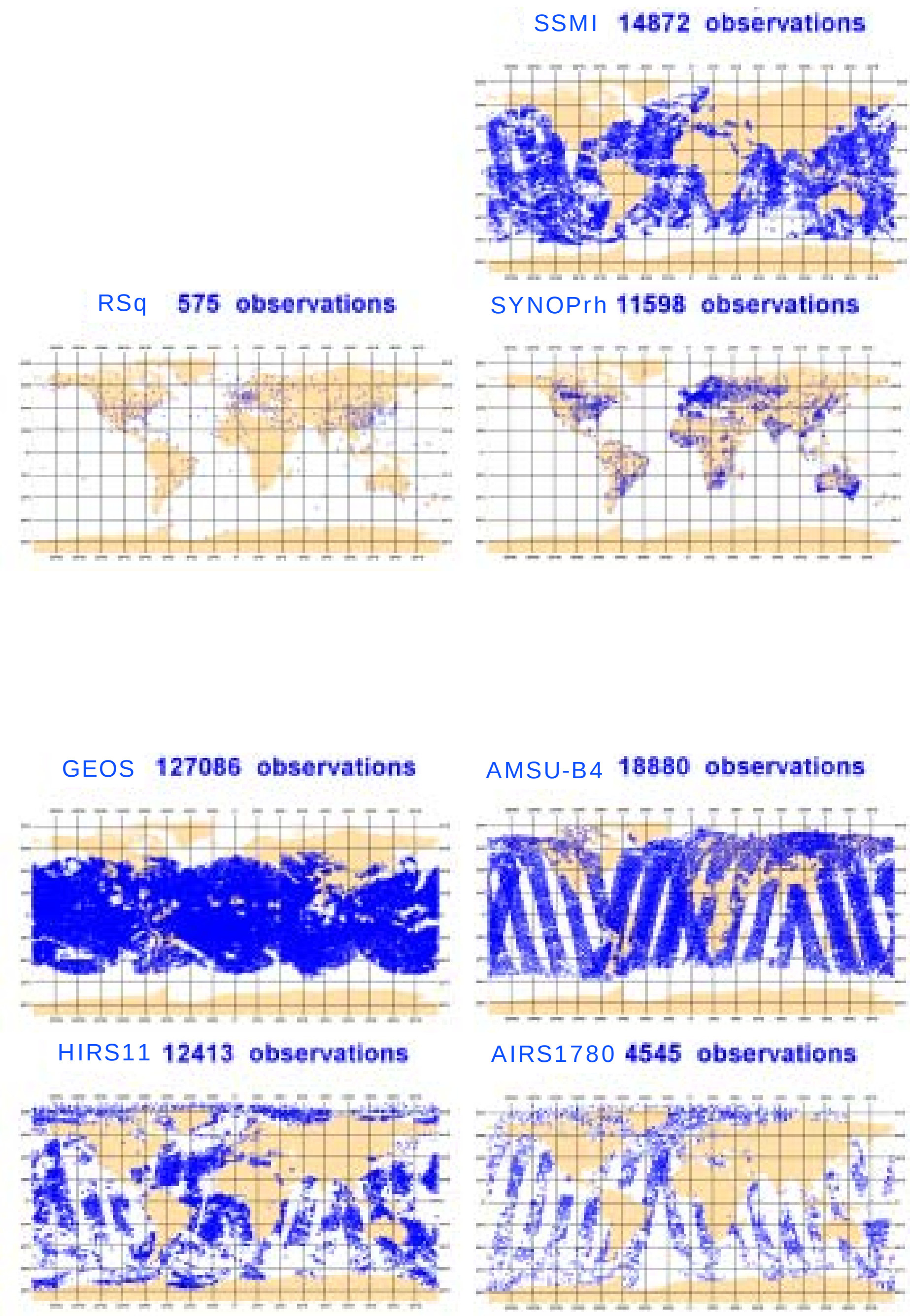

Figure 1 Typical 12-hour data coverage of assimilated data, 20030710-12 UTC, for each of the seven data types (see label) tested in humidity OSEs. For the radiance data only one representative channel is shown for each instrument.

3. Analysis impact

The analysis impact of any data type depends on the data coverage, the frequency of the data and their accuracy. The impact also depends on the specification of background errors in the assimilation scheme, and on the existence of any systematic deficiencies in the forecast model. In Figure 2 we display the analysis impact of each of the seven observation types in terms of r.m.s of analysis difference (with respect to the control assimilation), shown as vertical profiles for three geographical areas.

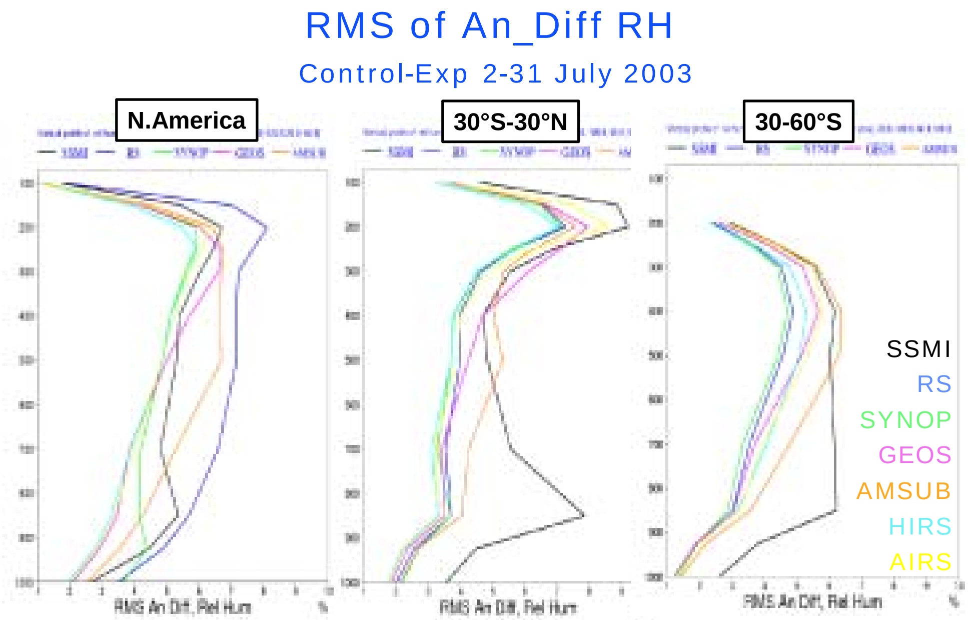

Figure 2 RMS of relative-humidity analysis differences between the Control and each of the experiments, colour coded as indicated in the label, for three geographical regions: North America, the tropics and the Southern Hemisphere mid-latitudes. The left-most curve at each level can be interpreted as indication of the level of noise in the humidity analysis, not controlled through assimilation of available data.

In land regions with good radiosonde coverage (N. America, left panel), radiosonde data dominate the humidity analysis, followed by AMSUB at 700 hPa and above, SSMI at 925 and 850 hPa, and by SYNOP nearest the surface. In the tropics SSM/I dominates in the lower troposphere with the second peak at 200 hPa provided through interaction with the convection parameterization of the model; AMSUB makes a significant contribution throughout the free atmosphere; AIRS and GEOS contribute in the upper troposphere; radiosondes show only a small contribution due to the poor coverage in the tropical region; HIRS and SYNOP are both at what can presumably be interpreted as the noise level, i.e. the level of r.m.s that is not controlled through assimilation of the available data. It should be noted that these impacts are with reference to the full system. For example, earlier experiments by McNally and Vesperini (1996), have demonstrated very significant impacts of HIRS data in the absence of SSMI, AIRS and SSMI, in the tropics. In the Southern Hemisphere mid-latitudes radiosondes and SYNOP give a negligible contribution as expected from their poor coverage, whereas SSMI and AMSUB dominate. HIRS, GOES and AIRS each provide similar, lesser contributions mostly in the upper and mid-troposphere, in the ECMWF humidity analysis.

The geographical distribution of the r.m.s. of relative-humidity analysis differences is highly variable (not shown). The results at 850 hPa indicate that SSMI undoubtedly provides the largest analysis impact of the seven observation types. SSMI dominates the 850 hPa humidity analysis in the subsidence-regions north and south of the ITCZ, but not within the ITCZ itself (where SSMI and other satellite data are not currently used due to the heavy cloudiness and the precipitation). SSMI also controls the moisture analysis in the storm-track regions, especially in the North Pacific and the North Atlantic in this period. Radiosondes and SYNOP have locally large impacts in some of the regions with dense coverage: North America, Europe, Central Asia, India and China. The SYNOP data have a strong effect along the southern edge of the Sahara. The humidity increments at the lowest model level are used as input to the soil-water analysis. It is likely that the SYNOP impact in this region is through its interaction with soil moisture. In the upper troposphere data impact can either be direct, introduced by analysis increments locally, or indirect through interactions with large-scale and convective precipitation in the model. The results at 300 hPa show that SSMI data, although not used in the rainy regions, has considerable influence on humidity at 300 hPa in the ITCZ and in the Indonesian region. SSMI impact at 300 hPa is also strong in all oceanic storm-track regions, indicating that it modulates large-scale precipitation. AMSUB has substantial impact in most regions of the globe, over land and ocean. The geostationary data have direct impact on upper-tropospheric humidity in the tropics (Köpken et al. 2004, Munro et al. 2004), whereas HIRS and AIRS impact is most apparent at high latitudes. Radiosondes and SYNOP affect 300 hPa humidity primarily over central North America, western Europe and central Asia, presumably through interaction with convection.

Systematic errors in the model and errors in the data contribute to bias in analyses (Dee and da Silva 1998; Dee and Todling 2000; Dee 2003). Satellite radiance data are bias corrected for air-mass dependent and scan-angle dependent biases, using the method of Harris and Kelly (2001). Bias differences between the control and each of the seven experiments are shown in Figure 3, in the form of north-south cross sections, averaged over the study period. The figures show that SSMI systematically adds moisture in the lower troposphere in the tropics. Geographical maps of the bias (not shown) indicate that the moisture is added in the subsidence regions, where the background fields are biased dry. The added moisture is advected to the ITCZ region by the trade winds, leading to increased precipitation (next section) there. Radiosondes and SYNOP have opposite bias in the boundary layer, over many continental areas – as seen here at 925 hPa in the cross section. The use of GEOS data leads to a localized dry bias in the upper troposphere in the ITCZ region. AMSUB shows large biases over several land regions, which later has been associated with an incorrect (too liberal) use of AMSUB channel 4 and 5 over land. HIRS shows a dry bias over high southern latitudes, possibly linked to sea-ice conditions. AIRS shows a complicated bias pattern with maxima in the upper troposphere and in the tropics. The AIRS bias shares common features with GEOS and HIRS, and seems to counter-act some of the bias due to AMSUB.

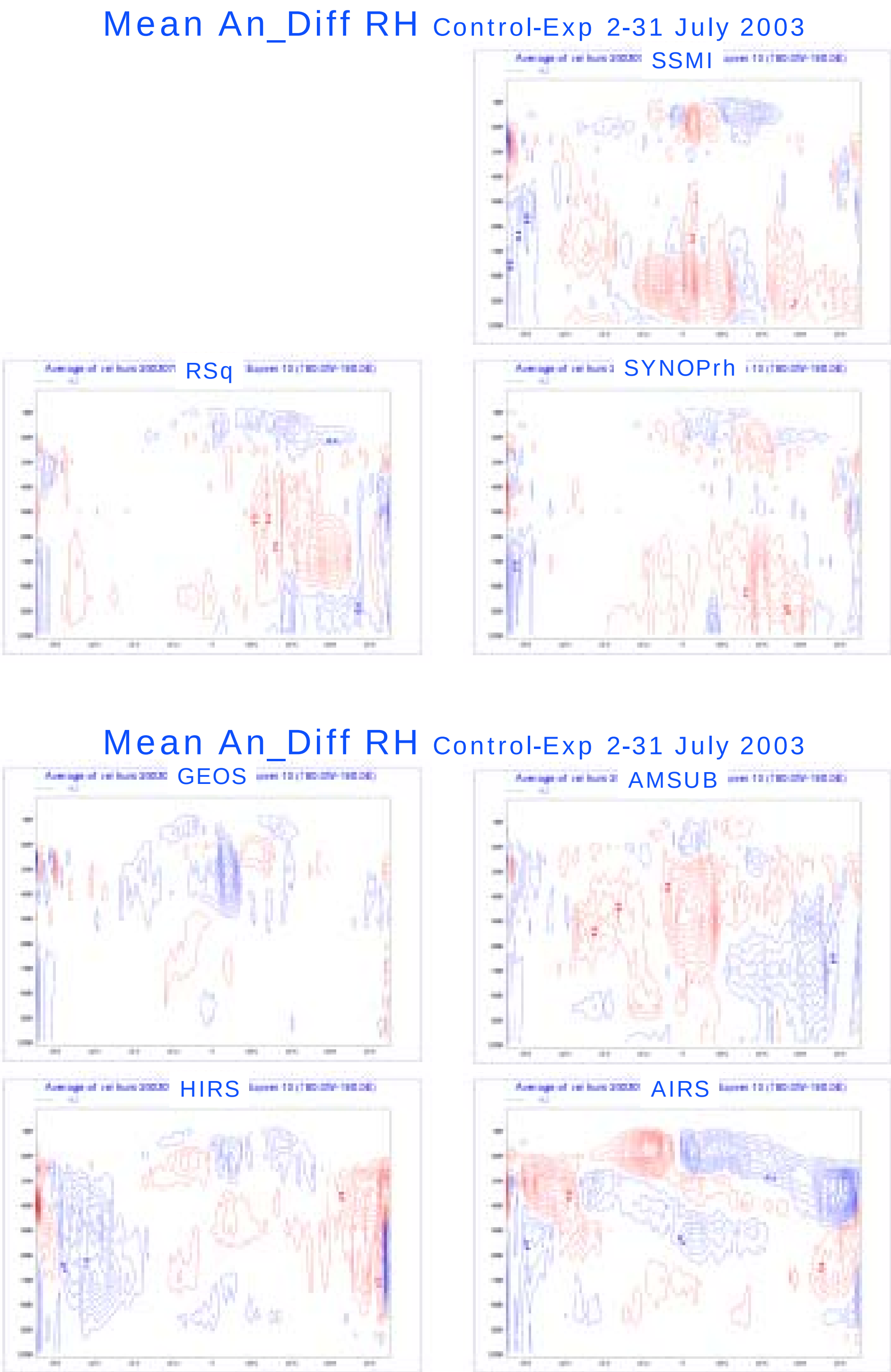

Figure 3 Zonal-mean monthly mean (2-31 July 2003) cross sections of relative-humidity analysis differences (%). The contour interval is 0.2 % with red (blue) indicating that the control assimilation is moister (drier) than the experiment withholding the data.

4. Forecast impact

The forecast impact has been investigated in terms of short-range forecasts of precipitation, and in terms of forecast scores. We focus on the short range because it was not possible to obtain significant results in the medium and longer ranges with the relatively short study period (one month).

Precipitation impact is shown in Figure 4 for the tropics and Figure 5 for the Northern Hemisphere. Plots are shown for SSMI, radiosondes and SYNOP. The GEOS, AMSUB, HIRS and AIRS precipitation impact is smaller (not shown), and mostly limited to what appears to be semi-random modulation of the rainfall in the storm-track region of the western North Pacific. Figure 4 shows that although SSMI data are little used in the ITCZ region, it nevertheless has a pronounced impact on the tropical precipitation. The rainfall in the first 12 hours of forecasts is increased in the ITCZ and in the Indonesian region. The precipitation rate adjusts quite rapidly over the first day of forecasts and becomes almost constant at lower rates thereafter (not shown) – this is the so-called 'spin-down' problem affecting tropical convective rainfall in the ECMWF system to various extent for many years now (Beljaars 2002). Kållberg (2002) has shown that this spin-down effect is a serious problem also in ERA-40 re-analyses, with variations over the 40-year period due to changes in satellite data usage. Contrary to the ERA-40 (which used an earlier version of IFS, cy24r3), our results are that observations types other than SSMI do not significantly contribute to the spin-down. Figure 4 shows that assimilation of radiosondes and SYNOP humidity data quite strongly influences the rainfall over India. SYNOP also have impact over parts of the Sahel region, where the data introduce a dry bias relative to the model.

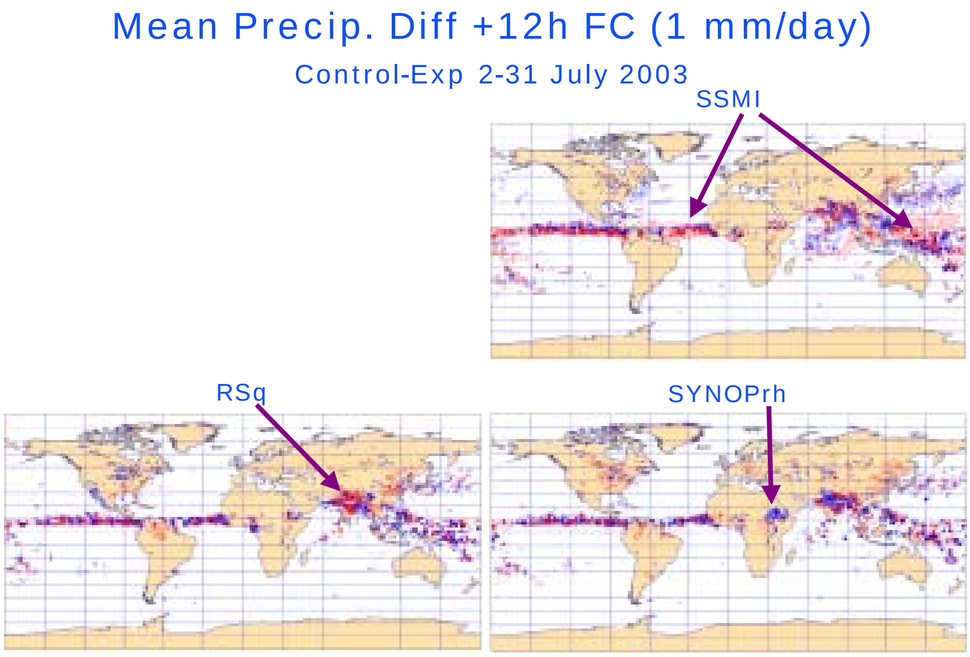

Figure 4 Difference in 2-31 July accumulated +12h precipitation between control and each of three experiments, as labeled. Red (blue) contours (1 mm/day) indicate that the use of the data has increased (decreased) precipitation.

Figure 5 shows the same data as Figure 4, but with a focus on the Northern Hemisphere. The top-left panel shows the monthly rainfall accumulation, for reference. We see that all three data types (SSMI, radiosondes and SYNOP) influence the rainfall in the North Pacific storm-track region, but in a semi-random manner. In the North Atlantic, however, radiosondes and SYNOP have little impact, while SSMI reduces precipitation.

There appears to be a dry bias between SSMI and the model in this area, which requires further study. We have seen from Figure 3 that radiosondes and SYNOP have opposite bias in the boundary layer over land. This is reflected in Figure 4, showing that radiosondes lead to reduced precipitation in parts of North America, Europe and central Asia, whereas SYNOP in similar areas lead to precipitation increase.

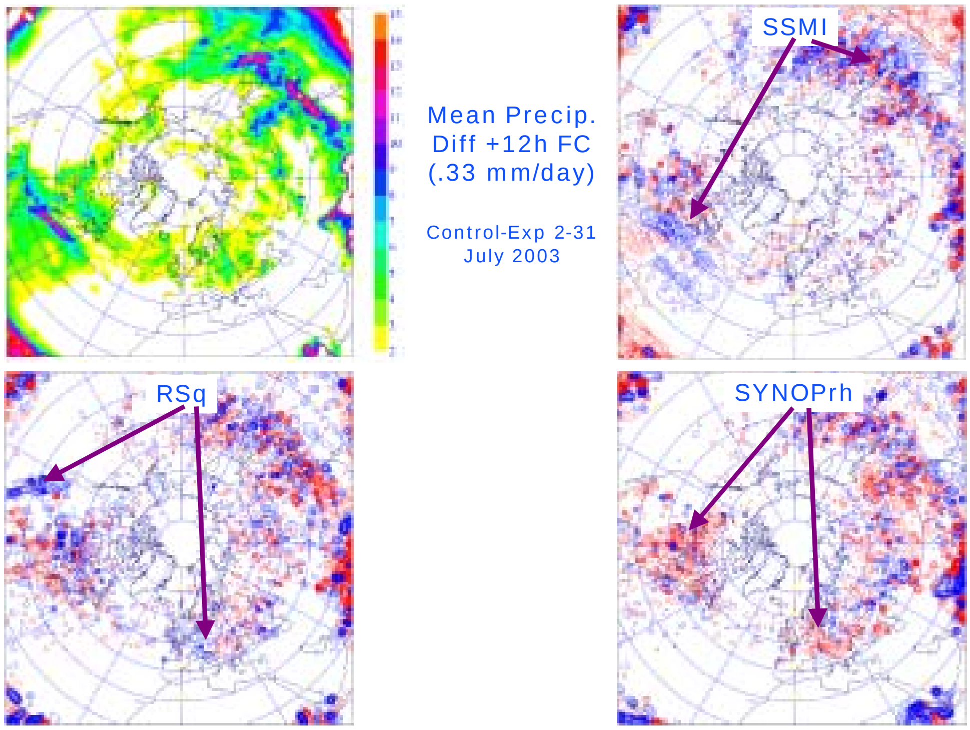

Figure 5 As Figure 4 focusing on the Northern Hemisphere. The top-left panel shows accumulated precipitation from 2-31 July 2003.

Differences in latent heat release associated with these differences in precipitation result in temperature differences throughout the troposphere (not shown). In forecasts, geopotential and wind are affected on larger scales where the evolution of weather systems is affected by changes in the moisture distribution. Daily ten-day forecasts have been run from the control and each of the seven experiments, and objective forecast verification scores have been computed. Forecast impacts are significant in the short-range: some are shown here in Table 3. The table shows two-day r.m.s of forecast error, in terms of differences between experiment and control. Positive values indicate larger forecast error in the experiment (one data type withheld) than in the control (which used all data). We can see that most of the results are positive in the sense that the use of humidity data contributes to forecast accuracy – even in terms of geopotential height scores. Radiosondes and AMSUB improve forecasts in the Northern Hemisphere, whereas SSMI provides substantial benefit in the tropics and in the Southern Hemisphere. AIRS is the newest data type in this test, and further improvements are expected from work in progress. Wind forecast verification give generally similar results (not shown). Forecast verifications in terms of humidity and precipitation are desirable, but have not yet been performed for this study.

Table 3: Rms of 48-hour forecast verification for 500 hPa geopotential (m2/s2), showing differences between the Control and each of the seven experiments, for three geographical areas. Positive values indicate benefit of the data.

Experiment	N.Hem	Tropics	S.Hem
NoSSMI	0.06	2.10	2.36
NoRSq	1.69	0.35	0.00
NoSYNOPrh	0.29	0.55	0.37
NoGEOS	0.88	0.00	0.15
NoAMSUB	1.61	0.88	0.62
NoHIRS6µ	0.96	-0.05	0.49
NoAIRS6µ	0.48	-0.41	-0.83

5. Summary and Conclusions

The analysis and forecast impact of seven main types of humidity data has been tested in a one-month observing system experiment (OSE). The impact has been evaluated in terms of differences with respect to a reference system (the control assimilation), which used all data. As there is some considerable overlap and redundancy between observing systems the impact measured in this way appears much smaller than it would have been if we had chosen as reference a system without humidity data. We chose to use the full system as reference in this study, as this is the most relevant option for evaluating the performance of ECMWF's operational system.

We have found that the data generally provide benefit to the analysis and forecast performance, and therefore we conclude that the new humidity analysis (Holm et al. 2002) performs well. Other studies have shown that the new humidity background-error formulation gives the appropriate weight to the various humidity data. Currently, the main problem is with relatively small biases in either model or data, which we have shown directly affect short-range precipitation forecasts. Through latent-heat release this also affects temperature and divergent wind in analyses and forecasts (not shown). Analysis differences between the experiments and the control showed that: SSMI dominates over sea, followed by AMSUB; radiosondes, SYNOP and AMSUB dominate over land; GEOS, HIRS and AIRS dominate at 200-300 hPa; Analysis increments from SSMI peak at 850 hPa, AMSUB at 400/500, GEOS and HIRS at 300 and AIRS at 200 hPa.

SSMI adds water in the sub-tropical subsidence areas due to a bias with respect to the model. The added moisture is advected equator-ward and increases precipitation in short-range forecasts, in the ITCZ and in the

Indonesian region – resulting is a rapid 'spin-down' in tropical convective rain-fall. The other six data types have negligible impact on spin-down in the current ECMWF system. Radiosondes and SYNOP create opposite biases in the boundary layer over land, with local influence on precipitation. The SYNOP data are biased wet and the radiosondes are biased dry with respect to the model.

Several sources of additional moisture information can be exploited in the near future: Assimilation of radiances affected by precipitation and clouds; A new instrument SSMI/S launched in October 2003; Radiosonde humidity sensors are improving, some could be used above 300 hPa (Nash 2002) below the tropopause; Extended and improved use of AIRS radiance data; MSG=Meteosat second generation was launched in August 2002 and has one additional water vapour channel; development of GPS radio occultation techniques; Several new aircraft humidity sensors are being developed; Dropsonde humidity have improved in quality and could now be assimilated; MIPAS stratospheric humidity retrievals are available from ENVISAT and finally; Ground-based GPS total-column data. Near real-time GPS networks are being coordinated in Europe, N. America and Japan, and real-time European data has been received at ECMWF since March 2004. The use of these new data types in assimilation will be explored in the coming years.

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References

Andersson, E., P. Bauer, A. Beljaars, F. Chevallier, E. Hólm M. Janisková, P. Kållberg, G. Kelly, P. Lopez, A. McNally, E. Moreau, A. Simmons, J-N. Thépaut and A. Tompkins, 2004: Assimilation and modeling of the atmospheric hydrological cycle in the ECMWF forecasting system. *Bull. Amer. Meteorol. Soc.*, **XXX,** xxx-xxx. Accepted.

Bauer, P., G. Kelly, and E. Andersson, 2002: SSM/I radiance assimilation at ECMWF. Proceedings of ECMWF/GEWEX Workshop on "Humidity Analysis", Reading, U. K., 8—11 July 2002, 167—175.

Beljaars, A. C. M., 2002: Some aspects of modeling of the hydrological cycle in the ECMWF model. Proceedings of ECMWF/GEWEX Workshop on "Humidity Analysis", Reading, U. K., 8—11 July 2002, 191—202.

Bouttier, F., 2001:The development of 12-hourly 4D-Var. *ECMWF Tech. Memo*. **348,** pp 21.

Chevallier, F., P. Lopez, A.M. Tompkins, M. Janisková, and E. Moreau, 2004: The capability of 4D-Var systems to assimilate cloud affected satellite infrared radiances. *Q. J. R. Meteorol. Soc.*, **130,** 917—932.

Courtier, P., J.N. Thépaut and A. Hollingsworth, 1994: A strategy for operational implementation of 4D-Var, using an incremental approach. *Q. J. R. Meteorol. Soc*. **120,** 1367—1388.

Dee, D., Detection and correction of model bias during data assimilation. Proc. ECMWF Seminar on “Recent developments in data assimilation for atmosphere and ocean”, Reading, U.K., 8—12 September 2003, 65—73.

Dee, D. P., and A. da Silva, 1998: Data assimilation in the presence of forecast bias. *Q. J. R. Meteorol. Soc.*, **124,** 269—295.

Dee, D. P., and R. Todling, 2000: Data assimilation in the presence of forecast bias: The GOES moisture analysis. *Mon. Wea. Rev.*, **124,** 269—295.

Harris, B., and G. Kelly, 2001: A satellite radiance bias correction scheme for radiance assimilation. *Q. J. R. Meteorol. Soc.,* **127,** 1453—1468.

Hólm, E., E. Andersson, A. Beljaars, P. Lopez, J-F. Mahfouf, A.J. Simmons and J.N. Thépaut, 2002: Assimilation and modeling of the hydrological cycle: ECMWF’s status and plans. *ECMWF Tech. Memo*., **383,** pp 55.

Kållberg, P., 2002: The ERA-40 hydrological cycle. Proc. ECMWF/GEWEX workshop on “Humidity Analysis”, Reading, U. K., 8—11 July 2002, 101—105.

Köpken, C., G. Kelly, and J.-N. Thépaut, 2004: Assimilation of METEOSAT radiance data within the 4D-Var system at ECMWF. Part II. *Q. J. R. Meteorol. Soc.*, (To appear July 2004).

Marécal, V., and J.-F. Mahfouf, 2003: Experiments on 4D-Var assimilation of rainfall data using an incremental formulation. *Q. J. R. Meteorol. Soc.,* **129,** 3137—3160.

Nash, J., 2002: Review of test results on the accuracy of radiosonde relative humidity sensors. Proc. ECMWF/GEWEX workshop on “Humidity Analysis”, Reading, U. K., 8—11 July 2002, 117—123.

McNally, A. P., and M. Vesperini, 1996: Variational analysis of humidity information from TOVS radiances *Q. J. R. Meteorol. Soc.,* **122,** 1521—1544.

McNally, A.P., and P.D. Watts, 2003: A cloud detection algorithm for high spectral resolution infrared sounders. *Q. J. R. Meteorol. Soc.*, **129,** 3411—3423.

Moreau, E., P. Lopez, P. Bauer, A. Tompkins, M. Janisková, and F. Chevallier, 2004: Variational retrieval of temperature and humidity profiles using rain rates versus microwave brightness temperatures. *Q. J. R. Meteorol. Soc,* **130,** 827—852.

Munro, R., C. Köpken, G. Kelly, J.-N. Thépaut, and R. Saunders, 2004: Assimilation of METEOSAT radiance data witin the 4D-Var system at ECMWF, Part I. *Q. J. R. Meteorol. Soc.*, To appear July 2004.

Rabier, F., H. Järvinen, E. Klinker, J.F. Mahfouf and A. Simmons, 2000: The ECMWF operational implementation of four-dimensional variational assimilation. Part I: experimental results with simplified physics. *Q. J. R. Meteorol. Soc*. **126,** 1143—1170.

Impact of Atmospheric Motion Vector Winds on the Global NWP System of the German Weather Service

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Introduction

Global wind field measurements are essential to improve our knowledge of atmos-pheric dynamics, including atmospheric transport processes of energy, water and airbourne particles. Unfortunately, coverage of wind observations is rather poor over the oceans and the polar regions. Atmospheric motion vector (AMV) winds derived from tracking clouds and water vapor in image sequences taken by geostationary satellites have been used to improve knowledge and description of atmospheric flow over the oceans and represent an integral part of the global observing system for numerical weather forecasting. Operationally, the global assimilation system of the German Weather Service (DWD) uses AMV wind data in the so-called "Satob" format, which is a high quality low-resolution subset of the full AMV wind data set disseminated by METEOSAT and NOAA/NESDIS. Since autumn 2003 the DWD has been receiving the full high-resolution AMV wind data set in a new "Bufr" data format from EUMETSAT for Meteosat 5 and 7 and from NOAA/NESDIS for the GOES 9, 10 and 12 satellites including quality information for each wind observation. Since the AMV wind vectors from geostationary satellites only cover the area 60°S to 60°N, there are still data-void regions around the poles. Only a few regular wind measurements are made along coastal areas of the Arctic, Antarctica and the interior of Canada, Alaska, Russia and Northern Europe, but there is little or no coverage of the interior of Antarctica, Greenland or the Arctic Ocean. Poor knowledge of the polar wind field is a major cause of larger than normal analysis and forecast errors in these regions, leading to occasional forecast "busts" in areas like Europe, influenced by synoptic disturbances originating in polar regions.

Recently a new satellite-derived wind product has become available, which provides information on polar wind fields. The winds are derived by tracking features in the IR window band at 11 μm and in the water vapour (WV) band at 6.7 μm from the Moderate Resolution Imaging Spectrodiameter (MODIS) instrument on board the polar-orbiting satellites Terra and Aqua and are available in areas north of 60°N and south of 60°S.

Atmospheric Motion Vector (AMV) Winds

The new AMV observations in "Bufr" format provide more information than the former wind data sets in so-called "Satob" code due to increased spatial and temporal resolution and the inclusion of quality information using the QI index. Since autuum 2003 the DWD has been receiving AMV wind data from Meteosat 5 and 7 and the opera-tional GOES 9, 10, 12 satellites. Compared to the usage of "Satob" coded winds several source code and blacklist modifications have been necessary to make possible the best use of the AMV winds in the assimilation cycle. The most significant change is the inclusion of quality information for each wind observation. The calculation of the QI indices is based on the MPEF quality control scheme developed at EUMETSAT. A concise description of the scheme and the derivation of the QI values can be found in Holmund, 1998 and Holmund et. al 2001. The AMV Bufr format contains three quality indices, which all reflect the agreement and consistency of a single wind vector within the neighbouring observations. These indices are ;

- Quality indicator (QI) containing no first guess information of a forecast model
- Recursive filter flag (rff), quality flag derived at NOAA/NESIDIS indicating the final fit to the analysis (Velden, et al., 1997)
- Quality indicator (QI) containing first guess information of a forecast model

Based on monitoring results at ECMWF (Rohn et al, 2001, van Bremen, 2003) the following QI thresholds have been selected for METEOSAT 5/7 and GOES 9/10/12 for three different channels, tropospheric layers and geographical regions and are summarised in Table 1. Only winds which passed the QI thresholds are active for assimilation. AMVs tracked from WV channels in clear sky conditions are not used in these study.

Besides the static QI thresholds a thinning step is used in the assimilation procedure in order to reduce the number of active wind observations for the assimilation and to take into account the high spatial correlation of the AMV winds. The routine thinning for the “Satob” winds is changed so that the QI index is included as a selection criterion, and in cases were several wind observations are within one thinning box, the wind with the highest QI index is retained active in the assimilation.

Area	Channel	Low 1000 – 700 hPa	Medium 700 – 400 hPA	High 400 – 100 hPa
Northern Hemisphere Latitude > 20oN	IR VIS WV cloudy	QI > 0.85 QI > 0.65 not used	QI > 0.90 not used not used	QI > 0.60 not used QI > 0.60
Tropics 20oS < latitude<20oN	IR VIS WV cloudy	QI > 0.85 QI > 0.65 not used	QI > 0.90 not used not used	not used not used QI > 0.85
Southern Hemisphere Latitude < 20oS	IR VIS WV cloudy	QI > 0.85 QI > 0.65 not used	QI > 0.90 not used not used	QI > 0.60 not used QI > 0.60

Table 1: Data selection according to quality indicator QI

Experiment setup

Using the global assimilation and forecasting system of the German Weather Service (DWD), two impact experiments for the period 1 January – 20 January 2004 were conducted to estimate the potential benefit of the AMV wind observations. In both experiments the “Satob” winds were replaced by the new AMV winds using the QI thresholds described in section 2 (Table 1). The AMV winds were used only over sea and in the visible channel below 700 hPa and in the water water cloudy channel only above 400 hPa. AMV’s tracked from clear sky atmospheric motions in the WV channel and AMVs were it is not clear whether they were derived from clear or cloudy conditions were not used in the experiments. The first experiment used the routinely used thinning box size of approximately 70 km and the second experiment used a larger thinning box of approximately 200 km taking into account recent results of large horizontal error correlations of AMV winds at spatial scales larger than 150 km (Bormann et al. 2003). Both experiments were compared to the operational forecast (control) which uses cloud motion vector winds in “Satob” code at the synoptic times (00, 06, 12, 18 UTC).

Impact studies

Figure 1 compares the background and analysis departures of the AMV winds in „Satob” code (left panel) with the AMV winds in the new “Bufr“ code (right panel) during the period in January 2004 for the Meteosat 7 satellite and the infrared channel.

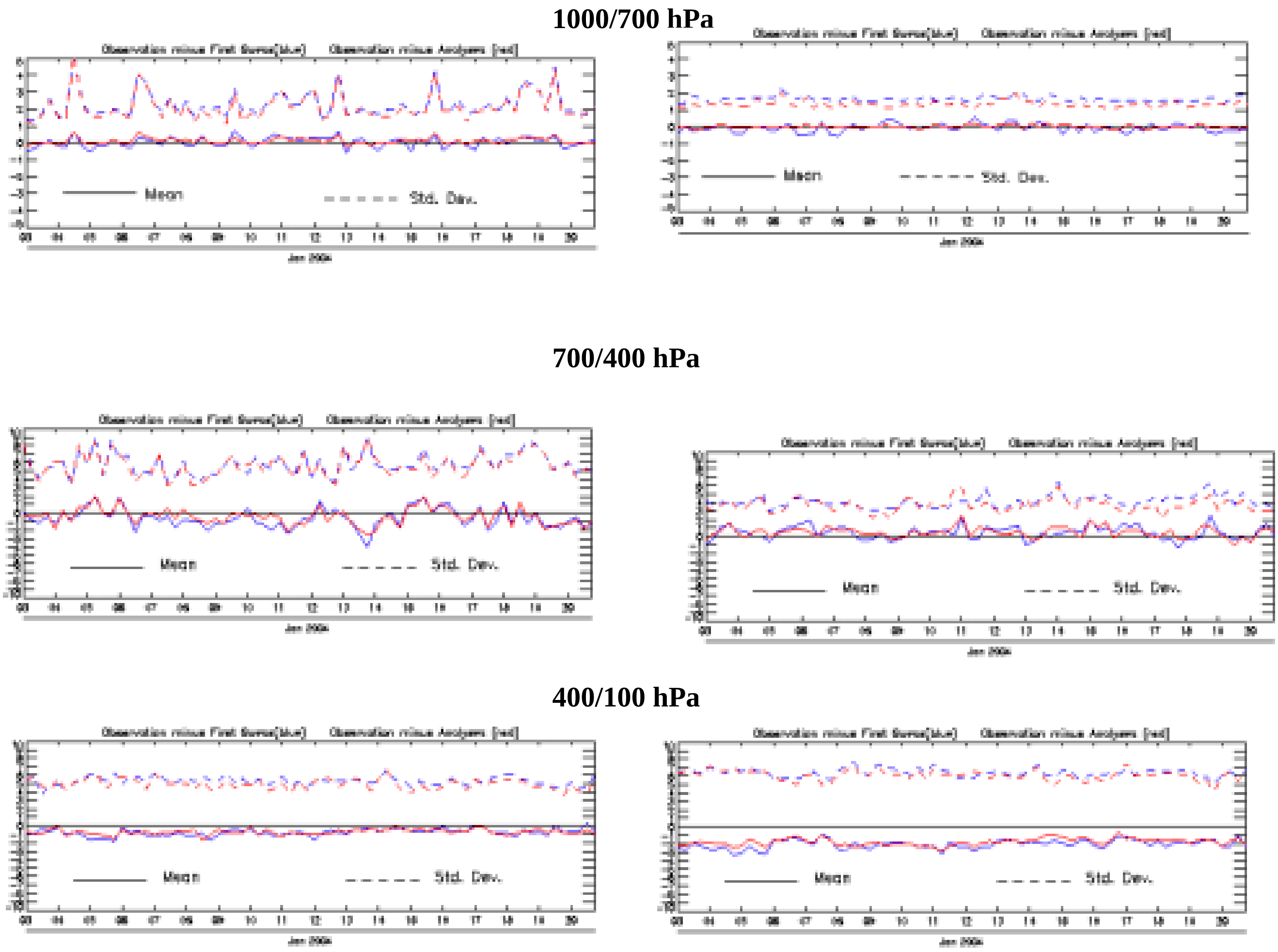

Figure 1: Time series of first guess (blue) and analysis (red) increments between AMV winds in “Satob“ Code (left) and new “Bufr“ Code (right) averaged over the whole Meteosat 7 dish

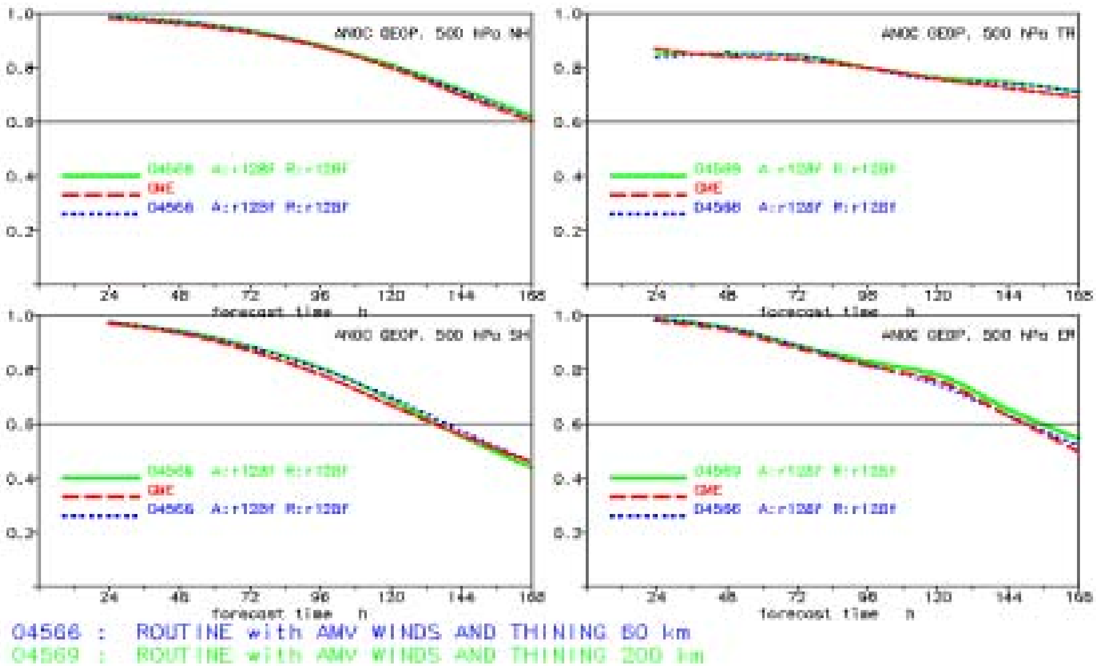

Figure 2: Anomaly correlation coefficient versus forecast time for the 500 hPa geopotential height averaged over 22 forecasts for the routine forecast (red), the forecasts with AMV winds and routine thinning (blue) and with a 200 km thinning box (green).

In the lower and middle troposphere the course of bias and standard deviation of the "Bufr" AMVs is smaller than for the "Satob" coded winds. Obviously, the peaks in the standard deviation are now almost gone in the "Bufr" AMVs. For the higher tropo-sphere, bias and standard deviation are slightly larger, perhaps due to a too lax use of the QI index in the upper troposphere and lower stratosphere. The same results are also valid for the GOES satellites (not shown).

Figure 2 compares the forecast impact of the experiment using the "Bufr" AMVs with routine thinning and the experiment with an enlarged thinning box to the routine forecast in terms of the 500 hPa geopotential height anomaly correlation coefficient.

Using the AMV wind observations with quality information has a positive impact on the forecast quality for all areas considered. The experiment with a larger thinning box has the highest impact ont the Northern Hemisphere, Europe and the Tropics. On the Southern Hemisphere, the impact of the experiment using the routine thinning is slightly greater than that of the experiment using a larger thinning box. Occasionally, the forecast quality for a limited area like Europe is disturbed considerably due to the use of low quality "Satob" wind observations from geostationary satellites (Fig. 3 red curve. Forecast starts: 13 Jan. 2004 12 UTC +120h). Using the new AMV wind observations leads to no improvement in forecast quality for that particular forecast (Fig. 3 blue curve). In contrast to this, enhancing the thinning box leads to a substantial improvement of the forecast quality of that event (Fig. 3 green curve).

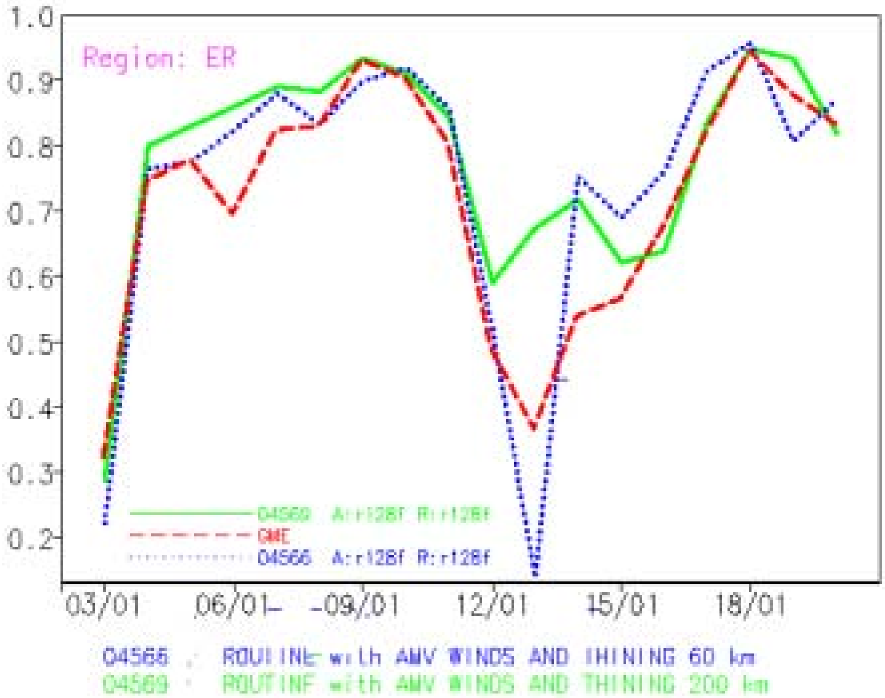

Figure 3: Times series of anomaly correlation coefficients of the geopotential height in 500 hPa averaged over Europe for the period 03 January – 20 January 2004 for the Control (red), the experiment with AMV winds and routine thinning (blue) and the experiment with a larger thinning box (green) for 120 h forecast

MODIS winds

To estimate the potential benefit of MODIS wind observations from the polar-orbiting satellites Terra and Aqua, two impact experiments – one in summer (June 2003) and one in autumm (October 2003) – were conducted. A good correspondence was found between MODIS statistics and similar statistics for AMV winds from geostationary satellites (Fig. 4). Obviously, there is a positive bias between observations and model (model too slow), which is more pronounced in the Southern Hemisphere than in the Northern Hemisphere. Comparing the two satellites Terra and Aqua, higher background and analyses departures could be found for Aqua, especially over Antarctica (not shown).

The MODIS winds have a large impact on the DWD polar analysis by introducing analysis increments into data void areas. The overall impact on forecast quality is positive for Europe and the Northern Hemisphere and neutral for the Southern Hemisphere for the summer experiment (Fig. 5). In the Northern Hemisphere, using the MODIS wind data leads to an improved forecast quality of up to 12 hours. The autumm case shows the opposite behaviour; a neutral impact for Europe and the Northern Hemisphere and a small positive impact for the Southern Hemisphere (not shown).

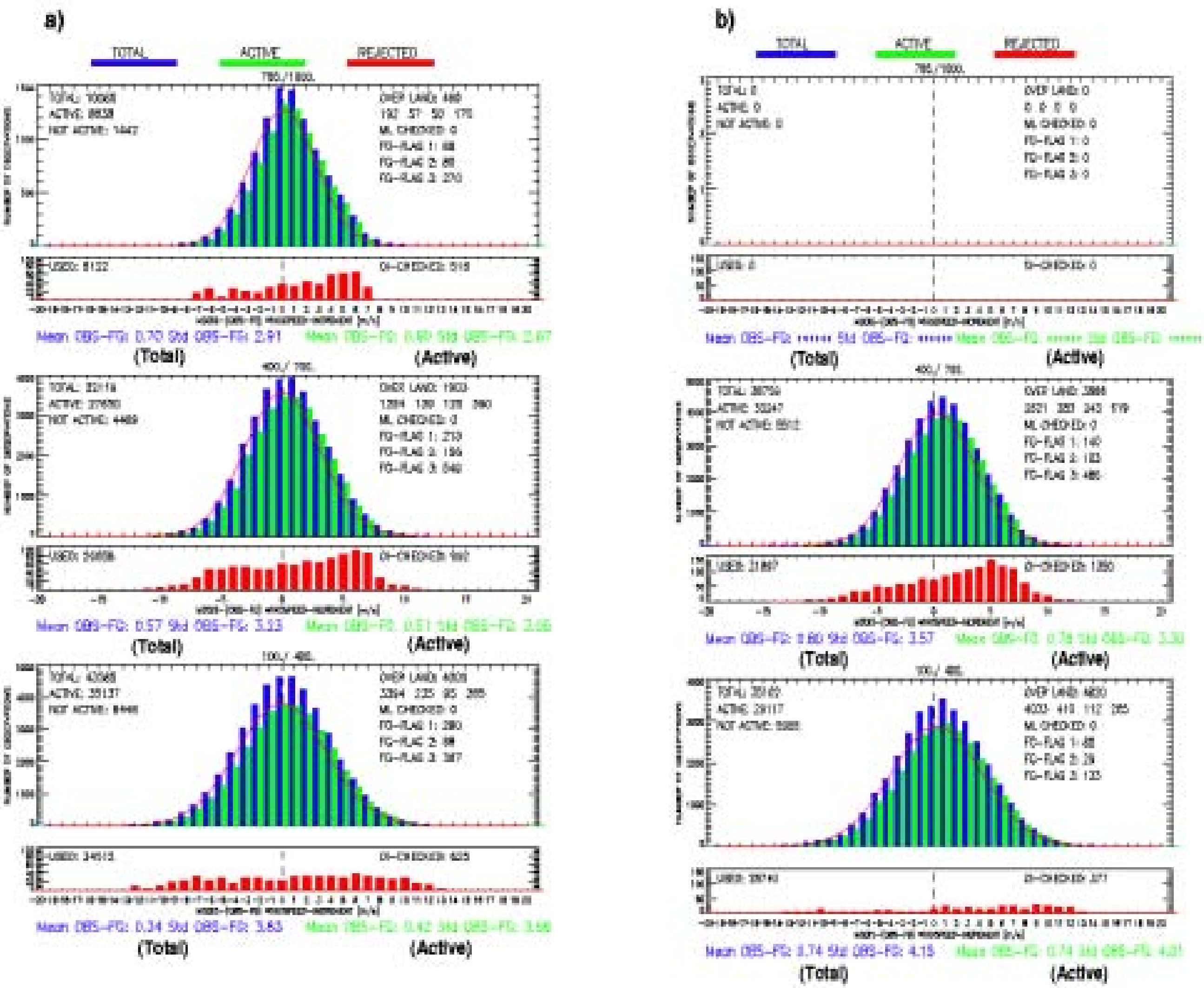

Figure 4: Frequency distribution of the difference between Modis (Terra and Aqua) and first guess windspeed and quality control statistics for the summer case (June 12 to July 9, 2003) for all (total; blue columns), active (after the quality control; green columns) data, including the mean and standard deviation for all and active data, separated for the Northern (a) and Southern Hemisphere (b). The red columns depict the data which were rejected by the OI check.

Obviously, the impact on forecast quality depends strongly on season and occasions in which the interaction between polar and mid-latitude flow patterns is particularly intense (Fig. 6: end of period). The relatively minor impact of the Modis data on the forecast quality of the Southern Hemisphere could be connected to height assignment problems over high topography or conditions such as low-level thin stratus, which make it difficult to identify trackable features over the Antarctic continent.

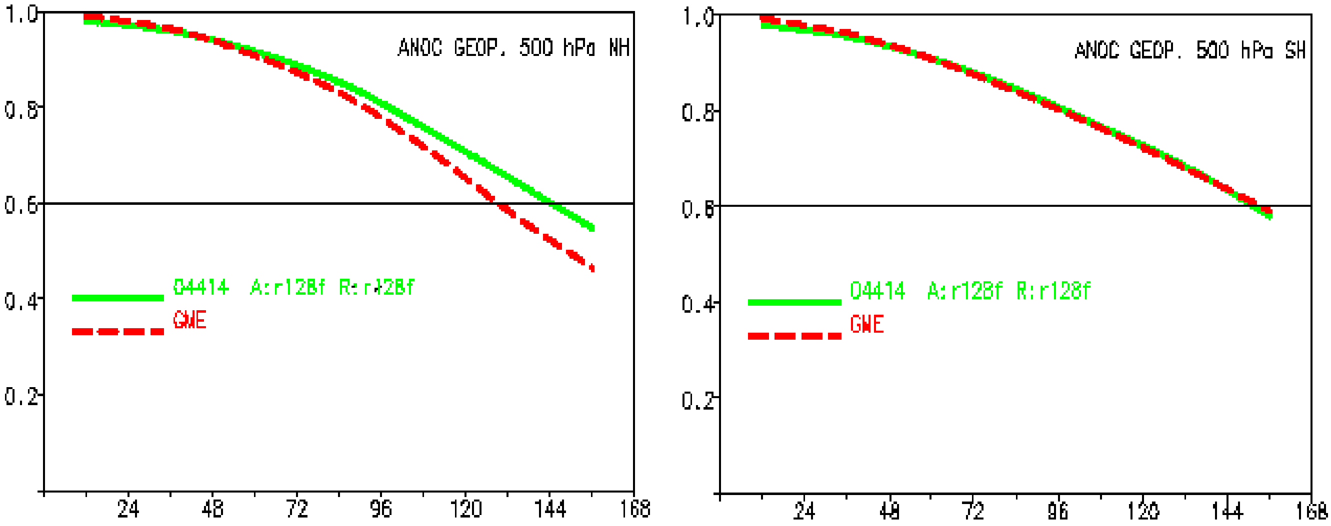

Fig. 5: Anomaly correlation coefficient versus forecast time for the 500 hPA geopotential height for the Control forecast (red, without Modis winds) and for an experiment using Modis winds (green) averaged over 23 cases (18 June – 9 July, 2003).

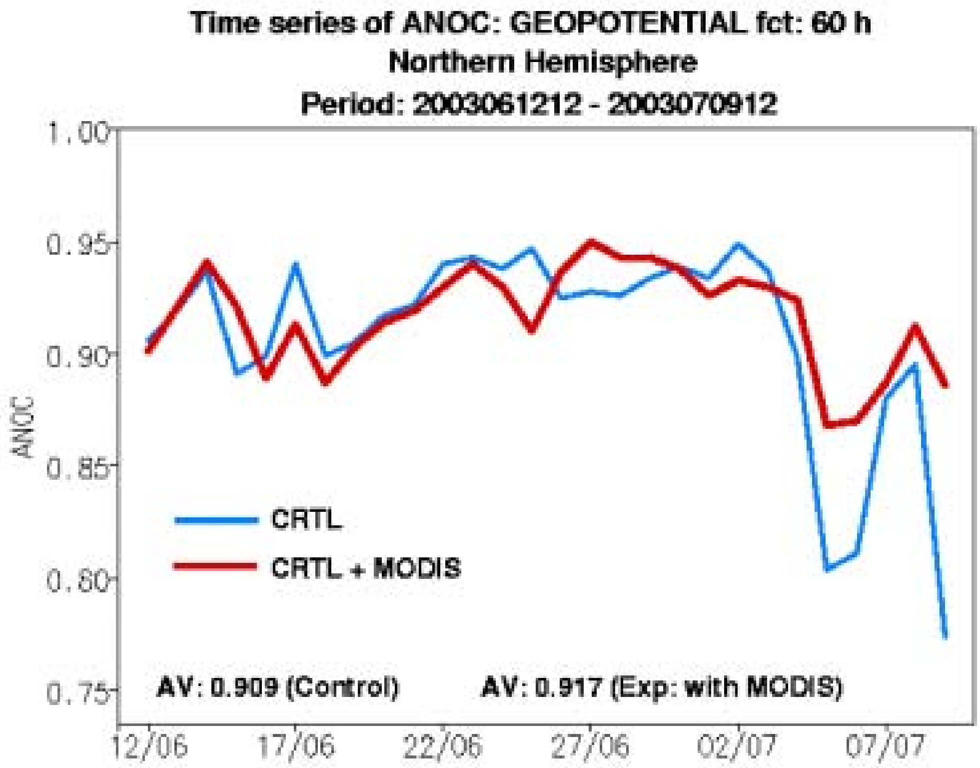

Figure 6: Times series of anomaly correlation coefficient of 60 h geopotential height forecasts in 500 hPa averaged over the Northern Hemisphere for the period 12 June – 09 July 2003 for the Control (blue) and the experiment using MODIS wind data in addition (red).

References

Bormann, N., Saarinen, S., Kelly, G., Thepaut, N-J., 2003: *The spatial structure of observation errors in Atmospheric Motion Vectors from geostationary satellite data*. Mon. Wea. Rev., 131. 706-718.

Holmund, K., 1998: *The utilization of statistical properties of satellite-derived atmospheric motion vectors to derive quality indicators*, Wea. Forecasting, 13, 1093-1104.

Holmund, K., Velden, C., Rohn, M., 2001: *Enhanced automated quality control applied to high-density satellite derived winds.* Mon. Wea. Rev., 129, 517-529.

Key, J.R., Santek, D. C.S., Velden, Bormann, Thepaut, J.-N., Riishojgaard, L.P. Zhu, Y., Menzel, W.P., 2002: *Cloud-drift and water vapor winds in the polar regions from MODIS*, IEEE Transactions on Geoscience and Remote Sensing, 41, 482-492.

Rohn, M., Kelly, G., Saunders, R. W., 2001: *Impact of a new cloud motion wind product from Meteosat on NWP analyses and Forecasts*, Mon. Wea. Rev., 129, 2392-2403.

Velden, C., Hayden, C.M., Menzel, W.P., Wanzong, S, Goers, J.S., 1997: *Upper-tropospheric winds derived from geostationary satellite water vapor observations*. Bull. Amer. Meteor. Soc., 78, 173-195.

Von Bremen, L., 2003: personal communications

Observing System Experiments with NCEP's Global Forecast System

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Introduction

Evaluation of current observing systems provides an important baseline for observing system assessment and planning as well as useful information for tuning and improving an operational numerical prediction system. Previous assessments at NCEP have been done at low resolution due to lack of resources but recently the opportunity has arisen to do a battery of Observing System Experiments (OSEs) with resources provided by the NASA-NOAA-DOD Joint Center for Satellite Data Assimilation and the NPOESS Integrated Program Office (IPO). While the main focus of the work described in this paper is the current POES system, other OSEs are planned which will include impact of conventional observing systems.

The version of the NCEP Global Forecast System (GFS) used in these experiments is the Spectral Statistical Interpolation (SSI) version scheduled for operational implementation in 2004. It includes the ability to assimilate AIRS data and uses the broad spectrum of satellite and conventional observations available operationally. The data assimilation system is run at operational forecast model resolution (T254L64), with a top at 0.2 hPa. Forecasts are made once daily at 00 UTC with configurations of T254/L64 to 84 h, T170L42 to 180 h and T126L28 to 360 h. The OSEs are conducted in a data denial mode, with each observing system being withheld separately from the data assimilation.

The experiments consist of 45 day data assimilation runs over two time periods, 1 Jan – 15 Feb '03 and 1 Aug – 20 Sep '03. The control experiment uses all operational observations, including 3 AMSU-A/B pairs and 3 HIRS instruments. AMSU-A on AQUA is not included at this time. The following denial experiments are described in this paper: 1) all AMSU-A/B; 2) all HIRS; and AMSU from NOAA-15. Further experiments will be run as resources permit.

Impact statistics are calculated as in Zapotocny (2002). In particular, the "forecast impact" statistic is the difference in root-mean-square (rms) error between the control and denial experiment normalized by the rms error of the control. In addition, standard anomaly correlation scores for 500 and 1000 hPa geopotential height and rms errors for tropical winds at 850 and 200 hPa are calculated. A small sample of these impact statistics is presented in this paper. It is important to note that the impact statistics are calculated for forecasts over the last 30 days of each experiment, thereby minimizing the influence of transient skill loss over the first 15 days of the denial period.

Results

Fig. 1 shows the global wintertime temperature forecast sensitivity to AMSU and HIRS radiances for various pressure levels between 100 and 1000 hPa. For 24 h forecasts, AMSU impacts range from more than 25% in the upper troposphere to 10% near the earth's surface. These impacts decrease with forecast length to approximately 5% at all levels through day 8 and somewhat less thereafter. These results show large and significant sensitivity to AMSU radiances. The impact of withdrawing HIRS radiances is much smaller, approximately 3% at all levels at 24 h and dwindling to 1% or less thereafter.

Fig. 2 shows the global wintertime zonal wind forecast sensitivity in the same format at Fig. 1. The sensitivity range is approximately the same for zonal wind as for temperature for both AMSU and HIRS.

Sensitivities to relative humidity (Fig. 3) are larger than temperature and winds, ranging from 15% in the lower troposphere to more than 35% in the lower stratosphere for AMSU, and exceeding 15% in the upper troposphere and lower stratosphere for HIRS. For AMSU, however, impacts remain at approximately 4% for more than five days, while for HIRS they are negligible after one day everywhere except the lower stratosphere.

Forecast anomaly correlations at 500 hPa (Figs. 4-5) for control and both AMSU and HIRS denial experiments show a 0.5 day increase in skill in the Northern Hemisphere and 0.75 day skill increase in the Southern Hemisphere due to AMSU, but no increase in skill when HIRS data are added in the presence of AMSU data.

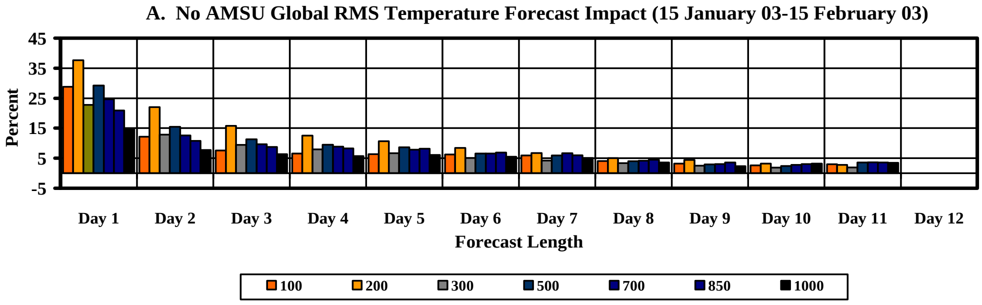
Finally, RMS wind vector errors are reduced by AMSU, but HIRS has virtually no impact on wind forecasts in the presence of AMSU data. AMSU impacts are felt beyond Day 5 and are equivalent to approximately 1/3 day of skill loss at 200 hPa and somewhat less at 850 hPa. Neither AMSU nor HIRS data reduce Day 1 forecast errors, which indicates that model errors dominate for short-term forecasts in the tropics.

Summary and Discussion

An initial set of OSEs have been conducted to determine the forecast sensitivity of AMSU and HIRS radiances with the NCEP GFS. In contrast to other studies, this work uses the full operational resolution of the GFS. Denial of AMSU radiances produces major forecast sensitivities of 15-35%, depending on the forecast variable and pressure level, while denial of HIRS radiances affects primarily the upper tropospheric moisture.

More experiments will be conducted to elucidate further the complex interplay of other components of the current observing system, including rawinsondes and aircraft data.

One should not conclude, on the basis of experiments described here, that HIRS data are of no value. Rather, in the presence of AMSU data, they add little extra value for temperature and wind forecasts and relatively small value for humidity.



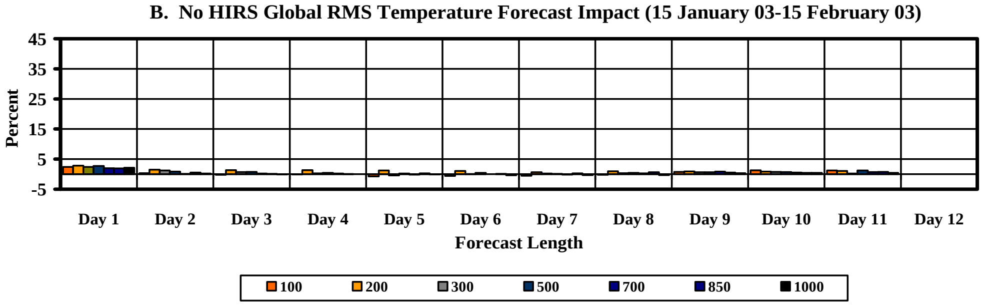
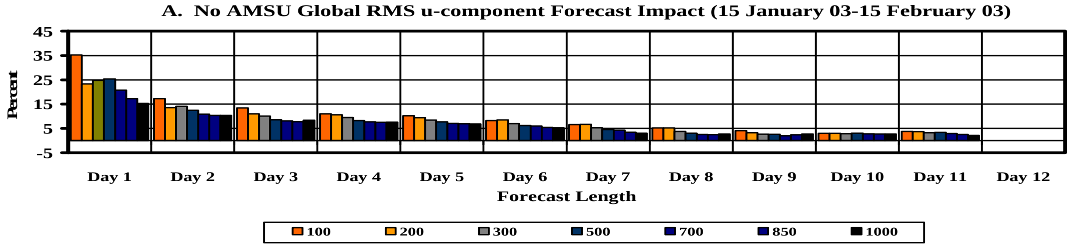


Fig. 1. Northern wintertime temperature forecast sensitivity (%) to removal of AMSU and HIRS radiances at pressure levels from 100 to 1000 hPa for forecast day 1 through day 11.



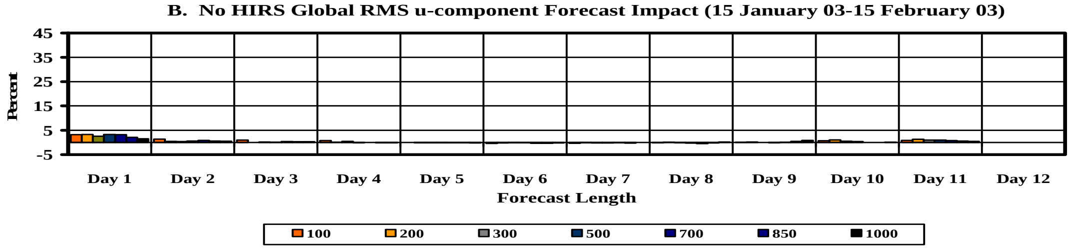
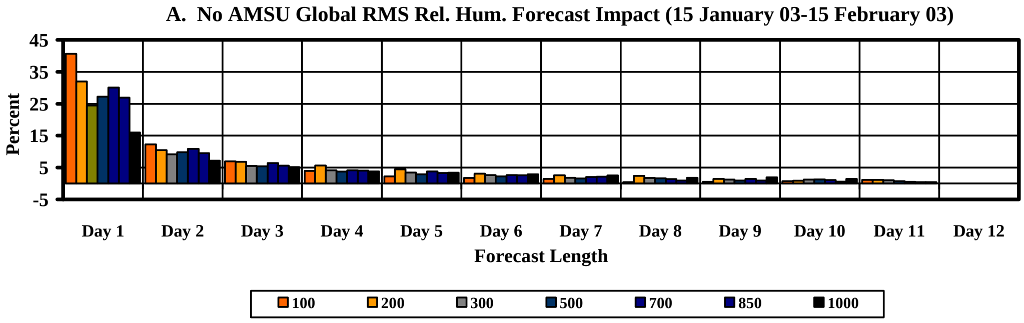


Fig. 2. As in Fig. 1, except for global zonal wind component.



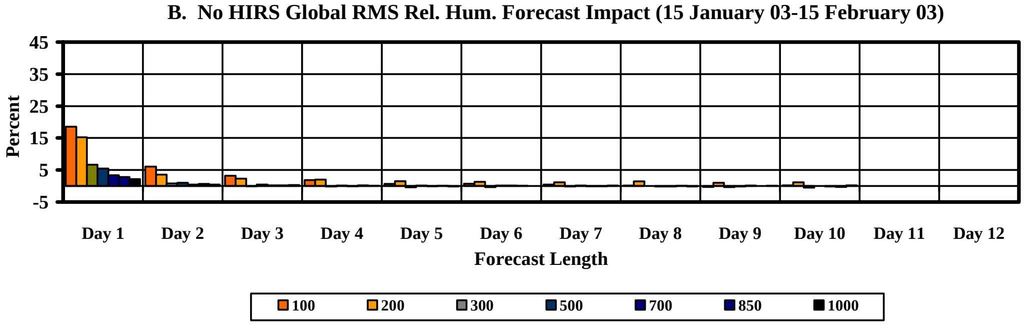


Fig. 3. As in Fig. 1, except for global relative humidity.

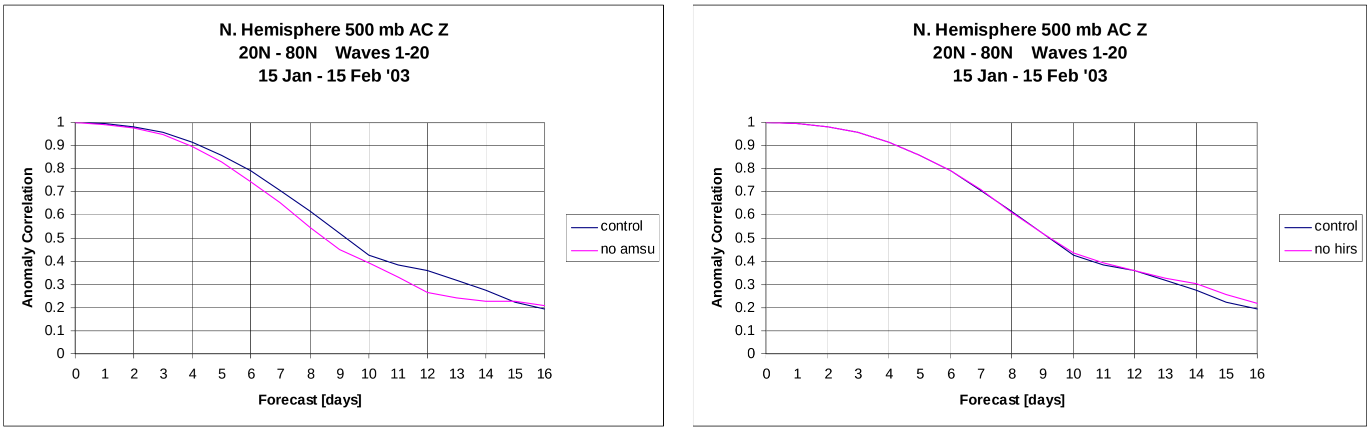


Fig 4. Northern Hemisphere wintertime forecast anomaly correlations at 500 hPa for days 1-16 for both control and AMSU denial experiments (left) and control and HIRS denial experiments (right).

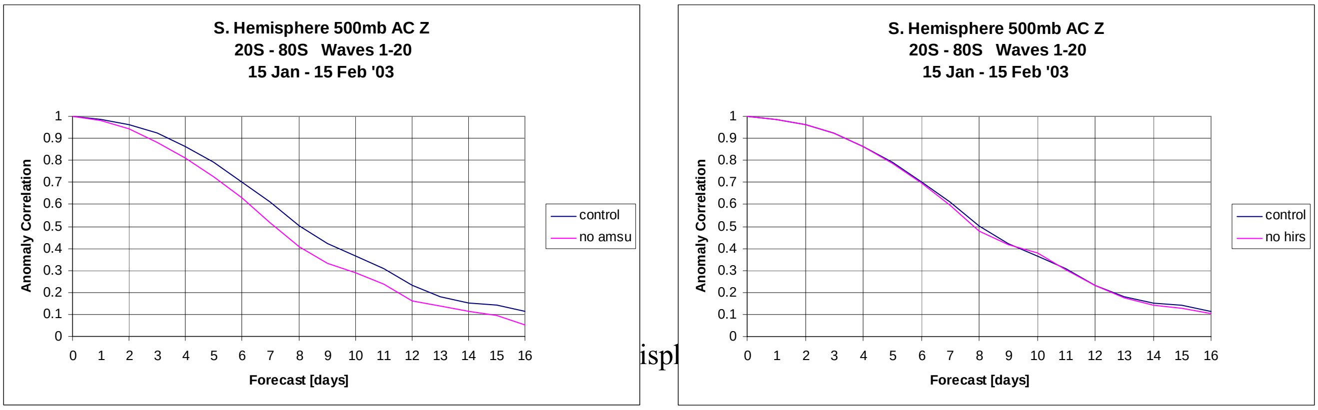


Fig. 5. As in Fig. 4, except for the Southern Hemisphere.

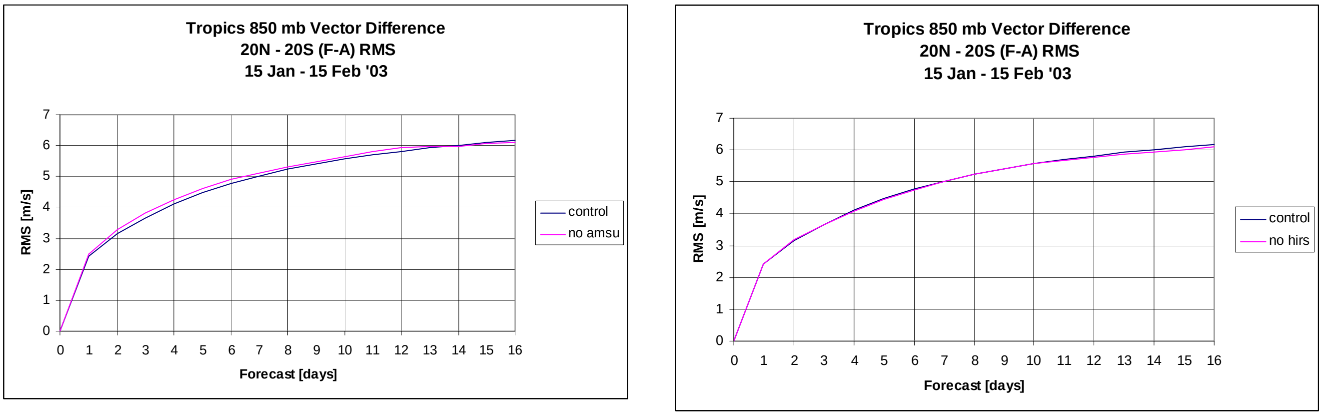


Fig. 6. Tropical rms vector error at 850 hPa for both control and AMSU denial experiments (left) and control and HIRS denial experiments (right).

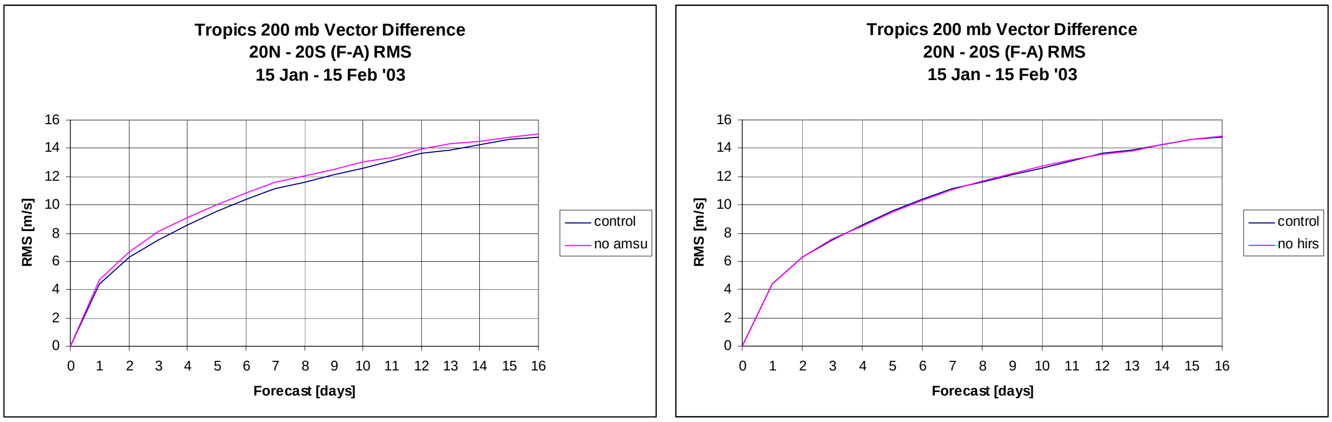


Fig. 7. As in Fig. 6, expect for 200 hPa.

OSEs of all main data types in the ECMWF operation system

Graeme Kelly, Tony McNally, Jean-Noel Thepaut, and Matthew Szyndel

Abstract

A series of Observing System Experiments (OSEs) were run with the operational version of the ECMWF system (January to October 2003) (T511 (40km) forecast model and T159 (120km) 4D-Var analysis). Two summer and two winter months have been evaluated. This is the longest full resolution impact study ever run at ECMWF (120 days in total). The following experiments have been compared:

(1)' control': The current operational system at ECMWF that assimilates 3 AMSU and 2 HIRS instruments from the NOAA satellites, Atmospheric Motion Winds from 5 Geostationary satellites and from one polar orbiter (TERRA), Clear Sky Water Vapour Radiances from 3 Geostationary satellites, 3 SSMI instruments from the DMSP platforms, Seawinds instrument from QuikSCAT, as well as conventional observations (radiosondes, temps and pilots, wind profilers, aireps, synops, drifting buoys and paobs).
(2) 'no sat': All satellite data removed (in that case, only radiosondes temps and pilots, wind profilers, aireps, synops, buoys and paobs are assimilated).
(3)'no airep': no airep winds and temperatures.
(4) 'no satob': no satob winds.
(5) 'no atovs': no atovs radiances.
(6) 'no upper': no radiosonde temps, pilots and profilers.

The main outcome of these OSEs is that satellite observations have much more impact in the Northern Hemisphere than in previous experiments performed several years ago (and incidentally have a larger impact than radiosondes and profilers combined). Very few busts, as defined by the anomaly correlation dropping to less than 0.6, at day four have been identified in the four-months of experiments. Finally the skill of Southern Hemispheric forecasts is very similar to the Northern Hemisphere forecasts.
At present ECMWF is testing a revised setup of their 4DVAR assimilation system called 'Early Delivery System'. It will provide products in a much more timely manner to the users and will be operational in July 2004. A short OSE was run with this new setup to see if the general conclusions found above are still valid. This OSE was only run for one month and limited to 'noupper' and 'nosat'. The overall conclusions are similar to those found the previous OSEs.

Introduction

What are the main motivations for running OSEs at ECMWF?
Some of these are:

1. To check if there are any negative interactions with the current observation usage in new operational cycles.

2. To ensure that the addition of new data types do not have any negative impact.

3. To determine how much redundancy there may be between different observation types.

4. To share our experience with data providers and WMO to help in planning of an optimized observing network.

The ECMWF data assimilation system uses a 12hour 4DVAR (see figure 1(a)). The new 'Early Delivery' System which will be operational at ECMWF in July 2004, (see figure 1(b)), uses the same 12 hour 4DVAR data assimilation as current operations with the addition of a short 4 hour data cutoff and a 6 hour 4DVAR. This provides the users an earlier 10 day forecast than with the present system. It has been found that the quality of this forecast is very similar to the current operationally product available much later. A typical late cutoff (8 hours) observational count and data coverage are shown in figure 2(a) and (b).

The evolution of the skill of the ECMWF forecasting system is shown in figure 3(a-d). The overall trend shows improvement in skill with time. After 1997 the forecast skill trend appears to have increased with the introduction of 4DVAR and the addition of more data, particularly from new satellites. In the comparison with other centers ECMWF forecasts are the most skillful. This may be partly due to the efficient way 4DVAR makes use of satellite data. At present one other operational center running global forecasts uses 4DVAR.

Before discussing the large OSEs (two months in summer and two months in winter) some forecasts run from ERA40 will be discussed. The ERA40 assimilation system was fixed during the entire period and changes in the forecast quality were only dependent on the observations used.

Next the results from some smaller OSEs will be presented. It has been found that in the current operational system there is a high degree of redundancy and it is often difficult the assess the true value of additional observing systems unless some current observing systems are removed. In addition there are many parameters one can use to measure the forecast impact and this paper will limit the evaluation to mass and wind except for the geostationary radiances. There are further papers in this workshop that discus impact on surface parameters and humidity on the ECMWF system. (Andersson et al., this volume) and (Thepaut and Kelly, this volume)

The results of the large OSEs (120 days) will follow including a comparison with the previous OSEs run at ECMWF in 1999 and finally a small OSEs run with the new ‘Early Delivery System’.

ERA-40 reanalysis

The ERA 40 production was completed at ECMWF in April 2003 using a reduced resolution version of the operational assimilation system (TL159/L60 3DVAR). The reanalysis covered 45 years and in this period satellite data was used from 1973 beginning with infrared radiances from the VTPR sensor and PAOBs derived from cloud imagery. In 1979 the TOVS system provided the first microwave radiances with a marked impact on the quality of Southern Hemispheric analysis. Next SSMI radiances and scatterometer surface winds improved the reanalysis and finally the more advanced instruments like AMSUA and AMSUB led to further improvements. Satellite derived winds from the geostationary satellites were used from the 1980’s.

Discussion

With the fixed data assimilation system, changes in the observing system can be measured by the skill of the ERA40 forecasts. The yearly average forecast scores are shown in figures 4(a) and 4(b). This overall skill of the ERA40 system is compared to operations 2002/3 and is similar the operational centres. In the Northern Hemisphere there is a rapid increase in skill up to 1980 then there was a more gradual improvement. The Southern Hemispheric forecast skill is more dependent on the satellite data. There is a modest improvement in 1974 with VTPR and a large change with the introduction of TOVS in 1979 and then with ATOVS in 1998. Of course the introduction of other new data have led to the overall improvement in skill with time. There has been a decrease in radiosondes during the later ERA40 period but new observations (surface based and space) has led to the an improvement in forecast skill with time.

The re-analysis system provides a control for future observing system experiments that could be run over extended periods. Extended runs with current operational system are very expensive.

Impact of some components of the ECMWF 4D-VAR system

Impact of GEO clear radiances from 5 satellites using current operational system
In the current operational system water vapour radiances from five geostationary satellites are used. The coverage from four satellites is shown in figure 2(b). The data are generally provided every hour and ideally suited to a 4DVAR assimilation system. It was hoped there would be an impact on the wind field indirectly though 4DVAR by providing a mechanism for tracking the motion of the upper water vapour field. The impact on mass and wind in the forecasts is very small. Figures 5 (a) and (b) show results

averaged over 62 cases. Figure 5(c) shows some humidity verification and the early range in the tropics where there is some skill. Figure 5(d) displays a vertical zonal cross section of the improvement in the 12 hour humidity forecasts.

Impact of AIRS

A reduced amount of AIRS radiance data is provided in near-real-time for use by NWP centres via a joint effort between NASA and NOAA/NESDIS. These data consist of 324 sampled channels (out of the available 2378) and one spot (the central one) from every 9 soundings. A very conservative "day-one" assimilation system has been constructed. This uses only channels which are flagged clear at a given location and excludes channels in parts of the spectrum with more complicated radiative transfer (e.g. ozone and 4 micron shortwave bands).

(a) Using current operations as control.

Initial evaluations indicated that the quality of the AIRS radiance measurements was very good. While shorter periods of parallel testing showed some good impacts of the AIRS data, the scores shown in figure 6, averaged over a much larger sample of 100 cases, suggest that the AIRS gives only a very small improvement in forecast skill over the full operational system. It is not clear if this lack of impact stems from the initially conservative use of AIRS measurements or whether there is some intrinsic redundancy in the information brought by these data to the full system.

(b) Using a reduced operational observation set.

To further investigate the impact of AIRS radiances a series of hypothetical single instrument experiments have been performed. In these, all satellite sounding data are removed from the system (AMV and SCAT data are retained) and then radiance data from just one of either a single AIRS or AMSUA instrument are assimilated (selected from platforms in as near as possible similar orbits). Results from a total of 50 cases (equally split between summer and winter) are shown in figure 6b for forecasts verified using the operational analyses of the time (which did not use AIRS data). These suggest that in the Northern Hemisphere there is little to choose between the impact of any single instrument used in isolation. However, in the Southern Hemisphere the use of AIRS clearly has the largest impact of any single instrument. While this impact is more encouraging for the AIRS (and suggests that even a conservative use of these data is of value) the results verified in different regions using radiosondes are less clear and more mixed (figure 6 c,d) and this study needs further investigation.

Observing System Experiments

A series of Observing System Experiments (OSEs) were run with the current operational version of the ECMWF system (T511 (40km) forecast model and TL159 (120km) 4dvar analysis). Two summer and two winter months have been evaluated. It should be pointed out that this is the longest full resolution ever run at ecmwf (120 days in total). Six data streams have been compared:

1. control: The current operational system at ECMWF that assimilates 3 AMSU and 2 HIRS instruments from the NOAA/AQUA satellites, Atmospheric Motion Winds from 5 Geostationary satellites and from one polar orbiter (TERRA), Clear Sky Water Vapour Radiances from 3 Geostationary satellites radiances, 3 SSMI instruments from the DMSP platforms, Seawinds instrument from Quickscat, as well as conventional observations (radiosondes temps and pilots, wind profilers, aireps, synops, drifting buoys and paobs).

2. nosat: All satellite data removed (in that case, only radiosondes temps and pilots, wind profilers, aireps, synops, buoys and paobs are assimilated).

3. noairep: no airep winds and temperatures.

4. noAMSUA -- all satellite used with the exception of AMUSA together with radiosondes temps and pilots, profiles, aireps, synops, bouys and paobs.

5. noupper: no radiosondes temps and pilots and profilers.

6. nosatob -- no satob winds.

The noAMSUA experiment was run because the AMSUA instrument plays an important role in the global observing system and there is some pressure not to replace these satellite instruments in case of failure.

The six experiments have been broken up into two sets for the purpose of this discussion. In both sets the control and no sat are present. The first set (conventional OSE) contains control, nosat, noupper and noairep. The other set (satellite OSE) contains the control, nosat, noAMSUA and nosatob.

(a) conventional OSE

The aim of these OSEs is to explore the relation between some components of the conventional system, the impact of the surface data are discussed in a separate paper. The 500 hPa geopotential anomaly correlations of these four experiments are shown in figures 7 and 8. In figure 7(a) the Northern Hemispheric scores show a separation between all experiments at about day five but towards day eight the noupper and no airep experiments merge. All these experiments are all verified using an analysis from operations. The nosat experiment has much more impact than either of the others. This pattern has not been observed in previous OSEs. A similar Northern Hemispheric impact is found in figure 8, where radiosondes are used for verification.

In the Southern Hemisphere with all variables and either choice of verification (figures 7(a) and 8) there is a clear separation between all experiments and the satellite data has the largest impact. The nosat experiment is very poor in skill as also shown in the past OSEs and the radiosonde data impact is small but slighty larger than the aireps.

Global plots of the normalized error as defined by:

[rms(experiment1)-rms(experiment2)]/max[rms(experiment1)-rms(experiment2)]

of 200 hPa geopotential height are shown in figure 11. These plots give a good geographical view of how the forecast error varies. Two forecast periods (12 hour and 48 hour) are shown. Positive regions indicate the improvement of the control.

The nosat experiment shows a positive impact for the control in all regions as expected. There is a reduced impact over the land in the Northern Hemisphere indicating the other data types are important. In the noupper experiment the most positive regions for the control are over land and the impact decreases with time. The impact of the aircraft data is less than the noupper and mostly over North America.

Time series of 500 hPa geopotential anomaly at day four are shown for these experiments in figure 12. In the Northern Hemisphere (figure 12(a)) there are no clear busts in all experiments and a clear gap can be seen between control and the nosat. The Southern Hemispheric results are similar except for the nosat (figure 12(b)). The time series for North America is a little different figure 12(c), here there are some poor forecasts and are many occur in the nosat OSE. Europe, on the other hand (figure 12(c)), does not show the same variability as North America possibly due the good upstream conventional data.

(b) satellite OSE

These experiments were run to look at the impact of two satellite data types, AMSUA radiances and satobs (AMV's). The 500hPa geopotential anomaly correlation scores of these four experiments are shown in figures 9 and 10. In figure 9(a) and (b) the Northern Hemispheric and European scores show a large separation between the nosat and control. At day five there is a small gap between the noAMSUA but disappears later and the impact of the satobs is small. All these experiments are verified using the operational analysis. The nosat experiment has much more impact than either of the others. As found with the conventional OSEs similar impact is found 200 hPa wind verifications, see figure 9(c).

In the Southern Hemisphere and Australian Region there is a clear separation between all experiments, the noAMSUA experiment has more impact than in the Northern Hemisphere and the nosatob has an impact at later periods in the forecast (figure 9(a)).

During previous discussions reference has been made to the increasing importance of satellite data on the ECMWF assimilation system. Figure 10 shows a comparison between the 1999 ECMWF OSEs and the present satellite OSEs. There is now a clear gap between the radiosonde and satellite data impact in all three areas. Also the improved skill of the latest control is evident.

Some important findings are:

The satellite data have more impact in the Northern Hemisphere than in previous OSEs even more than radiosondes and profilers combined.

In the four months of assimilation there are very few busts as defined by the anomaly correlation dropping less than 0.6 at day 4. The Southern Hemispheric forecasts are as good as the Northern Hemispheric forecasts.

The short range RMS wind and temperature forecasts are of excellent quality and show the importance of satellite data.

Early Delivery Observing System OSE

The performance of the 'Early Delivery System' (Figure 1(b)) has been found to be the same as the much later data cut off even though the forecast is run off an analysis containing little satellite data due to delays of reception and the cut off time.

It was considered important to examine the data impact with a small OSE to determine if the general conclusions found in the above OSEs run with the late data cut off are still valid. The reduced data analysis relies on the previous late cut off 12 hour run to pass the global satellite data via the guess forecast. This reduced set of OSEs (control, nosat and noupper) was run for one month but results give an indication of what to impact to expect, of course a longer run will be made later. Figure 13(a) shows the results for the 4 hour data cut off and figure 13(b) shows results with a similar set up to the previous OSEs but in a later period (march 2004). ECMWF found that with this configuration that the forecast quality does not suffer from the short 4 hour data cut due to lack data. It was not clear if the radiosonde data may be more important in the 6 hour 4DVAR but this does not appear to be so.

Conclusions

In the ECMWF operational system there is a strong dependence on satellite data but radiosonde and profiler data are still important. The impact of aireps and satobs is positive.

The forecast improvement with time, as shown by ERA40, show the increasing importance of satellite and new conventional measurements.

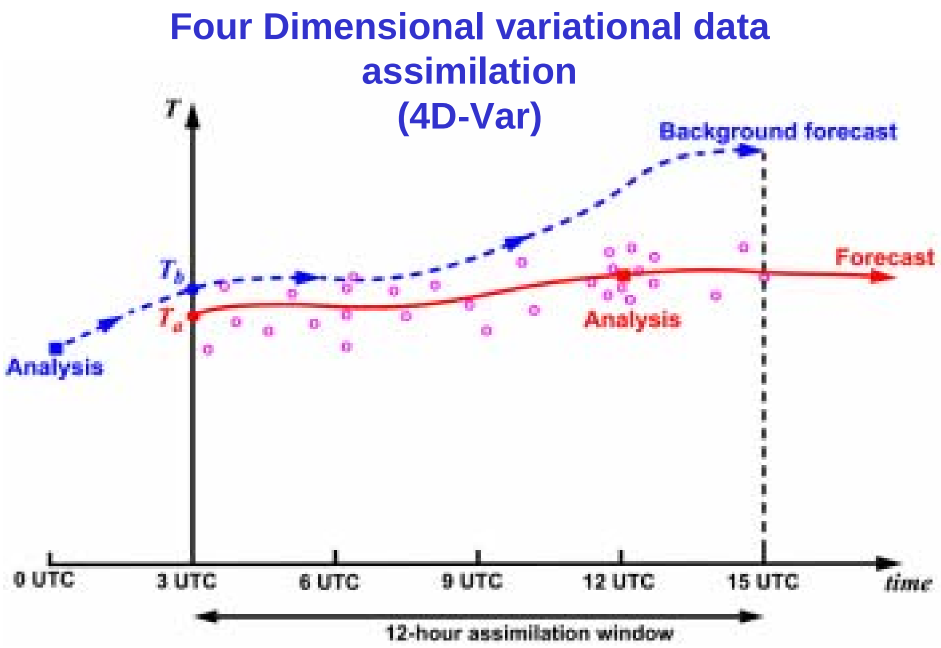
With the current ECMWF system the global network of AMSU-A radiances are the most important of the satellite measurements, however if they are all removed the Northern Hemispheric forecasts are only slightly degraded. In the Southern Hemisphere there is more loss of forecast skill.

The impact of the global geostationary radiances is mostly on the upper level humidity fields.

The AIRS clear radiances have little impact on the full system based on the results presented. If all satellite radiances are removed and AIRS added then some positive impact can be found in the Southern Hemisphere.

The general conclusions of the large OSEs appear still valid for the ECMWF 'Early Delivery system'. The lack of satellite data in the early analysis is compensated through the guess from the previous late data cut off.

New OSEs are required on an on-going basis to understand the relative importance of various components of the current observing system.



Forecast TL511 (~40km) 60 levels analysis TL159 (~80km)

Figure 1 (a) ECMWF assimilation system summer 2004.

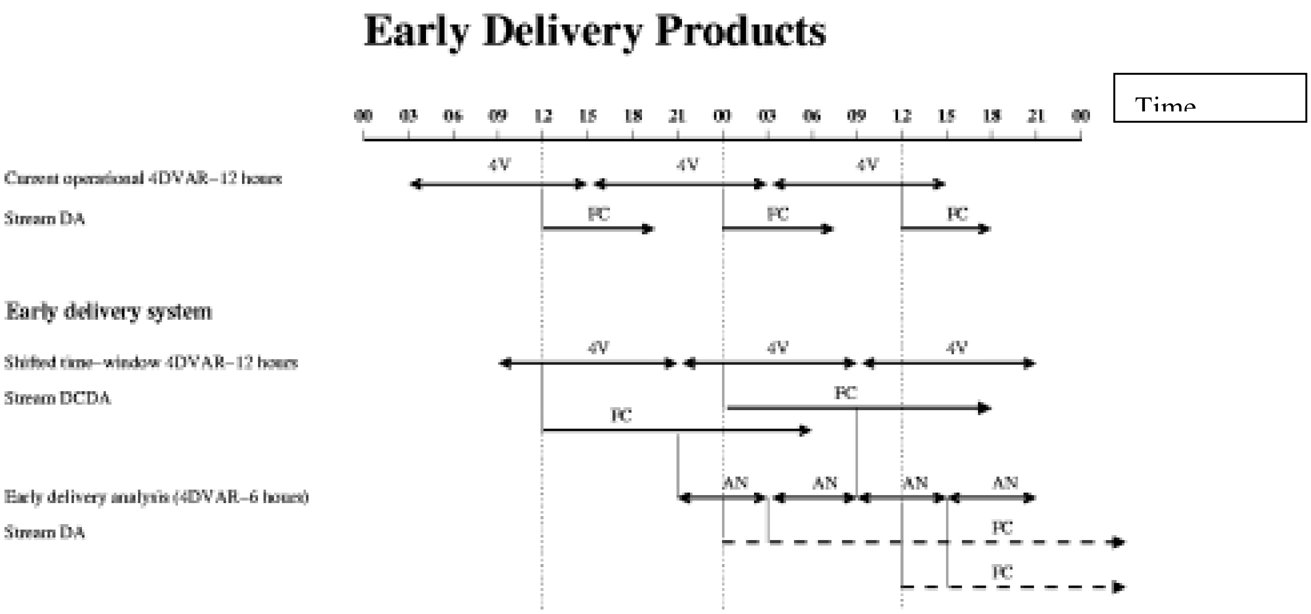


Figure 1(b) 'Early Delivery System' after Summer 2004.

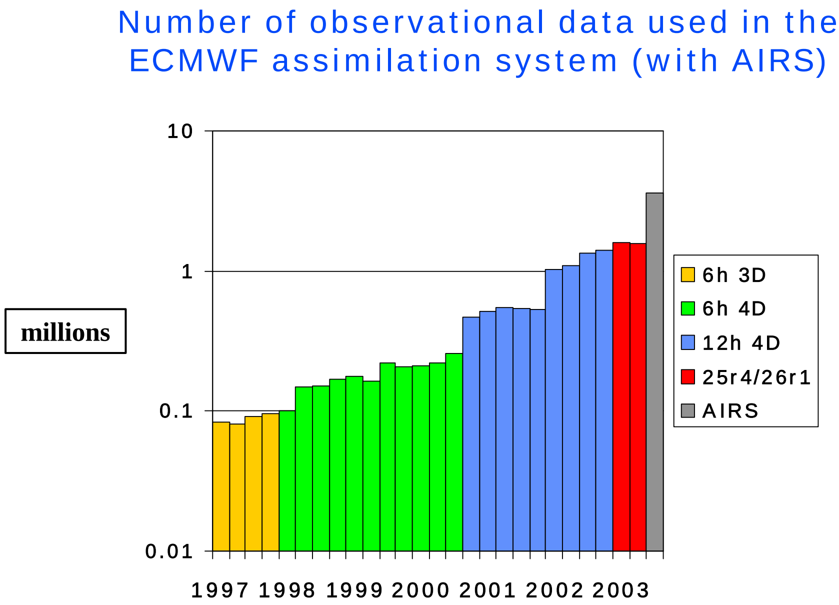


Figure 2(a) Resent Growth of observational usage and ECMWF assimilation changes.

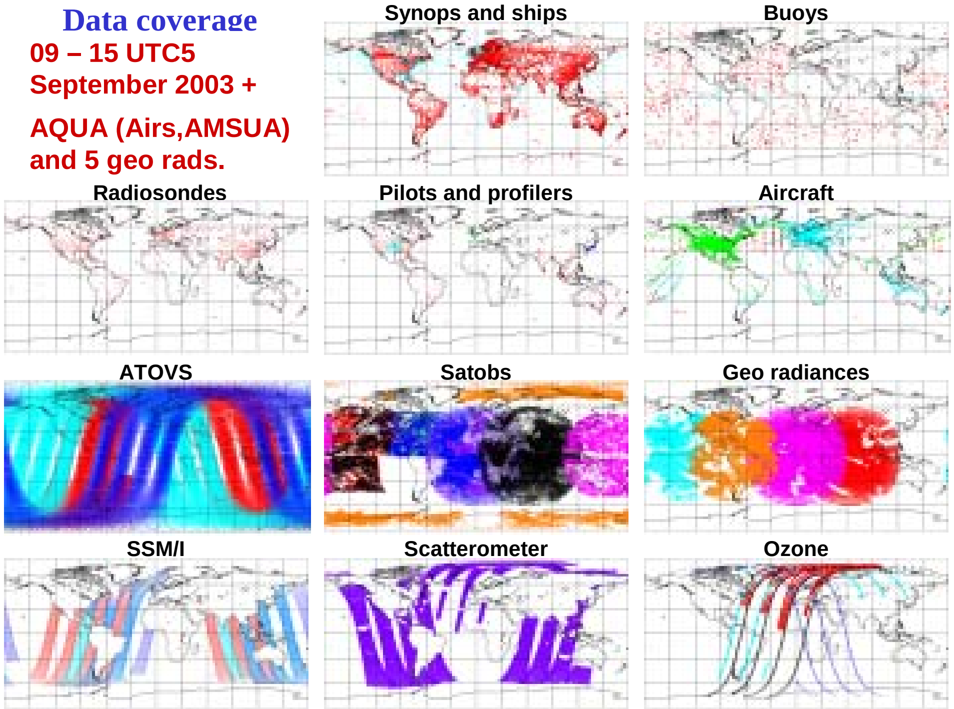


Figure 2(b) Date coverage for a typical six hour period of data used in operations on 5-10-2003.

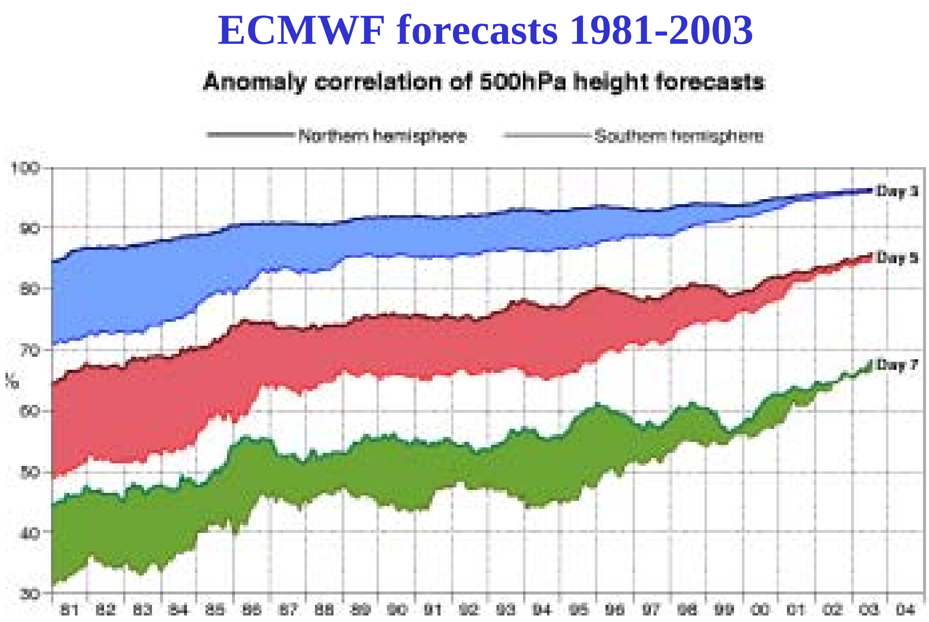


Figure 3(a) Improvement in 500 hPa height anomaly ECMWF forecasts (1981-2003).

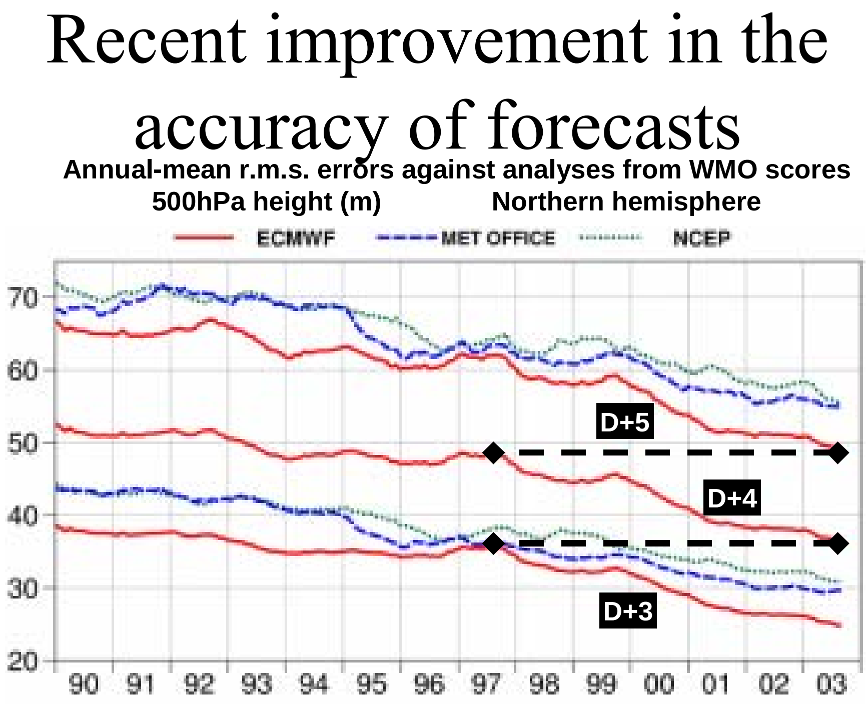


Figure 3(b) Improvement in 500 hPa rms error of ECMWF forecasts (1981-2003).

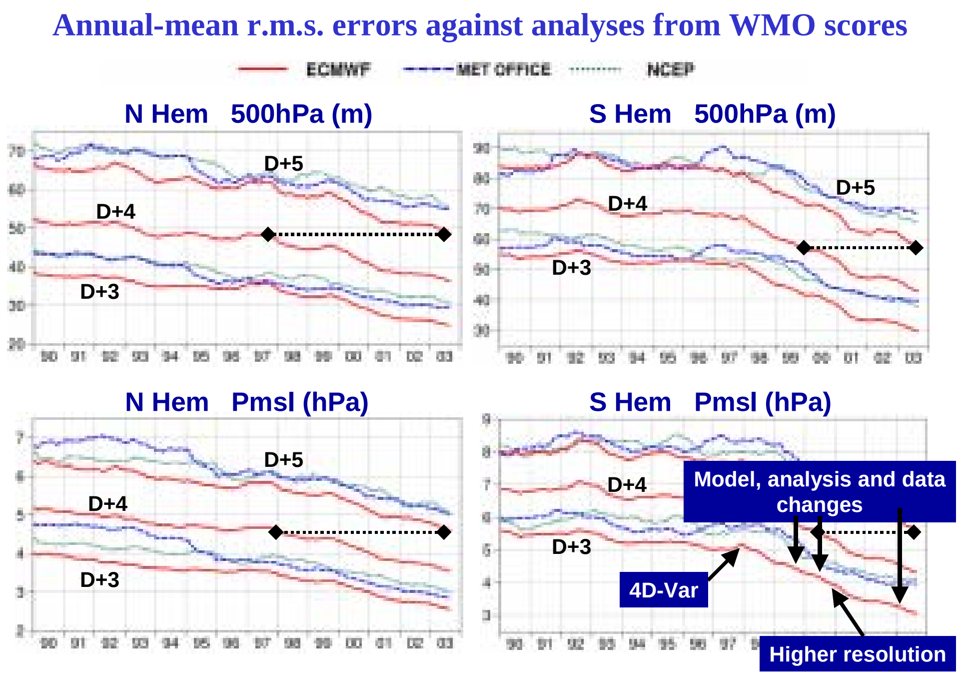


Figure 3(c)Improvement in 500 hPa rms error of ECMWF forecasts (1981-2003).

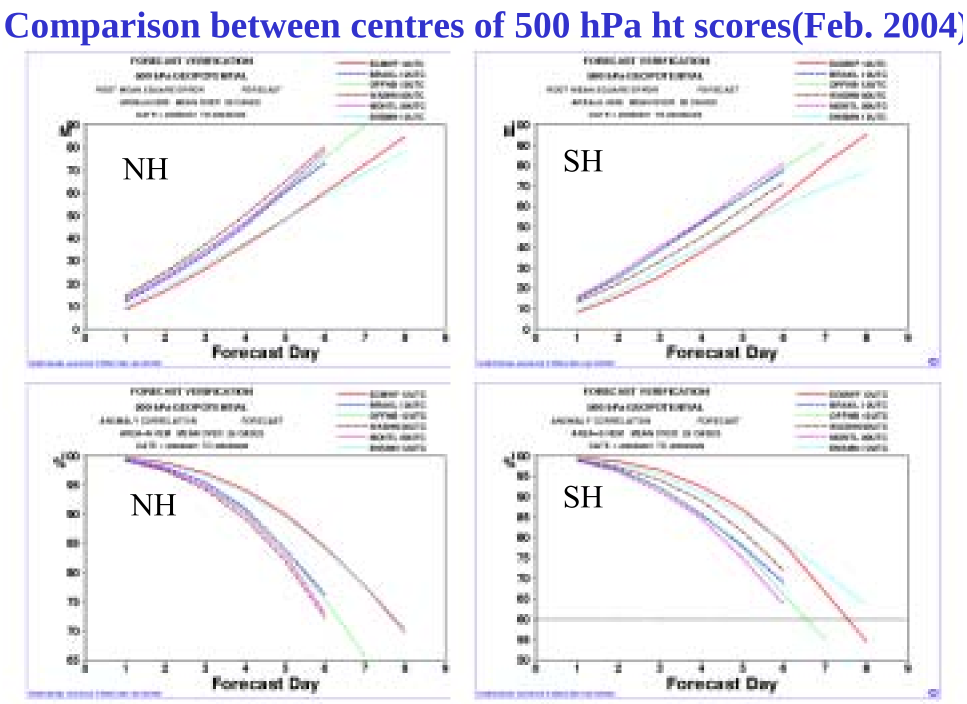


Figure 3(d) Comparison of 500 hPa scores for other centers for February 2004.

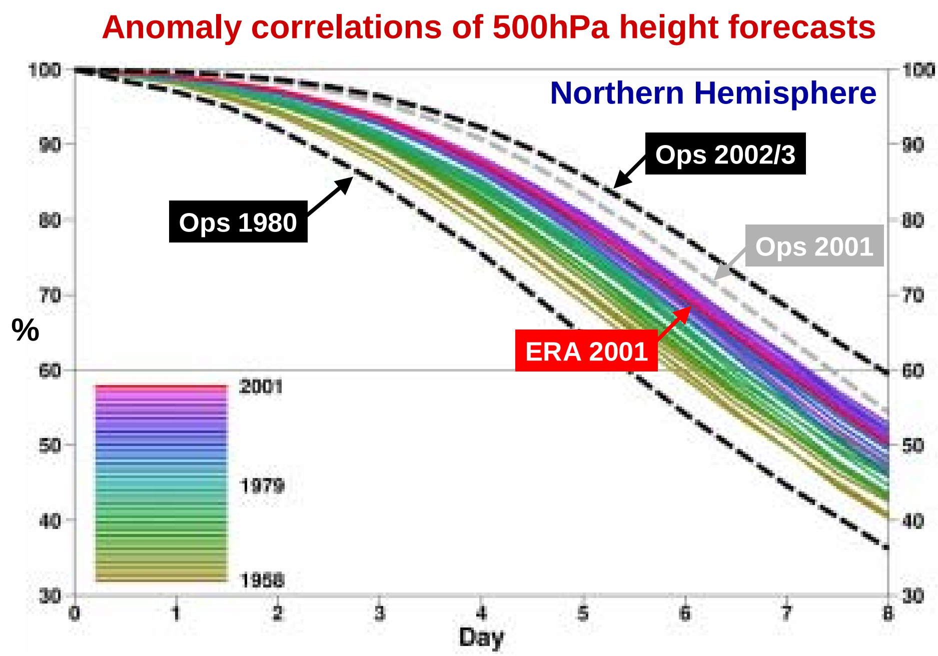


Figure 4(a) ERA40 forecast scores for Northern Hemisphere.

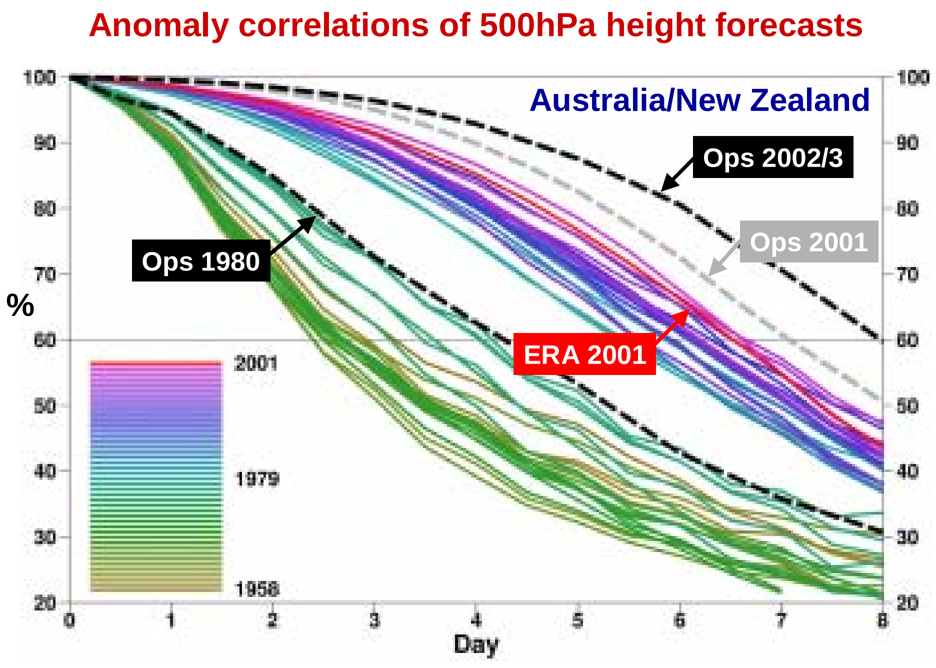


Figure 4(b) ERA40 forecast scores for Southern Hemisphere.

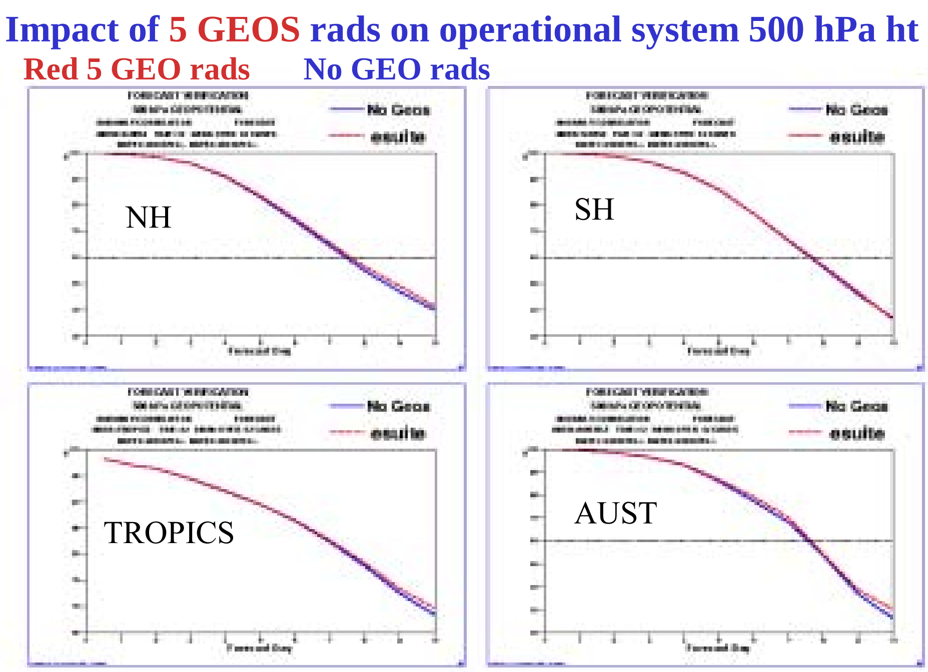


Figure 5(a) Impact of water vapor geostationary radiances on 500 hPa anomaly correlation for 62 cases.

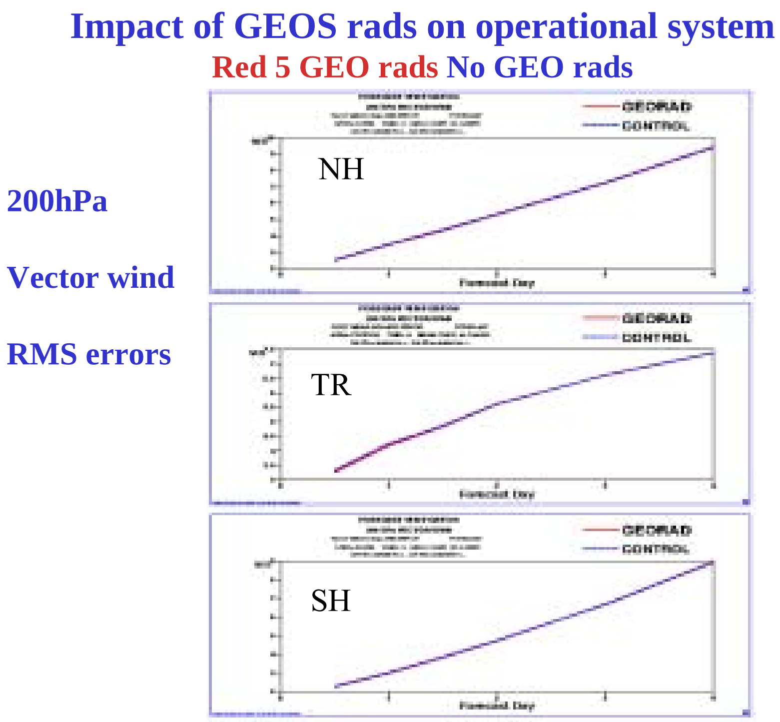


Figure 5(b) Impact of water vapour geostationary radiancies (200 hPa vector wind for 62 cases).

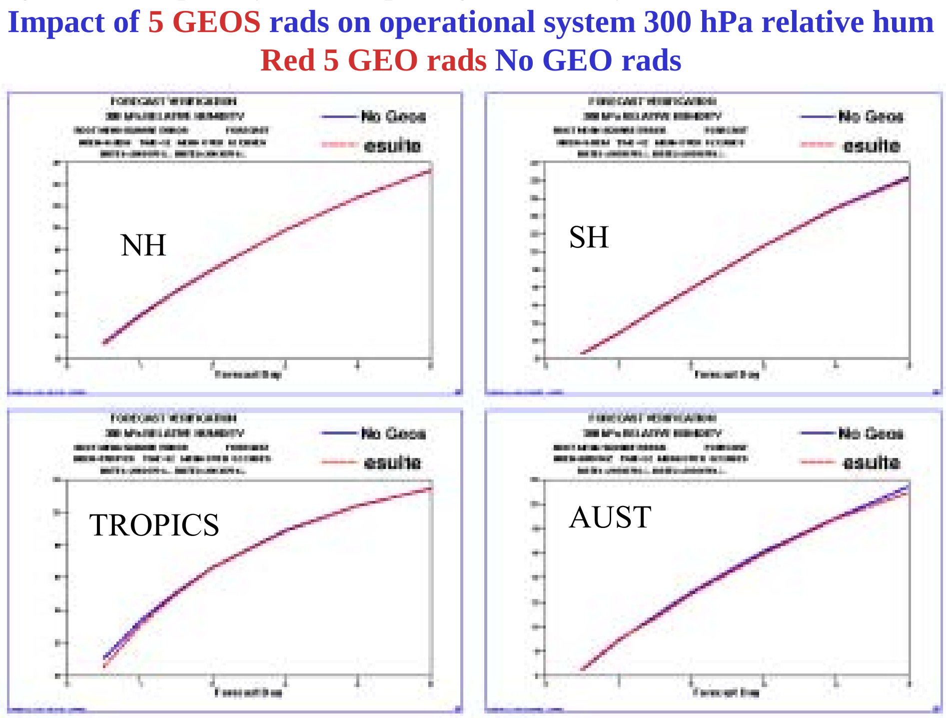


Figure 5(c) Impact of geostationary radiances on operational system 300 hPa relative hum (62 cases)

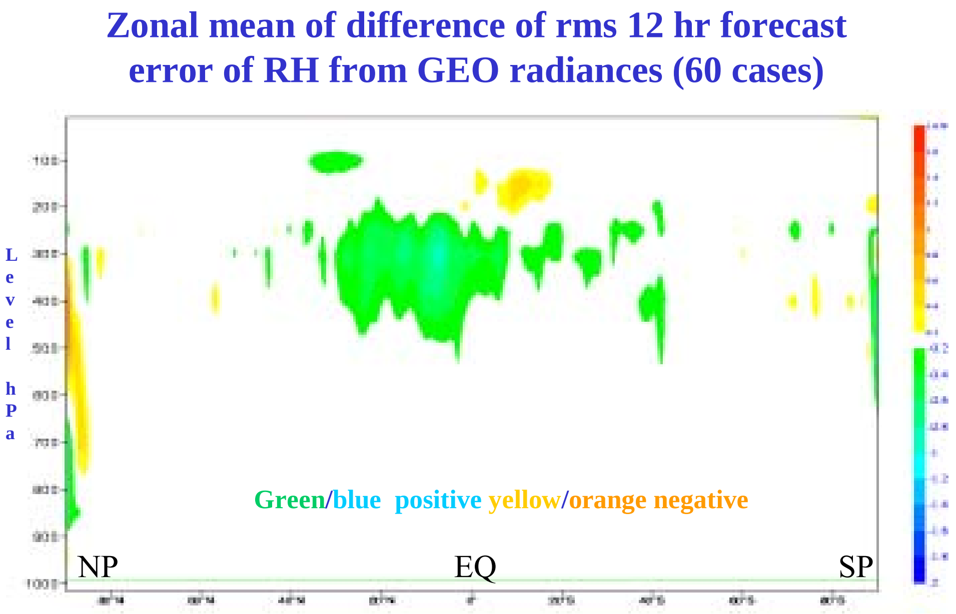
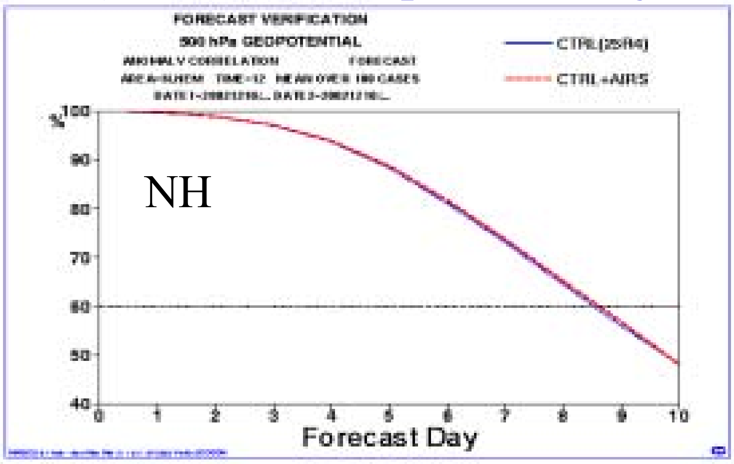


Figure 5(d) Difference of rms 12 hr forecast error of RH for geostationally radiances and control.

Impact of AIRS (100 cases) on operational system 500 hPa geo

RED
AIRS

BLUE
OPS



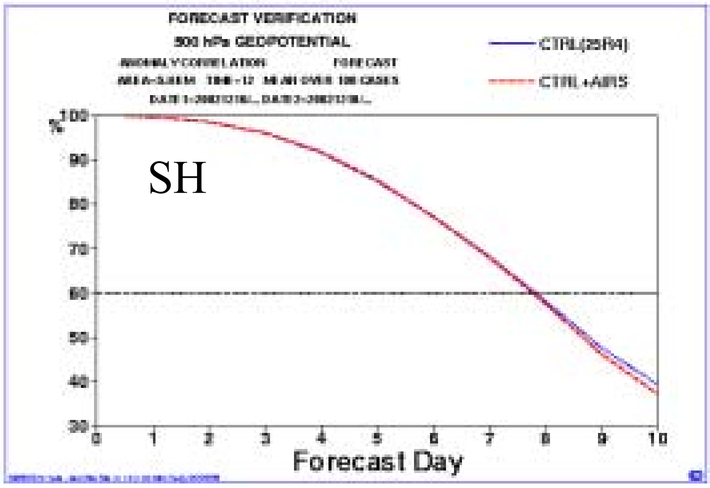


Figure 6(a) Impact of AIRS on the operational system (500 hPa geopotential anomaly correlation for 100 cases).

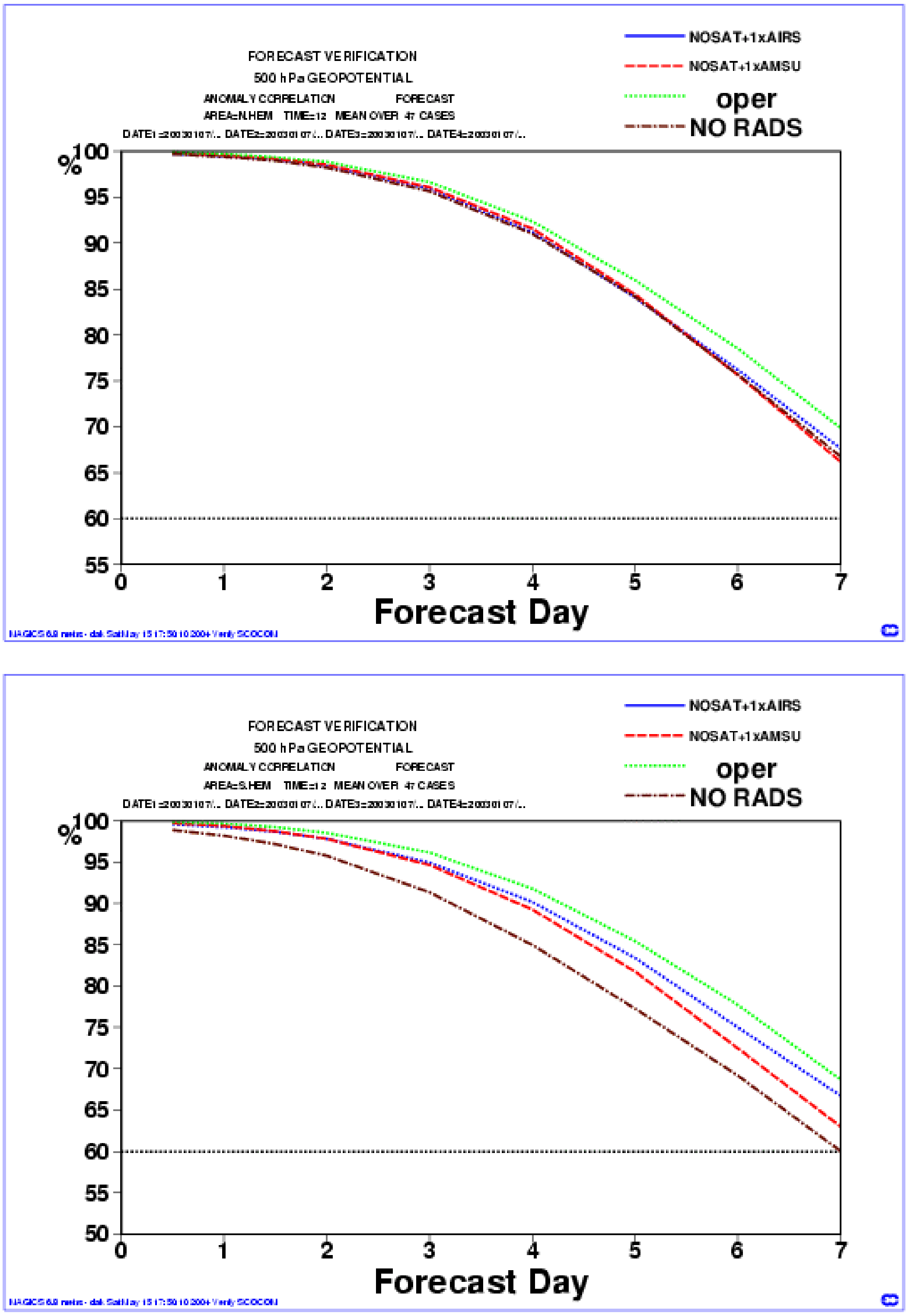
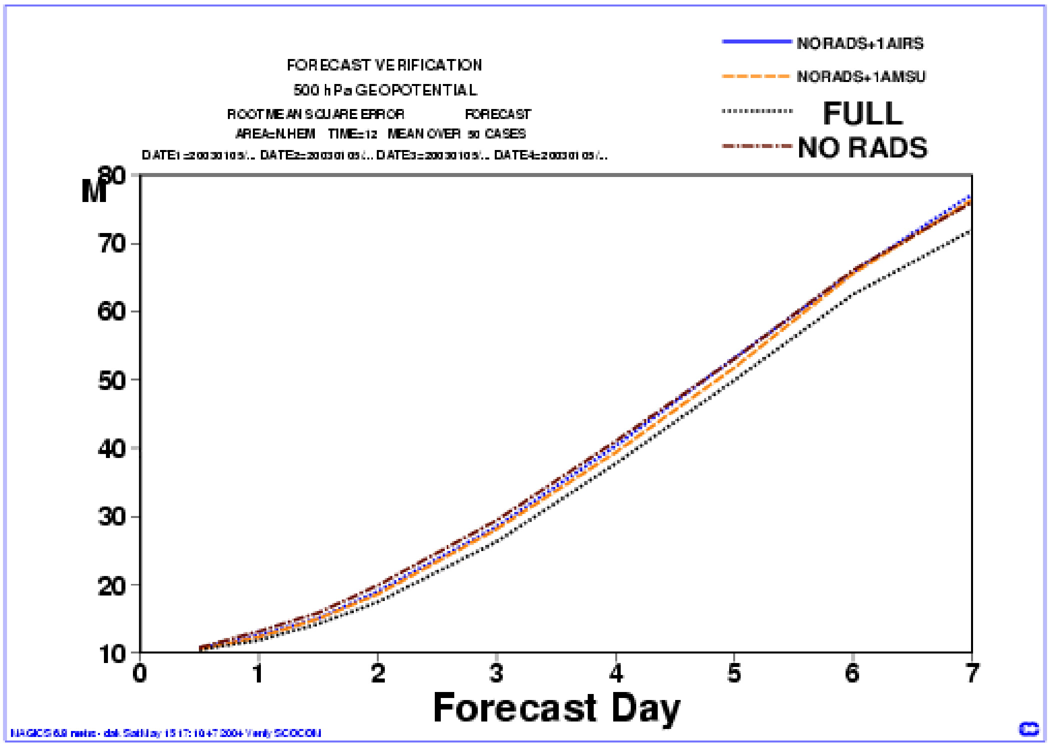


Figure 6(b) Impact of single instrument on a minimal system verified using operational analyses (47 cases).



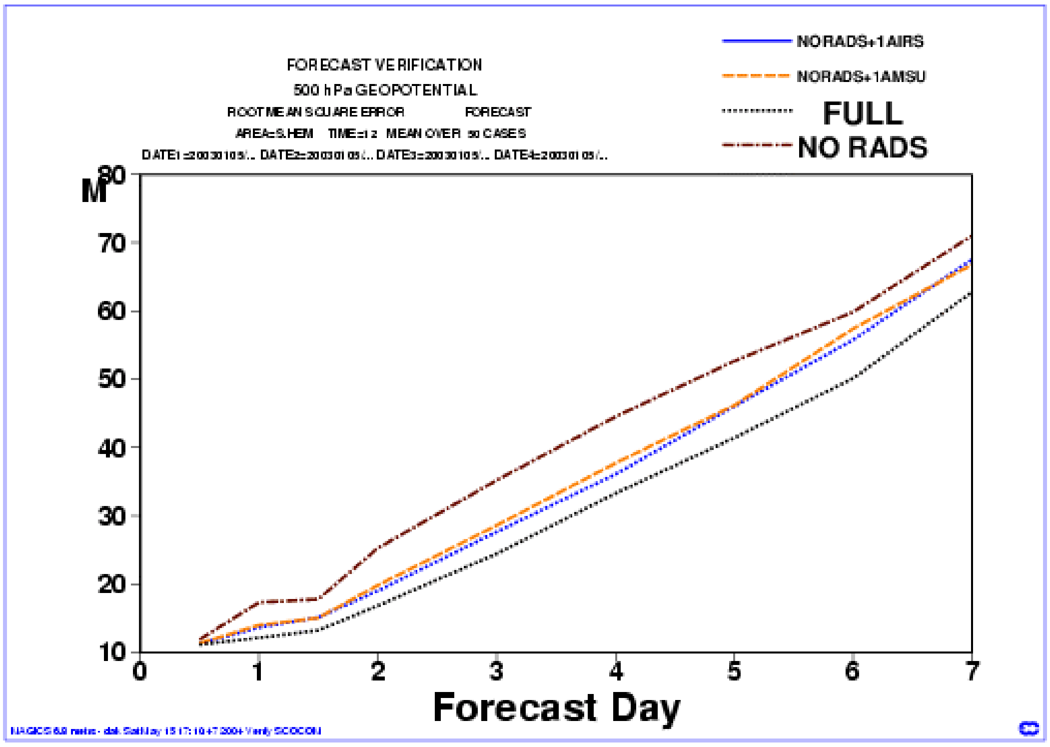


Figure 6(c) Impact of single instrument on a minimal system verified using radiosondes (50 cases).

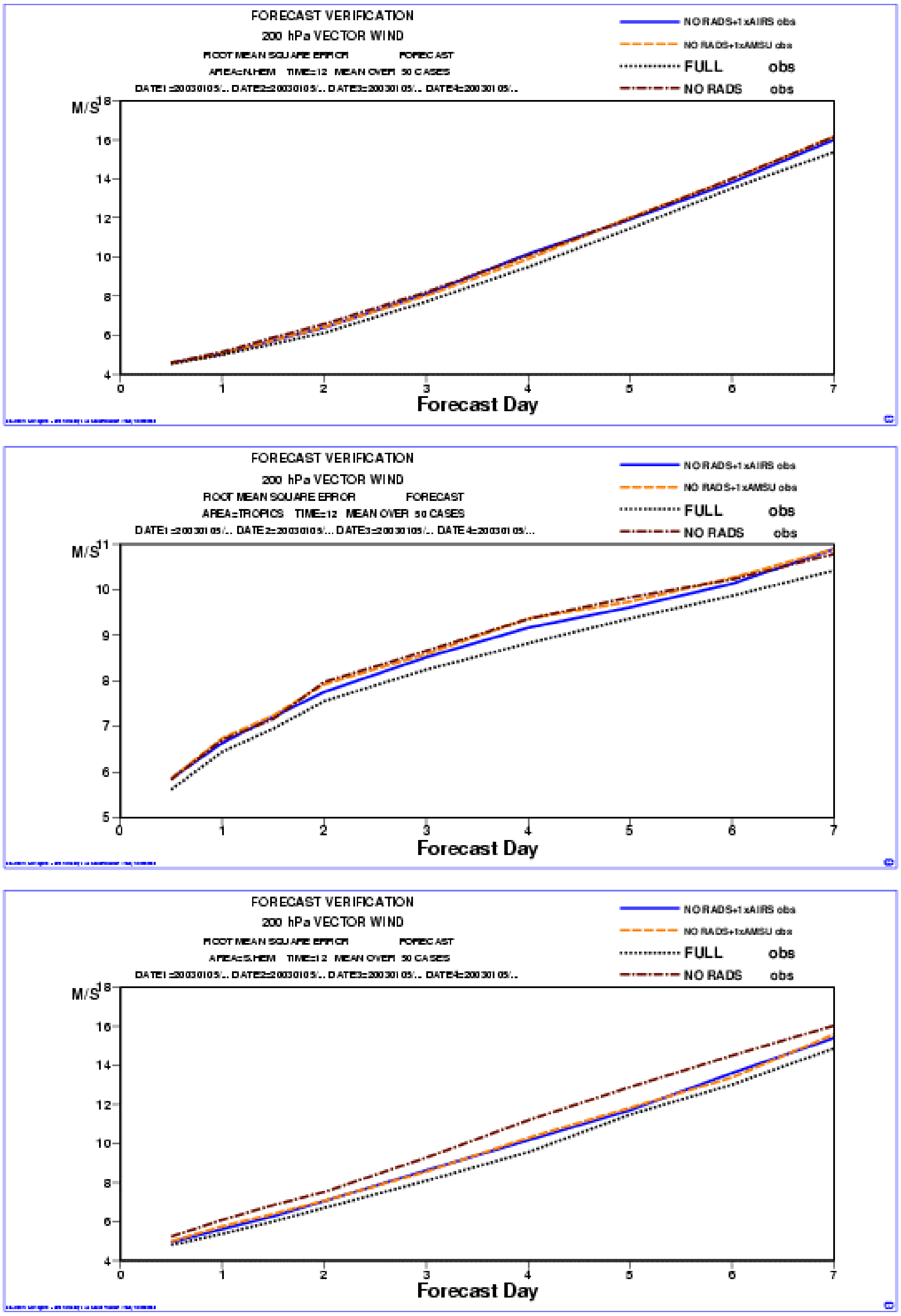
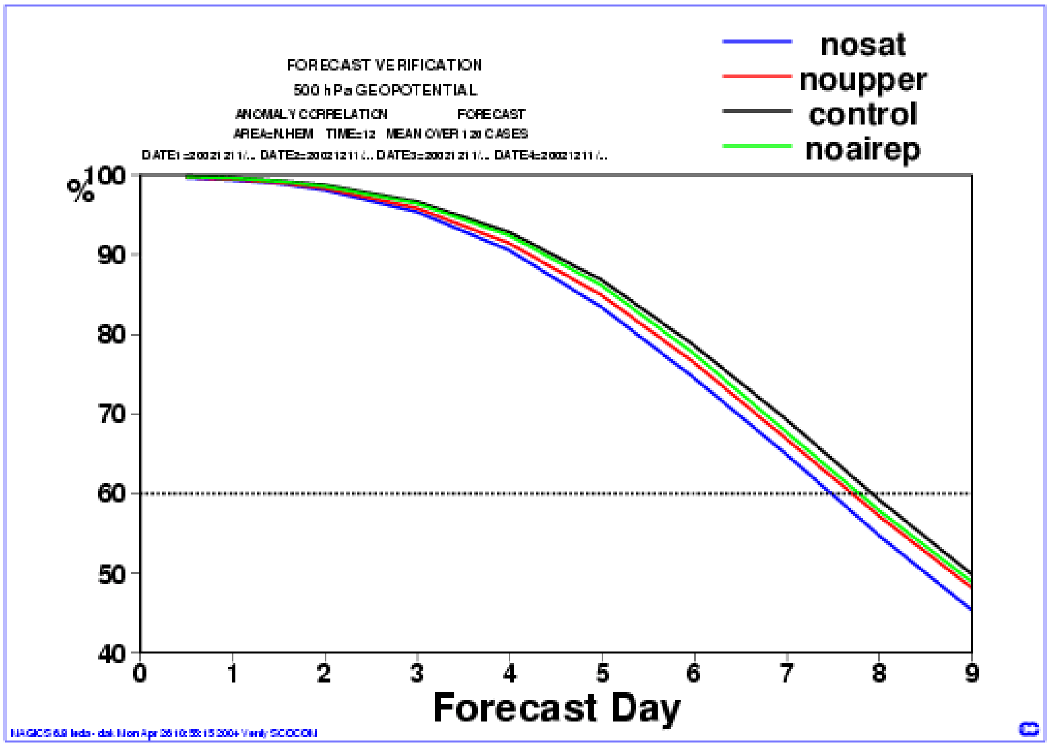


Figure 6(d) Impact of single instrument on a minimal system verified using radiosondes (50 cases)



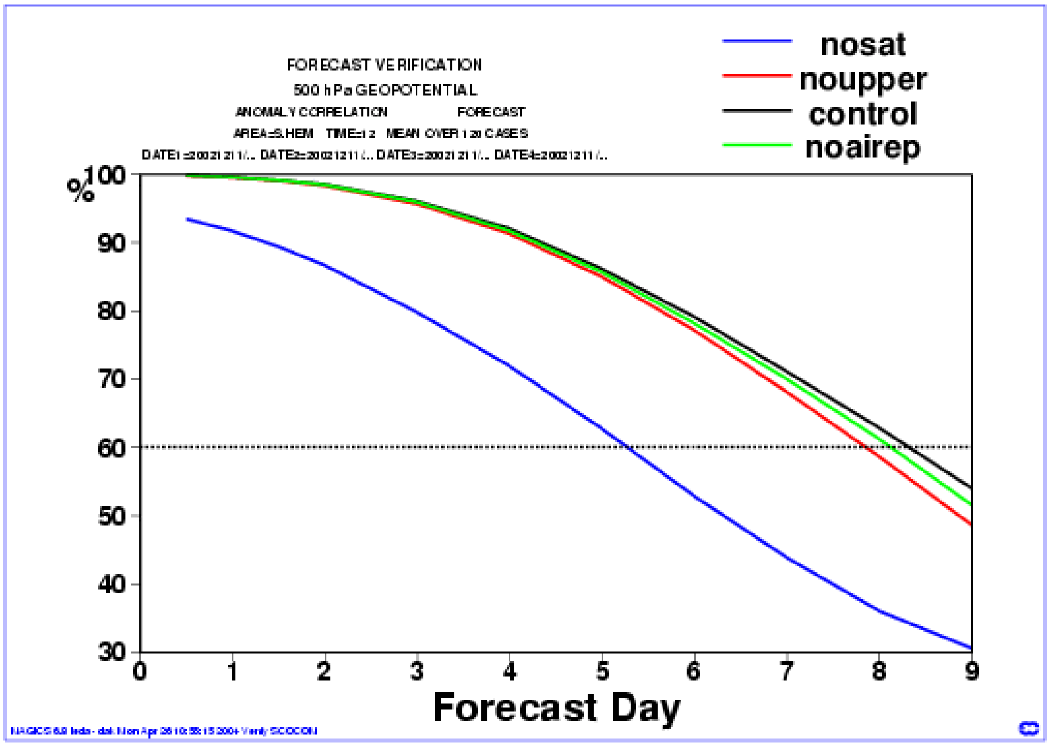


Figure 7(a) Hemispheric 500hPa anomaly correlation 120 day OSE experiment verified using operational analysis (120 cases).

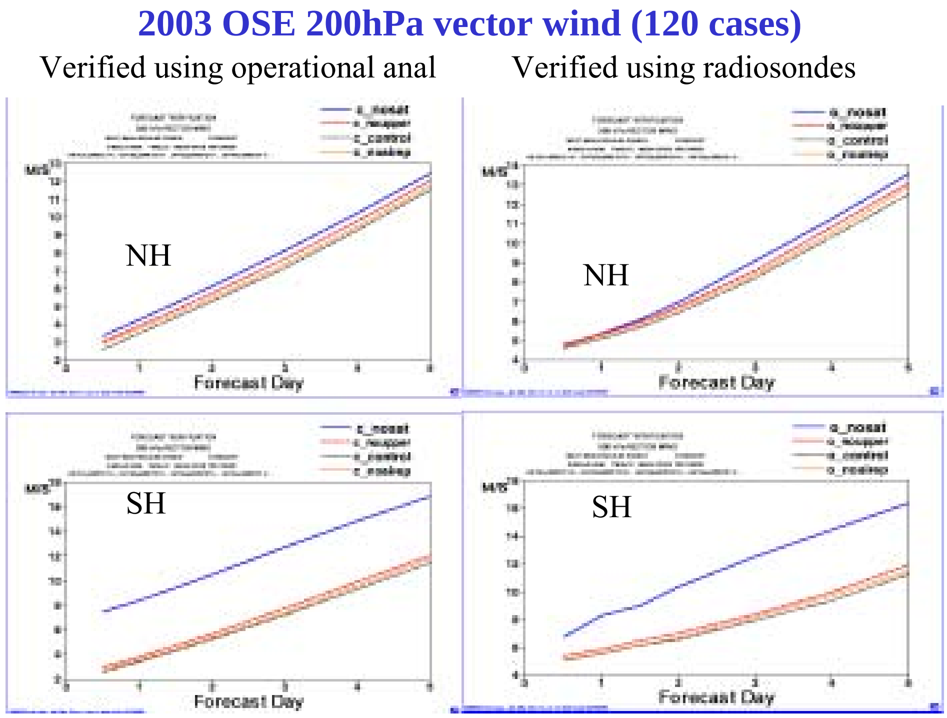


Figure 8(a) Hemispheric 200hPa vector wind 120day OSE experiment verified using radiosondes (120 cases).

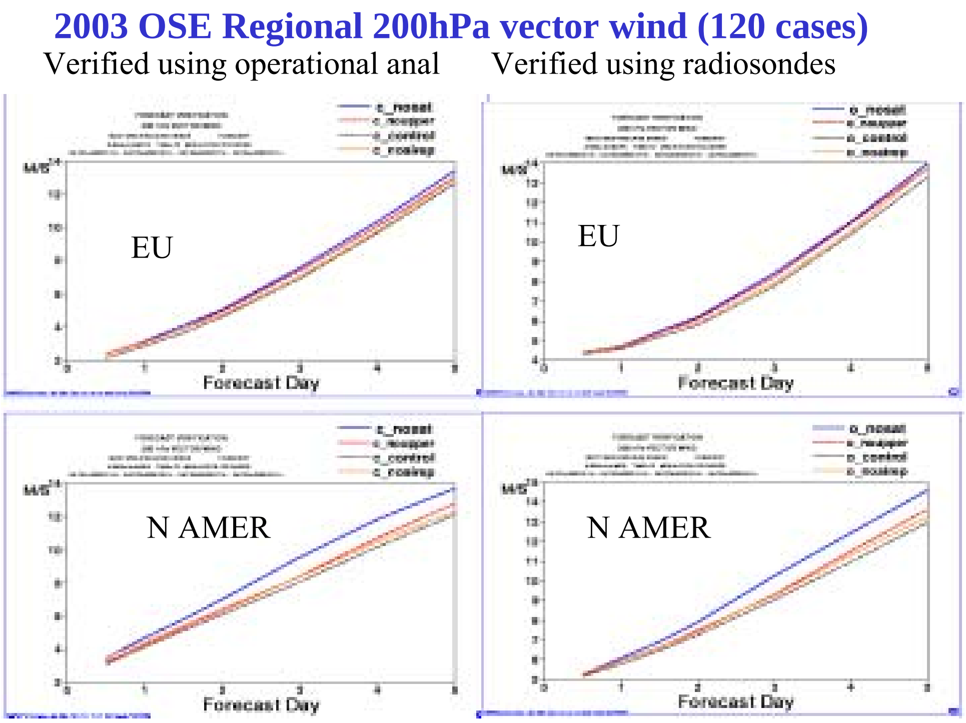
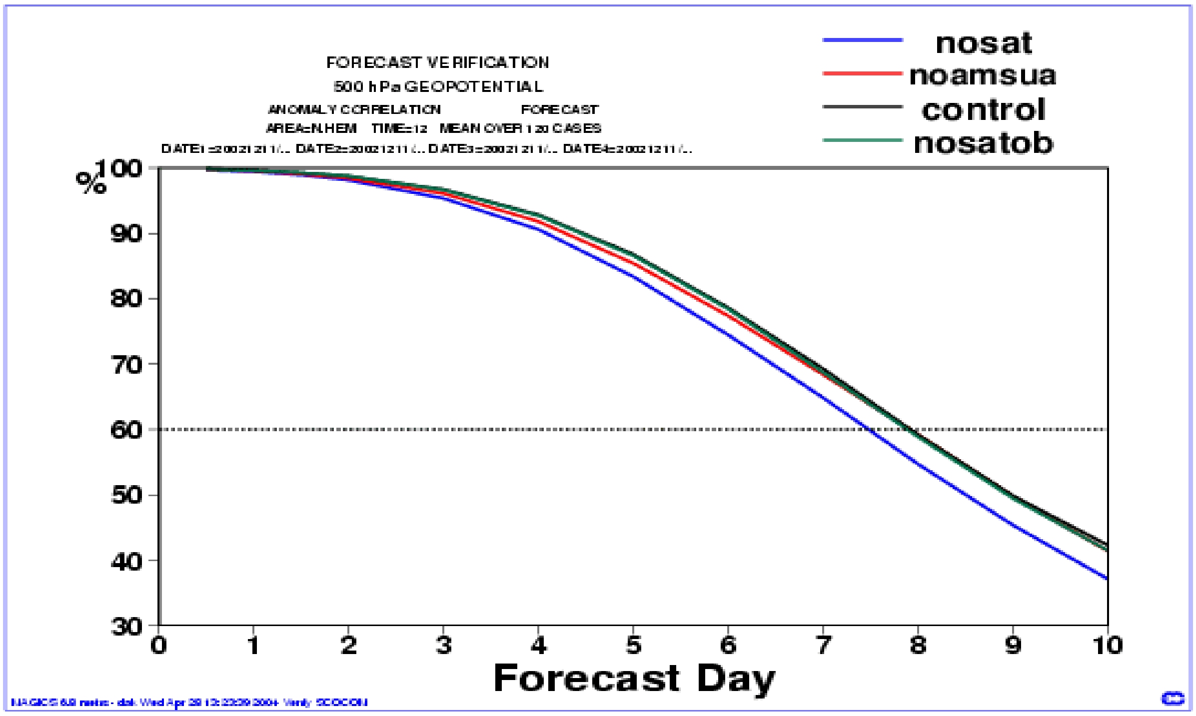


Figure 8(b)Regional 500hPa anomaly correlation 120day OSE experiment verified using radiosondes(120 cases).



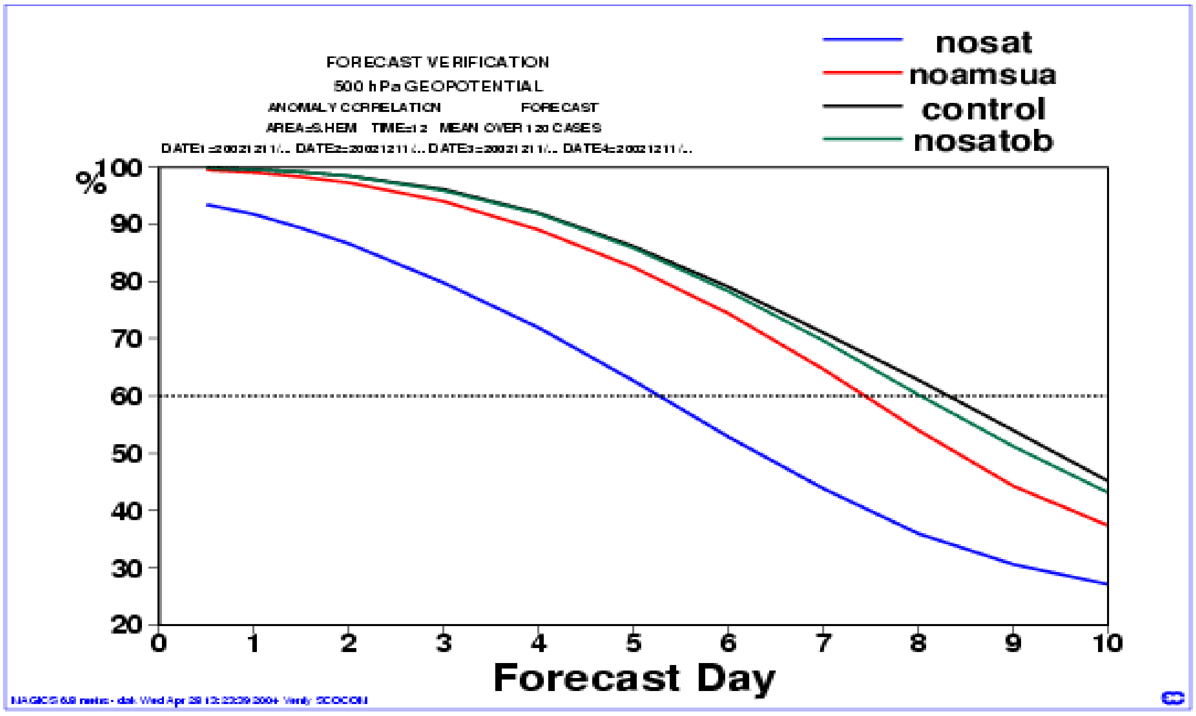
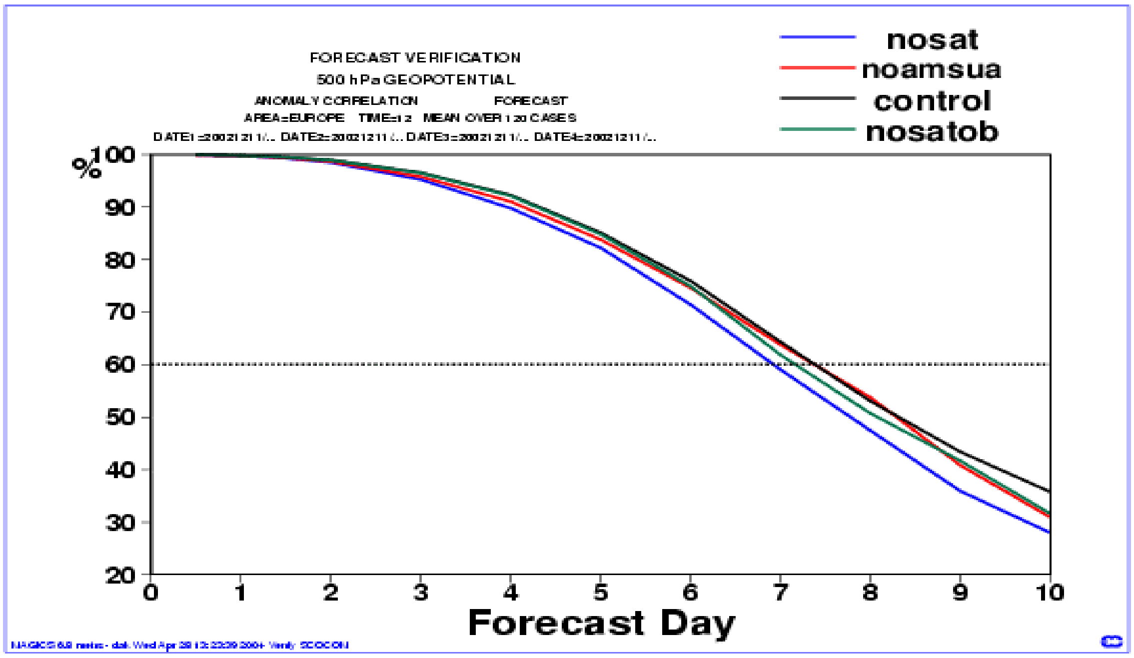


Figure 9(a) Hemispheric 500hPa anomaly 120day OSE experiment verified using operational analysis (120 cases).



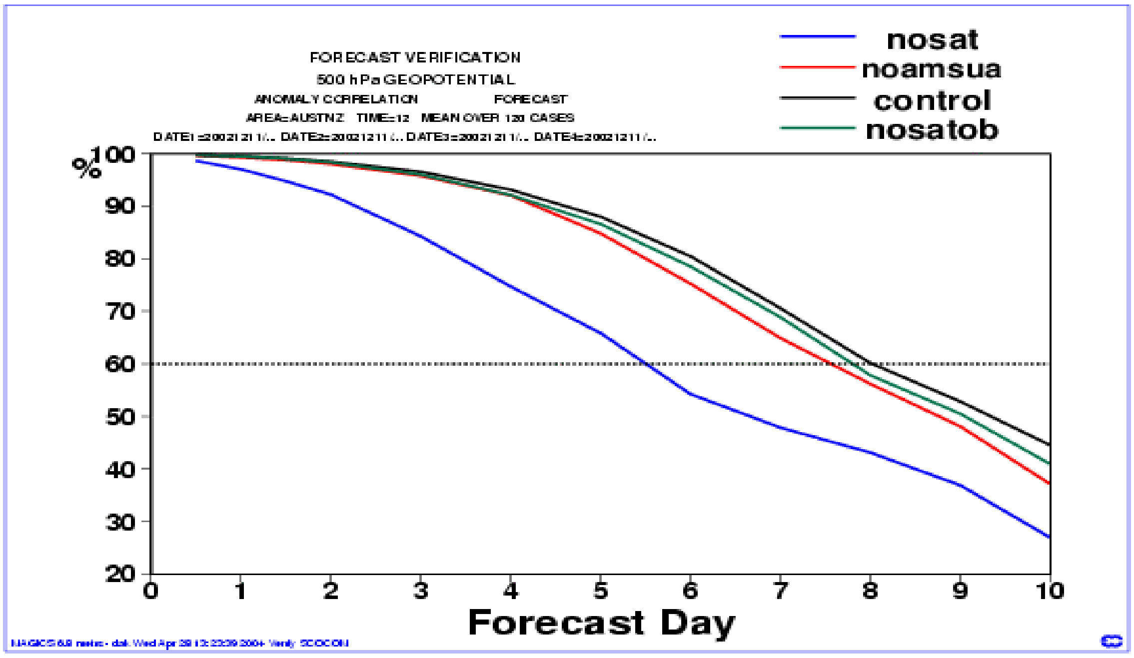
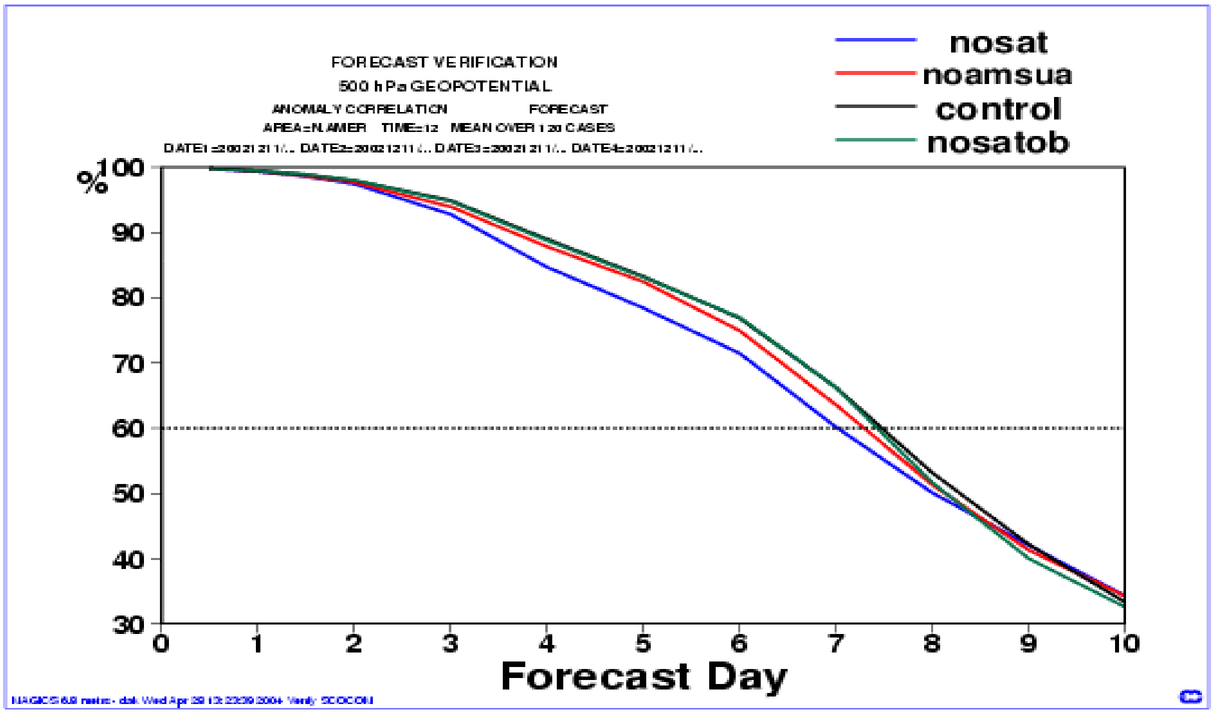


Figure 9(b) Regional 500hPa anomaly 120day OSE experiment verified using analysis (120 cases).



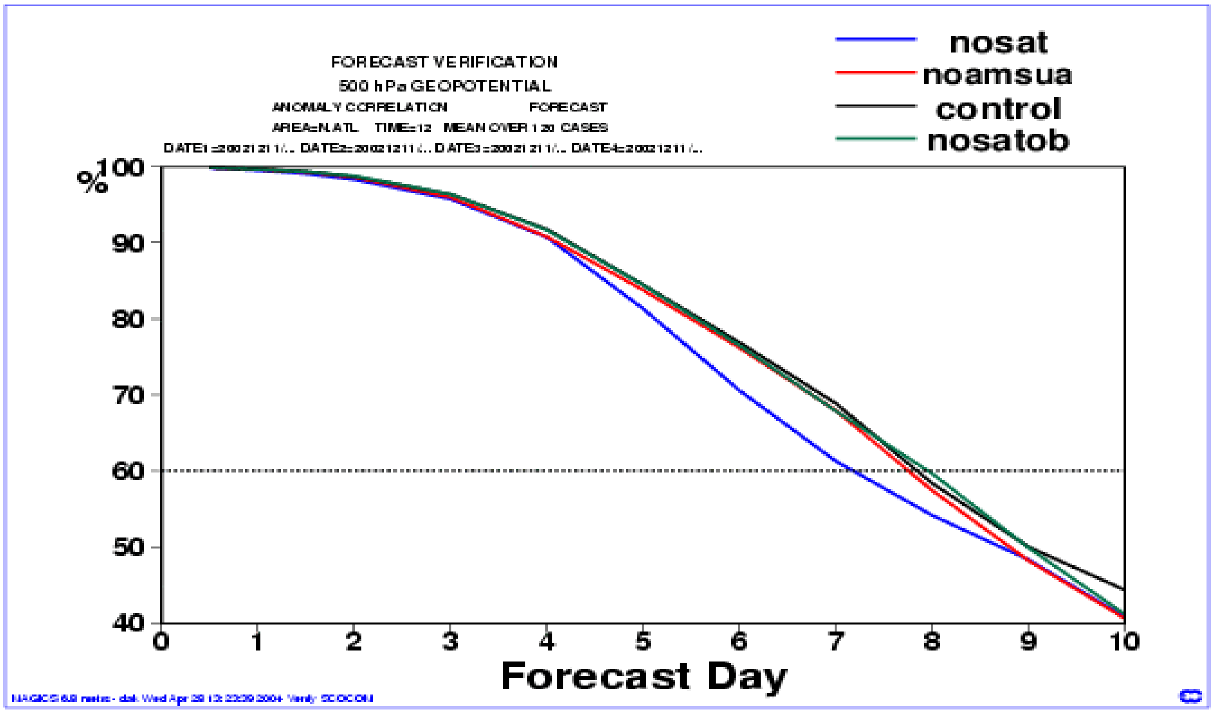


Figure 9(c) Regional 500hPa anomaly 120day OSE experiment verified using operational analysis (120 cases).

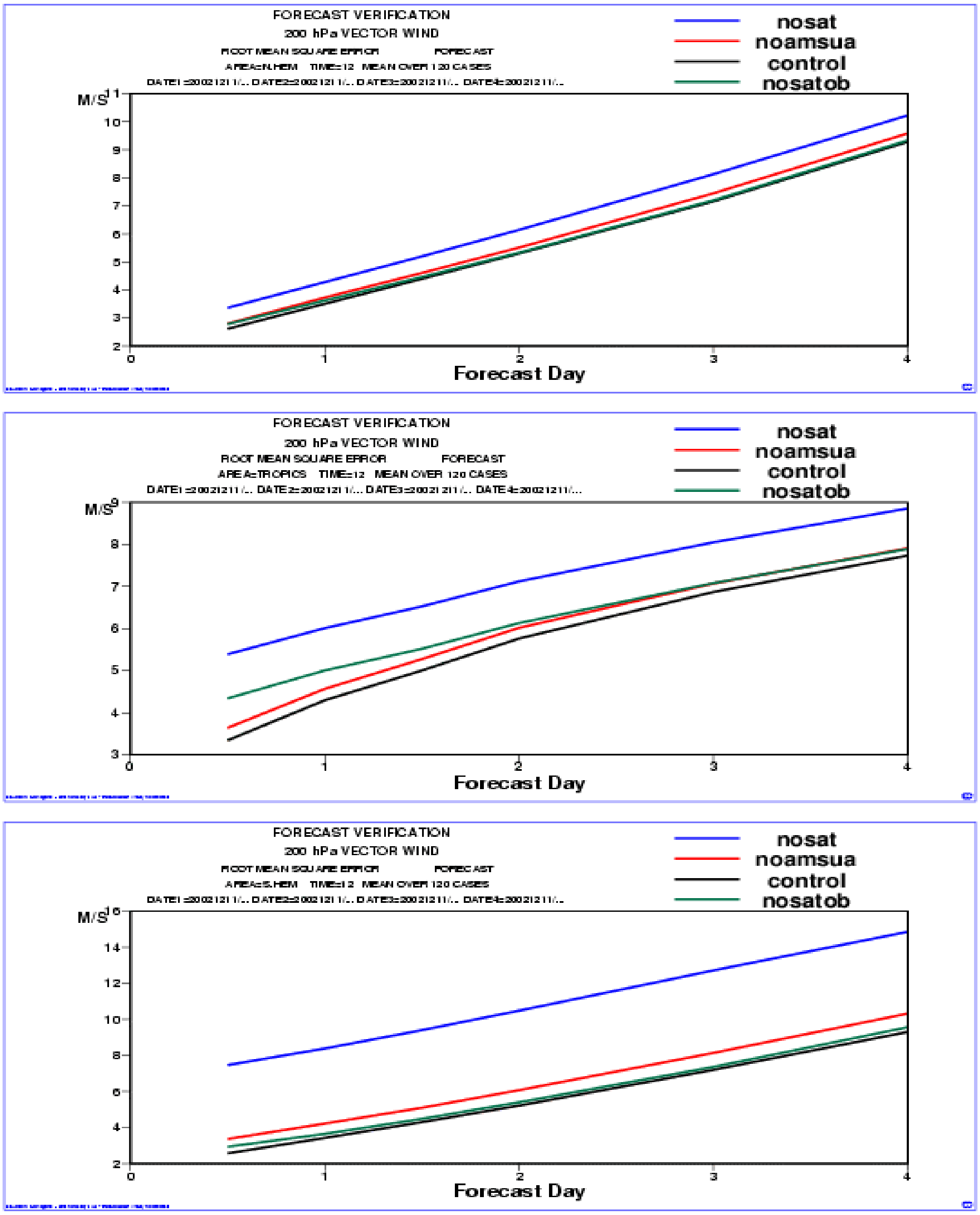


Figure 9(d) Hemispheric 200hPa vector wind 120day OSE experiment (120 cases).

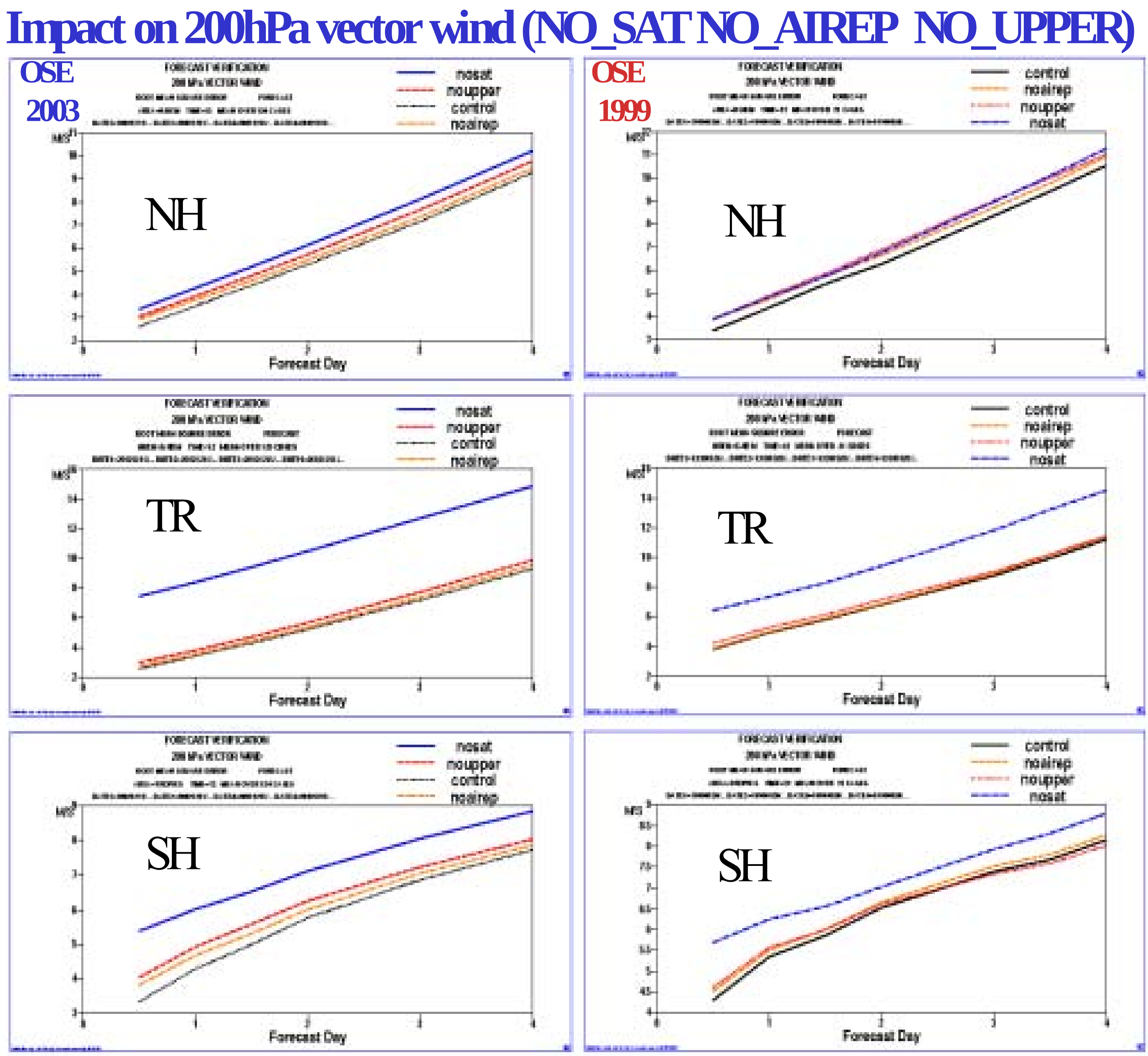


Figure 10 Comparsion of 2003 and 1999 hemispheric 200hPa vector wind OSEs experiments verified using operational analyses.

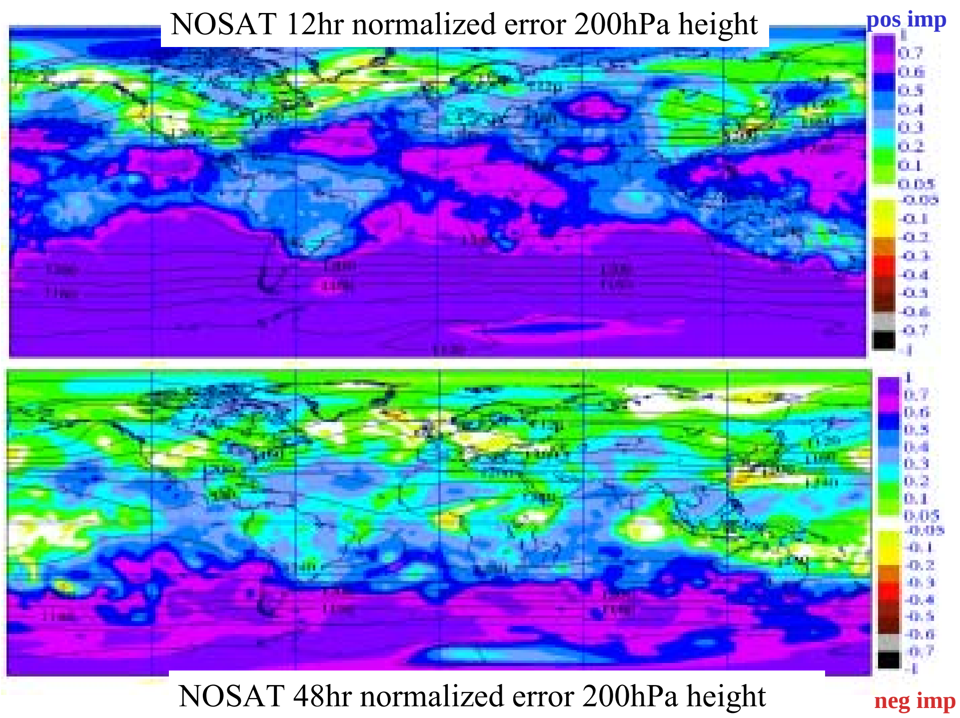


Figure 11(a) NO SAT Normalized error 200hPa height

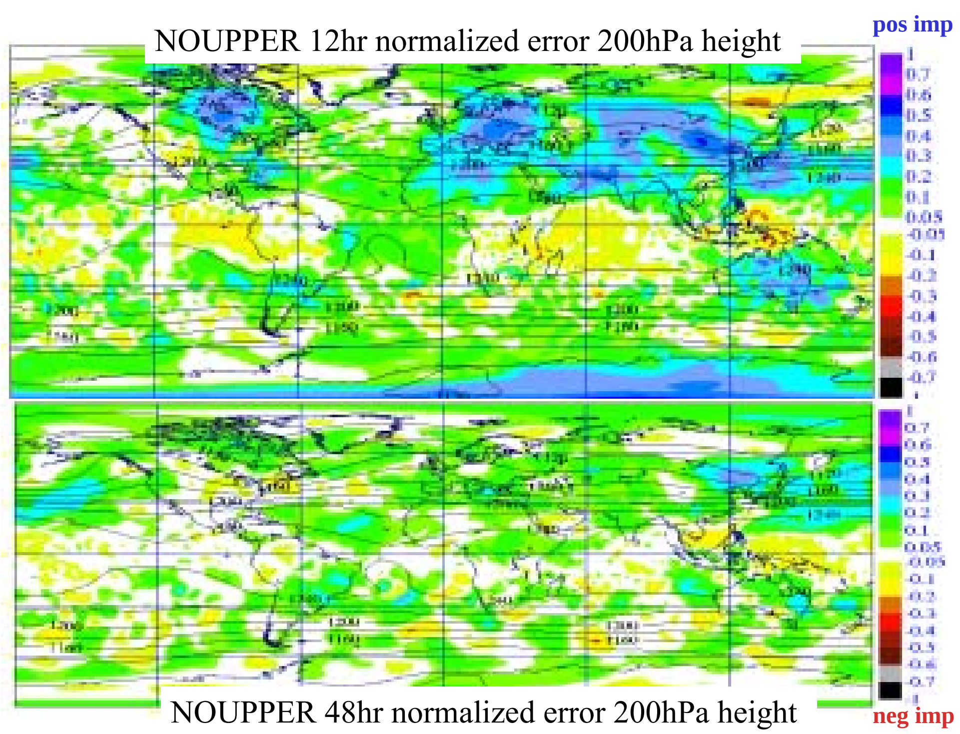


Figure 11(b)NO UPPER Normalized error 200hPa height

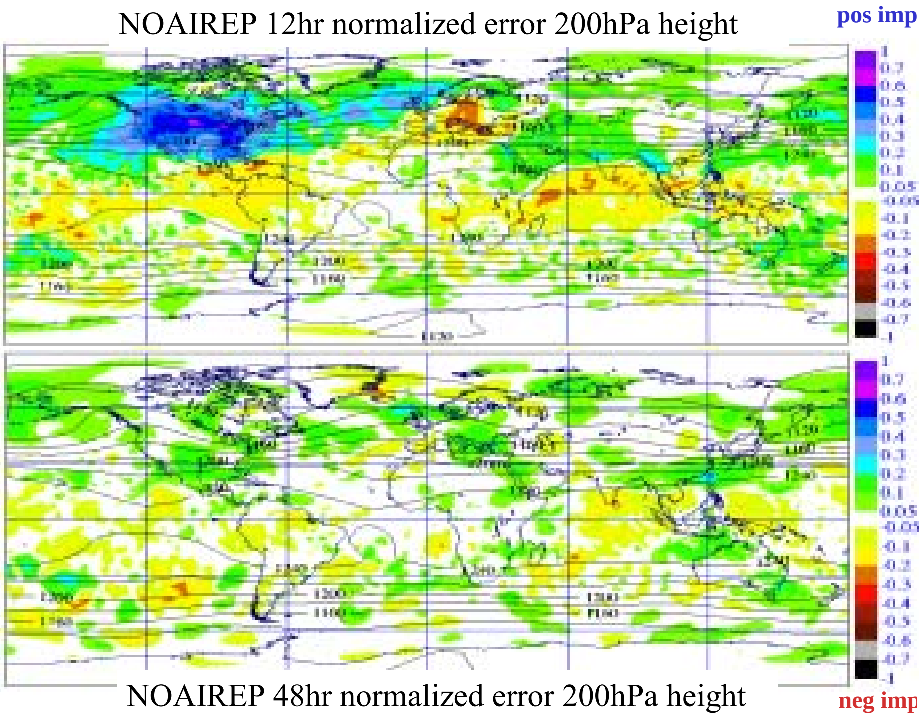


Figure 11 (c)NO AIREP Normalized error 200hPa height

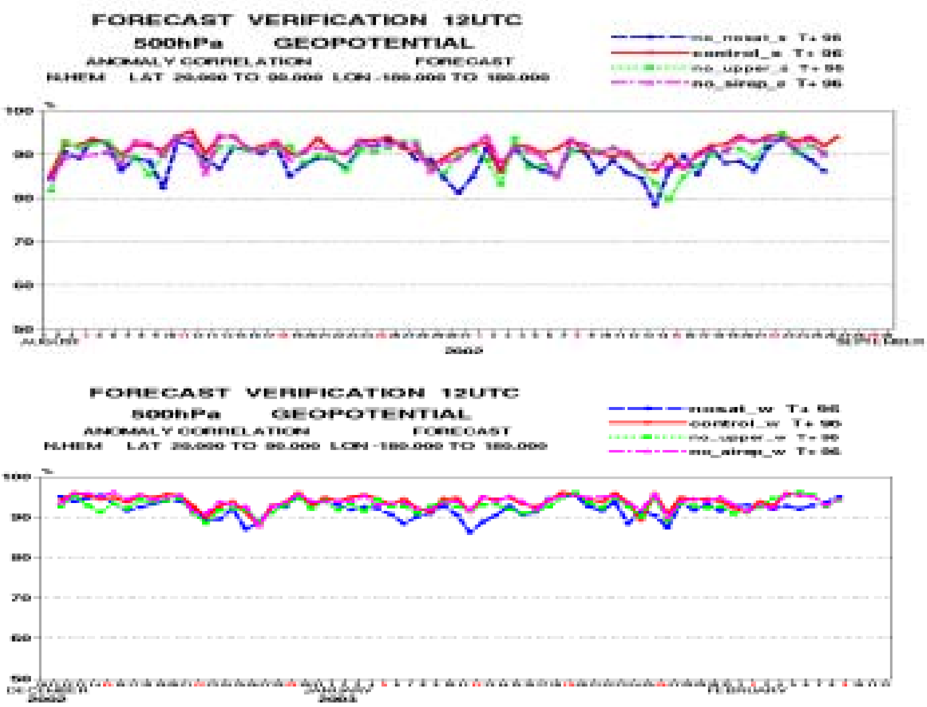


Figure 12(a)Time series of 500 hPa height anomaly correleration

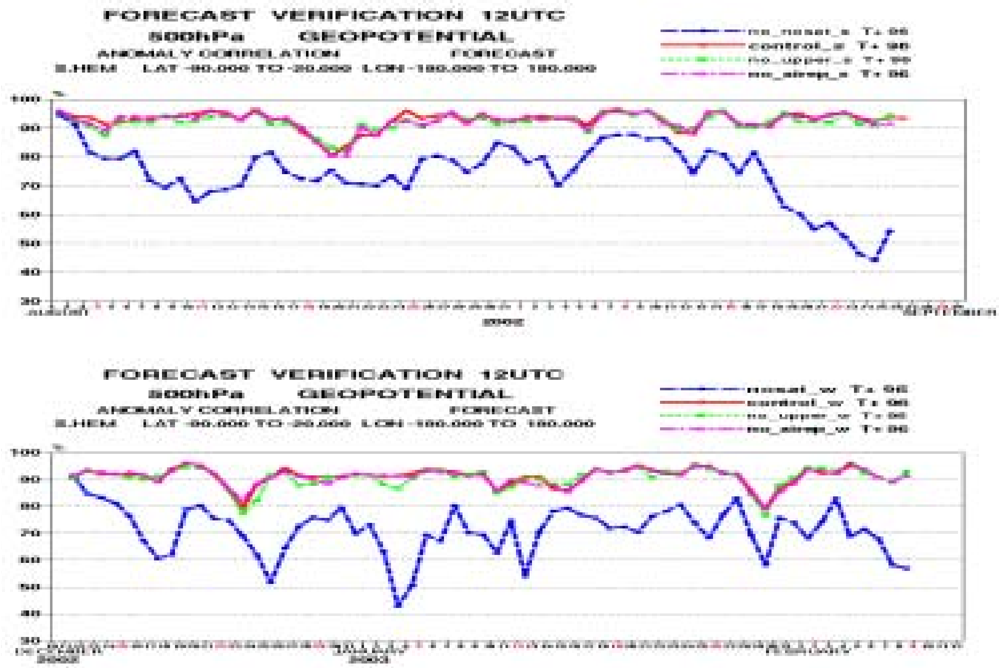


Figure 12(b)Time series of 500 hPa height anomaly correleration

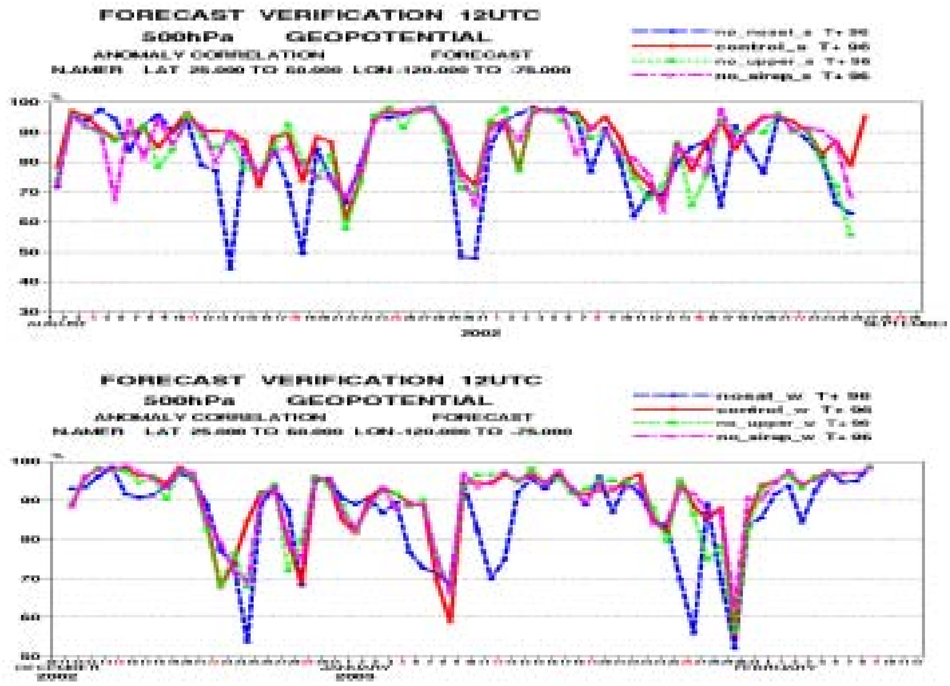


Figure 12(c)Time series of 500 hPa height anomaly correleration

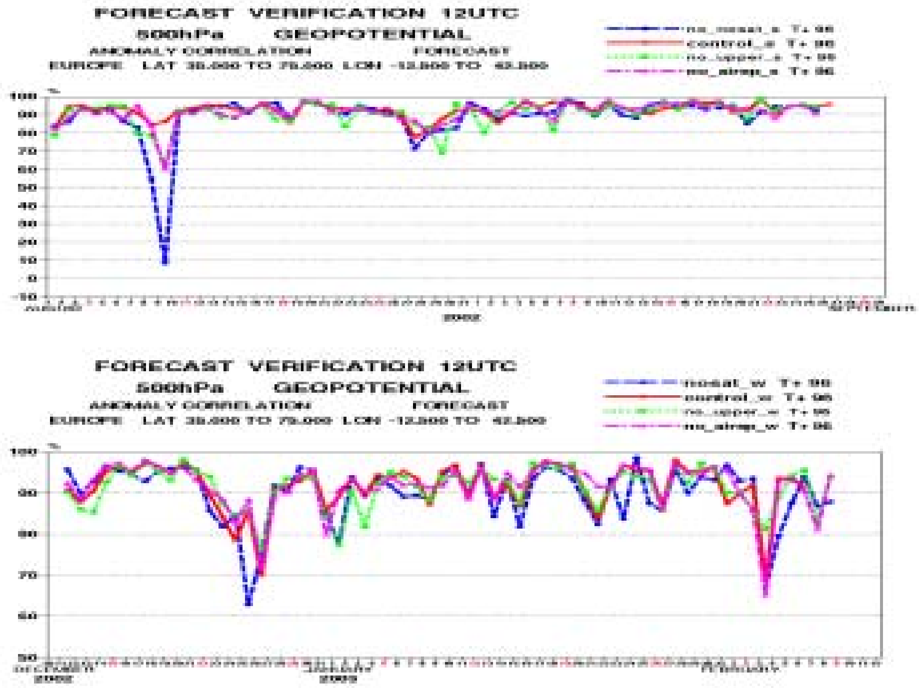
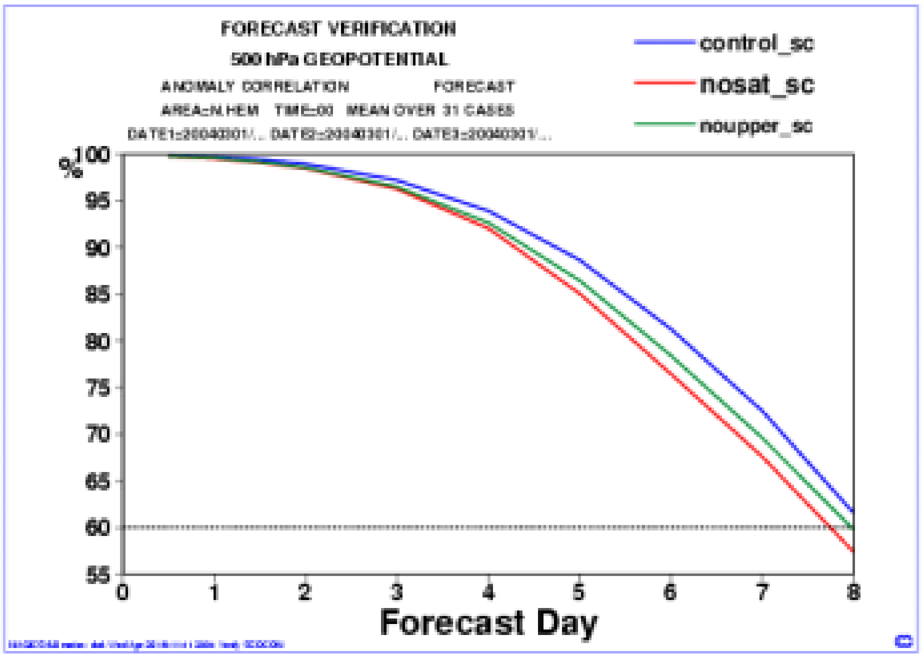


Figure 12(d)Time series of 500 hPa height anomaly correlation



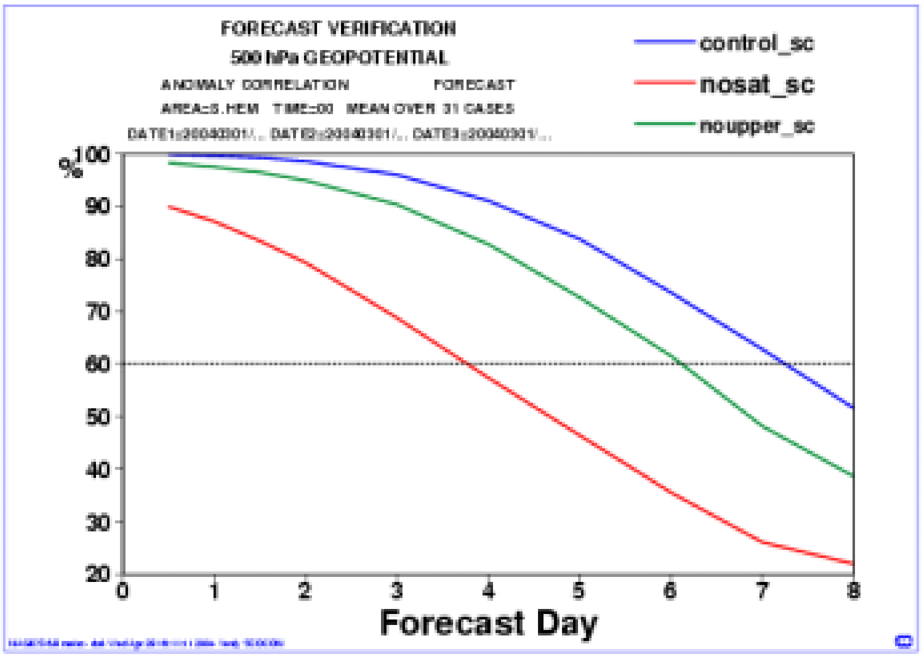


Figure13 (a) Hemispheric 500hPa anomaly correlation early delivery OSE (early delivery 4hr cut off) experiment verified using operational analysis (31 cases)

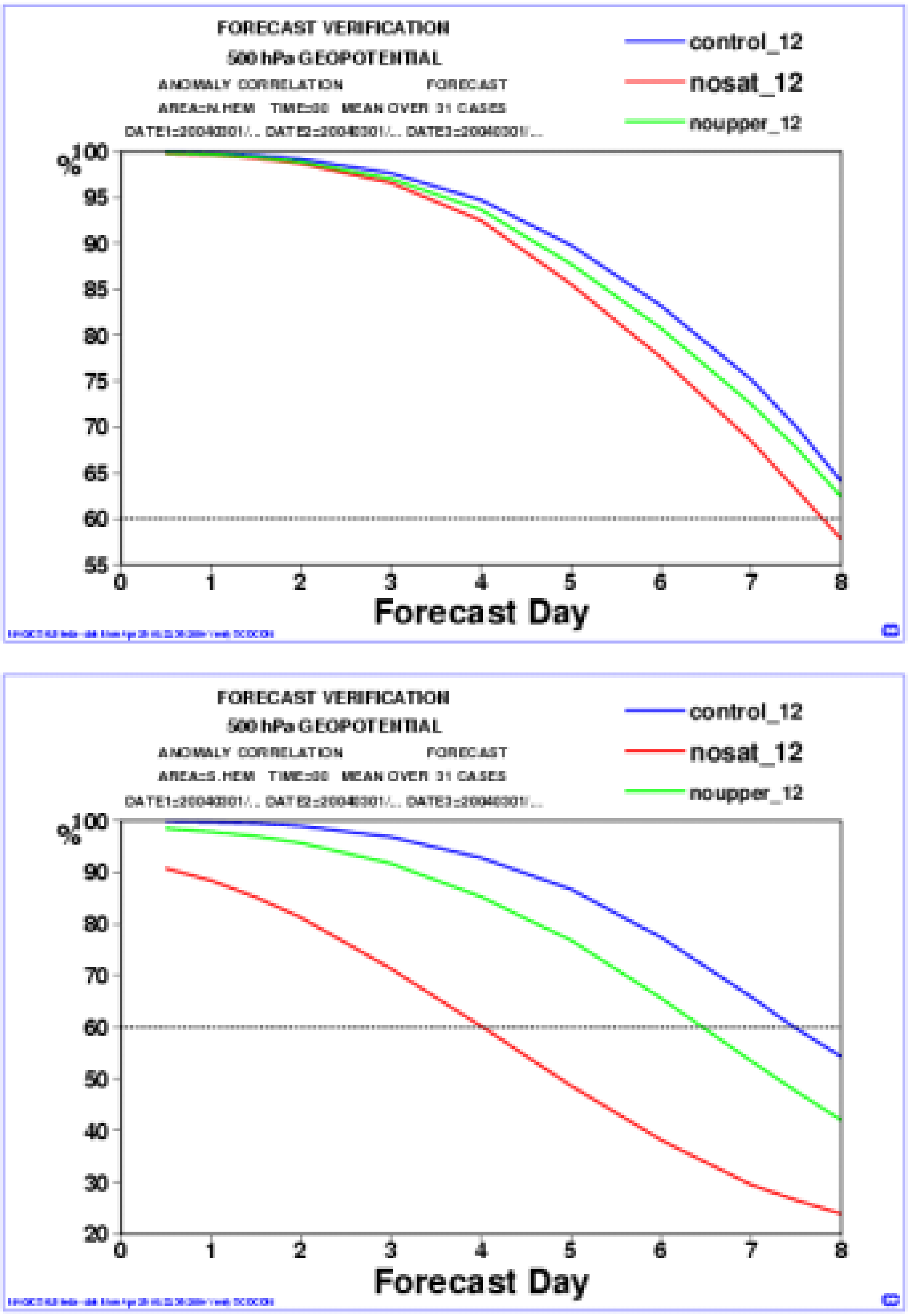


Figure 13(b) Hemispheric 500hPa anomaly correlation early delivery OSE (late cut off) experiment verified using operational analysis (31 cases).

Observing System Experiments Using the Met Office Global Model

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1. Global data denial

The OSE was run using a version of the Met Office unified forecast model (Cullen, 1993) and 3D-Var data assimilation scheme (Lorenc et al, 2000) using the configuration that was operational in December 2001. In order to reduce the computational expense, the forecast model was run at a reduced horizontal resolution (90 km rather than 60 km) but at the operational vertical resolution of 30 levels. Two one-month periods from different seasons - July 2001 and January 2002 - were chosen in order to sample a large variety of flow regimes. 6-day forecasts were run from the 12 UTC analysis on each day of both periods.

The reference or ALL DATA run used the following observations:

- (i) 'in-situ' profile observations of temperature, wind and humidity from TEMP, PILOT, dropsonde and wind profiler reports;
- (ii) satellite radiance data from the HIRS/3, AMSU-A, AMSU-B instruments on NOAA-15 and NOAA-16;
- (iii) AMVs derived from infrared images produced by GOES 8/10; infrared, water vapour and visible images produced by METEOSAT 5/7; infrared, water vapour and visible images from GMS;
- (iv) aircraft wind and temperature observations from AREP, AMDAR and ACAR reports;
- (v) surface pressure from SYNOP and drifting buoy reports, surface pressure and wind from ship, moored buoy, rig and platform reports;
- (vi) surface wind speed from the SSM/I satellite;
- (vii) a small number of 'BOGUS' and 'TCBOGUS' data.

Six data denial scenarios were run in which the following observations were removed from the data assimilation system.

1. NO SONDE: 'in-situ' profile observations.
2. NO STRAD: satellite radiance data.
3. NO AMV: AMV data.
4. NO SAT: satellite data in the NO STRAD and NO AMV runs and SSM/I winds.
5. NO AIRCRAFT: aircraft data.

6. NO SURF: observations from the surface network.

Note also that a small number of 'bogus' data were eliminated in scenarios 1, 5, 6.

For each of these scenarios, sixty forecasts up to 6-days were assessed.

Additional runs investigated the impact of the sub-components of the surface network. These runs used July 2001 data only and thus 30 forecasts up to six-days were assessed. The following observations were eliminated from the data assimilation system.

1. NO SYNOP: SYNOP reports.
2. NO MARINE: observations from surface marine reports (buoys, ships, rigs and platforms).
3. NO SHIP: observations from ships, platforms and rigs.
4. NO BUOY: observations from moored and drifting buoys.

All the forecasts were verified against both observations (radiosonde and surface) and the analyses from the ALL DATA run. Since the statistics have been averaged over sixty forecasts from two different times of year, it is expected that the mean statistics estimate the impact of different observing systems on a large variety of different flow regimes. Ideally, OSEs should be run over even more flow regimes covering many seasons but such comprehensive testing was not possible in this experiment due to limited availability of computing resources. Conclusions from the study were made only if they were based upon impacts that were consistent over forecast parameter, level and forecast range. Since a large number of statistics were examined, for brevity only a representative sample is presented.

Impact of satellite data

The impact of satellite data on height and wind forecasts is illustrated in Figures 1 & 2. The main points to note are as follows.

- ***Satellite data have the largest positive impact on both geopotential height and wind forecasts in the southern hemisphere***. In the southern hemisphere, satellite data improve the skill of geopotential height forecasts by 24-48 hours [Figure 1(c)]. In the tropics the impact is less but greatest on the geopotential height field (18-36 hours) compared with the wind field (up to 18 hours) [Figures 1(b), 2(a) & 2(c)]. In the northern hemisphere, the total impact is much smaller at less than 6 hours for both height and wind forecasts [Figures 1(a) & 2(b)].
- ***Satellite radiance data have a larger positive impact on forecasts in general than AMV data.*** The impact of AMV on 500 hPa height forecasts in both the northern and southern hemispheres is neutral, whereas satellite radiance data have a positive impact of up to 6 hours in the northern hemisphere and about 30 hours in the southern hemisphere [Figures 1(a) & 1(c)]. Satellite radiance data also have

much bigger impact on wind forecasts than AMV data in both the northern hemisphere [Figure 2(b)] and southern hemisphere [Figure 2(e)].

- ***The benefit of AMV can be most clearly seen in the tropics.*** For 850 hPa wind forecasts in the tropics, the most of the benefit of satellite data is due to AMV data [Figure 2(a)], although at 200 hPa the impact is neutral [Figure 2(c)]. For forecasts of 500 hPa geopotential height in the tropics, AMV data give a benefit of about 12 hours up to T+72 [Figure 1(b)]. Such positive impacts are not seen in either the northern hemisphere [Figures 1(a) & 2(b)] or southern hemisphere [Figures 1(c) & 2(e)].
- ***The impacts of satellite radiance and AMV are not additive.*** By comparing the NO SAT and NO STRAD curves in Figure 1(c), it can be deduced that AMV data only have a measurable impact on southern hemisphere forecasts of 500 hPa height if satellite radiance data are not present. A similar result is seen for 500 hPa height forecasts in the tropics where the combined effect of removing all satellite data is greater than removing the observation types individually [Figure 1(b)]. For wind forecasts in the tropics, AMV data have a large impact of about 12 hours when satellite radiance data are not present [Figure 2(c)].
- ***The impact of satellite data over Europe is neutral in these runs.*** A small impact is seem against both 500 hPa geopotential height [Figures 1(d)] and 850 hPa wind [Figure 2(d)].

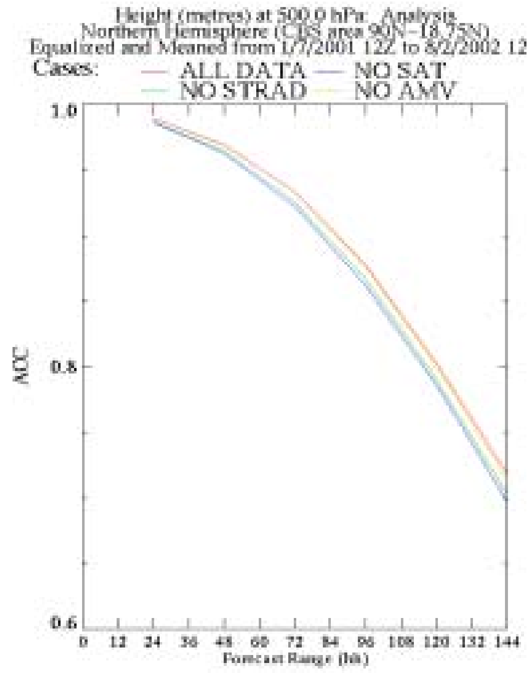
Impact of satellite data vs surface-based data

The impact of satellite observations is compared with the impact of surface-based observations in Figures 3 & 4. The plots shown are the same as those in Bouttier & Kelly (2001), Figures 3 & 4. The main points to note are as follows.

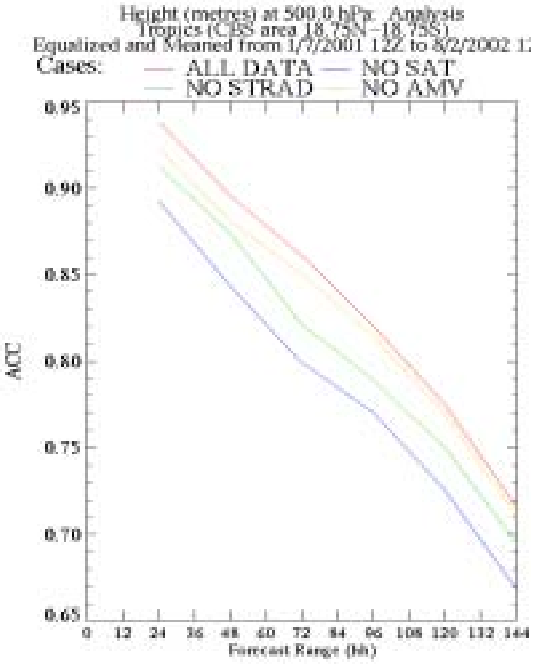
- ***Radiosonde data have the largest impact on forecasts of wind and geopotential height in the northern hemisphere.*** For example, for 500 hPa geopotential height forecasts in the northern hemisphere, radiosonde data are the most important data source, followed by satellite data and aircraft data [Figure 3(a)]. For 500 hPa wind forecasts over Asia, radiosonde data give a benefit of about 24 hours whereas the other observation types have neutral impact [(Figure 4(d)]. For 500 hPa wind forecasts over North America, radiosonde data have the largest impact of up to 12 hours [Figure 4(b)].
- ***Satellite data have the largest impact on forecasts of wind and geopotential height in the southern hemisphere.*** For 500 hPa geopotential height forecasts in the southern hemisphere, satellite data have by far the largest impact of all observation types; the impact at all forecast ranges up to T+144 is about 40 hours [Figure 3(c)]. A similar large impact is seen on wind forecasts (not shown).
- ***In the tropics satellite data have the largest impact on geopotential height forecasts, and both satellite and radiosonde data have a marked impact on wind forecasts.*** For 500 hPa geopotential height forecasts in the tropics, satellite data have the largest impact which varies between about 18-30 hours depending on forecast range. Radiosonde data are the next most important data source at almost all forecast ranges up to T+144. Up to T+72, aircraft data having a bigger overall impact than surface data whereas at longer forecast ranges surface data have a bigger impact [Figure 3(b)]. For wind

forecasts at 500 hPa in the tropics, radiosonde data have the largest impact up to T+72 [Figure 4(c)] but at longer forecast ranges and other levels, satellite data have the largest impact [Figure 2(e)].

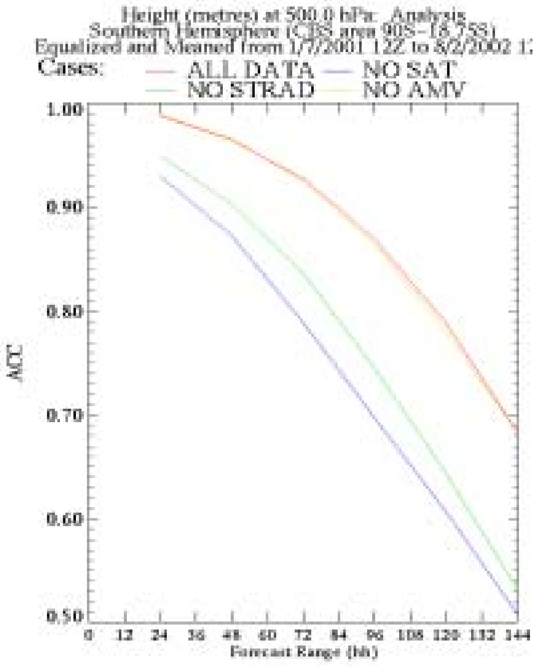
- ***Aircraft data play a relatively important role, particularly for short-range wind forecasts in the northern hemisphere and tropics.*** For 500 hPa wind forecasts over Europe, aircraft data have an impact of up to 6 hours over the forecast ranges 24-72 hours compared with radiosonde data which have the largest impact of all observation types of up to 12 hours [Figure 4(a)]. For 500 hPa wind forecasts in the tropics, aircraft data have an impact of about 6 hours up to T+48 and a smaller impact at longer forecast ranges [Figure 4(c)].
- ***Surface data have a positive impact on forecasts, particularly in the southern hemisphere.*** For the forecasts of 500 hPa height in the southern hemisphere, surface data are the second most important data source after satellite data with an impact of about 6 hours at all ranges up to T+144 compared with radiosonde data that have an impact of less than 3 hours [Figure 3(c)].
- ***For forecasts over Europe, all observation types have a neutral impact on geopotential height forecasts, but radiosonde, aircraft and to a lesser extent satellite data, have a positive impact on wind forecasts.*** The mean impact of all observing systems on 500 hPa height over Europe is shown in Figure 3(d). It can be seen that the overall impact of any observing system is neutral. However, radiosonde data and to a lesser extent aircraft and satellite data, have a clear benefit on 500 hPa wind forecasts [Figure 4(a)].
- ***The impact of individual observing systems in the northern hemisphere is small.*** The impact of removing any one observing system is small. For example, for 500 hPa height forecasts, a maximum impact of less than 12 hours on 500 hPa height is seen when radiosonde data are removed [Figure 3(a)].



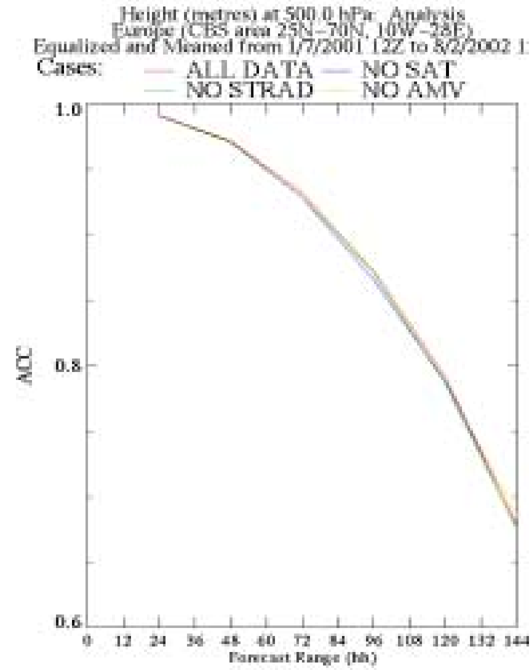
(a)



(b)



(c)



(d)

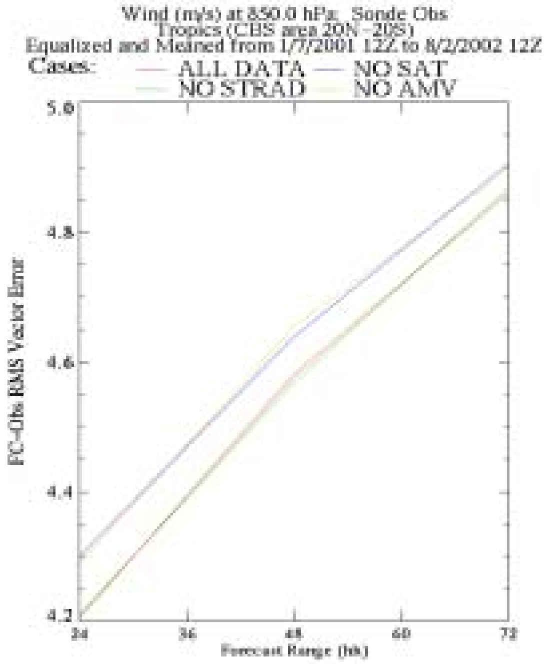
Figure 1. Comparison of satellite data impact. Anomaly correlation coefficient (versus 'All data' analysis).

(a) Northern hemisphere (90N - 18.75N) 500 hPa height

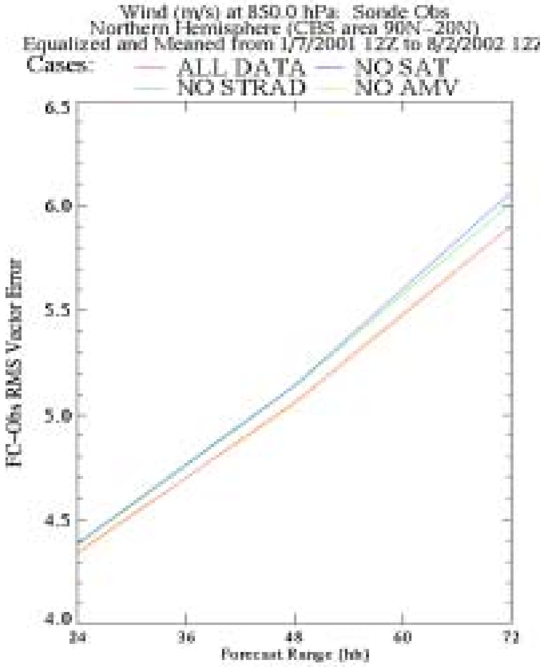
(b) Tropics (18.75N - 18.75S) 500 hPa height;

(c) Southern hemisphere (90S - 18.75S) 500 hPa height

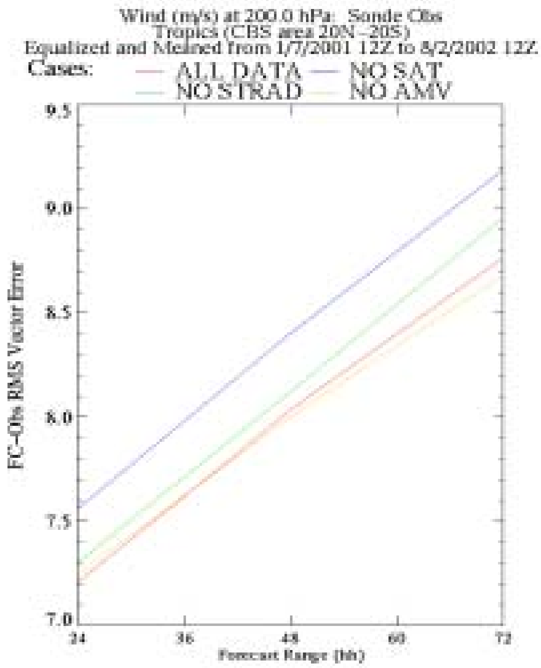
(d) Europe (25N - 70N, 10W - 28E) 500 hPa height


Wind (m/s) at 850.0 hPa: Sonde Obs
Tropics (CBS area 20N–20S)
Equalized and Meaned from 1/7/2001 12Z to 8/2/2002 12Z
Cases:
ALL DATA
NO SAT
NO STRAD
NO AMV
FC–Obs RMS Vector Error
Forecast Range (hh)
4.2
4.4
4.6
4.8
5.0
24
36
48
60
72

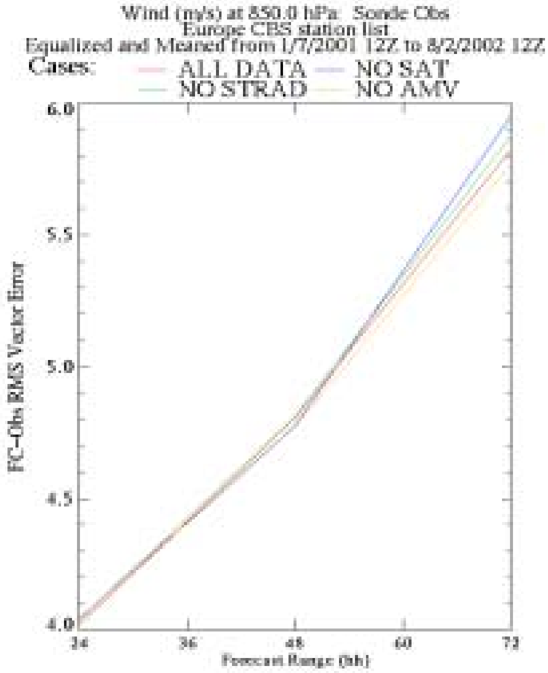
(a)


Wind (m/s) at 850.0 hPa: Sonde Obs
Northern Hemisphere (CBS area 90N–20N)
Equalized and Meaned from 1/7/2001 12Z to 8/2/2002 12Z
Cases:
ALL DATA
NO SAT
NO STRAD
NO AMV
FC–Obs RMS Vector Error
Forecast Range (hh)
4.0
4.5
5.0
5.5
6.0
6.5
24
36
48
60
72

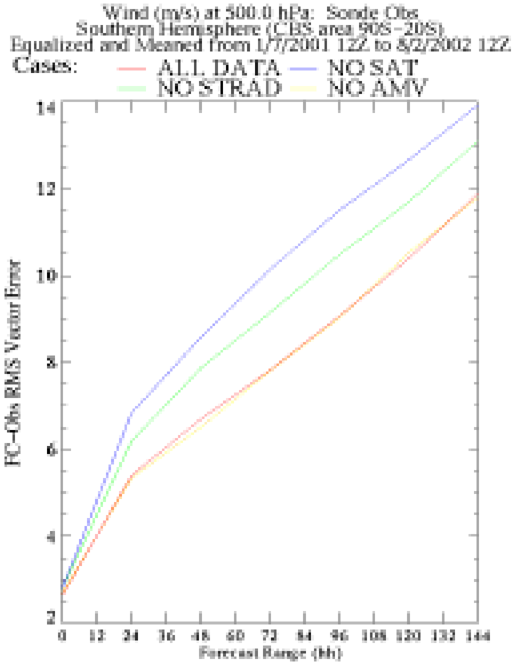
(b)


Wind (m/s) at 200.0 hPa: Sonde Obs
Tropics (CBS area 20N–20S)
Equalized and Meaned from 1/7/2001 12Z to 8/2/2002 12Z
Cases:
ALL DATA
NO SAT
NO STRAD
NO AMV
FC–Obs RMS Vector Error
Forecast Range (hh)
7.0
7.5
8.0
8.5
9.0
9.5
24
36
48
60
72

(c)


Wind (m/s) at 850.0 hPa: Sonde Obs
Europe CBS station list
Equalized and Meaned from 1/7/2001 12Z to 8/2/2002 12Z
Cases:
ALL DATA
NO SAT
NO STRAD
NO AMV
FC–Obs RMS Vector Error
Forecast Range (hh)
4.0
4.5
5.0
5.5
6.0
24
36
48
60
72

(d)



(e)

Figure 2. Comparison of satellite data impact for wind. RMS vector wind errors versus radiosondes.

(a) Tropics at 850 hPa

(b) Northern hemisphere at 850 hPa

(c) Tropics at 200 hPa

(d) Versus Europe CBS station list at 850 hPa

(e) Southern hemisphere at 500 hPa

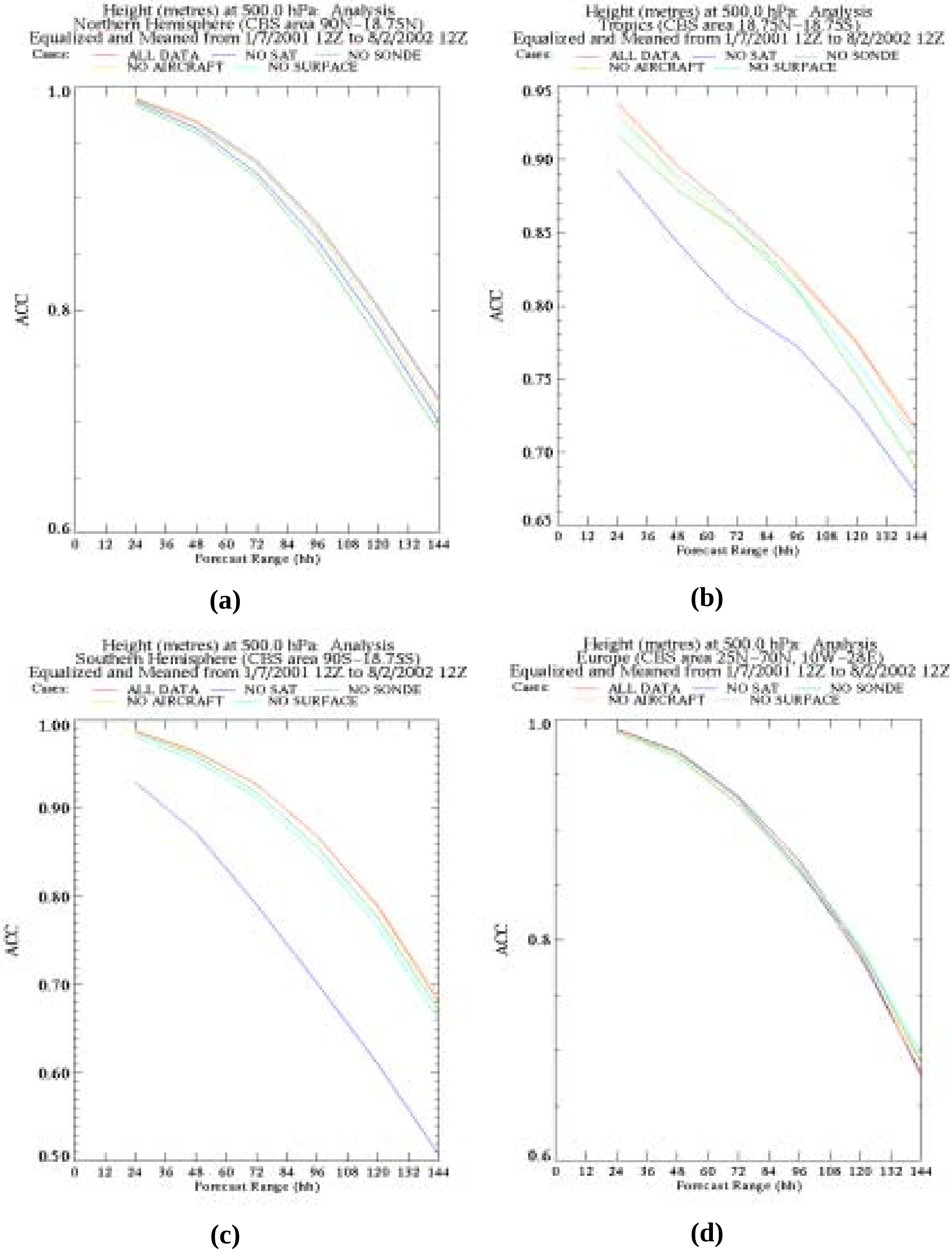


Figure 3. Comparison of satellite and surface-based data. 500 hPa height anomaly correlation coefficient for (a) northern hemisphere (b) tropics (c) southern hemisphere (d) Europe.

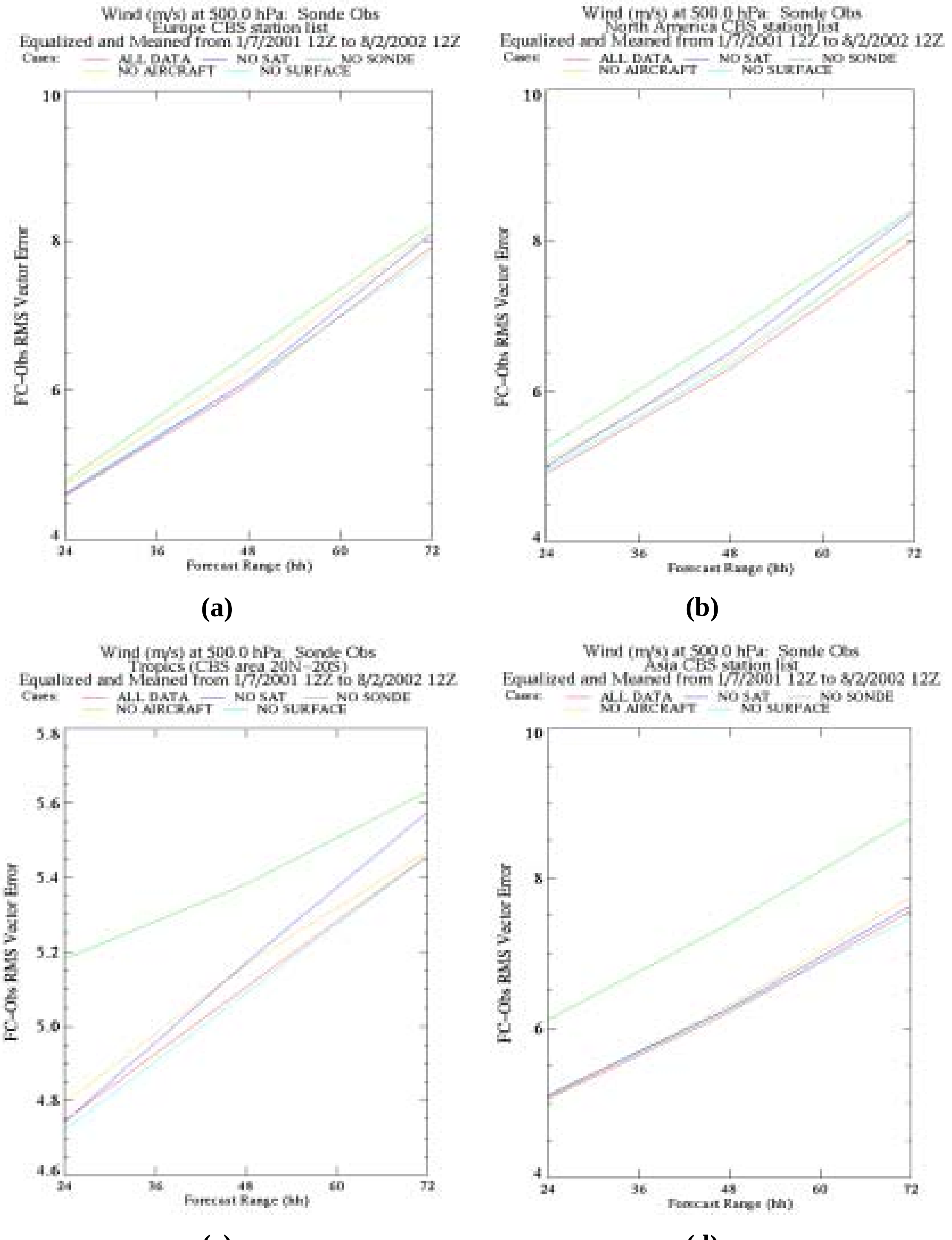


Figure 4. Comparison of satellite and surface-based data. Root mean square vector wind error for 500 hPa wind versus radiosondes for (a) Europe (b) North America (c) tropics (d) Asia.

Impact of surface data

From Figure 5 it can be seen that surface data have a large impact on forecasts of mean sea level pressure. Similar results exist for the tropics and southern hemisphere, but are not shown here. It should be noted that the Met Office global data assimilation system uses surface pressure from all surface reports, whereas surface wind observations are used only from ships, moored buoys, platforms and rigs and no surface temperature observations are used. It is thus concluded that 'in-situ' surface pressure observations are essential for Met Office forecasts. It appears that the data assimilation scheme cannot produce a realistic surface pressure field using upper air observations only.

From Figure 5 it can also be seen that removing whole sub-components of the surface network makes very little difference to the mean scores, except for forecasts up to T+24 in the case when all SYNOP reports are removed. This result suggests that whilst some 'in-situ' surface pressure observations are essential, the Met Office global NWP system run at 90 km resolution cannot fully utilise all the information provided by a dense surface network.

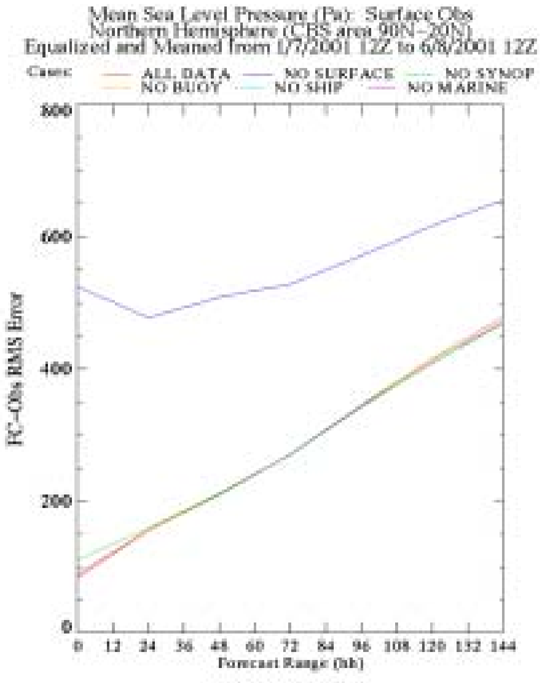


Figure 5. Impact of surface observations. Root mean square errors versus observations meaned over the northern hemisphere for mean sea level pressure.

2. Impact of 'in-situ' profile measurements in tropical regions

Surface-based profile observations have a significant impact on NWP forecasts, despite the use of increasing amounts of satellite data that can be effectively assimilated using variational techniques (Bouttier and Kelly, 2001). Currently, and for the next few years, improvements in the benefit of satellite data for NWP are likely to be limited due, for example, to the problems of obtaining useful information in cloudy areas which are highly correlated with initial condition sensitivity (McNally, 2000). A complimentary, global network of surface-based observations will be necessary to ensure continuing improvements to NWP (WMO, 2002).

There are large land areas of the tropics where the coverage of surface-based observations is sparse, particularly over tropical Africa. This led the WMO Expert Team on Observational Data Requirements and Re-design of the Global Observing System (ET-ODRRGOS) to request that leading NWP centres investigate the potential value of an enhanced surface-based profile network in the tropics. The results presented here attempt to answer the questions posed by the Expert Team.

Given the relatively dense coverage of radiosonde data in south-east Asia (see Figure 6), the Expert Team suggested that impact studies be carried out in which radiosonde data was denied from an area covering south-east Asia. Should it be found that the data have a positive impact on NWP forecasts, for the local region or outside, then it may be concluded that an improved surface-based profile network over say, tropical Africa, would have a similar benefit. The Expert Team suggested two experimental scenarios designed to assess the impact of adding either profile measurements from aircraft or radiosonde TEMP reports that include humidity data.

An Observing System Experiment was run using the Met.Office operational forecast model and 3-D variational data assimilation scheme. In order to reduce the computational expense, the forecast model was run used at reduced (90 km) horizontal resolution. A one month trial was performed using July 2001 observations and thirty 6-day forecasts were verified against both radiosondes and analyses.

The area of south-east Asia over which data were denied is shown in Figure 6. Three runs were performed:
(i) using all available observations of all data types
(ii) as (i) but with no radiosonde or aircraft profile data from south-east Asia
(iii) as (i) but with no radiosonde humidity information or aircraft profile data from south-east Asia.
Scenario (ii) represents the current situation over some parts of the tropics, for example, Africa. Scenario (iii) represents the inclusion of AMDAR profile data, and scenario (i) the inclusion of sonde data. Note that the analysis fields from run (i) (the 'all data' run) were used in calculating the anomaly correlation coefficients.

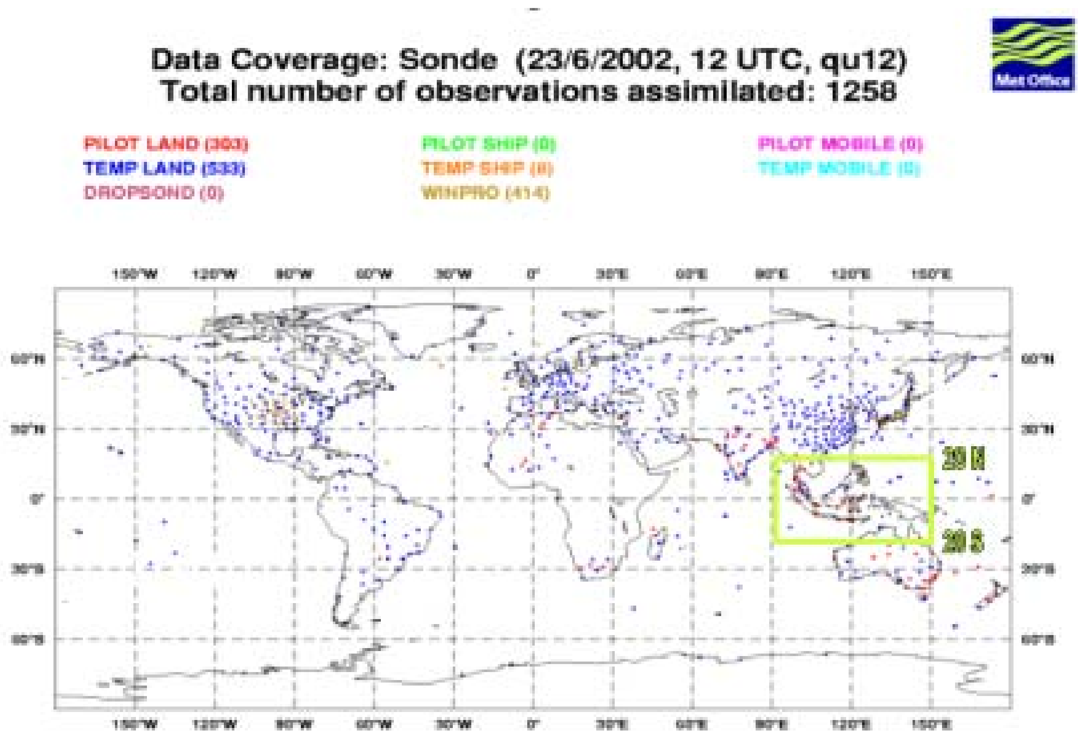
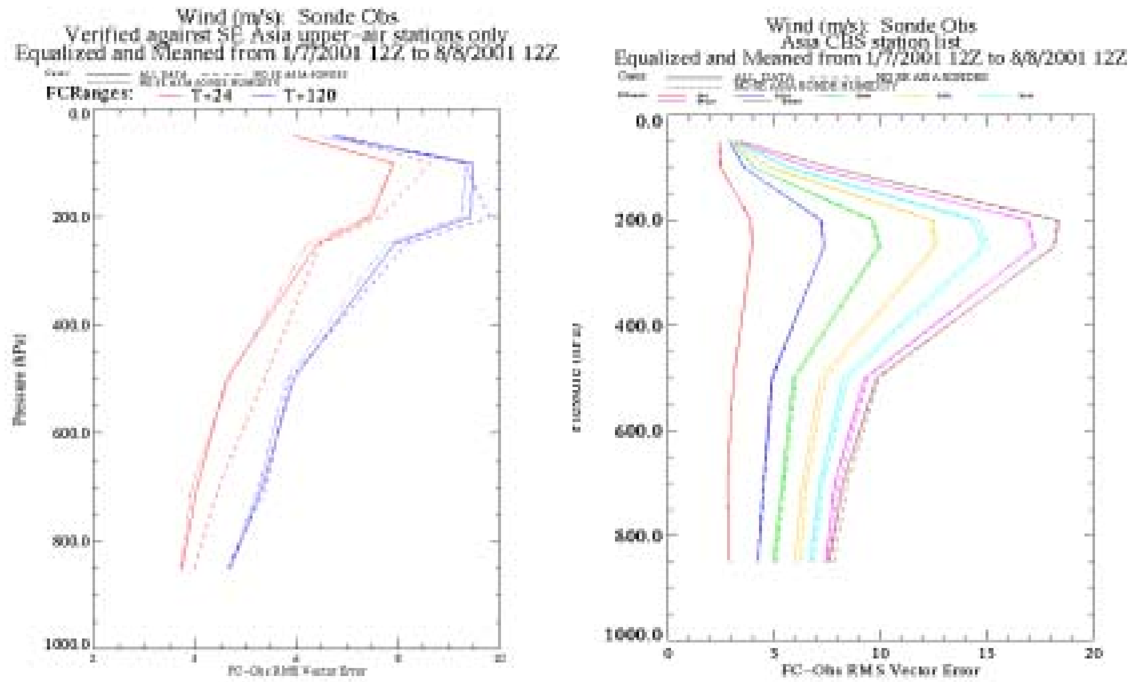


Figure 6. Global distribution of radiosondes. Box indicates the area of south-east Asia from which reports were denied.

Verification scores against radiosondes within the south-east Asian region are plotted in Figure 7(a). It can be seen that profile data have a positive impact on forecasts. Since the effect of removing humidity data is neutral or slightly positive, it appears as though the benefit of the profile data comes largely from temperature and wind measurements.

The impact of the tropical profile data on forecasts in a region (Asia) adjacent to where the observations were made is indicated in Figure 7(b). A small positive impact from the radiosonde data can be seen at some levels and forecast ranges. However, the impact of humidity data is neutral suggesting that the positive impact of the full profile is also due to the temperature and wind components.

It appears from these results that extra 'in-situ' temperature and wind profile measurements in the tropics would benefit wind and height forecasts in the regions where the observations are taken. However, the benefit of extra 'in-situ' humidity measurements is not clear. It is thus likely that extra AMDAR profile measurements over Africa would benefit forecasts for the region.



(a) **(b)**

Figure 7.. Impact of 'in-situ' profile data from south-east Asia. Mean RMS vector wind errors (m/s). Mean values are calculated over 30 forecasts.
(a) For 24-hr and 120-hr forecasts verified against radiosondes in south-east Asia plotted for selected pressure levels. (b) Against Asian radiosondes plotted for selected pressure levels.

3. Impact of extra North Atlantic ASAP[1] reports

Various recent studies have suggested that improved observational coverage over the North Atlantic is needed for the production of better NWP forecasts over Europe. For example, Bader and Saunders (2001) found cases where a scarcity of observations to the west of France and Iberia may have resulted in poor short-range NWP forecasts over Europe. Such studies have encouraged EUCOS to consider the deployment of more 'in-situ' observations in the Atlantic.

As an initial step towards the enhancement of the North Atlantic observation network, an observational field campaign took place during September and October 2001. During this period, extra ascents from 12 Atlantic ASAP ships were made, and the Azores radiosonde (08508) reported four times each day. The aim of this pilot experiment was primarily to check the technical feasibility of producing extra ASAP

1 Automatic Ship Aerological Program

reports at variable times, and secondly to evaluate the impact on NWP forecasts of the extra data (Gerard, 2000).

During the field campaign, the number of temperature and wind reports that were assimilated by the Met Office model increased by 22% compared with the previous two month period.
However, examination of individual cases suggested that on many occasions some regions of the flow containing notable features may not be observed by the ships.

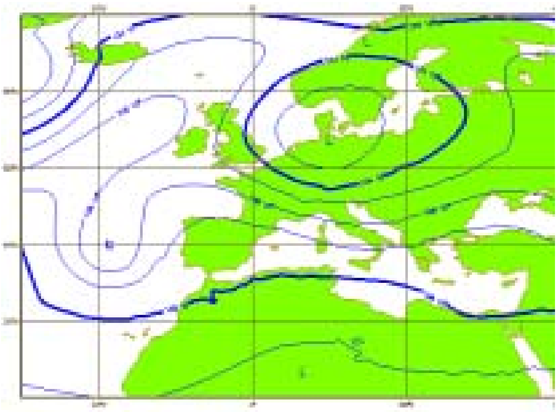
The Met Office operational global model (Cullen, 1993), which uses a three-dimensional variational assimilation scheme, was run for the two-month period of the E-ASAP field campaign. In order to reduce the resources required to complete the OSE, the forecast model was run at less than operational horizontal resolution (approximately 90km compared with 60km) but at full vertical resolution. Two runs were performed:

(i) Using all available data, including all the extra data from the ASAPs and Azores radiosonde (the 'All data' run)

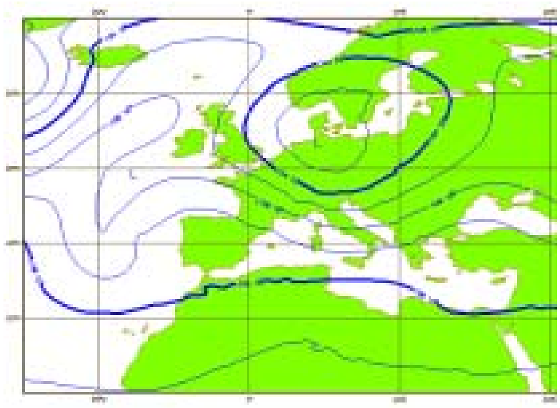
(ii) Using all data less all data from all ASAP ship reports, including those not part of the field campaign, and all Azores radiosonde reports (the 'No ASAP' run).

Scenario (ii) is designed to test the ***maximum*** impact that ASAPs and the Azores radiosonde could have. For each run, 6-day forecasts were produced every day from 12UTC data. The forecasts and analyses were verified over a comprehensive set of regions covering the whole globe.

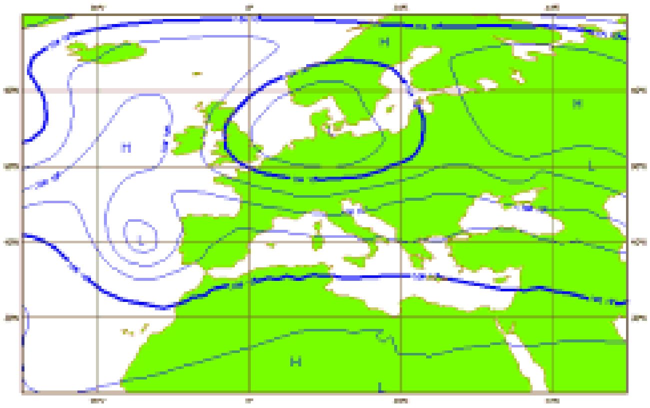
Only small differences in RMS errors, averaged over the trial period, have been found.
Thus time series of differences in RMS errors were examined to identify cases in which inclusion of ASAP data gave noticeable impact on the forecast. Figures 8(a) & 8(b) show the T+96 forecast of 250 hPa height from the 'All data' and 'No ASAP' runs respectively from a case where such differences were observed. It can be seen that the trough to the west of Iberia is deeper in the 'All data' run than the 'No ASAP' run.



(a)



(b)



(c)

Figure 8. Impact of ASAP data on T+96 forecast of 250 hPa geopotential height valid at 12UTC 21/9/01. Contour interval is 100 metres.
(a) T+96 forecast from the 'All data' run. (b) T+96 forecast from the 'No ASAP' run. (c) Analysis valid at 12UTC 21/9/01 from the 'All data' run.

The forecast from the 'All data' run is more similar to the 12UTC 21/9/01 analysis (Figure 8(c)) than is the forecast from the 'No ASAP' run.

In this OSE, the data from up to 13 North Atlantic radiosondes were denied, although typically no more than about 6 were reporting simultaneously. However, Pailleux (1997) suggests that the data from 10 or more North Atlantic radiosondes need to be denied in order to get a measurable impact on forecasts over Europe. Moreover, Pailleux's conclusion was based on studies performed before the profile data from current satellites were available. The assimilation of these data using recently implemented variational techniques has led to satellite sounding data having an increased benefit on forecasts in the Northern Hemisphere (Bouttier & Kelly, 2001). Thus 'in-situ' sounding data over the North Atlantic are now unlikely to have as much impact as observed by Pailleux. Thus it would be expected that many more than 6 additional radiosonde reports over the North Atlantic would be required to obtain significant benefit on forecasts over Europe.

The relatively small impact may be due to an 'undersampling' of the synoptically sensitive parts of the flow over the Atlantic. The weather over the Atlantic during September and October 2001 was markedly anticyclonic with, in particular, anti-cyclones or weak flow persisting over the Azores for significant periods (Met Office Daily Weather Summary, September & October 2001). Sounding data taken in such conditions are unlikely to produce a large impact. Given that no more than 6 soundings were typically available at any one time, it is likely that the parts of the North Atlantic that were sensitive to synoptic development were not observed from the ASAP ships.

It is important that the results from this experiment are not interpreted to mean that in-situ profile data have little value in a GOS containing increasing amounts of profile information from satellites. The benefit of radiosonde data as a whole on global forecasts has been confirmed by recent studies carried out at the Met Office (see section 1) and ECMWF (Bouttier & Kelly, 2001). Despite the planned improvements in satellite sounding data, it is likely that in situ profile observations will still be necessary to provide observations especially where the satellite data are less accurate, such as at lower levels and in cloudy conditions.

REFERENCES

Bader, M.J. & Saunders, F.W. (2001). The Requirements for extra Observations to the West of France and Iberia for NWP over Europe. *The Met Office NWP Forecasting Research Technical Report* No. 345.

Bouttier, F. & Kelly, G. (2001). Observing System Experiments in the ECMWF 4D-Var data assimilation system. *Q.J.R. Meteorol. Soc.,* 127, pp 1469-1488.

Cullen, M.J.P, (1993). The unified forecast/climate model. *Met. Mag.,* 122, 81-94.

Gerard, F. (2000). Targeted observation experiment from ASAP. Specifications of an EUCOS-COSNA feasibility study (Unpublished report).

Lorenc, A.C., Ballard, S.P., Bell, R.S., Ingleby, N.B., Andrews, P.L.F., Barker, D.M., Bray, J.R., Clayton, A.M., Dalby, T., Li, D., Payne, T.J., and Saunders, F.W. (2000). The Met. Office Global 3-Dimensional Variational Data Assimilation Scheme. *Q.J.R. Meteorol. Soc.,* 126, 2991-3012.

McNally, A.P. (2000). The occurrence of cloud in meteorologically sensitive areas and the implications for advanced infrared sounders. *Technical proceedings of the 11th International TOVS Study Conference,* Budapest, Hungary, 20-26 Sep 2000.

Pailleux, J. (1997). Impact of observations in NWP models. Summary of recent results and perspectives. WMO, *World Weather Watch Report No. 18.* Impact of various observing systems on numerical weather prediction. Proceedings of CGC[2]/WMO Workshop, Geneva, 7-9 April 1997.

WMO (2002). *Expert Team meeting on Observational Data Requirements and Redesign of the GOS,* Reduced Session (Oxford, United Kingdom), 1-5 July 2002, AnnexVI (see http://www.wmo.ch/web/www/reports.html#GOS)

[2] Co-ordination Group for COSNA (Composite Observing System for the North Atlantic)

Some Surface Data Impact Studies at ECMWF

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1. Introduction

A number of Observing System Experiments (OSEs) have been carried out at ECMWF to assess the relative importance of some components of the Surface Observing System. This work was originally triggered by a request from EUMETSAT for an assessment study on the relative merits for Numerical Weather Prediction (NWP) of measuring surface pressure versus measuring surface wind over sea. The studies were therefore designed to provide some guidance about required accuracies and subsequently possible scope for measuring surface pressure from space. Further interest was expressed by EUCOS and also internally about the impact of the current surface network in a heavily space-based constrained NWP system such as ECMWF.

OSEs presented in this paper have therefore been designed to provide guidance to the following questions:

1. What are the relative merits of the current surface pressure Observing System versus the current surface wind Observing System?
2. What is the impact of degrading the accuracy of surface pressure measurements?
3. Is the combination of surface pressure measurements over land and surface winds over sea able to control globally the surface pressure field?
4. What is the impact of reducing the current surface pressure Observing System over Sea?

Several denial type experiments have been carried out to answer these questions. Impacts have been generally measured in terms of short to medium-range forecast performance (always verified against the operational analysis at the time), in a mean sense but also on specific synoptic cases. The experimental set-up is described in Section 2. A first set of low resolution OSEs has been performed during winter and summer periods, based on the ECMWF cycle 25R1 that was operational until 2002 and results are presented in Section 3. A second reduced set of high resolution OSEs consistent with that of Kelly et al. (2004) has also been carried out (cy25r4 from the IFS, operational from January to September 2003) and results are presented in Section 4. Summarizing conclusions are drawn in Section 5.

2. Experimental Set-up

The assimilation system at ECMWF uses 4D-Var (Rabier et al., 1998) with 12-hourly cycling (Bouttier, 2001) at a resolution of T511L60 (~40 km) whith analysis increments computed at T159L60 (~120km) (Courtier at al. 1994). At the time when the studies were initiated, computer resources were insufficient to run a series of OSEs at the resolution of the operational suite. Therefore a first set of OSEs was run for two periods (20020201-20020317 and 20010615-20010801) with the following configuration (LOWOSE):

IFS cycle 25R1 6 hour 4DVAR (T319/T63)

This configuration is to a large extent consistent with what had been used in Bouttier and Kelly (2001). Conventional observations actively assimilated at that time consisted of surface pressure from Synops, surface pressure and wind from Ships and Buoys, surface pressure from PAOBS, temperature, wind and humidity from radiosondes, wind from Pilots and profilers, temperature and wind from aircrafts. Remotely sensed observations comprised AMSU-A radiances from NOAA-15/16 platforms, HIRS (water vapour channel 12) radiances from NOAA-14, wind speed and total column water vapour (TCWV) from SSM/I on board DMSP13/14, Seawinds wind vectors from QuikScat, Atmospheric Motion Vectors from GOES/Meteosat/GMS, Clear Sky Radiances from Meteosat-7, ozone column from GOME onboard ERS and ozone profiles from SBUV onboard NOAA16.

More recently, a second set of OSES has been run (HIGHOSE) with the following configuration:

IFS cycle 25R4 12 hour 4DVAR (T511/T159)

This configuration is very close to the current operational ECMWF assimilation system, and the period under investigation matches that of Kelly et al. (2004), that is 20020801-20020930 and 20021211-20030209. Conventional observations are used in a similar way as in the LOWOSE context. Concerning satellite observations, the system is much more constrained: 3 AMSU-A platforms are used (NOAA-15/16/17), HIRS channels from NOAA-16/17 are used in a more comprehensive way (CO_2 and water vapour channels are now used thanks to an improved cloud detection scheme). Radiances from SSM/I are assimilated directly in 4D-Var. Last, polar Atmospheric Motion Vectors from MODIS/TERRA (Bormann and Thépaut, 2004) are included in the assimilation. This second configuration is therefore more challenging for conventional surface observations, due to the use of a wealth of satellite data.

The error statistics specified in the assimilation system are summarized in the table 1 below (figures are average values for the background errors that have some degree of flow dependence:

Table 1: error characteristics (observations and model background) used in the different sets of OSEs

Observation type	**LOWOSE errors**	**HIGHOSE errors**
SYNOP surface pressure	0.7 hPa	0.7 hPa
SHIP surface pressure	1.2 hPa	1.2 hPa
Buoy surface pressure	0.8 hPa	0.8 hPa
PAOB surface pressure	3.0 hPa	3.0 hPa
SHIP winds	2.0 m/s	2.0 m/s
BUOY winds	1.8 m/s	1.8 m/s
Scatterometer winds	2.0 m/s	2.0 m/s
SSM/I winds	2.4 m/s	N/A
Model background	**LOWOSE errors**	**HIGHOSE errors**
Surface pressure	0.8 hPa	0.8 hPa
Surface wind	0.9 m/s	0.9 m/s

3. Results of the low resolution OSES (LOWOSES)

As mentioned above, the core of LOWOSES have been run for 6/7 weeks during both winter and summer periods. The winter LOWOSES are summarized in Table 2 below:

	Experiment name	**Description**
1.	CTL	control experiment: all observations included
2.	NOSURFWIND	all surface wind data excluded (QuikScat, buoys, SHIPs, SSM/I)
3.	NOSPSEA	all surface pressure data excluded over sea (Buoys, PAOBS and SHIPs)
4.	NOSPBUOYSEA	surface pressure data from buoys excluded
5.	NOSURF	all surface data excluded
6.	NOSURFWIND2hPa	similar to NOSURFWIND but with all surface pressure observation errors specified to 2 hPa
7.	NOSP	all surface pressure data excluded

Among those, only the first four prime experiments were also rerun during the summer period (see explanation below).

Fig.1 represents the 1000 hPa geopotential mean forecast errors (averaged over 32 cases) for CTL, NOSURF and NOSP experiments. One clearly see that in the total absence of surface observations (NOSURF - green curve), a bias of about 2 to 3m occurs all the way through the forecast range, indicating that the model may not conserve mass completely. Geographical maps show that the degradation at the surface is global (not shown). Interestingly, the mean error remains very similar (although slightly improved) for the NOSP experiment. Therefore surface wind observations (that provide indirectly pressure gradient information), in the absence of surface pressure observations, cannot correct for this model deficiency. NOSP actually exhibits larger mean forecast errors in the Southern Hemisphere (not shown). Not surprisingly, these results prove that genuine surface pressure observations are necessary to anchor the surface pressure field that cannot be recovered from surface wind information alone.

Another question we tried to address is whether or not observing surface pressure over land only is sufficient to anchor the large scales of the surface pressure field, provided surface wind observations over sea recover the missing information (experiment NOSPSEA). The performance of NOSPSEA is illustrated in Fig.2 that displays the time series of the Northern Hemisphere 1000 hPa geopotential height RMS forecast error at day 2 and day 4 for the CTL and NOSPSEA experiment.

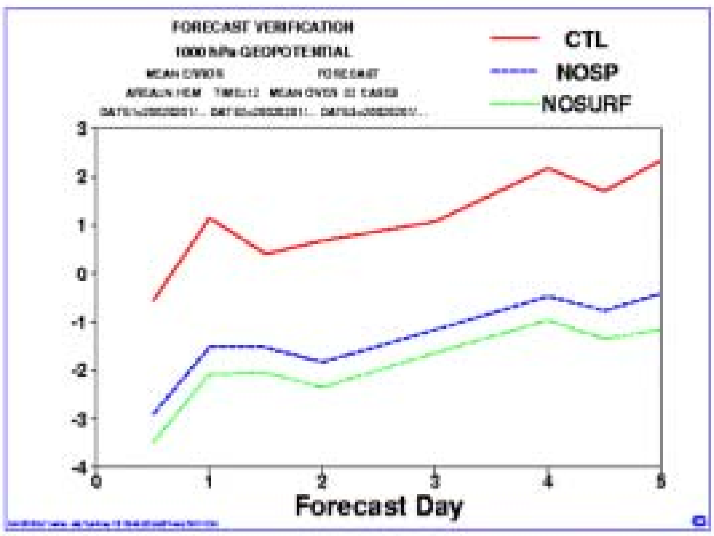

Fig.1: mean 1000 hPa geopotential height forecast error (verified against the operational ECMWF analysis) averaged over 32 cases for CTL (red), NOSURF (green) and NOSP (blue) LOWOSES (winter period).

Clearly, the CTL scores (blue and green curves at respectively 48h and 96h range) are consistently better than the NOSPSEA scores (red and pink curves at respectively 48h and 96 range), indicating a significant degradation of the forecast performance when surface pressure observations over sea are removed. It looks therefore mandatory to have direct measurements of surface pressure over sea.

To comparatively assess the importance of the surface wind observing system (only used over sea at ECMWF), a NOSURFWIND experiment has been run and results have been compared with the CTL and

NOSPSEA experiments. Fig. 3 displays one among many diagnostics that have been produced to perform the comparison. Fig. 3 represents a scatter plot comparing the forecast score performance of NOSURFWIND versus NOSPSEA.

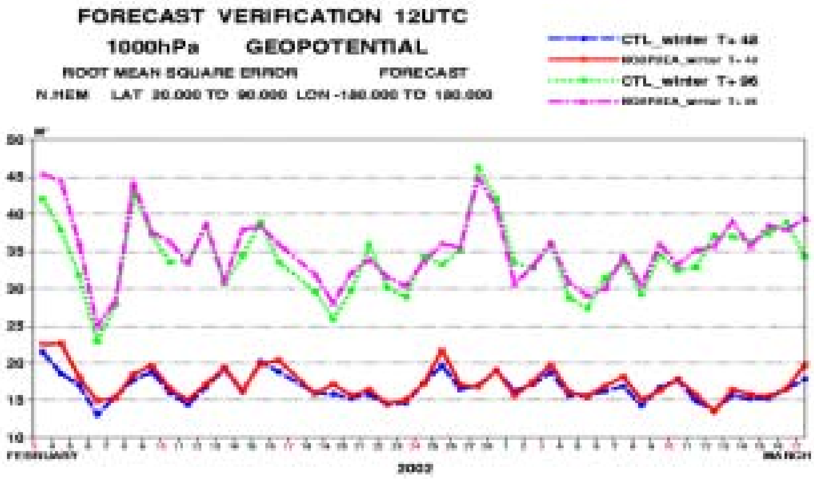

Fig. 2: Northern Hemisphere 1000 hPa geopotential height forecast error time series (verified against the operational ECMWF analysis). CTL (blue and green curves at respectively 48 and 96h range) versus NOSPSEA (red and pink curves at respectively 48 and 96h range).

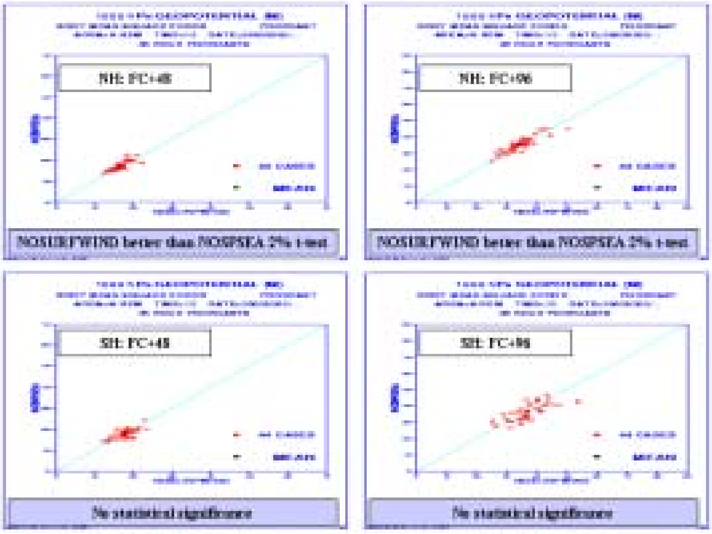

Fig. 3: Scatter plot of NOSPSEA (y axis) and NOSURFWIND (x axis) 1000 hPa geopotential RMS forecast error scores in Northern Hemisphere (top row) and Southern Hemisphere (bottom row). Left column refers to 48h forecast range. Right column refers to 96h range. Statistical significance is indicated in the light blue boxes.

The results, accumulating 44 cases in total, are presented for 48 and 96h range, for both the Northern and Southern Hemispheres, and are accompanied with statistical significance information. If in the Southern Hemisphere, the impact of surface wind observations does not differ significantly from that of surface pressure observations, there is a significantly larger impact of surface pressure observations in the Northern Hemisphere, and this despite that the number of wind observations is substantially larger (note that as stated above, QuikScat and SSM/I wind information are also withdrawn in the NOSURFWIND experiment). The largest difference between NOSURFWIND and NOSPSEA concerns Europe (not shown), pointing to the importance of the buoy/Ship surface pressure network for North Atlantic.

Additional information is provided in Fig.4 which displays the 1000 hPa geopotential height forecast anomaly correlation (averaged over 44 cases) for CTL (red), NOSPSEA (blue), and also NOSPBUOYSEA (green) where only surface pressure observations from buoys are withdrawn from the assimilation (Ships are kept in the system).

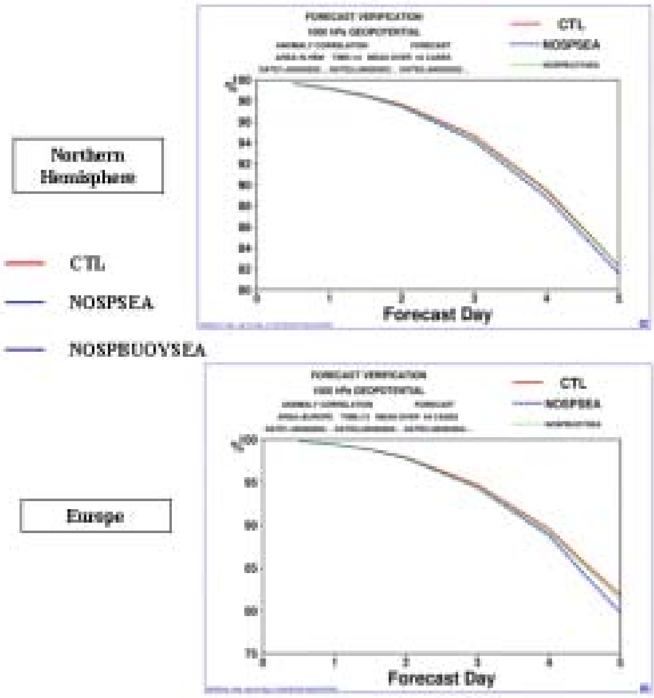

Fig.4: 1000 hPa geopotential height forecast anomaly correlation for CTL, NOSPSEA and NOSPBUOYSEA (see text for details)

Over the Northern Hemisphere (and especially over Europe -bottom plot- and North America -not shown-), withdrawing surface pressure observations over sea clearly degrades the forecast performance. However, NOSPBUOYSEA merely shows a slight degradation versus the CTL experiment. This result seems to indicate that, if there is no doubt that surface pressure observations over sea are crucial for global NWP, the current network (provided by buoys and ships) may be somewhat redundant (see Fig. 5). On has to be careful though with this conclusion as only mean scores are presented here, that do not give any insight about individual cases where degrading the current buoy network could have a strong negative synoptic impact (see section 4).

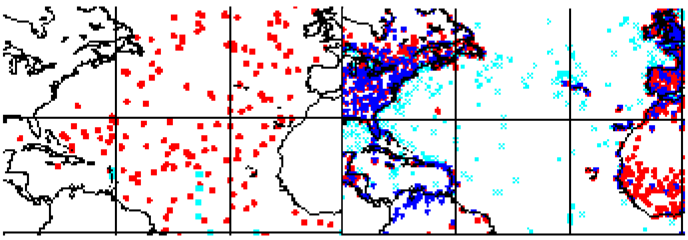

Fig. 5: buoy (left) and ship typical data coverage over North Atlantic.

A last LOWOSE has been run to assess the impact of a potential degradation of the accuracy of the surface pressure observing system (the rationale behind this last experiment being an evaluation of what could be offered from space with the current technology). NOSURFWIND2hPA, where surface pressure observations from Ships and buoys were set to 2 hPa (maximum accuracy achievable from space), was also run for the winter period. As a result, a systematic degradation of the forecast performance was observed for the Northern Hemisphere (not shown).

As stated above, the main LOWOSES (CTL, NOSURFWIND, NOSPSEA and NOSPBUOYSEA) were run over 6 weeks during a Northern Hemisphere summer (20010615-20010801). Although the main findings did not change fundamentally between the two periods, the overall impact of surface observations was smaller than in winter, and the scatter of the impact much larger (this was also found in Bouttier and Kelly 2001), making the statistical significance smaller.

4. Results of the high resolution OSEs (HIGHOSES)

As mentioned in introduction, triggered by further interest from the EUCOS community, a reduced set of high resolution OSEs with surface observations has been performed within the framework described in Kelly et al (2004). This environment is more realistic (very close to the current ECMWF operational system) and also more challenging for surface observations due to the use of a wealth of satellite observations. The question at stake in this context was: do conventional surface observations over sea still matter (no discrimination anymore between surface pressure and wind information)?

Three HIGHOSES (matching the CTL experiment described in Kelly et al. 2004) have been run and are summarized in table 3.

	Experiment name	**Description**	**Duration**
1.	NOSHIPBUOY	all ship and buoy data excluded from the assimilation	120 cases
2.	NOSHIP	all ship data excluded from the assimilation	60 cases (summer)
3.	NOBUOY	all buoy data excluded from the assimilation	60 cases (summer)

Fig. 6 represents the 1000 hPa geopotential height forecast anomaly correlation scores for the CTL (red curve) and NOSHIPBUOY (blue curve) experiments, averaged over 120 cases. There is a consistent degradation of the scores when buoys and ships are removed from the system, and this despite a heavily constrained system by satellite observations over sea.

Worth noting is the stronger impact of surface observations in the Northern Hemisphere, especially in winter, probably explained by the relatively scarcer distribution of the surface network (especially from ships) and a globally more aggressive use of satellite observations in the Southern Hemisphere (not shown).

Time series of RMS forecast error scores at day 1, 2 and 3 for the CTL (respectively red, pink, brown curves) and NOSHIPBUOY (respectively dark blue, green and light blue) are displayed in Fig. 7 for the Northern Hemisphere summer period (60 days). This figure clearly indicates a systematic degradation of the scores when surface observations over sea are withdrawn. One could argue that the verifying analysis (CTL in this case) plays an important role and penalizes the experiments for which data have been withdrawn. However, this argument is unlikely true at day 3 where one can still see a very strong and systematic signal in the NOSHIPBUOY experiment.

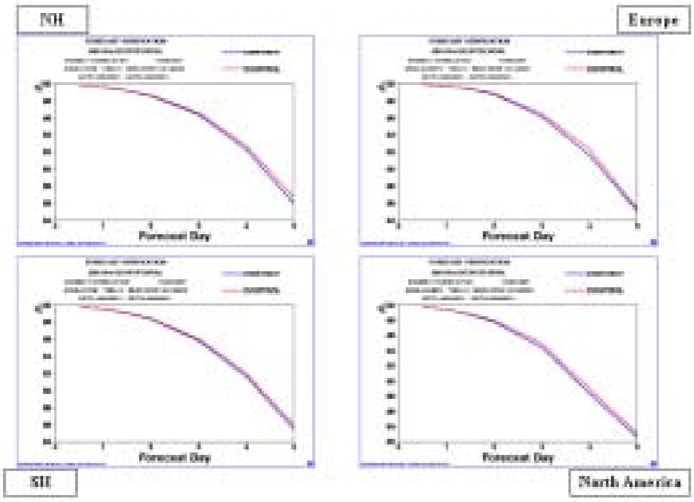

Fig. 6: 1000 hPa geopotential height forecast anomaly correlation (averaged over 120 cases) for the CTL (red curve) and NOSHIPBUOY (blue curve) experiments. Scores are presented for the Northern Hemisphere (top left), Southern Hemisphere (bottom left), Europe (top right) and North America (bottom right)

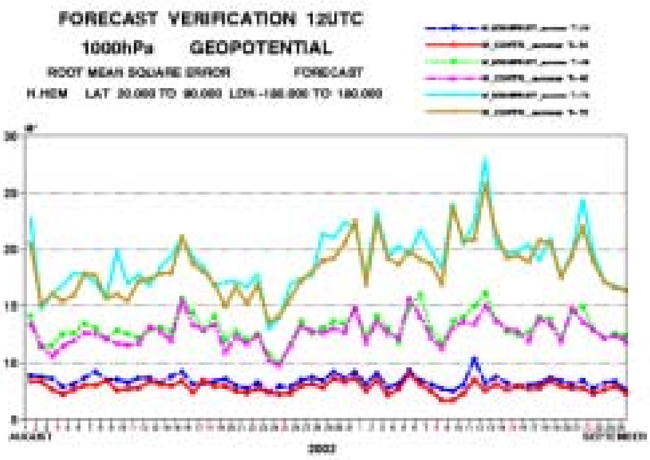

Fig. 7: Time series of RMS forecast error scores at day 2, 3 and 4 for the CTL (respectively red, pink, brown curves) and NOSHIPBUOY (respectively dark blue, green and light blue). Northern Hemisphere, Summer 2002.

Fig. 8 displays similar statistics as Fig. 7 over Europe. As expected, due to the small verification area, a larger scatter in the results is observed. Nevertheless, one can spot a large number of days for which forecast scores are largely degraded at day 2 and 3 when surface observations are withdrawn (see for example the circled case on 20020809, or on 20020829), the opposite being hardly observed over this summer period.

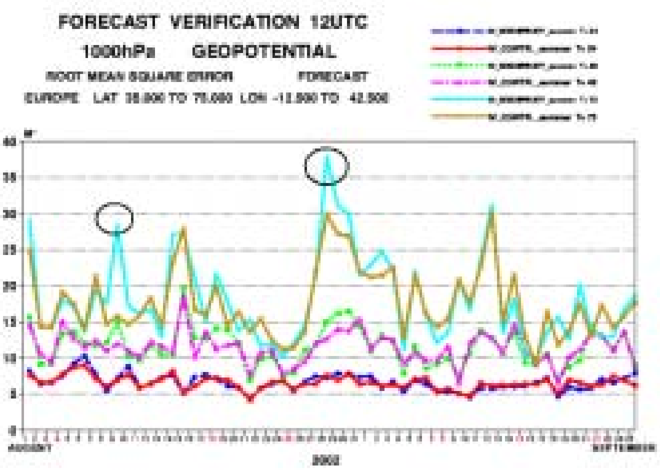

Fig.8: as Fig.7 but over Europe

The synoptic situation for 20020809 was studied further and the large difference of 3-day forecast performance over Europe (NOSHIPBUOY missing completely a large depression over Central Europe) could indeed be traced back to small surface pressure differences in the initial conditions over the West Atlantic in areas well covered by ships and buoys. This points to the fact that, even if on average and in a global NWP environment the impact of conventional surface observations remains small (but positive), the impact can be dramatic on some individual synoptic cases.

NOSHIP and NOBUOY experiments have been evaluated individually and we will only summarize the outcome here. In a nutshell, buoys and ships seem of equal importance on average (as measured by forecast performance as previously described), with perhaps a small advantage to the ships in the Northern Hemisphere. Both buoys and ships contributed equally to the improvement of the forecast for the 20020809 synoptic case, confirming the high sensitivity of this meteorological situation to small perturbations in the initial conditions.

5. Conclusions

A number of low resolution and high resolution OSEs has been performed at ECMWF to assess some aspects of the relevance of the surface observing system. With the precautions required due to the usual limitations of the OSEs, (in particular the always too short periods of investigations, the verification criteria, the simplicity of the scenario, etc…), the LOWOSES seem to indicate that:

1. Surface data are an essential element of the current Observing System
2. Some surface pressure observations (over sea and land) are absolutely essential to anchor the surface pressure field

3. Surface wind observations provide too partial surface pressure information to be used in isolation

4. A degradation of the accuracy of the current surface pressure Observing System would have a detrimental impact on forecast performance (this may entail that there is very little scope to obtain surface pressure information from space at the accuracy by currently required by NWP systems)

5. In presence of surface wind observations over sea, a reduced number of surface pressure observations (for example ships - note that the symmetric experiment withdrawing ships only has not been performed -) seems sufficient to obtain "good" forecast performance

HIGHOSES that have been run in a more realistic and challenging context show that:

1. Even in a NWP system overwhelmed by satellite observations, the conventional sea surface network provided by buoys and ships has on average a noticeable positive impact

2. Surface observations over sea can have a very large positive impact on specific synoptic cases (large negative impacts were not found during the period under investigation)

3. Ships and buoys show a similar impact on the ECMWF forecast performance

Overall, these studies confirm the high level of complementarity of the space and terrestrial networks, despite an escalating use of satellite data in modern global NWP assimilation systems.

References

Bormann, N., and J.-N. Thépaut, 2004: Impact of MODIS Polar Winds in ECMWF's 4DVAR Data Assimilation System. *Mon. Wea. Rev.,* **132**, 929-940.

Bouttier, F., 2001: The development of 12-hourly 4D-Var. *ECMWF Tech. Memo.,* **348***,* pp21

Bouttier, F., and G. Kelly, 2001: Observing system experiments in the ECMWF 4D-Var data assimilation system. *Quart. J.R. Meteor. Soc.*, **127,** 1469-1488.

Courtier, P., J.-N. Thépaut and A. Hollingsworth, 1994: A strategy for operational implementation of 4D-Var, using an incremental approach. *Quart. J.R. Meteor. Soc.*, **120,** 1367-1388.

Kelly, G., A. McNally, J.-N. Thépaut and M. Szyndel, 2004. Observing System Experiments of all main data types in the ECMWF operational system. *This volume.*

Rabier, F., J.-N. Thépaut and P. Courtier, 1998: Extended assimilation and forecast experiments with a four-dimensional variational assimilation system. *Quart. J.R. Meteor. Soc.*, **124**, 1861-1887.

Data impact studies in the CMC global NWP system

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1. Introduction

Since June 2000, a series of major modifications have been implemented in the CMC global NWP system, resulting in substantial improvements to the quality of forecasts. In particular, the direct assimilation of ATOVS (AMSUA and AMSUB) radiance data, better use of wind and temperature data from automated aircraft reports, as well as a revised 3D-Var algorithm performed directly on the model η levels using temperature and surface pressure data rather than geopotential heights.

The CMC operational global forecast model (GEM) has a horizontal resolution of 0.9º and 28 η levels in the vertical. The analysis program is a 3D-Var assimilation program on model surfaces at a spectral resolution of T108. Background errors were obtained from the so-called 24-48h method. The observation quality control is now a two step approach: a background check prior to the analysis and a variational QC during the analysis process itself. The CMC continuous assimilation cycle is a 6-hourly 3D-Var system. The observations cut-off times are T+9hrs for 00 and 12 UTC analyses and T+6hrs for the 06 and 18 UTC analyses. These relatively long cut-off times are used in order to wait for the arrival of most of the observations before doing the analyses. Operational forecasts are issued twice a day at 00 and 12 UTC. But the forecasts must be issued before the delay imposed by the final analyses of the assimilation cycle. So the global forecasts are made from an early analysis with a T+3hrs observational cut-off time. Given the current reception time of some observations, especially circumpolar satellite observations, a reduced volume of observations is included in the analyses used for the operational forecast. Regional forecasts are produced from analyses with an even shorter cut-off time of T+1hr40, following a 12-h regional spin-up cycle.

During the year 2002, a series of observing system experiments (OSE's) were prepared to evaluate the impact of various types of observations in the CMC global NWP system. This series of experiments is really the first major set of OSE's ever performed by the CMC. In these experiments one or more type of observation is removed from the assimilation cycle and the impact on the forecast quality gives an indication of the value of that type of observation in the system. The experiments performed, as well as the verification methodologies, are described in the next section, while the results are presented in section 3. Only a few results will be presented as the Power Point file presented at the workshop in Alpbach is available on the WMO web site. Results from a few other experiments done more recently are discussed in section 4. Conclusions are discussed in the last section.

2. Experimental framework and verification methodology

Assimilation and forecast experiments have been performed in order to investigate the impact of different observation configurations. The observing systems tested were ATOVS radiances (AMSU/A only), cloud drifts or water vapor atmospheric motion vectors (AMV), humidity estimates from satellite (HUMSAT), aircraft, radiosonde and surface observations. In this study, the control run is the CMC operational 3D-Var assimilation system, using a long cut-off time (version of the global system following the Dec 2001 implementation). In accordance with recommendations from the previous workshops, as well as from the CAS-WGNE, attempts were made to select sufficiently long periods, and to include some estimate of the statistical significance of the results. The evaluation was done for two 6-week periods, winter: from December 17, 2001, 00 UTC to January 27, 2002, 12 UTC; and summer: June 17, 2002, 00 UTC to July 31, 2002, 12 UTC. During these two periods, we ran 6-day forecasts twice a day at 00 and 12 UTC, from the final analyses of the modified assimilation cycle (a single day of spin-up was done).

Each experiment is identified according to the following nomenclature:
CNTRL the reference, it is the control done with CMC global operational assimilation and forecast system, using a long cut-off time.
NOTO is the control minus the ATOVS radiances, AMSU-A channels 3 to 10 from NOAA-15 and NOAA-16.
NOSW is the control minus the AMVs from GOES-8&10, METEOSAT-5&7 and GMS-5.
NOHU is the control minus HUMSAT humidity data.
NOSAT is the control minus all satellite data, i.e. ATOVS, AMVs and HUMSAT.
NOUA is the control minus all radiosonde data, including TEMP, PILOT and dropsonde.
NOAI is the control minus all aircraft data (wind and temperature), including AIREP, ACARS and AMDAR observations.
AITT is the control minus all aircraft temperature data.
AIUV is the control minus all aircraft wind data.
NOSF is the control minus all surface observations, including SYNOP, SHIP, DRIFTER and BUOY, however the surface level from radiosonde stations still included.

Note that AMSUB and GOES radiance data were not present in the configuration that was used for these experiments. The impact of different observing systems was evaluated over both data-rich (North America and Northern Hemisphere) and data-poor (Tropics and Southern Hemisphere) areas. For a more complete evaluation, verification against observation as well as against analyses has been performed. The evaluation against observation is done by comparing analyses and forecasts to a (common) global set of quality controlled radiosonde observations, and according to the WMO recognized standards. The verification against analyses has also been done according to the WMO standards, with one exception. Usually, when evaluating impacts of modifications to the operational NWP systems, each system (operational and parallel suites) is verified against its own analyses. However, in the context of data impact studies, it is believed that a more accurate representation of the impact of each data type is obtained when the analyses of highest quality are used to perform the verification. In our situation, these were the control analyses.

3. Results

Let us first examine some verification against radiosonde, of the 6-hour forecast (first guess) of the NOUA and NOSAT experiments, compared to the control (Figs. 1, 2 and 3). This is a good indication of the impact of the data during the data assimilation cycle, and the fit of the first guess to the radiosonde data. Figure 1 compares the results of the CNTRL and the NOUA experiments for Northern Hemisphere, for the summer (left panel) and winter (right panel) periods. It shows the RMS and BIAS differences for wind components (UU, VV), temperature (TT), geopotential (GZ) and dew point depression (Es) evaluated at standard pressure levels against the radiosonde data of the Northern Hemisphere. Figure 2 is similar to Figure 1 but for the NOSAT experiment, while Figure 3 is for the NOSAT experiments but for the Southern Hemisphere. Although the impact of satellite data on the first guess is very clear in the Northern Hemisphere (wind and mass fields), it is very obvious that the conventional radiosonde data still dominates in the very short range. The moisture analyses are also greatly influenced by the radiosonde data. In the Southern Hemisphere, the situation is clearly dominated by the satellite data which have a huge impact on the first guess. One result (shown at the workshop) is the positive and significant synergy between the satellite winds and the satellite radiance data (AMSUA). This is clearly seen in the Tropics and the Southern Hemisphere.

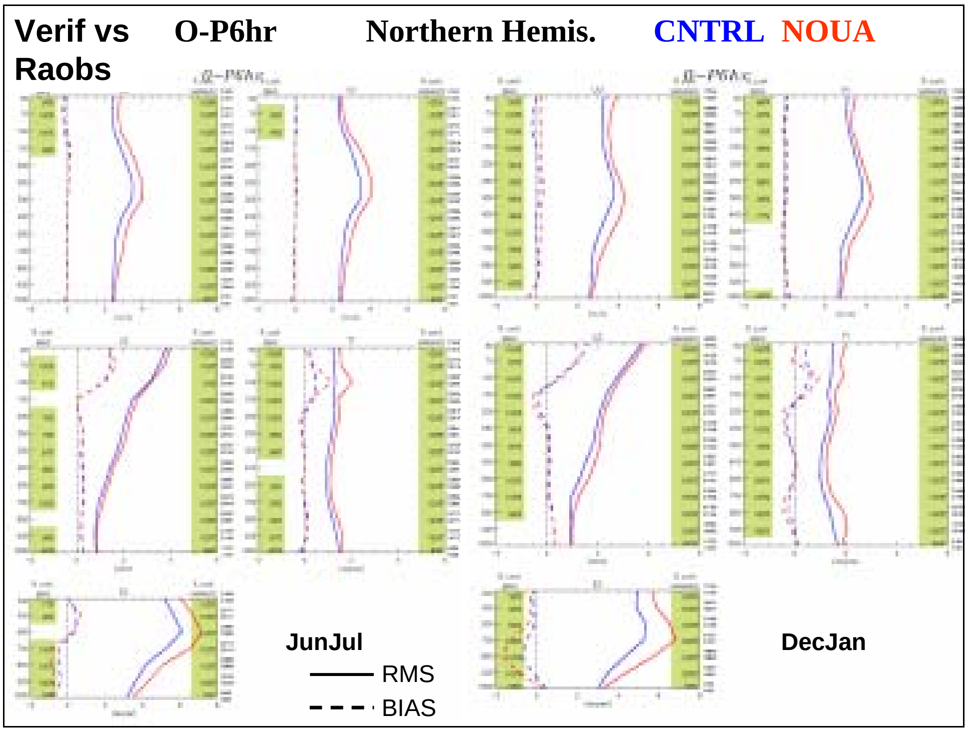

Figure 1. RMS (full) and BIAS (dashed line) errors against the Northern Hemisphere network for the 06h forecasts. The blue lines are for CNTRL and the red lines for the NOUA experiment. Highlighted % values are statistical significance test results. Results are for summer (left panel) and winter (right panel).

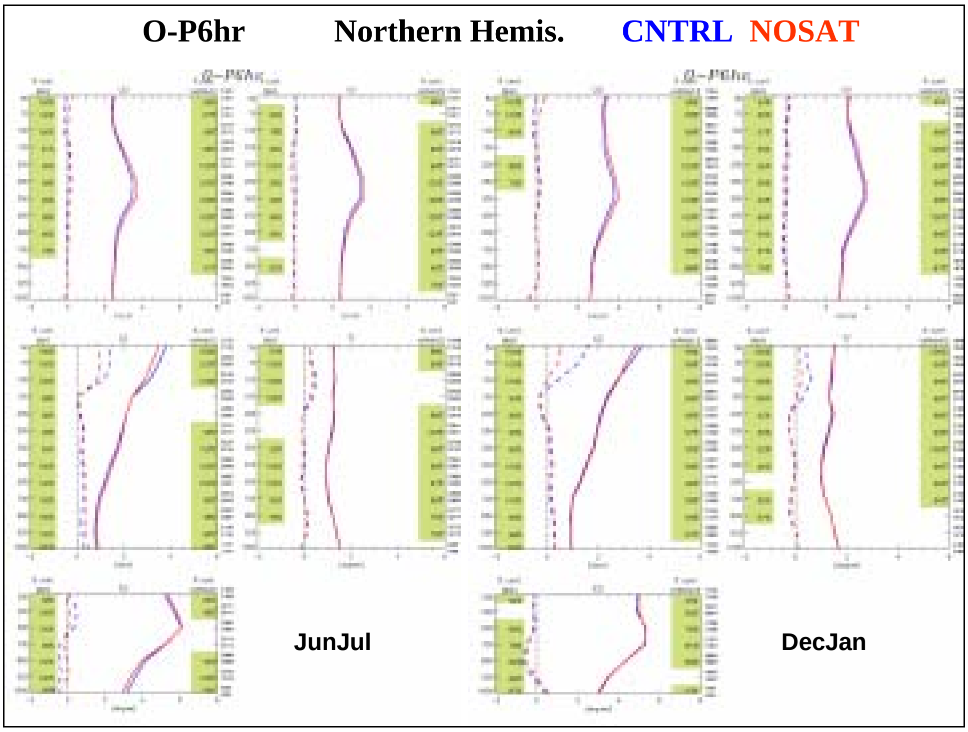

Figure 2. Same as Fig. 1 but for the NOSAT experiment.

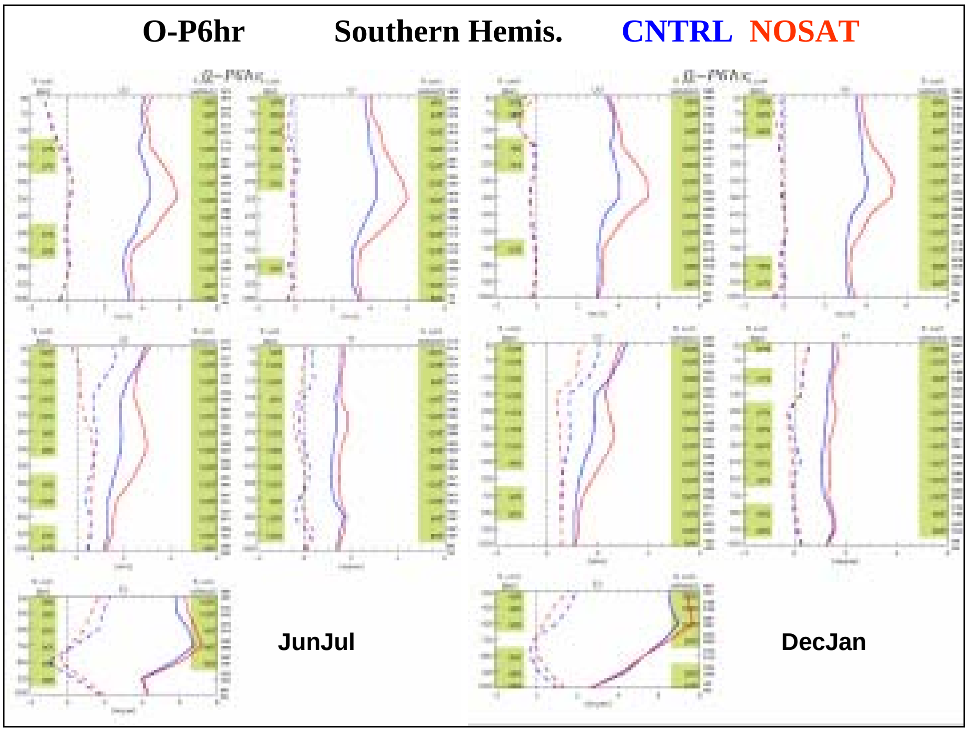

Figure 3. Same as Fig. 2 but for the Southern Hemisphere network.

Let us next examine the impact of the various observing systems on the resulting NWP model forecasts. This is first done using the RMS forecast impact (FI) (Zapotochy et al. 2002). The FI of an individual data type is evaluated as the RMS error of the denied forecast minus the RMS error of the control forecast this difference is divided by the RMS error of the control forecast and multiplied by 100 to normalize the result. It provides a percentage improvement with respect to the control forecast. A positive FI value means that the forecast quality is improved when the data type is included.

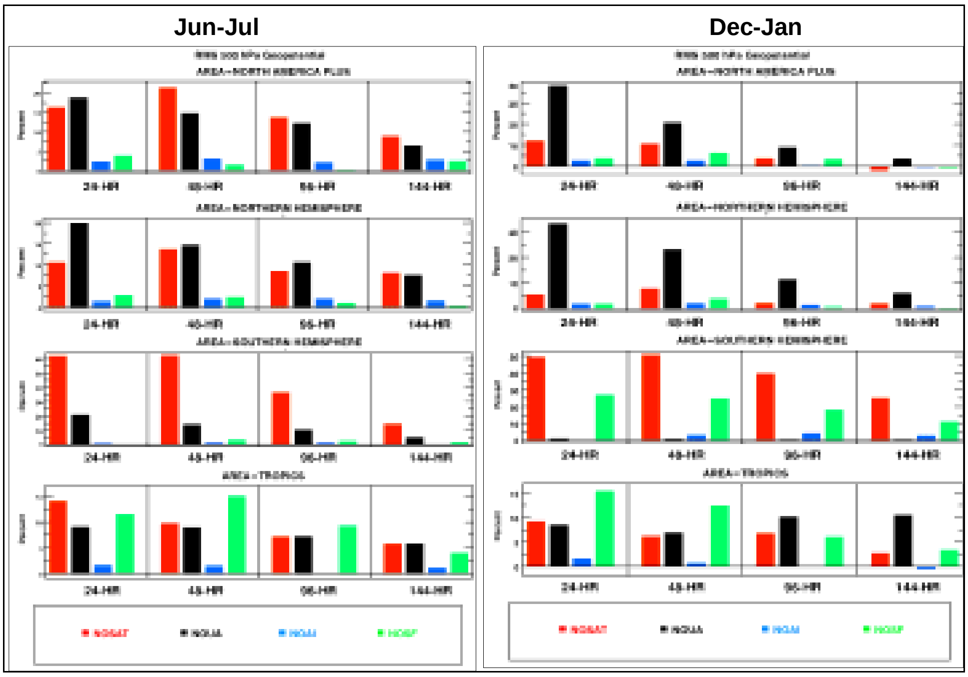

Figure 4. Forecast impact (%) for 500 hPa GZ for the four experiments: NOSAT, NOUA, NOAI, and NOSF. Forecast periods are: 24, 48, 96 and 144 hours. Summer: left panel, Winter: right panel.

The FI for GZ for the 500 hPa geopotential heights is illustrated in Figure 4 for the 24, 48, 96 and 144 hour forecast periods, over the four geographical areas. Results are shown for the summer (left panel) and winter (right panel) periods, and the NOSAT, NOUA, NOAI and NOSF experiments are compared to the CNTRL. The results indicate that for North America and the Northern Hemisphere, the largest forecast impact is obtained from radiosonde observations during winter, however the impact of satellite data is similar to that of radiosonde data in summer. Aircraft data have a small, but positive impact at all time ranges, with more impact in summer than winter. In the Southern Hemisphere the satellite data have a forecast impact much larger than the radiosonde data, both in summer and winter, while surface data have a significant impact in winter. Finally in the Tropics, the impact of the surface data on GZ is quite large, sometimes even larger than the impact of radiosonde and satellite data.

Figure 5 also illustrates FI results, but this time for the NOTO, NOSW, NOHU and NOSAT experiments compared to the CNTRL, again for both the summer and winter periods. This allows us to examine the impact of various component of the satellite observing system. The positive impact of ATOVS data alone is more important in the extratropics especially for the Southern Hemisphere. In the Tropics, where the relation between heights and wind is weaker, the AMVs have a large positive impact on the forecast quality. Note that the impact of withholding all satellite data types (NOSAT) is larger than the impact obtained with the denial of a single data type (NOTO, NOSW and NOHU) and clearly different from their sum, especially in the Tropics and Southern Hemisphere. This result is another example of positive synergy between ATOVS and AMVs data. The GOES moisture bogus data (HUMSAT) also seems to provide small but positive impact in the Tropics. Another result not shown here is that satellite data also has a large impact on all forecast variables.

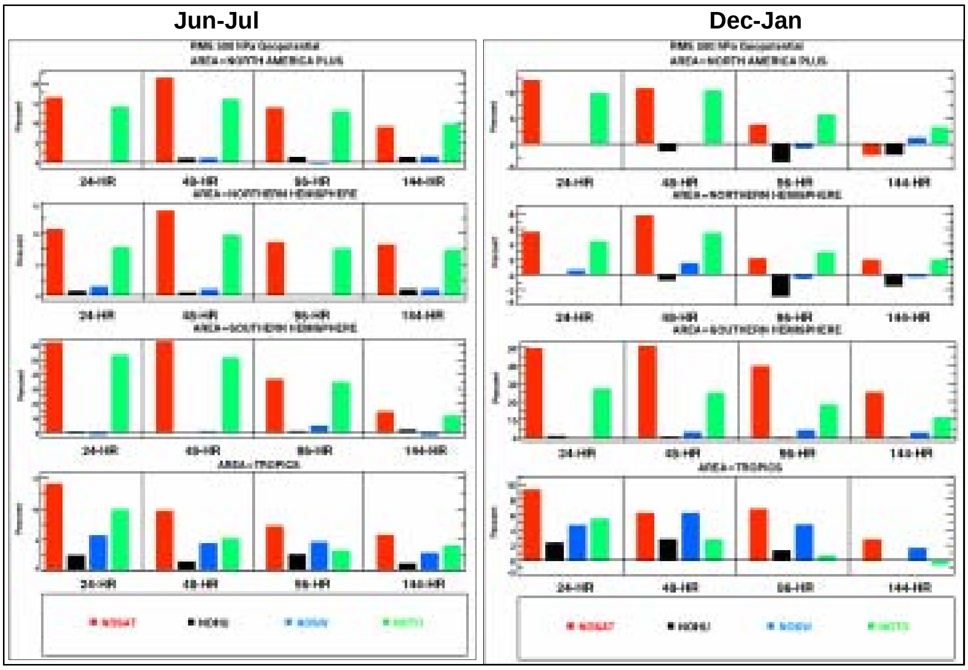

Figure 5. Forecast impact (%) for 500 hPa GZ for the four experiments NOSAT, NOHU, NOSW and NOTO. Forecast periods are 24, 48, 96 and 144 hours. Summer: left panel, winter: right panel.

Figure 6 is an illustration of the FI for aircraft data, but the summer period only over North America. This time the impact on the first guess (6-h forecast) is also included, in addition to the other 4 periods. There are 3 experiments: NOAI, NOTT and NOUV in order to examine the impact of wind versus temperature data from aircrafts. As expected, the impact of aircraft data is more important over North America and the Northern Hemisphere, and there is significant impact in the short-term forecasts in the Tropics. The results also indicate that there is usually more impact from the wind observations than from the temperature observations. However, temperature data have more impact on temperature forecasts than wind data.

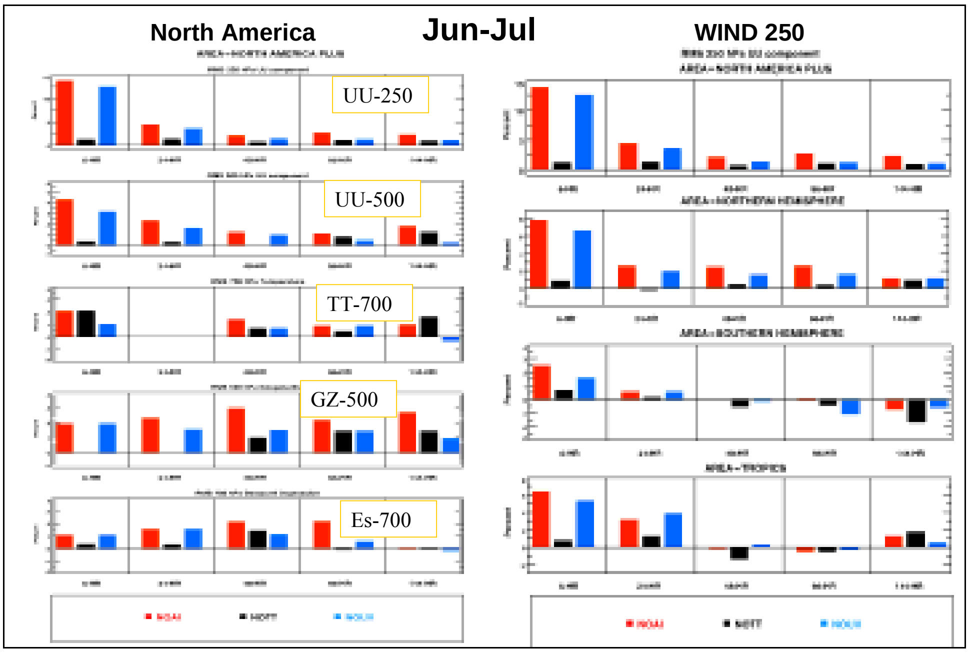

Figure 6. Forecast impact (%) for the three experiments NOAI, NOTT and NOUV. Forecast periods are 06, 24, 48, 96 and 144 hours, summer period only. Left panel: North America for various elements and levels; right panel: wind at 250 hPa for various areas.

Only one result of verification against analyses will be presented here. Figure 7 is an illustration of the anomaly correlation scores, for GZ at 500 hPa, for both forecast periods over North America. We clearly see that the impact of satellite data is comparable to that of radiosonde data in Summer, however, the signal is dominated by radiosonde data in Winter, particularly for the medium range forecasts. The impact of aircraft data is clear in Summer while the impact of surface data is more evident in Winter than in Summer.

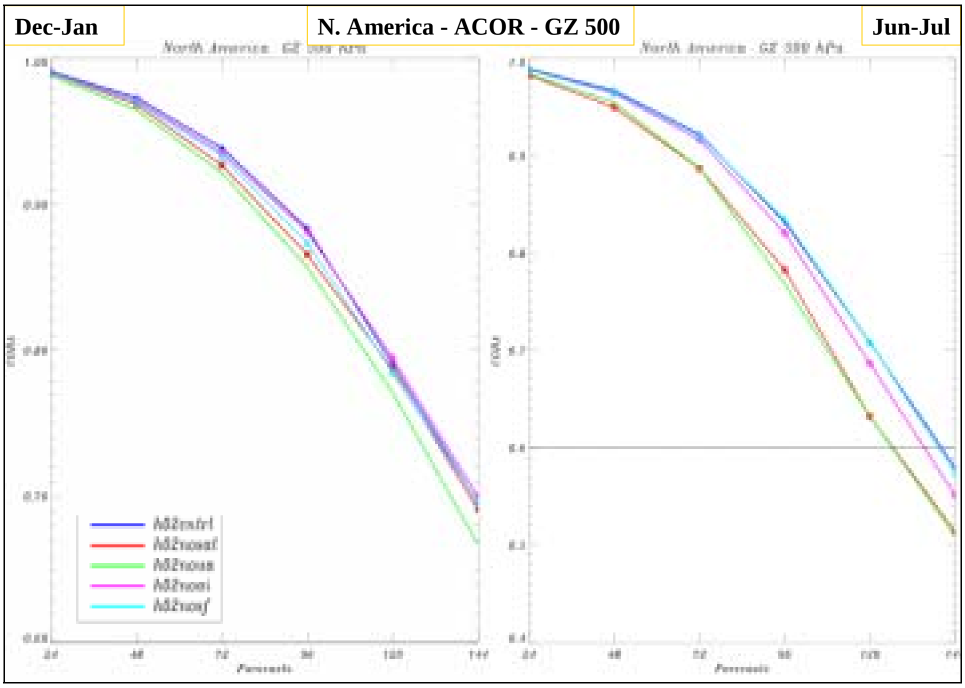

Figure 7. 500 hPa GZ anomaly correlation scores, over North America for the CNTRL, NOSAT, NOUA, NOAI and NOSF experiments, for forecast periods extending to day 6. Winter: left panel, summer: right panel.

4. Recent experiments and results

A few other experiments have been done more recently, but results were not available at the time of the workshop. In particular, OSE's have been done to evaluate the impact of the MODIS polar winds, and to evaluate the impact of satellite data in the revised 3D-Var following the implementation of the AMSUB and GOES-10 radiance data.

The first result comes from Sarrazin and Zaitseva (2004) and illustrates the impact of the MODIS winds produced by NOAA, for the period of 8 November 2003 to 25 January 2004. The results are shown in Figure 8, which shows the difference in the RMS of 24 hour forecast errors, between the control and the polar winds experiment (verification done against the analysis with the polar winds). The impact on the 500 hPa wind vector is very clear and positive and mostly benefits the Arctic and Antarctic areas. MODIS polar winds are part of a new version of the 3D-Var proposed for a parallel run at CMC during the spring of 2004.

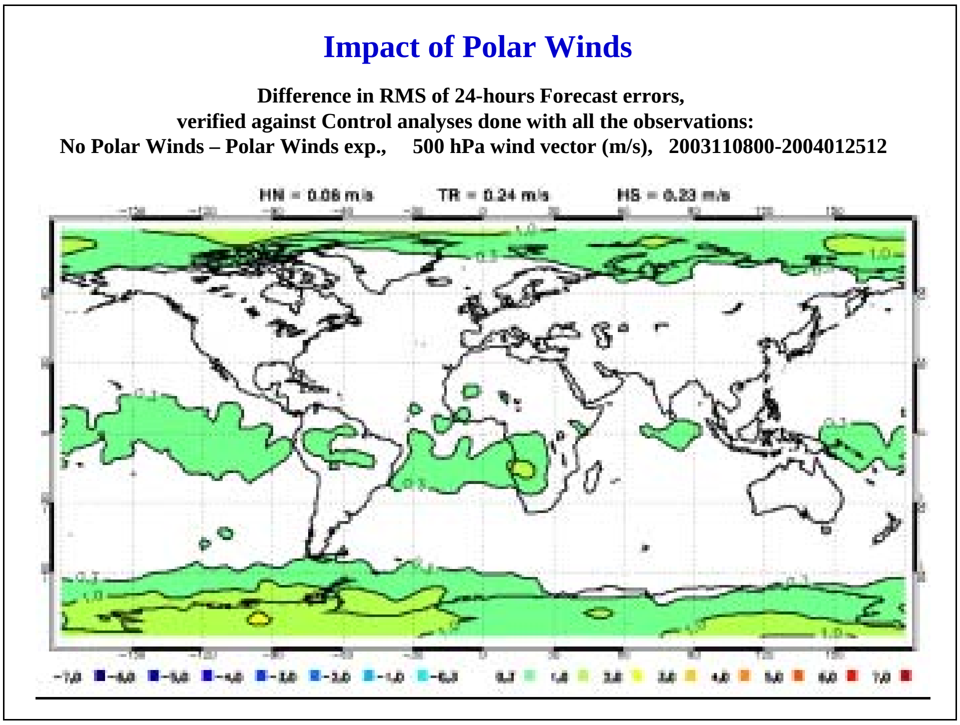

Figure 8. Difference in the RMS of 24 hour forecast errors, for the control minus the polar winds experiment. Positive values indicate mean a positive impact of the polar winds.

A second series of experiments have been performed, combining the impact of all satellite data currently (or soon to be) assimilated (AMSUA, AMSUB, SATWINDS (including MODIS) and GOES radiances), for the period of November 8 to December 31, 2003. An experiment without radiosonde data has also been performed for the same period. The results are illustrated as 500 hPa GZ anomaly correlation scores, over the Northern Hemisphere (Figure 9), the Southern Hemisphere (Figure 10) and North America (Figure 11). Comparison is made against the results (for the winter period) obtained from the first series of OSE's discussed in section 3 of this article.

Results clearly show that for the 2003 set of OSE's, there is much more impact due to satellite data in the CMC 3D-Var system than in the 2002 set. In fact, satellite data now has as much (if not more) impact over the Northern Hemisphere, and over North America, as the radiosonde data. In addition, the impact of satellite data in the Southern Hemisphere in increased by about 10 hours. We also note that, although there is much more satellite data assimilated in the winter 2003 experiment, the scores of the control, particularly over North America, are worse than for the winter 2002, indicating a more difficult season to forecast. It is interesting to note that this level of impact of satellite data in the CMC system is obtained for the first time, and the CMC system is still a 3D-Var system. It is possible that the result may be actually related to the forecast period (winter 2003) rather than the differences in the assimilation systems.

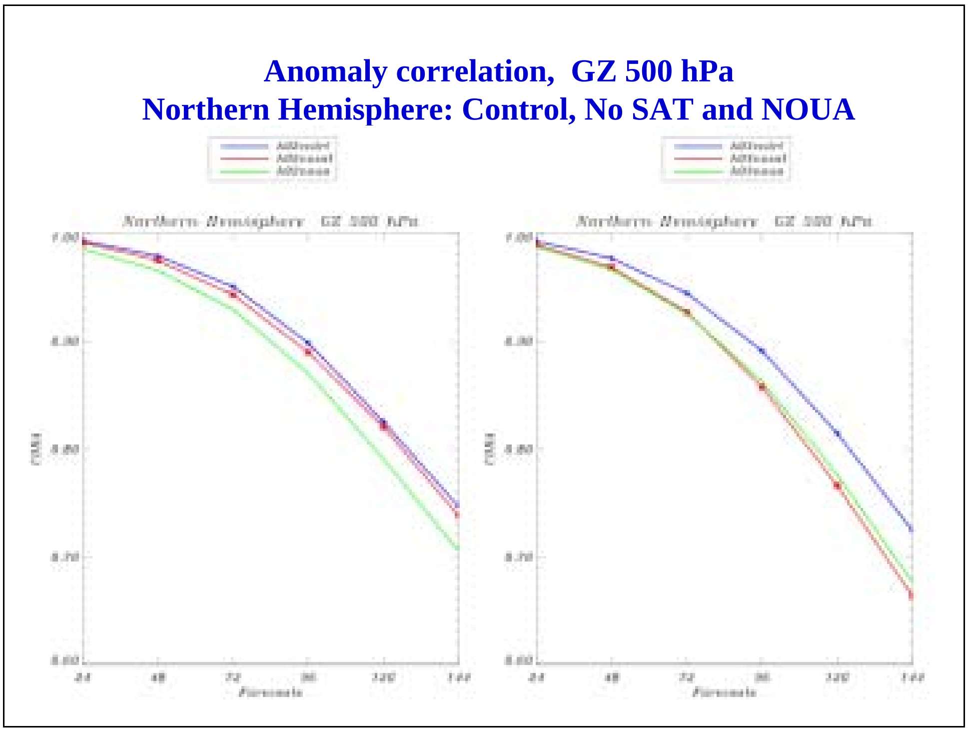

Figure 9. 500 hPa GZ anomaly correlation scores, over the Northern Hemisphere for the CNTRL, NOSAT and NOUA experiments. Winter 2002 (h02) is shown on the left panel and winter 2003 (h03) on the right panel.

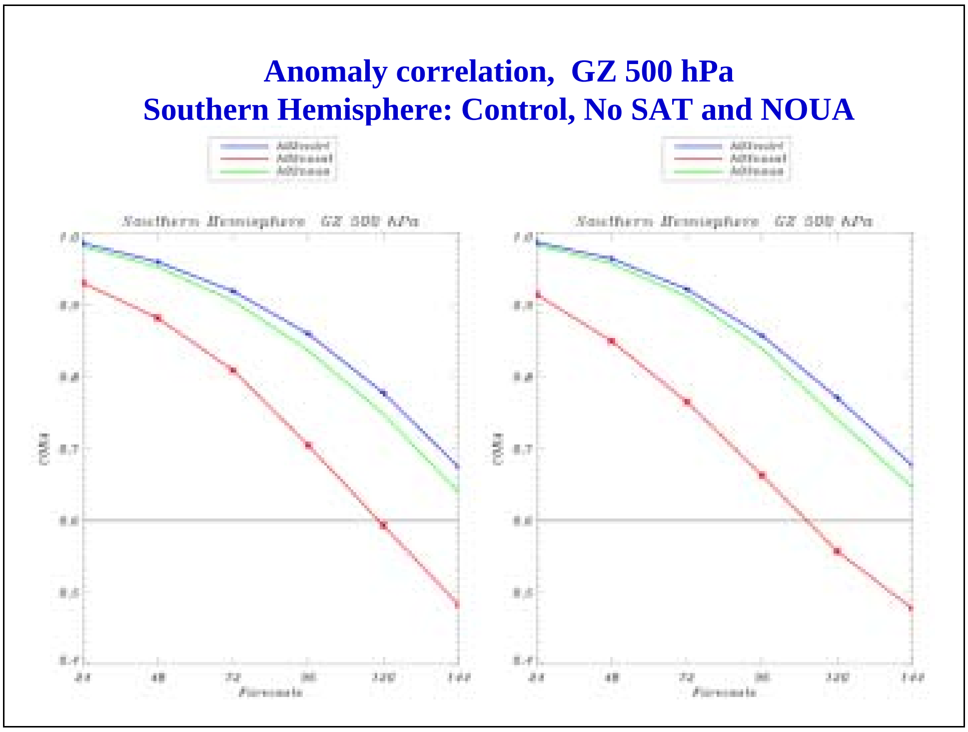

Figure 10. Same as Figure 9 but over the Southern Hemisphere.

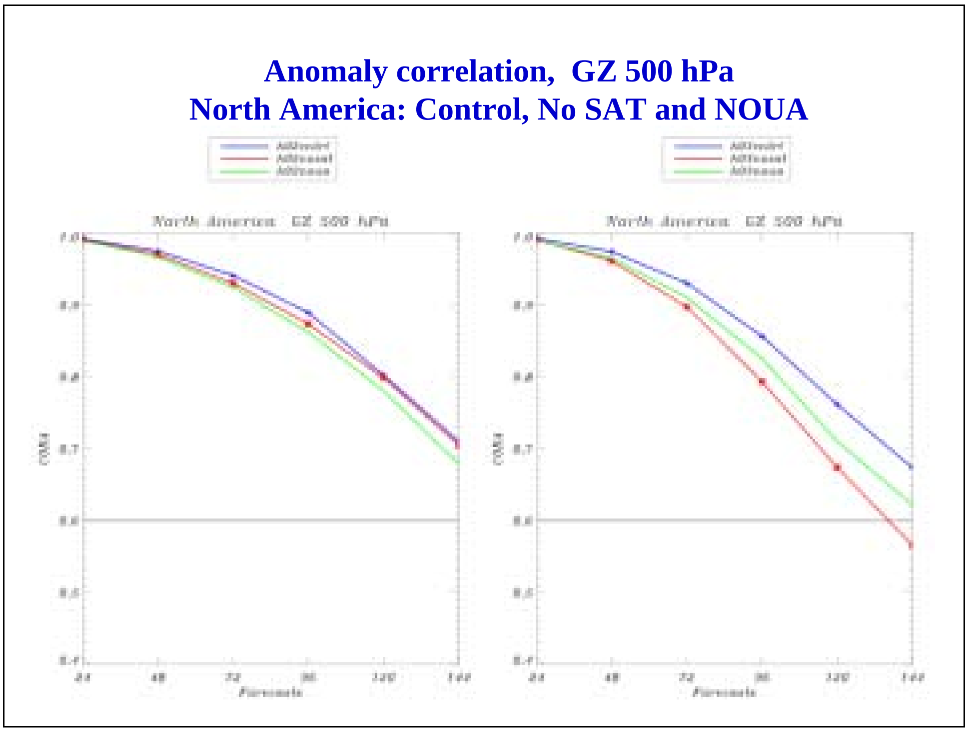

Figure 11. Same as Figure 9 but over North America.

5. Conclusions

Results based on verification against observations as well as against control analyses clearly indicate the importance of satellite and conventional radiosonde data in the CMC global forecast system. There is a major impact from satellite observations (mostly from ATOVS data), which totally dominate in the Southern Hemisphere. During summer, the impact of satellite data is similar to that of radiosonde data, over the Northern Hemisphere and over North America. However, during winter, the signal is dominated by radiosonde data in these two areas. In the Tropics, all types of data show a positive impact. Synergy between some types of satellite data is also observed. It has also been shown that all observation types, without exception, have a positive impact in the system. Over North America, both wind and temperature data from aircraft have a positive impact, with wind data having a much larger impact than temperature data in the short range. It is also important to note that the impact of various observations varies depending on the chosen verifying element, vertical level or forecast period. There is also a dependency on the period chosen to perform the experiments.

Finally, in a more recent set of impact studies, the addition of MODIS polar winds was found to be beneficial, and the level of impact of satellite data in the CMC 3D-Var system has been increased with the assimilation of additional satellite data. The impact of satellite data now appears to be as significant (or even more) than that of radiosonde data.

References

Chouinard, C., C. Charette, J. Hallé, P. Gauthier, J. Morneau, R. Sarrazin, 2001, The Canadian 3D-VAR Analysis Scheme on Model Vertical Coordinate**,** *Proc. AMS 14th Conference on Numerical Weather Prediction,* 30 July–2 August, Fort Lauderdale, Florida, pp. 14-18.

Chouinard, C, J. Hallé, 2003, Use of moisture sensitive satellite radiances in the Canadian Meteorological Centre Unified 3D-var system. *Proc. SPIE Int. Soc. Opt. Eng. 4895 Applications with Weather Satellites*, pp 63-74.

Chouinard C., J. Hallé, C. Charette, and R. Sarrazin: Recent improvements in the use of TOVS satellite radiances in the Unified 3D-Var system of the Canadian Meteorological Centre. ITSC XII proceedings, Lorne, Australia, 27 February-March 5, 2002.

Gauthier, P., C.Charette, L.Fillion, P.Koklas and S.Laroche, 1999: Implementation of a 3D variational analysis at the Canadian Meteorological Centre. Part I: The global analysis. *Atmosphere-ocean*, **37**, 103-156.

Sarrazin, R., and Y. Zaitseva, 2004: MODIS polar winds assimilation impact study with CMC operational NWP system, to be presented at the 7th International Winds Workshop.

Undén, P., Kelly, P., Le Meur, D. and Isaksen, L., 1997: Observing system experiments with 3D-Var assimilation system. ECMWF Research Department Technical memorandum, **244,** Available from ECMWF, Shinfield Park, Reading RG29AX, UK.

Zaitseva, Y., Sarrazin R. and Verner G., 2003; Data Impact Studies using the Global Assimilation System of the Canadian Meteorological Centre, *Proc. AMS Seventh Symposium on Integrated Observing Systems, 9-13 February 2003, Long Beach, California, P1.2*

Zapotocny Tom H., W. Paul Menzel, James P. Nelson III and James A. Jang, 2002: An impact study of five remotely sensed and five in situ data types in the eta data assimilation system. *Bull. Amer. Meteor.Soc.*, **4**, 263-285.

Impact Studies Performed with the Global ARPEGE NWP System

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ABSTRACT

IFS-ARPEGE is a global NWP system developed and maintained jointly between Météo-France and ECMWF. The system contains different versions of spectral models and data assimilation systems (3D-VAR; 4D-VAR). The main operational model at Météo-France is based on a stretched (variable mesh) version of the spectral model which is initialized through a 4D-VAR assimilation.
Various versions of ARPEGE (and its assimilation) have been used by different scientists in Météo-France to perform OSEs assessing the impact of several observing systems. Some are conventional observations, but most of them are satellite data: ATOVS (from the NOAA satellites) and Meteosat cloud motion winds. The potential of a meso-scale analysis for bringing high resolution details to a large-scale analysis like ARPEGE is also shown.

1. PRESENTATION OF THE ARPEGE NWP SYSTEM

The main operational model at Météo-France is a global spectral model (ARPEGE), similar to the ECMWF model on many aspects, with a variable resolution leading to a zoom effect over France (Courtier et al., 1991). It has 41 levels in the vertical with the top level at 1 hPa. In the horizontal, the average resolution is T358 with a stretching factor of 2.4, and a linear grid whose resolution is 23 km over France and 133 km at the antipode. The more recent resolution change (June 2003) corresponds to a 60% increase of the average horizontal resolution and a reduction of the stretching factor from 3.5 to 2.4 (vertical resolution unchanged).

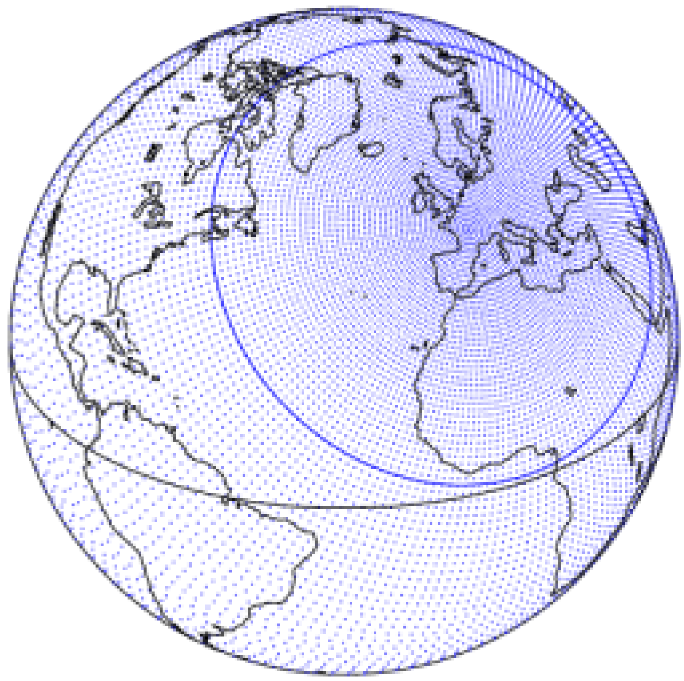

Figure 6. T358/c2.4 ARPEGE stretched grid as it is used in operations at Météo-France in 2004. The resolution varies from 23km over France to 133km at the antipode.

A uniform (unstretched) version of ARPEGE is also run for territories inside the tropics, it is called "ARPEGE – Tropiques". This ARPEGE version has also been used for running some OSEs which are described hereafter. Finally, for detailed forecasting over western Europe, one version of ALADIN is run operationally (ALADIN – France). ALADIN is the limited area version of ARPEGE (many common features in the dynamics, same physics).

The main assimilation system is a 4D-VAR which updates the ARPEGE stretched model 4 times a day (see figure 2). It has been developed jointly with ECMWF and is similar on all the principles. These principles are described in Rabier et al. (2000) and Mahfouf and Rabier (2000). The ARPEGE 4D-VAR has also its own characteristics such as:

- a 6 hour time window centered on each synoptic time (00, 06, 12 and 18 UTC);
- an incremental technique, with the analysis increments evaluated through two consecutive minimisations, at T107 and T149 respectively without stretching (T149 is then the uniform resolution of the 4D-VAR increments);
- the use of a weak constraint based on digital filter computations in the minimisations (see Gauthier and Thépaut, 2001).

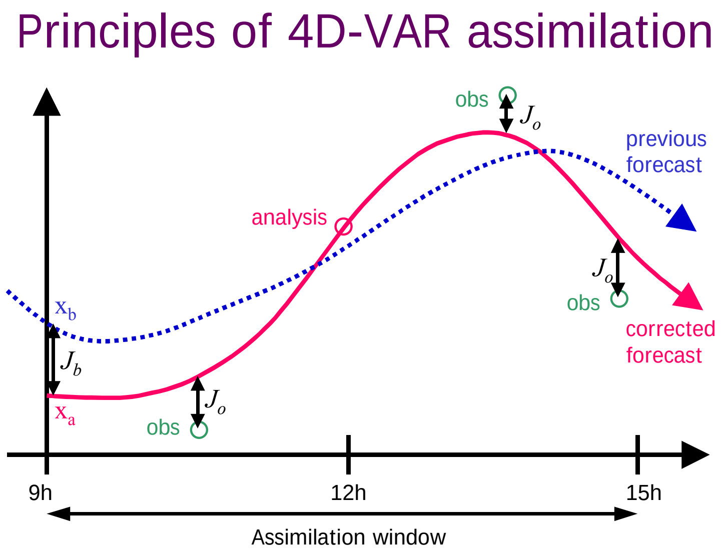

Figure 2. 6h 4D-VAR as it is implemented in the ARPEGE system. The assimilation updates the previous model trajectory (dotted line) in order to create a new model trajectory (full line) which takes into account all the observations of the 6h time window.

Each assimilation run (00, 06, 12, 18 UTC) is performed twice, once with a short cut-off (1h50' with respect to the main synoptic time) in order to produce the model forecasts directly used for operational activities, and once with a long cut-off (around 6h). Note that when the 4D-VAR is run with the short cut-off, the effective time window is less than 5 hours instead of 6 hours.

The ARPEGE – Tropiques model has its own 4D-VAR assimilation, but for economising computer resources the increment resolution is T107. It is run from 00 and 12 UTC every day with a 3h30' cut-off time.

There is no operational data assimilation system especially designed for ALADIN – France whose initial conditions are interpolated from the stretched ARPEGE analysis. Indeed the stretched ARPEGE 4D-VAR assimilation provides initial and lateral boundary conditions to a dozen of ALADIN models which are run on different European and North-African areas. A 3D-VAR assimilation is used in experimental mode for producing higher resolution ALADIN analyses. Some impact studies have been performed with various versions of the ALADIN model, and are presented in a companion paper: Wang (2004).

The operational 4D-VAR uses the surface pressure observations from SYNOP stations over land, from ships and buoys over sea. The near-surface wind observations are used only over sea for the time being (September 2003), although some experimentation is carried out to use also 10m wind observations from some land stations. The conventional radiosonde observations (wind, temperature, humidity) and aircraft observations (wind, temperature) are also used as well as the wind data from some European and North

American profilers.

Two types of satellite data are currently used in the Météo-France operational assimilation, after an appropriate screening:

- Automated motion winds from geostationary satellites (cloud winds, water vapour winds);
- ATOVS raw radiances from the NOAA satellites (NOAA15, 16 and 17 in Spring 2004): currently only the global data sets transmitted from US to Europe are used, but experiments are also carried out with the locally-received ATOVS data set.

Studies have been performed in Météo-France on the assimilation of scatterometer and SSM/I data, but they are not used operationally yet. No study has been performed on the MODIS winds although there are plans to try to use them operationally.

2. USE AND IMPACT OF SOME CONVENTIONAL OBSERVATIONS ON THE ANALYSES AND FORECASTS

2.1. Tropical radiosonde data

The impact of the whole radiosonde network on the ARPEGE analyses and forecasts has not been investigated. However a specific Observing System Experiment (OSE) has been performed in order to assess the impact of the part of the radiosonde network situated inside the tropics, between 20N and 20S. All the radiosondes inside this tropical belt have been removed from a specific ARPEGE assimilation, run on a 20-day period, in parallel to a control assimilation which includes all the observations normally used in operations. ARPEGE forecasts with and without tropical radiosondes have been run every day from 00UTC, and the results have been compared.

The data assimilation and forecasting system used for this particular OSE is a version which is cheaper than the operational one described above: the variable mesh option is not used in ARPEGE; the model is run with a T199 triangular truncation and 31 levels in the vertical; the corresponding latitude-longitude quadratic grid has a 0.6° resolution. The assimilation system is 3D-VAR rather than 4D-VAR. More details can be found in Tounkara et al. (2003).

Through the usual RMS scores evaluating the pairs of forecasts, the impact of tropical radiosondes is modest. However, the 24h wind RMS score at 500 hPa is almost systematically improved by 0.5 to 1 m/s inside the tropics (verification against the radiosonde data): this means that on average the signal coming from the tropical radiosonde is kept for 24h at least. Moreover, the signal can occasionally propagate to mid-latitude areas like Asia and affect forecasts up to 96h and up to 50 to 60 degrees of latitude. One case is found where the 96h ARPEGE forecast is improved by the use of tropical radiosondes both on a mid-latitude wave pattern over Japan and on a weather system inside the tropics. The geographical location of this positive impact is obviously related to the relative high availability of radiosonde data between longitudes 100E and 160E compared to the rest of the tropical belt.

2.2. Wind profiler data

Since October 2002, some wind profiler data over USA and Europe (a few dozens observation points) have been used in the operational 4D-VAR assimilation at Météo-France. Before the operational introduction of this new data type, an OSE was run at Météo-France to evaluate its individual impact. The ARPEGE assimilation and forecasting system was used as it was in operations in 2002: stretching factor of ARPEGE equal to 3.5, T298 truncation with a linear grid, 41 levels in the vertical, 4D-VAR assimilation with increments evaluated at T161.

ARPEGE forecasts are run with and without profiler data on a 20-day period. The RMS scores averaged on this period show a very significant positive impact on the European and North American areas, at all forecast ranges up to 96h. However, when checking the score time series, it turns out that this positive impact is due to a small number of cases where the forecast synoptic situation is dramatically improved by the use of wind profiler data. Most of the cases were evaluated as neutral. This "occasional" impact is confirmed by the experimental suite, run just before the operational change of October 2002, which was evaluating the combined effect of some satellite data and the wind profiler: the overall positive impact was not as big as before.

2.3. Surface SYNOP data

Experiments have been carried out evaluating the impact of 10m wind observations from land SYNOPs (not used in operations), and evaluating also the impact of assigning the wind observation of SYNOP-SHIPs at the proper height above the sea level. No significant impact is found in these large scale experiments performed with one operational version of ARPEGE. In general the impact of surface observing networks seems difficult to demonstrate in large scale models, easier at mesoscale (see below).

3. USE AND IMPACT OF SOME SATELLITE OBSERVATIONS ON THE ANALYSES AND FORECASTS

3.1. Automated motion winds from satellite

Until the end of 2003, the Meteosat winds which were used in the ARPEGE assimilation were the one transmitted as the SATOB data set, i.e. lower resolution winds than the Meteosat winds transmitted in BUFR format. Moreover the BUFR wind data set contains more information such as a quality index which can be used for a better screening and a better quality control.

In 2002-2003 the Meteosat BUFR winds have been tested in the 4D-VAR ARPEGE assimilation versus the SATOB data set, with an appropriate screening. The change to the new high resolution data set appears useful, mainly in terms of better fit of the first guess to the observations in the assimilation, and of smoother and smaller analysis increments. The impact on longer term forecasts is almost neutral. The change was introduced operationally in December 2003.

3.2. ATOVS data

In the operational ARPEGE assimilation, two recent changes were made about the use of ATOVS data:

- Use of AMSU-A raw radiance data in place of preprocessed radiances, first from NOAA15 and NOAA16 satellites (October 2002), then adding NOAA17 (December 2002);
- Use of HIRS raw radiance in addition to AMSU-A (December 2003).

AMSU-B data are still unused in operations in Spring 2004, they are under test.

Before the operational change of October 2002, an experimental suite parallel to operations was run, which showed a consistent positive impact of AMSU-A raw radiances versus the use of preprocessed radiances. This impact is (as expected) more marked in the southern hemisphere. This experimental suite is not a pure OSE in the sense that it does not measure the impact of one observing system; it compares two different ways of using ATOVS data. In addition, the October 2002 operational change contains modifications on other observing systems, such as the use of profiler data.
This is why a real AMSU-A OSE was run for the period (23 December 2002, 13 January 2003) when 3 satellites were available: NOAA15,16 and 17. This was run with the "ARPEGE – Tropiques" unstretched configuration of the assimilation and forecasting system. The impact of 3 AMSU-A sounders is very large over the southern hemisphere (as expected taking into account that the run without AMSU-A does not contain any other satellite sounder data), much smaller over the northern hemisphere, but still very significant and consistent in time (see fig.3).

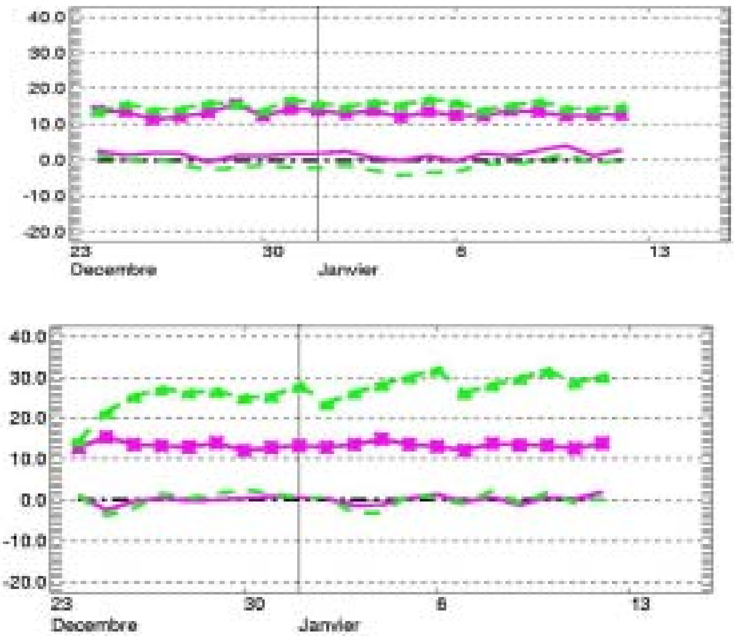

Fig. 3. 500hPa geopotential height scores at 24h range computed on daily pairs of forecasts from 23 December 2002 to 12 January 2003. Top curves are RMS errors, bottom curves are biases. Green curves are forecasts without any ATOVS data , purple curves include AMSU-A raw radiances from NOAA15, 16 and 17.

The use of locally received satellite data (EARS and Lannion) in addition to the global data set does show some additional positive impact, limited to the Europe-Atlantic area, and limited to short range forecasts (can be detected on 12h forecast European scores).

The HIRS raw radiances used on the top of AMSU-A radiances shows also some positive impact, much more modest than the impact of AMSU-A as such. This impact is especially visible on the humidity fields. The general effect of HIRS data is a drying effect in the assimilation with the total cloud water content of ARPEGE reduced by 5 to 10% on average on the whole globe. This is largely due to a wet bias in the ARPEGE model which tends to be compensated by the HIRS water vapour channels.

The work is ongoing on the use and impact of AMSU-B radiances, and also of AIRS data. Not enough results are available and no significant measure of their impact can be provided at this stage, although some individual cases of improvement have already been identified.

IMPACT OF THE CUT-OFF TIME ON THE ANALYSES AND FORECASTS

The main ARPEGE cut-off time (i.e. the one corresponding to the largest utilisation by the forecasters) is 1h50'. This is a short cut-off, especially for satellite data, as only a small percentage of the data are available on the 6h time window going from H-3h to H+3h (H being the initial time of the run). Since December 2003, the ARPEGE assimilation and forecast have been repeated with a long cut-off, once a week, from 00UTC. Fig.4 shows the improvement over Europe brought by the long cut-off run to the short one. This improvement is systematic and large beyond 72h range, in spite of the small sample (12 cases). This result stresses again the importance of rapid availability of data in general for operational forecasting, the polar orbiting sounding data being currently the more critical.

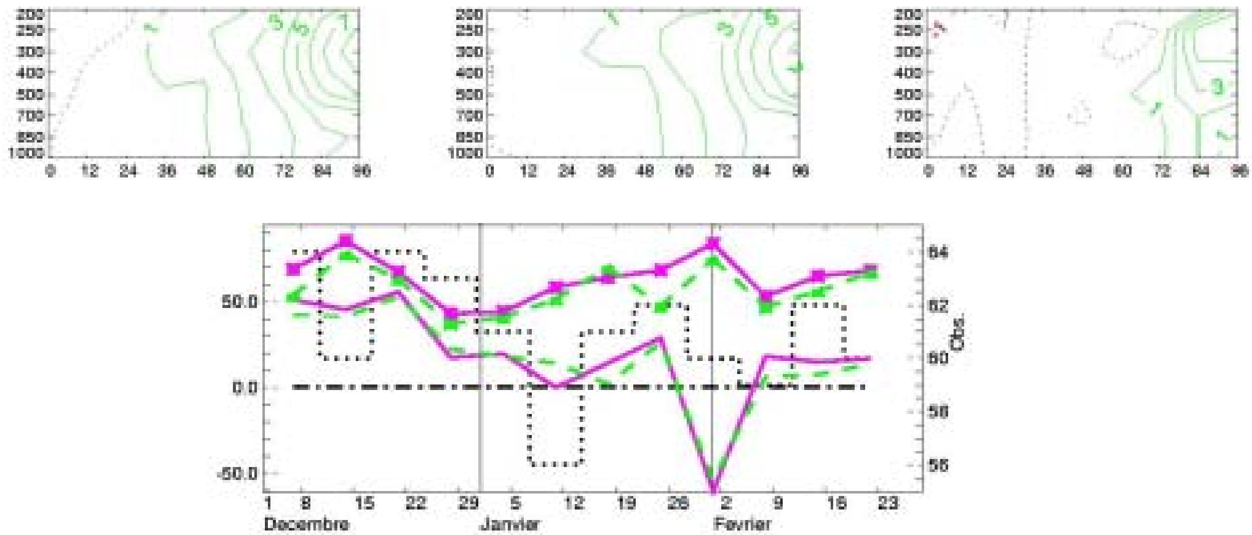

Fig.4. 500hPa geopotential height scores for 12 ARPEGE forecast pairs, once a week from December 2003 to February 2004, run with a 1h50' cut-off versus a 8h cut-off.

- *Top : differences between the 1h50' cut-off scores and the 8h ones, for RMS errors (left), standard deviation (middle) and bias (right). These score differences are plotted versus forecast range in h (horizontal axis) and vertical levels in hPa (vertical axis). Green colour means that the 8h cut-off is producing a better score; red colour means the opposite (there is none!).*
- *Bottom: time series of the 96h forecast scores (RMS and biases) with green colour corresponding to the 8h cut-off, purple colour to the 1h50' cut-off (almost always worse, as expected).*

4. TOWARDS MESO-SCALE ASSIMILATION

All the above-mentioned OSEs have been carried out with a large scale NWP system and with a variational assimilation having an increment resolution between T107 and T161. This is an obvious limitation for evaluating the whole impact of an observing system. Surface SYNOP is an observing system whose impact has always been difficult to identify in large scale NWP systems.

The impact of the French surface mesoscale observing network has been evaluated on a research mesoscale non-hydrostatic model Meso-NH, down to a resolution of 2.5 km. Details about the Meso-NH model can be found in Lafore et al. (1998). The analysis tool is a multivariate optimal interpolation system tuned for a mesoscale analysis. Surface pressure, 2m temperature and humidity, 10m wind data have been entered in this mesoscale analysis, from SYNOP observations plus all similar French stations. Then Meso-NH has been run from:

- this high resolution analysis;
- the ECMWF operational analysis (i.e. a 4D-VAR with a T151 resolution in the increments).

The impact of this surface data set on short-range forecast, through an appropriate optimal interpolation analysis, is particularly large on the case of 2 November 1999, where both the structure and the position of the precipitation and cloud areas are considerably improved by this mesoscale experimental analysis using the French surface data. The improvement in Meso-NH is very significant up to 12h range. It can also be verified objectively against the Meteosat satellite imagery.

5. CONCLUSIONS

From a series of impact studies carried out in Meteo-France with the ARPEGE system, the following conclusions can be drawn:

- Tropical radiosonde data have a modest positive impact on the ARPEGE scores. The impact is neutral most of the time, but an occasional large impact is encountered on some weather events, including outside the tropics.
- The same type of conclusions can be drawn for wind profilers: neutral most of the time, but occasional big impact.
- Surface SYNOP wind data do not show any impact on the ARPEGE scores; however the usefulness of surface data in general can be demonstrated in other models at high resolution.
- ATOVS data have a significant positive impact on the ARPEGE scores including on the northern hemisphere. The impact is dominated by AMSU-A data. However the additional impact of HIRS

radiances can still be measured, especially on the humidity field. The evaluation of AMSU-B is promising but not completed (same for AIRS data).

- It seems useful to improve operational ATOVS coverage, either by longer cut-offs, or by more rapid data collection (currently a local and rapid dissemination appears useful).

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REFERENCES

Courtier, P., C. Freydier, J.-F. Geleyn, F. Rabier and M. Rochas, 1991: The Arpege project at Météo-France. ECMWF Seminar 91: Numerical methods in atmospheric models, Volume II, pp. 193-231.

Gauthier, P. and J.-N. Thépaut, 2001: Impact of the digital filter as a weak constraint in the pre-operational 4D-Var assimilation system of Météo-France. Mon. Wea. Rev., 129, pp. 2089-2102.

Lafore, J.P., J. Stein, N. Asencio, P. Bougeault, V. Ducrocq, J. Duron, C. Fischer, P. Héreil, P. Mascart, J.P. Pinty, J.L. Redelsperger, E. Richard and J. Villa-Guerau de Avellano, 1998: The Meso-NH atmospheric simulation system. Part I: Adiabatic formulation and control simulations. Ann. Geophys., 16, 90-108.

Mahfouf, J.-F. and F. Rabier, 2000: The ECMWF operational implementation of four dimensional variational assimilation. Part II: Experimental results with improved physics. Q. J. R. Meteorol. Soc., 126, pp. 1171-1190.

Rabier, F., H. Jarvinen, E. Klinker, J.-F. Mahfouf and A. Simmons, 2000: The ECMWF operational implementation of four dimensional variational assimilation. Part I: Experimental results with simplified physics. Q. J. R. Meteorol. Soc., 126, pp. 1143-1170.

Tounkara, M., P. Caille and J. Pailleux, 2003 : The impact of tropical radiosonde data on the ARPEGE analyses and forecasts. WGNE publications (see http://www.cmc.ec.gc.ca/rpn/wgne/).

Wang, Y., 2004: Impact studies performed with the LAM system ALADIN. In this volume.

Met Office Satellite Data OSEs

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1. Introduction

Increasing amounts of satellite data are now available to NWP centres. The use of ATOVS, SSM/I, satellite winds and scatterometers is well established. New datatypes including advanced IR sounders such as AIRS, GPS path delay and radio occultation are becoming available. This paper will attempt to address one main question: given a thorough examination of the impact of ATOVS how large an impact is it realistic to expect from a new observing type such as AIRS. To achieve this goal the impact of ATOVS will be measured as well as the separate impacts of AMSU and HIRS, extra ATOVS data and the number of ATOVS satellites. The AIRS impact in a single OSE will then be considered in the context of these results. The paper will also briefly record key results from a range of recent OSEs.

2. OSEs

Most of the OSEs described in this paper were conducted over a 40 day period in May and June 2003. Some experiments are for other periods and where this is the case it will be made clear. The following experiments have been run.

1. Control (ThreeSat)
2. No ATOVS (NoATOVS)
3. No AMSU (NoAMSU)
4. No HIRS (NoHIRS)
5. Add “late” ATOVS (LateATOVS)
6. Add “highland” ATOVS (HighATOVS)
7. Remove NOAA-17 ATOVS (TwoSat)
8. Remove NOAA-15 and 16 ATOVS (OneSat)
9. Remove radiosonde temperature and humidity (NoSondeT)
10. Add AIRS (AIRS) and AIRS control

In the paper the experiments will be referred to using the names in brackets. The AIRS experiment is for December 2002 and July 2003. All others listed above are for May/June 2004. All experiments are ThreeSat with the change (e.g. no ATOVS) specified. Thus ThreeSat is the control. The AIRS experiment ran its own (also three ATOVS) control. The purpose of experiments 1-4 is to measure the relative value of HIRS and AMSU compared to “full ATOVS”. This will enable us to compare AIRS impact to HIRS impact for different parameters. Experiments 5 and 6 give an indication how much impact can be achieved by adding ATOVS observations where little or no ATOVS data is currently used. Experiments 7-9 show the impact of a 1, 2 or 3 ATOVS system against using no ATOVS data. Experiment 10 shows the impact of AIRS when three ATOVS systems are available.

3. OSE results

3.1 Comparison of AMSU and HIRS

When ATOVS was first introduced the impact was substantial at most NWP centres (see for example English *et al*. 2000, McNally and Kelly 1999, Derber 1999). This improvement was generally attributed to AMSU. Since then few centres have been able to demonstrate a large impact from HIRS whereas many centres have continued to show a substantial impact from ATOVS. As a result it has been assumed that most of the substantial positive impact of ATOVS arises from AMSU. In this study we removed separately AMSU, HIRS and ATOVS (ATOVS = AMSU and HIRS). It was found that indeed the impact of HIRS (ThreeSat-NoHIRS) was very small for most fields and the impact of ATOVS (ThreeSat-NoATOVS) and AMSU on its own (ThreeSat-NoAMSU) was large and comparable. This appears to confirm that an infra-red sounder with only slightly better vertical resolution than AMSU such as HIRS will provide very little benefit when AMSU data is available from three satellites. Past experiments (English *et al*. 2000) have shown some positive impact from HIRS when only 1 or 2 AMSUs were available. This may imply that with increasing amounts of AMSU available the redundancy of HIRS has increased. However one exception was found. The impact of HIRS on low level humidity was still significant. In the Met Office data assimilation system only the mid and upper tropospheric microwave humidity channels are used, because it has been found both for AMSU and SSM/I that assimilating low altitude moisture sensitive radiances in cloudy regions adds moisture to the analysis which can trigger an unrealistic model response. It remains unsolved as to whether this is solely a model problem or a combination of model and data assimilation. However assimilating moisture sensitive radiances in cloud-free regions causes fewer problems. As a result AMSU has no advantage over HIRS, since data can not be used in cloud regions, and removing HIRS reduces moisture in the tropics. The patterns are broadly similar to those implied from AMSU (not shown) assimilated at higher altitudes, but with some interesting differences, notably over the Indian Ocean where HIRS adds more moisture than AMSU. ThreeSat – HIRS differences are shown in Figure 1.

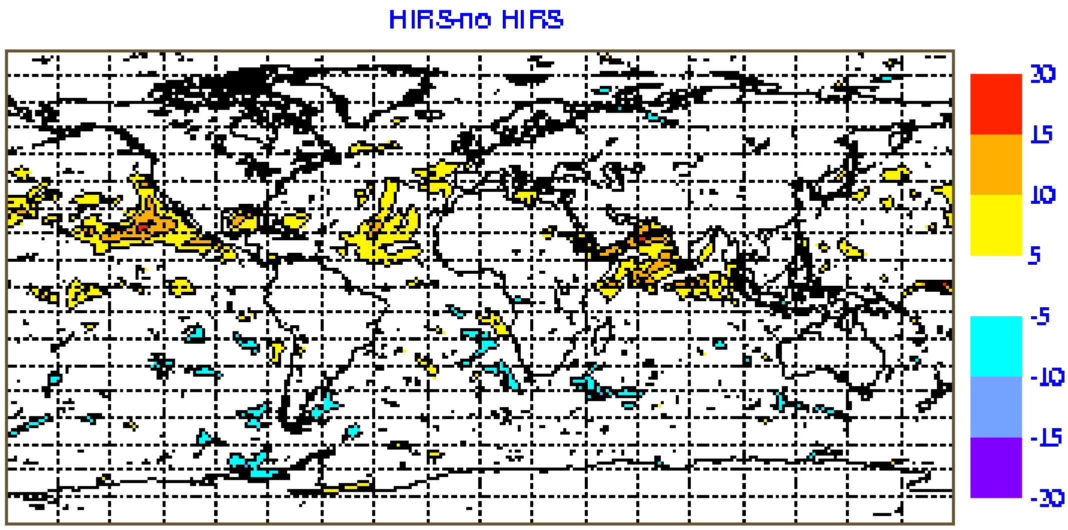

Figure 1: Impact of HIRS on mean 850 hPa relative humidity (%).

In the absence of AMSU HIRS continues to have a very significant impact on mass and wind fields. The impact of adding HIRS to a NoATOVS run is about 1/3rd of the impact of AMSU, averaging RMSE scores for geopotential height, wind and temperature globally and at forecast ranges out to six days. This is seen in Figure 2 where ThreeSat-NoATOVS is much greater than ThreeSat-NoAMSU, especially for geopotential height for verification of six hour forecasts against observations (a tough test for satellite data to improve the analysis near existing observations at short forecast range).

3.2 Use of additional ATOVS radiances

All NWP data assimilation systems must impose a data cut-off time. Data arriving after this time will not be used in the assimilation unless a later "update" run is employed to generate a new background for the next assimilation cycle. For the Met Office global data assimilation system this cut off is 1 hour and 55 minutes. Unfortunately only about 20-30% of ATOVS arrives this quickly. An update assimilation cycle is run with a cut off of 7 hours. Most, but not all, ATOVS arrives in time for this update cycle. An experiment was run to use the ATOVS data as if it had all arrived in less than 1 hour 55 minutes. This measures the potential benefit of improving the speed of delivery of global ATOVS datasets. Some of the benefit could also be obtained by regional fast delivery systems such as the EUMETSAT ATOVS Retransmission Service (EARS). As might be expected the impact of the late arriving date varied geographically in a similar way to the total impact of ATOVS. Figure 3 shows the impact as a time series for NH pmsl. At T+0 small improvements in fit to radiosondes are seen in almost every cycle. Many of these result in no significant difference in the T+24 forecast, clearly reflecting days when the late arriving data was not in a sensitive development region. But in a significant number of days the T+24 forecast error is substantially reduced. For example the very large impact on 19 May was traced to a poorly analysed low pressure system in the Pacific which was 9 hPa too shallow in the T+24 forecast without ATOVS, an error change to 1 hPa too deep when the ATOVS was used. Impacts are larger in the southern hemisphere with some forecast impact almost everyday (not shown).

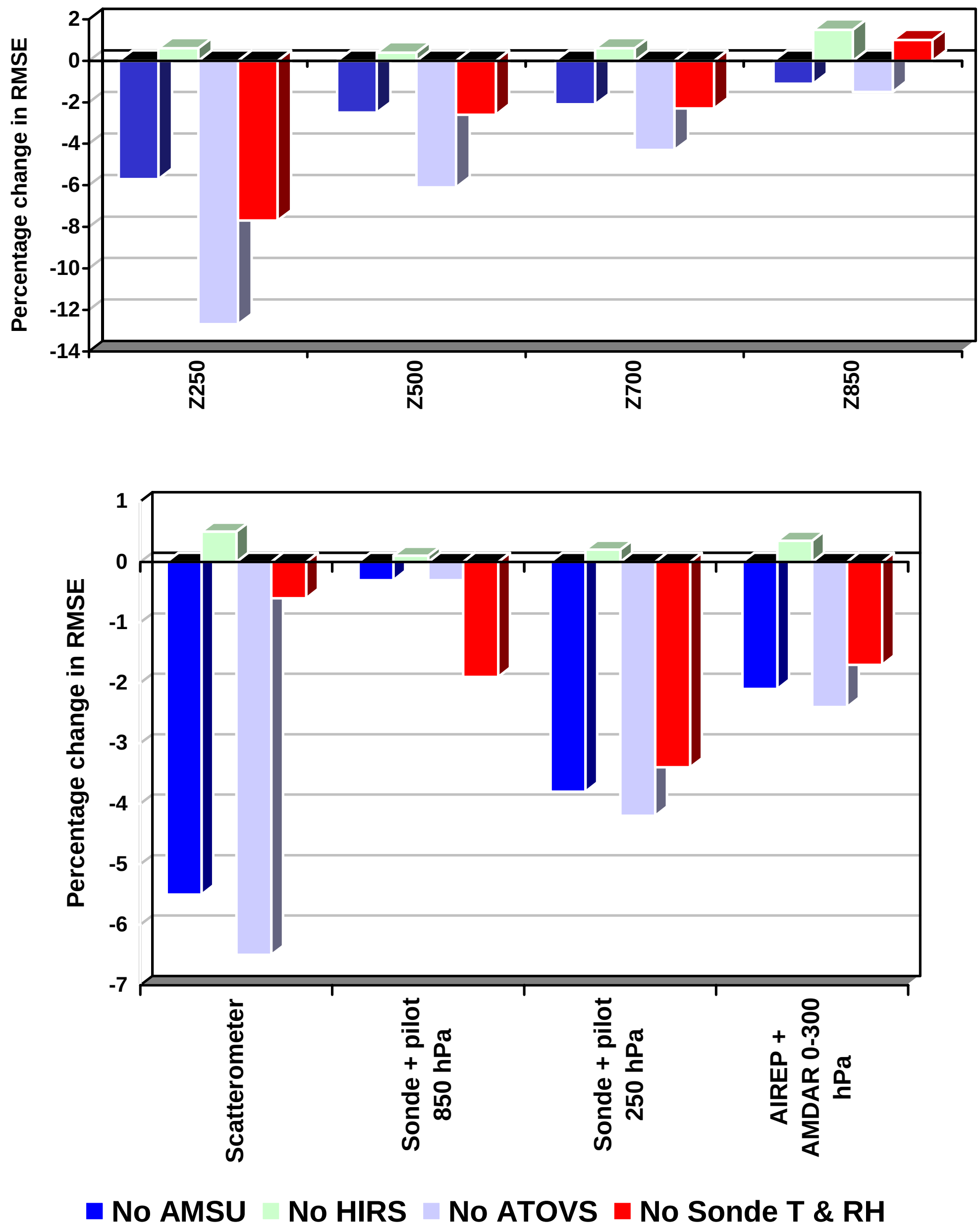

Figure 2: Comparison of ThreeSat-NoATOVS, ThreeSat-NoAMSU, ThreeSat-NoHIRS and ThreeSat-NoSonde for May-June 2003 RMSE change in six hour forecast difference from radiosonde 250, 500, 700, 850 hPa geopotential height (upper plot) and scatterometer, radiosonde and aircraft winds (lower plot).

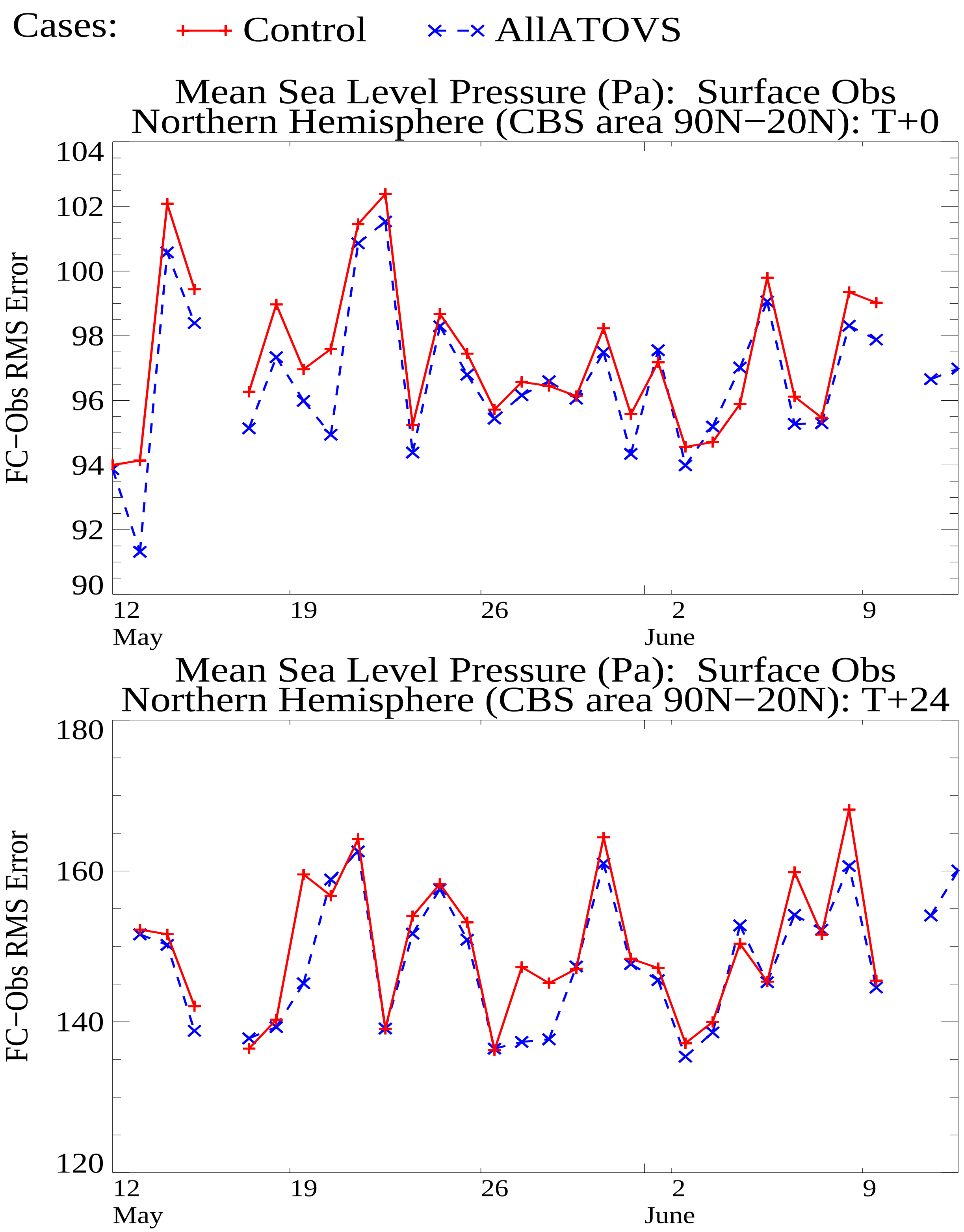

Figure 3: Time series of RMS difference between T+0 (initialised analysis) and T+24 forecast and surface mean sea level pressure observations for 20N-90N for May 12 2004 – June 10 2004.

Apart from those caused by late arriving data the main ATOVS data void in the Met Office ATOVS data assimilation system is over high land regions. This is a particular problem of the bias correction scheme used at the Met Office and a new method allowed use of data over high land which had previously been excluded. The primary land regions where this was occurring were Antarctica, Greenland, Tibet and other areas over 1000m.

The impact of the high land data is perhaps inevitably less than the late ATOVS. Whereas late ATOVS increases the data volume in the main forecast run by up to 200% the high ATOVS data only increases the total data available by 10-15%, albeit in the update runs too. It is interesting to compare this with the increase in data available from different numbers of satellites in the NOAA-15, 16 and 17 orbits. NOAA-17 typically increased the data coverage of assimilated data by 10-15%. Therefore switching ATOVS on over high land is comparable to the impact of the third ATOVS satellite. This is borne out in the results. Typically experiment mean pmsl and 500 hPa height fields RMS against observations and analysis are improved by 1-2% (not shown). This will be further discussed in the next section.

3.3 Impact of 1, 2 and 3 ATOVS

When NOAA-17 ATOVS was first tested it was found that modest (1-2% RMSE reduction) improvements in key fields (pmsl, 500 hPa height) were achieved. The average impact across a set of meteorological fields used for standard verification at the Met Office (geopotential height, temperature, wind, relative humidity for days 1 to 6 of the forecast) was 0.5%.

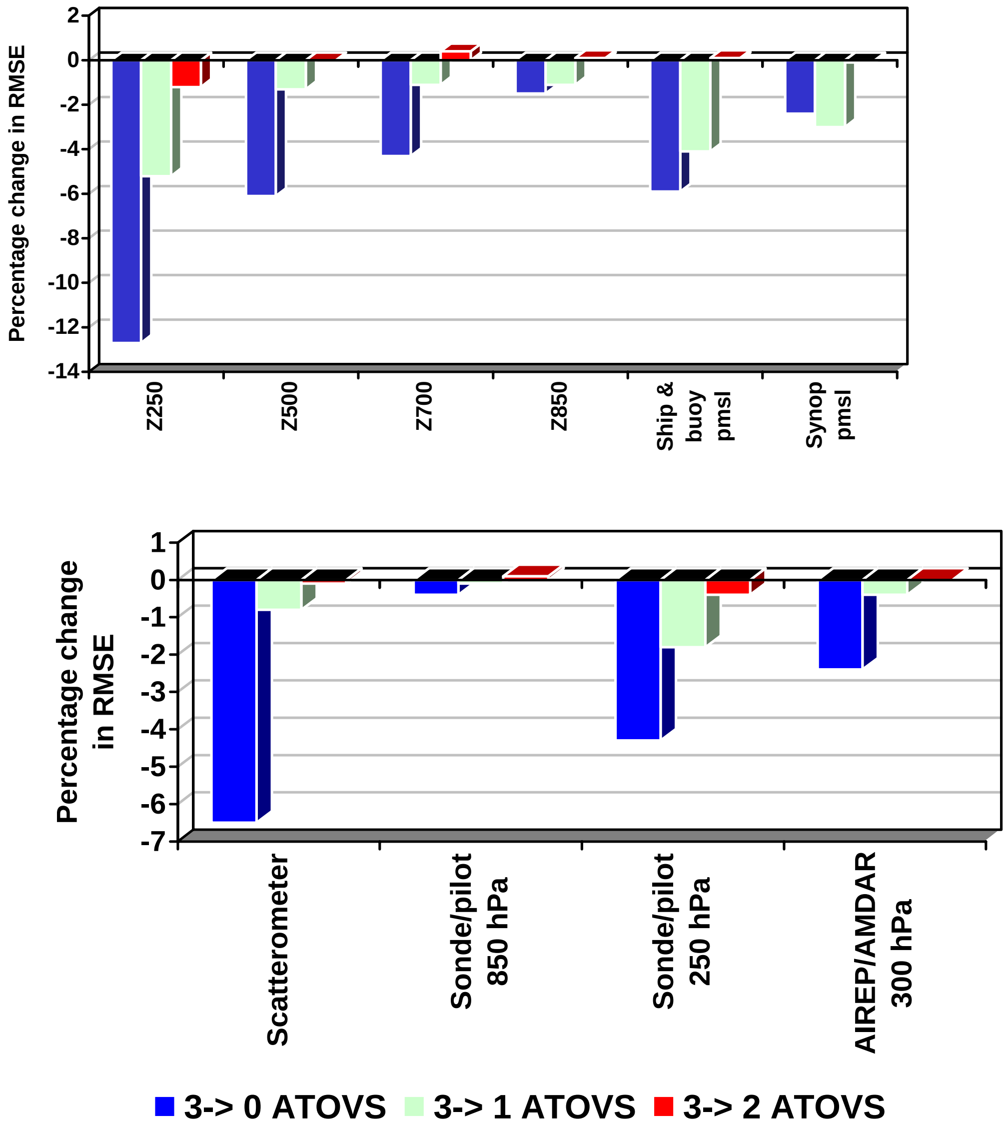

Figure 4: Percentage change in RMSE fit of six hour forecast to radiosonde 250, 500, 700 and 850 hPa geopotential height and synop/bouy mslp data (upper plot) and scatterometer, radiosonde and aircraft winds (lower plot) for May-June 2004

Figure 4 shows the fit of the six hour forecast to observations. The largest improvement arises from the first satellite with a further but smaller improvement for the second and an even smaller and mixed impact from the third. As noted in section 3.1 verification against observations at very short range is a tough test for satellite data assimilation. However there is still a clear improvement from the third satellite at jet levels (250 hPa). These is some indication that the third ATOVS satellite, in this case NOAA-17, slightly increases the RMSE mis-fit of the short range forecasts to radiosondes at low levels.

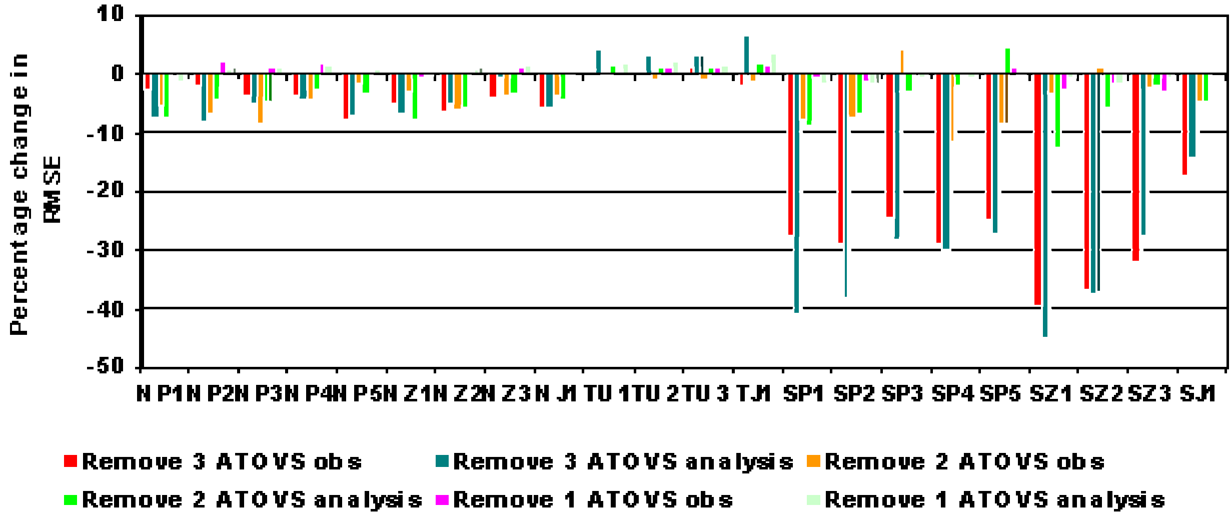

Figure 5: Forecast impact for 1, 2 and 3 ATOVS. The area/periods are denoted as N=Northern hemisphere, T=Tropics, S=Southern hemisphere, p=pmsl, Z=geopotential height at 500 hPA, J=j2t level (250 hPa) winds, U= 850 hPa wind, 1-5 are forecast range in days. So NP1 = northern hemisphere pmsl at day 1.

When NOAA-16 was first assimilated at the Met Office improvements in RMSE of order 4-8% were found against radiosondes in the southern hemisphere from days 1 to 3 of the forecast (English *et al*., 2002). The average global impact for geopotential height, wind, temperature and relative humidity on standard levels from day 1 to day 6 of the forecast was 2%. The new OSEs were run to compare difference in impact of 1, 2 or 3 ATOVS for the same period. The results were broadly similar to the original “data addition” experiments and are shown in Figure 5 for a range of parameters, regions and forecast ranges. Comparing ThreeSat with TwoSat the overall impact was close to neutral, almost all impacts being less than a 1% change in RMSE and the global “average” impact being neutral. However the improvements seen at jet level (250 hPa) in the six hour forecast were maintained at longer range (geopotential height RMSE v radiosondes at 250 hPa at day one was 4% lower with the third satellite in the southern hemisphere for example). Comparing ThreeSat with OneSat we see a much larger degradation, as might be expected, averaging around 2% globally and thus very consistent with the original introduction of NOAA-16 described in English *et al.* (2002). Tropospheric geopotential height fields have RMSE 5-10% higher in OneSat than ThreeSat in the southern hemisphere, the largest differences being at short range. The OneSat experiment global data coverage is less than 40% even for “update” runs, and as low as 10-15% in the main forecast runs. This compares to around 70-80% coverage for TwoSat and 80-90% coverage for ThreeSat (the range for each experiment is because it is different for different times of day, and slight variation from day to day).

We have a case of diminishing returns with increasing satellite data coverage but the increase in return is still very significant for the second satellite. The benefit of the third satellite will be very sensitive to how much it increases data coverage. If this is marginal naturally the benefit too will be only in increased robustness. However if data coverage increase is significant (e.g. because it compensates for late arrival of other data) the benefits may be more than just increased robustness. This implies that the benefit of a third satellite can not be defined except in the context of the design of both space and ground segment.

3.4 Evaluating impact of AIRS compared to radiosonde temperature and ATOVS

AIRS was added to a control using ATOVS from three satellites for July 2003 and December 2002. The impact was found to be small but significant, with southern hemisphere geopotential height RMSE improved by 0-5% and impacts generally 0-2% in the northern hemisphere and tropics (for forecast range 1 to 6 days). Impact for a range of parameters, regions and forecast periods is shown in Figure 6. At first sight this impact may look small compared to ATOVS, which reduces RMSE errors by between 20 and 50%. However when compared to the impact of HIRS the impact is large, as HIRS shows no positive impact in a system using three ATOVS. Furthermore the impact is larger than the impact of the third ATOVS satellite (out of three). This is particularly significant especially noting that the Aqua orbit is almost identical to NOAA-16. A fairer test of the significance of the AIRS result is to compare it to the OSE for radiosonde temperature and humidity, to test how effectively the NWP data assimilation system uses high vertical resolution temperature and humidity information in the presence of AMSU. The radiosonde OSE gave an impact overall twice as large as AIRS. This shows that the AIRS impact is highly significant, but also shows that even more should be expected of AIRS. Given the uneven data coverage of radiosondes, and the fact that the number of observations assimilated from AIRS (taking one spectra to be one observation) and radiosondes is comparable, it must be hoped that a less conservative use of AIRS might give an impact in a data denial OSE comparable with radiosonde.

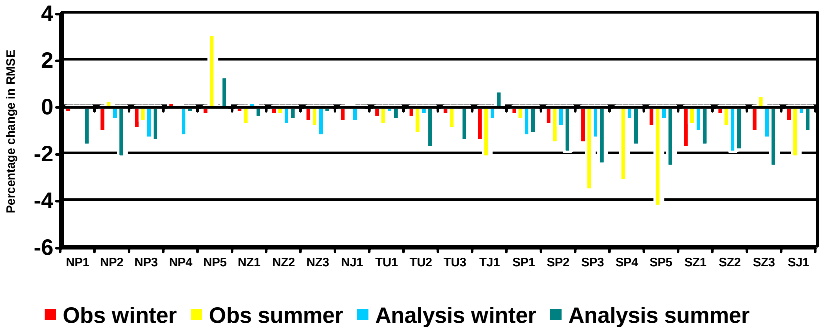

Figure 6. AIRS impact for two seasons (areas and forecast ranges are as in Figure 5).

3.5 Other OSEs at the Met Office

The Met Office has undertaken several other recent OSEs at both global and mesoscale resolution. The assimilation of CHAMP radio occulation data was found to give remarkably good impact at tropopause height, illustrated by a 7% fall in RMSE for a one day forecast for southern hemisphere 250 hPa temperature. Further experiments with total column water vapour from SSM/I have continued to face the problem discussed in 3.1, that the SSM/I data adds low level moisture to the analysis, especially in cloudy regions, and the model response to this is unrealistic. Winds from MODIS have been assimilated from both Terra and Aqua, and also separately, but all three combinations have shown negative impact, more especially in the southern hemisphere. AMSU-B radiances have been shown to improve cloud and visibility forecasts when used in a mesoscale model data assimilation for the UK, and have also been introduced into a regional limited area model for Europe and the portable UK mesoscale model. However no beneficial impact has been found for precipitation from use of AMSU-B radiances in these models.

4. Conclusions

It has been demonstrated that in the presence of AMSU HIRS has no impact on mass and wind fields. However in the absence of AMSU HIRS still has a major impact. This shows that assimilation of radiance information only in cloud-free regions can still improve weather forecasts. The sensitivity to number of satellites showed a diminishing return for three satellite compared to two, but the third satellite still gives some modest benefits, more especially at jet level (250 hPa). Despite the difficulty demonstrated in achieving substantial impact when 2 (or more) AMSUs are available and assimilated, AIRS and radiosonde temperatures and relative humidities do show a benefit even in the presence of AMSU, the AIRS impact being about half that of the radiosondes. This is interpreted as a very positive result for AIRS, but also one which encourages that further benefits may be realised through improved assimilation of AIRS in cloudy regions. Encouraging results have been found for CHAMP radio occultation data assimilation, and AMSU-B assimilation at mesoscale resolution.

References

English, S.J., Renshaw, R.J., Dibben, P.C., Smith, A.J., Rayer, P.J., Poulsen, C., Saunders, F.W. And Eyre, J.R., 2000: A comparison of the impact of TOVS and ATOVS satellite sounding data on the accuracy of numerical weather forecasts. Q J R Meteorol Soc, 126, 2911-2931.

McNally A.P. and G. Kelly, 1999: The use of raw TOVS/ATOVS radiances in the ECMWF 4D-var assimilation system. ECWMF/EUMETSAT Workshop on the use of ATOVS data for NWP assimilation. 2-5 November 1999, ECMWF, UK, 23-32.

Derber, J.C., 1999: The use of ATOVS data at NCEP. ECWMF/EUMETSAT Workshop on the use of ATOVS data for NWP assimilation. 2-5 November 1999, ECMWF, UK, 33-38.

English S.J., R.J. Renshaw, A.J. Smith, C. Poulsen, K. Whyte, J.K. Hutchings and D.C. Jones 2000: Current status of the assimilation of TOVS and ATOVS radiances at the UK Met Office. The Technical Proceedings of the Eleventh International TOVS Study Conference, Budapest, Hungary, 20-26 September 2000., Budapest. 79-89.

English S.J., D.C. Jones, A.J. Smith, F. Hilton and K. Whyte, 2002: ATOVS and SSM/I assimilation at the Met Office. The Technical Proceedings of the Twelfth International TOVS Study Conference, Lorne, Australia, 27 February-5 March 2002., 72-78.

Impact of Various Observing Systems on the BMRC NWP Systems

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1. INTRODUCTION

A new observation space assimilation scheme has been developed at the Australian Bureau of Meteorology Research Centre (BMRC) for use within a suite of operational NWP systems. This new system is now scheduled for operational implementation and is capable of utilizing most operational observing systems. Observing system experiments are being carried out to ensure that the impact of currently used observing systems is as expected. Further experiments are also being performed to ensure that newly introduced observing systems increase forecast skill. The results of these tests will be summarised in this report, with more detailed descriptions becoming available in the near future.

2. EXPERIMENTAL FRAMEWORK

The experiments discussed here were primarily designed to assess the performance of the new analysis system, Generalized Statistical Interpolation (GenSI), within existing operational NWP models. The processing of observations within GenSI has been kept as similar as possible to the operational system. Spatially dense data is thinned or combined into super-observations to a spacing that depends on the typical length scale of the background field and any possible observation error correlation. GenSI performs a sequence of local analyses over groups of grid points using all of the thinned observations within a large scan radius. The ability to use all processed data within a very large area is the fundamental difference between the design of GenSI and the operational scheme. The use of the large scan radius is made possible by use of a pre-conditioned conjugate gradient minimization using a similar algorithm to that of Cohn et al. (1988). There have also been many other enhancements to observation processing and covariance modeling, but these did not have a significant influence on the fundamental design of the system. Experiments have shown that groups of grid-points approximately 1000km square and a scan radius of approximately 3300 km provides close to continuous analyses between neighbouring groups of grid points, and that extending the scan radius to 4500km or more has negligible impact.

3. ATMOSPHERIC MOTION VECTORS

Early testing of the GenSI assimilation with the operational T239L29 global spectral model showed degradation with respect to operations as shown in the left-hand panel of Fig.1. The tests used the same general error covariance structure as operations, in order to provide a reasonably clear assessment of the effect of different observing systems within the GenSI system relative to the current operational “boxed

OI" system, (Seaman et al., 1995). The operational assimilation system further sub-samples the thinned data, and for atmospheric motion vectors (AMVs) in the global system, the extra sub-sampling significantly reduces the number of observations that are analyzed. This means that for the tests described the main difference between the operational system and GenSI is the removal of both extra sub-sampling and the assumption of locally constant error covariances. Other tests have been performed to assess the impact of improved background error specification, but will not be described here.

Operationally, SATOB motion vectors have been routinely used in the NWP systems, with these winds being sub-sampled by the data selection. The strong sub-sampling in the configuration for the global operational system leads to the quality control of the AMVs not being a major issue for this system. The inclusion of all of the data by GenSI however requires more sophisticated quality control and data thinning, such as that obtained by using the quality indicator information (Holmlund et al., 2001) from the observations distributed via BUFR code. This was confirmed by the results form limited data-withholding experiments where AMV's had a significant negative impact on the early version of GenSI, but only a minor impact on operations.

The observation errors for AMVs were adjusted from 3.0, 3.5 and 4.0 ms^{-1} for low, middle and high level winds to 3.3, 4.5 and 6 ms^{-1} respectively. The tolerance for background innovation checks was also tightened from 10 standard deviations of the expected difference to 4 standard deviations. Quality indicator thresholds for each geostationary satellite, level, latitude band and image type were set to ensure that the observations used in GenSI were consistent with these observation errors. The use of four parameters to determine the thresholds is necessary due to the population distributions of the AMVs as a function of quality indicator varying with each of these parameters. The quality indicator thresholds were deliberately set to exclude middle level winds. With these changes, GenSI now demonstrated comparable forecast skill to the operational system as shown in the right-hand panel of Figure 1. The important point to note about these figures is that the later version of GenSI has significantly improved relative to the earlier version due to the use of the quality indicator information. The 100hPa tropical height verifications were chosen as these were where the early version of GenSI was particularly poor. At lower levels, the older version was comparable to operations, whereas the later version of GenSI provides a significant improvement relative to operations (and by inference the earlier version of GenSI).

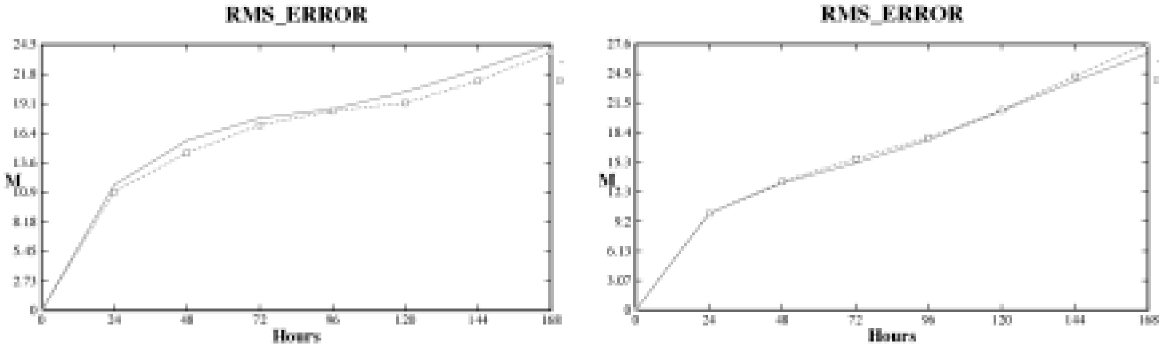

Fig 1. RMS errors for 100 hPa height in the tropics as a function of forecast time. The operational scores are in dashed lines between squares, and GenSI scores are the solid lines. An early version of GenSI is compared against operations for 27 days during February 2003 on the left. The right hand panel shows the latest version of GenSI for 59 days during September and October 2003

A re-examination of a 12-day period where the AMV data was withheld indicated that the cloud drift winds were now having positive impact as shown in Fig.2. This experiment will be repeated when GenSI is operational so as to assess the impact in the latest version of the forecast models, during a period of reliable data reception and with the all new data sources included, in particular scatterometer data. This test is also expected to involve some re-tuning of the quality indicator thresholds.

The requirement to thin the AMVs to 120km density is required to compensate for the observation error correlations being ignored. Initial experiments have shown little sensitivity to the thinning density. In high-resolution models, however thinning is not desirable as it is likely that significant information is lost, particularly around tropical cyclones. As a result, further experiments with AMVs are anticipated with the limited area NWP system and GenSI using estimates of observation error standard deviation and correlation generated at the same time as the wind estimates.

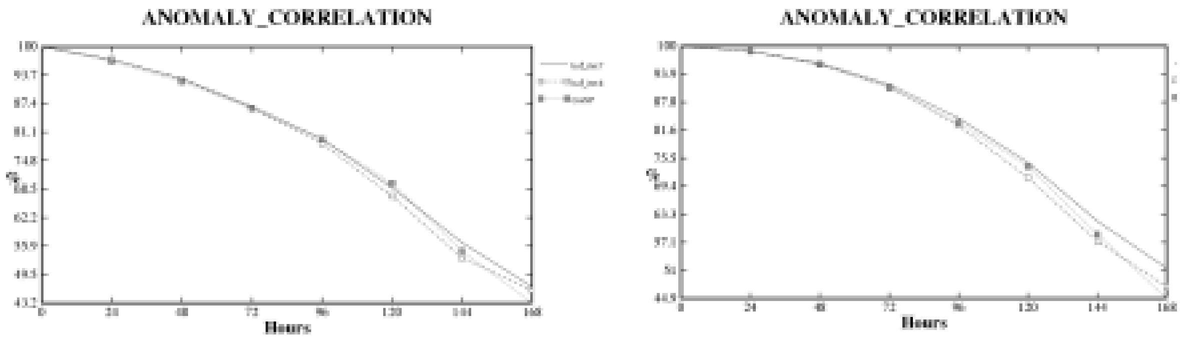

Figure 2. Northern Hemisphere anomaly correlation scores as a function of forecast time for MSLP (left) and 500hPa height (right). The three curves are GenSI with AMVs (solid), GenSI without AMVs (dashed with open squares) and operations (dotted with grey squares). This limited trial used forecasts starting from 2nd April to 13th April, 2003.

4. ATOVS DATA

Current operational systems use the ATOVS data available over the GTS in a 1dVAR system which uses NESDIS retrievals to provide information above the top model levels. The regional NWP system therefore often misses crucial orbits due to the early data cut-off. Furthermore neither system has access to AMSU-B data. To overcome these problems it is intended to use local ATOVS data in the regional system and level-1d data from the MetOffice in the global system. In either case there are no retrievals to provide information above the model lid and no discrimination between clear and cloudy soundings. This has led to experimental systems with the top model level at 0.1hPa with various window checks on the radiances to detect cloud-contaminated soundings.

Tests have also been conducted to assess the impact of level-1c AMSU-A data only rather than the remapped level-1d ATOVS (HIRS+AMSU-A) data. In general, there was significant degradation of the skill in the tropical upper-troposphere (as shown in Fig. 3) for the level-1c experiment due to the lack of moisture information in AMSU-A relative to the information from HIRS. This can be seen in Fig. 4, which illustrates that the bias in the HIRS-12 channel is noticeably worse in the tropics when only AMSU-A is used. The conclusion was made that the moisture information within the HIRS is crucial to the performance of the current system, particularly in the tropics. The moisture information obviously impacts directly on the moisture analysis, but also is important for the quality control of the micro-wave data. The issue of using 1c as against 1d data may need to be reassessed once radiances are used directly by the 3d-analysis rather than via the current 1dVAR system.

Further tests have shown that additional pre-processing of the radiances such as sub-sampling and cloud checks can be performed successfully within 1dVAR. As a result the capability to use minimally processed level-1d data is being developed. It should be noted that all of the tests involving ATOVS data were performed using the current operational system rather than GenSI. The results however are expected to also apply to GenSI as the differences between the two assimilation systems are small when considering the use of satellite soundings in the tropics. The differences noted in the discussion with AMVs do not apply here as the operational system does not sub-sample the 1dVAR retrievals (unlike the severe sub-sampling of AMVs).

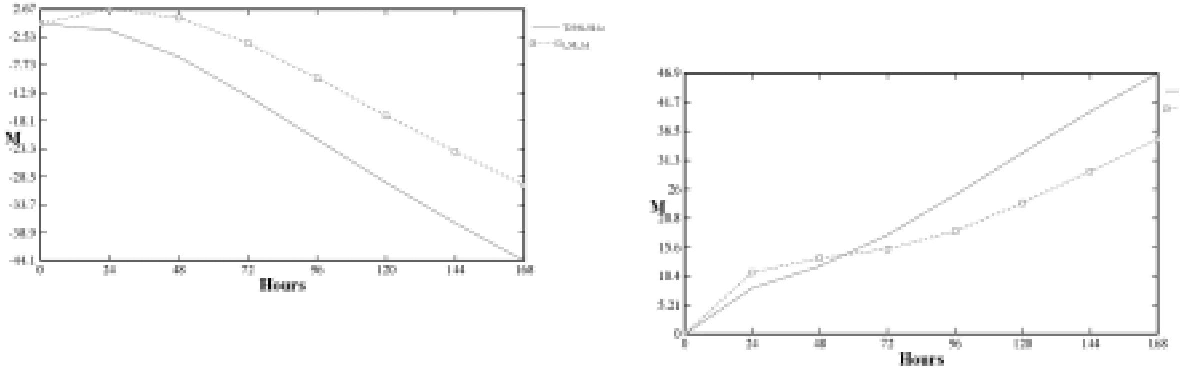

Figure 3. Bias(left) and RMS(right) 100 hPa height error within the tropics as a function of forecast period for an experimental 50 level (top level at 0.1 hPa) with level-1c AMSU-A data only (solid line) and level-1d AMSU-A + HIRS data (dashed line + squares).

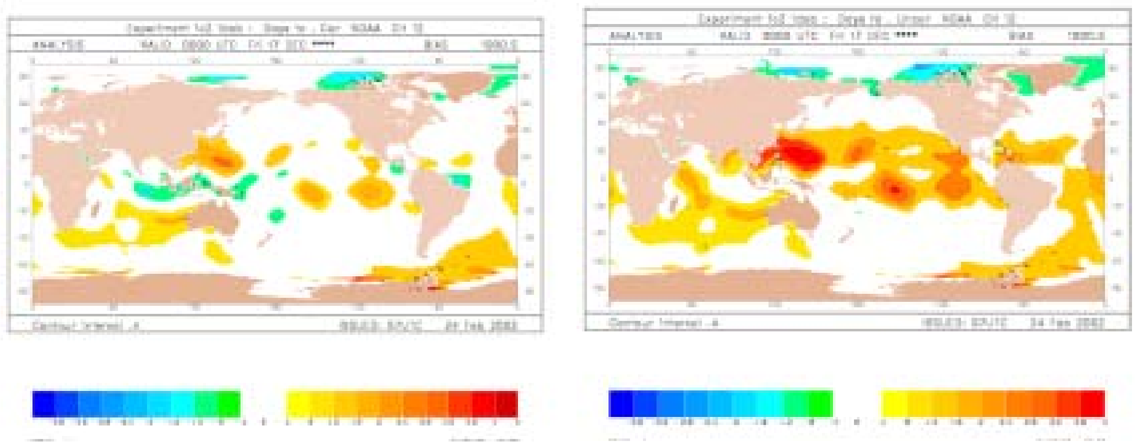

Figure 4. Observation vs. background bias for HIRS 12 from experiments using level-1d AMSU-A + HIRS (left panel) and level-1c AMSU-A only (right panel).

5. SCATTEROMETER DATA

The value of wind data from scatterometers has been demonstrated in the current system, particularly in the short term. Enhanced quality control procedures, and improved vertical interpolation using a physically based scheme, and a lowest model-level near 10m (rather than the 75m used operationally) were required to obtain this impact. The quality control procedures include checks for land and sea-ice, rain/ice contamination, wind speeds that are too low (< 3 ms^{-1}) or too high (>30 ms^{-1}) and wind consistency background checks. Verification scores for a limited trial are shown in Fig.5. Subsequent prolonged trials have shown similar results, namely a small positive gain at low to mid tropospheric levels. In earlier trials there were problems with scatterometer data conflicting with AMV data, although this problem has not been revisited since the latest version of AMV processing incorporating quality indicator information was introduced.

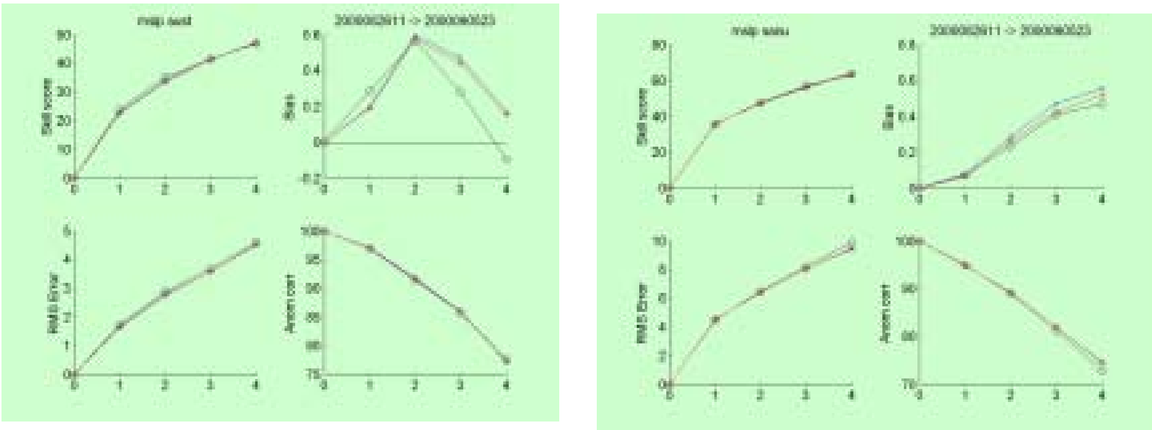

Figure 5. Verification scores for MSLP for the Australian Region and Southern Annulus (20S to 60S) for experiments with QuickSCAT data - (+) used an observation error of 2ms^{-1}, (x) used 4ms^{-1} and (o) used no QuickSCAT data. The experiment ran from 11Z, August 26th to 23Z, September 5th, 2000.

Scatterometer data has considerable amount of detail in the near surface marine winds, and so can be of particular value in the analysis of small scale tropical disturbances. The added value of this information however will not have a significant impact on broad scale scores such as regional RMS or anomaly correlations. The value of this meso-scale information is best illustrated by examining particular case studies, although such comparisons are complicated by the need for the instrument to be in the area of a significant event. Nevertheless initial tests, for a limited number of cases show that this data can be particularly useful when used in conjunction with cloud information from geostationary satellites as can be seen in Figs.7-10.

These tests used the TC-LAPS system of Davidson and Weber (2000) which uses the satellite derived heating rate estimation and the operational assimilation system tuned for use within a 15km resolution tropical NWP model. The estimated heating rates use geostationary imagery to introduce heating rates in the model consistent with both the imagery and the convection scheme. The scatterometer data were thinned to 80km resolution and the data selection selects all of the thinned data.

The geostationary imagery of cloud top temperature and scatterometer wind data are shown in Fig. 6. This should be used as "verification" for Figs.7-10 which show the impact on analysis and 12 hour forecast of scatterometer and satellite derived heating, both individually and together. In Figs. 7-10 the coloured field is the vertical motion on sigma level $\sigma = 0.25$ which is a convenient proxy for convection, and the arrows indicate the wind on the lowest sigma level ($\sigma = 0.9943$). The control assimilation, using neither scatterometer winds nor heating estimates is

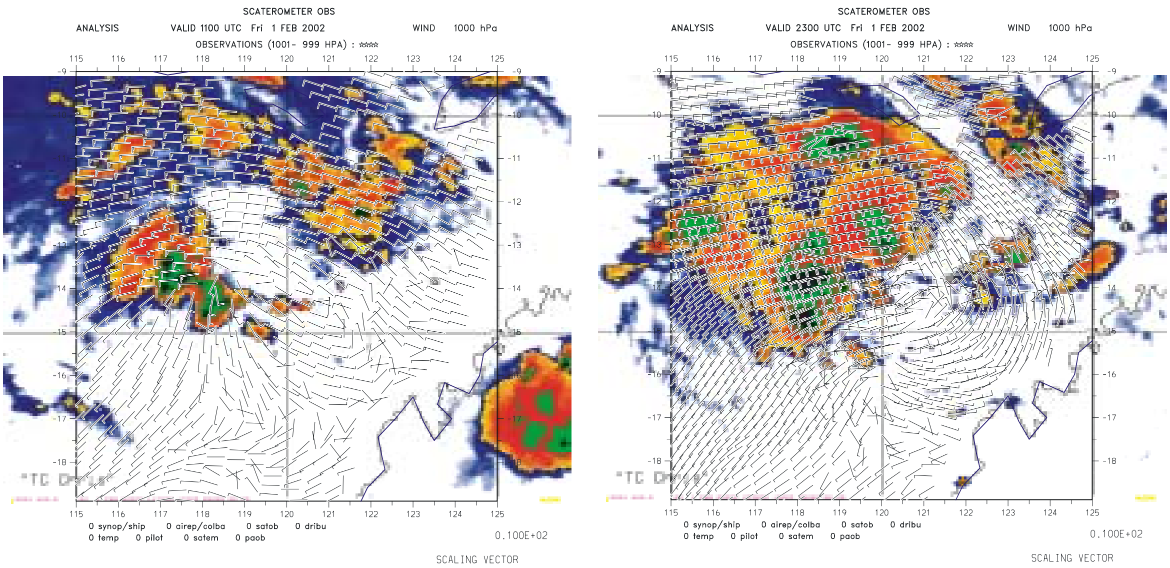

Figure 6. Digitized cloud top temperatures from GMS-5 (coldest temperatures black and green) and most probable QuickSCAT winds around tropical cyclone "Chris" for 11Z and 23Z on the 1st of February, 2002.

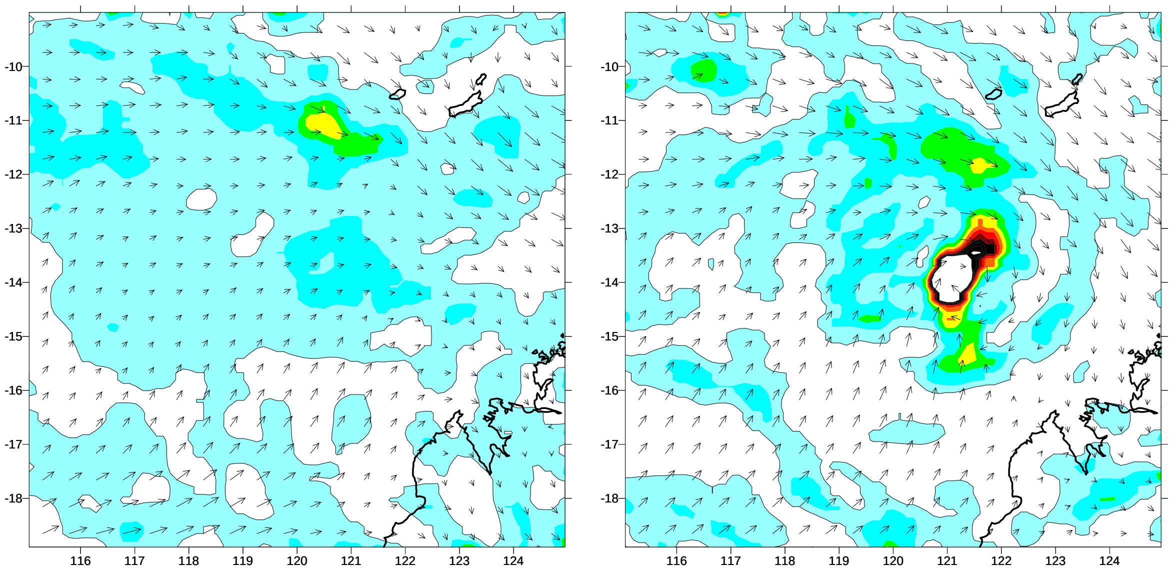

Figure 7. Low level winds at σ = 0.9943(left) and vertical motion at σ = 0.25 (right) for an analysis and 12 hour forecast without QuickSCAT data or satellite derived heating. The vertical motion field at this level is a suitable proxy for deep convection.

shown in Fig. 7. There is clearly no vortex at the start and 12 hours later only a weak vortex develops to the east of that indicated by the scatterometer data in Fig 6. Adding the QuickSCAT data provides a better location of the low level vortex, although the convection is misplaced and rather weak, especially in the analysis. Fig. 9 shows the effect of adding the satellite heating only, which is to improve the specification of the convection, particularly the strength. The location of the convection, particularly in the forecast is southeast of that indicated by the geostationary imagery. The complementary nature of the two sources of data produces the benefits of both the previous examples as shown in Fig. 10, where the location and strength of both the convection and low-level vortex is in close agreement with Fig. 6 for the analysis and forecast.

The results in Figs. 7-10 also used the operational assimilation scheme, rather than GenSI, although again the results should carry over, as the sub-sampling of the data selection was configured so as to have minor effect.

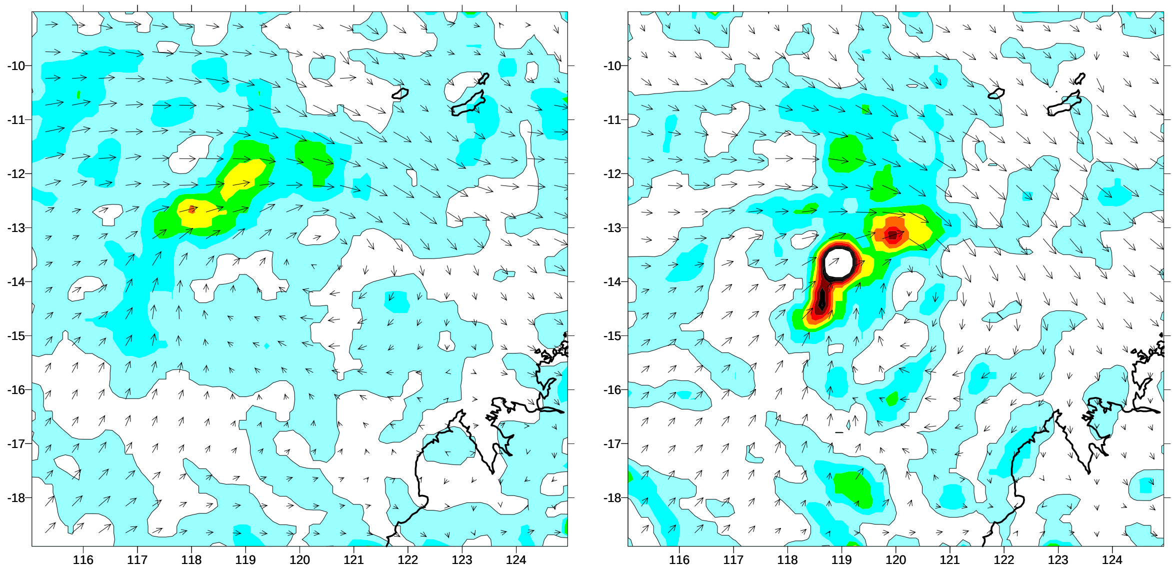

Figure 8. As for Fig. 7, but with QuickSCAT data

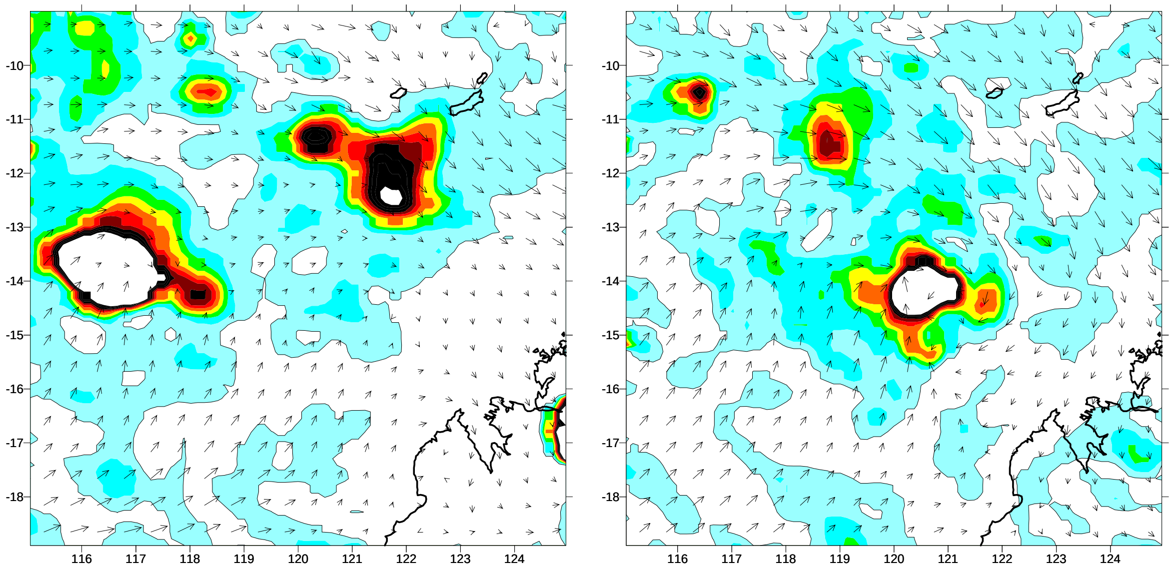

Figure 9. As for Fig. 7, but with satellite derived heating data

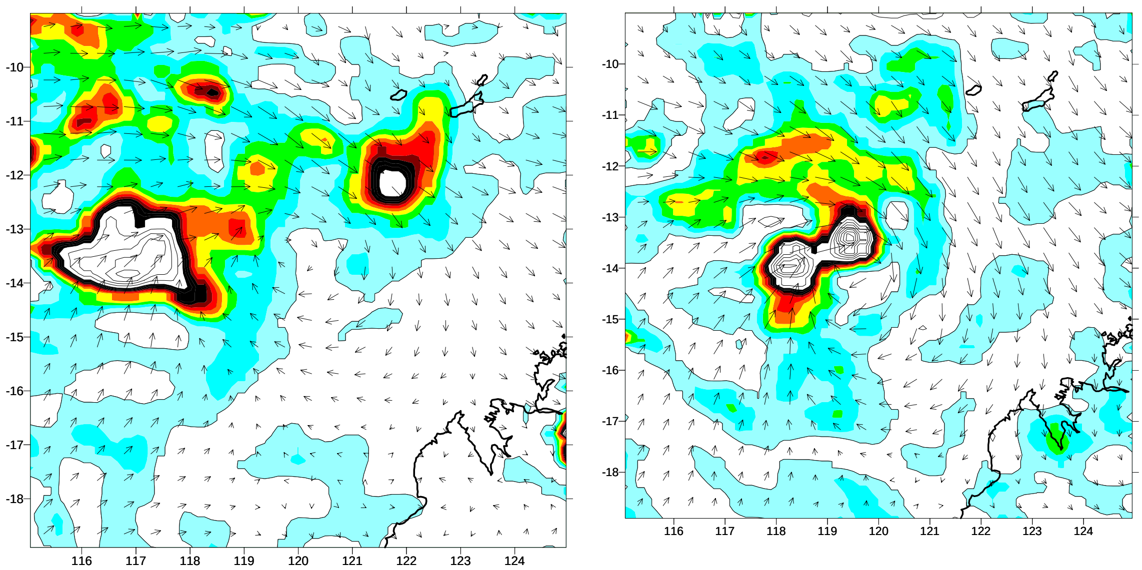

Fig 10. As for Fig. 7 but with both QuickSCAT and satellite derived heating.

6. SURFACE MOISTURE DATA

The use of surface moisture observations has in general been very successful within the BMRC regional assimilation system(LAPS). These observations not only providing valuable atmospheric information, but also being used to overcome temperature and moisture biases in the land surface parameterization. There have been instances however, of severe negative impact associated with malfunctioning instruments. As these instruments are often operated by other agencies, for reasons other than general weather prediction, the operational monitoring of individual stations is paramount to their information consistently adding value to rainfall and cloud amount forecasts.

An example of the problems due to malfunctioning sensors is shown in Fig.11. The effect of repeated reports from an erroneous sensor is magnified by the combination of orography and data selection to produce an unrealistic range of near-surface dewpoints in the operational analysis (values were too low in some places and too high in others). This case was a problem in particular as the high dew-points near the SE coast (an area of elevated terrain) produced excessive cloud over Canberra during the subsequent 24 hour forecast. The GenSI analysis is shown as a comparison, and provides a better estimate of the 2m moisture field. While there have been no instances of GenSI producing similar errors to those of the operational system it is unlikely to be completely immune to such problems.

There are also cases where two isolated sensors failed in similar fashion that are relatively close to each other, producing consistent but erroneous data. This type of problem means that quality control systems built around instantaneous three-dimensional comparisons of implied analysis increments (i.e. the OI check of Lorenc, 1981) will generally accept the data. For these reasons more sophisticated quality monitoring of observations is being developed.

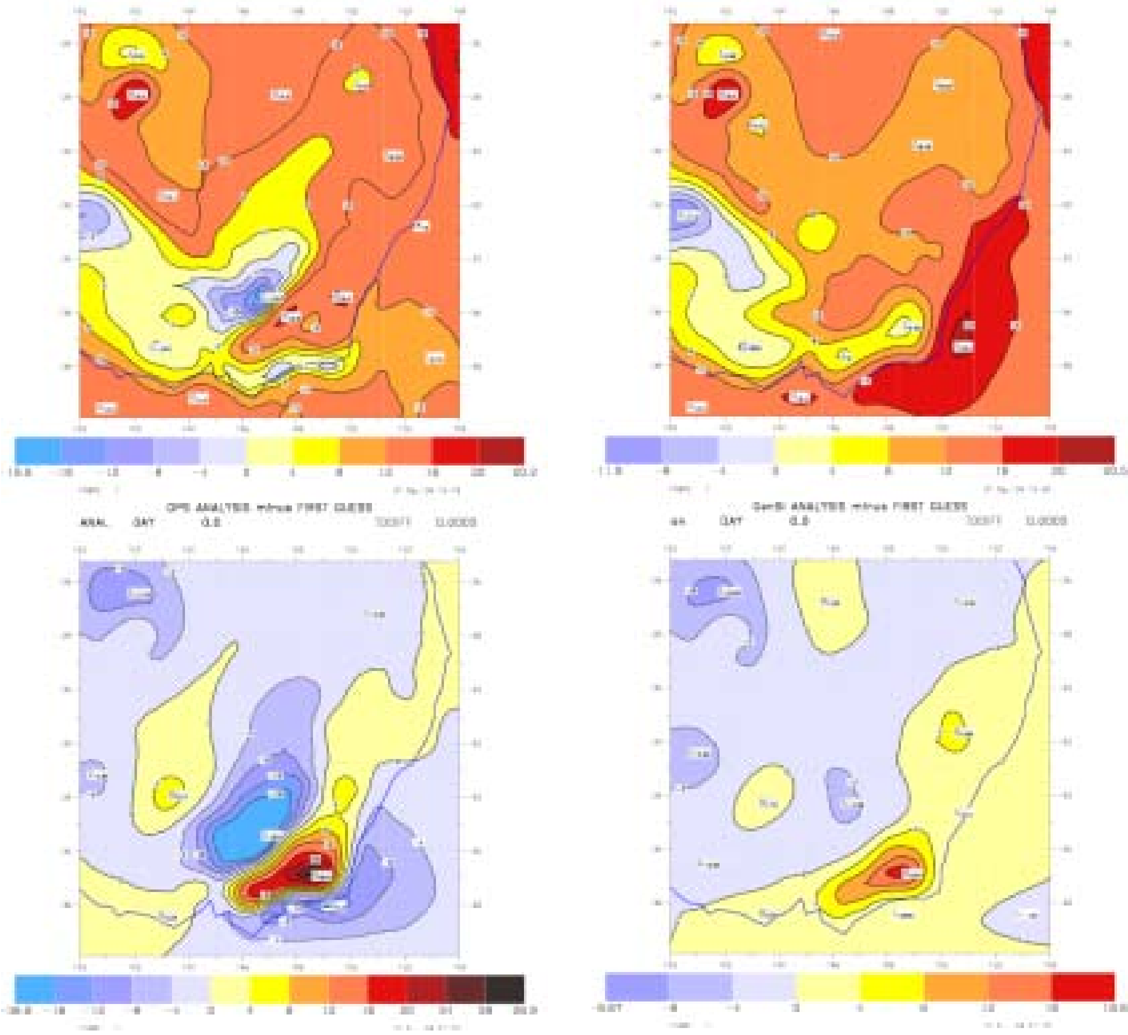

Figure 11. 2m Dew-point analysis (top) and increments (bottom) for operations (left) and GenSI (right). Note that contour interval for the operatio/bm/flush1/pxs/assim/nal increments is 5°C, but for the GenSI increments, the interval is 2.5°C

8. CONCLUSION

A new assimilation scheme, GenSI has been developed within BMRC and parallel trials have shown generally superior forecast skill to current operational systems. As part of the development and assessment of this scheme various OSE's have been performed. These impact experiments have attempted to use as a configuration of observation processing and error covariances that are as close as possible to operations in order to assess the impact of the new analysis algorithm. Some changes were necessary due to the increase in the amount of data, such as AMVs that are actually used.

Adjustments to the quality control and observation error specification were required to ensure that AMVs do not significantly degrade the assimilation system. It was noted that the AMV's caused problems in the upper troposphere in particular, and that the adjustments to he observation handling meant that the new system was comparable to the operational system. At lower levels and in the stratosphere, the new system now provides significant improvement relative to operations. Further tests and refinements are required using the most up-to-date configuration of the NWP system to ensure that the AMVs add value to the analysis. These tests will include higher vertical resolution, improved physical parameterizations and additional data such as scatterometer winds.

Investigations into using AMSU-A only, versus AMSU-A and HIRS data highlighted the need for the moisture sensitive channels to be used within the assimilation. To include AMSU-B, new model configurations are being tested so level-1d data from either local readout or as available from the MetOffice.

Scatterometer data has shown small positive impact in gross scores in the global model. There have however been indications of significant gains in the TC-LAPS (15km) assimilation of scatterometer wind observations when used in conjunction with other data related to convection. The positive impact from using the combination of scatterometer and satellite derived heating estimates has been repeated with a number of different cases.

The use of near-surface moisture data from automatic sensors has in general been very useful in improving rainfall and cloud forecasts as well as mass and wind forecasts. There are however numerous instances of isolated stations causing very poor forecasts due to sensor maintenance problems. As is frequently the case, the consistent positive impact of an observing system depends on the thoroughness of the quality control.

9. REFERENCES

Cohn, S., et al. 1998. *"Assessing the Effects of Data Selectionwith the DAO Physical-Space Statistical Analysis Sytem"*. Monthly Weather Review, **126**, pp.2913-2916.

Davidson, N., and Weber H., 2000. *"The BMRC High-Resolution Tropical Cyclone Prediction System: TC-LAPS"*. Monthly Weather Review, **128**, pp. 1254-1265.

Holmlund, K. et al. 2001. *"Enhanced Automatic Quality Control Applied to High-Density Satellite-Derived Winds"*, Monthly Weather Review, **129**, pp. 517-529.

Lorenc, A. 1981. *" A Global Three-Dimensional Statistical Interpolation Scheme"*. Monthly Weather Review, **109**, pp. 701-721

Seaman, R., et al. 1995. "*Evolution of the Bureau of Meteorology's Global Assimilation and Prediction System. Part I: Analysis and Initialization"*. Australian Meteorlogical Magazine, **44**, No. 1, pp. 1- 18.

Impact of Research Satellite Observations in a Data Assimilation System for the Troposphere-Stratosphere

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ABSTRACT
Research satellite data is increasingly being assimilated into operational Numerical Weather Prediction (NWP) systems and sophisticated photochemical models. At the UK Data Assimilation Research Centre (DARC), data from the UARS MLS, GOME and Envisat MIPAS instruments has been assimilated into the Met Office stratosphere-troposphere operational system. This has included Observing System Experiments (OSEs) and Observing System Simulation Experiments (OSSEs) to assess the impact of research satellite data. A chief motivation of this work is to build a coupled dynamics/chemistry assimilation system. We discuss the use of OSEs to: (i) evaluate satellite ozone datasets, and (ii) demonstrate the advantages of combining limb and nadir geometries. We also discuss how OSSEs can be used to evaluate in a quantitative manner future Earth Observation (EO) missions, focusing on the proposed SWIFT instrument. Finally, we provide pointers for future developments in the assimilation of research satellite by the EO community.

1. Introduction

It is now well recognized that satellite data play a major role in improving the accuracy of operational forecasts. For example, current ECMWF 7-day extra-tropical forecasts (of 500 hPa geopotential height) are as accurate as 5-day forecasts were 20 years ago, and the current accuracy of Northern Hemisphere (NH) and Southern Hemisphere (SH) extra-tropical forecasts is comparable (this is mainly due to the increased use of satellite data). Thépaut (2003) provides more details.

Parallel to the increased role of satellite data, atmospheric models also are being extended in many ways. The horizontal resolution is being increased (e.g. ECMWF currently produce analyses at T511 resolution, ~0.3^o, ~40 km). The vertical resolution is being increased in the UTLS (Upper Troposphere/Lower Stratosphere) region, which is recognised as a key region for the radiative balance of the atmosphere, and transport between the troposphere and stratosphere (SPARC 2000). The top of atmospheric models is being also extended upward to include a comprehensive stratosphere. For example the Met Office and ECMWF models now have versions with a top at 0.1 hPa (~65 km).

Increases in resolution and extensions of the model domain help provide more accurate representations of the atmosphere. Together with data assimilation methods and adequate computer resources, these model developments can improve our forecasting and long-term capability in a number of ways: (1) extending the range of validity of forecasts, (2) allowing forecasts of novel geophysical parameters, e.g., tropospheric ozone, (3) providing novel analyses, e.g., stratospheric water vapour, (4) making climate models more consistent and realistic, and (5) using objective methods to confront and evaluate forecast and climate models with value-added information produced using data assimilation techniques.

The assimilation of stratospheric measurements of temperature, humidity and photochemical species such as ozone, is increasingly taking place for both research and operational purposes. Photochemical species (chiefly from research satellites) are routinely assimilated into sophisticated photochemical models (typically chemistry-transport models, CTMs) driven by off-line winds and temperatures (e.g. Fisher and Lary 1995; Elbern *et al.* 1997; Khattatov *et al.* 1999; Errera and Fonteyn 2001; Štajner *et al.* 2001; Eskes *et al.* 2003).

Ozone data (chiefly from research satellites) have been assimilated into global NWP systems (e.g. Struthers *et al.* 2002; Dethof 2003). Figure 1 shows an example from DARC. Total column ozone data from GOME were assimilated into the ECMWF operational system during the period April 2002-June 2003 (the assimilation was stopped due to problems with the transmission of data from GOME to the ground segment). Ozone profile data from MIPAS have been assimilated into the ECMWF operational system since late September 2003.

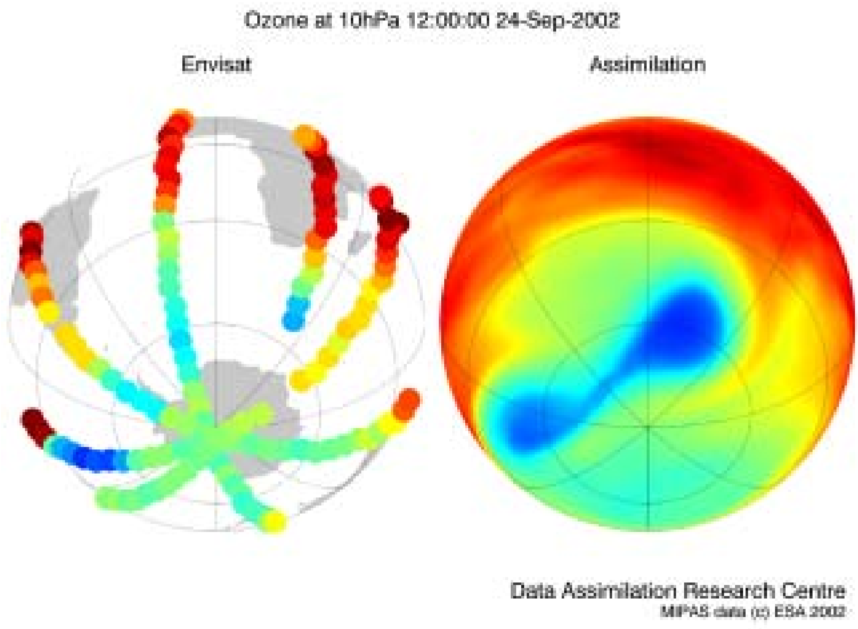

Figure 1. Representation of how data assimilation adds value to EO data. Left-hand panel: MIPAS orbits showing ozone measurements. Right-hand panel: Quality-controlled analysis of the ozone distribution. In both panels, the ozone data are for 10 hPa at 12 UTC on 24 September 2002 (red indicates high values, blue low values). Figure courtesy Alan Geer, DARC.

Research groups across the world also are developing algorithms to couple NWP systems (focusing on dynamics-radiation feedbacks) with CTMs (focusing on chemistry-radiation feedbacks). More details can be found at the EU-funded ASSET (ASSimilation of Envisat daTa) project website: http://darc.nerc.ac.uk/asset.

A big driver in these developments (e.g. inclusion of stratospheric parameters, assimilation of photochemical species, inclusion of models with sophisticated photochemistry in assimilation systems) has been an interest in ozone in the EO community. This interest is chiefly due to: (1) concerns about ozone depletion, (2) recognition that one must develop a coupled climate/chemistry capability to understand, simulate and predict climate change, and (3) the potential to extract wind information in the tropics from tracer observations, including ozone. Another big driver in this development (particularly for the NWP community) has been the recognition that many of the nadir-sounding satellite instruments used for operational purposes have deep weighting functions that, although they peak in the troposphere, can span a substantial part of the stratosphere.

In this article, we describe work at the DARC to assimilate research satellite data into the Met Office troposphere-stratosphere operational system (Swinbank *et al.* 2002). Section 2 discusses the use of research satellite observations. Section 3 discusses impact studies performed at the DARC using OSEs (e.g. Struthers *et al.* 2002; Lahoz *et al.* 2003b), and OSSEs (e.g. Lahoz *et al.* 2003a, 2004). Section 4 provides conclusions and pointers for future work.

2. Use of research satellite observations

Satellite platforms can be divided into several categories, including: (a) operational and research satellites, (b) geostationary and low Earth orbit satellites (typically polar satellites), and (c) sun-synchronous and non-sunsynchronous satellites. Further details can be found in Lahoz (2003) and Thépaut (2003).

Research and operational satellite data provides opportunities for synergy. Different viewing geometries (limb and nadir) can be used with techniques such as data assimilation to improve the representation of the atmosphere, and partition information between the stratosphere and troposphere. This approach is being used to combine nadir and limb geometries to estimate the global distribution of tropospheric ozone, which is very difficult to measure directly from space (Lamarque *et al.* 2002). This approach is also being use to combine nadir and limb geometries to produce quality-controlled analysed datasets that are objectively better than those produced using just one of the two geometries (Struthers *et al.* 2002).

Synergy between research and operational satellites, and the potential benefits to the NWP agencies accruing from this synergy, can make it attractive to use research satellites operationally. This can happen in a number of ways: (1) one-off use of research satellite data (e.g. measurement of a key photochemical species such as ozone, or of a novel geophysical parameter such as stratospheric winds), (2) regular use of research satellite data (e.g. a satellite series that can extend the time record of key geophysical parameters such as ozone and water vapour), and (3) use of the research satellite instrument design in future operational missions.

Satellite data provides other potential synergies. For example, dynamical quantities (temperature, winds and water vapour, often measured by operational satellites) and photochemical species (ozone and others, often measured by research satellites) observed from satellites are being assimilated into a variety of atmospheric models with the aim of improving the representation of the feedbacks between dynamics, radiation and chemistry.

Increasing interest in chemical forecasting and climate/chemistry feedbacks, has made more attractive the inclusion of ozone and photochemistry into atmospheric models. Three approaches can be identified: (1) General Circulation models (GCMs) with a sophisticated dynamics formulation, and incorporating relatively simple photochemical parametrizations (e.g. the Cariolle scheme for ozone, Cariolle and Déqué 1986), (2) CTMs with a sophisticated photochemical formulation, forced by off-line winds, (3) coupled dynamics/chemistry models (e.g. GCM coupled to a CTM). The work at DARC builds toward approach (3). OSEs are a way of assessing these approaches.

The main advantage of GCMs for data assimilation is that they tend to provide the most complete description of atmospheric dynamics, and incorporate feedbacks between dynamics and radiation. GCMs can also incorporate data from operational and research satellites. By incorporating into a GCM a hierarchy of photochemical models, GCMs can take into account the feedbacks between dynamics, photochemistry and radiation. However, because GCMs tend to be complex, it can be expensive to incorporate sophisticated photochemical models into GCMs, and techniques such as the Kalman filter (requiring a very high level of computational effort) tend not to be used with GCMs. Partly for this reason, assimilation using GCMs tends to be implemented using variational techniques (3d- and 4d-variational).

Assimilation of photochemical data into models with sophisticated photochemistry (CTMs) is increasingly taking place. The techniques used include simplified versions of the Kalman filter, and 4d-variational assimilation. Their main advantage is their relatively simpler configuration compared to a GCM. This allows the inclusion of a large number of photochemical species. It also provides a tool for investigating the distribution and variability of atmospheric photochemical species, testing photochemical theories, and producing fields of observed and unobserved species (using the model photochemical relations). Their main disadvantage is that they do not allow feedbacks between the dynamics and photochemistry.

An alternative to using GCMs or CTMs, is to couple a GCM to a CTM. For example, dynamical and photochemical variables could be assimilated in the GCM and CTM, respectively. The GCM provides the temperature, winds and humidity input to the CTM. After the assimilation of photochemical variables, the CTM passes the ozone analysis back to the GCM, where it is used in the GCM radiation scheme. The cycle then repeats. This coupling allows feedbacks between the dynamics, radiation and photochemistry, and aims to combine the advantages of assimilation into a NWP system (assimilation of operational data, sophisticated representation of dynamics and radiation), with the advantages of a CTM (sophisticated representation of photochemistry).

Current mission plans of the space agencies will lead to a wealth of operational and research EO satellites with advanced measurement capabilities. It is recognized that these EO measurements, supplemented with data from *in situ* observation networks, and the use of increasingly powerful models and assimilation techniques, will provide an unprecedented potential for a wide range of uses, including climate research and monitoring of environmental changes. For this potential to be realized, it is important that data suppliers (e.g. instrument teams, space agencies) and end-users (e.g. EO community, met agencies) communicate with each other. There is also a need to recognize the importance of evaluating objectively future and expensive observing systems. OSSEs are a way of doing this.

3. Impact studies

3.1 Observing System Experiments

A standard way to assess the impact of novel (but available) data types (e.g. ozone, stratospheric water vapour) is to carry out an OSE (see, e.g., WMO 2000). OSEs are essentially data-denial exercises. In an OSE, two experiments are carried out: one including all available data, the other including all available data less the observation of interest. Comparison between the analyses from the two assimilation experiments provides information on the impact of the observation of interest.

In this section we describe a number of OSEs carried out at DARC to assess the impact of research satellite data in the Met Office troposphere-stratosphere NWP system. In particular, we describe OSEs that: (1) provide information to evaluate ozone datasets, and (2) assess the synergy from incorporating ozone observations with nadir and limb geometries.

Nadir sounders have good horizontal resolution but poor vertical resolution, whereas limb sounders have poor horizontal resolution but good vertical resolution. Furthermore, data from limb sounders, which have height-resolved stratospheric information, often have little or no tropospheric information. On the other hand, total column data from nadir sounders can provide constraints that, combined with stratospheric height-resolved information, allow the determination of the tropospheric column. Another potential advantage of nadir/limb geometry synergy is analyses that are objectively better than those just using one of the two geometries.

Struthers *et al.* (2002) discuss OSEs in which ozone profiles from UARS MLS, and total column ozone from GOME are added to the operational suite of observations assimilated by the Met Office troposphere-stratosphere NWP system. The OSEs are used to evaluate the ozone analyses by self-consistency tests, e.g., tests for Gaussian errors, tests against the Best Linear Unbiased Estimate (BLUE) hypothesis (Talagrand 2003), and by comparison against independent data (i.e., not used in the assimilation).
Evidence is presented that the MLS and GOME configuration performs better than either the MLS only or GOME only configuration. In particular, the MLS and GOME configuration is more consistent with the expected results from a BLUE. These results are corroborated by the comparisons between the analyses from the different configurations and independent information (ozonesondes, HALOE profiles, TOMS total column ozone).

The results of Struthers *et al.* suggest that the combination of ozone profile and total column ozone data from Envisat instruments (e.g. MIPAS and SCIAMACHY) will provide better analyses than using the profile or column information separately, and that these analyses will provide a realistic representation of the atmospheric ozone distribution. Furthermore, the results from Struthers *et al.* feed into the following areas: (1) studies to extract information on tropospheric ozone, (2) development of background error covariances for ozone and other species of interest such as stratospheric water vapour (see, e.g., http://darc.nerc.ac.uk/asset), and (3) the use of Envisat data with limb and nadir geometries.

A number of OSEs involving the assimilation of MIPAS ozone data are been done currently at DARC (preliminary details can be found in Lahoz *et al.* 2003b). The OSEs are still at an early stage, to some extent due to the relatively preliminary nature of the MIPAS data. These OSEs are being carried out to evaluate the MIPAS ozone data and assess its impact. In particular, quality-controlled ozone analyses are being produced to study the unprecedented SH major warming that took place in September 2002.

This work is being carried out in the context of the ASSET project. One of the objectives of ASSET is to assess a number of strategies for the assimilation of Envisat data. For example, the representation of photochemistry in models, and the use of retrievals or radiances will be investigated. The use of different models (GCMs, CTMs) provides a robust assessment of this strategy, and of the quality-controlled ozone analyses.

A summary of the preliminary results concerning MIPAS ozone data for September 2002 is as follows:

- MIPAS ozone retrievals show large bias before 18th September. This will be corrected in future assimilation runs.
- MIPAS/model errors are consistent with Gaussian statistics.

- Analysed ozone is generally consistent with independent data (ozonesondes, HALOE profiles, and GOME and TOMS total columns), but: (1) at 2 hPa the model underestimates ozone, (2) the lower/mid stratosphere shows 0.3-0.7 ppmv too much ozone – this could be due to a combination of biases in the MIPAS ozone data and in the Cariolle scheme, and (3) in the polar vortex, lower stratospheric ozone appears too high - this could be due to biases in GOME and MIPAS ozone data, a bias in the Cariolle scheme, or excessive vertical transport in the model.
- An error budget of the analyses errors is being carried out.

OSEs to evaluate the impact of stratospheric water vapour data from MIPAS are still at a very early stage, chiefly due to shortcomings in the data, and in the background error covariances in the "Old dynamics" Eulerian formulation of the Met Office model. The "Old Dynamics" is due to be replaced by the "New Dynamics" Semi-Lagrangian formulation during the second quarter of 2004. Nevertheless, some issues have already been identified:

- Given the large variability in water vapour between the troposphere and stratosphere, what is the best control variable (e.g. relative humidity -RH, specific humidity) for assimilating water vapour in the troposphere and stratosphere?
- The background error covariance matrix for stratospheric water vapour may be ill-conditioned.
- There is evidence of excessive increments in the lower stratosphere (e.g. 50 hPa). These could be due to spurious correlations between the lower stratosphere and the upper troposphere.

The Met Office, together with DARC, is investigating the performance of stratospheric water vapour in the "New Dynamics". As part of this work, the following studies are being implemented: (1) development of a new background error covariance matrix for troposphere-stratosphere water vapour (involving, e.g., a special treatment of the tropopause), and (2) an assessment of the best control variable – candidates include a normalised RH (Hólm *et al.* 2002) and a pseudo RH (Dee and da Silva 2003).

3.2 Observing System Simulation Experiments

A standard way to assess a proposed addition to the Earth Observing System is to carry out an OSSE (see Atlas 1997 for details). The first component of an OSSE is a "nature run" (or "Reference Atmosphere"). The nature run can come from a model run (e.g. a GCM integration), or from meteorological analyses. Then, a complete set of observations is simulated from the nature run. These observations are a complete reproduction of the operational network (or the expected configuration of the network at a future time). In addition, the measurements from the proposed new observation type are also simulated. Typically, the observations would be assumed to be unbiased and have Gaussian errors. Two assimilation experiments are run: (1) one with a data assimilation system using all the simulated operational observations (the "control" run), and (2) one using the new observations in addition to all the simulated operational observations (the "perturbation" run). Both assimilation experiments are compared to one another, and with the Reference Atmosphere, to assess the impact of the new observation type.

Setting up a system for carrying a complete simulation of all the different observation types is a major undertaking – comparable to writing the assimilation system itself. The performance and evaluation of the assimilation experiments is also a time-consuming exercise. Nevertheless, it is often a worthwhile undertaking, especially considering the possible benefit in the objective evaluation of very expensive observing systems.

OSSEs have a number of shortcomings:

- They are expensive. To alleviate the problem one can perform a "reduced OSSE" (e.g. use profiles instead of radiances). In general, reduced OSSEs are only suitable when the observation of interest is a significant addition to the observing system (e.g. stratospheric winds).
- They are difficult to interpret because of the model dependence of the results. One can alleviate the problem by using conservative errors, and using several methods to investigate the impact.
- "Incest", where the model used to derive the Truth is the same one used to perform the assimilation. One can alleviate the problem by using different models to construct the Truth and perform the assimilation

Nevertheless, despite their shortcomings, the high cost of EO missions means that OSSEs often make sense to the space agencies such as ESA. The NWP agencies often use ideas of "information content" (rather than OSSEs) to assess future EO missions (see, e.g., Prunet *et al.* 1998).

An example of a recent ESA-funded OSSE involves the SWIFT instrument, which is designed to measure stratospheric winds and ozone (see Lahoz *et al.* 2003a, 2004 for details). SWIFT was originally due to fly aboard the JAXA GOSAT platform in 2007/2008, but as from December 2003, SWIFT will no longer be onboard GOSAT due to JAXA budget cuts. Nevertheless, results from the study of the impact of SWIFT stratospheric winds and ozone are still useful (not least because alternative platforms for SWIFT are likely to be sought). In particular, stratospheric winds and ozone are important geophysical parameters for: (1) studies of stratospheric dynamics and photochemistry, and (2) extending the global Earth Observing system.

The SWIFT instrument (http://swift.yorku.ca) is based on the UARS WINDII measurement principle. It measures the two wind components using two measurements at ~90^o of the thermal emission of an ozone line at 1133 cm^{-1}. SWIFT will make global measurements of wind and ozone profiles (~20-40 km), and will be in a sun-synchronous orbit (N-look: 87°N-53°S; S-look: 53°N-87°S). The errors chosen for the OSSE are based on studies made for the SWIFT Mission Requirements Document (MRD), and are conservative. More details can be found in Lahoz *et al.* (2003a, 2004).

The motivation for SWIFT is two-fold:

- Shortcomings in the current observing system. In particular, there are no operational observations of winds for levels above those of radiosondes (~10 hPa). Note that indirect information on winds can be obtained from nadir soundings of temperature, through thermal wind considerations, but this approach breaks down in the tropics.
- Science. (1) climatologies of tropical winds, and (2) transport studies (e.g. ozone fluxes). The SWIFT project envisages using data assimilation to obtain 4-d quality-controlled datasets for scientific studies (e.g. climate change and its attribution)

The design of SWIFT OSSE is described in Lahoz *et al.* 2003a, 2004. To summarise:

- Models used: (1) "Truth" (T): ECMWF directly, or forcing a CTM; (2) Assimilation system: Met Office.
- Simulated observations: (1) Operational: "control" experiment, C. Temperature, winds, humidity, and ozone from MetOP, MSG, sondes, balloons, aircraft, and surface observations; (2) SWIFT: C plus SWIFT ozone and winds in the stratosphere. This is the "perturbation" experiment, P. The "reduced OSSE" approach is used.
- Several assimilation experiments were carried out. The assimilation set-up was evaluated prior to the evaluation of the impact of the SWIFT observations.

- A number of qualitative and quantitative tests were carried out to evaluate the SWIFT impact. The quantitative tests included significance tests (see Figure 2 below).

The SWIFT OSSE also looked at several scientific aspects for robustness: (1) tropical winds, (2) wintertime variability (with a focus on winds), and (3) the Brewer-Dobson circulation. Details can be found in Lahoz *et al.* (2003a, 2004).

The conclusions from the SWIFT OSSE were as follows:

SWIFT winds:

- They can have a significant impact in the tropical stratosphere (except the lowermost levels).
- The can have a significant impact in the extra-tropics when: (i) SWIFT observations are available, and (ii) the flow regime is variable (i.e., relatively fast changing).
- They have scientific merit in that they improve: (i) information on tropical winds, and (ii) wintertime variability.
- They provide forecasts and analyses that help studies of climate change and its attribution. These forecasts and analyses can contribute to: (i) better models, (ii) better initial conditions, and (iii) model evaluation.

SWIFT ozone:

- It has significant impact at 100 hPa and10 hPa, i.e., in regions of relatively high vertical gradients in the ozone field.

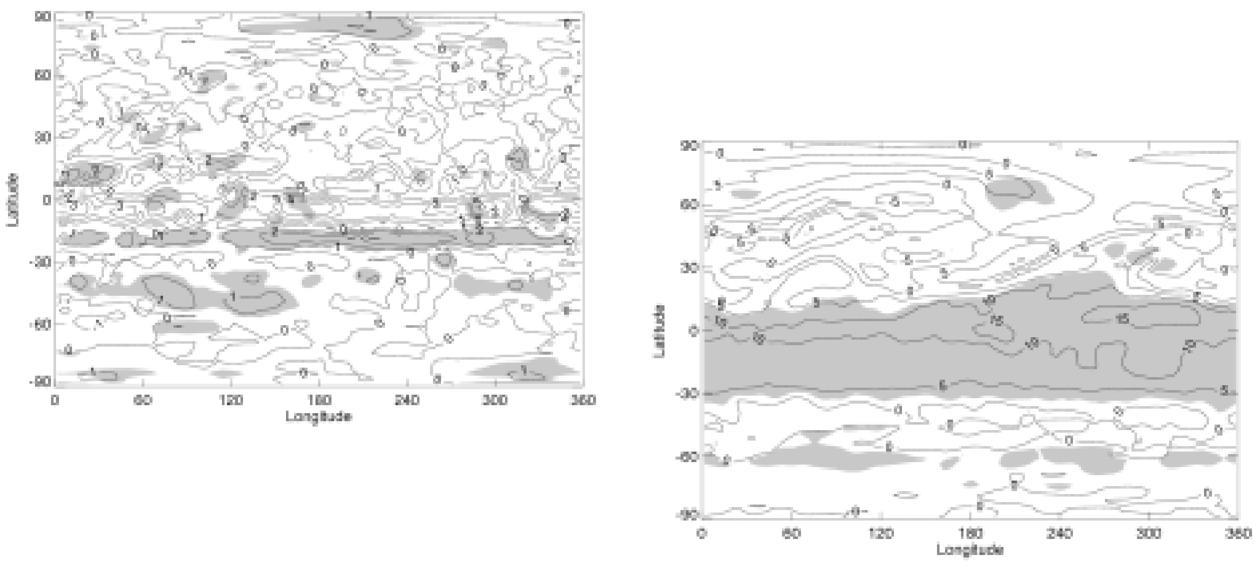

Figure 2. (a) Left-hand side: Zonal wind monthly mean (ms^{-1}), January, 10 hPa. Abs(C-T) – Abs(P-T). Shading indicates where both (i) the difference between the monthly means for (C-T) and (P-T) is significant at the 0.95 confidence limit, and (ii) "perturbation" analyses are closer to the "Truth" than "control" analyses. (b) Right-hand side: as Left-hand side, but at 1 hPa.

There are a number of caveats associated with these conclusions:

- Use of the "reduced OSSE" approach. Use of radiances would be expected for AMSU-A and IASI at the time of the SWIFT launch. The expectation is that the impact in the tropics and extra-tropics will remain unchanged. This is because the thermal wind relationship does not hold in the tropics, and is not accurate in regions where the flow regime is relatively fast changing.

- Higher horizontal resolution in the assimilation model at the time of SWIFT launch, implying less thinning of the satellite data (AMSU-A, IASI). This would impact the stratospheric wind analyses in the extra-tropics, but the conclusions for winds in the tropics and for ozone should remain unchanged.

Overall, the SWIFT OSSE study strongly recommended that the development, construction and subsequent launch of the SWIFT instrument be implemented.

4. Conclusions and future work

With the increasing assimilation of research satellite data (in particular, photochemical data) for operational and research purposes, the ways in which such an assimilation is performed need to be assessed. Due to the recognition of the increasing importance of climate/chemistry feedbacks and tropospheric pollution, the route to coupled dynamics/chemistry assimilation and chemical weather is of great interest. These reasons provide a strong motivation for DARC to develop a coupled dynamics/chemistry assimilation system.

To map out the route toward coupled dynamics/chemistry assimilation and chemical weather, we need:

- To assess the strategies for the assimilation of EO data. This entails taking advantages of synergies such as the combination of: (i) limb and nadir geometries, (ii) operational and research satellites, and (iii) dynamical and photochemical data. OSEs will play an important role in this effort.
- To develop and improve the assimilation systems needed to make use of research satellite data. Efforts by the met agencies and the broad EO community will have to keep up with the evolution of the Global Observing System. Current mission plans of the space agencies will lead to the launch, during this decade, of a large constellation of operational and research EO satellites with advanced measurement capabilities. It is recognized that these EO measurements, supplemented with data from *in situ* observation networks, and the use of increasingly powerful models and assimilation techniques, will provide an unprecedented potential for a wide range of uses, including climate research and monitoring of environmental changes. For this potential to be realized, it is important that data suppliers and end-users communicate with each other.
- To recognize the importance of evaluating future and expensive observing systems. OSSEs are one way of doing this. In Lahoz *et al.* (2003a, 2004) it is recommended that space agencies (possibly in conjunction with met agencies) fund the development of a full OSSE capability which could be used to assess of future proposed space missions in a more credible and sophisticated manner.

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References

Atlas, R.M. (1997). Observing System Simulation Experiments: methodology, examples and limitations. CGC/WMO Workshop, Geneva 7-9 April 1997, WMO TD No. 868.

Cariolle, D., and M. Déqué (1986). Southern hemisphere medium-scale waves and total ozone disturbances in a spectral general circulation model. *J. Geophys. Res.,* **91**, 10825-10884.

Dee D., and A. de Silva (2003). The choice of variable for atmospheric moisture analysis. *Mon. Weather Rev.*, **131**, 155-171.

Dethof, A. (2003). Assimilation of ozone retrievals from the MIPAS instrument onboard ENVISAT. *ECMWF Tech Memo 428.*

Elbern, H., H. Schmidt, and A. Ebel, 1997: Variational data assimilation for tropospheric chemistry modelling. *J. Geophys. Res.*, **102**, 15967-15985.

Errera, Q., and D. Fonteyn (2001). Four-dimensional variational chemical data assimilation of CRISTA stratospheric measurements. *J. Geophys. Res.*, **106**, 12253-12265.

Eskes, H.J, P.F.J. van Velthoven, P.J.M. Valks, and H.M. Kelder (2003). Assimilation of GOME total-ozone satellite observations in a three-dimensional tracer-transport model. *Q. J. R. Meteorol. Soc.*, **129**, 1663-1681.

Fisher, M., and D.J. Lary (1995). Lagrangian 4-dimensional variational data assimilation of chemical species. *Q. J. R. Meteorol.Soc.,* **121**, 1681-1704.

Hólm, E., E. Andersson, A. Beljaars, P. López, J-F. Mahfouf, A. Simmons, and J.-N. Thépaut (2002). Assimilation and modelling of the hydrological cycle: ECMWF's status and plans. *ECMWF Tech Memo 383*.

Khattatov, B.V., J.C. Gille, L.V. Lyjak, G.P. Brasseur, V.L. Dortsov, A.E. Roche, and J.W. Waters (1999). Assimilation of photochemically active species and a case analysis of UARS data. *J. Geophys. Res.*, **104**, 18715-18737.

Lahoz, W.A. (2003). Research satellites. In *Data Assimilation for the Earth System*, NATO ASI Series, eds. R. Swinbank, V. Shutyaev and W.A. Lahoz. Kluwer, ISBN: 1-4020-1592-5.

Lahoz, W.A., R. Brugge, D.R. Jackson, S. Migliorini, R. Swinbank, D. Lary, and A. Lee (2004): An Observing System Simulation Experiment to evaluate the scientific merit of wind and ozone measurements from the future SWIFT instrument. *Q. J. R. Meteorol. Soc.*, accepted subject to revision.

Lahoz, W.A., R. Brugge, S. Migliorini, D. Lary, A. Lee, R. Swinbank, and D. Jackson (2003a). *SWIFT – Application of Stratospheric Wind Measurements to Process Studies and Meteorology*. Final Report, March 2003, ESTEC Contract No. 15344/01/NL/MM.

Lahoz W.A., S. Migliorini, R. Bannister, R. Brugge, and A. O'Neill (2003b): Evaluation of Envisat data using a NWP system: A vortex-centred view. ESA Special Publication SP-531. Available from: http://envisat.esa.int/pub/ESA_DOC/envisat_val_1202/proceedings

Struthers, H., R. Brugge, W.A. Lahoz, A. O'Neill, and R. Swinbank (2002). Assimilation of ozone Lamarque, J.-F., B. Khattatov, and J. Gille (2002). Constraining tropospheric ozone through data assimilation. *J. Geophys. Res.*, **107**, 10.1029/2001JD001249.

Prunet, P., J.-N. Thépaut, and V. Cassé (1998). The information content of clear-sky IASI radiances and their potential for numerical weather prediction. *Q. J. R. Meteorol. Soc.*, **124**, 211-241.

Štajner, I., L.-P. Riishøjgaard, and R.B. Rood (2001). The GEOS ozone data assimilation system: Specification of error statistics. *Q. J. R. Meteorol. Soc.*, **127**, 1069-1094.

Stratospheric Processes and their Role in Climate (SPARC) (2000). SPARC Assessment of upper tropospheric and lower stratospheric water vapour. WCRP-113, WMO/TD No. 1043, SPARC Report No. 2, eds D. Kley, J.M. Russell III and C. Phillips.

profiles and total column measurements into a global general circulation model. *J. Geophys. Res.*, **107**, 10.1029/2001JD000957.

Swinbank, R., N.B. Ingleby, P.M. Boorman, and R.J. Renshaw (2002). A 3D variational data assimilation system for the stratosphere and troposphere. *Forecasting Research Scientific Paper No. 71, Met Office*.

Talagrand, O. (2003). A posteriori validation of assimilation algorithms. In *Data Assimilation for the Earth System*, NATO ASI Series, eds. R. Swinbank, V. Shutyaev and W.A. Lahoz. Kluwer, ISBN: 1-4020-1592-5.

Thépaut, J.-N. (2003). Assimilation of remote sensing observations in Numerical Weather Prediction. In *Data Assimilation for the Earth System*, NATO ASI Series, eds. R. Swinbank, V. Shutyaev and W.A. Lahoz. Kluwer, ISBN: 1-4020-1592-5.

World Meteorological Organization (WMO) (2000). Proceedings of the Second CGC/WMO Workshop on the Impact of Various Observing Systems on Numerical Weather Prediction. WMO/TD No. 1034, eds. J. Pailleux and H. Böttger.

Recent OSE studies with the revised CMC 3D-Var system in hybrid coordinates with lid at 0.1 hPa

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1. Introduction

The CMC operational global forecast system is continuously being updated to improve its ability to assimilate current data sources and to be ready to assimilate the affluence of new satellite data types. There were many updates to the CMC 3D-Var during the last three years; first the direct assimilation of ATOVS radiances (Chouinard et al. 2001), secondly, the major revision of December 2001 described in Chouinard et al. 2002, and in this publication by Verner et al. 2004 and, most recently, the implementation of AMSU-B radiance data (Chouinard and Hallé, 2003). This latest version was the backbone for the development of what will de referred to as the stratospheric version used in this study.

The radiative transfer for ATOVS needs an atmospheric state vector that extends to 0.1 hPa and, because our NWP model has a top lid condition at 10 hPa, it is necessary to extrapolate the profiles of moisture and temperature between 10 and 0.1 hPa. This has been a concern for the satellite data assimilation group because it has a detrimental effect on the analyses that is most noticeable when higher peaking channels are assimilated. This is why AMSU-A channels 11-14 are not currently assimilated as they peak above the current model top level at 10 hPa.

The top lid condition has also been a concern to our modeling group as it also adversely affects the lower stratosphere large scale dynamics. Recently S. Edouard et al. (2004) designed and tested a new hybrid coordinate system for the current operational global forecast model keeping the lid at 10 hPa. The advantages of the hybrid coordinate are well known and allow for a smoother transition from terrain following to a purely isobaric coordinate system in proximity to the top. As they were able to show, this coordinate has very positive impacts on short term forecasts particularly over high topography such as over Western Canada and Asia.

In a first phase of the design of the stratospheric Data Assimilation System (DAS), the forecast model was fitted with a fully revised hybrid vertical coordinate and the top lid condition raised to 0.1 hPa in order to accommodate the radiative transfer model used to assimilate ATOVS radiances. The impact of raising the top lid to 0.1 hPa was very beneficial on 10-day forecasts initialized with initial conditions prepared from CMC analyses extended in the stratosphere using the Met Office stratospheric analyses. The same analyses were subsequently used to prepare an ensemble of 24 and 48-h forecasts to arrive at first estimates of background error statistics in this new hybrid coordinate with lid at 0.1 hPa.

In the second phase, the hybrid coordinate was introduced in the 3D-Var analysis system. The use of data at and above 10 hPa was completely revised, and data which had previously been blacklisted or simply not used, were re-introduced. Higher peaking radiances that had never been assimilated as they peaked above 10 hPa were finally introduced. After many trials and adjustments, in particular related to the assimilation of radiosonde moisture data, the 3D-Var stratospheric system produced quality analyses.

Finally, a set of OSEs was prepared with the current operational and the new stratospheric analysis/forecast system to 1), measure the impact of denying AMSU-B data in each of the systems and 2), a separate set of OSEs to measure the impact of denying radiosonde data above 100 hPa in the same two analysis systems.

2. Stratospheric model description

The model used in this study differs from the operational CMC model in that it has a lid that was raised from 10 hPa to 0.1 hPa. The hybrid vertical coordinate was introduced in the model as it is very beneficial in reducing and controlling noise particularly in proximity to steep topography. The number of levels in this hybrid coordinate system was increased from the current 28 to 80 levels. This gives an effective resolution of better than 600 m in the 1000-100 hPa layer, 1500 m in the 10-100 hPa layer and finally 5000 m from 10-0.1 hPa. The large number of levels in the troposphere has been necessary to stabilize the cloud parameterization scheme and its impact on the radiative balance. The horizontal resolution of the model remains 100 km as the operational global model. With the exception of the radiative transfer, the model physics of the stratospheric system remains about the same as the current operational global model.

3. Stratospheric 3D-Var description

The hybrid coordinate was also introduced in the 3D-Var system and the top raised from 10 to 0.1 hPa. The new vertical coordinate has been coded such as to support the current 28-level η coordinate and another variant of the hybrid used by the climate modeling group in Toronto (CMAM). As in the current operational system, the analyses are produced directly on the hybrid levels and no vertical interpolation is needed to initialize the forecast model.

First results with the stratospheric analysis system revealed serious deficiencies with the upper level moisture analyses. The specific humidity at and above 100 hPa was in some areas significantly higher than acceptable climatologic extremes. After careful investigation, it was shown that the use of radiosonde moisture data above 200 hPa was in some areas very problematic (large areas close to saturation for many weeks) and should be avoided. We first decided to blacklist the moisture data from radiosondes over Russia, Siberia, and China, but in the final version, after careful examination, all radiosonde data above 200 hPa were blacklisted. Since a large part of the signal of the AMSU-B radiances, is effectively in proximity to the 200 hPa, particularly in the lower latitudes, the influence of these data can extend as high as and above 100 hPa. As an added control on the moisture, the moisture of the final analyses are constrained to the same climatological extremes (min and max) that are used by the radiative transfer model (RTTOV7) for the assimilation of AMSU-A and AMSU-B radiances.

Because the lid of the stratospheric model is at 0.1 hPa, AMSU-A channels 11-14 of the NOAA series were finally introduced in the analysis system. These channels are currently withheld in the operational system as they peak above the current model top level. A bias correction algorithm was developed for the full set of AMSU-A and AMSU-B radiances used in the stratospheric system.
Background error statistics were obtained from 24-48 h forecasts initialized with CMC analyses extended in the stratosphere using the Met Office stratospheric analyses. These were subsequently revised based on first analysis cycles.

4. Validation of the stratospheric 3D-Var system from first analysis cycles

The analysis and trial fields of two-month cycles with the stratospheric system were evaluated with the usual comparison to quality-controlled radiosonde data. As shown in Fig. 1, the trial fields in the lower stratosphere and upper troposphere were significantly improved.

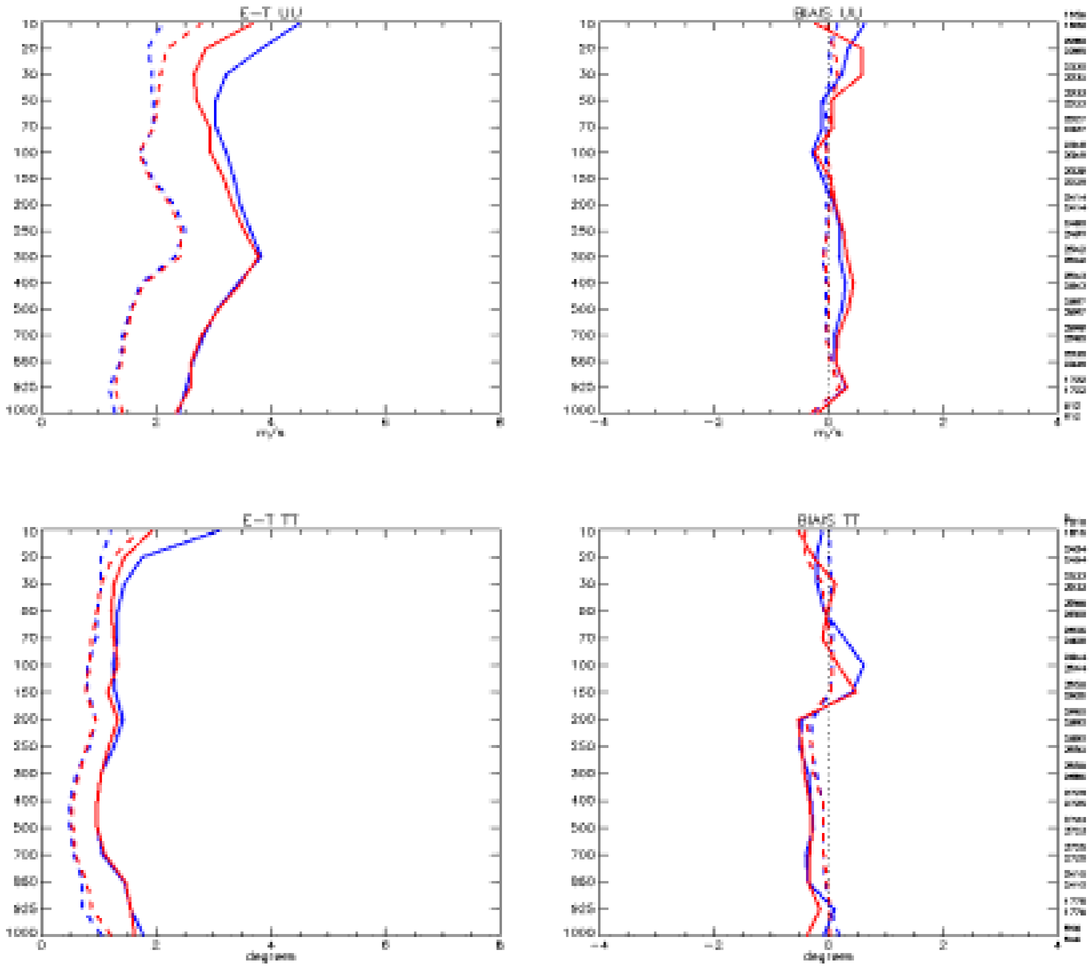

Figure 1. RMS (left) and BIAS (right) errors of observed – trial (O-P) (full) and observed – analysis (O-A) (dashed) against NH radiosondes. The blue lines are for OPERATIONAL with lid at 10 hPa, and the red lines for the STRATOSPHERIC system with lid at 0.1 hPa. Results are for the months of January and February 2002. Units are degrees and m/s.

In Fig. 2, the 10-day forecasts prepared with the final stratospheric system are also evaluated against quality-controlled radiosonde data. The improvements in the stratosphere are very large as indicated but remain mostly above the tropopause. The improvements are very significant for winds, temperature, and geopotential. The temperature bias at the lid is much improved. Given these results, the model was judged appropriate to undertake the set of OSEs presented in the next section.

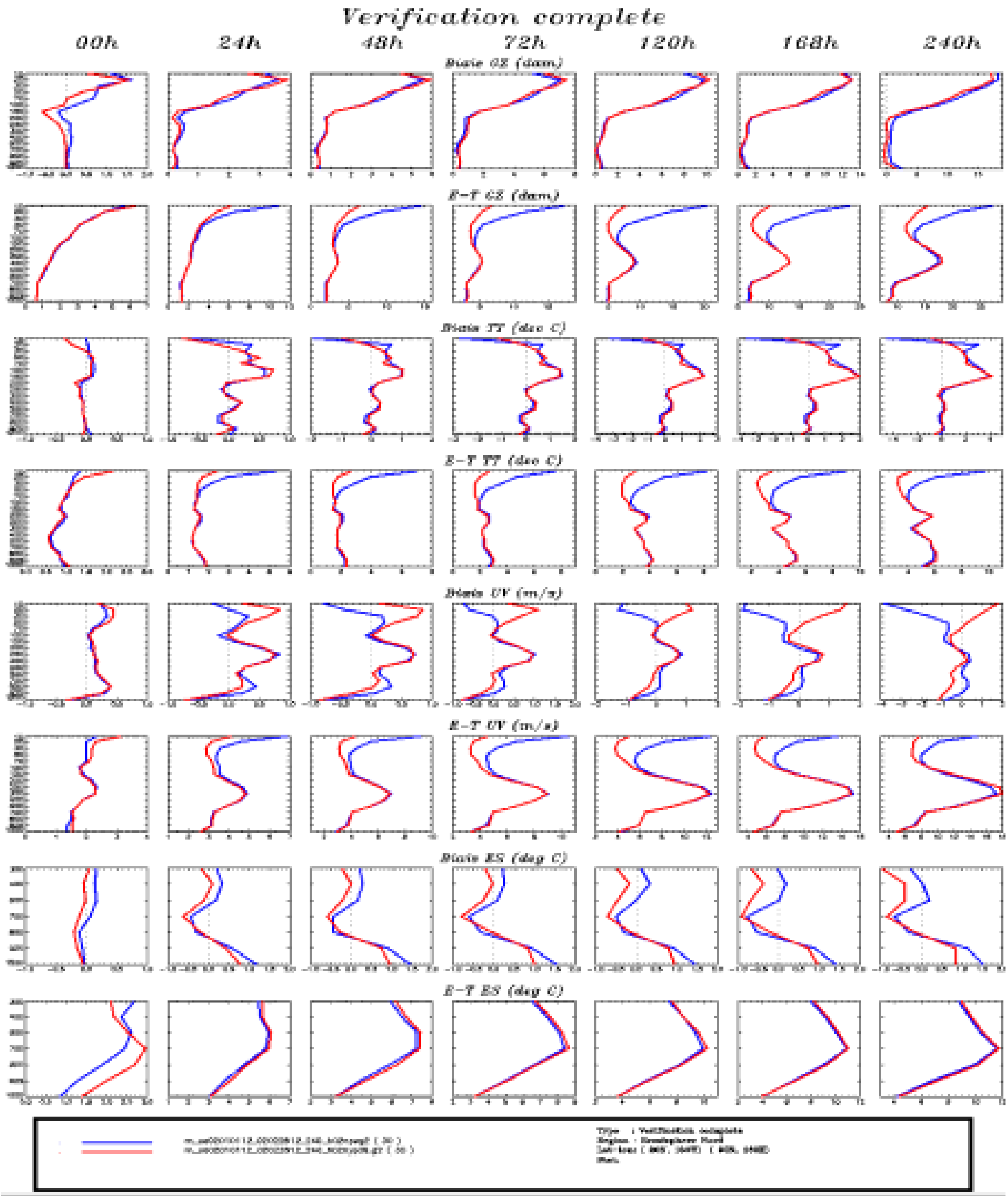

Figure 2. BIAS and STD) errors against Northern Hemisphere radiosondes for the 00, 24, 48, 72, 120, 144, 168, and, 240-h forecasts of geopotential (top 2 rows), temperature (next two rows), winds (next two rows), and dew point depression (last two rows). The blue lines are for OPERATIONAL with lid at 10 hPa, and the red lines for the STRATOSPHERIC system with lid at 0.1 hPa. Results are for January and February 2002. Vertical axis same as Fig 1, and units are degrees and m/s.

5. Experimental setup for the OSEs; results

Assimilation and forecast experiments have been performed in order to investigate the impact of different observation configurations pertaining to the stratosphere. The observing systems tested were ATOVS radiances (AMSU-A and AMSU-B), cloud drifts or water vapor atmospheric motion vectors (AMV), GOES 6.7 radiances, aircraft, radiosonde, and surface observations. In this study, the control run is the CMC operational 3D-Var assimilation system as of June 2003 which includes moisture sensitive radiances from AMSU-B and GOES 6.7, using a long cut-off time (version of the global system following the Dec 2001 implementation). In accordance with recommendations from the previous workshops, as well as from the CAS-WGNE, attempts were made to select sufficiently long periods, and to include some estimate of the statistical significance of the results. The evaluation was done for 10 “winter” weeks: 22 Dec. 01 – 28 Feb. 2002; every 36h. During this period, we ran 10-day forecasts twice a day at 00 and 12 UTC, from the final analyses of the modified assimilation cycle.

A total of 6 experiments were performed, identified, and color coded according to the following nomenclature:

CNTRL the reference, it is the control done with each of the operational and stratospheric systems, using all data with long cut-off time. These are labeled TROPO and STRATO respectively.

NORAOB100 is the control minus the RAOB above 100 hPa, one for each of the operational and stratospheric systems, labeled TROPO and STRATO respectively.

NOAMSU-B is the control minus the AMSU-B radiances from NOAA15 and NOAA 16, one for each of the operational and stratospheric systems, labeled TROPO and STRATO respectively.

The impact of different observing systems was evaluated over both data-rich (North America and Northern Hemisphere) and data-poor (Tropics and Southern Hemisphere) areas. For a more complete evaluation, verification against observation as well as against analyses has been performed. The evaluation against observation is done by comparing analyses and forecasts to a (common) global set of quality controlled radiosonde observations, and according to the WMO recognized standards. The verification against analyses has also been done according to the WMO standards, with one exception. Usually, when evaluating impacts of modifications to the operational NWP systems, each system (operational and parallel suites) is verified against its own analyses. However, in the context of data impact studies, it is believed that a more accurate representation of the impact of each data type is obtained when the analyses of highest quality are used to perform the verification. In our situation, these were the control analyses.

As in Zapotocny et al. (2002), the OSE results are expressed in terms of the so-called FI index expressed as;

FI = 100 x (RMS experiment - RMS control) / RMS control

The RAOB denial above 100 hPa OSE results can be best summarized by looking at levels 10 and 50 hPa FI scores. As shown in Fig. 3, the operational tropospheric version (blue) is very significantly degraded by the RAOB denial much more so than the stratospheric version (black) because the latter uses upper-peaking radiances. The temperatures are more affected than the winds, and even the stratospheric version winds are affected. In the Tropics, the 50 hPa winds and temperatures are very negatively affected. Same is true in the SH, and one can safely say that over all regions either winds or temperatures are much degraded.

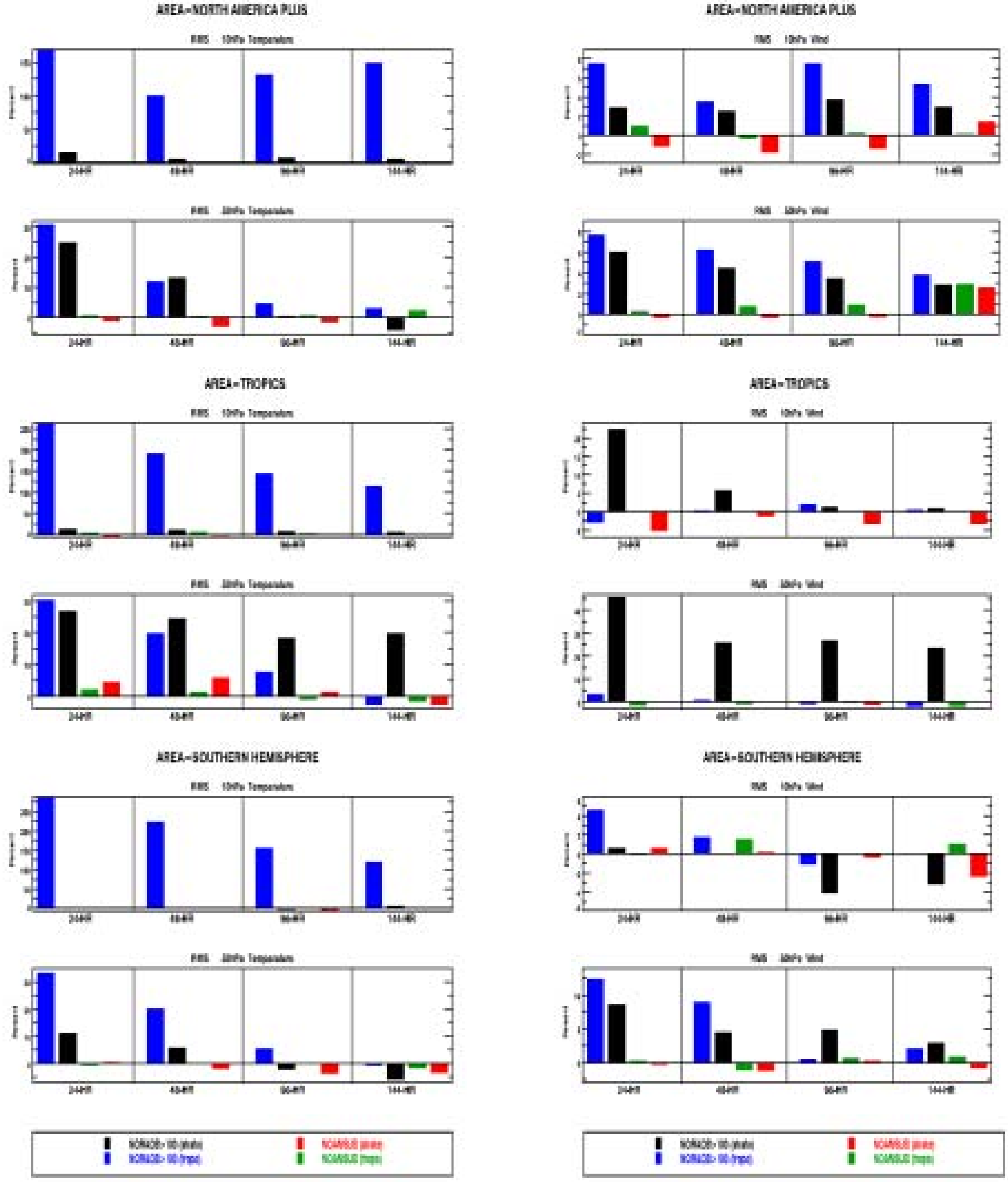

Figure 3. Forecast impact (%) for 10 and 50 hPa TT (left) and winds (right) for the two experiments: NORAOB100 (blue and black), and the two experiments NOAMSUB (green and red). Forecast periods are: 24, 48, 96 and 144 hours. Top two panels for NA, middle two for TROPICS, and bottom two for the SH.

The AMSU-B denial OSE results can best be summarized by looking at levels 250, 500 and, 850 hPa. The results for NA and the Tropics clearly indicate that the shorter term forecasts of temperature and winds are not affected but the denial has a progressively larger impact at day 4 and day 6.

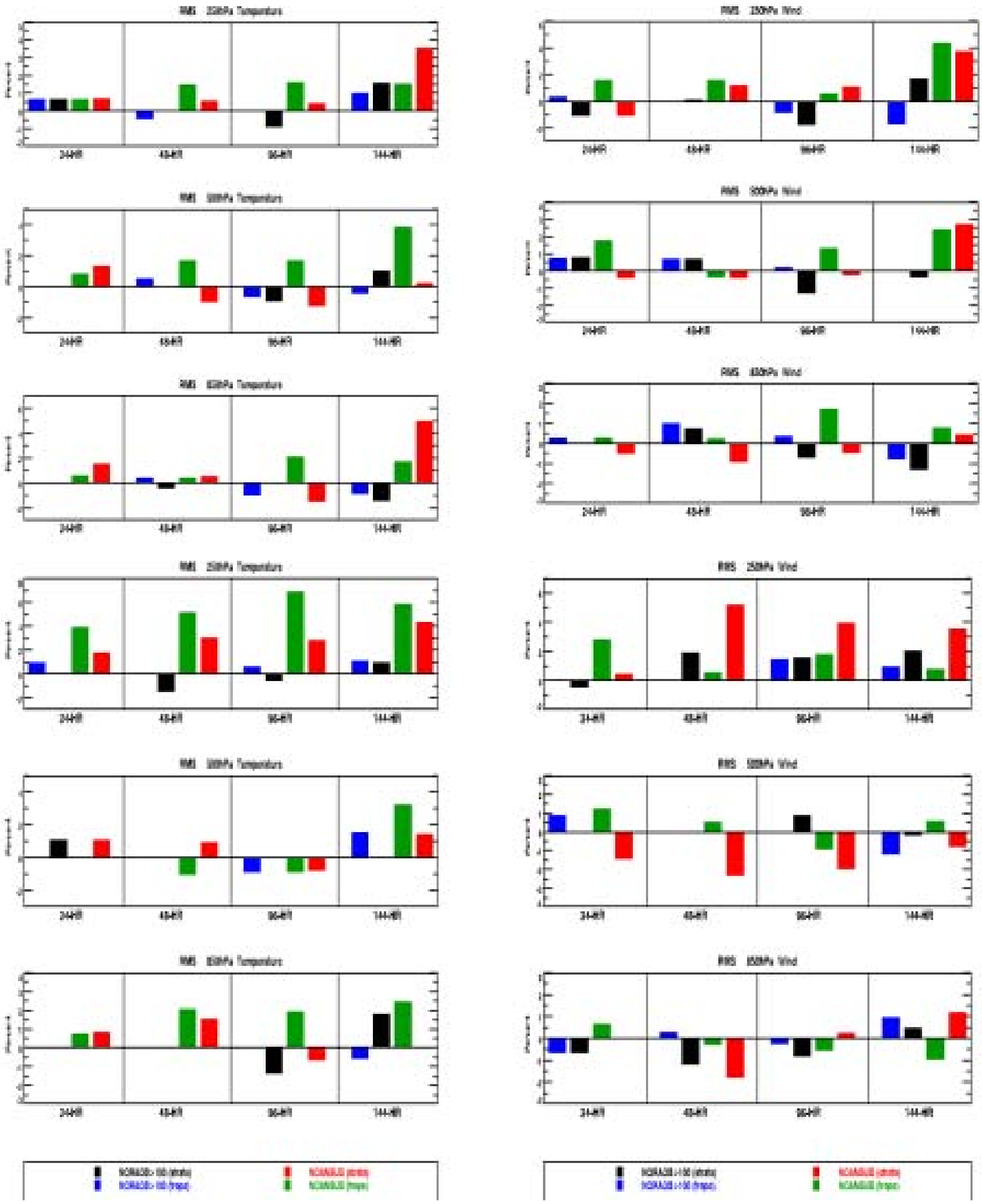

Figure 4. Same as Fig 3 but for levels 250, 500, and 850 hPa. Only the NA (top three rows) and TROPICS (bottom three rows) are shown. Color code is the same as Fig. 3.

Anomaly correlation scores for the SH are very interesting in that they show a very large impact at the higher 100 hPa level and generally less below the tropopause. Exceptionally, the impact of denying RAOB data above 100 hPa has a significant impact at 500 hPa particularly after day 3.

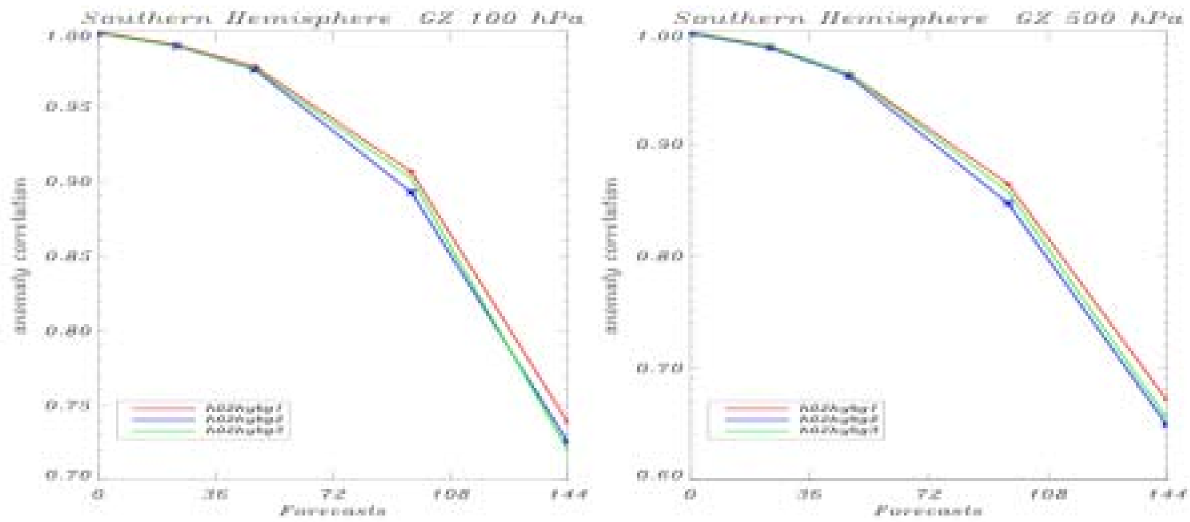

Figure 5. 6-day GZ anomaly correlation scores at 100 hPa (left) and 500 hPa (right) over SH for the stratospheric CNTRL (red), NORAOB100 (green), and the NOAMSUB (blue) experiments.

6. Conclusions

A stratospheric analysis system has been developed and the first results presented in this study are of very good quality. Major problems were resolved although some minor ones remain, but the system was certainly appropriate for experimenting with data denials.

The denials of radiosonde data in the OSEs of the 80-level stratospheric and 28-level operational systems have major negative impact above 100 hPa particularly in the short term 48-h forecast range. The presence of high-peaking AMSU-A radiances in the stratospheric system makes the stratospheric system more robust for temperature but the winds are still negatively affected by the denial. The long term impact although mostly trapped above the tropopause is not negligible below as indicated by 500 hPa anomaly correlation scores in the SH.

Similarly the denials of AMSU-B radiances from the 80-level stratospheric and 28-level operational systems show large but yet different negative impacts in each system. The direct impact on the moisture variable is most evident in the first 48 hours and very small afterwards. The negative impact on the wind and temperature gets progressively larger later in the forecast particularly by day 4 and beyond. Interestingly, the impact of AMSU-B has a non-negligible in the lower stratosphere.

References

Chouinard, C., C. Charette, J. Hallé, P. Gauthier, J. Morneau, R. Sarrazin, 2001: The Canadian 3D-VAR Analysis Scheme on Model Vertical Coordinate**,** *Proc. AMS 14th Conference on Numerical Weather Prediction,* 30 July–2 August, Fort Lauderdale, Florida, pp. 14-18.

Chouinard C., J. Hallé, C. Charette, and R. Sarrazin: Recent improvements in the use of TOVS satellite radiances in the Unified 3D-Var system of the Canadian Meteorological Centre. ITSC XII proceedings, Lorne, Australia, 27 February-March 5, 2002.

Chouinard, C, J. Hallé, 2003: Use of moisture sensitive satellite radiances in the Canadian Meteorological Centre Unified 3D-var system. *Proc. SPIE Int. Soc. Opt. Eng. 4895 Applications with Weather Satellites*, pp 63-74.

Chouinard, C, J. Hallé, 2003: The assimilation of AMSU-B radiances in the CMC global data assimilation system; their difficulties relative to AMSU-A radiances and their impact. ITSC XIII proceedings, Ste-Adele, Quebec, Canada, 29 October-November 4, 2003.

Edouard, S., S. Gravel, B. Dugas, and M. Roch: The use of a hybrid coordinate in the CMC-MRG Global Environmental Multiscale (GEM) Model. Submitted to MWR, March 2004.

Gauthier, P., C.Charette, L.Fillion, P.Koklas and S.Laroche, 1999: Implementation of a 3D variational analysis at the Canadian Meteorological Centre. Part I: The global analysis. *Atmosphere-ocean*, **37**, 103-156.

Undén, P., Kelly, P., Le Meur, D. and Isaksen, L., 1997: Observing system experiments with 3D-Var assimilation system: ECMWF Research Department Technical memorandum, **244,** Available from ECMWF, Shinfield Park, Reading RG29AX, UK.

Verner, G., R. Sarrazin, and Y. Zaitseva: Data impact studies in the CMC global NWP system. Third WMO Workshop on the Impact of Various Observing Systems on NWP Alpbach, Austria, 9 – 12 March 2004.

Zapotocny Tom H., W. Paul Menzel, James P. Nelson III and James A. Jang, 2002: An impact study of five remotely sensed and five in situ data types in the eta data assimilation system. *Bull. Amer. Meteor.Soc.*, **4**, 263-285.

Observation System Experiments using the JMA Mesoscale Four-dimensional Variational Assimilation System

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1. Introduction

One of the most important targets of mesoscale numerical weather prediction (NWP) is precise prediction of heavy rainfalls. The Japan Meteorological Agency (JMA) has been operating a mesoscale model (MSM) with horizontal resolution of about 10km to forecast mesoscale events over the Japan Islands (JMA, 2002).

It is widely known that accuracy of short-range NWP are largely affected by accuracy of the initial condition. In order to improve the accuracy of initial condition, JMA mesoscale four-dimensional variational assimilation system (Meso 4D-Var) was implemented in place of the previous system using an optimum interpolation scheme (Ishikawa et al., 2004). By the implementation of Meso 4D-Var, it has become possible to assimilate various kinds of observational data which could not be assimilated by the optimum interpolation scheme. Especially, accumulated values through time such as precipitation amount can be directly assimilated for the first time by a 4D-Var system.

In this paper, results from several kinds of observation system experiments (OSEs) using Meso 4D-Var are presented. The model and assimilation system are briefly described in Section 2. Experiment design and data description are presented in Section 3 where observation error setting and other data-specific issues are also discussed. In Section 4 the results from the experiments are presented. Section 5 provides concluding remarks.

2. Model and assimilation system

The MSM is a hydrostatic spectral model with a horizontal resolution of 10 km and 40 vertical levels up to 10 hPa. The lateral boundary condition is provided by a regional spectral model (RSM) with a horizontal resolution of 20 km starting from initial conditions at 00 and 12 UTC. The initial condition of MSM is prepared by Meso 4D-Var with 3-hour assimilation windows. The cost function of Meso 4D-Var system consists of a background term, observation terms and a penalty term for reducing gravity wave noise. The control variables are the initial and boundary conditions of unbalanced wind, temperature, surface pressure, and specific humidity. The background error statistics are obtained by using the NMC method. The horizontal background error correlation is assumed to be homogeneous and of Gaussian type to reduce memory requirement (cf. Ishikawa et al. 2004).

An incremental method is taken for reducing computational time. The forward model in this system has the same architecture as the forecast model (viz. MSM) except that its horizontal resolution is reduced to 20km. The adjoint model has the same dynamical process as the forward model while its physical processes include moist processes, boundary layer processes, long-wave radiation and horizontal diffusion only.

In the experiments in this paper, observational data from radiosondes, land surface stations, ships, buoys, aircraft, wind-profilers, atmospheric motion wind from geostationary meteorological satellites, NESDIS-retrieval temperature and relative humidity of TOVS as well as the radar-AMeDAS precipitation data (see subsection 3.1 for details) were assimilated to the system unless mentioned otherwise. An assimilation window length is set to three hours due to the limitation of computational resources. Since forecast model runs are conducted six-hourly, two consecutive 3-hour assimilation windows are set before each initial time. The observation terms of the cost function is evaluated hourly in the 4D-Var calculation. Hence all observations between -30 and +29 minutes to the clock time are regarded as observations at the clock time.

3. Data

3.1. Precipitation amount

The JMA has 20 operational C-band radars and about 1,300 automatic surface weather stations called AMeDAS. Using those observations, a multi-sensor precipitation nowcasting product is made as follows: First, radar echo intensity is converted to precipitation rate using the Z-R relationship $Z = 200R^{1.6}$. Then, the estimated precipitation rate is averaged over eight observations during one hour to produce an estimate of one-hour precipitation amount. Finally, the estimated amounts are calibrated using ground-based rain-gauges to provide one-hour precipitation amount distribution all over Japan and surrounding area with 2.5 km resolution (cf. Makihara, 2000). This nowcasting product is called "radar-AMeDAS precipitation analysis", whose grid point values are up-scaled to inner-model grids (20km) to be assimilated by Meso 4D-Var.

Since the precipitation amount has quite different error probability distribution from other elements such as temperature or wind speed, the Gaussian type cost-function is not appropriate for precipitation. Figure 1(b) shows scatter diagram of first-guess values of one-hour precipitation and departures of observation from first-guess. It is not symmetrically distributed around zero departure as in the case of temperature at 500hPa (Fig.1 (a)). If a small constant value like 1 mm/hour is given as observation error, observation cost of heavy rain becomes so large that dynamical balance in the analysis field might be corrupted in the process of reducing the observation cost. Even though precipitation distribution within the assimilation window can show good agreement with observations by employing such small observation error, the improvement in the precipitation forecasts is usually very small. On the other hand, if a large constant value like 10 mm/hour is given as the error value, small rain areas in the observation make almost no contribution to the analysis increment.

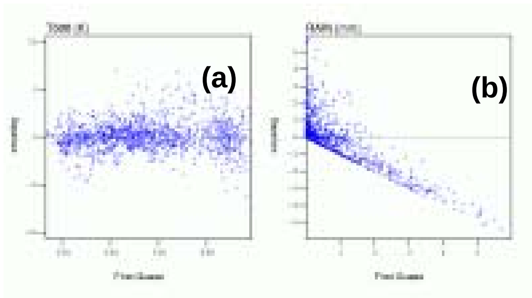

Fig. 1 scatter diagram of first-guess value and departure of observation from first-guess. (a) temperature at 500hPa, (b) one-hour precipitation amount.

Hence the cost-function for precipitation amount is devised as follows. First, probability density distribution of precipitation is assumed to follow the exponential distribution that is suggested from Fig. 1(b).

$$p(y \mid x) = \frac{1}{x}\exp(-\frac{y}{x}) \qquad (1)$$

where y denotes observed value and x denotes true model state.

Then the observation cost function can be obtained from the probability density function according to the maximum likelihood method as:

$$J_{rain} = -\log(p(y \mid x)) = \log(x) + \frac{y}{x} \qquad (2)$$

However, this formulation is not appropriate to be used in minimization algorithms that require gradient of the function because the gradient becomes too large when x approaches to zero. Since it is generally more preferable that the cost function has a quadratic form for the stability of minimizing process, Taylor expansion of the above function is made around its minimum point (x=y)

$$J_{rain} = 1 + \log(y) + \frac{1}{2y^2}(x-y)^2 + O((x-y)^3) \quad (3)$$

If truncated at the second order of (x-y), the function becomes Gaussian type with the observation error equal to y.
On the other hand, the original cost function (2) is not symmetric around its minimum point (fig. 2) which means that the observation error is assumed smaller in the case of x<y than in the case of x>y. This asymmetricity is also suggested from Fig. 1(b).

Considering these properties, we practically define the cost function as follows:

$$J_{rain}(x) = \frac{1}{2r^2}(x-y)^2,$$

where

$$r = \begin{pmatrix} r_c & (x \le y) \\ 3r_c & (x > y) \end{pmatrix}.$$

When y<1mm/h, r_c is a forecast error of precipitation (constant value) which is previously calculated for observation less than 1mm/h. Otherwise r_c is proportional to observed precipitation amount.

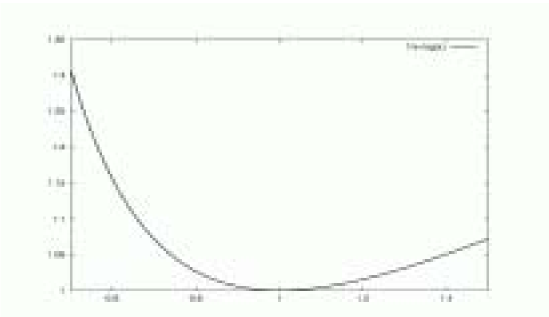

Fig. 2 Function (2) around its minimum point in the case of y=1

Using this cost-function for precipitation amount, a three-hourly forecast-analysis cycle experiment was performed during June 2001 with and without precipitation amount data and 18-hour forecasts were made four times a day at 00, 06, 12 and 18 UTC. In this experiment, wind-profiler wind was assimilated but SSM/I, TMI and Doppler radar radial velocity were not.

3.2. SSM/I and TMI : rain-rate and precipitable water

Rain rate (RR) and total column precipitable water (TCPW) data were retrieved from TMI and SSM/I data. TMI and SSM/I are satellite-borne microwave imagers. While some NWP centers assimilate the brightness temperature of SSM/I directly into the NWP models with a radiative transfer model, the retrieved RR and TCPW were used in this study to reduce the computational cost.

There are a number of methods proposed about retrieving RR and TCPW from TMI and SSM/I; e.g., Shibata(1994), Kummerow(1997). For this operation, the MSC method developed by Takeuchi and Kurino (1997) was employed. It is a simple statistical method and, therefore, the computational cost is affordable for the operational system, though the method is available only over the ocean.

Since the correlation of RR with radar-AMeDAS data is not so high (0.59) and RR is assimilated as the hourly rainfall data instead of instantaneous rain rate, the observational error of RR is set twice as large as the error of radar-AMeDAS data.

In contrast to RR, TCPW showed a good correlation with the value calculated from upper air sounding data (0.98). The observation error of 5mm is used. TCPW data is thinned to one data in a 40km by 40km area.

RR and TCPW are complements to each other since TCPW is not obtained in rain area and RR is not obtained in rain free area. Since TCPW data provide information of the water vapor fields before it forms precipitation, addition of TCPW data is expected to bring positive effect to RR assimilation.

Two sets of forecast-analysis cycle experiments were performed: one was for only RR during 6th to 12th September 2001 and the other was for both RR and TCPW during 3rd to 16th June 2003. In both experiments, wind-profiler wind and radar-AMeDAS precipitation amount were assimilated but Doppler radar radial velocity was not.

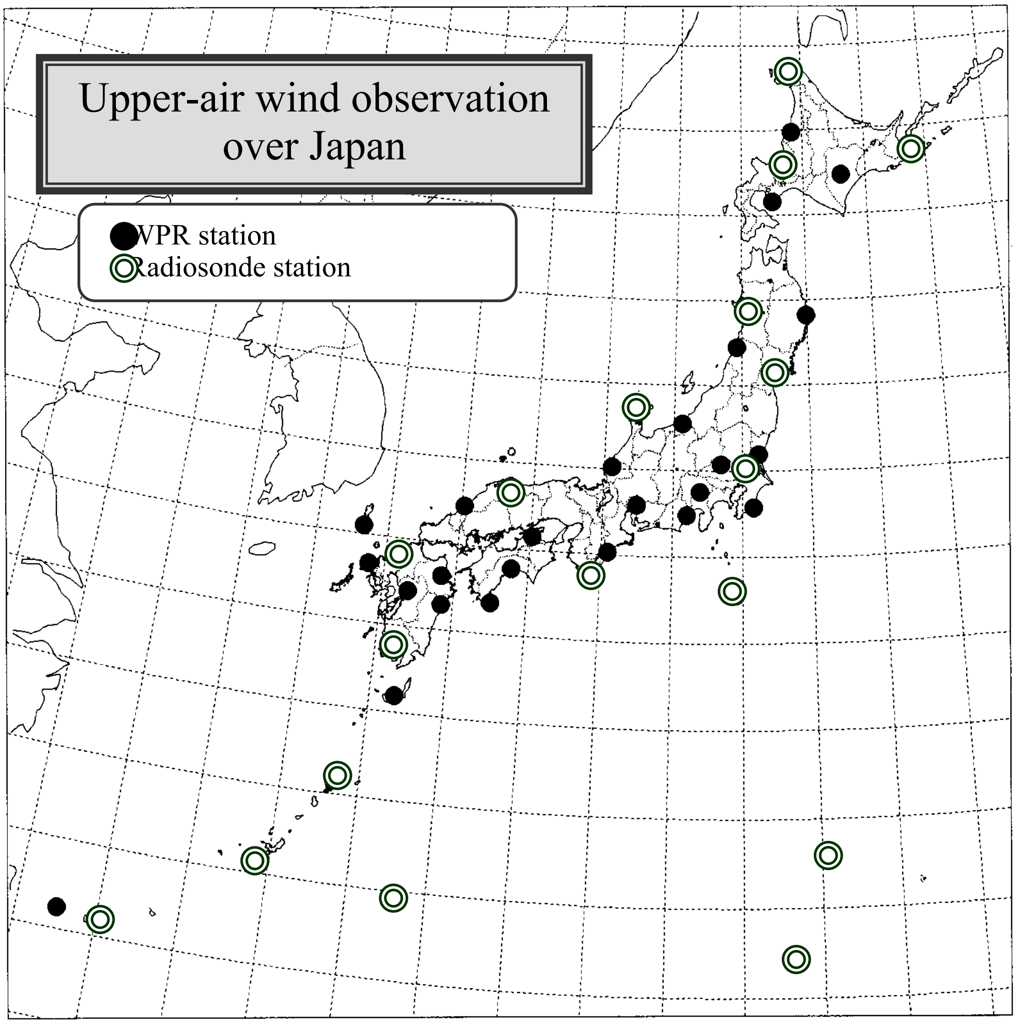

Fig. 3 Twenty-five WPR stations (black circles) were implemented in March 2001 in order to complement radiosonde observation (stations are shown by double circles).

3.3. Wind-profiler wind

Twenty-five wind-profiler radar (WPR) stations were installed in March 2001 for operational wind observations over the Japan Islands (Fig. 3). These 1.3 GHz WPRs make observations of wind up to about 5000m every ten minutes with a vertical resolution of circa 300 m. In the assimilation, hourly data were used after being vertically thinned to about 600 m apart. Observation error for WPR data was assumed to be the same as radiosonde observation based on a preliminary evaluation (Kato et al. 2003).

The impact test of the WPR data was performed during the Baiu season of 2001. In the experiment the forecast-analysis cycle was not employed, but analyses were made at one or two initial times (12 and/or 18 UTC) every day from 13th June to 7th July with and without WPR data. First-guess of each analysis was provided from the operational MSM forecast at that time. In this experiment, precipitation amount was also assimilated, but SSM/I, TMI and Doppler radar radial velocity were not.

3.4. Doppler radar radial velocity

Six airports in Japan are installed with operational doppler-radars (Fig.4). Though the main purpose of the radars is aviational one, the radial velocity data are provided to the NWP system with a resolution of 5 km (radial distance) and 5.625 degree (azimuth angle). An experiment was made to assimilate the radial velocity data by Meso 4D-Var.

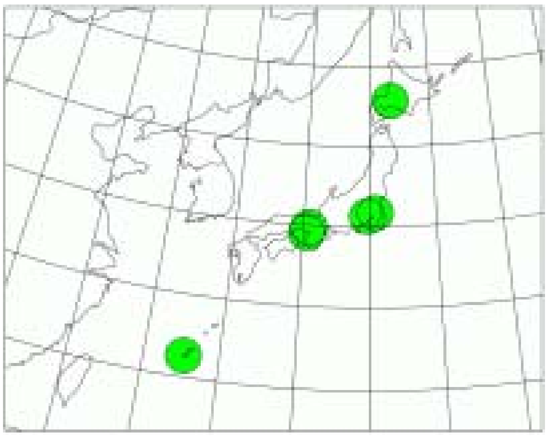

Fig. 4 Six doppler radars and their maximum ranges.

In order to avoid contamination from raindrops falling, data of the elevation angle larger than 5.9 degrees were not used. The data within 10km from a radar site were not used because of back-scattering noise. The provided radial velocity data are averaged values within a volume of 5 km x 5.625 deg., to which several information such as number of samples, standard deviation and max-min difference of wind-speed within each volume is added. Those additional information was used for quality-control. In the experiment, data were accepted when the following conditions are fulfilled.

1) the number of samples is above 10,
2) the standard deviation is below or equal to 10 m/s,
3) the max-min difference is below or equal to 10 m/s.

Moreover, data were removed when difference of observation from background value was larger than 10 m/s. Even though the quality-control procedure was applied, several data showed strange behavior. Figure 5 shows a scatter diagram of observation and background radial velocity of the radar at Kansai International Airport. The observation data between –5 m/s and 5 m/s show almost no correlation with background values. Such problematic data appeared also in other radars. The problem might be related to the land-echo removal procedure and is now being investigated. In the experiment, data between –5 m/s and 5 m/s were not used.

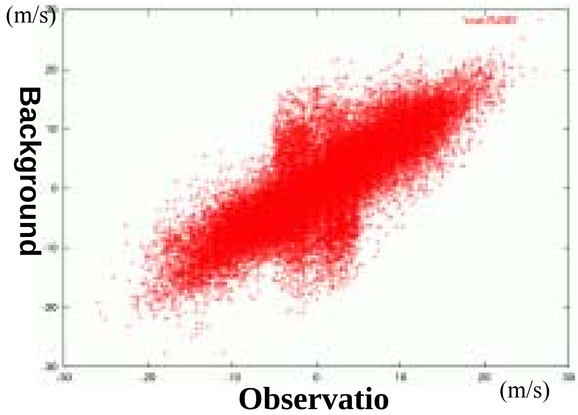

Fig. 5 Scatter diagram of observation and background value of radial velocity. The data of doppler-radar at Kansai International Airport during 10-12 Sep. 2003 are shown.

The data were thinned to about 20 km apart horizontally after the quality control process. The observation operator for radial velocity was constructed as follows:

1) *u*- and *v*- component of wind of background field at each model level were interpolated to the observation point
2) Since widened radar beam might cover several layers of model domain, background *u* and *v* at the height of beam-center were calculated assuming the beam intensity is a Gaussian function of distance from beam center:

$$u_b = \frac{\sum_{l=l1-2}^{l2+2} u_l \exp\{-(\frac{z_l - z}{r})^2\}}{\sum_{l=l1-2}^{l2+2} \exp\{-(\frac{z_l - z}{r})^2\}}$$

where u_b is a background value at beam center height, u_l is a background value at *l*-th model layer, z_l is height of *l*-th model layer and *z* is height of beam center. The beam center is in-between of l_1-th and l_2-th model layer. *r* denotes half of beam width when the angle of beam expansion is 0.3 deg. This method is slightly modified from the one employed in Seko et al. (2004).

3) radial component was calculated from u- and v- component at the observation point.

Three-hourly forecast-analysis cycle was performed with and without the radial velocity data in the following period: 1-3, 11-15 and 22-24 October and 2-5, 9-12, 19-20 and 24-29 November 2003 and 18-hour forecasts were made four times a day at 00, 06, 12 and 18 UTC. In this experiment, precipitation amount, SSM/I and TMI rain-rate and precipitable water and wind-profiler wind were assimilated.

4. Results

Since MSM is operated for prediction of hazardous weather, especially heavy rainfall, skill of precipitation forecast is most interested in. Hence the impact of each observation was mainly evaluated by scores of precipitation forecast.

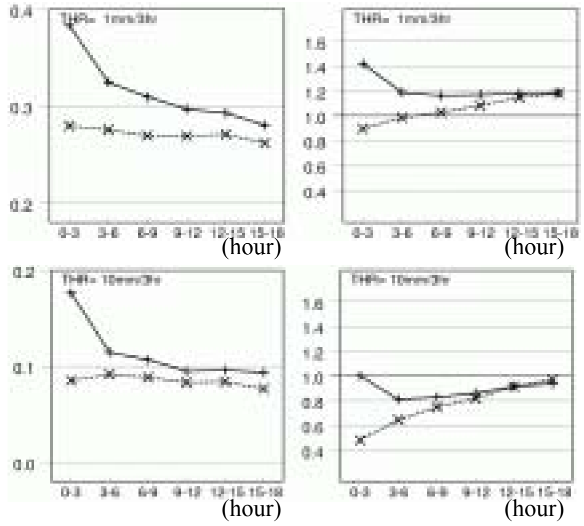

Fig. 6 Critical Success Index (left) and bias score (right) for 3-hour precipitation forecast starting from analysis with precipitation assimilation (solid line) and without one (dashed line). The threshold value is 1 mm per 3 hour (top) and 10 mm per 3 hour (bottom).

4.1. Precipitation amount

Figure 6 shows critical success indexes and bias scores of precipitation forecast over 1 mm per 3 hour and 10 mm per 3-hour with and without precipitation data assimilated. Assimilation of precipitation amount improves the forecasts throughout the 18-hour forecast time for both weak rain and moderate rain, though the impact is not so large except first three hours. The improvement of first few hours of forecast is achieved by ameliorating a model spin-up problem. Figure 7 shows that appearance rate of forecast precipitation is corrected to fit to observed one by assimilating precipitation data.

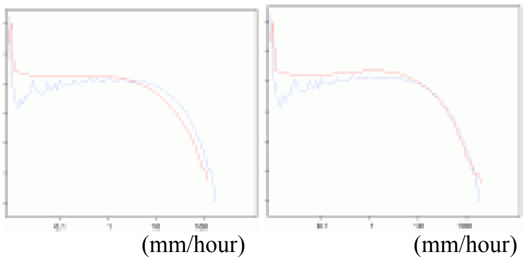

Fig. 7 Appearance rate of three-hour precipitation amount (log scale) calculated from the data of June 2001. Solid line is for forecast (ft=0-3) and dashed line is for observation. Left panel is without precipitation assimilation and right panel is with precipitation assimilation.

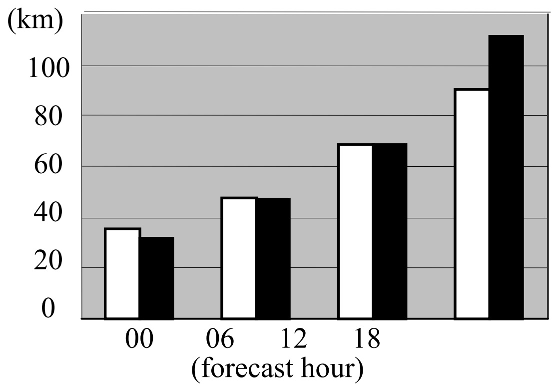

Fig. 9 Mean distance errors of the center positions of T0115 (Danas). White bars are of forecasts with SSM/I and TMI and black bars are of those without SSM/I and TMI.

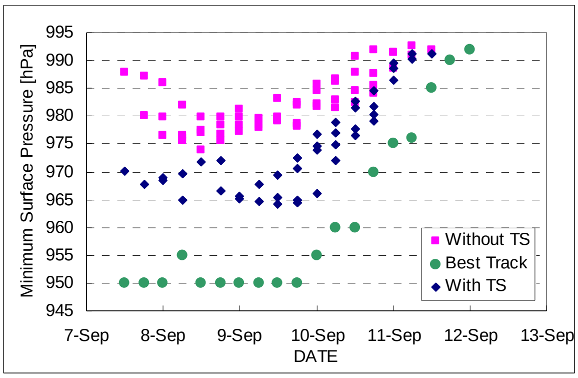

Fig. 8 Time sequences of center pressure of T0115 (Danas). Green circles are of the best track, pink rectangles are of forecasts without SSM/I and TMI and blue rhombi are of forecasts with SSM/I and TMI.

4.2. SSM/I and TMI : rain-rate and precipitable water

For the first experiment, track and intensity forecasts of Typhoon *Danas* (T0115) were verified (fig. 8 and 9). Assimilation of rain-rate from SSM/I and TMI improves the forecasts considerably, though the improvement is greatly reduced if the operational data cut-off time (e.g. 50 minutes) is applied (fig. 10).

For the experiment of assimilation of both rain-rate and precipitable water from SSM/I and TMI, critical success indexes for both 1 mm per 3 hours and 10 mm per 3 hours showed positive impact in the rainfall forecast after 12 hours (fig. 11). The result can be explained by that the water vapor field over ocean was improved with the additional data and it took several hours to flow over Japan islands.

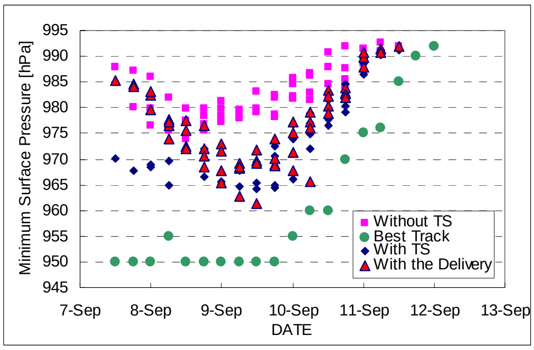

Fig. 10 Same as fig. 8 except additional red triangles, which show forecasts with SSM/I and TMI to which the strict data cut-off time was applied.

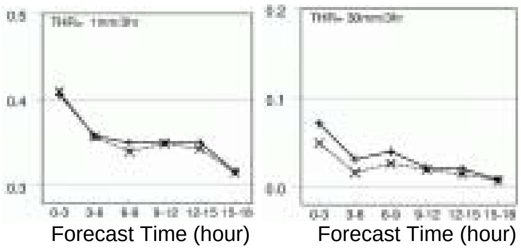

Fig. 12 Critical success index of precipitation forecast starting from analysis with WPR data (solid line) and without them (dashed line). The threshold value is 1 mm per 3 hour (left) and 30mm per 3 hour (right).

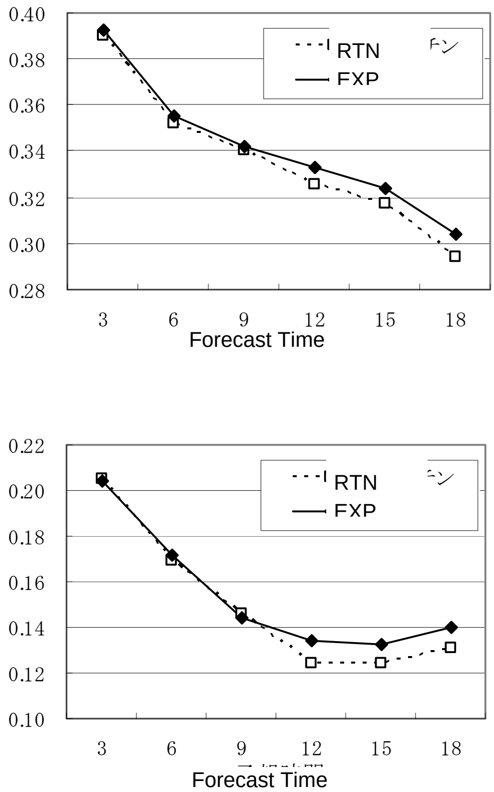

Fig. 11 The threat scores for weak (1mm/3hour; top) and moderate (10mm/3hour; bottom) rainfall forecasts. Solid lines are for forecasts with SSM/I and TMI and dashed lines are for those without SSM/I and TMI.

4.3. Wind-profiler wind

The impact of WPR data on precipitation forecast is positive though very small for 1 mm per 3-hour score (fig.12 left). The score for 30 mm per 3-hour (fig. 12 right) clearly shows improvement for first several hours though the statistical

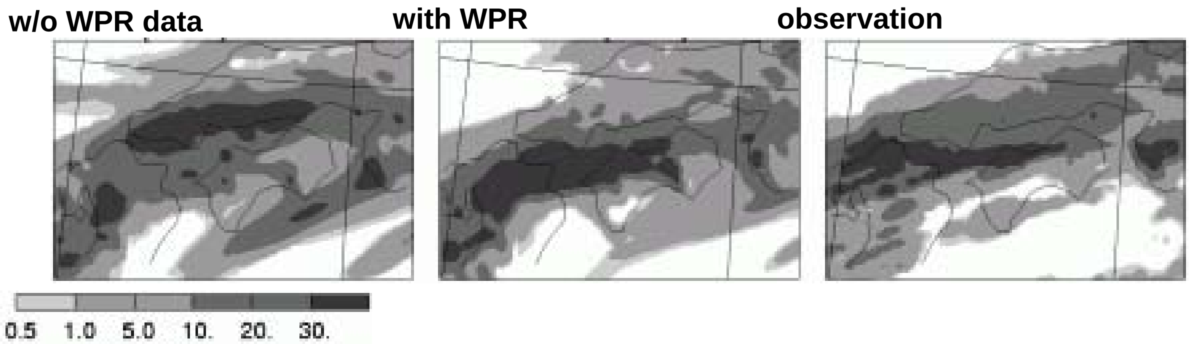

Fig. 13 Precipitation amount of 12 – 15 UTC 19th June 2001. Left panel: forecast from analysis at 12 UTC 19th June 2001 without WPR data, middle: forecast from analysis with WPR data, and, right: radar-AMeDAS analysis.

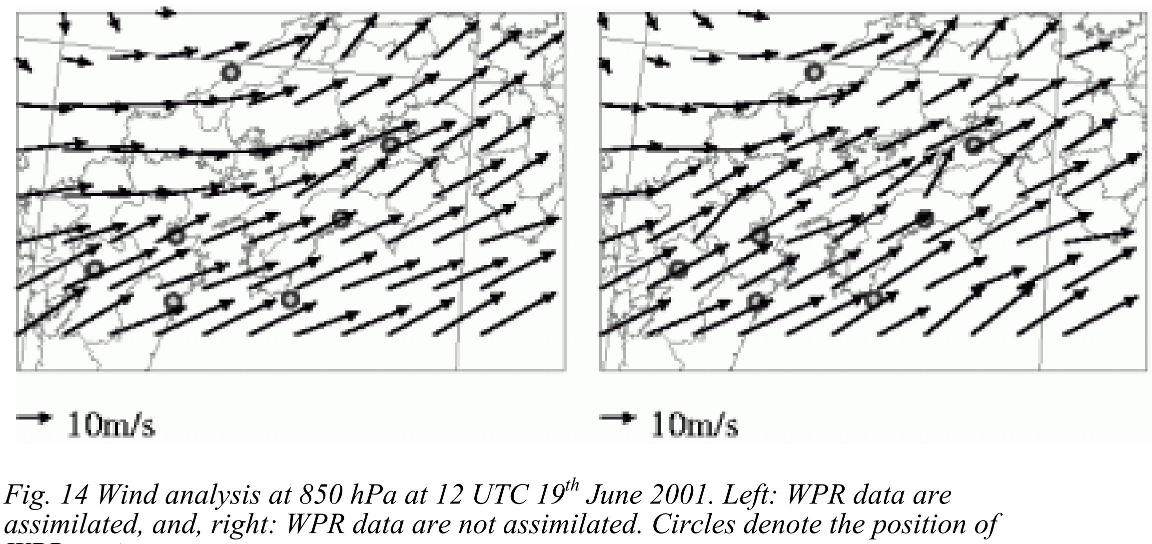

Fig. 14 Wind analysis at 850 hPa at 12 UTC 19th June 2001. Left: WPR data are assimilated, and, right: WPR data are not assimilated. Circles denote the position of WPR stations.

significance might not be very large because of small number of samples. Weak rain areas are mostly determined by synoptic-scale systems which can be analyzed by radiosonde data only but moderate-to-heavy rain areas come from smaller scale (e.g. meso-alpha) disturbances, which are not well captured by the radiosonde network but by dense-and-frequent WPR observations. Figure 13 shows a heavy rain event in 19th June 2001. In this case, a rain-band passed over Matsuyama-city causing landslide which claimed one life. The forecast starting from analysis with WPR data made a rain-band in very close position to observation while the rain-band in the forecast from no WPR analysis is displaced to north, which agrees with displacement of convergence zone at 850 hPa in the analysis (Fig. 14). Thus the WPR data seem to be effective to adjust the small scale structure of disturbance.

These improvements of the precipitation forecasts suggests that the assimilation of the WPR data improves the small-scale wind forecasts of MSM, which seems difficult to show directly. In another denial test of WPR data performed in June 2002 (Koike et al. personal communication), the root-mean square errors of 18-hour wind vector forecasts at 850 hPa, calculated against radiosondes in Japan, reduced from 4 m/s to 3.4 m/s with the assimilation of WPR data, though RMSEs of wind forecasts at 500 hPa and 250 hPa showed no impact.

4.4. Doppler radar radial velocity

The doppler-radar radial velocity shows similar property as WPR data (Fig. 15). The improvement is clearer again for moderate rain (10 mm / 3 hour) than small rain (1 mm / 3 hour). Differently from the WPR experiment, difference of wind analyses with and without Doppler radar data in the cases when the forecasts were clearly improved, often appeared outside of the radar ranges, which suggests that the information provided by the radars is distributed to the surrounding areas through the forecast-analysis cycle and it works to improve the successive analyses and forecasts.

Impacts on the RMSEs of forecast wind vector at 850, 500 and 250 hPa, calculated against radiosondes in Japan, were neutral. Since the WPR data were assimilated simultaneously, the sole improvement by the Doppler radars could not be captured by the relatively coarse radiosonde network.

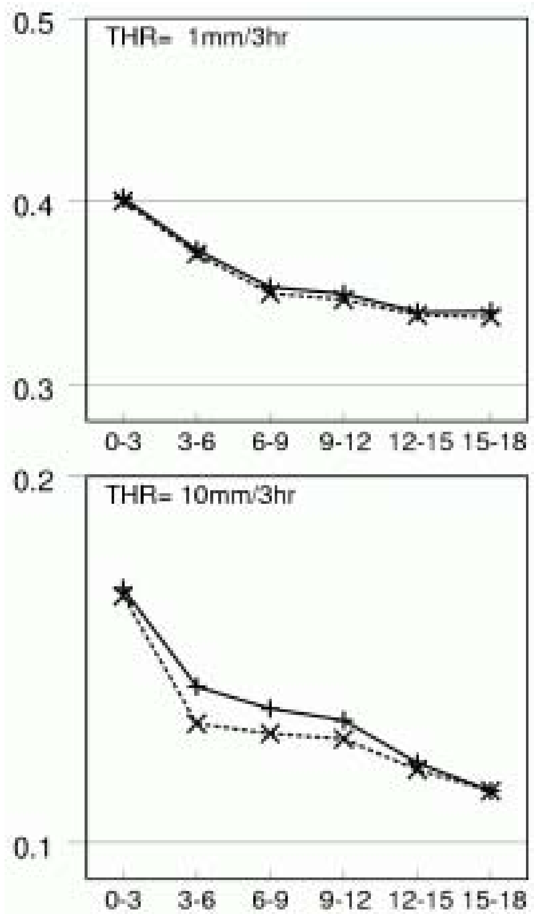

Fig. 15 Critical success index of precipitation forecast starting from analysis with radial velocity data (solid line) and without them (dashed line). The threshold value is 1 mm per 3 hour (top) and 10 mm per 3 hour (bottom).

5. Concluding remarks

With a variational method being implemented to data assimilation systems, various kinds of observation can be directly assimilated to numerical models. Especially direct assimilation of observations like precipitation amount was difficult for a long time until a four-dimensional variational method was introduced.

After the implementation of Meso 4D-Var in March 2002 at JMA, several observation system experiments were performed. The assimilation of precipitation amount improved the precipitation forecast throughout the 18-hour forecast time. The improvement for the first few hours was especially large because the spin-up problem of model precipitation was ameliorated. The same assimilation method was applied to the retrieved rain-rate from SSM/I and TMI, which made considerable improvement of typhoon forecasts (both for track and intensity).

Though the assimilation of precipitation data is very effective to improve the forecast, it is sometimes difficult to well reproduce precipitation in the analysis field. The model does not make precipitation when all model levels are unsaturated (e.g. the precipitation process is switched off), and the variational method cannot make the switch “on” because it can only make a continuous modification of the atmospheric state, not a discontinuous on/off change. That means that the background field should be accurate especially for the moisture field in order that the precipitation assimilation works efficiently. Among a few upper-air moisture observation, precipitable water retrieved from SSM/I and TMI was tested and it showed positive impacts on the forecasts of later hours. The ground-based GPS data are also expected to provide useful information about the moisture field (Nakamura et al. 2004, Koizumi and Sato 2004).

As for frequent-and-dense wind observations like WPRs and doppler-radars, the impact on the precipitation forecasts is small but definitely positive. That means that wind field in smaller-than-synoptic scale plays an important role in determining rainfall distribution. It is somewhat surprising that the positive impact by the doppler-radar data was clearly seen, because the observation covers very small portion of the model domain and WPRs have already provided information about meso-scale wind field. The result suggests that observation in a limited area can improve the analysis considerably by expanding the information through the forecast-analysis cycle.

REFERENCES

Ishikawa, Y., K. Koizumi and T. Tsuyuki, 2004: Operational JMA Mesoscale Four-dimensional Variational Data Assimilation System: Treatment of Background Error Covariance and Results from Parallel Run Tests, (submitted to *J. Met. Soc. Japan*)

JMA, 2002: *Outline of the Operational Numerical Weather Prediction at the Japan Meteorological Agency*, 158pp. Available from the Japan Meteorological Agency.

Kato, Y., T. Abo, K. Kobayashi, Y. Izumikawa and M. Ishihara, 2003: JMA Operational Wind-Profiler Observation (in Japanese), *Tenki* **50**, 891-907

Koizumi, K. and Y. Sato, 2004: Impact of GPS and TMI Precipitable Water Data on Mesoscale Numerical Weather Prediction Model Forecasts, *J. Met. Soc. Japan (in printing).*

Kummerow, C., W.S. Olson, and L. Giglio, 1996: A simplified scheme for obtaining precipitation and vertical hydrometeor profiles from passive microwave sensors. *IEEE Trans. Geosci. Remote Sens.,* 34, 1213-1232.

Makihara, Y., 2000: Algorithms for precipitation nowcasting focused on detailed analysis using radar and raingauge data, *Technical Reports of the Meteorological Research Institute* **39**, 63-111.

Nakamura, H., K. Koizumi and N. Monnoji, 2004: Data Assimilation of GPS Precipitable Water Vapor into the JMA Mesoscale Numerical Weather Prediction Model and its Impact on Rainfall Forecasts, *J. Met. Soc. Japan (in printing)*.

Seko, H., T. Kawabata, T. Tsuyuki, H. Nakamura, K. Koizumi and T. Iwabuchi, 2004: Impacts of GPS-derived Water Vapor and Radial Wind Measured by Doppler Radar on Numerical Prediction of Precipitation, *J. Met. Soc. Japan (in printing)*.

Shibata, A. 1994: Determination of water vapor and liquid water content by an iterative method. *Met. Atmos. Phys.,* 54, 173-181.

Takeuchi, Y and T. Kurino, 1997: “Document of algorithm to derive rain rate and precipitation with SSM/I and AMSR,” Algorithm description of PIs for SSM/I and ADEOS-II/AMSR, *2nd AMSR Workshop,* 61-1 – 61-9.

HIRLAM Observing System Experiments

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The HIRLAM-6 Project is a research and development cooperation between the National Meorological Services in Norway, Sweden, Finland, Denmark, Iceland, Ireland, Netherlands and Spain. Météo-France is partaking in the research collaboration. There is a clear goal of providing the best possible forecasting system for operational short range use in the member countries. HIRLAM is run in a relatively large area covering the North Atlantic and Europe in seven institutes. ECMWF forecast frames are used as boundary forcing.

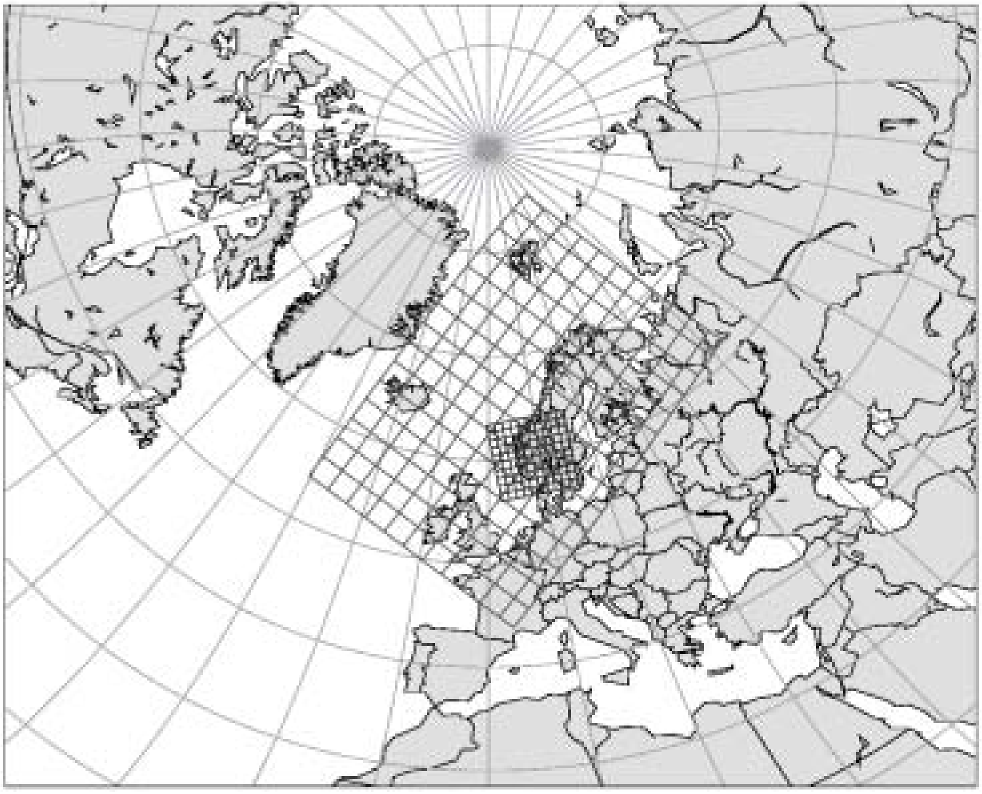

Figure 1: Areas covered by HIRLAM 20, HIRLAM 10 and HIRLAM 5

Iternally there may then be one or more nested models at higher resolutions. Fig. 1 shows as an example the met.no areas. HIRLAM is run at resolutions from 50 to 5 km and is a hydrostatic PE model with semi-Lagrangian semi-implicit integration. The data assimilation is 3D-VAR (or OI or 4D-VAR for research) and conventional as well as remote sensing data are assimilated in 6 hourly or 3 hourly cycles.

Observing system experiments have been performed in several of the institutes. Most are for ATOVS data, but also radar winds, QuikScat winds, Wind Profilers, GPS Zenith Delays, and MODIS winds and humidity have been evaluated. Conventional observations have not been tested so much, until a recent extensive set of experiments at DMI was done. Many HIRLAM reports as well as Institute reports have been published describing the methods and the results.

The following reports describe HIRLAM observing system experiments during the recent few years:

HIRLAM Technical Report 46, Dec 2000 *, by Bjarne Amstrup and Kristian Mogensen (DMI) describes impacts of AMDAR/ACARS and SATOB and with both OI and 3D-VAR.

HIRLAM Technical Report 52, Feb 2002 *, by Magnus Lindskog, Heikki Järvinen and Daniel Michelson, (SMHI and FMI), shows impact of Radar Doppler winds, both radial wind super observations and VAD profiles.

DNMI Research Note 84, Dec 2002, by Frank Thomas Tveter et al. (met.no) describes impact of QuikScat.

HIRLAM Technical Report 60, Apr 2003 *, by Harald Schyberg et al. (DNMI, SMHI, DMI, FMI) is a compilation of several ATOVS studies. It also provides extensive documentation of the how the data are used.

DMI Scientific Report 03-06, June 2003 **, by Bjarne Amstrup, shows ATOVS impact.

HIRLAM Technical Report 61, Aug 2003 *, by Xiang-Yu Huang, Magnus Lindskog, DMI/SMHI, is about the use and impact of European Wind Profilers.

met.no Report 153, Nov 2003, by Vibeke W Thyness, Harald Schyberg, met.no, describes use and impact of HIRS data.

NWP SAF Report, Jan 2004, by John de Vries, Kristian Sten Mogensen and Ad Stoffelen, KNMI/DMI, documents the Seawinds (QuikScat) implementation in HIRLAM and the first results.

A DMI report 2004 (draft) by Bjarne Amstrup and Kristian Sten Mogensen, DMI summarises very extensive impact studies of TEMP/PILOT, SYNOP, SHIP/DRIBU, AIREP, AMSU-A and also GPS and QuikScat.

Another DMI report 2004 (draft) by Bjarne Amstrup (DMI) is about the AMSU-A experiments for the same periods as the previous report.

Furthermore has there been DMI MODIS wind experiments by Kristian Sten Mogensen (DMI), which was presented at the EWGLAM meeting in Lisbon, 2003.

At SMHI ther have been MODIS IWV and GPS ZTD experiments by Martin Ridal and Nils Gustafsson, presented at several meetings.

*) hirlam.knmi.nl
**) www.dmi.dk

Conventional Observations.

At DMI a comprehensive set of experiments was run in connection with the new NEC SX-6 being available. Two periods of about 5 weeks were choosen, January-February 2002 and June-July 2002. Even more, the two levels of nesting was considered, so both the large area G in Fig.1 and the nested area E were tested together, with both areas using the same configuration of observations. The different experiments are listed below in Table 1. The ”4” in the experiment name indicates the large area G (coarse 50 km resolution) while the ”1”s indicate the area G at 17 km resolution.

Table 1: OSE description.

model	OSE
H4A/H1A	Control Run
H4F/H1F	No AIREPS (and no ACARS/AMDAR)
H4P/H1P	No TEMPs and no PILOTs
H4Q/H1Q	No humidity in TEMPs
H4R/H1R	No PILOTs
H4S/H1S	No SYNOPs
H4T/H1T	No TEMPs
H4V/H1V	No SHIPs
H4D/H1D	No DRIBU (buoys)
H4N/H1N	No NOAA16 AMSU-A
H4W/H1W	QuikScat added
H4G/H1G	ground based GPS added
H4B/H1B	No FGAT option

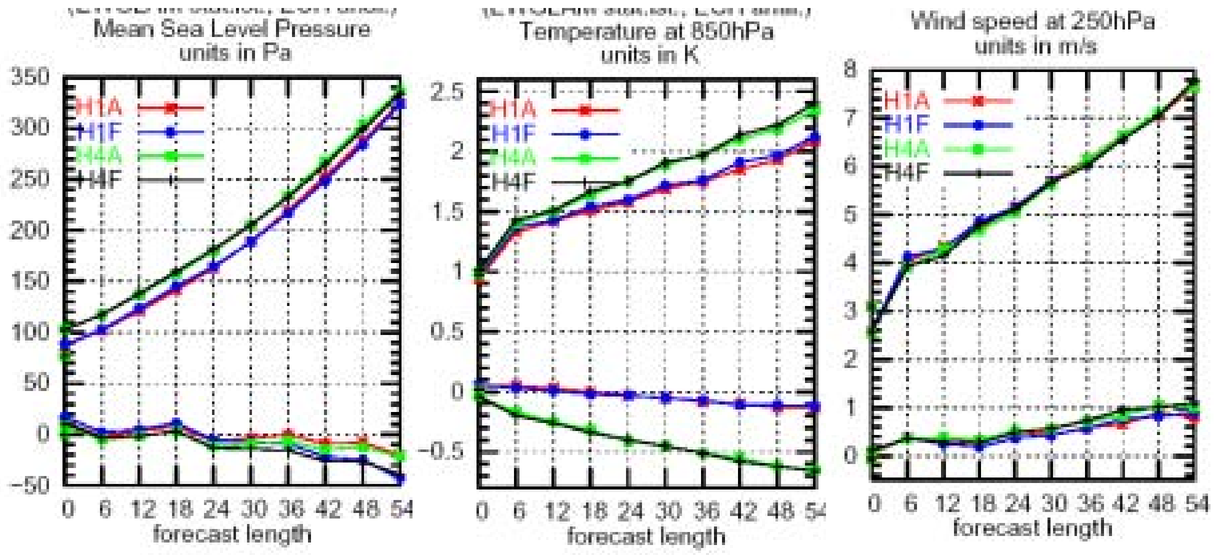

Figure 2. AIREP impact verification scores against EWGLAM stations for Jan/Feb. Mean Sea Level Pressure, 850 hPa temperature and 250 hPa windspeed. RMS error and bias.

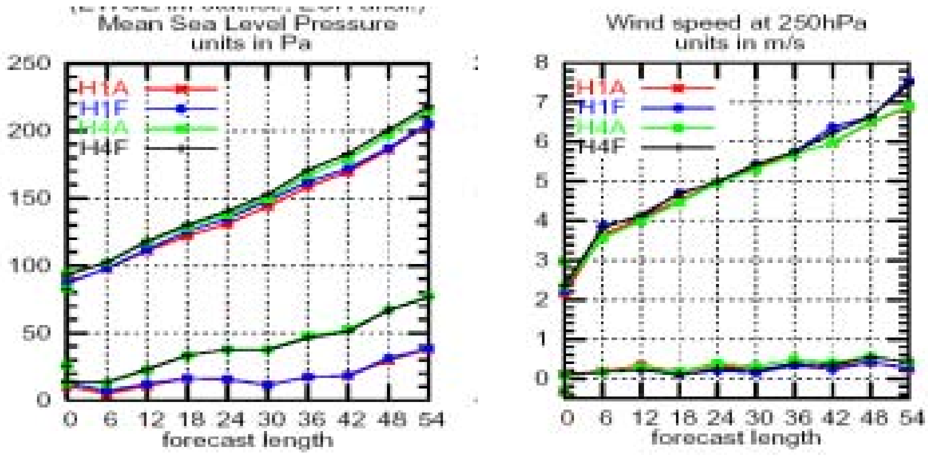

Figure 3. AIREP impact for Jun/jul. MSL pressure and 250 wind speed.

For conventional data, the AIREPs and ACARs have shown to have a small but positive impact in HIRLAM 3D-VAR. Fig.2 and 3 show a small positive impact for 850 hPa temperature in winter (and also for summer, not shown). The June/July period has positive impact also for MSL pressure. The high resolution scores are better than for the coarser resolution (the "4" experiments).

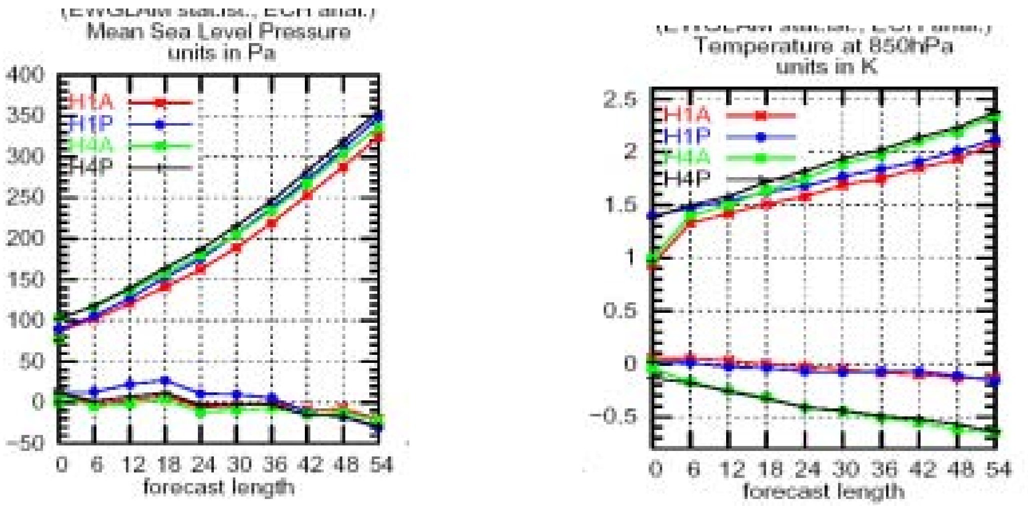

Figure 4. TEMP/PILOT impact for Jan/Feb.

The largest impact of all was achieved with the TEMP/PILOT data. (PILOT were insignificant and did not have any impact on their own). Fig. 4 shows a large separation between the blue and red curves (H1A/H1P, high resolution). There are quite large positive impacts throughout the forecast range and much larger than seen from any other instrument that has been tested in HIRLAM.

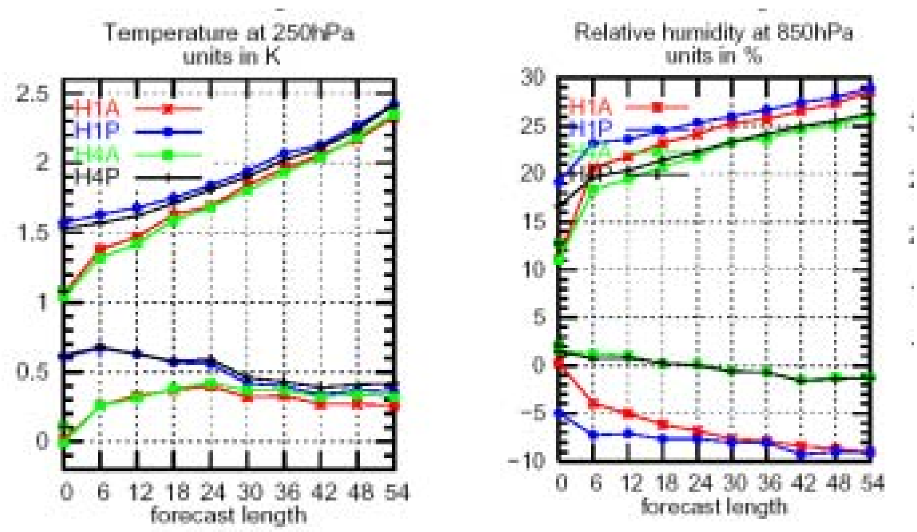

Figure 5. TEMP/PILOT impact for 250 hPa T and 850 hPa RH in Jan/Feb.

The impact for is large over the whole forecast range (remember that ECMWF boundaries impact gradually through the forecast range and they are the same with and without the TEMP/PILOTs). In very short/short range the impact is very large (Fig. 5). The same is true for the humidity forecast impact. It is very large for the first 6 hours and large for at least the first day. Fig.6 shows as large impact for June/July and also for 250 hPa wind speed. The impact for this level is large trough the whole forecast range. (The EWGLAM verification stations are over European land areas so the boundaries do not necessarily dominate).

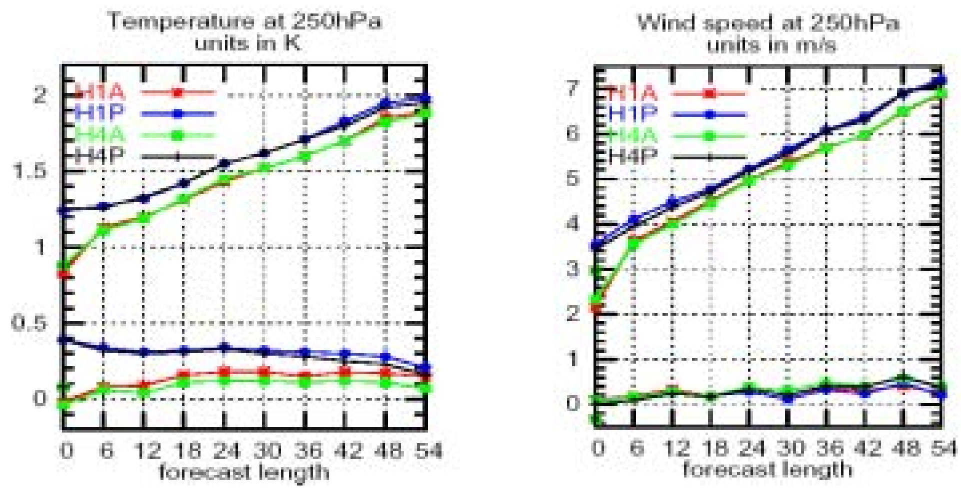

Figure 6. Impact of TEMP/PILOT on 250 hPa temperature and wind speed for June/July.

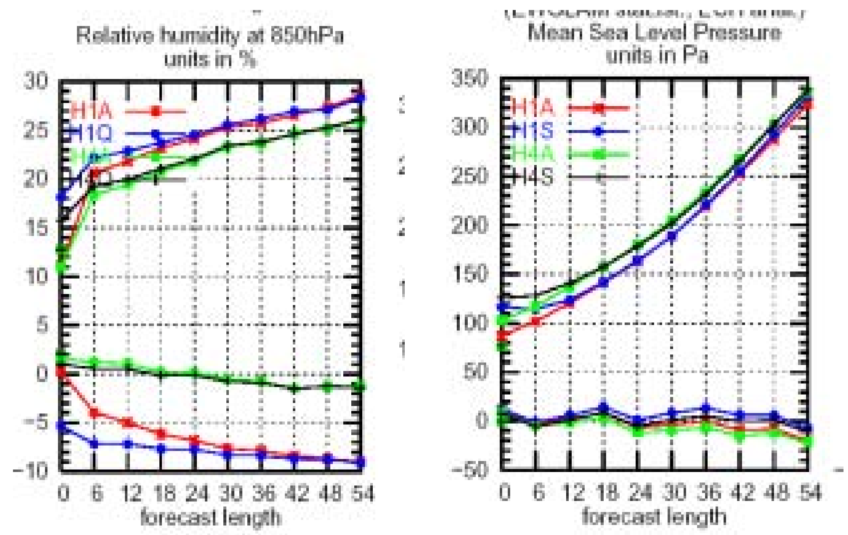

Figure 7. Impact of TEMP humidity on 850 hPa RH (left), and impact of SYNOP pressures on MSL pressure forecasts (right).

Just testing the humidity part of the TEMPs gives a strong impact on the humidity forecasts (Fig. 7). It is less than the impact of the whole TEMP report, but still a large part of that impact comes from the humidity observation. SYNOP (pressures) show a small positive impact but it is quite a strong positive one in the short range (Fig. 7, right). Note however that TEMPs contain surface pressures and those have been used in both experiments and they give at least the large scale surface pressure information.

DRIBUs have a noticeable positive impact at the end of the forecast range (for European land areas) whereas SHIP did not show much impact (not shown).

Remote sensing data

The ATOVS data have mainly been concerned with AMSU-A. Most of the remote sensing work in HIRLAM has been on ATOVS and AMSU-A, for many years, and a lot of development and many studies have been done. Table 3, below, gives a summary of those (from the above mentioned HIRLAM Techn. Report No 60).

Table 3: Overview of impact studies.

Period	Model	Data sources	Analysis window	Other information
December 1999	SMHI 44 km HIRLAM	ECMWF global archive BUFR data, NOAA-15	3 hours	Diag.O (Cloud mask bug)
February 2000	DNMI 50 km HIRLAM	DNMI Oslo antenna, NOAA-15	6 hours	Non-diag. O
1–6 May 2000	SMHI 22 km BALTEX HIRLAM	ECMWF global archive BUFR data, NOAA-15	3 hours	(Cloud mask bug)
21 May - 7 June 2001	DNMI 50 km HIRLAM	DNMI Oslo antenna, NOAA-15	6 hours	Non-diag. O
December 2001	DMI 0.45° HIRLAM-G	DMI Denmark and Greenland antennae, NOAA-16	3 hours	Non-diag. O
January 2002	DMI 0.45° HIRLAM-G	DMI Denmark and Greenland antennae, NOAA-16	3 hours	Revised non-diag. O

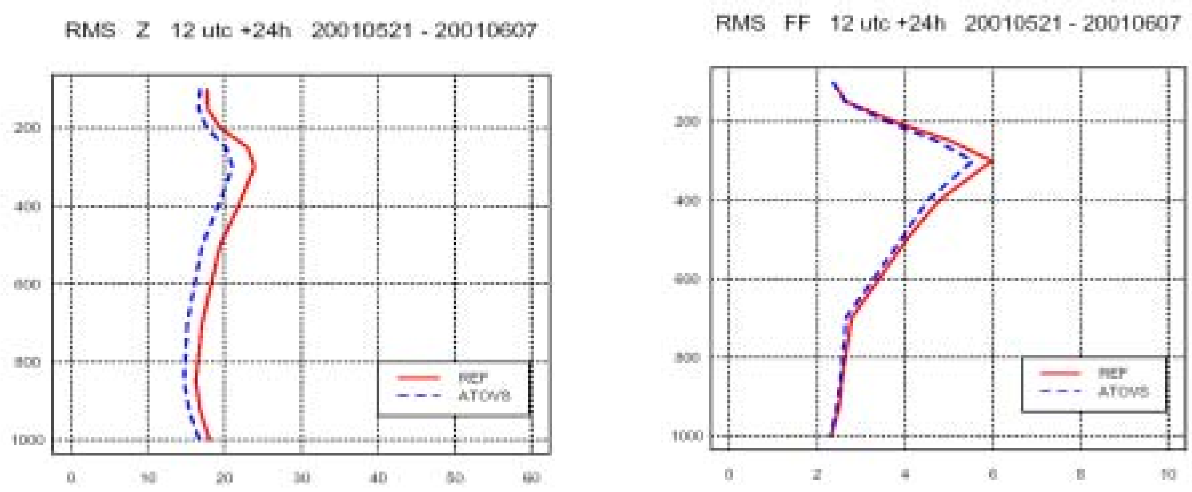

Figure 8. AMSU-A forecast impact on Atlantic radiosonde data for height and wind speed RMS errors.

The first impact studies showed positive to neutral impact. The early DNMI study showed promising impact when verified against 3 TEMPs around the North Atlantic area (and much less over land). (See Fig. 8).

Particular impact was found for important and sometimes extreme cyclonic developments. The SMHI study for the December 1999 period showed much improvement for the second French storm (Martin). It is crucial to have a good bias correction and quality control. Also the specifications of observation errors impact. In the more recent studies a diagonal observation error matrix was used. These later impact studies showed a more clear positive impact for most parameters and over several periods. (See Fig. 9 as a typical example for January 2002). The data distribution through EUMETSAT (EARS) has shown to be a very important component for providing enough data for a positive impact.

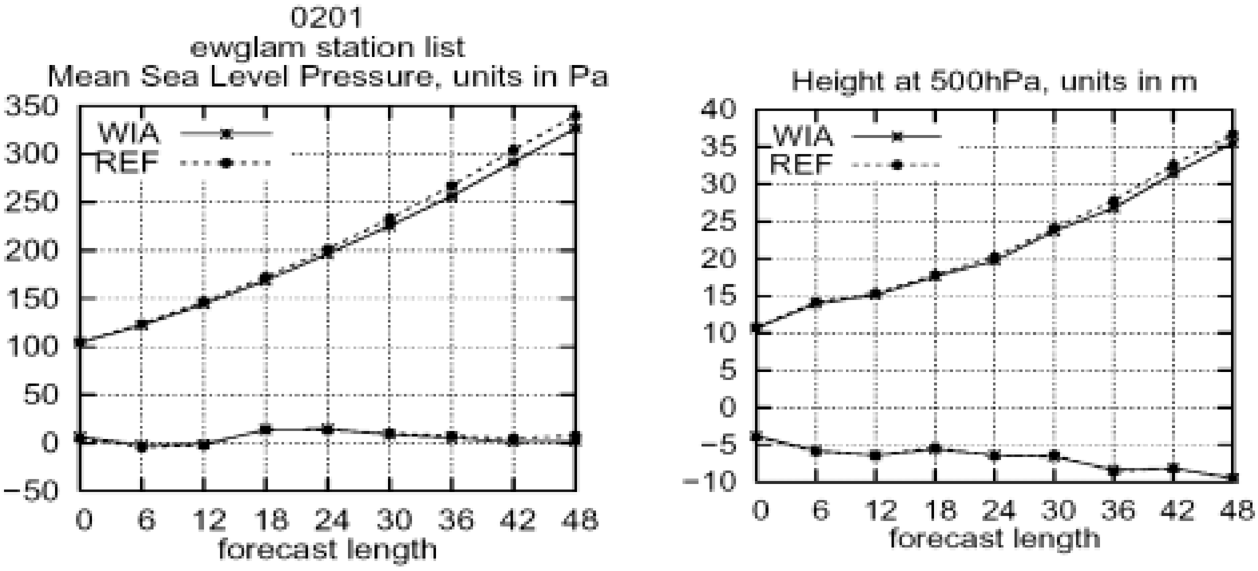

Figure 9. DMI impact study of AMSU-A for January 2002.

QuikScat winds have shown to be of neutral to weakly positive value.
It seems to be very situation dependent. The left graph in Fig. 10 below, in the first DNMI study, showed little impact in January but more in October (right). It was somewhat counter intuitive that there was no impact when there were intense low pressure systems (in January).

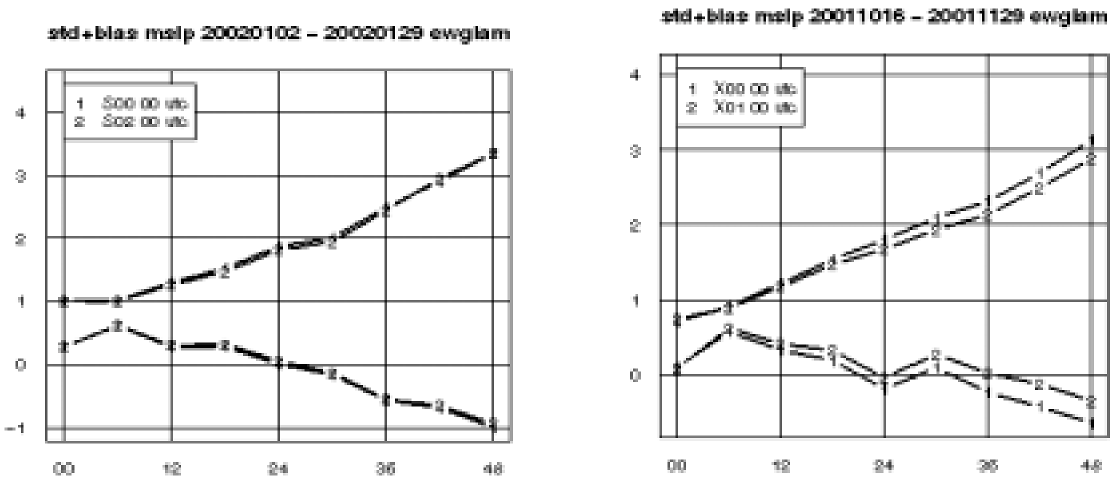

Figure 10. DNMI impacts of QuikScat for January (left) and October (right). Standard deviation of forecast error and bias of MSL pressure against pressure obseervations.
1=control and 2=with QuikScat added.

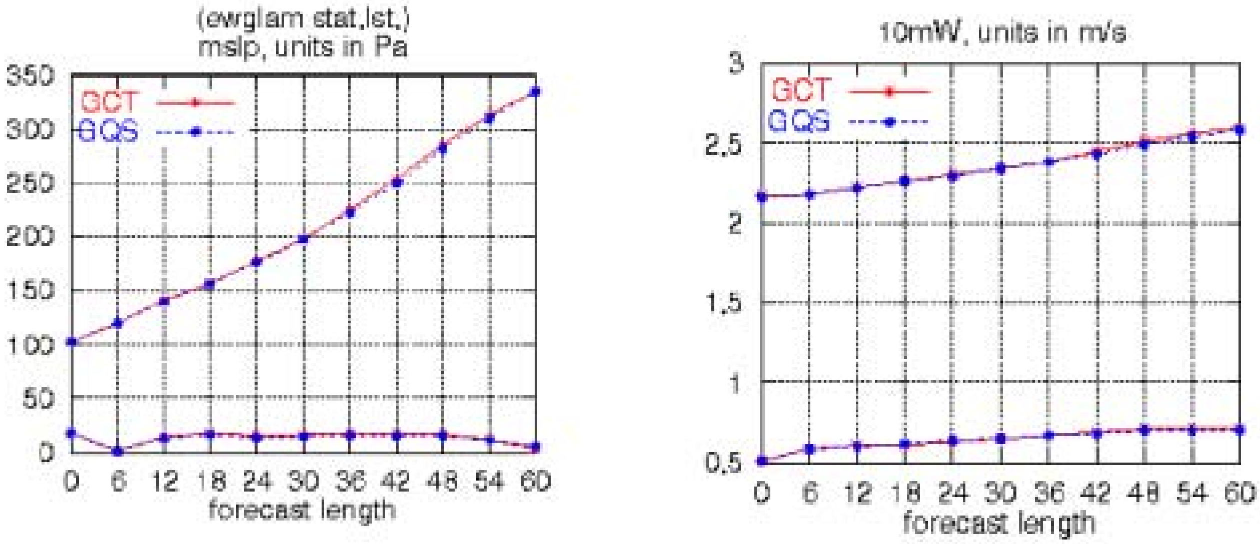

Figure 11. Impact of QuikScat in connection with implementation of the NWP/SAF software in HIRLAM, for December 2002. The red full line is with QuikScat; the blue dashed the control without the data.

GPS moisture have shown very little impact on scores, but seem to give more realistic precipitation patterns.

The European wind profilers can be assimilated with careful monitoring and data selection, but seem to provide a small positive to neutral impact (Fig. 12). The main benefit is the frequency of the data, and 3 hour cycling or more continuous (like 4D-VAR) is essential for any impact. At the intermediate hours the data amounts are very noticable.

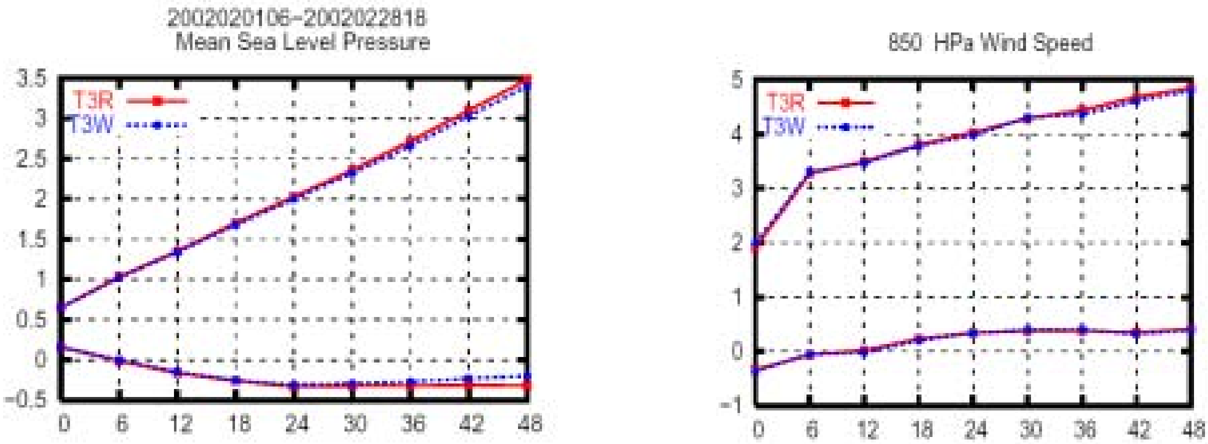

Figure 12. Impact of European Wind profilers in HIRLAM. RMS errors and bias. The red full curve is the Reference, the blue dashed with the wind profilers.

Conclusions

The TEMPs have the largest positive impact of all systems tested in HIRLAM 3D-VAR. This is for all variables. The TEMP humidities have a large impact on humidity forecasts and especially for short range. The PILOT data are insignificant in comparison with TEMPs. The AIREP (incl. AMDAR) data have a small positive impact in HIRLAM. The SYNOP pressures show a clear positive impact in the short range (but the impact was obscured by the pressure information already available from TEMPs). DRIBUs have a small positive impact.

The positive impact of AMSU-A in HIRLAM 3D-VAR has been clearly demonstrated. QuikScat has a small or neutral impact. GPS delays seem to give qualitatively good impact but it is hard to show any improvement in objective verifications so far. The European wind profilers give a weakly positive impact.

Regional Impact Studies with GRAPES 3D-VAR in CMA*

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1. A brief introduction of the CMA's GRAPES Project

Since 2001, Chinese Meteorology Administration (CMA) launched a national key project to develop next generation of Numerical Weather Prediction (NWP) system: **GRAPES** (Abbreviation of **G**lobal/**R**egional **A**ssimilation **P**r***E***diction **S**ystem). The major objectives of the project are (1) to develop new NWP systems for both operational and research applications based on the recent achievements in atmospheric sciences; (2) to set up a base for further development toward a new climate system model for the studies on climate change and operation of short term climate prediction; (3) to enhance the link between academic research and operation, and to accelerate the transfer of research results to operational applications. The project comprise four main components: (1) variational data assimilation systems (3DVAR/4DVAR) with stress on the direct assimilation of satellite and radar data; (2) unified model dynamic core suitable to multi-scales; (3) new global and regional NWP systems based on the unified dynamic frame with optimized physical package; (4) supporting software for the new NWP models on high performance computer environmental platform.

It is emphasized that new results of researches and developments in the fields of data assimilation and numerical models should be widely adopted in the new systems. The application of new technologies is expected to result in better performance of the new model systems and higher flexibility for the further upgrading of the systems.

The GRAPES project is one of the national key-research and development projects cosponsored and supported by Chinese Ministry of Science and Technology and Chinese Meteorological Administration. This five-year project consists of two phases. The researches in the first phase (2001-2003) focus on the development of new assimilation system and both meso scale and global prediction models. By the end of 2003, two experimental systems of new data assimilation and prediction model with regional and global configurations have been set up and some case trials have been completed. The preliminary results show the potential capability of the new systems to improve the global medium range and meso scale numerical predictions. The refine of the new systems based on experiments within operational environments will be emphasized in the second phase of the project (2004-2005). By the end of 2005, it is expected that new operational NWP systems will be implemented in CMA.

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2. A general description of GRAPES_3D-VAR system

Data assimilation is one of the key-factors in a numerical prediction system for research as well as for operation. It has recently made a significant progress and contributions to increase the numerical prediction and simulation accuracy by improving the initial condition quality with an advanced variational assimilation technique. In China, a sparse conventional data set is particularly available over the oceans and Tibetan Plateau, where most disastrous weather systems come from. An effective way to solve the data problem is using satellite data. To develop a variational assimilation system to solve the problem of using satellite data is in the first priority in CMA. In addition, there will be more than 120 Doppler radars (most s-band, some c-band) to be installed in next 3-5 years over Chinese territories (Fig.1). The availability of Doppler radar data urges the techniques of radar data assimilation to improve the meso-scale numerical weather prediction with these data. For these purposes, GRAPES_3D-VAR system was recently developed in CMA. The GRAPES_3D-VAR system consists of two main parts: GRAPES_3D-VAR frame and GRAPES_SISL model.

2.1 GRAPES_3D-VAR's frame

In general, a cost function for a 3D-VAR is defined as following equation:

$$J = J_b + J_o$$

$$J_b = \frac{1}{2}(x_b - x)^T B^{-1}(x_b - x) \qquad (1)$$

$$J_o = \frac{1}{2}[H(x) - y_0]O^{-1}[H(x) - y_o]$$

where x is the model state; x_b is the background state; B is the background error covariance matrix; O is the observation error covariance matrix; y_o is the observation vector; y_o is the observation operator which brings the model state to the observation state.

It is needed to find x which minimizes the cost function J. Like most 3DVAR schemes, the above cost function should be rewritten as an incremental "δx" mode. And in order to reduce the scale of B, a set of analysis variables, different from the model variable, was introduced in GRAPES-3D-VAR:

$$w = (\psi, x_u, \phi_u)$$

$$x_u = x - x_g \qquad (2)$$

$$\phi_u = \phi - \phi_g$$

where ψ is a stream function; x is a velocity potential; ϕ is a geopotential height. The subscript "g" denotes the balanced part, and "u" unbalanced part. The main features of the GRAPES 3D-VAR are as followings:

- The analysis is incremental in "δx" and conducted in standard pressure level.
- A latitude-longitude grid space of the analysis is specified for a limited area.
- Using a non-staggered Arakawa-A grid for the horizontal arrangement of the analysis variables.
- The observation operators are available to assimilate the conventional data sets via GTS (such as TEMP, SYNOP, SHIP, AIREP, SATOB, SATEM, and so on), as well as unconventional data sets (such as ATOVS radiances, Doppler radar radial winds, etc.).
- The model variables are defined as geopotential height or temperature, horizontal u-v wind components, specific humidity or relative humidity. The analysis variables are defined as stream function, unbalanced potential velocity, unbalanced height or temperature, relative humidity or specific humidity. The control variables are defined as $w = (PKU)^{-1}\delta x$.
- Using a simple geostrophic relationship (or a linear balance equation) for the mass/wind balance.

- The recursive filter is approximately used for the horizontal correlations, and the EOFs is used for the vertical correlations.

• The precondition is given as $\delta x = Uw = \sqrt{B}w$ to accelerate the convergences of minimization by reducing the number of iterations.

• Using Limited memory BFGS method for optimization of the algorithm.

2.2 GRAPES_SISL model

One of the four research aspects of the GRAPES project is to develop a new unified dynamic core for both regional/global applications with hydrostatic /non- hydrostatic approximated assumptions. Based on a wide investigation over the current operational NWP models, the meso-scale NWP models (such as MM5, ARPS, RAMS, NCEP-ETA model, Meso-NH and ALADIN of METEO-FRANCE, HIRLAM) and the other research NWP models, specially on the ECMWF model, UK-MO's new dynamic core, BSHB-90/QSS-98 models and CMC's GEM models, a new dynamic core was designed for the GRAPES. A primitive full compressible equation set is used in the new GRAPES dynamic core. The main characteristics of the new GRAPES dynamic core are consisted of ① Semi-implicit and semi-Lagrangian scheme (A. Staniforth and J. Cote, 1991); ② Latitude-Longitude grid point design (Fig.2); ③ Unified Regional and Global model (Fig.2); ④ Full compressible and Hydrostatic /Non-Hydrostatic approximation in option:

$$\delta_{NH} \frac{dw}{dt} = -\frac{1}{\rho}\frac{\partial P}{\partial z} - g + \frac{u^2 + v^2}{a} + f_{\varphi} u + F_w \qquad (3)$$

where $\delta_{NH} = \begin{cases} 1, & Non-hydrostatic \\ 0, & Hydrostatic \end{cases}$.

⑤ Using a staggered Arakawa-C grid for horizontal arrangement of variables (Arakawa and Lamb, 1977); ⑥ Using a Charney-Phillips vertical arrangement of variables; ⑦ a height-based terrain following vertical coordinate (Gal-Chen and Somerville, 1975); ⑧ a vector discretization to determine the Lagrangian trajectories (Bates et al., 1990).

In the new dynamic core, we have five major prognostic equations to be solved for 3 wind components, temperature and exner pressure. The four other equations depend on the exner pressure equation which is a typically elliptic equation, called as Helmholtz equation. The matrix of the SISL For a SISL model, it is very critical to have an effective solver of the Helmholtz equation, because In the new dynamic core, we have five major prognostic equations to be solved for 3 wind components, temperature and exner pressure. The four other equations depend on the exner pressure equation which is a typically elliptic equation, called as Helmholtz equation. The matrix of the SISL Helmholtz matrix of the model is very huge, but very sparse. In order to solve the GRAPES_SISL's Helmholtz equation, two methods have been tested: one is a Multi-Grid method (John C. Adams, NCAR); another is a Generalized Conjoint Residual method, GCR (Eisenstat S. C. et al., 1983). For the moment, we choose the GCR-solver for reason of practical calculation.

The physical package of GRAPES is from the physical schemes of WRF (Weather Research and Forecast), the operational HLAFS and T213L31 at NMC/CMA, and the CAMS's heavy rain prediction research model. It is possible to have different configurations of physical schemes for GRAPES. According to the typical weather events in China, the physical package was tuning and optimizing with GRAPES dynamical core. In 2003, the physical processes have been incorporated for parameterization experiments, including cumulus (deep & shallow) convection, microphysics, PBL process, land surface and radiation. The preliminary tunings results show that the Kain-Fritsch scheme is better than the Betts-miller for cumulus parameterization; the ECMWF radiation scheme is the best among all radiation schemes including both long wave and short wave radiation; the CAMS simple-ice scheme preceded the Kessler warm cloud scheme for the typical weather events in China. Although further tuning is necessary, the preliminary experiments proved that GRAPES work reasonably with the current configuration of physical package.

3. Regional Impact studies of ATOVS

Rammasun typhoon case study.

A tropical cyclone of Rammasun occurred over northwestern Pacific Ocean in earlier July 2002. The Rammasun typhoon brought rather heavy rain and strong wind along the coastlines from south to north of China, and until the Korean Peninsular, and caused enormous disastrous economic losts. The experiment was designed as: GRAPES_3DVAR for the analysis; WRF (Weather Research and Forecast) model for the numerical prediction; Initial time: 4th July 2002, at 15UTC; Conventional data with (or without) ATOVS radiances used for the simulation; Resolution of 0.5625º×0.5625º in horizontal and 31 layers in vertical; First guess and lateral boundary conditions provided by the global operational model T213L31 of NMC/CMA; 45 hours for the forecast time.

In comparison to the background, the 3D-VAR analysis results proved that the TOVS data is quite beneficial to improve the initial conditions of a tropical cyclone: much warmer core (Fig.3), cyclonic and anti-cyclonic tangential wind circulation better established (instead of an only cyclonic circulation) in vertical from low levels to upper levels (Fig.4) and more moist vertical structure. Consequently, the typhoon track predictions are significantly improved. For example, after 45 hours from the initial time, the position of Rammasun predicted by the model with 3D-VAR is clearly situated in East of the Korean Peninsular, very closed to the position observed. In contrary, the position of Rammasun predicted by the model without ATOVS is still stayed in West of the Korean Peninsular (Fig.5)!

KONI and IMBUDU double typhoon case study. Two typhoons, KONI and IMBUDU, appeared over northwestern Pacific Ocean during the same period in latter July 2003. KONI typhoon was approaching and very soon landing in southern coastlines of Guangdong province. The experiment was designed as: GRAPES_3DVAR for the analysis; GRAPES_SISL model for the numerical prediction; Initial time: 20th July 2003, at 12UTC; Conventional data with (or without) ATOVS (AMSU-A and AMSU-B) used for the simulation; Resolution of 0.5625º×0.5625º in horizontal and 31 layers in vertical; First guess and lateral boundary conditions provided by the global operational model T213L31 of NMC/CMA; 24 hours for the forecast time.

The number of data reports used for experiment, including ATOVS data, is about 15 times to those used by the current routine OI scheme: 32853 data reports against 2253 data reports (Fig.6). As expected, the better predictions of intensity, position and spiral cloud band structure for two typhoons: KONI and IMBUDU, were found in comparison to the simulations without ATOVS data (Fig.7). It proved again a positive impact of ATOVS on the analysis and prediction of tropical cyclone associated with the severe weather events.

A heavy snow case study. A heavy snow occurred on 6th November 2003 in North of China. That was a first heavy snow of the year. It was really high impact weather on the traffics, businesses, and societal/economic activities in Beijing. The experiment was designed as: GRAPES_3DVAR for the analysis; GRAPES_SISL model for the numerical prediction; Initial time: 6th November 2003 at 00UTC; Conventional data with (or without) AMSU-A used for the simulation; Resolution of 0.5625º×0.5625º in horizontal and 31 layers in vertical; First guess and lateral boundary conditions provided by the global operational model T213L31 of NMC/CMA; 24 hours for the forecast time. At the initial time, a small difference could be found between the analysis with AMSU-A and those without AMSU-A (Fig.8). After 24 hours of integration, the forecast of precipitation was improved. In fact, if one compare the forecast by the model without AMSU-A (right-upper of Fig.9) to the observation (bottom of Fig.9), it was found that the zone of precipitation from the northern part of Korean Democratic Republic to the central interior Mongolia of China (near North-East of Beijing) was obviously missed by the model without AMSU-A. In contrary, the model with AMSU-A successfully reproduced this zone of precipitation (left-upper of Fig.9). In addition, the GRAPES model with AMSU-A produced much more rainfalls in North of the middle-basin of Yangtz River and over the Taiwan Gorge and its surrounding areas in comparison to those by the model without AMSU-A. However, the quantity of precipitation was underestimated in Hebei province (South of Beijing) by the model with AMSU-A.

4. Concluding Remarks

GRAPES is a new NWP system based on a unified dynamic frame and a modularized code, and with different configuration options for both global and regional applications. A lot of research and experiments were well completed since CMA launched its key-national R & D project to develop new generation of GRAPES system in May of 2001. A regional version of the CMA's GRAPES is now available to application for the NWP experiments. The variational assimilation, full compressible non-hydrostatical/hydrostatical dynamical core and the optimized physical package are three essential aspects for CMA's GRAPES system. As showed above, GRAPES_3D-VAR was proved to be correct for directly assimilating satellite data sets as well as conventional observations.

Two cases of tropical cyclones/typhoons in summer time (Rammasun in 2002; Koni and Imbudu in 2003), and one case of heavy snow in wintertime of 2003 were randomly chosen for the impact studies of ATOVS with GRAPES_3D-VAR. The evaluation was simply made on the impacts.

The regional case study results showed that the positive impacts on simulations were significant. Over the oceans in which the sparse (or no) data is available, the satellite remote-sensing data sets (like as ATOVS radiances) are quite beneficial to more reasonably reconstruct the central structure of a tropical cyclone at initial time of integration. Taking the case of Rammasun, the typhoon core was warmed by the analysis with ATOVS up to 14ºC against 5ºC in background; and a typically conceptual structure (cyclonic in lower layer associated with anti-cyclonic in upper layer) of a tropical cyclone was well reconstructed by GRAPES_3DVAR system. The improvements could be positively found for the analysis and predictions of intensity and location of sever weather events over ocean as well as over lands.

All experiments presented above were carried out in a no-cyclonic mode. It is well recommended that the experiments need to be conducted in a cyclonic mode of assimilation to see the accumulative effects of the continual impact of data sets. In addition, the number of the impact study cases is quite limited. Hence, it is really necessary to carry out much more experiments to further assess the performance of GRAPES_3DVAR, and to give a more representative conclusion of the impact studies.

Acknowledgments

This work is a team-job. All of the persons (known and unknown), who joined the work on data assimilation, numerical model (dynamic and physic) and parallel computation for development of GRAPES, certainly involved into it and contributed to it. Without the great efforts of all team members, GRAPES could not be now available for this research work. They all merited first great thanks of the authors. Secondly, we would like to thanks the Center for Numerical Prediction Research (CNPR/CAMS) for providing an effective parallel computing facility to perform a so big computation of the work. We also very appreciated the enlightening discussions and scientific suggestions with/from our colleagues who should be in China or should be in foreign research institutions and operational centers. They all merited our sincere thanks.

References

Andersson,E., J.Pailleux, J-N.Thepaut, J.R.Eyre, A.P.McNally, G.A.Kelly, and P.Courtier 1993 "Use of cloud-cleared radiances in three/four-dimensional variational data assimilation" *Quart. J. Roy. Met. Soc.*, **120**, 627-653.

Anthes, R.A. and T.T. Warner, 1978: Development of hydrodynamic models suitable for air pollution and other meso-meteorological studies. Mon. Wea. Rev., 106, 1045 ~ 1078.

Arakawa A., and V. R. Lamb, 1977: Computational Design of the Basic Dynamical Processes of the UCLA General Circulation Model. Methods in Computational Physics, General Circulation Models of the Atmosphere, Academic Press, (17), New York (1977).

Benoit, R. M. Desgagne, P. Pellerin, S. Pellerin, Y. Chartier, and S. Desjardins, 1997: The Canadian MC2: A semi-Lagrangian, Semi-implicit wideband atmospheric model suited for finescale process studies and simulation. Mon. Wea. Rev., 125, 2382 – 2415.

Bougeault, Ph., 1992: Current Trends and Achievements in Limited Area Models for Numerical Weather Prediction Research . WMO/TD No . 510, PWPR No . 3.

Bougeault, Ph., and P. Mascart, 2001: The Meso-NH Atmospheric Simulation System: Scientific Documentation. Météo France and C.N.R.S.

Charney, J. G., and N. A. Philips, 1953: Numerical Integration of the Quasi-Geostrophic Equations for Barotropic and Simple Baroclinic Flow. J. Meteor., 10, P71 ~ 99.

Chen, D. H., D. X. Liao and H. L. Zhang, 2000: On new generation of multi-scale unified numerical prediction system I: a scientific design of non-hydrostatic dynamic core. Workshop of prediction theory and formation mechanism of the intensive and large-scale disastrous weather events in China. Dalian•China, 9-12 May 2000 (in Chinese).

D.H. Chen, J.S. Xue, X.S. Yang, J.L. Hu, H.L. Zhang, Z.Y. Jin, L.R, Ji, J.B. Chen, D.M. Zhang, L.P. Huang, X.J. Wu, 2000 ~ 2003: The technical documentation on new generation of multi-scale numerical prediction system. Available in Center for Numerical Prediction Research of Chinese Academy of Meteorological Sciences (in Chinese, under continually writting).

Chen, D.H., X.S. Yang, J.L. Hu and H.L. Zhang, 2003: A Strategy for Designing a non-Hydrostatic Multi-Scale Unified Model Dynamical Core. Journal of Applied Meteorology (in Chinese). Vol. 14, No. 4,2003, P452-461.

Courtier, P., E. Andersson, W. Heckley, J. Pailleux, D. Vasiljevic, M. Hamrud, A. Holling-worth, F. Rabier and M. Fischer, 1998: The ECMWF implementation of the three dimensional variational (3D-Var). Part I: Formulation. Q.J. R. Meteorol. Soc., 123, 1-26.

Courtier, P., J. –N. Thépaut, and A. Hollingsworth, 1994: A strategy for operational implementation of 4D-Var, using an incremental approach. *Quart. J. Roy. Meteor. Soc.*, **120**, 1367-1387.

Cote, J., S. Gravel, A. Methot, A. Patoine, M. Roch and A. Staniforth, 1998: The Operational CMC-MRB Global Environmental Multi-scale (GEM) Model. Part I: Design Considerations and Formulation. Mon. Wea. Rev., 126, P1374 ~ 1395.

Dudhia, J., 1993: A nonhydrostatic version of the Penn State /NCAR Meso-scale Model: Validation tests and simulations of an Atlantic cyclone and cold front. Mon. Wea. Rev., 121, 1493-1513.

ECMWF technical report, 1995: "Semi-Lagrangian Methods", Workshop Proceedings of European Centre for Medium-Range Weather Forecasts, 6 – 8 November 1995.

ECMWF technical report, 2000: "Numerical Prediction Model in high resolution", Workshop Proceedings of European Centre for Medium-Range Weather Forecasts, June 2000.

Fisher, 1998: The ECMWF implementation of three-dimensional variational assimilation (3D-Var). Part 1: formulation.*Quart. J. Roy. Meteor. Soc.,* **124,** 1783-1807.

Gal-Chen, T., and R. C. J. Somerville, 1975: On the Use of a Coordinate Transformation For the Solution of the Navier-Stockes Equations. J. Comput. Phys., 17, P209 ~ 228.

Grell, G.A., J. Dudhia, and D.R. Stauffer, 1994: A description of the fifth-generation Penn State/NCAR Meso-scale Model (MM5). NCAR Tech. Note NCAR/TN-398+STR.

Lafore, J. P., J. Stein, N. Asencio, P. Bougeault, V. Ducrocq, J. Duron, C. Fischer, P. Hereil, P. Mascart, J. P. Pinty, J. L. Redelsperger, E. Richard, and J. Vila-Guerau de Arellano, 1998: The Meso-NH Atmospheric Simulation System. Part I: Adiabatic formulation and control simulations. Annales Geophysicae, 16, 90-109.

Lorenc, A. C., S. P. Ballard, R. S. Bell, N. B. Ingleby, P. L. F. Andrews, D. M. Barker, J. R. Bray, A. M. Clayton, T. Dalby, D. Li, T. J. Payne, and F. W. Saunders, 2000: The Met.Office global three-dimensional variational data assimilation scheme. *Quart. J. Roy. Meteor. Soc.*, **126**, 2991-3012.

McQueen, J.T., R.R. Draxler, B.J.B. Stunder and G.D. Rolph, 1997: An overview of the Regional Atmospheric Modeling System (RAMS) as applied at the NOAA/Air Resources Laboratory. NOAA Technical Memorandum ERL ARL-220, 50 pp.

Qian, Jian Hua, Fredrick H. M. Semazzi and Jeffrey S. Scroggs, 1998: A global Non-Hydrostatic Semi-Lagrangian Atmospheric Model with orography. Mon. Wea. Rev., Vol. 126, P747～771.

Robert, Andre, 1982: A Semi-Lagrangian and Semi-Implicit Numerical Integration Scheme for the Primitive Meteorological Equations. J. of Meteor. Soc. of Japan. Vol. 60, No. 1, P319～325.

Semazzi, F.H.M., J.-H. Qian, and J.S. Scroggs, 1995: A global nonhydrostatic, semi-Lagrangian, atmospheric model orography. Mon. Wea. Rev., 123, 2534-2550.

Staniforth, A. and J. Cote, 1991: Semi-Lagrangian integration scheme for atmospheric models – A review. Mon. Wea. Rev., 119, P2206～2223.

Tanguay, M., A. Robert and R. Laprise, 1990: A Semi-Implicit Semi-Lagrangian Fully Compressible Regional Forecast Model. Mon. Wea. Rev., 118, 1970～1980.

Thepaut, J.-N., D. Vasiljevic, P. Courtier, and J. Pailleux, 1993 "Variational assimilation of conventional meteorological observations with a multi-level primitive-equation model." *Quart. J. Roy. Met. Soc.*, **199**, 153-186

Xue, M., K.K. Droegemeier and V. Wong, 2000: The Advanced Regional Prediction System – A multi-scale nonhydrostatic atmospheric simulation and prediction model. Part I: Model dynamics and verification. Meteorol. Atmos. Phys. 75, 161-193.

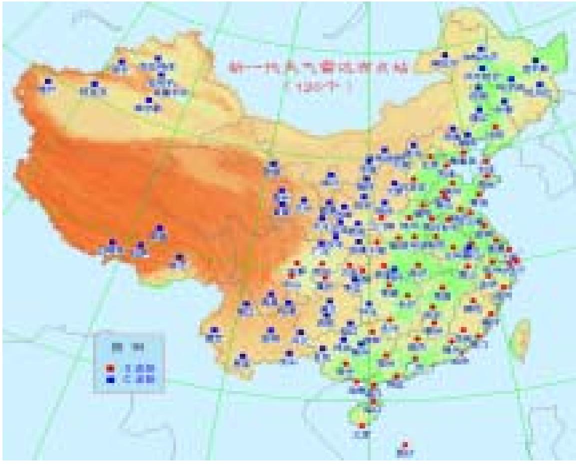


Fig.1 Radar network in China by end of 2005.

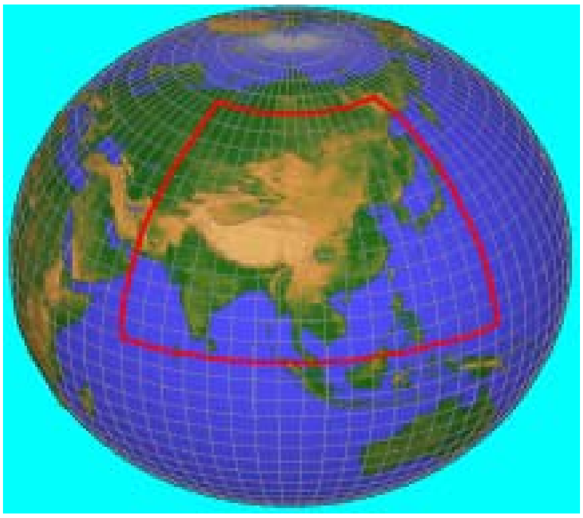
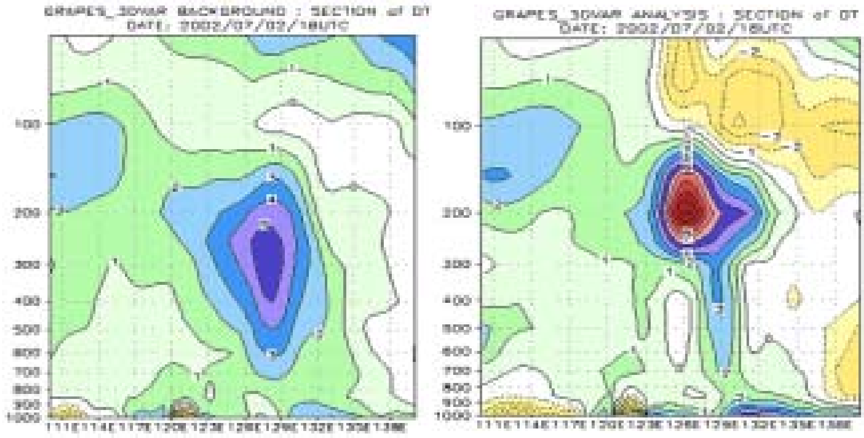
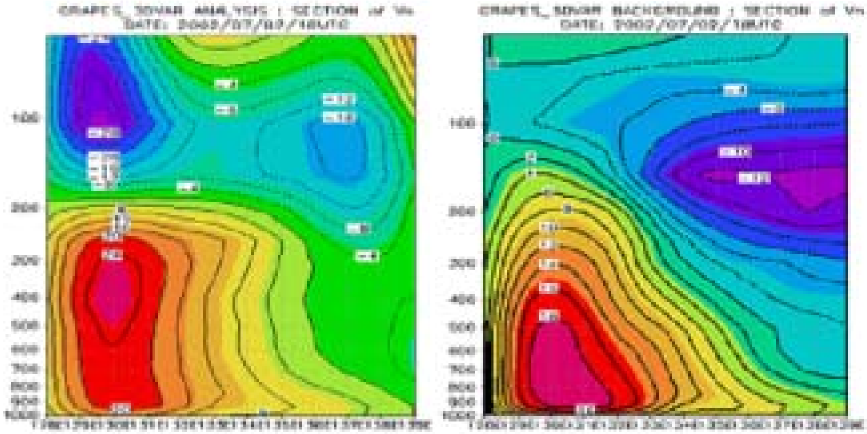


Fig.2 A Latitude-Longitude grid point design for GRAPES



(a) without ATOVS (b) with ATOVS by GRAPES-3D-VAR

Fig.3 The altitude-longitude cross section of the temperature deviation from the horizontal averaged-temperature along 23ºN.



(a) without ATOVS (b) with ATOVS by GRAPES 3D-VAR

Fig.4 The altitude-longitude cross section of the tangential wind V_n along 23ºN.

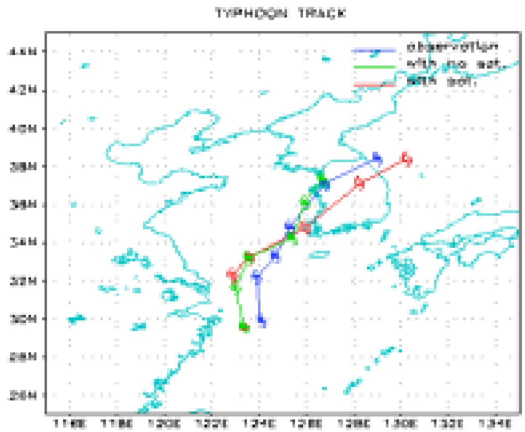


Fig.5 Rammasun typhoon tracks observed (blue line) and predicted (red line: with ATOVS, green line: without ATOVS).

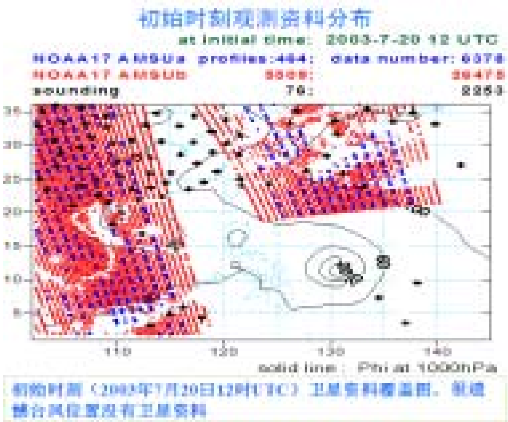


Fig.6 Coverage of observations introduced by GRAPES_3D-VAR at initial time of 12 UTC/20/07/2003 for the KONI and IMBUDU typhoon case studies. Blue points indicate AMSU-a profiles, red points: AMSU-b profiles, black crosses: radiosonde profiles. The ratio of the total observation reports used in GRAPES 3D-VAR assimilation against the radiosonde reports is 32853 against 2253, about fifteen times!

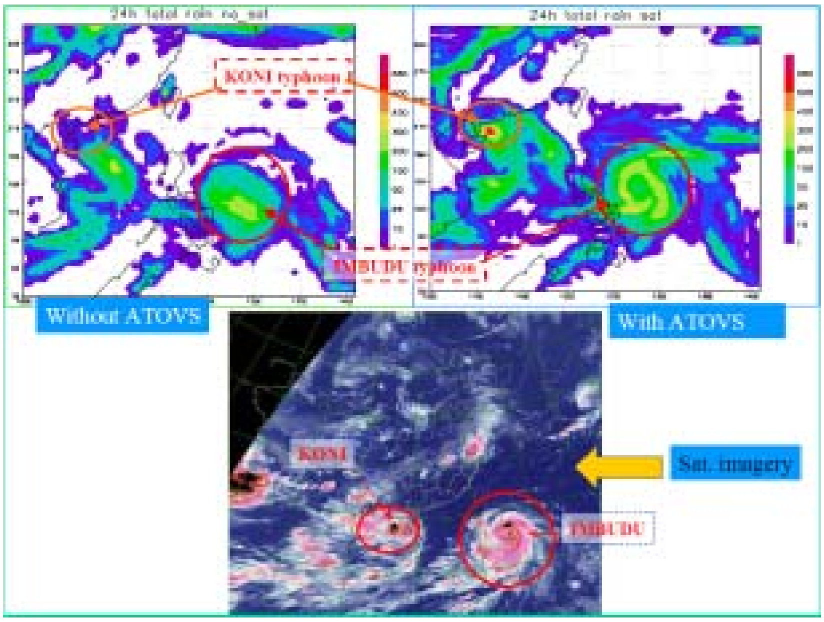


Fig.7 The fields of precipitations accumulated over 24 hours. Valid time: 00UTC/20/07/2003 ~ 00UTC/21/07/2003. On left-up, simulation by GRAPES without ATOVS; on right-up, simulation by GRAPES with ATOVS; at bottom, satellite imagery at 00UTC/21/07/2003.

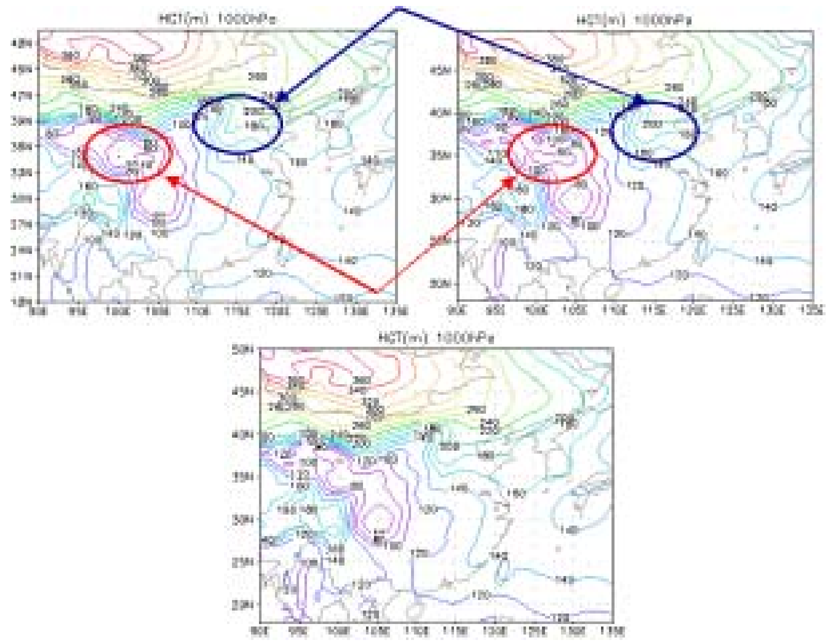


Fig.8 The fields of geopotential height at 1000 hPa. Initial time: 00UTC/06/11/2003. On left-up, analysis by GRAPES_3DVAR with ATOVS; on right-up, analysis by GRAPES_3DVAR without ATOVS; at bottom, analysis of the operational global model T213L31.

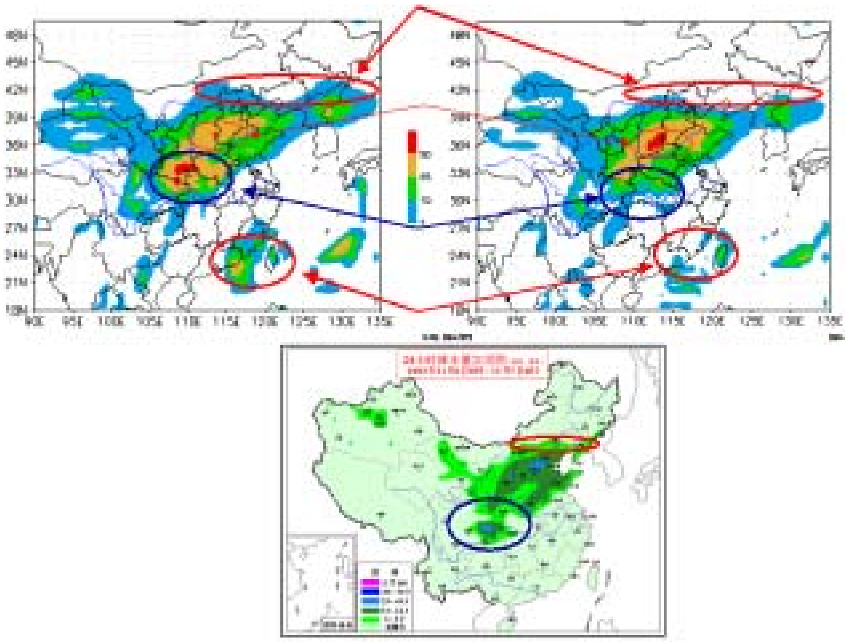


Fig.9 The fields of precipitations accumulated over 24 hours. Valid time: 00UTC/06/11/2003 ~ 00UTC/07/11/2003. On left-up, simulation by GRAPES with ATOVS; on right-up, simulation by GRAPES without ATOVS; at bottom, observations.

Impact of AMDAR Data in Regional ETA Model Forecasts over Southern Africa

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1. INTRODUCTION

Radiosonde observations have traditionally been the source of accurate and reliable upper-air data for numerical weather prediction. Because of financial constraints, the distribution of radiosonde stations is becoming ever more sparse, particularly over developing countries. A cost-effective alternative system, extensively used in America, Europe, and elsewhere, accesses in-flight information from aircraft, both at cruise level and during ascents and descents. AMDAR (Aircraft Meteorological DAta Relay) observations are also accurate and reliable (Stickland, 2003), where available, and have had a positive impact even over data-rich regions. World-wide over 130 000 automated aircraft observations are available daily and have been proved useful in numerical weather prediction (Moninger, 2003). This usefulness is confirmed in several observation impact studies, see for example Graham et al. (2000), Anderson et al. (2000) and Zapotocny et al. (2000 and 2002). A keynote address (Petersen, 2003) at the recent Conference of the South African Society for Atmospheric Sciences focussing on AMDAR questions, reported major impacts at NCEP especially of off-time AMDAR data on local forecasts in the 3-12 h range, and on significant positive impact on ECMWF global forecasts. Two major AMDAR impact studies carried out at the Canadian Meteorological Centre (CMC) showed an impressive reduction of error in jet-level winds (Fournier, 2003). A related CMC study suggests that improvements to forecasts can lead to significant increases in aircraft fuel economy.

A 1997 study (Tennant et al., 1997) of the effect of reduced radiosonde coverage over the southern Africa region showed the negative effect on regional and global forecasts of a hypothetical reduction of the number of upper-air ascents by about half. In the regional context, see also Riphagen et al. (1998). Compared to the 14 twice daily ascents in 1997, the actual situation currently shows a drastic reduction with differing summer and winter programmes to try to minimize the problem. On the day of writing there were five radiosonde ascents over the country at 0000 UTC and none at 1200Z. The shortage of conventional data has a serious impact on forecasts over the region (Edwards, 2003) and efforts have been made to alleviate the situation through the provision of the relatively cost-effective AMDAR data.

In 1988 WMO set up an AMDAR Panel to extend the AMDAR facility to less affluent and more data-poor regions, starting with pilot studies in southern Africa and the Middle East. Since August 2000 additional aircraft observations have been provided by airlines participating in the AMDAR Panel Pilot Project for Southern Africa. The aim is to provide AMDAR observations (notably data collected during ascents and descents) to augment the sparse network of upper-air observational data which is essential for the successful use of numerical prediction models.

The participating carriers for the southern African experiment are Aerolineas Argentinas (AR), Australia (AU), five European airlines (EU) financed by EUMETNET-AMDAR or E-AMDAR, KLM (KL), Lufthansa (LH), Air Mauritius (MK), and South African Airways (SA). Reports with a QF identifier (presumably Qantas) were also seen. One Air Namibia aircraft reports using a KL identifier. (Information courtesy of Jeff Stickland). On-going strenuous and often difficult efforts have been necessary to maintain and try to increase the provision of the AMDAR data over the southern African region and northwards. See, for example, the documentation on the Sixth Meeting of the AMDAR Panel in Pretoria, 15-17 October 2003, AMDAR Panel /6/Doc. 3.1(1).

Although sparse compared to other regions, where thinning is often necessary (see Cardinali et al., 2003), AMDAR coverage over southern Africa was presumed to have a positive effect on numerical forecasts. To test this hypothesis the South African Weather Service (SAWS) initiated a study in 2000 on the impact of AMDAR data on regional Eta model forecasts. Real-time with- and without-AMDAR versions of the

SAWS implementation of the NCEP Eta data assimilation and prediction system (see Black, 1994) were run in parallel from August 2000 to January 2003 and records were kept of the AMDAR data ingested. Interim results have been presented by Riphagen et al. (2001) and Riphagen (2003).

Initially conventional statistical comparisons evaluated each run against its own verifying analysis. However, since it is the analysis that is primarily affected here, a more valid option (Zapotocny, 2000, personal communication) was introduced after a few months, with extensions to more vertical levels and forecast hours, as well as spatial views, the following year. Provision was made for real-time visual evaluation by forecasters at the Johannesburg International weather office and for more intensive case studies, bearing in mind the scarcity of independent verifying observations. Verification against radiosondes was carried out after the close of the experiment from archived observational and model data. In Section2 the study method is described, namely the parallel experiment and evaluation methods. Results of the experiment, including an account of the AMDAR coverage during the run, are given in Section 3, with some concluding remarks in Section 4.

2. THE EXPERIMENT

Real-time with- and without-AMDAR versions of the local operational regional modelling system were run in parallel for nearly two-and-a-half years from August 2000 to January 2003, with automatic statistical evaluation and monitoring of aircraft reports. The word 'AMDAR' is used loosely here to cover all aircraft observations. The control was the operational model with access to all available observation types; the experiment was identical except for the exclusion of all aircraft data in the 3DVAR analysis. Apart from a gross check in the analysis system there is no quality control of AMDAR data. (When switched on for aircraft data, the sophisticated quality control in the observation preprocessor rejected all AMDAR reports.)

The model used was the SAWS implementation of the NCEP regional Eta model (see Black, 1994) at 48-km, 38-layer resolution, run twice daily with initial fields from a prior 12-h assimilation process. The Eta system has been operational at SAWS since November 1993 and has undergone several upgrades in step with NCEP. The assimilation procedure consists of a three-hourly 3DVAR analysis/Eta forecast cycle. The model is configured so that the transformed model grid is centred at (28 S, 20 E). This grid is included within an 'analysis domain' (62.5 S to 4.25 N and 45 W to 93.75 E), and includes the output domain (48 S to 9 S and 13 W to 53 E). Output resolution is half-degree on pressure levels at 50 hPa intervals from 1000 to 100 hPa. Eta analysis and prediction contours (differences and overlays), overlaid in turn with AMDAR and radiosonde observations if present, were made available after each run for daily subjective evaluation at the Johannesburg International Airport weather office. Similar preparations were made for identified case studies of interesting weather situations.

The existing conventional statistical evaluation system was used initially. However, it was realised that this system, while fair for comparisons where changes in the forecast model are the subject of the trial, is not suitable for observing system experiments. Seeing that the analysis is a version of the model forecast modified by observations, in model-change comparisons forecasts should be evaluated against the analyses they influence. However, where the forecast models are identical, guess and forecast differences are due entirely to observations and, presumably, the less the guess is altered in obtaining the analysis the better the fit will be between the forecast and the verifying analysis. For instance, if there were no observations there would be a perfect fit. Thus no-AMDAR forecasts are likely to fit better with no-AMDAR analyses than with-AMDAR forecasts fit with with-AMDAR analyses. It would therefore seem more valid to evaluate both with- and without-AMDAR forecasts against a common standard, namely the control analysis.

Consequently, the methodology of Zapotocny (2000 and 2002) was introduced in March 2000. Here time-averaged sensitivities and impacts were calculated with both runs now evaluated against the control with-AMDAR analyses. The formula used for impact is as Zapotocny (2000, personal communication), later amended in Zapotocny (2002). The RMS Forecast Impact FI of an individual data type is defined as:

$$FI = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(D_i - A_i)^2} - \sqrt{\frac{1}{N}\sum_{i=1}^{N}(C_i - A_i)^2}$$

where C and D are the control and denied forecasts respectively and A is the verifying analysis. The forecast impact FI evaluates which forecast is closer to the verifying analysis: a positive result indicates a smaller error for the control forecast. In Zapotocny (2002) this formula has been changed to calculate normalized percentages; here this is done as a separate step where applicable. Additionally, for four individual months of 2002, spatial fields of statistics such as RMS error were generated by replacing the averaging over horizontal grid points with averaging over all the runs in the month concerned. The Zapotocny-type statistics system was extended in April 2002 to cater for all available pressure levels and forecast hours so that, for instance, the vertical variation in impact could be determined.

During the experiment a system for verification against radiosondes was not in place, but an attempt was made after the run to compare the with- and without-AMDAR forecasts with radiosonde data using archived data. Unfortunately, this extended download discovered the deficiencies of the archiving system which relies on antiquated tape drives and there are many gaps in the series. The time-consuming nature of the process also meant that only data from August 2000 to April 2002 are included here. Five radiosonde stations with a fair number of runs during the period were selected and the strategy was to average over the time-series for each station, rather than over such a small sample of stations. It was hoped that a distinction might be seen in the results depending on the availability of AMDAR data at or near the station, either at low levels at locations where there were ascents and descents, or at high levels where a station might lie beneath a regular flight path. The five stations are Cape Town (68816), Irene (68263), Durban (68588), De Aar (68538) and Windhoek (68110). A philosophical difficulty with this form of evaluation revolves around the question of whether a forecast based only on radiosondes might not verify better against radiosondes than a system where the radiosonde observations are blended with AMDAR data.

The available AMDAR coverage during the experiment was analysed in various ways, separating mass (temperature) and wind report information, to show the distribution of reports according to analysis time or pressure level, for each carrier, and the variation in the availability over the run. Spatial views of the coverage were prepared to match the spatial statistics fields for April, May, June and July of 2002.

3. RESULTS OF THE EXPERIMENT

AMDAR availability over the southern African domain of the SAWS Eta data assimilation system is sparse compared to the US or Europe, with typical coverage as shown in Fig. 1. However, substantial amounts of AMDAR data became available from August 2000. Eight airlines participated with the European carriers (EU), Air Mauritius (MK) and South African Airways (SA) being the major contributors as can be seen in Tables 1 (wind) and 2 (mass). The counts here are for the domain shown in Fig. 1 and over the entire period of the experiment. These tables show that greater amounts of AMDAR data are received at off-times than at the main synoptic times. The off-time AMDAR observations are the only available upper air data at these times. In the vertical, as expected, the largest number of reports are located along flight paths between 200 and 300 hPa (see Tables 4 and 5). For instance, for winds SA has a count of 151 377 in this layer compared to say the 30 750 reports between 800 and 900 hPa. The increase to 45 276 in the layer above this is probably accounted for by ascents and descents at Johannesburg International Airport (elevation 1626 m). Fig. 2 gives an indication of the availability of AMDAR data over the period of the parallel run. The initial enthusiasm grew until about December 2002 when there was a general fall-off for all airlines. (The count dwindled drastically after the run closed but picked up again early in 2003.)

In the limited daily monitoring of observation/forecast overlays at the Johannesburg International weather office it was noted that inclusion of AMDAR data was accompanied by alleviation of model deficiencies. Forecaster comment on temperatures was that when the actual temperatures fall in the range -55 to -60 C, between the Equator and about 25 S, the without-AMDAR model is almost invariably 4 to 5 C too warm. The inclusion of the AMDAR data results in the error being roughly halved. For winds, on about 15% of occasions the winds from the without-AMDAR model can be out by as much as 30 degrees and 15-25 knots. The use of the AMDAR data tends to reduce this error, usually in the vicinity of the AMDAR observations. Fig. 3 gives an example of the type of views provided. Since the AMDAR observations are not necessarily located at the model output pressure levels, the actual AMDAR pressures are shown in a separate view. This example shows the quite considerable effect of the presence of AMDAR observations on the analysis.

Although formal evaluation of case studies has yet to take place, from even cursory examination it appears that often more marked differences are seen at upper levels along flight paths, with little change due to ascent and descent information near the main airports where radiosonde soundings are also available. This is illustrated in Fig. 4 where the two lower-level AMDAR observations nearly coincide with radiosonde reports and there is very little difference between the forecasts. In contrast the upper-level AMDAR observations provide information additional to the radiosonde reports, accompanied by substantial differences between the forecasts.

Zapotocny-type statistics averaged over a March 2001 to January 2003 period (about 1300 cases) are given in Table 5. For all variables evaluated the inclusion of AMDAR observations has an overall, albeit small, positive impact. There is a decrease in impact with forecast hour for all variables. The vertical variation, available from April 2002 to January 2003, is shown in Fig. 5. The impact is greatest at higher levels around 300 hPa for all variables and forecast hours, matching the greater number of AMDAR reports at these levels. It is interesting that specific humidity, which is not part of the AMDAR observation, also shows this pattern. There is considerable variation for individual runs (not shown here), with negative impact for more than a third of runs for most variables and forecast hours. Similarly, the monthly spatial views, such as for April 2002 in Fig.6, display considerable horizontal variation in impact, although areas of positive impact seem predominant. Figure 6 also displays the locations of all the mass or wind AMDAR reports for the month. It can be noted that for the variables shown the impact is positive over Gauteng where many flight paths converge, but not so for Cape Town.

Verification against radiosondes gave mixed results, perhaps understandably so because of the nature of the test as discussed above, and because of the lack of any but a very crude quality control for the radiosonde observations. However, there was often a positive AMDAR impact, for instance, for temperature analyses and 12-h forecasts at all five stations, see Table 6. Each of the stations lies at or near the regular flight paths (see the upper views of Fig.6) which may explain the positive AMDAR impact at early stages and at most levels for temperature. However, scores for winds (not shown) are less coherent.

4. CONCLUDING REMARKS

Statistically, it has been shown that the inclusion of AMDAR data has a small positive impact overall, diminishing as the forecast proceeds and peaking at upper flight levels where the number of AMDAR reports is greatest. Under-staffing in the SAWS weather offices has been a limiting factor in the real-time and case-study visual evaluation. However, more marked differences are evident at upper levels along flight paths, with little change due to ascent and descent information near the main airports where radiosonde soundings are also available. Forecasters have reported the correction of errors in the forecasts through the introduction of AMDAR data.

It is clear that these observations have a potentially important role to play in numerical weather prediction over southern Africa. South African Weather Service models are starved for upper-air data due to lack of resources. AMDAR observations have the potential to alleviate this lack and at present provide valuable additional information at high levels along the aircraft routes. However, their greatest potential is their ability to simulate radiosonde reports during aircraft ascents and descents. Efforts to ensure that such ascents and descents take place in upper-air data-sparse areas and not only at the two major airports which already have radiosonde coverage should be pursued vigorously.

Acknowledgments

Thanks are due to Cindy Bruyère for modifying the analysis program to exclude aircraft reports and save the relevant AMDAR information, and to Robert Graham for activating the system to plot observation locations. The labours of Ingrid Letshabo and Didi Enslin in battling with the archive tapes is much appreciated. As ever, gratitude is expressed to NCEP for the provision of the Eta codes.

REFERENCES

Anderson, S. R., R. J. Graham and M. J. Bader, 2000. The impact of observations on Mesoscale Model forecasts of three-hourly rainfall accumulations. Meteorol. Appl. 7, 193-203.

Graham, R. J., S. R. Anderson and M. J. Bader, 2000. The relative utility of current observation systems to global-scale NWP forecasts. Q. J. R. Meteorol. Soc. 126, 2435-2460.

Cardinali, C., L. Isaksen and Erik Andersson, 2003. Use and impact of automated aircraft data in a global 4DVAR data assimilation system. Mon. Wea. Rev., 131, 1865-1877.

Edwards, M., 2003. AMDAR over southern Africa.. Proc. SASAS 2003, Maintaining the Balance between Fundamental and Problem-Solving Research, Pretoria, 13-14 October 2003, p 1.4.

Fournier, G., 2003. Results from AMDAR data impact studies. Proc. SASAS 2003, Maintaining the Balance between Fundamental and Problem-Solving Research, Pretoria, 13-14 October 2003, p 1.2.

Riphagen, H. A., J. D. Gertenbach, M. P. de Villiers and K. J. Rae, 1998. The effect of radiosonde and buoy reduction on numerical prediction products at the South African Weather Bureau. Preprints: 12th Conference on Numerical Weather Prediction, Phoenix, Arizona, 11-16 January 1998, American Meteorological Society, 1.8.

Riphagen, H. A., M. Edwards and C. L. Bruyère, 2001. South African participation in the international AMDAR experiment: The effect of additional aircraft data on Eta model forecasts. Proc. SASAS 2001, Hypothesising the process, processing the hypothesis, Cape Town, South Africa, 6-7 September 2001, p 48.

Riphagen, H. A., 2003. Further results from the South African AMDAR observing system experiment. Proc. SASAS 2003, Maintaining the Balance between Fundamental and Problem-Solving Research, Pretoria, 13-14 October 2003, p 1.5.

Stickland, J, 2003. AMDAR data quality and requirements. Proc. SASAS 2003, Maintaining the Balance between Fundamental and Problem-Solving Research, Pretoria, 13-14 October 2003, p 1.3.

Tennant, W. J., H. A. Riphagen, J. D. Gertenbach, M. P. de Villiers and K. J. Rae, 1997. The effect of radiosonde and buoy reduction on numerical prediction products at the South African Weather Bureau. Proceedings of CGC/WMO Workshop on the Impact of Various Observing Systems on Numerical Weather Prediction, Geneva, 7-9 April, (Jean Pailleux, Editor), World Weather Watch Technical Report No. 18, WMO/TD No. 868, 165-183.

Zapotocny, T. H., and Co-Authors, 2002. W. Forecasting 15, 603-621.

Zapotocny, T. H., W. P. Menzel, J. P. Nelson III and J. A. Jung, 2002. W. Forecasting 17, 263-285.

Table 1. Total number of wind reports during the experiment by analysis time

WIND			TOTAL NUMBER OF REPORTS							
			AR	AU	EU	KL	LH	MK	QF	SA
00Z	t-12	for 12Z	5	2249	4064	189	26	7348	0	15083
03Z	t-9	for 12Z	138	2902	20646	4493	229	21611	0	30231
06Z	t-6	for 12Z	182	5253	26755	6536	478	26412	18	35004
09Z	t-3	for 12Z	92	13398	21740	4585	312	22139	93	34889
12Z	t	for 12Z	8	14476	12621	3630	265	19337	146	22499
12Z	t-12	for 00Z	0	11435	5447	1013	109	11565	0	20904
15Z	t-9	for 00Z	1	14364	25031	3322	392	21313	169	34590
18Z	t-6	for 00Z	430	14425	22037	5721	1081	15193	212	32998
21Z	t-3	for 00Z	128	14390	24661	5147	426	15511	207	27102
00Z	t	for 00Z	191	7887	10885	1458	250	16065	34	17806

Table 2. Total number of mass (temperature) reports during the experiment by analysis time

MASS			TOTAL NUMBER OF AIRCRAFT REPORTS							
			AR	AU	EU	KL	LH	MK	QF	SA
00Z	t-12	for 12Z	5	1376	2527	189	5	4106	0	8331
03Z	t-9	for 12Z	138	2279	16766	4493	160	17013	0	24039
06Z	t-6	for 12Z	180	3801	21456	6536	332	20848	18	27857
09Z	t-3	for 12Z	90	9264	17326	4585	241	18047	93	27409
12Z	t	for 12Z	6	9719	10728	3630	203	14494	146	16746
12Z	t-12	for 00Z	0	10481	3811	1012	88	8171	0	13796
15Z	t-9	for 00Z	0	13711	20927	3322	323	16535	169	28228
18Z	t-6	for 00Z	0	15489	20543	5333	381	13944	97	32411
21Z	t-3	for 00Z	3	10978	24550	5551	230	13087	117	22227
00Z	t	for 00Z	15	2370	9296	1383	44	12009	24	9911

Table 3. Vertical distribution of wind reports during the experiment

hPa	AR	AU	EU	KL	LH	MK	QF	SA
lt 100	0	0	0	1	0	7	0	0
200 - 100	16	15084	7965	4765	299	24702	122	46367
300 - 200	406	41382	91116	10418	1252	78826	320	151377
400 - 300	12	3057	11302	645	43	2240	47	9623
500 - 400	0	2422	4274	282	21	2161	26	3689
600 - 500	0	2443	21664	2515	169	11936	26	17800
700 - 600	0	2386	19063	2312	122	10941	26	16130
800 - 700	0	5138	47017	7412	313	13733	66	45276
900 - 800	3	2358	40926	4551	246	15142	31	30750
1000- 900	7	70	29158	2013	250	45780	0	31109
gt 1000	0	11	4716	324	31	4185	0	4675

Table 4. Vertical distribution of mass reports during the experiment

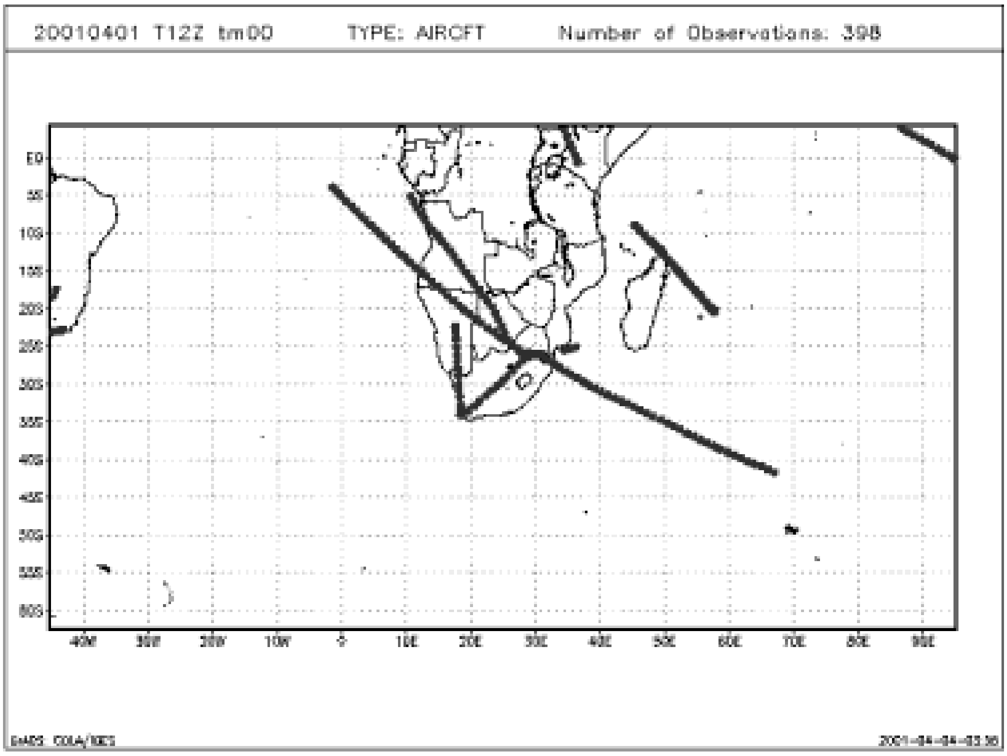
hPa	AR	AU	EU	KL	LH	MK	QF	SA
lt 100	0	0	0	0	0	3	0	0
200 - 100	16	10213	14749	4765	217	16306	122	30924
300 - 200	406	31362	74017	10418	801	59892	320	104352
400 - 300	10	2709	10282	645	39	1686	47	7956
500 - 400	0	2080	3607	282	19	1596	26	2888
600 - 500	0	2092	18302	2515	131	8776	26	14547
700 - 600	0	2060	16149	2312	104	8060	26	13371
800 - 700	0	4820	40028	7412	251	10123	66	36834
900 - 800	3	2200	34565	4551	206	11307	31	24857
1000- 900	2	70	24588	2013	216	33882	0	24789
gt 1000	0	11	3816	324	23	2912	0	3621

Table 5. Average RMS errors and impacts from 01031200 to 02112200 (approximately 1300 cases) for the parallel run testing the exclusion of AMDAR data. The impacts in the Zapotocny (2000) sense are the differences in RMSE between the two runs (NO-AMDAR minus AMDAR), with positive values indicating a smaller error for the AMDAR run.

FIELD	RUN	RMSE		IMPACT	
		24-h	48-h	24-h	48-h
PMSL hPa	AMDAR	1.811	2.474	0.006 (0.33%)	0.004 (0.16%)
	NO-AMDAR	1.817	2.478		
Z850 dam	AMDAR	1.328	1.787	0.004 (0.30%)	0.002 (0.11%)
	NO-AMDAR	1.332	1.789		
T850 K	AMDAR	1.606	2.188	0.003 0.19%)	0.003 (0.14%)
	NO-AMDAR	1.608	2.190		
Q850 g/kg	AMDAR	1.465	1.741	0.002 (0.14%)	0.002 (0.11%)
	NO-AMDAR	1.466	1.743		
RH850 %	AMDAR	15.30	18.37	0.011 (0.07%)	0.012 (0.06%)
	NO-AMDAR	15.31	18.39		
Z500 dam	AMDAR	1.569	2.422	0.003 (0.19%)	0.002 (0.08%)
	NO-AMDAR	1.572	2.423		
T500 K	AMDAR	0.977	1.386	0.004 (0.41%)	0.003 (0.22%)
	NO-AMDAR	0.981	1.389		
Z250 dam	AMDAR	2.176	3.500	0.013 (0.59%)	0.005 (0.14%)
	NO-AMDAR	2.189	3.506		
T250 K	AMDAR	1.030	1.408	0.006 (0.44%)	0.002 (0.14%)
	NO-AMDAR	1.036	1.410		
U250 m/s	AMDAR	0.462	0.619	0.005 (1.07%)	0.002 (0.32%)
	NO-AMDAR	0.467	0.621		
V250 m/s	AMDAR	0.466	0.640	0.004 (0.85%)	0.002 (0.31%)
	NO-AMDAR	0.470	0.642		

Table 6. Verification against radiosondes for temperature for the period August 2000 to April 2002. Percentage impacts are given for five stations: Cape Town (68816), Irene (68263), Durban (68588), De Aar (68538) and Windhoek (68110). NC is the number of cases for each comparison. Bold-face indicates positive AMDAR impact.

STATION		CAPE TOWN		IRENE		DURBAN		DE AAR		WINDHOEK	
h	hPa	NC	Impact %	NC	Impact %	NC	Impact %	NC	Impact %	NC	Impact %
00	850	464	**1.955**	297	**0.329**	282	-0.153	264	**0.549**	.	.
00	700	464	**0.924**	394	**1.055**	281	**2.250**	264	**0.290**	126	**5.274**
00	500	463	**0.927**	391	**0.770**	281	**0.894**	264	-0.759	125	**0.087**
00	250	460	**1.578**	386	**4.107**	281	**1.263**	264	**2.383**	123	**10.70**
12	850	464	**0.619**	297	**0.148**	282	**0.468**	264	**0.646**	.	.
12	700	464	**1.347**	394	**3.146**	281	**0.994**	264	**1.681**	126	**0.457**
12	500	463	-0.512	391	**1.827**	281	**1.670**	264	**0.033**	125	**3.520**
12	250	460	**0.761**	386	**1.062**	281	**1.016**	264	**1.190**	123	**5.765**
24	850	464	**0.342**	297	**0.036**	282	**1.601**	264	-0.558	.	.
24	700	464	-0.539	394	**0.716**	281	**1.599**	264	-0.291	126	**0.731**
24	500	463	-0.142	391	**1.267**	281	-0.996	264	**0.160**	125	-2.239
24	250	460	-0.936	386	-0.121	281	**1.746**	264	**2.317**	123	**5.306**
36	850	464	**0.386**	297	-0.423	282	-0.175	264	**0.702**	.	.
36	700	464	-0.357	394	**0.385**	281	-0.888	264	**0.314**	126	**1.115**
36	500	463	-0.081	391	-0.401	281	**0.145**	264	-0.555	125	**0.322**
36	250	460	**1.158**	386	-0.024	281	**0.136**	264	-1.112	123	**3.081**
48	850	464	**0.011**	297	**0.459**	282	**0.250**	264	**0.621**	.	.
48	700	464	**0.401**	394	-0.892	281	**1.898**	264	-0.173	126	**0.703**
48	500	463	-0.072	391	**1.745**	281	-0.174	264	**0.205**	125	**0.858**
48	250	460	**0.055**	386	-1.112	281	**0.542**	264	**2.342**	123	**1.429**



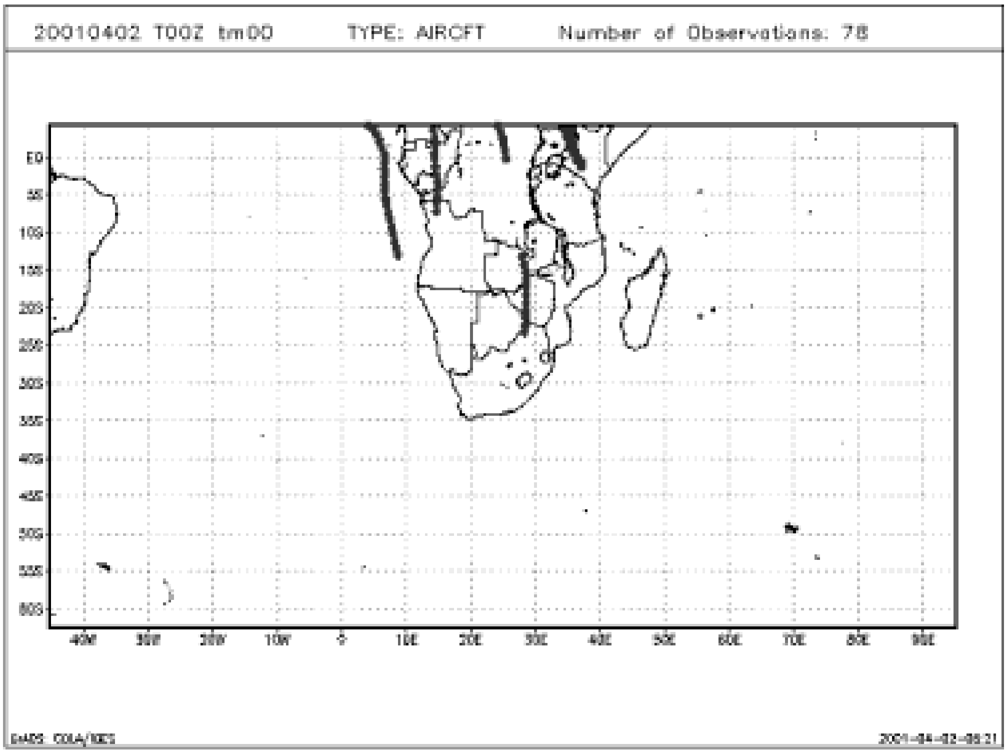


Figure 1. Typical AMDAR coverage over the southern African 'analysis region'

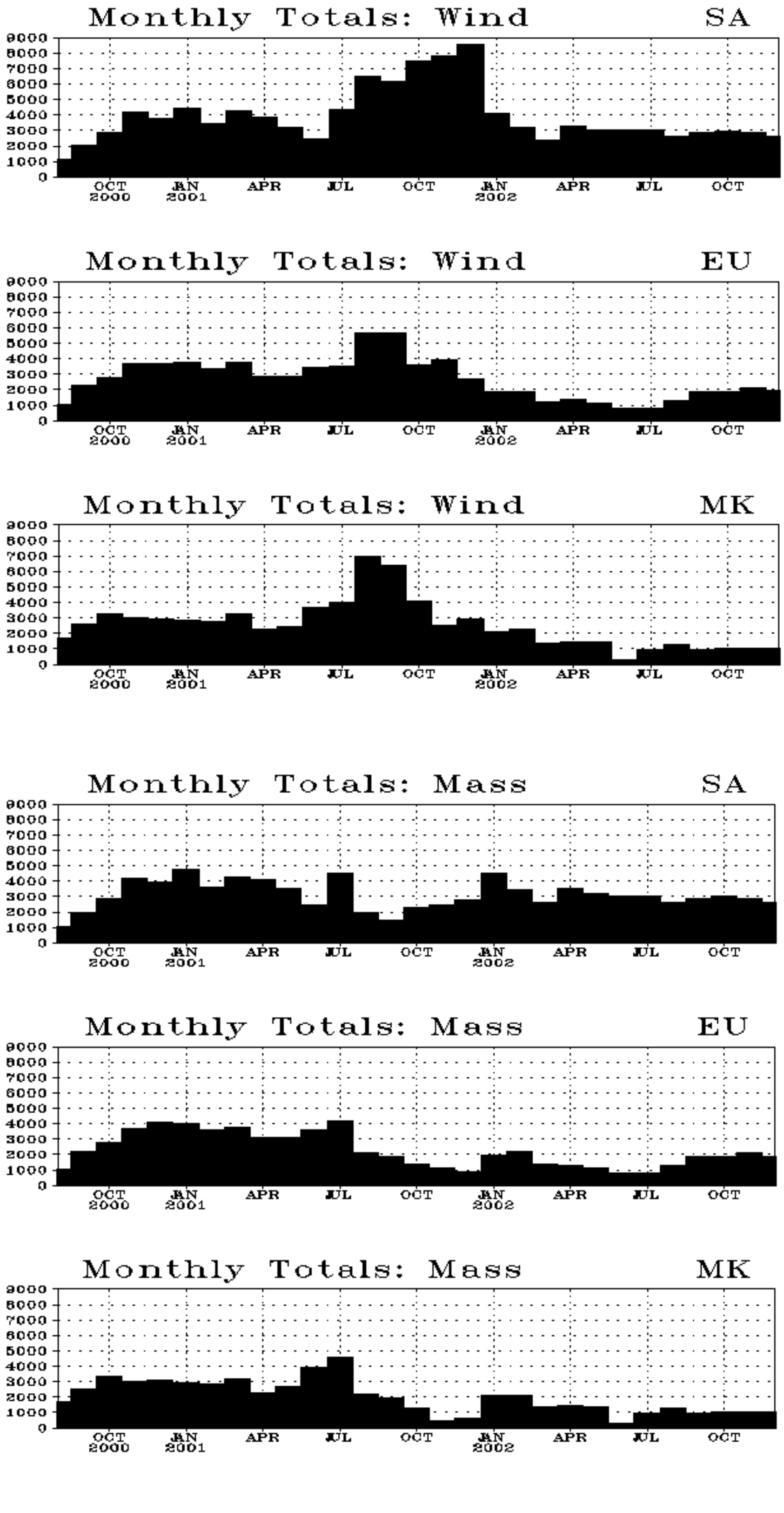


Figure 2. Monthly totals of AMDAR reports during the experiment

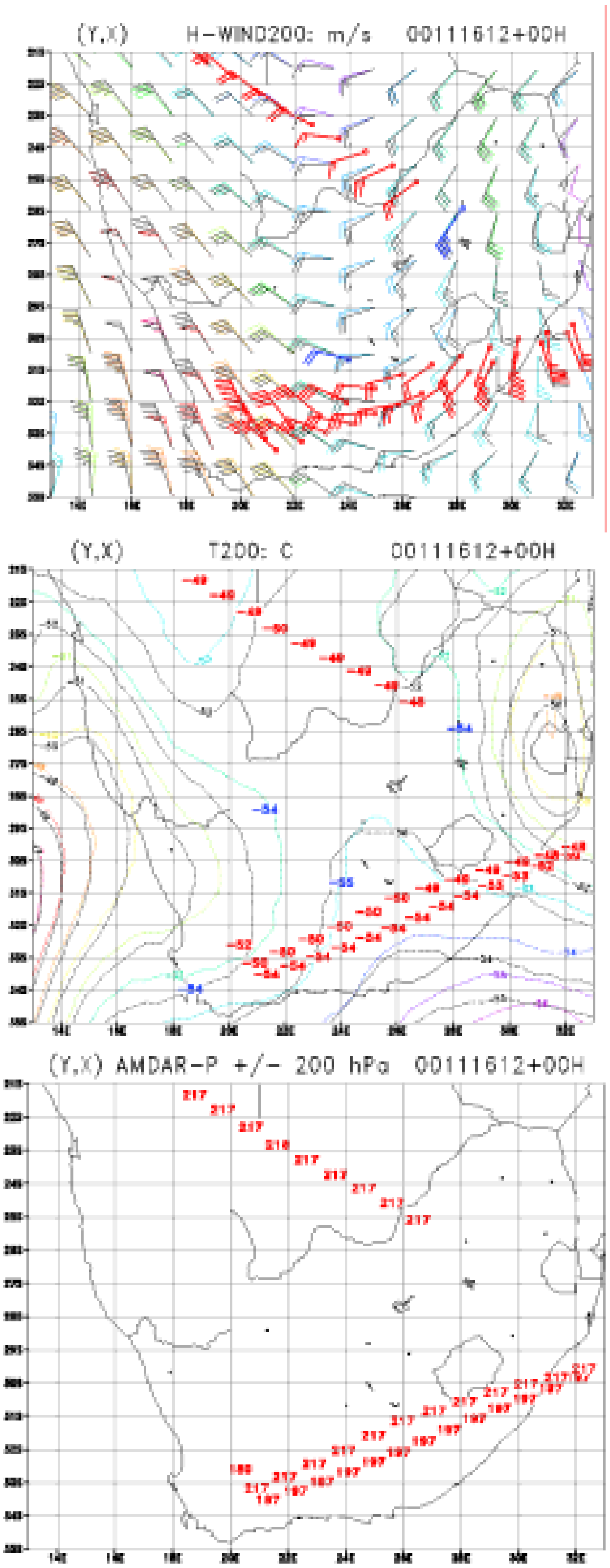


Figure 3. Overlays of with-AMDAR analyses (coloured), without-AMDAR analyses (black), radiosonde reports (solid blue) of wind and temperature at 200 hPa, together with AMDAR observations within 25 hPa of 200 hPa for 2000111612. The bottom view shows the actual pressures of the AMDAR observations.

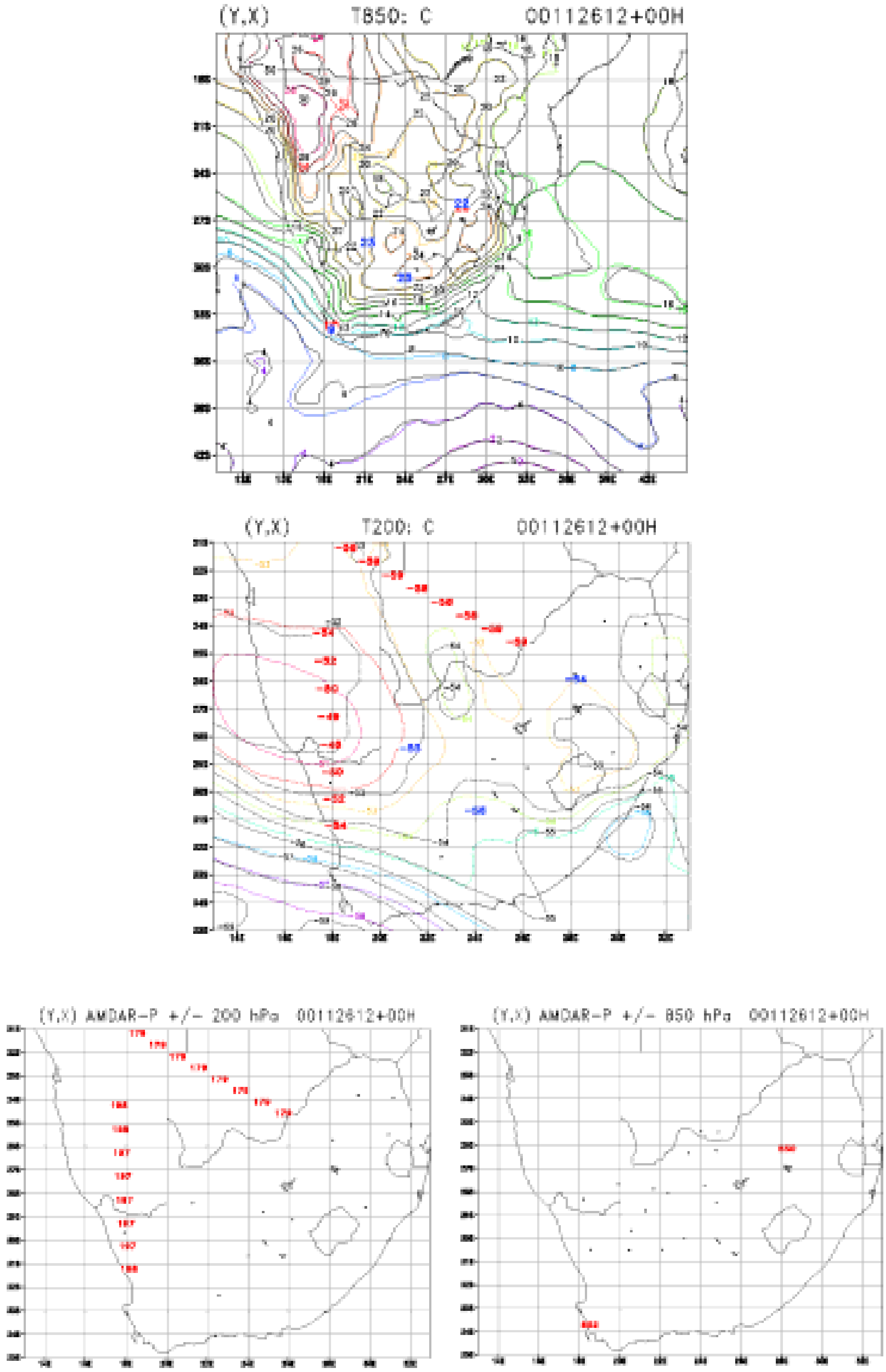


Figure 4. Overlays of with-AMDAR analyses (coloured), without-AMDAR analyses (black), radiosonde reports (solid blue) of temperature at 850 and 200 hPa, together with AMDAR observations within 25 hPa of 850 or 200 hPa for 2000112612. The bottom views show the actual pressures of the AMDAR observations.

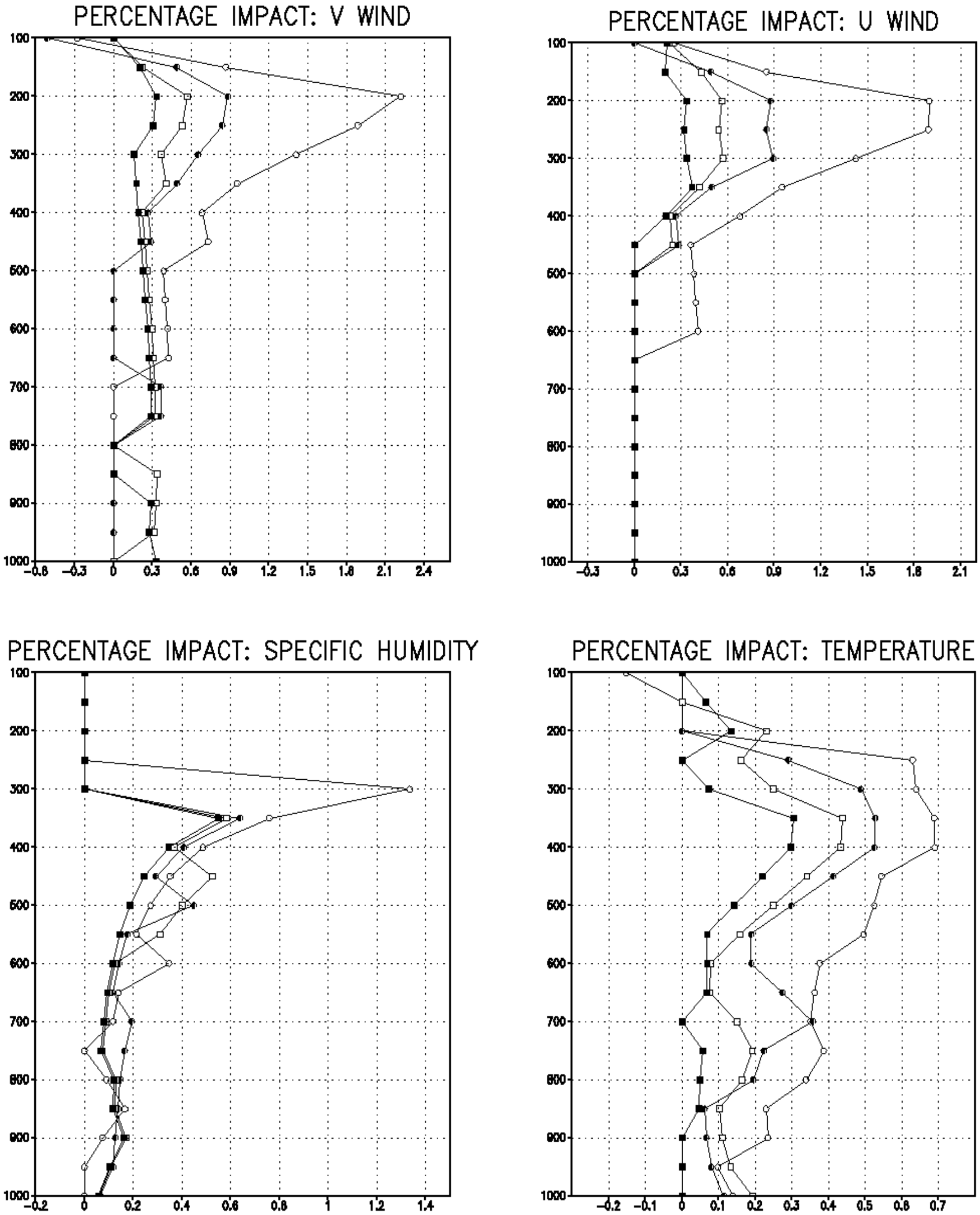


Figure 5. Vertical variation of percentage impact over the period April 2002 to January 2003 for temperature, specific humidity and u- and v-wind components for 12-h (open circles), 24-h (closed circles), 36-h (open squares) and 48-h (closed squares) forecasts.

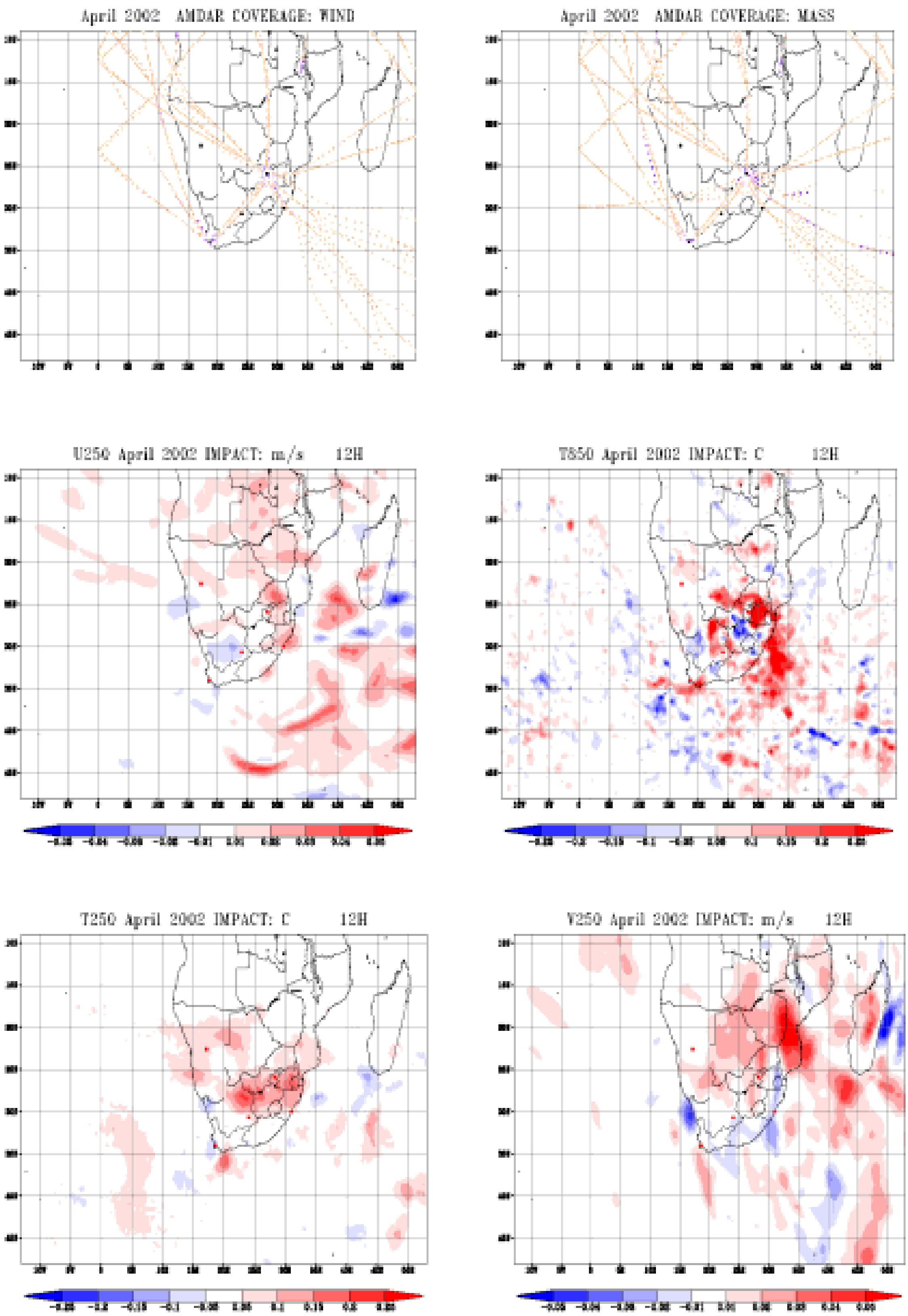


Figure 6. Average coverage and AMDAR impact for 12-h forecasts during April 2002. In the coverage views (one dot per report) orange indicates upper-level reports located at and above 300 hPa and purple reports below 300 hPa. Red indicates positive impact and blue negative in the impact views.

A Four-Season Impact Study of Rawinsonde, GOES and POES Data in the Eta Data Assimilation System

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1. Introduction

The impact of in-situ rawinsonde (RAOB) data and remotely sensed Geostationary Operational Environmental Satellite (GOES) and Polar-orbiting Operational Environmental Satellite (POES) data routinely used in NCEP's Eta Data Assimilation/Forecast System (EDAS) is studied for 15-day periods during Fall 2001, Winter 2001/2002, Spring 2002 and Summer 2002. During these periods, a 32-km version of the EDAS is run thirteen times at both 0000 UTC and 1200 UTC. The thirteen runs include a control run, which utilizes all data types routinely used in the EDAS; three experimental runs in which either all rawinsonde, GOES, or POES data are denied; and additional experimental runs where selected observing system components are individually denied. Differences between the experimental and control runs are then accumulated over the 15-day periods and analyzed to demonstrate the 24- and 48-hr forecast impact of these data types in the EDAS. Conventional meteorological terms evaluated include mean sea-level pressure as well as temperature, both components of the wind, and relative humidity. Comparisons are made on seven pressure levels extending from near the earth's surface to the lower stratosphere. The diagnostics are computed over both the entire horizontal model domain, and within a subsection covering the continental United States and adjacent coastal waters (extended CONUS).

2. Design of Observing System Experiment

All runs used the EDAS at the 32 km / 60 layer resolution. The experiments were run on the native Eta model E-grid, but all results were interpolated to, diagnosed and displayed on either the 91 km NGM Super C grid (104 grid, NCEP Office Note 388) or the AWIPS regional 40 km grid covering CONUS and adjacent coastal waters (CONUS 212 grid, Office Note 388). Horizontal and vertical interpolations of the Eta model variables to isobaric surfaces and diagnostic grids were performed within the NCEP Eta post-processor (Treadon 1993).

The RMS forecast impact (FI**)** is evaluated as

$$FI \;=\; 100\times\left\{\left(\sqrt{\frac{\sum_{i=1}^{N}(D_i - A_i)^2}{N}} \;-\; \sqrt{\frac{\sum_{i=1}^{N}(C_i - A_i)^2}{N}}\right) \Big/ \sqrt{\frac{\sum_{i=1}^{N}(C_i - A_i)^2}{N}}\right\} \quad . \qquad (1)$$

In (1) **N** is the total number of grid points in the diagnostic evaluation. The variables **C** and **D** are the 24-hr (48-hr) control and denied forecasts, respectively, and **A** is the 00-hr EDAS control analysis containing all data types valid 24-hrs (48-hrs) after the forecast began. In (1) the first term on the right hand side enclosed by parentheses can be considered the error in the denied forecast. The second term enclosed by parentheses can be considered the error in the control forecast. Dividing by the error in the control forecast in (1) and multiplying by 100 normalizes the results and provides a percent improvement with respect to the RMS error of the control forecast. A positive forecast impact means the forecast compares more favorably to the corresponding analysis with the data type included than with it denied.

All time-averaged forecast impact diagnostics exclude the first day of each seasonal time period. This delay in evaluating the statistics allows more time for the impact of the denied data to be removed from the model initial conditions and reduces the 16-day seasonal windows to 15 days diagnostically. Finally, it is important to note that all four 15-day periods used in this study were run with the EDAS operating in "full-cycling" mode. In the context of this work, full-cycling involves denying the particular aggregate data type for all model runs and carrying the results of each 12-hr assimilation cycle forward to the starting point for the next 12-hr assimilation.

Three aggregate data types are denied in this study, designated RAOB, GOES and POES. The RAOB aggregate data consists of both mass and wind information, while the GOES and POES aggregate data includes both radiance and wind information. Therefore, these aggregate denials are indicative of the impact that a satellite "failure" might have, or if the entire rawinsonde network were removed.

3. Results

The 24-hr domain-wide results show that a positive forecast impact is achieved from all three data sources during all four seasons. Figure 1 shows the four season results for the system aggregrates (RAOB, GOES, POES) and individual subsystems. Temp, RH, and U component wind impact distributions are quite similar. HIRS impact is stunted. Cumulatively, the rawinsonde data has the largest positive impact over both the entire model domain and extended CONUS. However, GOES data has the largest contribution for several fields, especially moisture during summer and fall 2001. In general, GOES data also provides larger forecast impacts than POES data, especially for the wind components. All three data types demonstrate comparable forecast impact in terms of relative humidity. Finally, RAOB and POES data display largest positive forecast impact in the lower stratosphere during three of the four seasons. Figure 2 shows the geographical distributions of the four season, time averaged, 24-hr forecast impact (%) for 300 hPa u-component from aggregate RAOB, GOES and POES observations. From the 00 hour sensitivity, the RAOB impact has drifted north into the arctic and GOES impact has moved from the Pacific over the western CONUS. POES impact has disappeared, even though the 00 hour sensitivity was as significant as the GOES aggregate.

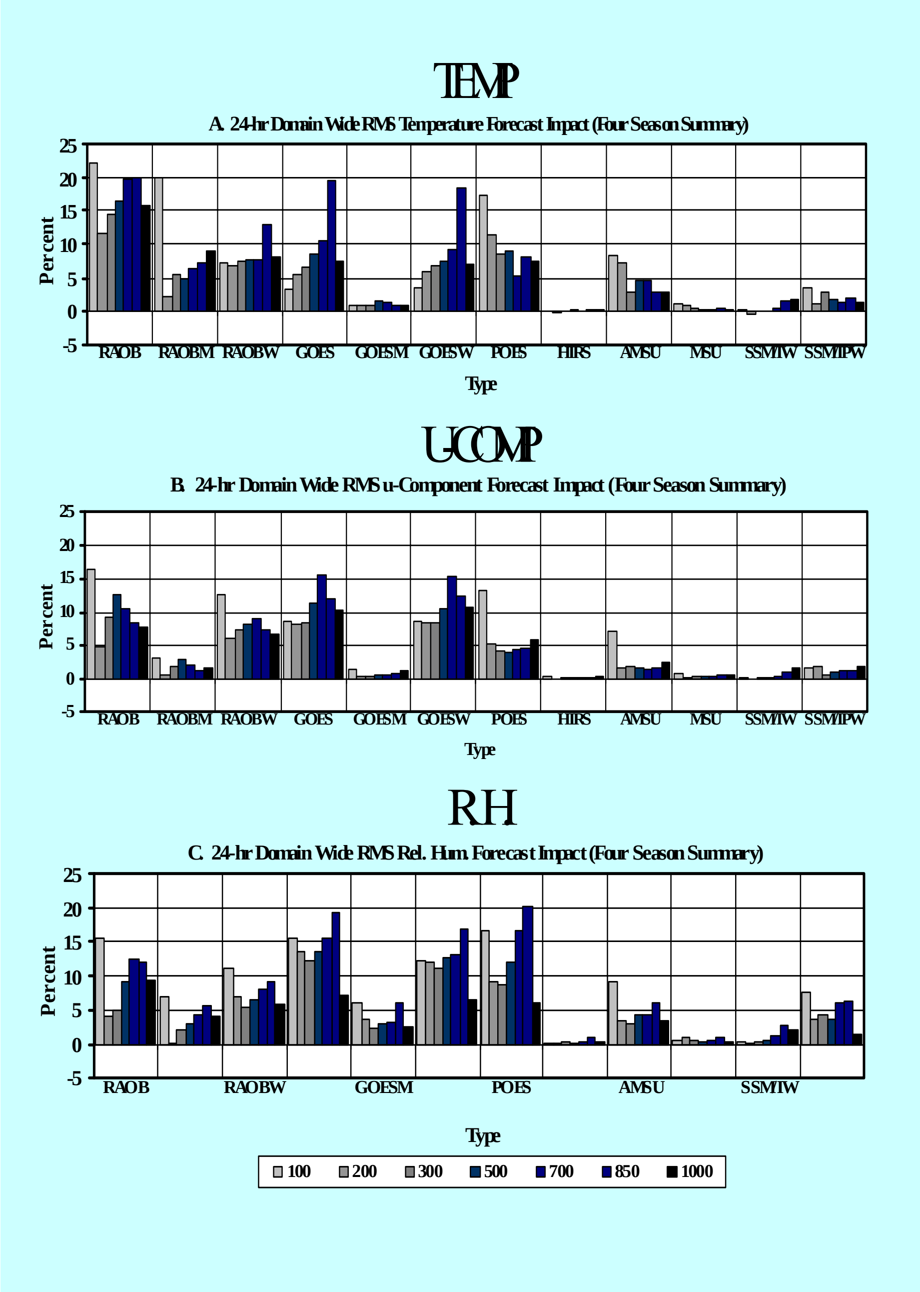

Figure 1: Four season summary of time averaged forecast impact (%) results for three standard meteorological fields after 24-hrs of Eta model integration without RAOB (temp and wind), RAOBM (temp only), RAOBW (wind only), GOES (temp and wind), GOESM (temp), GOESW (wind), POES (HIRS, AMSU, and MSU), HIRS, AMSU, MSU, SSMIW (low level winds), SSMIPW (total precipitable water). Only results for the 104 grid are shown. The time period examined utilizes a 32 km EDAS for both the assimilation and forecast.

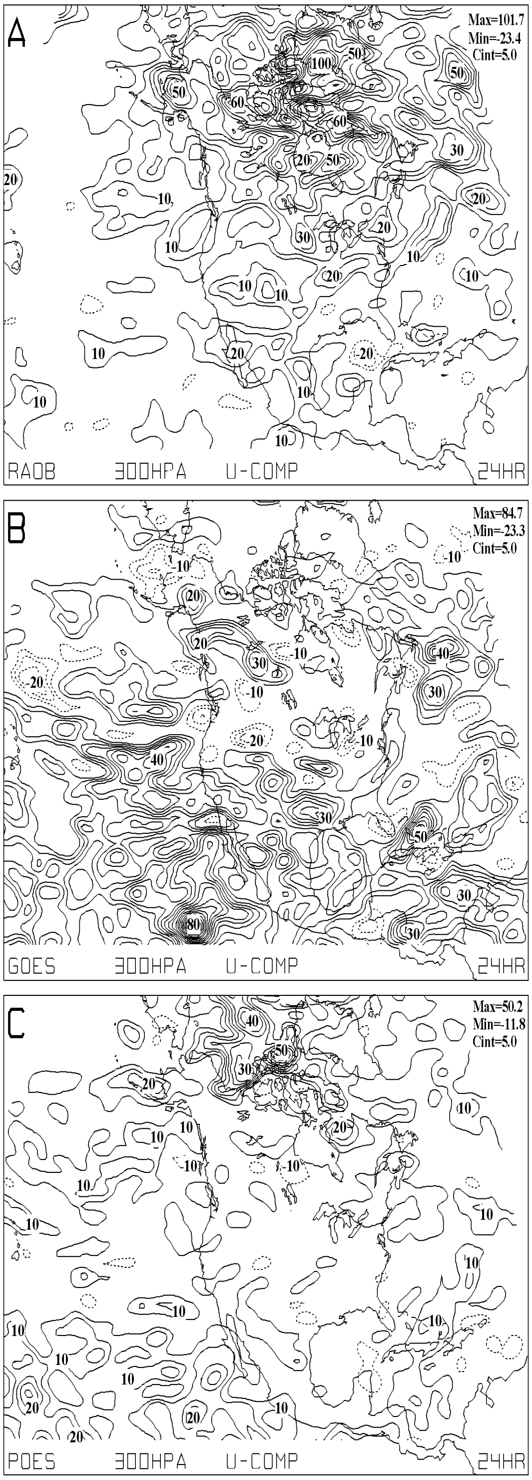

Figure 2. Geographical distributions of four season, time averaged, 24-hr forecast impact (%) for 300 hPa u-component from aggregate (A) RAOB, (B) GOES and (C) POES observations. The zero contour has been suppressed.

4. Conclusions

- All data types provide some positive forecast impact in the four season summary and each individual season.
- Largest forecast impact is seen at 100 hPa. It is especially noticeable from RAOB and POES observations.
- GOES and POES impact is as large as RAOB impact to RH in the four season summary.
- GOES and RAOB provide nearly equal impact to wind, with POES being somewhat less.
- RAOB and GOES wind observations are more important than mass observations.
- Forecast impact at 48-hrs of all data types drops by at least a factor of two during all seasons.
- GOES data shows a preference for providing nearly equal improvement to the 0000 and 1200 UTC forecast cycles, while RAOB and especially POES data provide asymmetric forecast impacts between 1200 UTC and 0000 UTC.

References

NWS, cited 2000b: EDAS. [Available online from http://www.emc.ncep.noaa.gov/mmb/gcp/logs/etalog]

Treadon, R., 1993: The NMC Eta model post processor: A documentation. Office Note 394, National Oceanic and Atmospheric Administration, 42 pp. [Available from NASA Goddard Space Flight Center, Wallops Flight Facility, Wallops Island, VA 23337.]

Zapotocny, T., W. P. Menzel, J. A. Jung, and J. P Nelson, 2004. A Four Season Impact Study of Rawinsonde, GOES and POES Data in the Eta Data Assimilation System. Parts I and II: Contribution of the Components. Conditionally accepted for publication in Weather and Forecasting.

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Impact studies performed with the LAM system ALADIN

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****HMS, Budapest, Hungary*
*****Maroc-Meteo, Casablanca, Morocco*

Abstract

The Limited Area Model ALADIN and its 3D-Var assimilation system have been used for investigation of the impact of various types of atmospheric observation, as MSG radiance, satellite bogus humidity profiles, satellite wind SATOB, ATOVS, AMDAR, European windprofiler and the additional observation data from the field experiment MAP. Noticeable and positive impact on short range forecast has been found from the case studies with ALADIN 3D-Var assimilation of MSG radiance, satellite bogus humidity profiles, satellite wind SATOB, only slightly positive or neutral impact on the forecasts from the experiments with ATOVS and AMDAR. The European windprofiler and the additional MAP observation in the MAP case study with ALADIN and ECMWF 4D-Var assimilation show generally remarkable impact on the mesoscale numerical simulation over mountainous area.

1. Introduction

In the recent years, more and more observation data have been becoming available for the NWP, like satellite radiance, commercial flight data, windprofiler and the additional observation data from the field experiment. To study the impact of the observations on NWP is important to help make effective use of resources for observation. Within the ALADIN community, an international co-operation among Meteo-France, ZAMG and 12 other European national weather services, several impact studies of observations on NWP have been conducted. In the following, we will give a brief report of the impact studies performed with the LAM system ALADIN.

2. Model

ALADIN is a limited area model with high resolution, which has been developed by Meteo-France, ZAMG, together with 12 other European national weather services, and is in use operationally in those European national weather services. The model can be used in hydrostatic mode (8-12 km horizontal resolution) and non-hydrostatic mode (2-7 km horizontal resolution) for scientific research. The main characteristics of the model are as follows:

- Hybrid vertical co-ordinates; spectral method with bi-periodic extension of the domain using elliptical truncation of double-Fourier series; two-time level semi-Lagrangian advection scheme; semi-implicit time-stepping; fourth order horizontal diffusion; Davies-Kalberg type relaxation and digital filter initialisation (DFI).
- Kessler-type scheme for large scale precipitation; Geleyn's scheme of shallow convection and simple radiation; Bougeault-type scheme of deep convection; Boer-type scheme of gravity wave drag; force-restore method for soil temperature and water; vertical exchange calculation taking into account a planetary boundary layer and a surface layer based on the Louis scheme.
- 3D-Var assimilation, NMC method for calibrating the background error statistics.

3. Results

a) Windprofiler and MAP additional observations

During Mesoscale Alpine Programme (MAP, Binder *et al.* 1996, Bougeault *et al.* 2001) Special Observation Period (SOP) a large number of additional upper-air soundings, instrument flights and high resolution surface observations have been collected. For investigating the impact of the additional MAP observations, mesoscale numerical simulations of MAP IOP2B, one of the most intense rainfall case observed during the MAP SOP from 00UTC 19 Sept. to 06UTC 21 Sept. 1999, have been carried out with ALADIN-AUSTRIA. The assimilation of the MAP additional observations was the ECMWF 4D-Var assimilation system T511/159L60 Cycle24R3 (Keil and Cardinali 2003), 4 assimilation experiments have been used for providing the initial conditions and lateral boundary conditions of the ALADIN simulations:

- **Control**: without any MAP additional observations and European windprofilers
- **Alldata**: with all MAP additional observations and 16 European windprofilers
- **Noprof**: no windprofilers, but with all MAP additional observations
- **MAPre**: MAP-reanalysis, same as **Alldata**, but only 12 European windprofilers

To validate the ALADIN numerical simulations especially over the complex mountainous area (Fig. 1), the precipitation analysis (version 2.0, 25km resolution) from ETH, Zürich, (Frei and Häller 2001); radar precipitation analysis provided by the MAP Data Center, Zürich are used.

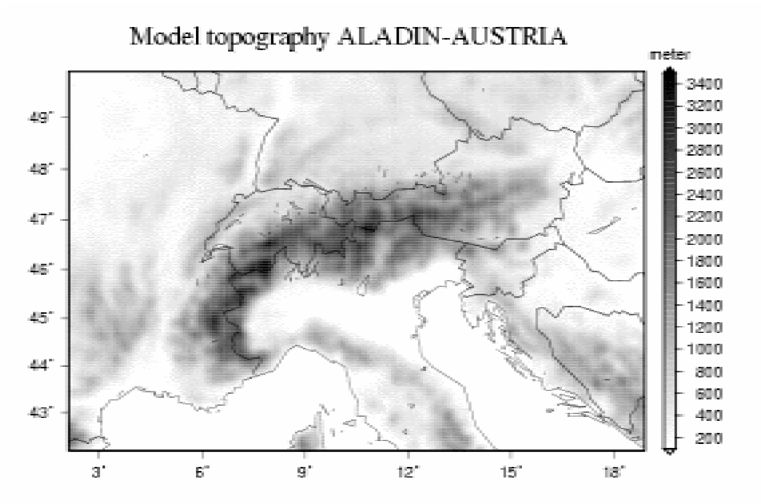


***Figure 1**: Domain of interest of ALADIN-AUSTRIA simulation.*

In Fig.2 and Fig.3, the daily accumulated precipitation from the gauge based precipitation analysis in 25km resolution and the numerical simulations of precipitation averaged onto the 25km grid with the 4 experiments for the 19th and 20th September 1999 are displayed. On the 19th , following the frontal system progression, the accumulated rain maxima are located on the France slopes of the Maritime Alps, Lago Maggiore and Massif Central. Differences between simulation and observation are found in all the experiments, weak rainfall maximum on the Massif Central, too more rain in Piedmont area, strong rainfall related to Apennines, and the rain fell a little bit earlier than the observation in Maritime Alps. The simulation with using MAP additional data **Noprof** doesn't improve the overestimation over Lago Maggiore and Piedmont area, Maritime Alps, and even leads an underestimation in Rhone Valley between France Alps and the Massif Central. The impact of the wind profiler **MAPre** is more positive in the Lago Maggiore area and in Rhone Valley than the experiment **Noprof**. It looks to dry the air in the Maritime Alps and Apennines. The 4 in the assimilation system denied windprofilers (due to the QC) experiment **Alldata** have more moistening impact in Piedmont and Maritime Alps, and drying influence in Rhone Valley, those are not agreed with the observation. During the second day 20th , strong rainfall belt more than 75 mm was found on the southern foothills of the Alps, with maxima over Lago Maggiore, in Dolomites and the strongest in Carnic Alps in north-eastern Italy. In all the simulations, a strong rainfall zone is recognisable on the southern slopes of Italy Alps, but the strongest rainfall maximum in the Carnic region north-eastern Italy is missed, and an overestimation on south side of the Apennines is recovered by all the simulations. No investigation on that failure has been carried on due to lack of the humidity radiosoundings in those two areas. The MAP additional observations **Noprof** intensifies the rainfall over Lago Maggiore, which is close to the observation (**Noprof** vs. **Control**), makes the rainfall maximum more west, i.e. drying the atmosphere in the region Dolomites and Carnic Alps, overestimates the rain north of the Alps in Bavaria. Windprofiler seems to dry the atmosphere in most of the region except in Bergamese and Bavaria (comparison among the experiments **MAPre**, **Noprof** and **Control**); the maximum in Lago Maggiore is remarkably reduced. The impact of the 4 denied windprofilers on the precipitation simulation is in certain sense positive (**Alldata** vs. **MAPre**), better agreement in Lago Maggiore, Dolomites and in north of the Alps Bavaria with the observation.

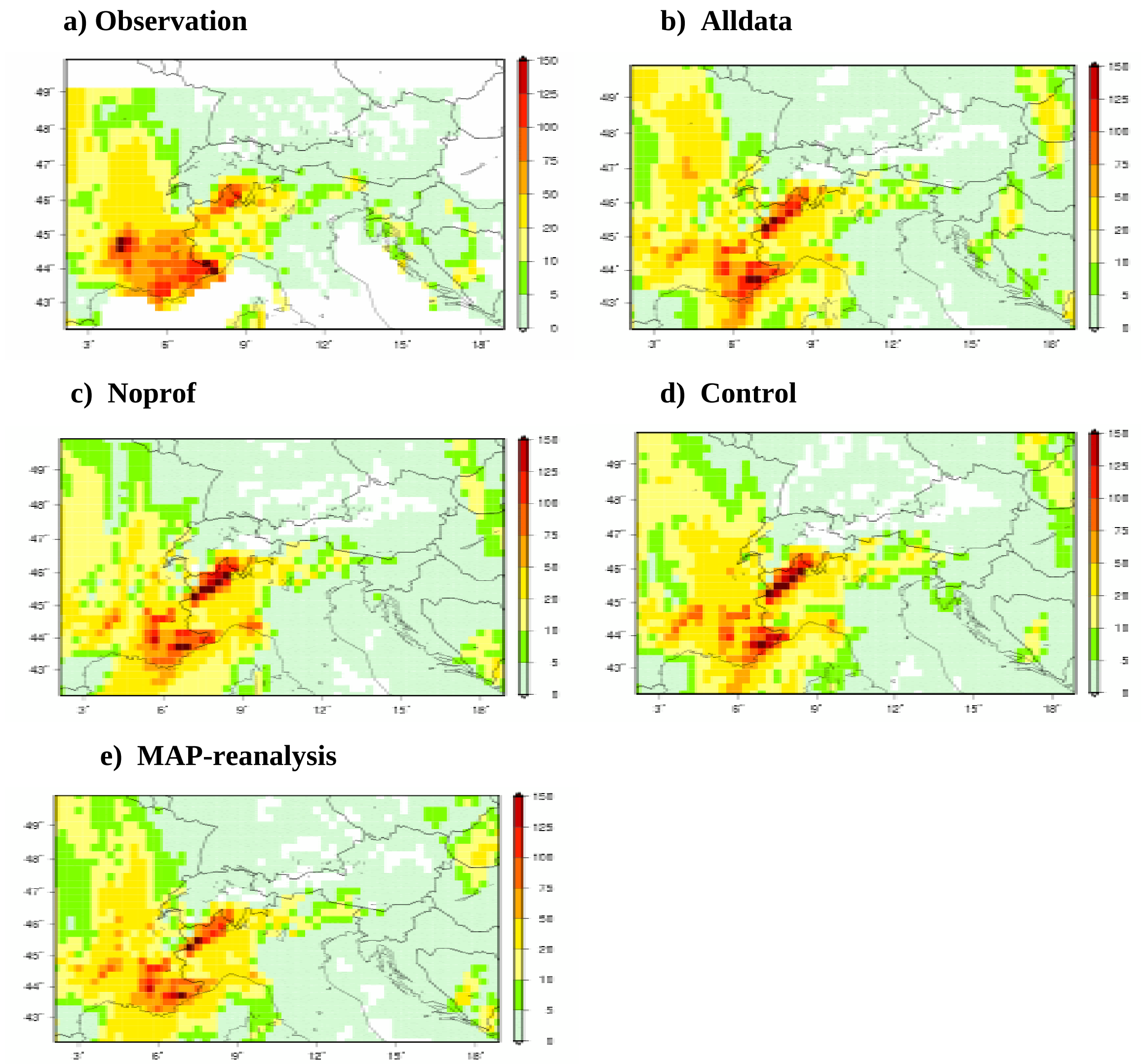
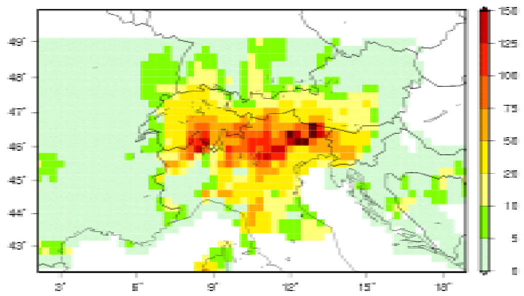


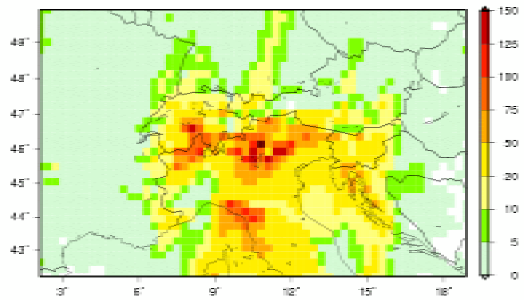
Figure 2: *24 hours accumulated rainfall from 06UTC 19 September 1999 to 06UTC 20 September 1999. All the simulations started at 00UTC 19 September 1999, and integrated to 54 hours.*

Further, in the simulation with MAP-reanalysis a considerable rain belt is over south Italy (not shown), which disappears in the simulation with the 4 denied windprofilers. Unfortunately the rainfall observations there are too sparse, we don't know the truth exactly, but from the satellite images there is no indication for rainfall in this region.

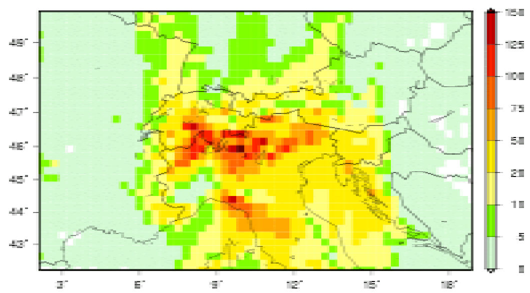
a) Observation



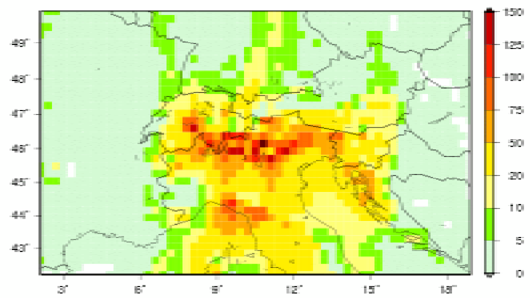
b) Alldata



c) Noprof



e) Control



e) MAP-reanalysis

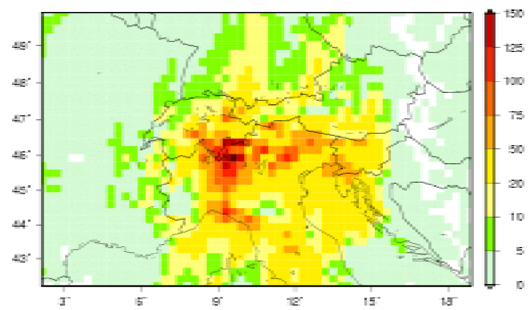


Figure 3: *24 hours accumulated rainfall from 06UTC 20 September 1999 to 06UTC 21 September 1999. All the simulations started at 00UTC 19 September 1999, and integrated to 54 hours.*

b) MSG/SEVIRI radiance *(by T. Montmerle, Meteo-France)*

Recently, the MSG/SEVIRI radiance data has become available. The radiance observations are in visible and infrared spectrum every 15 min. with a horizontal resolution about 5km over Europe. To study the impact of the MSG/SEVIRI radiance, ALADIN 3D-Var was used for assimilating the MSG observations. A case study on 13th. Feb. 2003 shows that positive impact has been found on humidity analysis in mid to high troposphere mainly due to the information carried out by WV channels, but negligible impact on the temperature analysis. The use of MSG/SEVIRI radiance seems to lead more realistic forecast of middle and high level cloud cover (not shown).

c) Satellite Bogus humidity profile *(by V. Guidard, Meteo-France)*

Fig. 4 shows the significant impact of the satellite bogus humidity profile generated from Meteosat imagery on ALADIN short range precipitation forecast. For the case study on 2. Nov. 1999, three experiments has been performed with ALADIN and its 3D-Var, 1) with conventional observation only, 2) Bogus humidity data and conventional observations, and 3) dynamical adaptation, namely, ARPEGE analysis.

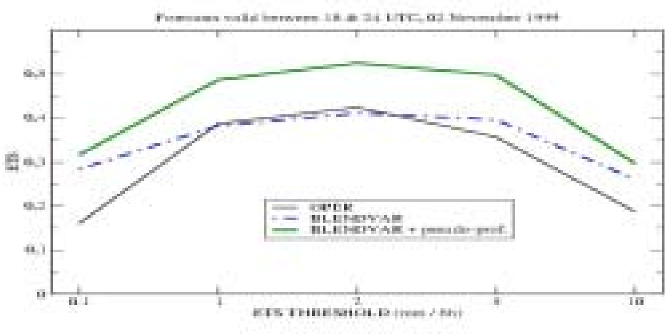


Figure 4. *ETS score of ALADIN short range (6-12h) precipitation forecast against the surface observation.* ***OPER****: ALADIN forecast with ARPEGE analysis;* ***BLENDVAR****: ALADIN forecast with its 3D-Var assimilation of conventional observation, and* ***BLENDVAR+pseudo-prof****.: ALADIN forecast with its 3D-Var assimilation of conventional observation and bogus humidity profile.*

c) Satob *(by Z. Sahlaoui, DMN-Morocco)*

For investigating the impact of the Satob observation, data denial experiments has been conducted for SYNOP, TEMP and Satob etc in DMN-Morocco. Significant impact of Satob has been found on the relative humidity forecast up to 60 hours over North Africa from the study on 4 Dec. 2003, where there are few observations in the region. The too wet structure over Morocco and Libya was improved by using Satob data (not shown).

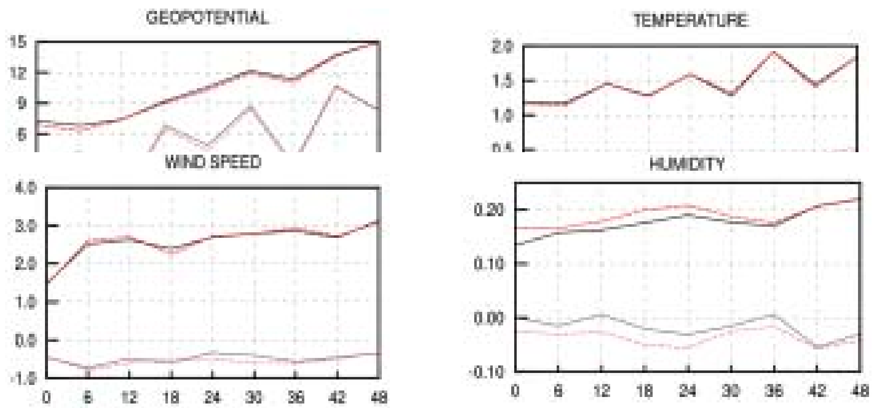


Figure 5. *RMSE and BIAS scores of 48hours forecast on 850 hPa.* ***Red****: ALADIN forecast with assimilated ATOVS data;* ***Black****: ALADIN forecast without assimilated ATOVS data.*

***d) ATOVS** (by G. Bölöni and R. Randriamampianina, HMS)*

The impact of the ATOVS data on ALADIN forecast is studied for the period from 2003.03.20 to 2003.03.06. In the study ALADIN 3D-Var has been used to assimilate the ATOVS data from NOAA15 and NOAA16, AMSU-A channels 5-12 over land and see. The air mass dependent bias due to the RT model for the radiance simulation was corrected by using the algorithm based on an air mass regression scheme (Harries and Kelly, 2001). The comparison of the forecast with the control run (ALADIN 3D-Var with SYNOP and TEMP only) is shown in Fig.5. The assimilation of the ATOVS data leads slight improvement in 850hPa *geopotential* (mostly neutral results for other levels), mostly neutral results for *temperature* and *wind* generally (850hPa is shown), and negative impact on *humidity* in general.

***e) AMDAR** (by G. Bölöni and R. Randriamampianina, HMS)*

In Hungary, an experiment with ALADIN 3D-Var has been carried out for estimating the impact of the wind and temperature reports collected by aircraft, AMDAR data. The test was for the period: 2003.04.18-2003.05.07. The verification scores of 850hPa forecasts of against the control one, which is the assimilation with conventional observations only, are shown in Fig.6. The main outcome of the experiment is that neutral or slight improvement for all variables.

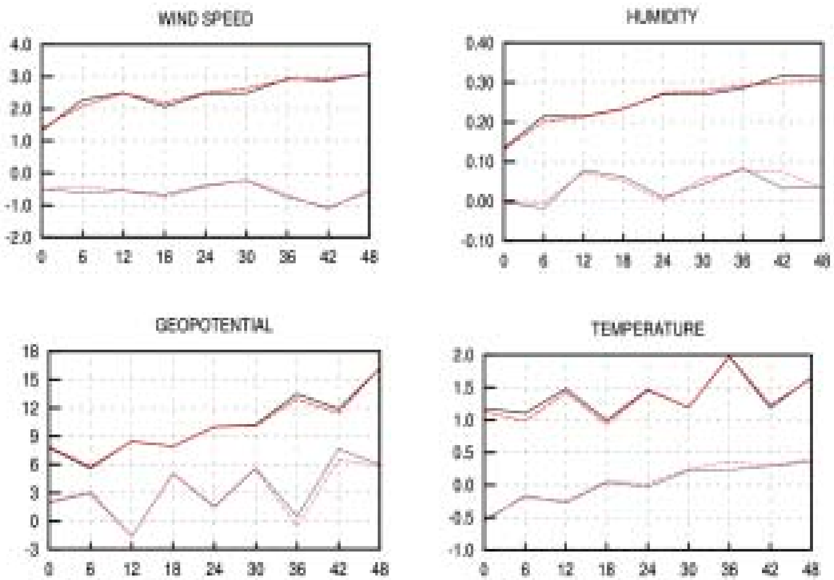


***Figure 6.** RMSE and BIAS scores of 48hours forecast on 850 hPa. **Red**: ALADIN forecast with assimilated AMDAR data; **Black**: ALADIN forecast without assimilated AMDAR data.*

4. Conclusion

Within the ALADIN community, several experiments and case studies with model ALADIN and its 3D-Var assimilation system have been performed for investigating the impact of various observation types on the NWP. We have studied the windprofiler, additional MAP observation data (high-resolution radiosonds, surface obs., and aircrafts and so on), MSG/SEVIRI, satellite bogus humidity profile, Satob, ATOVS and AMDAR. The main conclusions from those studies can be summarized in following:

- European windprofiler, the additional MAP observations (high resolution upper air soundings and surface observations, aircraft, European dropsonds) have significant influence on the mesoscale simulation over complex topography; MAP-reanalysis doesn't always provide the best simulation; the after QC denied windprofilers have remarkable impact on the simulation, sometimes it is positive.
- MSG/SEVIRI: reduction of humidity error in mid to high troposphere mainly due to the information carried out by WV channels, which leads more realistic mid and high level cloud cover forecast; negligible impact on temperature analysis.
- Satellite bogus humidity profile: positive impact on short range precipitation forecast.
- Satob: improvement on the humidity forecast.
- ATOVS & AMDAR: slightly positive or neutral impact on the forecast.

Acknowledgement

We gratefully acknowledge E. Bazile and F. Bouyssel for their help with the MAP case study.

References

P. Binder and C. Schär (eds) 1996, MAP Design Proposal, http://www.map.ethz.ch/proposal.htm.
P.Bougeault, P. Binder, A. Buzzi, R. Dirks, R. Houze, J. Kuettner, R. B. Smith, R. Steinacker, and H. Volkert 2001, The MAP Special Observing Period, *Bull. Am. Meteor. Soc.* **82**, 433-462.

C. Frei and E. Häller 2001, Mesoscale precipitation analysis from MAP SOP rain-gauge data, *MAP newsletter* **15**, 257-260.

C. Keil and C. Cardinali 2003, The ECMWF re-analysis of the Mesoscale Alpine Programme Special Observing Period, *ECMWF Technical memorandum*, **401**, 36pp

Impact of ground-based GPS data on the DWD limited-area model during August 2002*

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ABSTRACT

Two years (2001-2002) of near-real time data from a dense global positioning system (GPS) network in Germany have been monitored at the German Weather Service (DWD). Numerical experiments assimilating vertically integrated water vapour (IWV) observations from ground-based GPS stations into the operational limited-area forecast model of DWD have been carried out. The impact of the assimilation of the GPS data is large in the first 6 hours of the forecast, and negligible in the forecast range after 24 hours. Upper-air verifications against radiosondes show that GPS IWV slightly improves the 6-hour and 12-hour forecast. The use of GPS data was also found to improve some precipitation forecasts during the flooding events of August 2002.

1. INTRODUCTION

The limited-area model of DWD, namely the Lokal Modell (LM), is a non-hydrostatic forecast model for central and western Europe with a spatial grid resolution of approximately 7 km and 35 layers in the vertical. The analysis of LM is produced with a continuous assimilation cycle nudging the model variables towards observations. Only conventional observations are currently used, i.e. humidity information is provided by synops (only at lowest model level) and by radiosondes. Thus, GPS IWV data could be particularly beneficial to the LM moisture analysis because they fill the spatial/temporal gaps in the radiosonde network and are complementary to aircraft wind and temperature measurements. The half-hourly GPS data used in this study are from the dense network processed by the GeoForschungsZentrum, Potsdam within the GASP project (Fig.1).

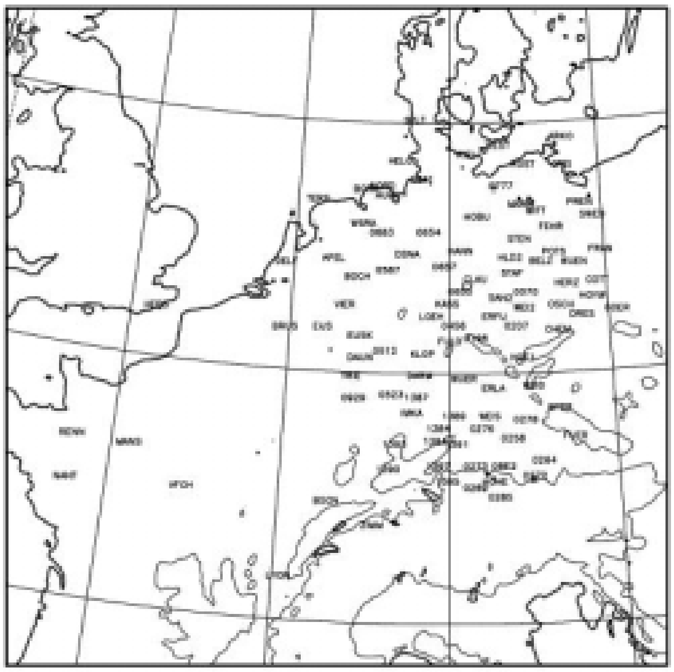

Figure1: The GPS stations used in the assimilation experiments.

The nudging of GPS PW has been implemented following Kuo et al. (1993), i.e. a "pseudo-observed" profile of specific humidity is obtained scaling iteratively the model humidity profile with the ratio of observed to model IWV. The retrieved profile of specific humidity is then nudged into the model. A vertical quality weight function proportional to the specific humidity at saturation and to the thickness of the level, is introduced. Thus, the GPS humidity profile is given greater weight at those levels which can contribute more

* Not presented at the workshop.
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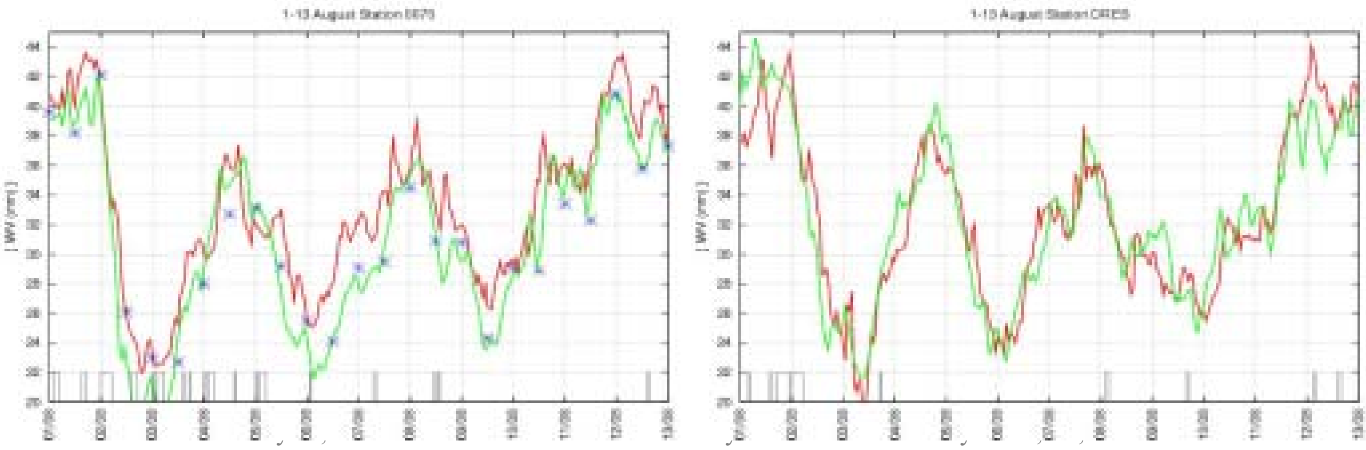
to the integrated value, normally between 700 hPa and 800 hpa, and less at other levels. In order to avoid modifications of the humidity field at upper levels that contribute very little to the GPS measurement, the retrieved GPS profile is neglected above 500 hPa. During the nudging process, the GPS derived profiles are treated like radiosonde profiles, except that the scale of the horizontal correlation function used to spread the GPS information is about 30 km (resulting in a 2-folding decay length of about 50 km at 850 hPa) instead 60 km in order to account for the high number of stations available.

2. ASSIMILATION EXPERIMENTS

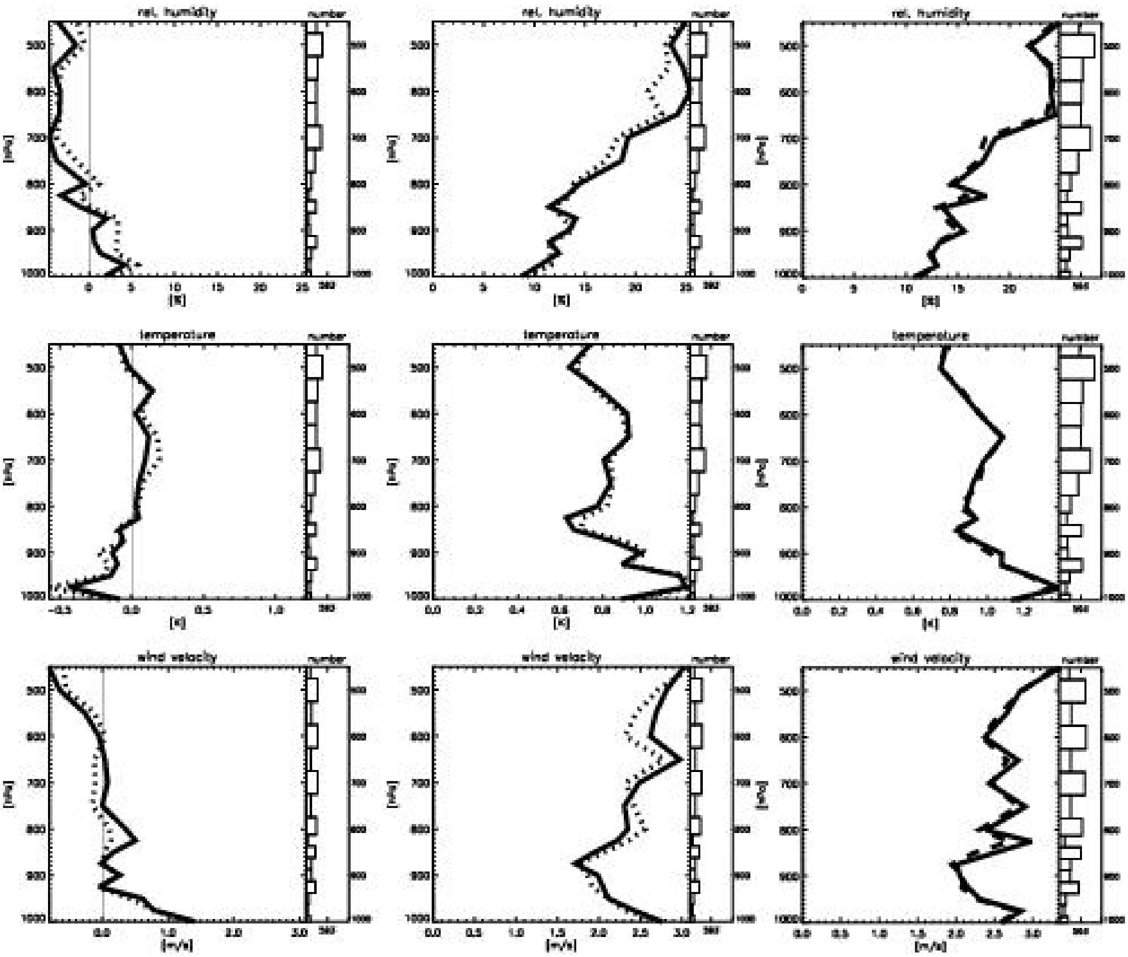
During the first two weeks of August 2002, extremely large amounts of rain fell in many parts of Central Europe, giving rise to overflowing rivers and causing severe damage. Several spells of intense rain afflicted the eastern German region Saxony, in particular the catchment area of the river Elbe, where many stations measured record values of precipitation within a day. For example, on 12 August 2002, 158 mm fell in Dresden, and the highest amount ever observed in Germany of 312 mm fell on a station on the Ore Mountains (Erzgebirge). The DWD´s operational model LM was able to give a fairly good picture of the overall meteorological situation; however, in many forecasts, rain fronts were misplaced and/or their intensity underestimated. The half-hourly IWV measurements were able to accurately capture the rapid evolution and strength of the event (Fig. 2). For example, in the night of 12 August the station in Dresden reported 45 kg m-2, which is the highest value ever observed at this station in the two years of IWV monitoring.



experiment *gps*, the data were used without correction, and in the second one *gpsbc*, a time-dependent bias correction was also applied previously to the GPS data. This correction reduces the GPS IWV values mainly during daytime to fit them better to the model (forecast) climatology. (Specifically, the reduction is set to 0.2 kg m-2 between 18 UTC and 8 UTC of the following day, and in between, it is set to 0.55 kg m-2 on average, with the highest value of 0.96 kg m-2 reached at 14UTC). Its introduction was intended to diminish cases of erroneously excessive rain particularly during the assimilation of GPS IWV as seen in previous experiments. The output of the experiments is compared to that of the operational runs *opr*.

3. RESULTS

The upper-air verification against radiosonde data shows an overall neutral impact of the GPS data in the



forecasts. The experiment with the bias correction performs better than the other, but the difference is very small (not shown). The impact of the GPS data on the rms errors of the 6-hour and 12-hour forecasts (Fig. 3) is slightly positive, whereas the 24-hour forecasts, particularly of upper-trospheric wind direction, are slightly degraded (not shown).

Figure 3: Upper-air verification of 2 daily forecasts started at 00 or 12 UTC against radiosonde data from Germany and sorrounding countries for 2-13 August 2002. Relative humidity (top panel), temperature (middle) and wind velocity (bottom) are verified for 2 daily forecasts started at 00 or 12 UTC for experiment gpsbc with GPS data and bias correction (dotted or dashed lines) and for the control opr without GPS data (solid lines). Left row: mean errors of 6-hour forecasts; middle: rms errors of 6-hour forecasts; right: rms errors of 12-hour forecasts.

A visual evaluation of precipitation patterns from both experiments and operational forecasts against analyses derived from SYNOP observations indicates a positive impact of the GPS data on average. The bias correction has very limited impact in most cases, although in some cases, it does moderately reduce the precipitation amounts. Compared to previous experiments for August 2001, there are fewer cases of spurious rain, but more importantly, some improvements occur in critical weather situations. The forecasts from the experiments with GPS data appear to be more accurate in position and strength of some rain patterns. In the *gps* 18-hour forecast of 12-hourly precipitation valid for 8 August, 18 UTC (Fig. 4), the intense cell of rain is closer to the Ore Mountains (at the plotted German - Czech border) than in the operational one. The same cell became too weak in the *gpsbc* experiment, though. It can also be seen that GPS IWV correctly enhances the rainy patterns in the Hamburg area. The operational 12-24-hour forecast started at 18 UTC of 11 August (valid for 18 UTC of 12 August) shows a band of strong rain which does not extend to the region between the river Elbe and the Ore Mountains, where the largest precipitation amounts were observed (Fig. 5 upper row). The same forecast started from the analyses with GPS data does generate more rain in the region of interest, in the *gpsbc* experiment with values of up to 50 mm. Improvements are also found in the forecast valid for the same time but started 6 hours later (Fig. 5 lower row), yet they are less relevant, likely due to the availability of radiosondes data at 00 UTC. Finally, all the 12-hour forecasts valid for 06 UTC of 13 August locate the cell of torrential rain correctly at the foot of the Ore Mountains, but the realistic values of 100 mm are reached only in *gps* and *gpsbc* (Fig. 6).

obs ***opr***

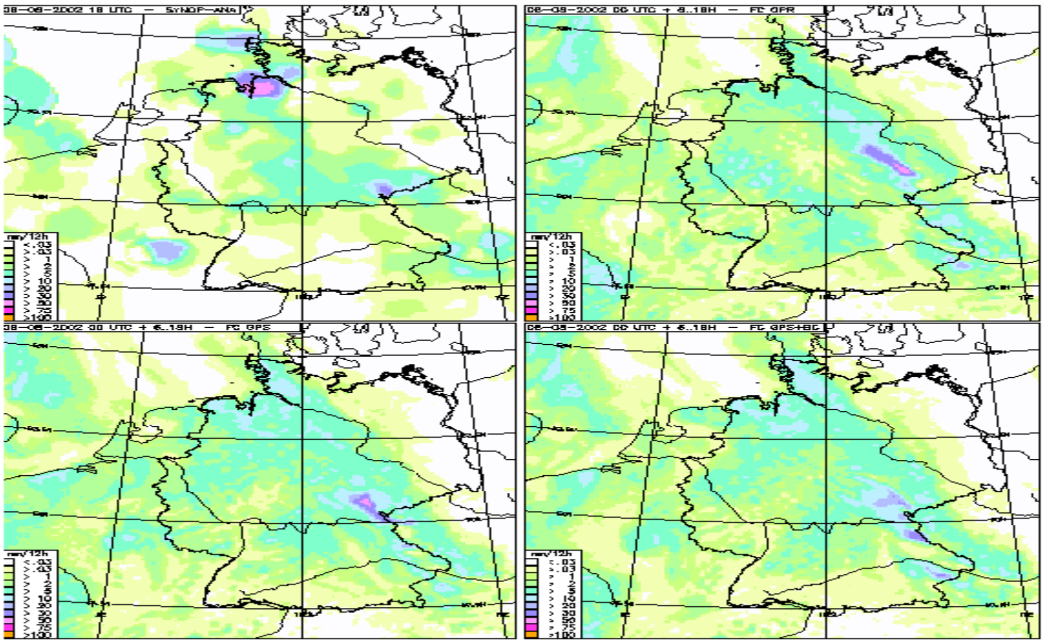


Figure 4: 12-hour sum of precipitation 8 August 2002, 18 UTC, as analysed from synop observations (top left), as forecast with a forecast lead time of 6-18 hours by control run *opr* without GPS data (top right), by experiment *gps* with GPS data (bottom left), and by experiment *gpsbc* with GPS data and bias correction (bottom right).

4. CONCLUDING REMARKS

In comparison to a similar experiment for an 8-day period in August 2001 (Tomassini 2002), the impact of the assimilation of GPS IWV data on the upper-air verification scores has turned out to be far less positive in this August 2002 experiment. In contrast, while the impact on precipitation was mixed and not positive on average in the 2001 experiment, the positive cases outnumbered the negative cases in the 2002 period. The two periods put together, it appears that in summer, a small overall benefit can be achieved from assimilating GP IWV with the current scheme. The diurnal bias correction, which is designed to fit the GPS IWV values better to the model (forecast) climatology in summer, has proven to be a small step in the right direction. Yet it has not resulted in fundamental improvement. The key issue related to the use of IWV is considered to be the vertical distribution of the vertically integrated observed quantity.

Acknowledgments: This study was carried out under the grant of the German Federal Ministry of Education and Research (BMBF) No. 01SF9922/2.

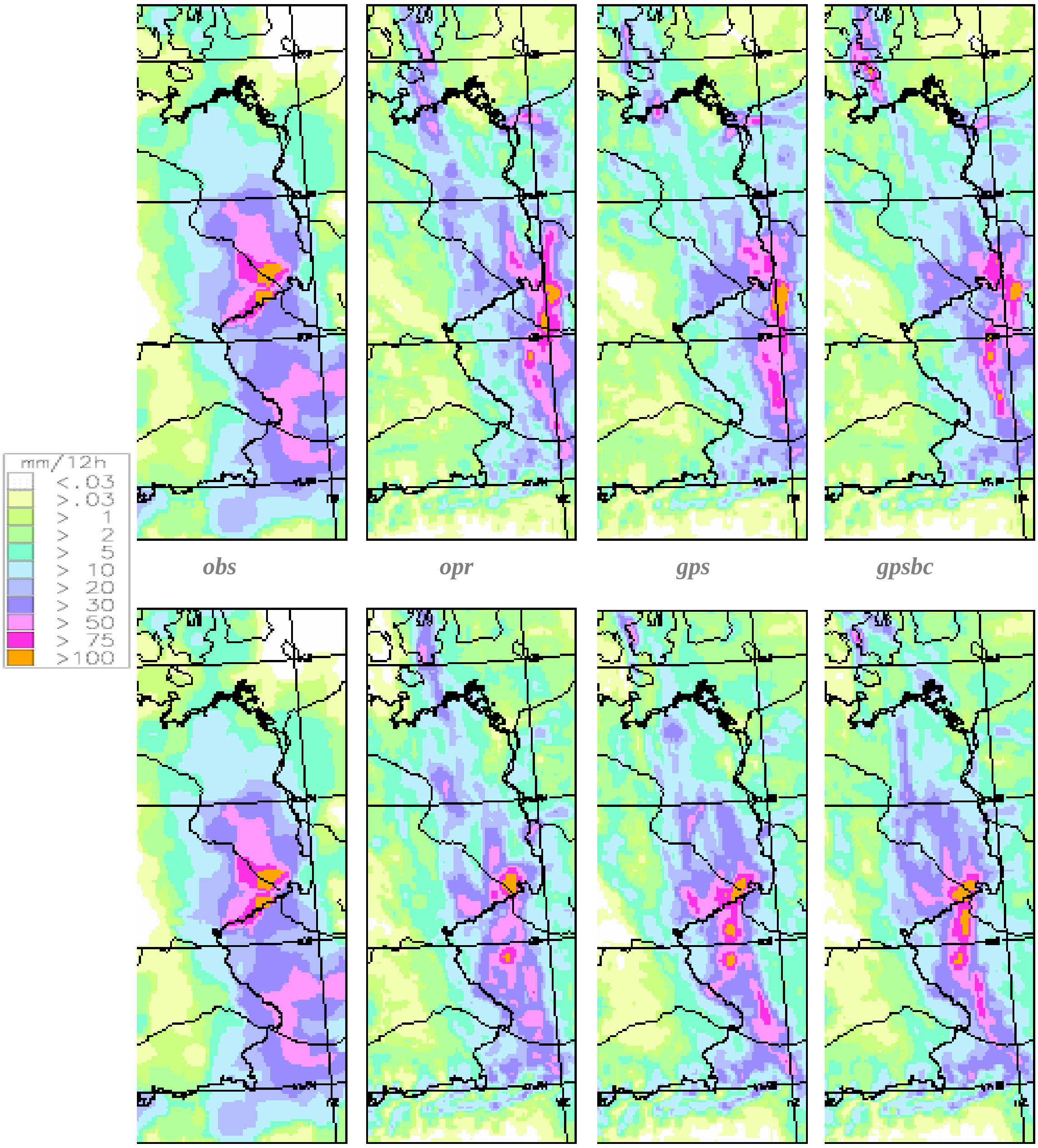


Figure 5: 12-hour sum of precipitation as in Fig.4, but valid for 12 August 2002, 18 UTC. From left to right: as analysed from synop observations (*obs*), as forecasted by control run without GPS data (*opr*), by experiment *gps* and by experiment gpsbc. Upper row: 12-24 hour forecast starting from 11 August 2002, 18 UTC; lower row: 6-18 hour forecast starting from 12 August 2002, 00 UTC.

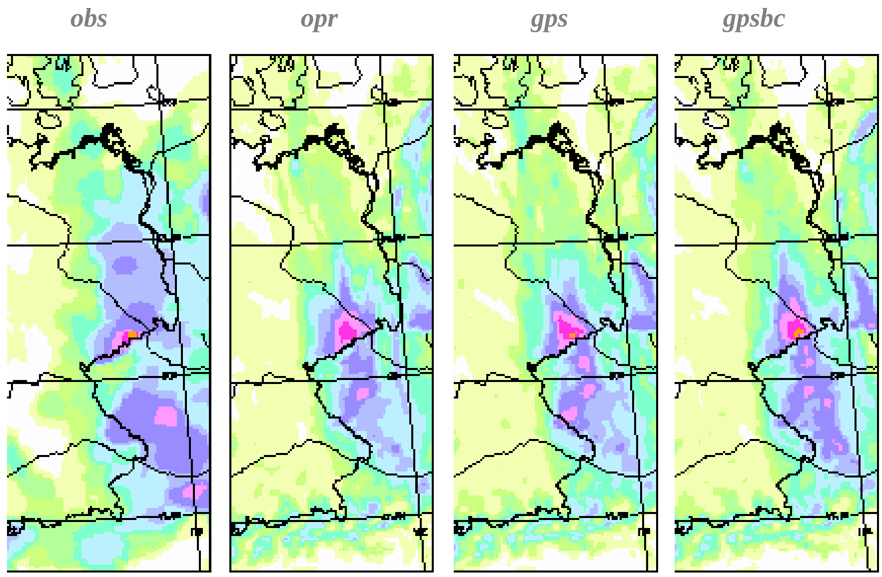


Figure 6: As Fig. 6, but for 6-18 forecast valid for 13 August 2002, 06 UTC.

REFERENCE

Bevis, M., S. Businger, S. Chiswell, T.A. Herring, R.A. Anthes, C. Rocken, and R.H. Ware, 1994: GPS Meteorology: Mapping Zenith Wet Delay onto Precipitable Water, J. Appl. Meteor., 33, 379-386.

Kuo, Y.-H., Y.-R. Guo, and E.R. Westerwater, 1993: Assimilation of Precipitable Water Meusurements into a Mesoscale Numerical Model, Mon. Wea. Rev., 121, 1215-1238.

Tomassini. M.: Assimilation of integrated water vapour from ground based GPS in the limited area model of DWD. ECMWF/GEWEX Workshop on humidity analysis, 8-11 July 2002, Proceedings available from ECMWF, Reading, UK.

Summary of Past and Current Efforts on Targeted Observations

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Craig Bishop
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The Marine Meteorology Division of the Naval Research Laboratory (NRL MMD) is engaged in basic and applied research to study the dynamics of rapidly growing perturbations, the development of targeted observing methods, and ensemble design. The numerical tools that we use include the Navy Operational Global Atmospheric Prediction System (NOGAPS), the NRL Atmospheric Variational Data Assimilation System (NAVDAS), and the adjoints of both NOGAPS and NAVDAS. NOGAPS is a spectral global model that uses state-of-the-art physical parameterizations for the physical processes. NAVDAS is an observation-space based 3-dimensional variational analysis system. With the use of these systems, we have tested hypotheses related to targeted observations based on singular vectors and adjoint-derived sensitivity gradients in field experiments such as the Fronts and Atlantic Storm Tracks Field Experiment (FASTEX) and the North Pacific Experiment (NORPEX). Recently, NRL MMD has built the adjoint of NAVDAS and is exploring new targeted observing methodologies, including variance singular vectors and observation sensitivity, within the context of The Observing System Research and Predictability Experiment (THORPEX). This presentation will provide our summary of past and current research related to targeted observations.

Estimation of Observation Impact using the NAVDAS Adjoint System

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An adjoint-based procedure for assessing the impact of observations on short-range forecast error in numerical weather prediction is described. The method is computationally inexpensive and allows observation impact to be partitioned for any set or subset of observations, by instrument type, observed variable, geographic region, vertical level or other category. The cost function is the difference between measures of 24h and 30h global forecast error in the Navy Operational Global Atmospheric Prediction System (NOGAPS) during June and December 2002. Observations are assimilated at 00UTC in the NRL Atmospheric Variational Data Assimilation System (NAVDAS). Largest error reductions in the Northern Hemisphere are produced by rawinsondes, satellite wind data, and aircraft observations. In the Southern Hemisphere largest error reductions are produced by ATOVS temperature retrievals, satellite wind data and rawinsondes. Approximately 60 (40) percent of global observation impact is attributed to observations below (above) 500 hPa. Currently, without consideration of moisture observations and moist processes in the forecast model adjoint, the observation impact procedure accounts for about 75 percent of the actual reduction in 24h forecast error.

Evolution of the EUCOS Operational Programme and Experiences from the THORPEX Atlantic TOST

S.J. Caughey *(EUCOS Programme Manager)* , B.S.Truscott *(EUCOS Operations Manager),*
D.S. Richardson *(Met Office Manager of Assimilation Studies)*

ABSTRACT

A brief overview of the EUMETNET Composite Observing System (EUCOS) operational programme is provided. The programme seeks to improve the quality of NWP products on the regional (European) scale through optimisation of existing operational networks and the capture of additional data. The main elements of the programme (i.e. E-AMDAR, E-ASAP and the recently established surface marine activities, E-SURFMAR) are noted including overall objectives, timescales, funding arrangements etc. Emphasis is placed on a description of the EUCOS studies programme including the high frequency AMDAR Special Operating Periods (SOPs) in 2003, the capture of additional surface marine data from climatologically sensitive areas of the N. Atlantic and the organisation and operation of the North Atlantic THORPEX Regional Campaign (A-TReC). The A-TReC involved targeting sensitive areas predicted by several NWP centres (ECMWF, the Met Office, Météo-France, NCEP and NRL) for additional observations from operational systems (EUCOS radiosonde network, E-AMDAR, E-ASAP, Canadian radiosondes and GOES rapid scan winds) as well as from research aircraft from DLR, NASA and NOAA. Over twenty TReC events were targeted and it is hoped that the results will guide the future development of EUCOS in particular and regional operational targeting more generally. Initial thoughts on the implementation of an interactive European observing - forecasting system are given.

1. INTRODUCTION

EUMETNET is an informal grouping of 18 National Met Services which provides a framework for collaboration and co-operation. EUCOS is a EUMETNET programme in the field of observing systems aimed at improving numerical weather predictions on the regional scale for 1-3 days ahead and introducing (where appropriate) integrated management and joint funding of programme elements. The EUCOS area of interest is, broadly speaking, the area from which observations impact on NWP, in the short range (Fig. 1).

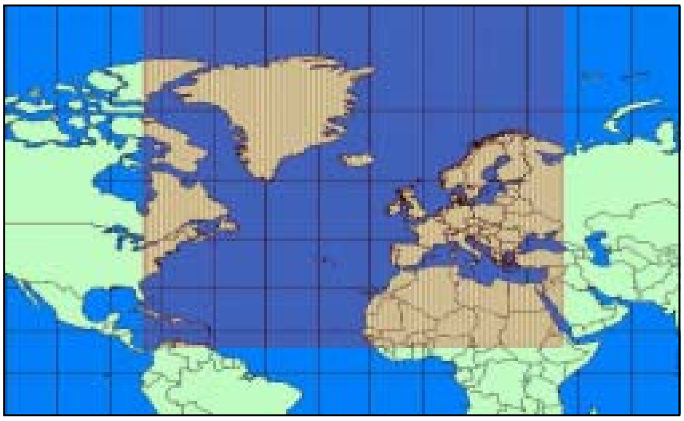

Figure 1: The EUCOS Area of Interest

(70W-40E, 10N-90N)

The challenge for EUCOS is to improve the quality and make more cost-effective regional NWP at European scale:

- through resource transfer from the mainly well observed territorial areas to the poorly observed maritime regions which exert a crucial influence on European weather at the 12 to 48 hour timescale.
- achieved by EUMETNET Members committing themselves to co-funding the new optimised facilities through a fair (GNI) cost sharing system.

EUCOS can also be regarded as a larger scale network across Europe and the surrounding sea areas which provides a framework for smaller scale networks (designed for very short range forecasting and nowcasting over national territories) and also contributes to medium range weather prediction over the globe. It can also be considered as an optimised regional component of the World Weather Watch of the WMO.

2. PROGRAMME STRUCTURE

It was clear at the outset that more upper air observations were needed upstream if the goal of improved NWP was to be realised. The Atlantic and Mediterranean areas are data sparse but generate damaging cyclones across Europe. On the other hand, observational coverage across mainland Europe on the larger scale is generally fairly good. This implies that some resource transfer may be justified – from rather well to poorly observed areas. During the Implementation Phase of the programme (1999-2002) design studies were conducted leading to overall development strategies for the various components. These were then finalised taking into account issues of affordability. The current EUCOS operational design **Ref (1)** is summarised in (Fig. 2). Most effort at the present time is involved in implementing this design and completing definitions where necessary as the system evolves and develops out to 2006.

		2001 (RBSN, COSNA)	2006 (EUCOS)
Oceanic Segment	Ocean platforms	OWS "M" (4 RW/day) and Ekofisk rig (2RW/day) (2190 TEMP/yr)	
	ASAP units	10 operated by Members and E-ASAP, producing 3000 TEMPSHIP/yr	18 units operated by E-ASAP producing a Minimum of 6300 TEMPSHIP/ year
	Data Buoys	Yearly deployment of approx. 50 drifting buoys operated under EGOS	To be defined pending Assessment under stage 1 of EUCOS Surface Marine Programme
	Moored buoys	EGOS buoys off the Continental shelf	
	Ships	Approximately 1700 VOS	
Aeronautic Segment	AMDAR units	140 aircraft operated by Members 8 000 000 msgs/yr	13 000 000 AMDAR observations/yr. Profiles from 140 European Airports and level flight data throughout the EUCOS area
Territorial Segment	Radiosonde Stations	69 stations 19 with 4 RW/day 63 510 TEMP/yr	46 stations 34 with 4 RW/day 59130 TEMP/yr
	Surface Stations	359 RBSN stations	Selected surface synoptic stations (list currently subject to approval)
Observation Targeting	ASAP, AMDAR, BUOYS		Season and area variable Deployment and activation
	Other systems		To be defined according to the results from the studies programme

Figure 2: The EUCOS Operational Design

3. THE STUDIES PROGRAMME

The evolution of EUCOS is guided by a Studies Programme - overseen by a Scientific Advisory Team chaired by ECMWF and comprising representatives from the main NWP centres in Europe. The three OSEs given priority in 2003 were:

- High frequency AMDAR data: testing the benefit of more frequent AMDAR profiles from European airports (hourly as opposed to 3-hourly) **Ref (2)**
- Additional surface marine data from climatologically sensitive areas in the Atlantic, **Ref (3)**
- Targeted observations (in conjunction with THORPEX – the 2003 Atlantic Thorpex Regional Campaign or A-TReC) **Ref (4)**

3.1 The Atlantic-THORPEX Regional Campaign

The Atlantic- THORPEX Regional Campaign (A-TReC - <previously named A-TOST>) was the most ambitious of these Observing System Experiments (OSE's). Planned by EUCOS within the THORPEX framework, the primary aim of the A-TReC was to test the real-time, quasi-operational targeting of observations using a number of platforms (including AMDAR, ASAP ships, extra radiosonde ascents, research aircraft and meteorological satellites). It is considered to be an essential preparation or 'proof of concept' for future targeting activities such as those proposed as an element of EUCOS (see figure 2).

A Special Observing Period (SOP) was arranged for the period 13th October – 12th December 2003. This was the first time that the real-time adaptive control of such a complex set of observing platforms had been attempted. In addition to EUCOS funded resources (including use of the DLR Falcon research aircraft, ASAP ships, AMDAR aircraft and selected radiosonde stations), the experiment was supported by Canadian radiosonde stations, NOAA and NASA research aircraft and GOES-12 super rapid scan wind data. Sensitive area predictions where provided by Meteo-France, the Met Office and ECMWF, NCEP and NRL.

Additional data from these observational resources could be used adaptively (or targeted) by specifying the time and/or location of deployment. The aim was to test the benefit of targeting additional observations within regions and at times that were predicted to be particularly sensitive. In order to do this it was necessary to:

- Identify suitable cases that could warrant targeting (in terms of a forecast verification region and time);
- For each case, compare the various predictions of the location of sensitive areas and decide on the observation target regions;
- Have in place mechanisms to request extra observations in these regions at short notice;
- Monitor and maintain records describing the decision making process and observational response.

In total 31 cases where identified, 21 of which where considered interesting enough to target.

Figures 3, 4 and 5 show an example of one of these cases. Two sensitive area predictions are illustrated together with the observational response.

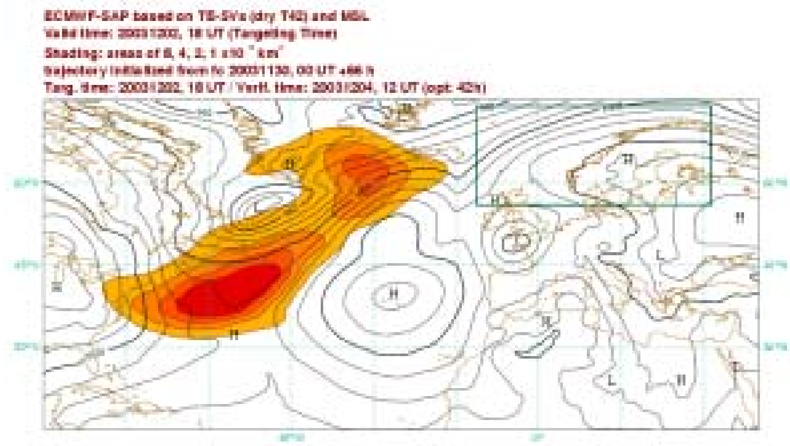

Figure 3: An example of an ECMWF A-TReC sensitivity prediction. The verification area (illustrated by the box) is predicted to be particularly sensitive to observations within the shaded region. The darker the shading the more sensitive the region. The observation target time is 18UTC 02/12/03 and verification time 00UTC 04/12/03.

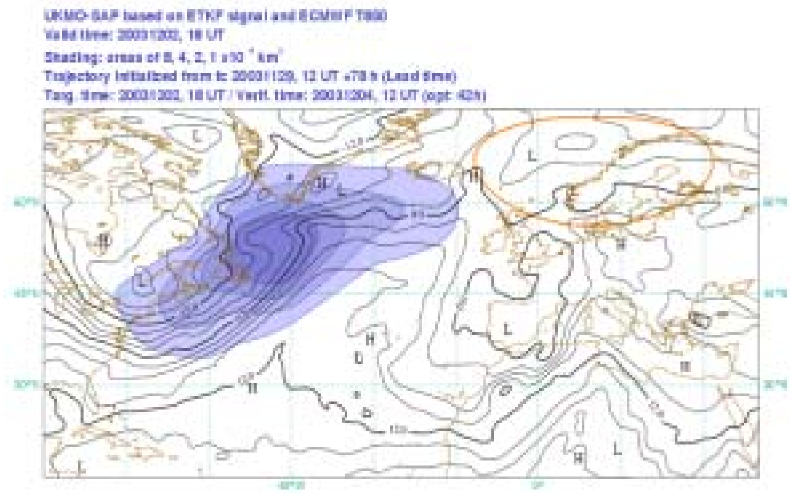

Figure 4: An example of a Met Office A-TReC sensitivity prediction.

For the same case as for the ECMWF prediction above

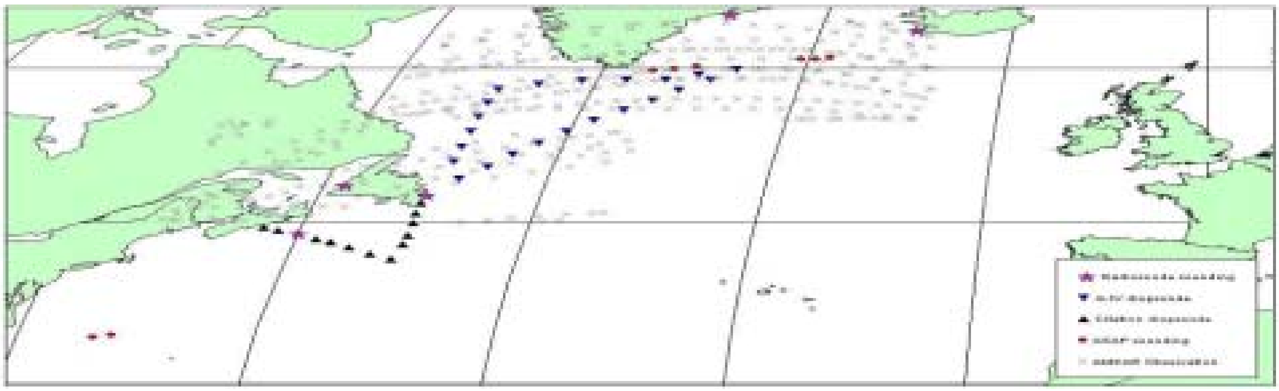

Figure 5: The Observational Response

Initially a relatively quiet weather pattern provided a number of low priority cases. From the start, the observational responses were good. The decision making process, despite relying on international conference calling, quickly proved to be successful.

Work has recently focused on documenting the special observing period and creating the experimental datasets. The lead has now been transferred from EUCOS to the European THORPEX Regional Committee, which is now responsible for co-ordinating the scientific assessment phase. Several NWP centres plan to carry out data impact assessments which initial results expected by the end of 2004.

Those interested in obtaining access to the datasets in order to conduct assessments are encouraged to contact David Richardson (david.s.richardson@metoffice.com), co-chair of the European THORPEX Regional Committee.

3.2 An Interactive European Observing - Forecasting System

As our knowledge and experience of selecting suitable cases and identifying the sensitive regions develops, it is perhaps realistic to envisage an operational interactive European observing – forecasting system. In such a system additional observations would be triggered in the event of an uncertain forecast of a potentially high impact event. These observations would then hopefully improve subsequent forecasts and thus influence the future requirement for data. Figure 6 below provides a graphical illustration of this process.

Figure 6: Interactive European Observing – Forecasting System

Acknowledgements

Sincere thanks to all those organisations involved in the planning, operation and evaluation of the THORPEX Regional Campaign. These include:

DLR
ECMWF
Environment Canada (MSC)
EUCOS participating national meteorological services
EUMETSAT
Met Office
Météo-France
NASA
NCAR
NCEP
NOAA
NRL
University of Munich
University of North Dakota
University of Wisconsin
US Air Force

References

1. EUCOS Detailed Design by Francois Gerard. EUCOS-PRG-010. September 2001

2. P. Arthur, E-AMDAR High Frequency Trial, EUCOS/PRG/014, 11th Feb 2003.

3. EUCOS Sensitivity Study by Gert-Jan Marseille and Francois Boultier. EUCOS-REP-30. September 2000

4. Atlantic-THORPEX Observing System Test, Atlantic-TOST Planning Team (D. Manfield, D. Richardson, B. Truscott, S. Stinger), EUCOS/SP/105. 22nd August 2003.

Optimization of Siberian RAOB Network by Maximization of Information Content

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Abstract

Dynamic of Siberian radiosonde observation (RAOB) network during last 15 years was considered. Lack of sondes after 1998-th year financial crisis was evaluated. It was found a small set of stations provided the regular profile measurements twice per day during 2001-2002 and estimated its information content. Information model for Siberian RAOB based on information content measure was developed. A numerical method providing the maximization of information content for a sonde network was developed and applied to optimize a configuration of Siberian RAOB. Existing network mainly covers the interior Siberian areas. In contrast, the optimal RAOB should have a priority along Arctic and Pacific Ocean coasts. It was found that most meteorological parameters have largest variance just in these regions. These areas also perform the most important low oscillation patterns: North and West Pacific oscillations, Polar-EuroAsian oscillation and others. Those regulate the airflow not only over Asia, but also over North Pacific and Western coast of North America. For example, when West Pacific oscillation attains negative magnitudes RAOB stations at Kamchatka and Chukotka peninsula deliver important pieces of data to predict weather over Polar Canada and California for medium terms. Optimal network has advantage in objective analysis accuracy for temperature and geopotential height fields with respect to existed network and remote sensing systems. Latter is due to considerable contamination of outgoing radiation by cloudiness. Heavy clouds occur most part of the year in these areas. H500 objective analysis accuracy providing by optimal RAOB is equal to 40-50 m, while existed network delivers only 60-70 m and NOAA remote sensing system - about 70-80 m.

Key words: *Optimal design, observational network, information content, optimization, low oscillation*

1. Introduction.

The global meteorological observing system is extremely expensive and in the present economical situation some conventional observations such as radiosondes begin to be severely reduced. Measurements at Siberian radiosonde observation (RAOB) network were substantially reduced after financial crisis of 1998. Number of available sondes dropped to 5-10 units per day over vast territory, which spreads from Ural Mountains to Pacific coast (see table1). Afterwards number of daily sonde profiles slowly, but monotonously enhances over Russian Asia. Nonetheless, it still does not achieve pre-crisis level. Moreover, some RAOB stations locating in such synoptically important ranges, as Arctic and Pacific shore, were closed because of economical reasons and these regions are covered only by satellite data of lower accuracy. Another key weather domains in Siberia: Chukotka and Kamchtka Peninsulas, Sakhalin and Kuryl Islands, were provided only by sparse and irregular (in time) measurements.

On other hand, during last years the tendency of increasing of RAOB density in South Siberia might be found. It is explained by extension of sonde observations carried out in interest of flight companies who supported these measurements along main traffic roots. Lack of finance in last quarter of 2003 was a reason why RAOB data became unavailable for 12.00 Z. Therefore there is an urgent necessity to substantiate and develop a minimal RAOB network in Siberia. This net should provide the regular atmosphere sounding and catch principal weather phenomena over Siberia.

In our early papers (Beliavsky, and Pokrovsky, 1984; Pokrovsky, 1999; Pokrovsky, 2000a, 2000b) we proposed the criteria of maximization of information content contribution in the meteorological field objective analysis and forecasting in order to develop optimal network configuration. Main distinguished feature of our technique is that it permits to determine an optimal design for stationary network. It is necessary to note that there is another direction in optimal design studies related to determination of the additional (adaptive) observations. This approach was discussed in several papers (Buizza and Montani, 1999; Gelaro et al,1999; Lorenz and Emanuel, 1998; Palmer et al, 1998). Above approach proved to be useful to perform supplementary observations in flexible mode as a response to some specific atmospheric circulation patterns.

The aim of this paper is to implement mentioned approach to the problem of determination of optimal Siberia RAOB net configuration. The paper is structured as follows. The methodology and data set are described in next two sections. Results are discussed in sections 3 and 4.

2. Methodology.

Our approach is based on several key items. Our first assumption is that the past datasets based on more complete, dense and regular RAOB measurements than those for our day might be considered as a background for an optimal design of the observational networks. In the case of Siberia RAOB proper data set is that might be referred to period of 1970-1985 years when sonde network consisted of more than hundred stations uniformly distributed over the whole territory. Another point is that the most complete is reanalysis dataset, which include only mutually consistent, controlled and corrected measurements relevant to different parameters and arrived from various observing systems (ground-based and remote sensing satellite). Therefore, it is reanalysis dataset that we used in our study on optimal design. Since the most analysis and forecasting field criteria are supposed to be linked to root mean square or error magnitudes, we assume that the meteorological parameter variability might be considered as a background principle for observing system design.

In fact, it is clear in general that the more variability in a given spatial point is occurred, the more desirable measurement to be carried out there. It is necessary to note that classic information content measures (Fisher or Shannon) include the expression for the covariance matrices of a given random vector *X* describing a sample grid field (Pokrovsky, 2000b).

We used re-analysis grid fields *X* in this study. Let us assume that $\Omega_p = \{\omega_1,...,\omega_p\}$ is a set of stations having geographic coordinates $\omega_1,...,\omega_p$ and $X(\Omega_p)$ is a vector of meteorological values observed at these stations. Then $X(\Omega_p)$ is linked to grid fields vector *X* by linear expression:

$$X(\Omega_p) = H(\Omega_p)\cdot X + \varepsilon(\Omega_p) \qquad (1)$$

Interpolation operator $H(\Omega_p)$ and error vector $\varepsilon(\Omega_p)$ also enters in formula (1). Error vector $\varepsilon(\Omega_p)$ includes contribution of both observing noise and interpolation error described by standard deviation magnitudes: $\sigma_\varepsilon(\omega_1),...,\sigma_\varepsilon(\omega_p)$. Our task is to retrieve unknown grid field vector *X* when having in disposal a vector of observations $X(\Omega_p)$. However, the estimate $\hat{X}$ (of *X*) is a functional of $X(\Omega_p)$ and as consequence it depends on site location Ω_p and diagonal matrix $\Sigma_\varepsilon = diag\{\sigma_\varepsilon^2(\omega_1),...,\sigma_\varepsilon^2(\omega_p)\}$ describing measurement uncertainties. Hence, the interpolation problem is reduced to the solution of inverse problem (1), which is ill posed as well as usual grid interpolation. Latter means that large perturbations in solution may correspond to small deviations in measurement data $\varepsilon(\Omega_p)$ caused by observation noise. Let us call relationship (1) as *information model* of observing system Ω_p. It links a set of observing data acquired at a given network to true grid field *X* magnitudes contaminated by noise term $\varepsilon(\Omega_p)$.

It is known (Draper, and Smith, 1981) that *the estimation uncertainty* attributed to $\hat{X}$ in (1) is described by covariance matrix:

$$\Sigma_{\hat{x}}(\Omega_p) = \{\Sigma_x^{-1} + H^T(\Omega_p)\cdot\Sigma_\varepsilon^{-1}\cdot H(\Omega_p)\}^{-1} \qquad (2)$$

Keeping in mind above assumptions we are interested in minimization of estimation uncertainty. Most appropriate uncertainty measures are trace or determinant of covariance matrix $\Sigma_{\hat{x}}$ defined in (2). It is worth to note that the uncertainty covariance matrix $\Sigma_{\hat{x}}^{-1}$ is exactly *the information matrix in the sense of Fisher* (Anderson, 1958). Implementation of the information content measures $tr(\Sigma_{\hat{x}})$ or $det(\Sigma_{\hat{x}})$ permits us to come to formulation of the *optimal design problem* (Fyodorov, 1972) for the selection of k the most informative observing stations within a set Ω_p.

In this context, it appears questionable the appropriate choice for the size k of the experimental design and the numerical method to find the maximum value. Both of them are of practical significance. The optimal choice of k is related to two aspects: the first one is the number of available sites for RAOB measurements-*M*; the second one is the relevance of any additional information inferred from measurements carried out at new (additional) site (O'Reagan, 1969). The realization of a numerical minimization is, however, a difficult task. Direct minimization requires M^k calculations of cost function (2). It is a long task for computer even in a simple case when $M=10^2$ and k=10. In our early paper (Pokrovsky 1969) a consecutive algorithm was proposed to define the locations of sites providing the minimum values for error grid fields (2). This method only requires about M*k times to calculate of the cost function (2) against M^k calculations required in direct search. The basic idea of this method relies on a formula aimed at increasing the information content when incrementing the number k of measurements. This formula was initially developed for the treatment of an inverse problem with respect to one unknown function (Pokrovsky, 1969), but later was generalized to arbitrary number of unknown functions (Pokrovsky, 1972).

We are going to apply mentioned approach to solve a problem stated above. Therefore, at each optimization step instead of handling with Ω_p we have to find a single point $\omega_i (i = 1,...,k)$, which provide a minimum of a given functional $F\{\Sigma_{\hat{x}}(\omega,\sigma_\varepsilon(\omega))\}$. Actually, our task at first optimization step is to seek for

$$\omega_1^* = \arg\min_{\omega}[F\{\Sigma_{\hat{x}}(\omega,\sigma_\varepsilon(\omega))\}] \qquad (3)$$

When extreme point ω_1^* was found, it was fixed and we have to come to the second step. Here we have to look for extreme value of $F\{\Sigma_{\hat{x}}(\Omega_2,\sigma_\varepsilon(\Omega_2))\}$ in a set of two variables $\Omega_2 = (\omega_1^*,\omega)$, first of which is fixed. Hence our optimization procedure at this step is again reduced to a search of extreme point and similar to (3):

$$\omega_2^* = \arg\min_{\omega}[F\{\Sigma_{\hat{x}}(\omega_1^*,\omega;\sigma_\varepsilon(\omega_1^*),\sigma(\omega))\}] \qquad (4)$$

At each algorithm step, a point leading to a new optimal design system requires M runs of the cost function. Hence, an optimal design system Ω_k is acquired after k steps. Above algorithm might be recursively repeated until some stop criterion is fulfilled (Pokrovsky, 1969). Our experience proved that the criterion of equality of the additional information increment (the signal) to the noise contribution $\sigma_\varepsilon(\omega_k)$ in site ω_k is efficient to be used in many cases (Pokrovsky, and Roujean, 2002).

Tangent linear model (TLM) related to non-linear forecasting model was used in adaptation observation approach developed in several recent paper (Buizza and Montani, 1999; Gelaro et al,1999; Lorenz and Emanuel, 1998; Palmer et al, 1998). But, however, there are, al least, three disadvantages, which prevent this approach explicit implementation in the optimal design of stationary network. Firstly, this approach permits only to add supplementary site to some existed network, but does not built the whole network. Secondary, TLM depends on points of current trajectory in phase space. These trajectories are very changeable. Therefore, TLM is also changeable and it is difficult to take into account TLM variability in optimal design study for stationary network. Thirdly, TLM depends on forecasting model including particular parameterization schemes and other internal model modules and tools. Those reasons prevent to apply adaptation observation method to substantiate the background RAOB network.

3. Data.

The global daily and monthly atmosphere temperature, height, moisture and wind grid fields used in present study were acquired from NCEP/NCAR reanalysis data set. The original daily data were provided by NCEP and then averaged over monthly intervals. The dataset covers a period from January 1958 to December 1999. The annual cycle and inter-annual linear trend were removed from analysis fields. The anomalies (departures from climate means) were used in all modifications of information model.

The data used were divided into learning and verification sets. All calculations for subsequent model building (covariance matrices and mean fields) were derived from learning set only. The data contained in verification set were used only for error field and cost function evaluation. It should be pointed out that linear trend, calculated on each grid after annual cycle removal is related either to artificial factors (measurement errors) or to variability having large time scale (equivalent or larger than a century), which is not relevant to predictive problem concerned here. The amplitude of the linear trend is very small. However, it may give rise to a trajectory shifting in phase space and thus affect the selection of nearest fuzzy set activated in nonlinear model. Therefore, this filtering procedure might be considered as necessary step in present context.

4. Result discussion.

Siberian territory plays an important role in development of weather and climate variability processes spread further over South-East Asia, North America and Arctic Basin. Consideration of Siberian key regions might be started from analysis of low atmospheric oscillation areas. According to classic works of Wallace and Gutzler (1981), and Barnston and Livezey (1987), there is a set particular low oscillation over Eastern and North-Eastern Siberia, which govern atmospheric circulation and substantially impact on transfer of heat and moisture momentum to Western Hemisphere in the Southeastern and Northern directions. Most important phenomena are Western-Pacific (WP) and Polar-Eurasian (PE) patterns (table 2).

Our calculations based on re-analysis data demonstrated very stable location of both south and north poles responded to each of them at time interval of 1948-1998. However, there was found a single exception in calculations carried out for 1999, when Northern pole of PE oscillation was unexpectedly moved westward. The most transparent explanation of this phenomenon is that during 1999 Siberian RAOB provides the regular sounding at only two sites located in Western region of Siberia. Another conclusion following from this fact is that the remote sensing measurements without RAOB updating do not permit to trace above key atmospheric circulation pattern with sufficient accuracy. To confirm it we evaluated the temperature profiles retrieved from the remote sensing measurements in Siberia region.

We carried out a comparison of RAOB against SATEM profiles for 1982, which might be considered as the period of most complete and reliable sonde data acquired from RAOB network. To do that we calculated the standard deviations (STD) between RAOB and SATEM temperature magnitudes at 500, 700, 850 and 950 HPa levels. Fifty seven RAOB stations, which provided regular measurements and represented various climate zones, were included in this verification study. Samples were created at monthly basic. There was found that STD magnitudes vary in wide interval 1.8^{o} - 4.6^{o} C. Seasonal dependence with the winter maximum, the summer minimum and the amplitude of 0.7-1.9^{o} C have been revealed. Main cause of this phenomenon is that an annual cycle in cloudiness amount has a winter maximum in region of East Arctic and North-West Pacific coast.

Another important finding of this study is the sharp contrast in STD values between minimum (1.8^{o} –2.4^{o} C) acquired in interior Siberia regions and maximum (2.8^{o} – 4.6^{o} C) magnitudes derived in regions close to Ocean (Arctic and Pacific) coasts. Our survey of both archives: meteorological and satellite imagery data showed that there is a very stable heavy cloud coverage during most part of the year in the coast and island regions. Another disturb factor impacting on satellite radiances is high variability of air humidity in these regions. Therefore, it is this heavy cloudiness and variability in air moisture, which prevents accurate retrievals of the temperature and height profiles, is a cause of high deviations between RAOB and SATEM data. That is another point, which proves an urgent necessity in Siberian RAOB reservation. North-eastern and Ocean shore regions represent a particular interest because of high uncertainties in air temperature, humidity and height fields inferred from remote sensing data.

Method described in section 2 was applied to determine an optimal RAOB network for Siberia. Study was carried out in three directions. Firstly, we calculated the optimal design based on daily statistics for 1970-1979. Secondly, we performed the same calculations for monthly data of 1958-1998 to compare with first scenario and to investigate influence of various meteorological parameters on optimal site selection. These studies were conducted for scalar fields (air temperature, height and humidity). At last, we considered vector atmospheric flow fields consisted of the zonal and meridian wind velocity components. We carried out a classification of those fields and found various atmospheric circulation types.

Covariance matrices for air temperature, height and humidity grid fields were calculated and related variance fields were mapped. It turned out that those variance fields are very inhomogeneous in spatial coordinates. As it follows from climate theory variance in regions closely located to Ocean coasts variance of meteorological parameters exceed those for interior continental areas. Therefore, ocean coast band of Siberia has a primary importance from the point of view of information content of RAOB measurements. And it is not surprisingly that priority of H500 height measurements at first step of optimisation procedure was found in eastern and northern regions (fig.1). Information content of RAOB measurement attains a maximum value at the Pacific coast site. Therefore, a marked site provides a minimum magnitude in corresponding error field (fig.1). Continuation of this algorithm permits us to find a minimal network for synoptic weather monitoring. It includes 12 sites located in Chukotka and Kamchatka peninsulas, Sakhalin and Kuril Islands, at the Kara, East Siberian and Okhotsk Sea coasts, in Yakutya, Kolyuma, to east of Baikal Lake.

Covariance matrices calculated for monthly grid fields were used in above algorithm to select an optimal set of GUAN sites for GCOS network. Similarity of covariance matrices and variance fields derived from daily and monthly fields, respectively, explains that corresponding minimal networks are very like each other. Pacific coast sites were found to be most informative with respect to both air temperature and height fields (T500 and H500) at first step of optimisation algorithm (fig.2). In general, optimal GUAN network looks like synoptic RAOB discussed above. Another important finding of this study is that the optimal network obtained for H500 is coherent with those derived for temperature T500 and humidity Q850 fields. This fact is very significant to formulate some general recommendations for network configuration because of conventional option that GUAN network should be subset of synoptic RAOB net.

Wind velocity components enter in a list of key meteorological parameters using in numerical weather forecasting. There is one principal difference between scalar and vector meteorological fields when statistical techniques are applied. It is related to a view of the criterion function. In the case of vector field this function should be vector-valued function. Under this circumstance another version of optimisation procedure should be developed. It will require additional efforts in future. But now we were restricted in our investigation by more consistent statistical analysis of vector wind fields over Siberia. Our aim here was to define main atmospheric circulation patterns. We considered pair (U700, V700) of zonal and meridional fields and carried out classification of corresponding stream function fields. We used a fuzzy logic approach (precisely, "min-max" algorithm) developed and successfully implemented in our early paper (Pokrovsky ey al, 2002). Classification of monthly wind velocity fields led us to three atmosphere circulation types: (i) primary zonal flow, (ii) "wide front" of Pacific air inflow with its southward turning and mixing with zonal flow, (iii)"narrow front" of Pacific air inflow with zonal flow splitting into southern and northern branches. Fig.3 demonstrates third type of circulation. RAOB net configuration should respond to requirement related to trace of turning points in stream function field. Fig.3 shows that most of such turning points locate in Arctic and Pacific Ocean band areas as well as over Kamchatka/ Chukotka Peninsulas, and Sakhalin/Kuril Islands. These results lead us to conclusions about net configuration, which is similar to those obtained above by optimisation algorithm.

Final minimal Siberian RAOB network is presented at fig.4. One can see site locations and their synoptic numbers at fig.4. It includes 14 stations uniformly distributed over Asian Russia. Two of them are positioned in Pacific Ocean. One ocean station is existed, but other proposed to be installed. Two continental sites coincide with GUAN stations. But five other GUAN stations do not coincide with our network. It is necessary to note that total set includes 7 GUAN stations. We analysed a list of RAOB stations in 2002 and 2003, when economic situation was considered as relatively stable. It turned out that, for example in 2003, January, only 15 RAOB stations carried out regular (daily) sounding. (It is necessary to note that other 14 stations performed scarce observations, probably, in interest of flight companies.) These stations were located in continental areas. Most of them were positioned in South Siberia. Therefore, these stations could not catch key information in ocean band area with a maximum variability. As a consequence, corresponding error objective analysis fields for H500 and T500 have the maximal magnitudes in weather key areas: Arctic and Pacific Ocean band areas as well as over Kamchatka/ Chukotka Peninsulas, and Sakhalin/Kuril Islands. For example, H500 error reaches a value of 80 meters and T500 – 4.5^o C. Above error magnitudes for grid fields might be considered as extremely high to be used in numerical weather forecasting (table 3). In contrast, optimal/minimal RAOB network provides much more uniform error distribution over land and more exact retrievals of grid fields. More precisely, the mean objective analysis error for H500 does not exceed a value of 50 meters (fig.5) and T500 – 2.5^o C over land surface.

5. Conclusion

Our study showed that existing RAOB network configuration is far away from being optimal. That is happened by objective reasons. Firstly, it is appeared because of urgent necessity to reduce the number of sites and available sondes in shortest term (after financial crisis). Secondly, it is happened because of absence of any theoretical background for rational network design.

Early conceptions were based on network configuration close to uniform distribution of sites. RAOB configuration in time of Soviet planned economy was finely responded to such concept. Authorities in Roshydromet were not ready to substantial network reduction. Decisions on this subject were transferred to the regional level structures. The regional decision makers accepted solutions, which were determined by stochastic reasons: distance from local habitant place, availability of fuel, existence of solvent user etc. Since main solvent users of RAOB data are flight companies, net configuration principally responds to their requests, e.g. the airport positions, flight traffic and times. It is evident, that these requirements are far away from numerical weather forecasting requirements. Therefore, RAOB optimal design problem solution is very urgent. We made first attempt to solve it. There are several advantages of our approach: generality, universality, relatively simplicity. This method implementation permits us to formulate general recommendation for number and spatial distribution of RAOB sites, which are relevant not only to weather forecasting, but to climate monitoring as well.

There are several problems, which leave to be solved. Firstly, it is the generalization of the optimisation technique from scalar to vector fields and its subsequent application to wind velocity fields. Secondly, approach area extension to European part of Russia, South-Eastern Asia in Eastern Hemisphere and to Western coast of North America in Western Hemisphere. Another challenge regions are RAOB sparse areas: Africa and South America.

References

Anderson, T.W., 1958, An Introduction to Multivariate Statistical Analysis, N.Y., John Wiley and Sons Inc., 548 p.

Barnston. A., and Livezey G., 1987, Classification, seasonality and persistence of low-frequency atmospheric circulation patterns, *Mon. Weather Rev*., v.115, p. 1083-1126.

Beliavsky A.I., and O.M. Pokrovsky 1984. An Optimization of the System for Observation of the Atmospheric Pressure in Northern Hemisphere.- *Earth Research from Space*.,N 3, p.8-13 (Gordon and Breach Publ.).

Buizza R., and A.Montani, 1999, Targeting observations using singular vectors. *J. Atm. Sci.,* v.56, p.2965—2985.

Draper, N. and H. Smith, 1981, Applied regression analysis, second edition, N.Y., John Wiley and Sons Inc., 1981, 467 p.

Gelaro R., R.H.Langland, G.D.Rohali and T.E.Rosmond, 1999, An assessment of singular vector approach to targeted observing using FASTEX dataset. *Quart.J.Roy.Met.Soc.*, v.125, p.3299-3327.

Lorenz E., and K. Emanuel, 1998, Optimal sites for supplementary weather observations: simulation with a small model. *J. Atm. Sci.*, v.55, p.399-414.

Palmer T.N., R.Gelaro, J.Barkmeijer, and R.Buizza, 1998, Singular vectors, metrics and adaptive observations, *J.Atm.Sci.,* v.55, p.633-653.

Pokrovsky, O.M., 1969, Optimal design in remote sensing. Proc. Soviet Acad. Science, Series: “Physics of Atmosphere and Oceans”, v.5, p.1169-1172 (translated and published in English by AGU).

Pokrovsky, O.M., 1972, Optimal design in remote sensing: a multi-parameter case. Proc. Soviet Acad. Science, Series: “Physics of Atmosphere and Oceans”, v.8, p.445-450 (translated and published in English by AGU)

Pokrovsky O.M., 1999. On the Technique of Representative Meteorological Station Optimal Selection. - Russian Meteorology and Hydrology , N 2, p.55-67 (Allerton Press Inc., NY).

Pokrovsky O.M., 2000a. On the Optimization of Regional Meteorological Networks - Russian Meteorology and Hydrology , N 8, p.5-21 (Allerton Press Inc., NY).

Pokrovsky O.M., 2000b. Direct and Adjoint Sensitivity Approach to Impact Assessment of Ground-Based and Satellite Data on Weather Forecasting. Proceedings of Second CGC/WMO Workshop on the Impact of Various Observing Systems on Numerical Weather Prediction. World Weather Watch Technical Rep. N 19 (WMO/TD N1034), WMO, Geneva, 2000, p.99-118.

Pokrovsky O.M., Roger H.F. Kwok and C.N. Ng, 2002, Fuzzy logic approach for description of meteorological impacts on urban air pollution species: a Hong Kong case study, *Computers and Geosciences*, v. 28, p. 119-127.

Pokrovsky, O.M., and J.L. Roujean, 2003 , Land surface albedo retrieval via kernel-based BRDF modeling: II. An optimal design scheme for the angular sampling , *Remote Sens. Environ.*, issue 84, p.120-142.

O’Reagan, R.T., 1969, Relative cost of computerized error inspection plans. *Journal of American Statist. Assoc.,* v.64, p.1245-1255.

Fyodorov V.V., 1972. The theory of optimal design, ”Nauka”, Moscow, 345p. (in Russian)

Wallace J.M., and D.S. Gutzler, 1981. Teleconnection in geopotential height field during The Northern Hemisphere winter.- Mon.Weath.Rev.,v.109, p.784-812.

Table 1. Siberian RAOB statistics after 1998

Years	Sonde Number per day	
	Regular observations	Total
1999	2-3	7-9
2000	8-10	16-19
2001	11-14	26-32
2002-2003	14-16	34-56

Table 2. Atmosphere low frequency oscillations over Siberia (after Barnston, Livezey, 1987**)**

Name of pattern	Interaction type	Pole Location	Impact Area
1) West Pacific	North –South Dipole (Winter and Spring)	Kamchatka Peninsula South-Eastern Asia	Western US
2) West Pacific	North –South –East Triple (Summer and Fall)	Kamchatka Peninsula Alaska-Beaufort Sea South-Eastern Asia	Western US
Polar/ Eurasian	North-West-East Triple (Winter and Spring)	Polar region Europe Eastern Siberia	Eastern and South-Eastern Asia
Scandinavia	North-West-East Triple (Winter and Spring)	Scandinavia-Arctic Ocean- North of Siberia Western Europe Mongolia	Western Russia, Siberia
East Pacific	North –South Dipole (Winter, Spring, Autumn)	Alaska-West coast Canada Hawaii region	North-Western US, Northern California
North Pacific	North –South Dipole (Spring and Summer)	Siberia-Alaska Western and central North Pacific	Western and Midwestern US
Tropical/Northern Hemisphere	West-East-South Triple (Winter)	Gulf of Alaska Hudson Bay South-Eastern US	North Central and South-Eastern US
Pacific Transition	North-West-East Triple (Spring and Summer)	Gulf of Alaska- Labrador Sea Eastern US	North-Western and Midwestern US

Table 3. Root Mean Square (RMS) efficiency of the optimal net

RAOB Network	Number of sonde stations	H500 RMS (m)	Ratio of RMS to variance (%)
January 2003 daily	15	67.2	39
Optimal	11	51.1	31

Figure 1.

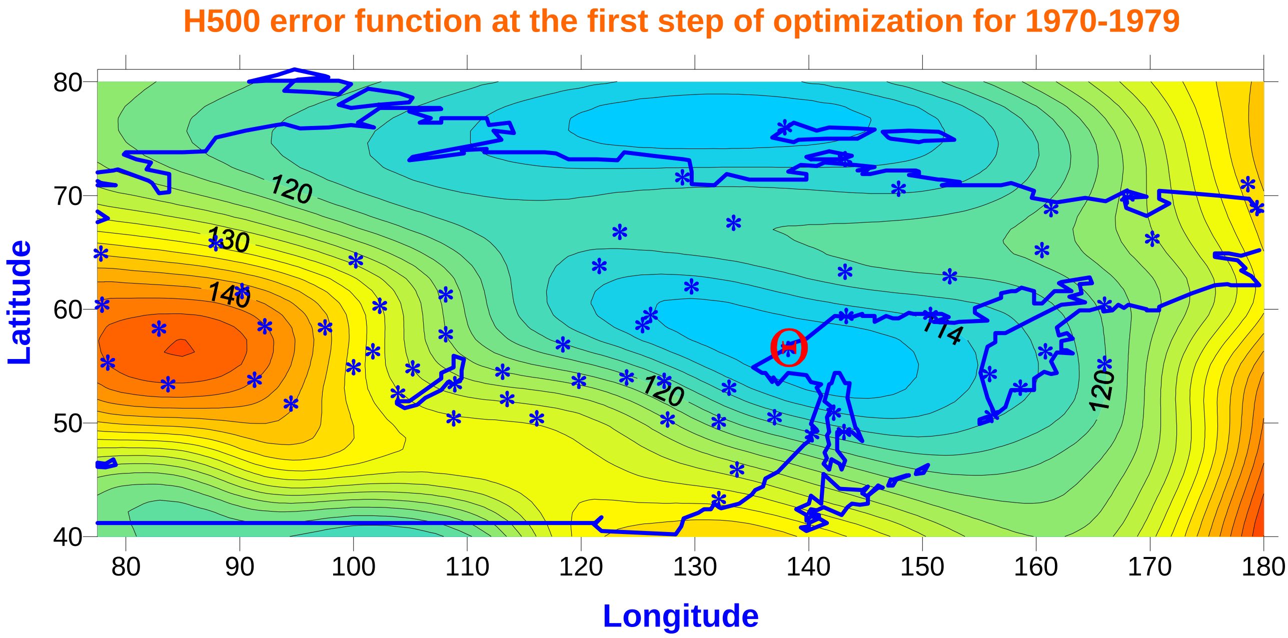

H500 error function at the first step of optimization for 1970-1979
Latitude
Longitude
80
70
60
50
40
80
90
100
110
120
130
140
150
160
170
180
120
130
140
120
114
120

Figure 2.

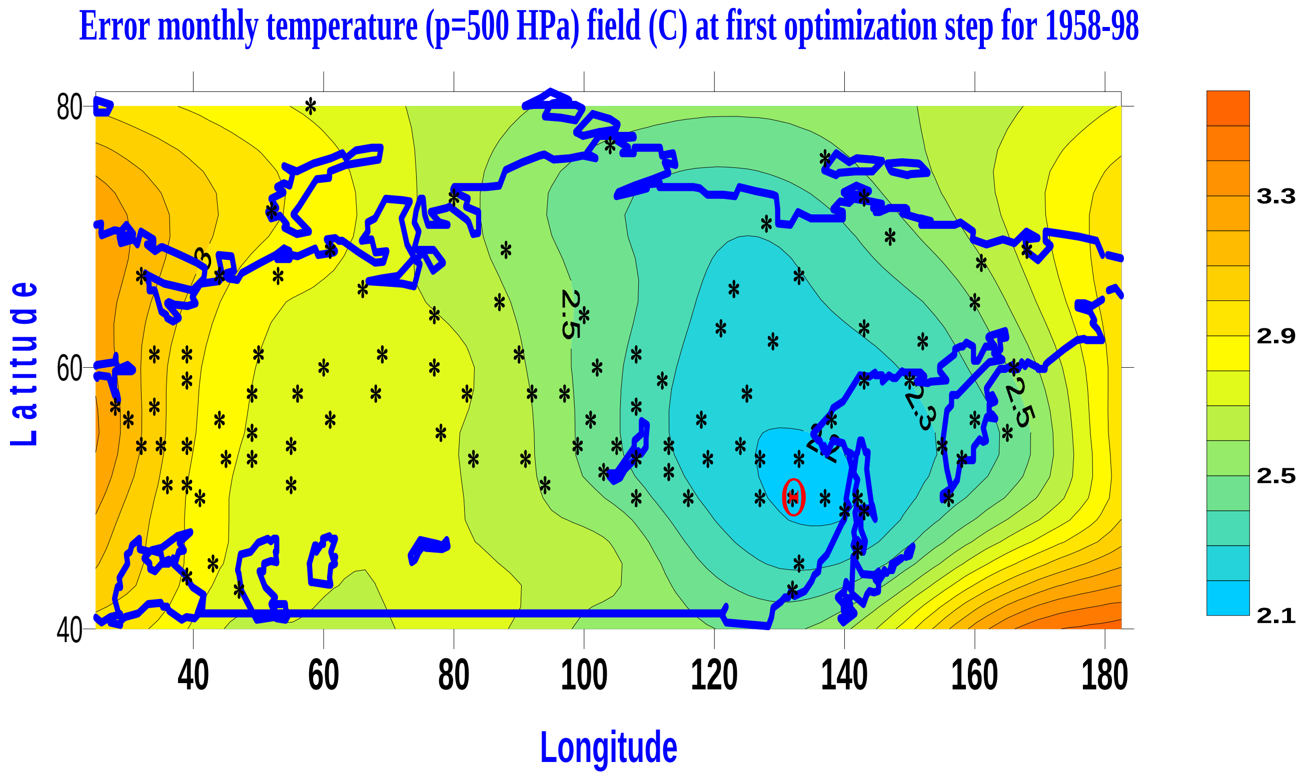

Error monthly temperature (p=500 HPa) field (C) at first optimization step for 1958-98
80
60
40
40
60
80
100
120
140
160
180
Latitude
Longitude
2.5
2.3
2.5
3.3
2.9
2.5
2.1

Figure 3.

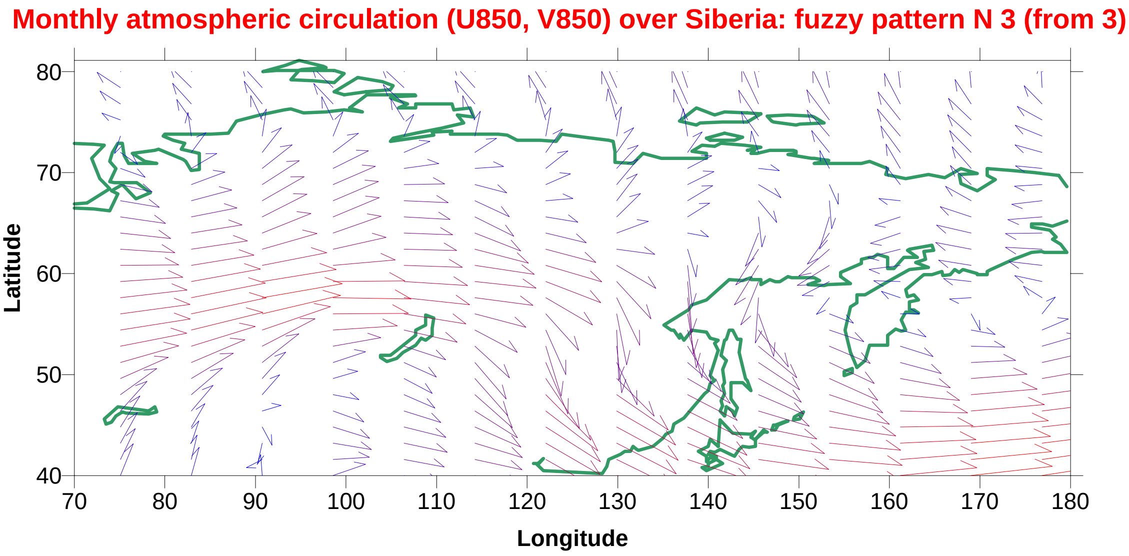
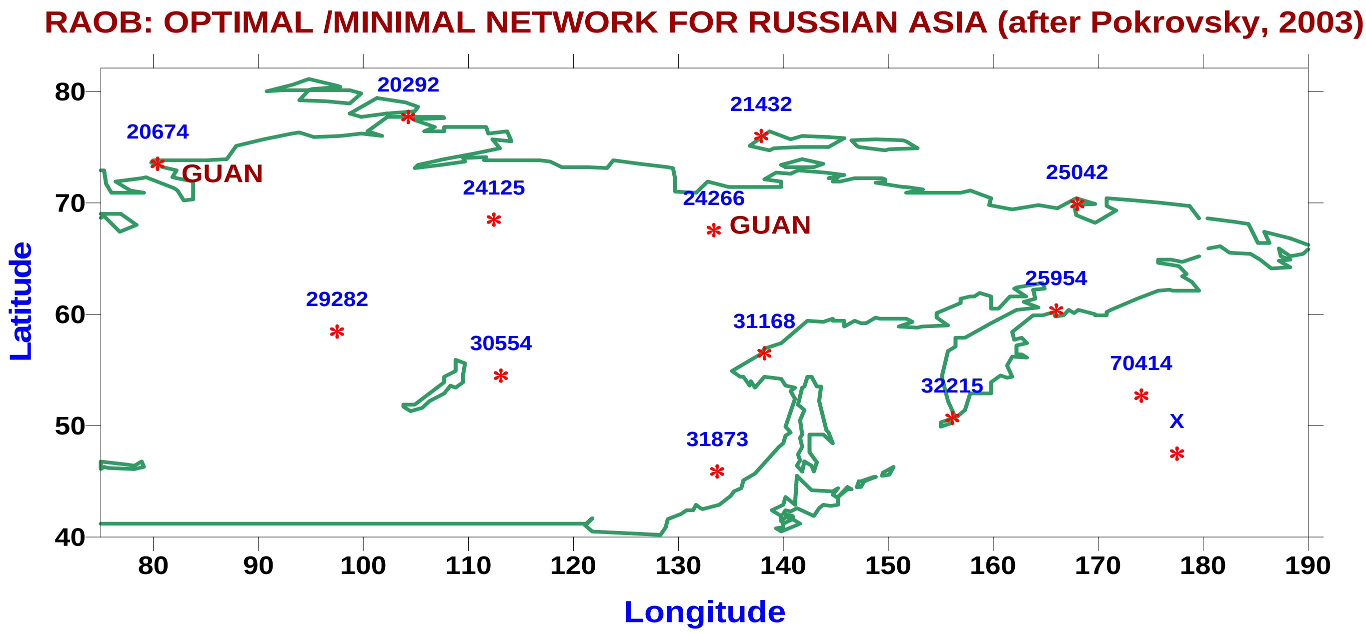
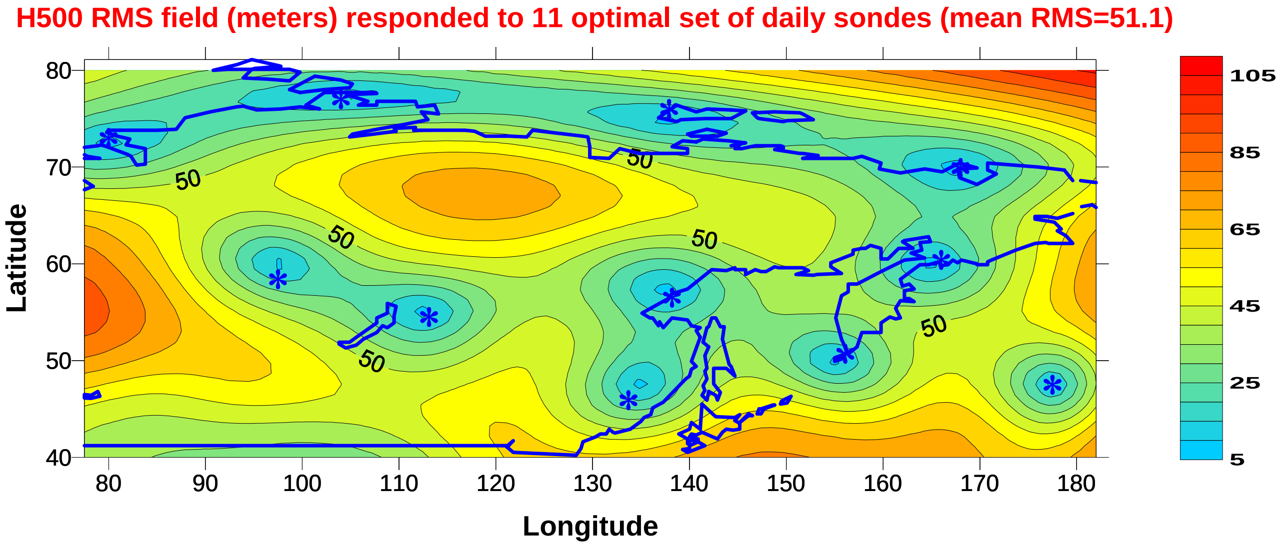

Monthly atmospheric circulation (U850, V850) over Siberia: fuzzy pattern N 3 (from 3)
Latitude
Longitude
80
70
60
50
40
70
80
90
100
110
120
130
140
150
160
170
180

Figure 4.



RAOB: OPTIMAL /MINIMAL NETWORK FOR RUSSIAN ASIA (after Pokrovsky, 2003)
20292
21432
20674
GUAN
24125
24266
GUAN
25042
25954
29282
31168
30554
70414
32215
X
31873
80
70
60
50
40
Latitude
80
90
100
110
120
130
140
150
160
170
180
190
Longitude

Figure 5.


H500 RMS field (meters) responded to 11 optimal set of daily sondes (mean RMS=51.1)
Latitude
Longitude
80
70
60
50
40
80
90
100
110
120
130
140
150
160
170
180
50
105
85
65
45
25
5

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The Global AMDAR System

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1. Introduction

1.1. Automated reporting and exchange of meteorological observations from aircraft is generically named **A**ircraft **M**eteorological **Da**ta **R**elay (AMDAR). The global program is coordinated by a group of interested countries through the World Meteorological Organization (WMO) AMDAR Panel and the work of the Panel is funded entirely by voluntary contributions from some Panel members.

1.2 The WMO recognizes that AMDAR data form an important part of the upper air component of the Global Observing System. National meteorological services have shown these cost-effective high quality AMDAR observations contribute to improved short to medium term numerical weather forecasts and provide a valuable tool to real-time forecasters for a wide range of operational services including severe weather, aviation, defence, marine, public weather and environmental monitoring. Since AMDAR observations are used for a wide variety of operational functions, they are considered to be basic data and can provide valuable asynoptic in-situ information in data sparse areas that otherwise would not be available. AMDAR has shown that it can form an important component of national, regional and global composite observing systems.

1.3 Evaluation of AMDAR data over many years has shown the observations to be of high quality comparable to operational radiosonde data. Rigorous data monitoring and control systems have been established by many of the providers of AMDAR data to ensure that only good quality data are provided for local operations and exchange to other users on the WMO Global Telecommunications System (GTS). An important element of the monitoring system is the feedback provided to and from participating airlines that cooperate by quickly taking remedial action on faults. A further important element is the free exchange of quality information on AMDAR data between monitoring centres and the respective participating weather services.

1.4 AMDAR data are exchanged freely for operational use in appropriate bulletins on the GTS in one of 2 code forms: FM42 AMDAR Text and FM94 BUFR. Although the principle reported elements include location in space and time, temperature and wind speed and direction and maximum wind, other elements are slowly being introduced including humidity, turbulence and icing.

2. Data Requirements

Desirable horizontal spatial and temporal density:

Europe	**US**
1 profile on 250km grid at 3 hourly intervals	1 profile on 100km grid at 30 min. intervals

BASIC Data

Element	Unit	Range	Output resolution	Desired accuracy
Pressure Altitude	Foot (ft)	-1000 to 50000	10	100$^{(1)}$
Static Air Temperature	°C	-99 to 99	0.1	0.5$^{(2)}$
Wind Direction	° from true N	1 to 360	1	Note (2,3)
Wind Speed	Knot (kt)	0 to 800	1	Note (2,3)
Latitude	Degree:minute	90:00S to 90:00N	1.0min	Note (4)
Longitude	Degree:minute	180:00E to 180:00W	1.0min	Note (4)
Time (UTC)	Hour:Minute:Second	00:00:00 to 23:59:59	1 min	1s

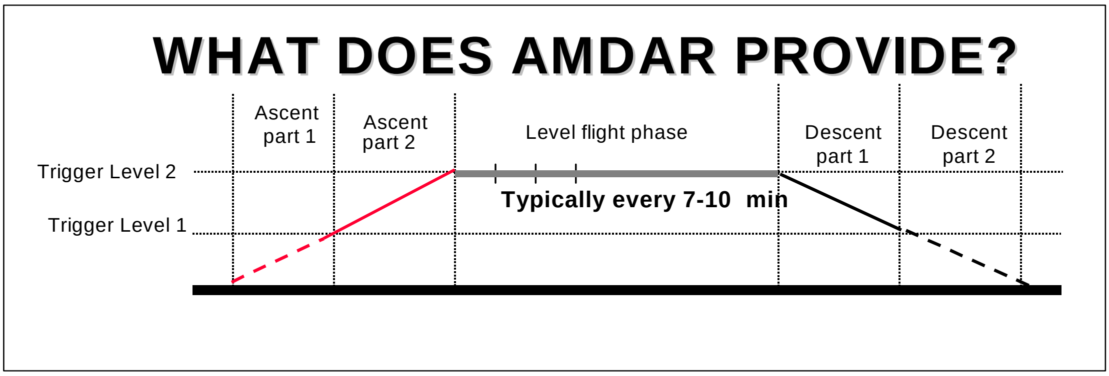
Notes:

(1) required to preserve temperature accuracy
(2) WMO requirement for NWP in troposphere
(3) 2ms^{-1} (4kt) vector error
(4) 5Nm equivalent (specified for ASDAR)

Additional Data

Element	Unit	Range	Output resolution	Desired accuracy
Maximum wind	kt	0 to 800	1	4
Turbulence (g)	g [(4)]	-3 to 6	0.1	0.15[(1)]
Turbulence(EVG)	ms^{-1}	0 to 20	0.25	0.5[(1)]
Turbulence(EDR)	$m^{2/3}s^{-1}$	0 to 1	0.05	0.1[(1)]
Humidity(RH)	%	0 to 100	1	5[(2)]
Humidity (dew pt)	^oC	-99 to +49	0.1	Note 5
Humidity(mixing ratio)	gram/kg	0 to 100	0.001	$1:10^3$ (measurement)[(3)]

Notes:
(1) Determined by output categories required
(2) WMO requirement for NWP in troposphere
(3) To meet stratospheric humidity requirement
(4) Acceleration due to gravity. 'Zero' reference on aircraft is usually +1.
(5) Equivalent to 5% RH error.



Pressure Based Triggering	Time Based Triggering
Ascent Part 1: 5 or 10 hPa intervals for first 100 hPa	3 to 20 second intervals (default 6) for 30 to 200 seconds (default 90)
Ascent Part 2: 25 or 50 hPa intervals above first 100 hPa	20 to 60 second intervals (default 20) for 490 to 1050 seconds (default 510)
Enroute:	1 to 60 minute intervals (default 7)
Descent Part 1: 25 or 50 hPa intervals from TOD to last 100 hPa	20 to 300 second intervals (default 40) from top of descent to surface.
Descent Part 2: 5 or 10 hPa intervals for last 100 hPa	

3. System Status – The AMDAR Panel

3.1 The work of the AMDAR Panel over the past 12 months has continued to consolidate AMDAR as a cost effective observing system for upper air observations. Significant achievements have been made in the 4 high priority projects and new development projects were commenced. The Panel welcomed Chile as a new member to the 2002 annual meeting and Argentina to the October 2003 meeting. Chile has commenced working with two other South American countries. Moderate progress has also been made in the Middle East. Of significance is the commencement of a targeted observations program in the ASECNA group of countries in Central and Eastern Africa in collaboration with the E-AMDAR regional program. There was a modest increase in the daily number of AMDAR observations exchanged on the GTS despite difficulties being experienced by 2 national programs. Progress has been achieved in configuring smaller regional (Bombardier Dash 8) aircraft but a major problem has been identified that serves as a substantial caution that hopes to implement AMDAR on many smaller aircraft, will not necessarily be straight forward. A number of administrative changes have taken place with responsibility for project management of E-AMDAR passing from the UK to Sweden and the relocation of the AMDAR Panel Technical Coordinator from UK to Australia. The US has appointed a new national AMDAR Focal Point who is achieving very good results in rebuilding the US program. Work with the various WMO OPAGs, Expert Teams, ICAO and other government and intergovernmental agencies continued as did extensive collaboration with the aviation industry.

3.2 Of special interest to the Panel has been the recognition by various WMO bodies including recent sessions of ET-ODRRGOS (Jan 2002, Nov. 2003), the Second Session of the ICT/IOS (Oct. 2002), and Fourteenth Congress (May 2003), the Fifty-Fifth Session of Executive Council (May 2003), the First Session of ET-UGRN and the 3 technical commissions CBS, CAeM and CIMO, that AMDAR is an important component of the Global Observing System and that it should be more fully integrated into the WWW Programme. Plans are being developed to implement changes that will ensure ongoing support for AMDAR activities, their sustainability in the future and the desirability of funding these activities. Initial steps were taken at a meeting of the CBS Management Group in October 2003 to address Congress and EC directives on the AMDAR Programme. A number of possible mechanisms were proposed to more fully integrate AMDAR activities into the WWW Programme that have been taken up by 2 WMO Expert Teams. These matters are now being addressed by the Panel.

4. Major Projects

4.1 The AMDAR Reference Manual was published by WMO as WMO 958 in English only, after a delay of several months. This completes a substantial effort by a number of people within the Panel and the WMO Secretariat and provides a wide range of information.

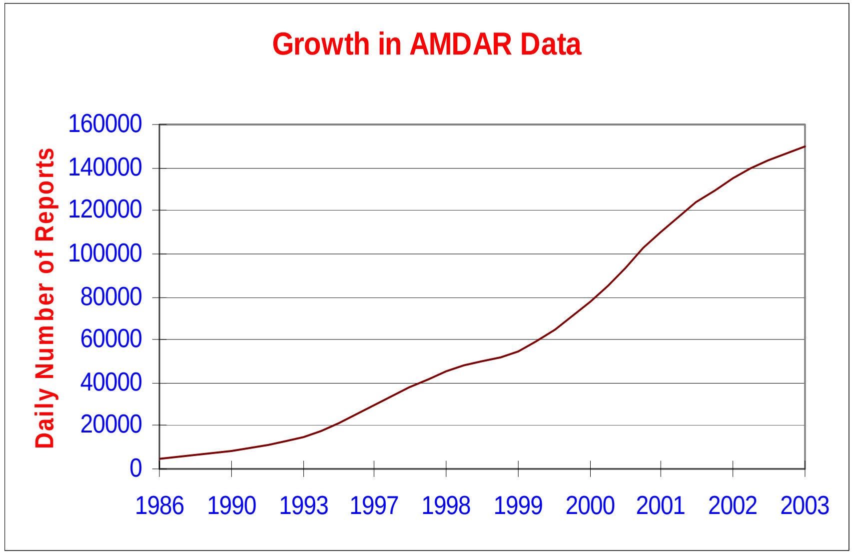
4.2 Following some unexpected delays, testing of new onboard software developed using the AAA Ver.2 specification was completed on KLM aircraft and installations on BA aircraft have commenced. Continuing assessment of the improved DEVG turbulence algorithm selected by E-AMDAR is ongoing.

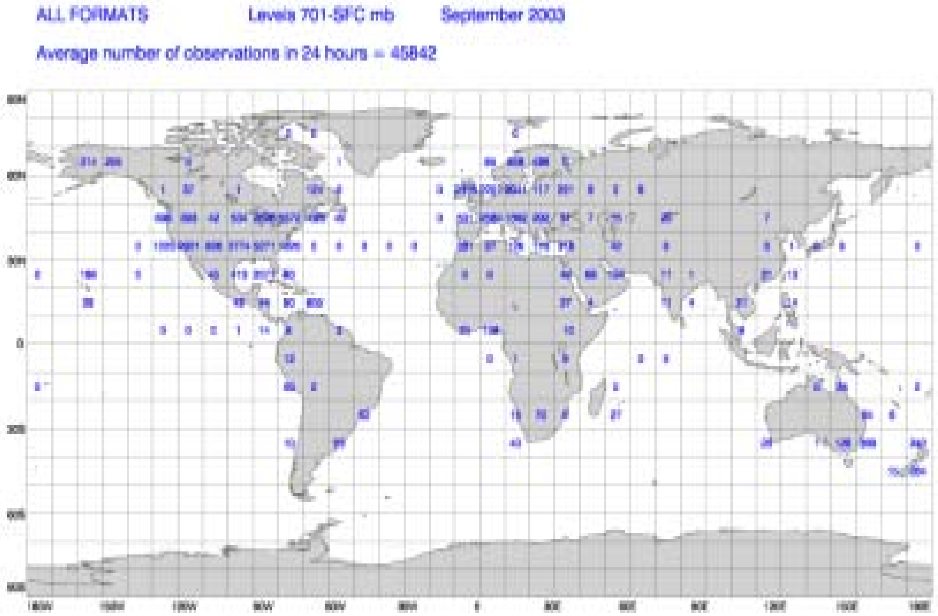
4.3 The Panel has continued its valuable collaboration with the Airlines Electronic Engineering Committee (AEEC) through the Data Link Systems Sub-committee. The new ARINC 620 Ver. 4 onboard software specification was adopted as a new ARINC standard in October 2003 and plans are being prepared in collaboration with the avionics industry to develop operational systems for implementation on aircraft as soon as possible. ARINC 620 Ver. 4 is based on the upgraded E-AMDAR AAA Ver.2 specification and effectively becomes a new international standard. It is proposed that the avionics companies will adapt the package to suit many different types of aircraft ranging from the largest long haul models to small regional aircraft.

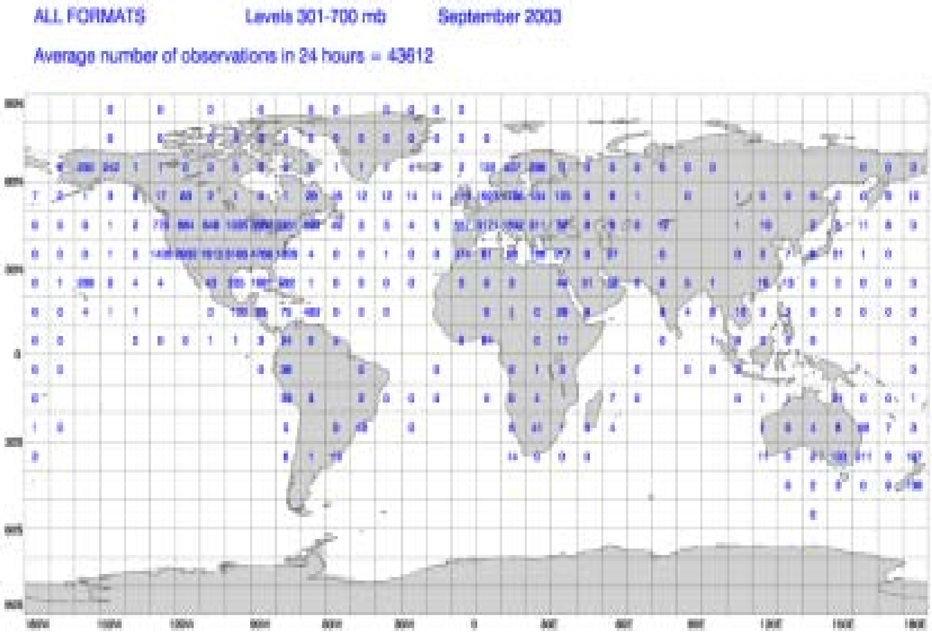
4.4 Proposed changes to the AMDAR BUFR code were accepted by CBS in 2002 and recommended for operational use in November 2003 subject to satisfactory testing by 2 WMO Members. A testing program was conducted in August 2003 between DWD and KNMI. New regional bulletins of FM42 AMDAR reports in text format have also been approved and are being implemented operationally by most originating AMDAR centres. These will make it easier for countries with basic GTS message processing capability to handle data that is relevant to their specific area of interest.

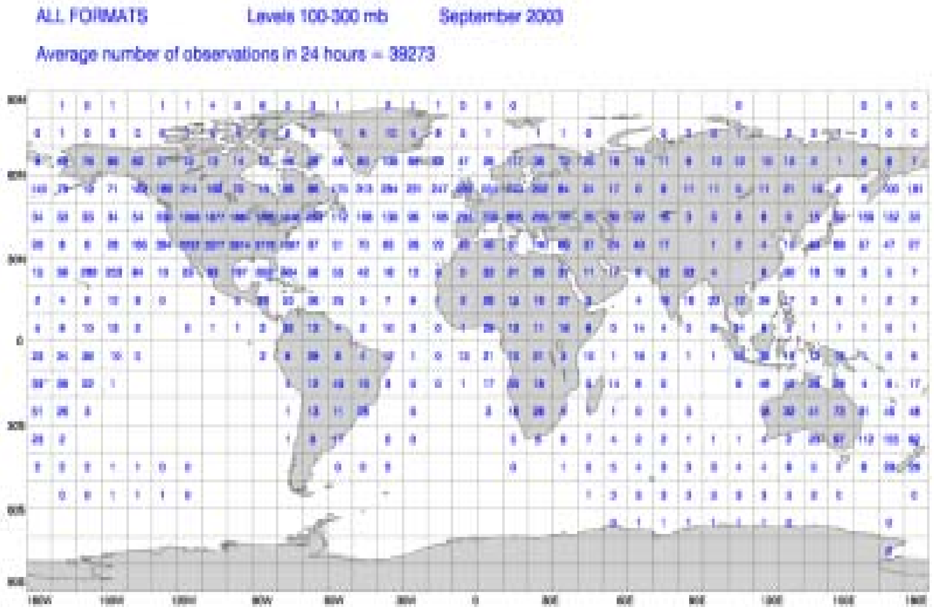
4.5 The AMDAR Panel's plan to develop its own web site has moved a step closer through acceptance of Hong Kong China's offer to develop the site in collaboration with the Panel and WMO. Initial planning of site content has commenced. In the mean time, a temporary AMDAR site has been included on the WMO site under the Aviation Meteorology Programme (http://www.wmo.int).

5. Data Growth and Coverage









6. Existing Systems

6.1 The number of daily observations exchanged on the GTS has increased from around 140,000 in 2002 to about 150,000 in mid 2003. This is despite a reduction in the number of observations from E-AMDAR due to improvements to the very effective data optimisation system. A small reduction also resulted from a further decrease in the number of operational ASDAR aircraft.

6.2 Australia's attempts to rebuild its domestic AMDAR program following the demise of Ansett Airlines have been slowed by a variety of technical and business reasons. New Zealand has increased the number of equipped aircraft but carefully controls the number reporting because of budget constraints.

6.3 Although E-AMDAR has continued to expand its aircraft fleet equipped with AMDAR from approximately 300 aircraft a year ago to about 500 aircraft in mid 2003, the number of daily reports has declined from about 25,000 to 23,000 per day as mentioned above. This has resulted in a much better controlled program governed by the competing components of budget constraints and the need to provide more data. It is now technically feasible to fine-tune the program on a daily basis. The various participating airlines have undergone substantial changes to their operational fleets following the down turn in the aviation industry. New components have been added to the data acquisition system including a financial package that allows for micro-management of costs for each individual airline, and the ability to inhibit selected measured elements from being reported in the data message on the GTS. Selection is based on data quality information. It was mentioned earlier that E-AMDAR has changed the EUCOS member responsible for management in line with normal EUCOS procedures requiring the rotation of major tasks amongst members. Improvements have also been made to the various targeting systems within the E-AMDAR program making it easier to control data from aircraft involved in specific targeted programs.

6.4 The US has begun a major overhaul of its MDCRS/ACARS program under the guidance of a new national Focal Point. Changes to the funding base have been implemented following the very serious financial positions of the larger participating airlines. Plans are being prepared to develop the program along similar lines to E-AMDAR. This has required the unprecedented cooperation and collaboration of the airlines and various government agencies. The number of observations continues to increase slowly despite the financial constraints. Additional data are being produced as part of evaluation trials that are not exchanged on the GTS because of concerns with data quality. These trials consist of ongoing turbulence reporting and a new project to establish the benefit of icing reports.

6.5 South Africa has faced a number of operational difficulties during the year that have resulted in extensive periods with no reports. However, most of them have been resolved and the possibility still exists for a substantial increase in the number of reporting aircraft, subject to the usual budgetary constraints.

6.6 A decision was taken by the AMDAR Panel to formally close the operational ASDAR programme at the end of 2003. This follows a gradual decline over the years in the number of reporting aircraft and in the operational and technical support by the Panel. Only 2 aircraft report routinely, one over the Indian Ocean and parts of Africa and Asia, and the other over Africa. No further maintenance or repairs are possible and changes have been made to the data quality monitoring system. The Met Office closed the ASDAR Centre in March 2003 and KNMI took over part of the monitoring service.

6.7 The ICAO automatic Dependant Surveillance (ADS) system showed a small increase in reported data following the installation of corrected software by some airlines. A number of important operational matters are being considered by ICAO that will help clarify the need for air traffic control authorities to obtain and pay for data. The need for and establishment of a global data quality monitoring system is being considered.

7. Developing Programs

7.1 The past year has seen significant progress being made by members in either developing and testing new programmes, or planning new programmes. Although no new systems have reached the stage of being able to exchange data on the GTS during that time, several are very close to doing so and it is only a matter of time before this will happen. Of special note are the 4 new national programs currently under test in East Asia, and the progress being made by potential new programmes in the Middle East and South America. Also, the first large collaborative program of targeted observations is under development in the data sparse areas of Central and West Africa through the leadership of ASECNA. The AMDAR Panel stands ready to assist these countries in converting these various national programmes into well-coordinated mutually supportive regional programmes.

Canada

7.2 The comprehensive Canadian program that was about to go operational a year ago struck a major problem with the quality of temperature data that also impacted on wind data quality. The cause was traced to inappropriate sensor exposure on the Dash 8 100 aircraft. Later analysis showed this was also the cause of unusual aircraft in-flight performance resulting from the poor quality temperatures impacting on the flight management system. The participating airline (Air Canada Jazz) has undertaken to replace the sensors. (The same problem was discovered on later model SAS Dash 8 aircraft where the impact is likely to be reduced engine efficiency during take off. Data transmissions were terminated on these aircraft.) Testing of data from new Canadian aircraft that should not be affected by this problem is expected in the next few months.

7.3 The result is disappointing to all concerned as it was the first attempt to establish AMDAR on smaller regional aircraft. There is clearly a warning to be noted from this exercise that the broad hope to extend AMDAR into extensive regions not served by the larger aircraft may not be as easy as was first thought.

7.4 Canada is also breaking new ground with the development of alternative, non- conventional ways of implementing AMDAR in remote data sparse areas of the country. Four major studies addressing different areas of concern to AMDAR have also been completed.

Japan

7.5 Japan has established a successful and substantial trial operational programme in collaboration with 2 national airlines, JAL and ANA. Data impact evaluation trials are being undertaken by JMA and activities are under way to place data on the GTS.

Hong Kong China

7.6 Hong Kong China is beginning to see the benefits of its efforts over the past 2 years in pursuing the development of an AMDAR programme with its national airline Cathay Pacific. Data are being produced routinely from one aircraft as part of a trial phase for quality and impact assessment. A second component is also being developed in collaboration with the aviation authority.

China

7.7 China is developing a substantial AMDAR programme and is producing a small number of observations daily as part of a pilot program. Data are being assessed and used operationally in a limited capacity and will be exchanged on the GTS in the near future. China has requested the assistance of the UK Met Office to conduct a user-training program.

Republic of Korea

7.8 The Republic of Korea has made very good progress in less than 12 months by developing its AMDAR programme in collaboration with Korean Air and producing its first test data during the third quarter of 2003. Although many aircraft are already configured with software, further implementation progress including placing data on the GTS will be subject to high level decisions.

Saudi Arabia

7.9 The Middle East program continues to advance slowly although there are promising signs of new planned systems, described below. Saudi Arabia continues to evaluate data being transmitted from several Saudia MD90 aircraft that are being received by PMA. Data will be exchanged on the GTS once some minor encoding issues have been resolved and quality has been established. E-AMDAR has offered to conduct routine data quality monitoring and advise on follow up activities. The program will then be extended to the entire MD90 fleet.

8. Planned New Systems

8.1 The past 2 years has seen a significant deterioration in airline profits and their ability to remain viable with the direct result that they are less prepared to participate in any non-essential activities such as developing AMDAR systems. This situation has slowed progress in some countries with developing new programmes, however, work has continued with planning of new national and regional AMDAR programmes.

8.2 The Russian Federation and Morocco continue to express interest in developing national programmes as they prepare basic infrastructure in their respective meteorological services. E-AMDAR provides en-route data and a limited number of profiles in cities of both countries as part of its normal program. Of special interest are the expressions of interest and activities being undertaken in South America and the Middle East. Chile continues with the development of a pilot program and regular contact is being maintained by the airline Lan Chile. The meteorological agency of Argentina together with the national airline Aerolineas Argentinas are exploring possibilities of developing a national programme. Brazil has also taken the first steps with discussions between relevant heads of government departments responsible for meteorological services. The AMDAR Panel has had brief discussions with the heads of all 3 South American meteorological agencies. The main problem in Argentina and Brazil is the potential lack of resources that can be accessed to implement these programmes.

8.3 Activity has recently increased in the Middle East with Saudi Arabia continuing system development as the project leader and Oman expressing strong interest in developing a program. Discussions are taking place with local and regional airlines exploring potential collaboration. The United Arab Emirates (UAE) is now actively working to develop a programme. The airline and the meteorological service are in discussions with the AMDAR Panel as well as Lufthansa/Lido on the initial steps that need to be taken. Iran has requested program information and has informally indicated its desire to develop a program. However, current international relations are preventing any concrete steps being taken. A number of coalition countries are working to re-establish meteorological services in Iraq. Initial planning included AMDAR and it is known that the ACARS communications infrastructure will be improved in 2004 with the establishment of 2 ground stations, one each in Basra and Baghdad. E-AMDAR provides targeted profiles in many of the cities in the region as part of its basic programme.

8.4 Poland and Hungary have indicated their intention to develop programs and have been consulting with E-AMDAR, but recent changes in government situations have slowed progress. E-AMDAR keeps a monitoring watch on and provides encouragement to several countries in the region who have indicated interest in the past including Finland, Ireland, Spain, Portugal, Switzerland, Austria, Italy, Iceland and Belgium.

9. Workshops

9.1 The AMDAR Panel has been offering to assist countries considering the development of new programs by holding national or preferably, regional workshops.

Arrangements are being made to hold workshops in the following countries:

United Arab Emirates – 15-16 March 2004;

Saudi Arabia – May 2004

China – September 2004.

9.2 Additionally, formal invitations to conduct workshops have been received from the following countries:

Morocco (national programme);

Argentina (South America regional programme); and

Hungary (East European regional programme).

9.3 The Russian Federation has informally indicated interest in holding a workshop.

10. Targeted Programs

10.1 Development of an extensive collaborative program of targeted observations is well under way between E-AMDAR and ASECNA, an intergovernmental agency representing 14 Central and West African countries plus Madagascar. This follows a very successful 2-day workshop conducted by the AMDAR Panel in Dakar, Senegal in November 2002. E-AMDAR will provide controlled data from appropriate aircraft from 3 of its airlines that operate into the region. Data is being provided already for a small number of countries on a daily basis. Ghana and Nigeria although not part of the ASECNA, will also be included. ASECNA will in turn reimburse E-AMDAR for the marginal costs of providing the data. Once the targeted program is fully operational, the next stage will commence to explore opportunities to develop AMDAR programs in collaboration with local airlines.

10.2 E-AMDAR continues to provide data in a small demonstration targeted program in the Caribbean region. This is controlled remotely by Meteo France as a further demonstration of how cost effective and easy targeting can be.

10.3 With the completion of a financial package and new data control elements in its data acquisition system, E-AMDAR now has the infrastructure to provide similar targeted program services any where in the world, provided the data are either exchanged on the GTS or sent direct.

11. Data Optimisation

11.1 Improvements to the E-AMDAR automated optimisation system have continued to further enhance this very sophisticated and powerful system. It was used on several occasions to quickly adjust regional coverage taking advantage of built-in redundancy when short, unexpected circumstances (such as airline strikes) caused large blocks of AMDAR reporting aircraft from flying. The system could be expanded and adapted to provide similar services for almost any airline in the world. The system is also used on an irregular basis to fine-tune the volume and coverage of data to help meet budgetary targets. The next major component will be to develop the remaining infrastructure to use the system to meet special short or long-term meteorological events. The system was put to good effect with the implementation of 2 intense observing periods in 2003 to assess the impact of higher frequency data as part of a EUCOS experiment.

11.2 Canada has also developed an optimisation system and the US and Australia are also planning the development of similar control systems.

12. Other AMDAR Systems

12.1 Significant progress has been made in several alternative forms of AMDAR systems. Design of the US TAMDAR system has been finalised and prototype testing has been completed. Various versions are being developed for the first operational trials. In addition to those being undertaken by the company, an extensive operational trial is due to commence in the north central US early in 2004 with 62 systems being installed on Saab 340 regional aircraft. Data impact studies as well as detailed system performance will be studied by a number of NOAA and NASA agencies. Additionally, Meteo France will commence testing a system on behalf of the E-AMDAR group later this year. Possibilities exist for Germany and the UK to also conduct independent evaluation programs. The company has been working closely with Canada to test a system as part of a new fully integrated AMDAR system on a variety of different aircraft. Australia is also planning to evaluate TAMDAR systems as part of a new program to equip aircraft providing services over the Southern Ocean between Australia and its Antarctic research stations.

12.2 The Canadian meteorological service in collaboration with another company, has also taken the first steps to develop a second alternative system using aircraft already equipped with appropriate sensors but with different on-board data collection and communication technologies. The system being developed by Air Services Australia as an appropriate alternative to be fitted on small aircraft operating in data sparse areas underwent some basic testing, but the program is on hold subject to new funding being identified.

13. Sensors

13.1 Development and testing of the new air intake device for the US WVSSII water vapour sensor has been completed following a number of evaluation trials. 30 sensors will be installed on UPS 757 aircraft in the first half of 2004 for an operational trial. Additional discussions have taken place with Airbus Industries to have the sensor certified on Airbus aircraft, a process that is likely to include Australia as it plans to install a small number for operational evaluation. A number of other countries including Canada and Europe are also considering conducting trials.

13.2 As mentioned earlier, initial testing of the TAMDAR system that contains a full set of sensors, has been completed and the first operational trials will take place later this year. A great deal of interest has been shown by a number of countries in different parts of the world in this system as a potential provider of humidity data in the boundary layer and lower-to-mid troposphere. It will not have the capability of humidity measurements in the upper troposphere. Work continues in the US and UK on development of aviation humidity sensors. Interest in accelerating work on the UK sensor being developed by Cambridge

University has increased with several groups indicating interest in deploying it. The Russian Federation has also proposed that a well-proven research sensor be modified to suit routine service on commercial aircraft.

13.2 Testing of the Eddy Dissipation rate algorithm continues in the US by NCAR for the FAA and ICAO and new work has commenced in an alternative method at NOAA Forecast Systems Laboratory at a low level. The technique using pressure fluctuations in the Pitot static Tube is similar to the one adopted by TAMDAR.

13.3 Development and testing of icing sensors by several companies continues in the US with a reporting and operational evaluation trial under way. Canada is also planning to conduct its own evaluation program. Changes have been introduced to the WMO FM94 BUFR code to be able to report basic icing “on/off” situations.

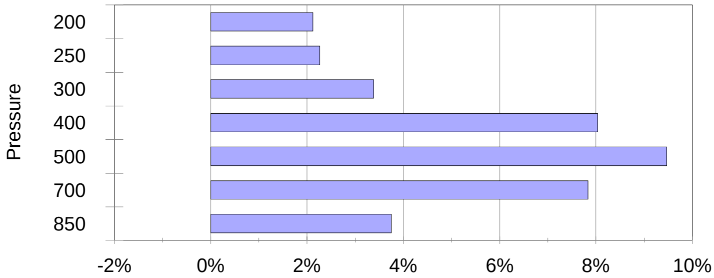
14. Data Impact

14.1 A number of studies have been completed by at least 6 major centres, namely, ECMWF, FSL, NCEP, UK Met Office, and Canadian Met Centre on the impact of AMDAR data on NWP. All studies have shown that automated wind and temperature reports from commercial aircraft have **Major Impact** on analysis and forecast skill at times ranging from a small number of hours out to at least 7 days on the global scale. Further studies are continuing to determine the impact of higher frequency data. Short studies and operational reports conducted by the US and Australia show that AMDAR data has significant impact on operational forecasting by meteorological offices, particularly for severe weather and aviation weather services.

After 9 hrs, ascent/descent data have
improved tropospheric forecasts by yet another 1-2%

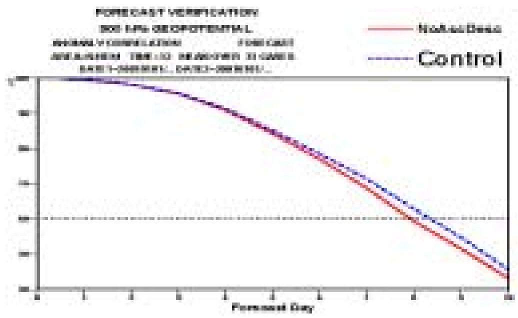
3 Hr Wind Forecast Difference

Improvement with Ascent/Descent Data



Exp: Forecast impact

- **Exp: Denied ascending and descending aircraft, p>350 hPa**
- **Higher Values** ***(Dashed)*** **indicate ascent/descent data added value**



The Ascent/Descent data add ~0.4 days of forecast skill at day 8 –
a 5% improvement in forecast skill - - this is significant

Summary of Impact Tests of Automated Wind / Temperature Reports from Commercial Aircraft

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1. Introduction

This paper presents a summary of three separate studies of the impact of automated aircraft wind and temperature reports on Numerical Weather Prediction (NWP) guidance at scales of hours to days to a week in the future. The studies include 1) *subjective findings* by the Forecast Systems Laboratory (FSL) from several years' experience regarding the availability of aircraft data on forecasts from the Rapid Update Cycle (RUC), 2) an objective *medium-range* forecast data denial test by the European Centre for Medium Range Weather Forecasts (ECMWF) focusing on ascent/descent data, and 3) an objective *short-range* forecast data denial test over the US by the National Center for Environmental Prediction (NCEP) using the RUC which also focuses on the impact of ascent/descent aircraft data. This last study is then contrasted with a similar test of the impact of Wind Profiler data on RUC performance over the full US.

2. Early findings regarding wind forecast improvement from increased aircraft data reports

This section presents a summary of early FSL findings regarding the relationship between the quantity of automated aircraft reports over the U.S. and RUC forecast skill (Benjamin, personal communication, 2004). The studies related the reduction in automated reports of wind and temperature data from commercial aircraft over the contiguous United States (CONUS).

The first study related the skill of wind forecasts from the RUC on weekdays versus weekends. (Here as in other sections of this paper, results have been normalized by dividing the difference in errors between the different forecast groups by overall forecast error.) At the time of this study in 2001, the typical number of automated aircraft temperature and wind reports received by NOAA during the overnight period between 0000 and 1200 UTC ranged from 35,000 on Tuesday through Saturday to 15,000 on Sunday and Monday. The difference in data volume was caused by the lack of reports from package delivery services, which generally do not fly over the weekends. The reduction in

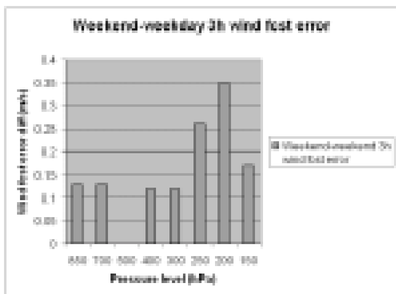


Figure 7: Normalized difference in RUC

weekend observations corresponded with as much as a 0.35 ms^{-1} increase in the typical 5.0 ms^{-1} Root Mean Squared Vector (RMSV) error present in the RUC wind forecasts for 200 hPa (see Fig. 1). This improvement of ~7% during weekdays was observed consistently for several different seasons.

A second, unplanned test of the impact of aircraft data occurred immediately after the events of September 11, 2001, when all civil aviation operations were suspended in the U.S. The complete loss of automated aircraft data during this period resulted in a 20% loss of 3h RUC wind forecast skill at 250mb, with the 3 hr forecast skill dropping back to nearly that of the 12 hr forecasts from the 0000 and 1200 UTC rawinsonde time. The combination of all other off-time data sources added little skill to the off-time RUC analysis and forecast updates. aircraft were allowed to fly anywhere in the US. These results showed an immediate step function decrease in forecast skill, with several periods showing no, or negative, improvement ????

Although it has been shown that 3 hr RUC wind forecasts are generally more accurate than earlier 12 hr forecasts valid at the same time, these findings suggested that RUC wind forecasts became
less accurate when fewer aircraft reports were available. Although the decrease of aircraft data during weekends was attributed to the package carrier flight schedules, the study did not address the question of whether the over-weekend loss of ascent/descent reports that are predominantly made by these carriers had more or less impact on wind forecast skill than en-route reports and, if so, in what portion of the atmosphere. The following studies address those questions.

3. Global Impacts of Ascent / Descent Data from Aircraft

An effort to determine the impact of observations made during aircraft ascent and descent data was made by the ECMWF (Cardinali et al.,2002). The study focused on medium range global forecasts. In these tests, the removal of ascent and descent data was simulated by removing all aircraft reports below 350 hPa over North America (25 - 60 N, 120 - 75 W) and Europe (35 - 75 N, 12.5 W - 42.5 E) from the data assimilation during a period from 1-31 January 2001. This resulted in reducing in the number of aircraft reports available for use in the data assimilation system by approximately 13,000 reports (T, u, v) per 12-hour cycle. (It should be noted that at this time, ECMWF was applying a thinning procedure to the aircraft data, so the number of reports removed from the experiments was substantially smaller than were available.) All other data types were used normally. The resulting experimental forecasts were then compared with operational control forecasts using all data.

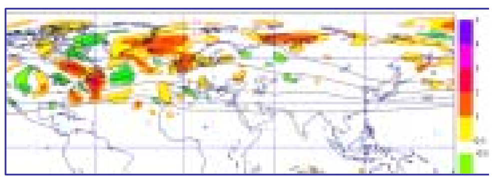
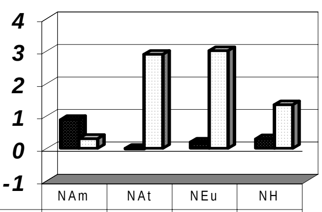


Figure 8: Change in 120 hr 500 hPa RMS height



	NAm	NAt	NEu	NH
48 hr	0.89	-0.02	0.2	0.3
120 hr	0.31	2.9	3.02	1.35

Figure 3: Change in 48 and 120 hr 500 hPa RMS height error due to aircraft ascent / descent data

Although the aircraft data were removed only below 350 hPa, the analyses showed impact at 300 hPa and above, especially over North America and the North Atlantic. The forecast results in Figs. 2 and 3 show not only an increase in impact with forecast time, but also a progression of the regions of maximum impact eastward across the Northern Hemisphere from the U.S. toward Europe. Forecast impact was measured at 500 hPa as the difference in Root Mean Square (RMS) error with and without the use of aircraft ascent/descent data, with positive values indicating that the aircraft data improved the forecasts. Although the forecast impact over North America decreased from 48 to 120 hrs into the forecasts, the impact in the North Atlantic and over Northern Europe increased markedly. Over the full Northern Hemisphere, the impact increased by over a factor of four from 48 to 120 hrs.

In the longer range (see Fig. 4), the inclusion of automated wind and temperature reports taken during aircraft ascents and descents showed positive impact through 10 days, with approximately 0.4 days being added to the period of skillfull forecasts at day 8, where the lower limit of skillfull forecasts is indicated by the 60% line. Compared with many other observing systems, this 5% improvement in forecast skill is noteworthy.

Although the results of the tests revealed some bias between rawinsonde and aircraft data, the study concluded that the aircraft ascent and decent reports of wind and temperature produced a very significant impact on the assimilation and forecasts. In addition, the authors suggested that future expansion of the AMDAR/ACARS coverage should provide further benefits.

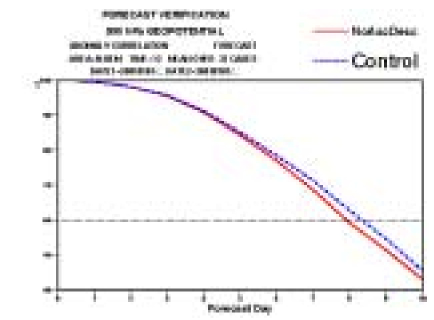


Figure 4: Northern Hemisphere 500 hPa Anomaly Correlations from ECMWF forecasts with (dashed) and without (solid) aircraft ascent / descent data.

4. Regional/Short Range Impacts of Aircraft Ascent / Descent Data

As an expansion of the ECMWF study, the National Centers for Environmental Prediction (NCEP) (see Petersen et al., 2004) conducted studies of the very short range, regional impact of both automated aircraft ascent and descent data and Wind Profiler data over the U.S. Both studies used the operational 20 km RUC system (with optimal interpolation analysis and isentropic forecast components).

The aircraft ascent/descent denial test was conducted for three weeks in early June 2002. As in the ECMWF study, all aircraft wind and temperature reports were removed below 350 hPa in the experimental runs. Unlike the ECMWF tests, no thinning of the aircraft data was done in the control or experimental runs. The experimental analyses and 3, 6, 9 or 12 forecasts were then compared with rawinsonde data over the CONUS at 0000 and 1200 UTC. The RMS temperature, humidity and RMSV wind errors from the experiment were then compared with the control. Positive values indicate improvements in tests using the ascent/ascent data.

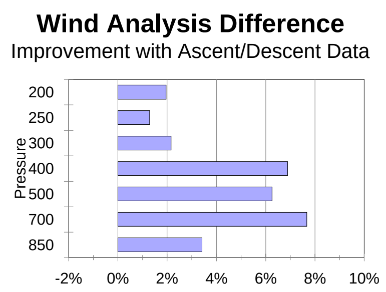


Figure 5: Normalized differences in RMSV fits of RUC wind analyses with rawinsonde data over the CONUS for 0000 and 1200 UTC analyses with and without aircraft ascent / descent data

As shown in Fig. 5, the addition of ascent/descent data on the data assimilation system showed a consistent improvement in the "on-time" 0000 and 1200 UTC analyses, with positive impacts at all levels. Although the effects are larger below 300 hPa, improvements were noted in analyses of both observed parameters, wind and temperature (see Fig. 11 below). Improvements in the humidity analysis (see Fig. 11) reflected improvements in the advection of the moisture fields by the updated wind fields prior to the analysis time.

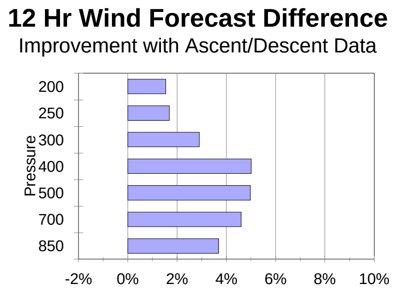


Figure 6: Normalized differences in RMSV errors of 12 hr RUC wind

The impact of these 0000 and 1200 UTC analysis differences was then determined by comparing forecasts from the two systems. Again, the impacts were positive and extended across all variables. For wind, the results in Fig. 6 showed improvements above 25,000' that were comparable to the initial analysis differences. Below 25,000', the impacts of the ascent and descent data were slightly smaller than originally in the analysis, but still substantial, averaging about 4%. For reference, the improvements in the troposphere were greater than those obtained by increasing the RUC resolution from 40 to 20 km, a change which required a 10-fold increase in computing resources.

The fundamental purpose of the RUC is to use 'off-time' data to make repeated corrections to traditional 'on-time' model guidance. As such, another appropriate measure of data impact for this application was obtained by determining the amount of improvement made by including off-time' data in successive (shorter range) forecasts made between 0000 and 1200 UTC and also valid at those times.

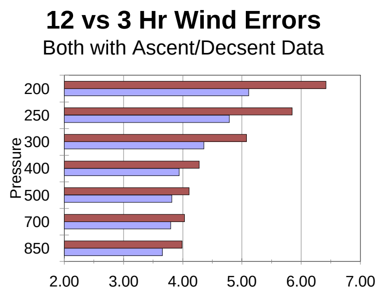


Figure 7: Comparison of RMSV Wind Errors (ms^{-1}) between 12 hr (red) and 3 hr (blue)

In order to establish a reference, the benefit of including all asynoptic observations into the successive hourly RUC analysis updates between 0000 and 0900 UTC and 1200 and 2100 UTC reduced errors in the 12 hr forecasts (see Fig. 7) was first determined at 0000 and 1200 UTC. The resulting improvements of between 0.2 and 1.2 ms^{-1} were attributable entirely to the use of asynoptic data and corresponded to reduction of in 12 hr forecast error ranging from about 5% at lower levels to 30% aloft.

Because a number of different data sets were available over the U.S. in the periods between conventional 0000 and 1200 UTC rawinsonde observations (most notably hourly Wind Profiler data), the specific impact of aircraft ascent/descent data was also determined by measuring the amount of the reduction in 12 hr forecast error by the RUC updates due solely to aircraft reports (see Fig. 8).

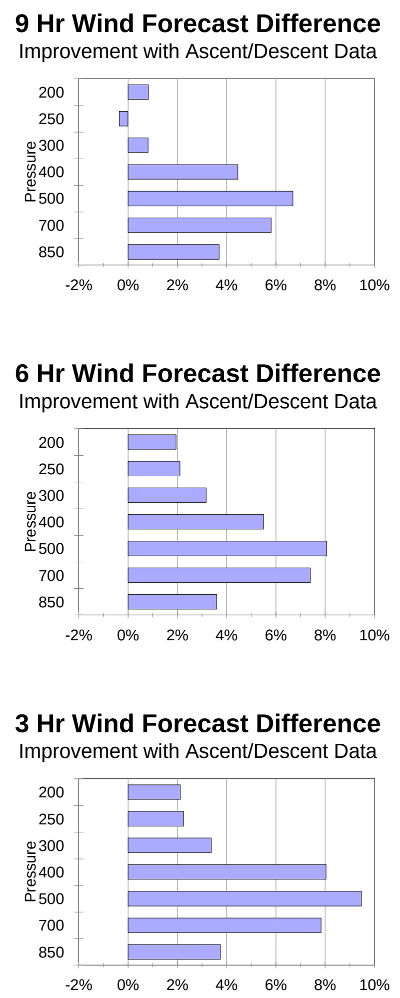


Figure 8: Normalized difference in RMSV wind errors in RUC 9, 6 and 3 hr forecast updates (all valid at 0000 and 1200 UTC) with and without aircraft ascent / descent data.

Within 3 hrs, ascent/descent data improved tropospheric forecasts by 4-7%, with smaller improvements at two of the high level flight levels.

After 6 hrs of updating, the ascent/descent wind and temperature reports have improved forecasts at all levels by an additional 1-2%. The improvements at the highest flight levels occurred even though flight level data were used in both systems.

Differences between 12 hr "on-time" RUC forecast and corresponding 3 hr "off-time" forecast updates showed that incorporation of 9 hrs of aircraft ascent/descent data reduced the 12 hr forecast errors by another 1-2%, an overall improvement between 8 to 9.5 % throughout much of the troposphere. The results underscore the importance of including sufficient mid-tropospheric wind and temperature data within the model and analysis to define the fronts supporting the upper-level jet streaks adequately.

These results are consistent with those obtained by Benjamin et al. (Fig. 9, personal communication, 2004) in an experiment where they eliminated all aircraft data in a similar winter-time test of the RUC conducted in 2002. In that case, the impacts below 400 hPa were comparable, while at higher levels the inclusion of en-route aircraft data improved the value of the RUC updates by as much as 19% at 250 hPa.

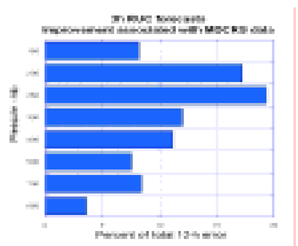


Figure 9: Normalized difference in RMSV wind errors in RUC 3 hr forecast updates (valid at 0000 and 1200 UTC) with and without any aircraft data.

Figure 10 shows that the amount of improvement in the 200, 250 and 300 hPa wind updates attributable to the use of aircraft ascent and descent reports increased from 18 to 20%, 16 to 18% and 11 to 14%, an overall positive impact of between 10 and 30%. In the mid- to lower-troposphere, the use of ascent and descent data appeared to be responsible for *all* of the off-time update benefits, with 700 and 500 hPa even showing some degradations to the traditional 12 hr forecasts when the aircraft ascent/descent data were not used.

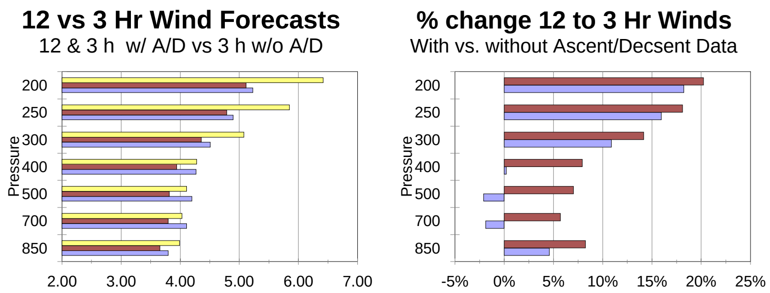


Figure 10: Left - Comparison of RMSV Wind Errors (ms-1) between 12 hr (yellow) and 3 hr RUC update forecasts with (red) and without (blue) aircraft ascent / descent data, all valid at same 0000 and 1200 UTC. Right – Normalized difference in improvement in RMSV wind errors between 12 hr and 3 hr RUC update forecasts (both valid at 0000 and 1200 UTC) with and without aircraft ascent / descent data.

When these results were averaged vertically and compared with rawinsonde data (Fig. 11), the net impact of including aircraft wind and temperature data from the ascent and descent portions of flight on domestic analysis and very short range forecast updates was positive at all times and for all parameters, including moisture. The forecast improvements were greatest for the 3 and 6 hr forecasts valid at 0000 and 1200 UTC. The especially large temperature improvements reflected not only the availability of thermal data in the aircraft reports, it also the improved interaction between improved details in the wind and temperature fields in the model's advection calculations. The slightly lower level of impact in the 0000 and 1200 UTC analysis (as compared to the 3 hr forecasts) was likely due to presence of all three analysis parameters in the rawinsonde profiles used at those times. The analysis improvement shown by including aircraft ascents and descents resulted from the combination of the use of additional, high-quality data in the synoptic time analysis and the use of an improved "analysis first guess" field, as represented by the improvements in the 3 hr forecasts.

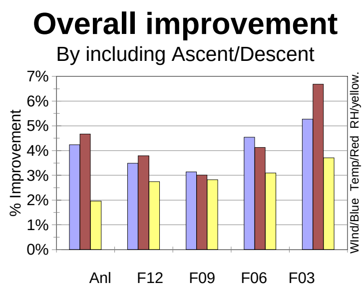


Figure 11: Vertically averaged and normalized difference in RMSV wind errors in RUC analyses and 12, 9, 6 and 3 hr forecasts (all valid at 0000 and 1200 UTC) with and without aircraft ascent / descent data.

5. Regional/Short Range Impacts of Wind Profiler Data

The previous studies showed a distinct positive impact from aircraft ascent and descent data in short to medium range forecasts. The studies, however, left open the question of the importance of the aircraft data relative to other "off-time" land-based profile data sources, the primary one over the U.S. being the Wind Profiler Demonstration Network (WPDN). The WPDN provides hourly profiles of wind from the surface to above 100mb at approximately 30 sites in the Central U.S. The observations are considered to be of similar quality to aircraft data and have the advantage of being available every hour throughout the day, every day of the week and at uniform spacing. Unlike the aircraft reports, however, the WPDN profiles only contain wind observations.

A second RUC impact test was undertaken in which all aircraft data were included but none of the WPDN data was used. Unlike the previous test where both temperature and wind data were affected, only wind data were excluded in these tests. The study was run in the three-week period immediately after the aircraft data denial test and results are presented in a manner parallel to that used for the previous study.

As shown in Fig. 12, the inclusion of ascent/descent data in the data assimilation system showed a consistent improvement in the "on-time" 0000 and 1200 UTC analyses, except at 200 hPa. Although the greatest impact was noted between 400 and 500 hPa, the accuracy of the analysis compared with rawinsonde data improved by about 2% throughout most of the troposphere. As with the aircraft ascent/descent tests, impacts were noted for all variables. However, the average impact from the denial of the WPDN wind data was less than half of that from the exclusion of wind and temperature data from aircraft ascent/descents. The maximum impact was also reduced by a factor of more than three.

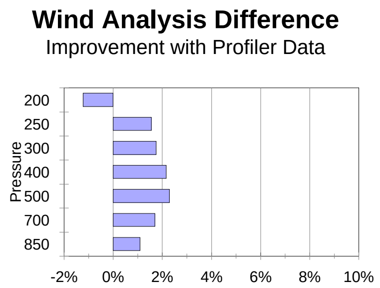


Figure 12: Normalized differences in RMSV fits of RUC wind analyses with rawinsonde data over the CONUS for 0000 and 1200 UTC analyses with and without Wind Profiler data.

The effect of these 0000 and 1200 UTC analysis difference on the associated 12 hr forecasts shown in Fig. 13 was positive at all levels and for all variables. For wind, the impacts at all levels were greater than the improvement in initial analyses. Unlike the tests with aircraft ascent/descent data, where the forecast improvements were greatest in the mid-troposphere and approached 5%(see Fig. 6), improvements with the WPDN data were more uniform across all levels and ranged from 2-3%.

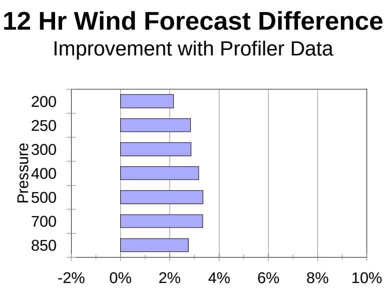


Figure 13: Normalized differences in RMSV errors of 12 hr RUC wind forecasts valid at 0000 and 1200 UTC

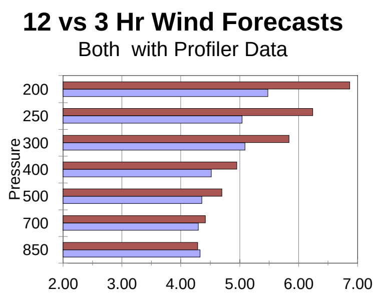


Figure 14: Comparison of RMSV Wind Errors (ms-1) between 12 hr (red) and 3 hr (blue) RUC forecasts valid at same 0000 and 1200 UTC times during period of Wind Profiler data denial tests.

The effect of including all 'off-time' data into nine successive corrections to traditional 'on-time' model guidance made by the hourly RUC analysis updates performed between 0000 and 0900 UTC and 1200 and 2100 UTC was again determined at 0000 and 1200 UTC as a reference. The results for this test period again showed reductions in 12 hr forecasts errors at most levels (see Fig. 14), ranging from slight degradation at 850 hPa to improvements of nearly 1.5 ms^{-1} at 200 hPa. Because these results are very similar to those obtained during the earlier aircraft ascent/descent denial tests, comparisons of the relative degree of impact between the two different data types should be valid, even though the test periods varied. The amount of the change in 12 hr forecast error by the RUC updates by including hourly WPDN wind data was again determined and normalized by the overall forecast error (see Fig. 15).

Within 3 hrs, the use of WPDN data improved tropospheric forecasts by approximately 2% at all levels except 200 hPa, where slight degradations were noted.

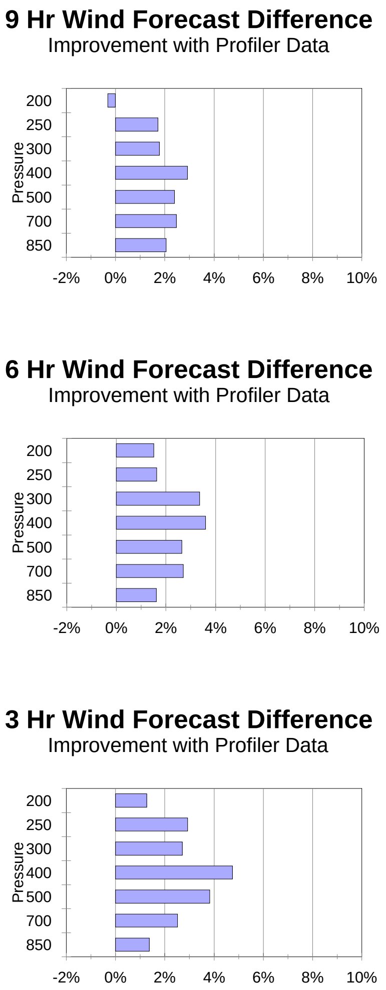


Figure 15: Normalized difference in RMSV wind errors in RUC 9, 6 and 3 hr forecast updates (all valid at 0000 and 1200 UTC) with and without Wind Profiler data.

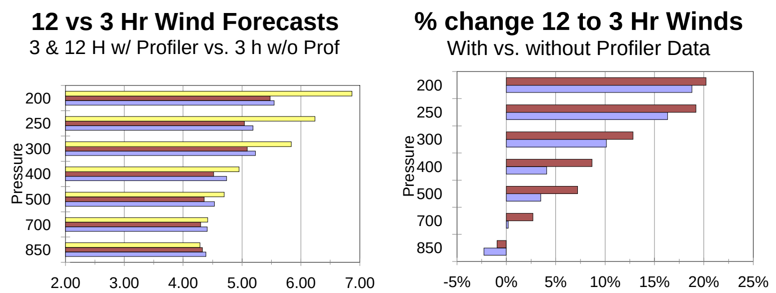


Figure 16: Left - Comparison of RMSV Wind Errors (ms-1) between 12 hr (yellow) and 3 hr RUC update forecasts with (red) and without (blue) Wind Profiler data, all valid at same 0000 and 1200 UTC. Right - Normalized difference in improveme in improvement in RMSV wind errors between 12 hr and 3 hr RUC update forecasts (both valid at 0000 and 1200 UTC) with and without Wind Profiler data.

After 6 hrs of updating, the inclusion of WPDN wind data reports improved forecasts by ½ to 1% in the troposphere, with greater improvement at 200 hPa.

Difference between 12 hr operational RUC forecast and corresponding 3 hr forecasts from systems with and without WPDN data after incorporating of 9 hrs of 'off-time' data showed reduction in the 12 hr forecast errors by another 1% at several levels, although some other levels showed little improvement from the addition of another 3 hours of Wind Profiler data.

Figure 16 shows that the use of WPDN wind reports improved 200, 250 and 300 hPa wind updates by from 19 to 20%, 16 to 19% and 10 to 13%. This is comparable to the change noted by including aircraft ascent/descent data. In the mid- to lower-troposphere, the use of WPDN data produced for about ½ of the off-time update benefits at 400 and 500 hPa, while at 700 hPa, the profiler data had a major effect.

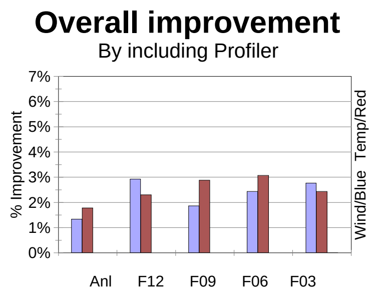


Figure 17: Vertically averaged and normalized difference in RMSV wind errors

When these results are averaged vertically and compared with rawinsonde data, the net impact of including Wind Profiler data on domestic analysis and very short range forecast updates (Fig.17) was positive at all times for both wind and temperature forecasts. The forecast improvements were greatest for the 12 hr forecasts. The WPDN data also showed progressively larger impact from the 9 to 6 to 3 hr forecasts valid at 0000 and 1200 UTC. The magnitude of these changes is approximately ½ of those due to aircraft ascent/descent data. The smaller improvement in temperature relative to the aircraft ascent/descent tests was probably a reflection of the lack of any new thermal or moisture information in the WPDN data. The slightly lower level of impact in the 0000 and 1200 UTC analysis (as compared to any of the forecasts) was likely due to inclusion of vertical profiles of all three analysis parameters in the rawinsonde data used at those times.

5-Summary

A series of tests of the impact of automated reports from commercial aircraft were discussed, including 1)

a subjective summary of findings by FSL using the RUC, 2) an objective medium-range forecast data denial test by ECMWF focusing on ascent/descent data, and 3)
an objective short-range forecast data denial test over the US by NCEP using the RUC focusing also on the impact of ascent/descent aircraft data.

All three independent evaluations indicated that the automated aircraft wind and temperature reports had consistently positive impact on both analysis and forecast skill at time ranges from hours to days and at both regional to global scales. The exclusion of data reported during ascent and descent results in a significant decrease in forecast skill throughout the troposphere, as well as decreasing the quality of wind forecasts at upper levels, even when aircraft data are used there.

The impacts of the aircraft ascent/descent data across the US were also compared with those of hourly wind information from the Wind Profiler Demonstration Network in the Central US. The results for the late spring/early summer period indicated that the aircraft data had as much as twice the impact as Wind Profiler data over the CONUS - and at a lower cost.

These results leave the following questions unanswered:

-How do we determine the ‘overall’ impact (or benefit) of any data set?
-Are we using the data optimally for *all* NWP problems, especially considering differences between the synoptic and sub-synoptic scales?

-Are we using the proper evaluation standard, since specific system impacts will change with application, e.g., precipitation vs. aviation wind and turbulence, . . .

-Is it more important to improve the average scores or remove the most egregious forecast ‘busts’?

In all cases, we must consider the <u>total</u> use of the data. Again, we have to ask a nunber of questions, including:

-Are data only useful if they improve NWP?

-What is their importance to subjective forecasting and how do we measure this against their impact to NWP?
-Are the data more important for nowcasting vs synoptic vs medium range NWP and how do we weight the relative value of each?
-What is their value to ‘non-traditional weather applications, e.g., air quality or energy use forecasting?
-And very importantly, how do the impacts of the systems compare with their associated costs, both initial and sustaining?

All of these questions need to be answered in order to determine the
‘overall’ impact (or benefit) of any data set. In the case of the aircraft data, they are conservatively 5-10 times less costly than data from the WPDN. Although the quantitative tests show overall greater forecast impact from the aircraft data over the CONUS, results often vary locally. Aside from the proposed water vapor sensors, the aircraft systems have the advantage of not requiring major infrastructure investment. For many applications in developing parts of the world, they also have the advantage of not requiring local maintenance. Although aircraft data are not available in all weather, airport closures tend to be short and very few reports are lost. When all of these factors are considered together, the aircraft data appear to be a far more cost effective alternative to Wind Profilers.

However, the Wind Profiler data are available every hour of the day, while aircraft data are not.
Although the NWP tests shown here may point out the advantages of aircraft data, forecasters use wind profiler data as a matter of course, depend on their hourly availability and have found them to be indispensable for specific events.

In the end, impact test results have to be thorough and independent of observing system proponents. The best NWP-based tests are those that are corroborated by multiple centers.
Finally, they have to include all known uses, not just NWP, and must be forward looking enough to account for as many probable future users as possible.

7 – References:

Benjamin, S., 2004: Personal Communication, NOAA Forecast Systems Laboratory, Boulder, CO, USA.

Cardinali, C., L. Isaksen and E. Andersson, 2002: Use and impact of automated aircraft data in 4D-Var, ECMWF Technical Memorandum, Reading, England, UK.

Atmospheric Soundings of Temperature, Moisture and Ozone from AIRS

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Introduction

The NASA EOS AQUA high-spectral resolution Atmospheric InfraRed Sounder (AIRS) and the Advanced Microwave Sounding Unit (AMSU) were successfully launched on May 4, 2002 and placed into a low earth sun-synchronous polar orbit at an altitude of 705 km. Five months later, NESDIS started to distribute spatially and spectrally thinned radiances to Numerical Weather Prediction (NWP) centers. The thinned dataset contains 324 out of 2378 channel radiances for every 18th AIRS fields of view (fov). There are 3x3 AIRS 15 km fov's within every AMSU 42 km fov;, therefore, the 18th fov is the center AIRS fov associated with every other AMSU fov. Each dataset include observations from a six minute period, hence there are 240 such "granules" per day. The thinned granule dataset also include all of the AMSU channels. The impact of AIRS at ECMWF was been reported to be "small, positive and persistent" (McNally, private communication) and the data are now used operationally. One interesting note is that there are currently 25 instruments in the ECMWF assimilation. Experiments in which AIRS was added to an assimilation without satellite information showed significant improvement over those using only AMSU measurements in the southern hemisphere (McNally, private communication). The impact at NCEP was reported to be slightly positive, and much smaller than the impact when assimilating the first NOAA AMSU sounder data in 1998. One of the first questions that come to mind is how can a technically advanced high-spectral resolution infrared sounder like AIRS with its excellent signal to noise performance and relatively high vertical resolution have such a small impact. The answer may be due to spatial and spectral thinning and the current methodology for radiance assimilation, which is to use only those channels and scenes that are determined to be unaffected by clouds. The percentage of assimilated AIRS channel radiances can range from 100% of the spectrally and spatially thinned data for channels peaking in the upper stratosphere, above the clouds, to 5% of the thinned data for channels peaking in the lower atmosphere. However, because the vertical resolving power of AIRS is concentrated in the lower atmosphere, the lower peaking and likely cloud contaminated AIRS channel radiances are the most important. Given the very small areal coverage of AIRS data being assimilated, due to clouds, the small impact of AIRS, especially in the lower troposphere, is to be expected. So how can AIRS have a larger impact? We believe the answer is to use more AIRS data by assimilating cloud-contaminated or cloud-cleared radiances. Another option is to assimilate the AIRS retrievals of atmospheric temperature, moisture and ozone profiles, which will become available in near real-time during 2004. An important reason for distributing AIRS products to NWP centers is to enable the NWP community as well as the product generators to learn how to best produce and utilize high-resolution infrared sounder data prior to the EUMETSAT IASI and NPOESS CrIS instruments become operational. So the early assessments of a small assimilation impact should be followed by intensive activities to use more AIRS data. One of the goals for 2004 from the AIRS Science Team is to demonstrate the high quality of AIRS cloud-cleared radiances and deliver reliable radiances to the NWP community. The yield of successful cloud-cleared fov's is about 50%. The purpose of this paper is to show the large improvement in retrieval accuracy using AIRS, when compared to AMSU, in the presence of clear and partly cloudy fov's, and also for cases that have been cloud-cleared. We hope the outstanding performance of AIRS retrievals shown in this paper will encourage the NWP community to assimilate cloud-cleared radiances. The algorithms for deriving products, including clear detection and cloud-clearing, from AIRS /AMSU can be found in the special AQUA IEEE issue (Goldberg *et al*. (2003) and Susskind *et al*. (2003)).

Retrieval Accuracy in Clear and Partly Cloudy Conditions

The clear fov detection techniques and application methodogy are described in greater detail in Goldberg et al. (2003). There are three key tests. The first test predicts a single AIRS channel radiance at 2390 cm^{-1}, which peaks near 850 mb, from brightness temperatures in AMSU channels 4, 5 and 6. The second test computes the spatial variability of the 2390 cm^{-1} radiance for a 3 x 3 array of AIRS fov's. The third clear test, which is used only in ocean scenes to remove errant cases from the training, compares the sea surface temperature (SST) derived from the AIRS retrieval with the ECMWF SST analysis. The results shown in this paper will be based on regression, trained using the ECMWF analysis. The regression algorithm is based on Principal Component Analysis (PCA) and details are also given in Goldberg et al. (2003). Eighty five Principal Component Scores (PCS) along with AMSU brightness temperatures are used for linear regression predictors. The first experiment was to generate a set of coefficients for scenes determined to be clear by the tests mentioned above. The ECMWF data used for training is screened for errant cases, called "outliers", because we cannot assume that the model is perfect everywhere. However for many situations the model analysis is rather accurate. The outliers are determined by removing cases with large differences between measured and computed radiances. We also generated coefficients for a mixture of clear and partly cloudy situations. These cases were determined by simply using the first test. If the difference between the predicted AIRS minus the observed 2390 cm^{-1} AIRS is larger than 2 K, the fov is determined to be clear enough to be used (clear, partly cloudy or low clouds). This accounts for about 40 % of the data. The fov's declared clear by all three tests are approximately 5% of the data. Figure 1 compares retrieval accuracies from clear-only and partly cloudy situations. The accuracy of the AIRS and AMSU-only retrieval are also compared in this figure. The "accuracy" curves shown in this figure are the root mean square (RMS) differences between the retrievals and ECMWF analysis for an independent ensemble. The solid curves are the retrieval RMS differences for ocean clear cases, whereas the dashed curves are the RMS differences for global non-clear cases. The results demonstrate the large improvement of AIRS over AMSU, as well as the very good performance of AIRS even in the presence of cloud contamination. The coverage for the clear - partly cloudy areas area shown in Figure 2.

Retrieval Accuracy from Cloud-Clearing

The cloud clearing algorithm is described in Susskind *et al*. (2003). Cloud-clearing begins with an AMSU physical retrieval (Rosenkranz, 2001) of atmospheric temperature, moisture (liquid and vapor), microwave spectral emissivity, and skin temperature. The AMSU retrieval is used to compute an estimate of the AIRS radiances for the clear component of the scene. Cloud clearing assumes that the only difference between a set of AIRS fov's is the amount of clouds, therefore, the clear radiance estimate can be used to retrieve a set of extrapolation parameters from a set of AIRS cloudy fov's. Scenes that fail the cloud clearing assumptions, have a poor clear state estimate, or are too cloudy are rejected. The extrapolation parameters for accepted scenes are then used to compute the cloud cleared radiances for any channel that is sensitive to clouds. Channels that are not sensitive to clouds are averaged over the 9 fov's.

In Figure 3, a comparison of measured AIRS radiances and radiances computed from the ECMWF is shown for a scene that is determined to be cloud-free. There are differences on the order of 3 K that are attributed to differences in moisture between the ECMWF model and the real scene. The window region agrees to within a fraction of a Kelvin, indicated that there is very little cloud contamination in this scene.

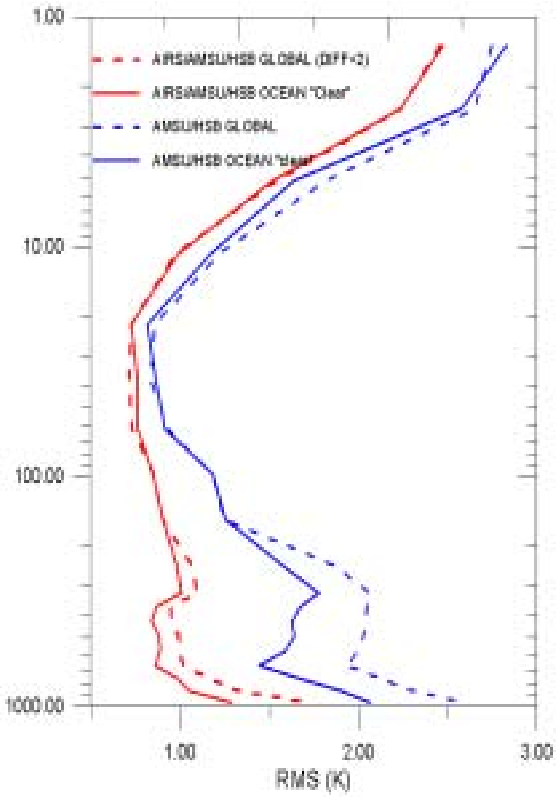


Figure 1: Retrieval RMS Errors

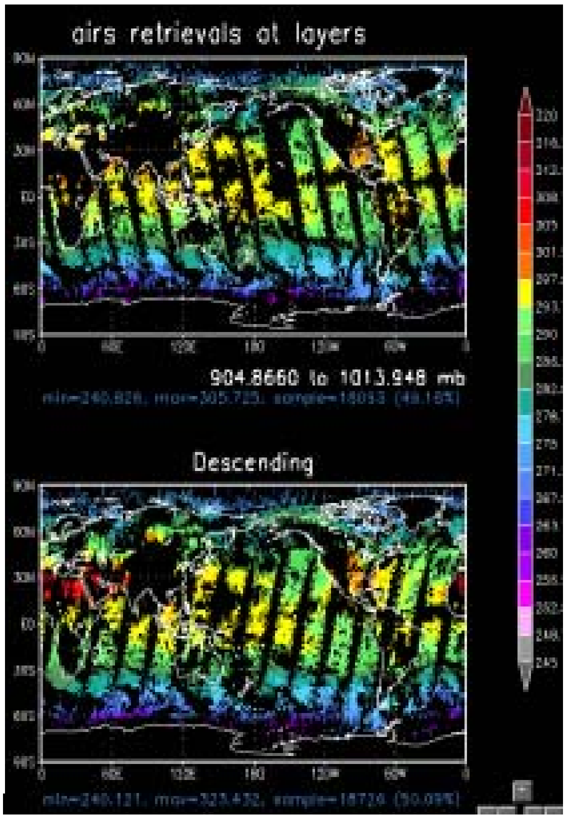


Figure 2: Coverage of partly cloudy areas.

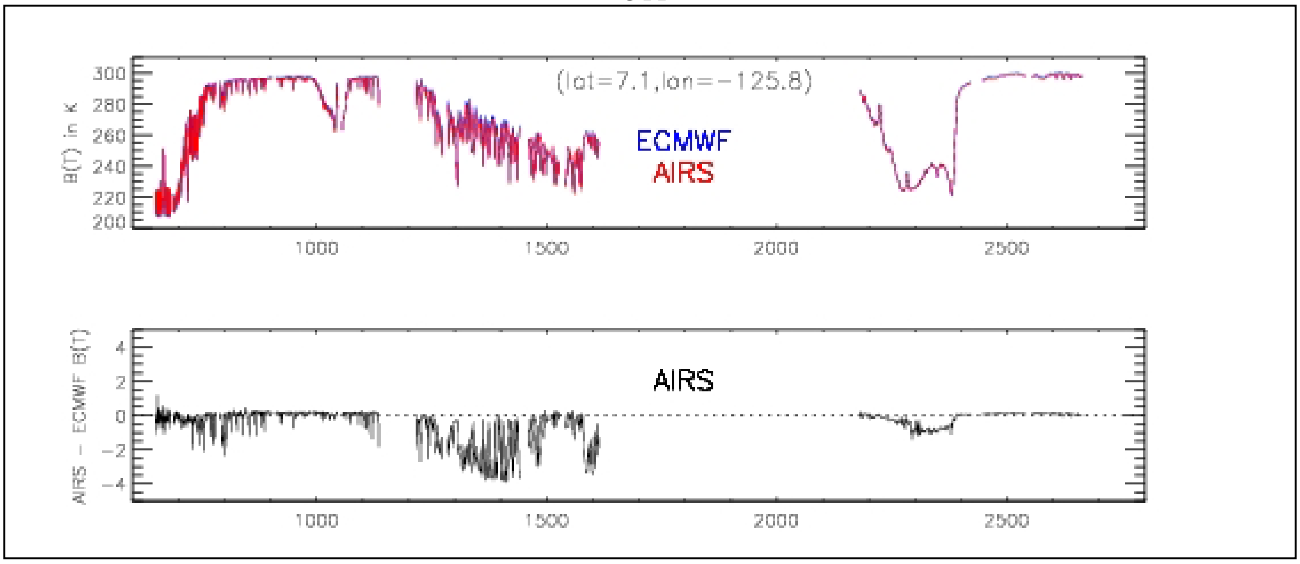


Fig. 3: Top Panel: Example of AIRS radiances (RED) and radiances computed from the ECMWF forecast (BLUE) for a ocean nighttime scene that has been determined to be cloud-free. The difference is shown in the bottom panel.

In Figure 4 a scene with approximately 30% cloudiness that is located 330 km from the scene in Figure 3 is shown. The top panel shows the AIRS radiance and the radiance computed from ECMWF, as in Figure 3. The middle panel shows the difference of the top panel and it can be clearly seen that there is approximately 4 K of cloud contamination in the AIRS window regions. In the lower panel the difference between the derived cloud cleared radiances for this scene and radiances computed from the ECMWF are shown as a black curve. Also the clear scene radiances differences from Figure 3 are reproduced here in green. There are very small differences between the residuals of clear scenes and cloud cleared scenes in these two cases. The differences are attributable to the forward model error or errors in moisture in the forecast model; however, the cloud cloud cleared radiances have successfully removed the effects of the clouds in this case.

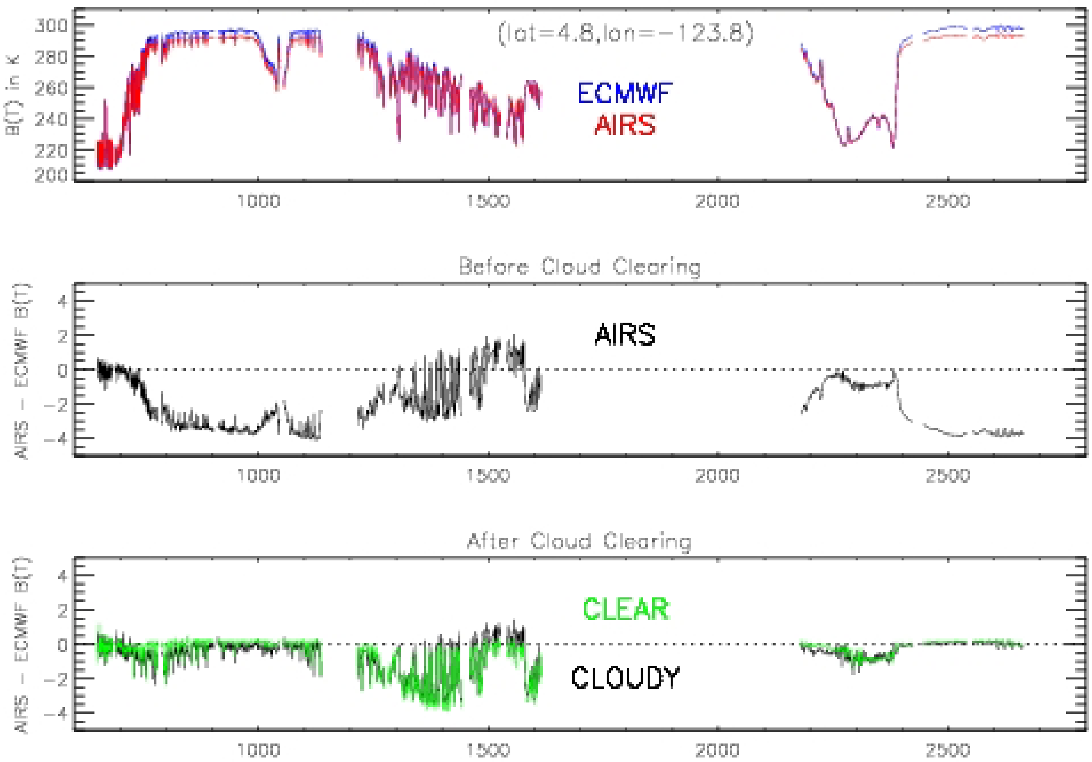


Figure 4: Example of radiance differences from radiances computed from ECMWF forecast for a single scene.

In Figure 5 we show the RMS statistics of AIRS radiances minus radiances computed from ECMWF for a full AIRS granule consisting of 1350 retrievals scenes. This granule was chosen because it contains a large number (approx. 100) of scenes determined to be clear. We kept separated statistics for radiance differences (similar to the ones shown in Figures 3 and 4) for all the accepted scenes (cloudy or determined clear) and the determined clear scenes. The AIRS radiances were simply averaged and used without modification in the retrieval process if the scene was determined to be clear. The statistics for clear scenes are shown in red and the cloud cleared scenes are shown in blue. In the top panel the RMS of the AIRS cloudy radiances minus radiances computed from ECMWF are shown. There is roughly 8 K RMS of cloud contamination in these scenes and less than 1 K RMS of contamination in the scenes determined to be clear. In the middle panel, the RMS of cloud cleared radiances minus radiances computed from ECMWF are shown in blue and the RMS of the differences of the averaged AIRS radiances from ECMWF for the clear scenes are shown in red. The two curves are virtually identical indicating that the cloud clearing is performing as well as cloud filtering for this granule The RMS of differences for cloud clearing is slightly larger than clear filtered scenes, as expected, because cloud clearing amplifies the instrument noise. The bottom panel shows the retrieval residual (measured radiances minus radiances computed from the retrieval solution) for both the cloud cleared (blue) and determined clear (red) scenes. The retrieval quality is the same in both the cloud cleared and determined clear scenes, indicating that the cloud cleared radiances are not inherently different from scenes determined to be clear. However, the yield of cases is only 7% for determined clear (this granule was selected for a large yield of clear) whereas the yield was 90% for cloud clearing (this is a relatively cloud free granule and has a high yield).

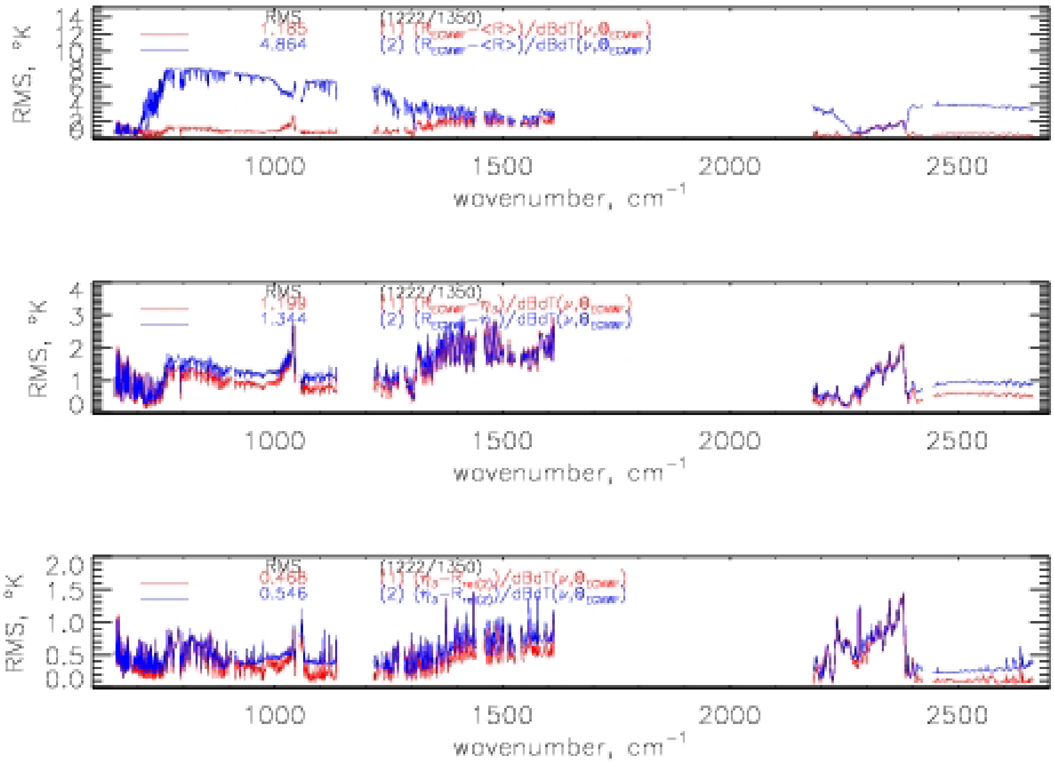


Figure 5: RMS statistics of radiance differences for a full granule of cloudy radiances. Statistics for the 1222/1350 scenes accepted by the AIRS science team algorithm are shown in blue. The observed radiances from 100 scenes determined to be clear are shown in red.

In the NOAA NESDIS processing approach a subset of cloud cleared radiances (1500 AIRS channels) are transformed into 85 PCS that are used as regression predictors for deriving the AIRS/AMSU temperature, moisture and ozone retrieval. The conversion of PCS back to radiances can be thought of as a noise-reduced AIRS spectrum because the inherent redundancy in information content within the 1500 AIRS channels allows averaging of the noise. The standard deviation of the difference between the cloud cleared radiances and the reconstructed radiances, over of the 1500 channels, is called the Reconstruction Score (RS). The RS provides a measure of how well the radiances can be reconstructed, when compared to the input radiances. A reconstruction score of unity indicates that the reconstruction fit is at the noise level. For cloud-cleared radiances, the score can vary from 0.33 to a number much greater than one. The RS is near 0.33 when the entire 3x3 array of AIRS fov's is clear and the cloud clearing algorithm simply averages the radiances from the 9 fov's. When the score is greater than one, the cloud clearing has amplified the noise with respect to a single fov.

In Figure 6 we show maps of the RS for different thresholds of RS. The map on the upper left (RS<0.5) show the areas (~5%) that have been declared clear (i.e. all 3x3 fov's are clear). The map on the upper right shows the regions where the cloud-cleared radiance have noise characteristics that are smaller than the original instrument single fov noise (RS< 1). The yield of RS<1 is about 60% of the total. The lower left shows areas where the score is less than 2, and we have observed that the larger RS values in this ensemble are typically near the edge of clouds.

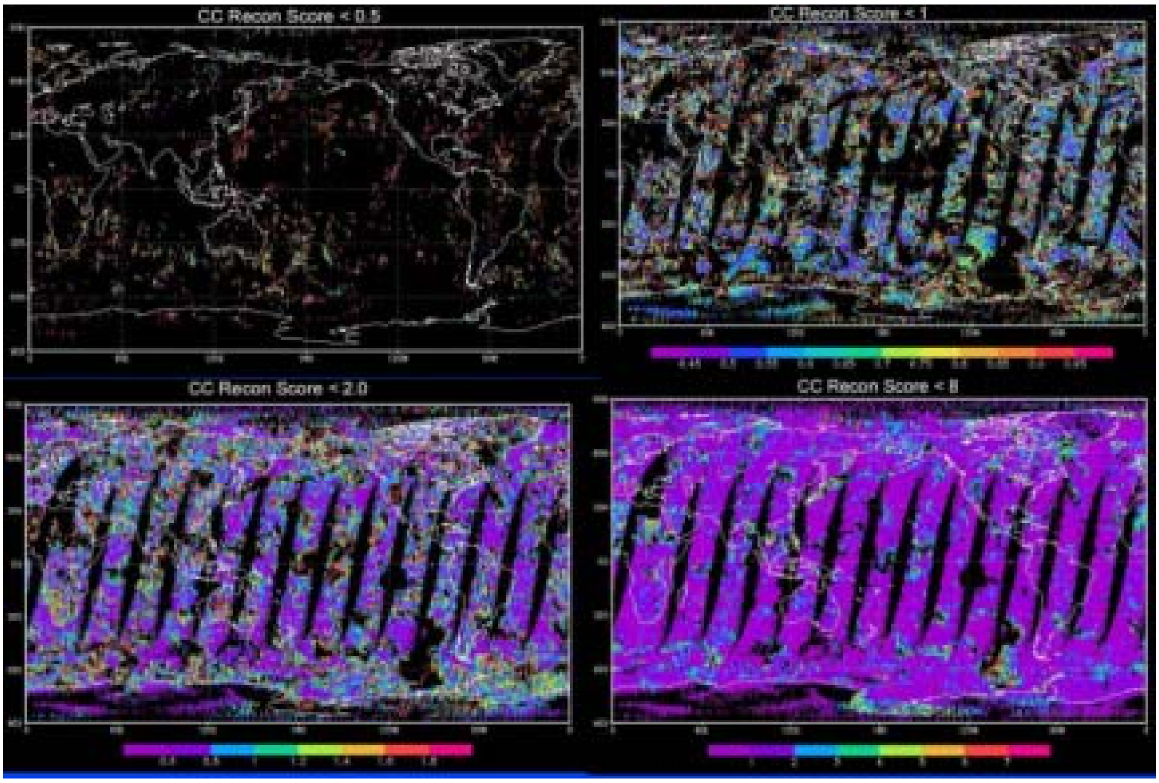


Figure 6: Reconstruction scores computed from cloud cleared radiances. Each panel shows the cases which pass the reconstruction score of 0.5, 1.0, 2.0, 8.0, respectively.

Regression coefficients were generated from a training set of cloud-cleared radiances collocated with the ECMWF analysis of temperature, moisture and ozone. The ECMWF data are screened by requiring a 2 K agreement between the measured radiances and those computed from ECMWF for 12 channels: 702.7, 706.7, 711, 712.7, 715.9, 724.8, 746.0, 759.57, 965.4, 1468.83, 1542.35 and 1547.88 cm^{-1}. The training set was derived from three different days (September 2002, January 2003 and June 2003). Figure 7 shows a typical training population for a given day. The retrieval accuracy, compared to ECMWF for dependent and independent ensembles are shown in Figure 8. The RMS differences are similar to those obtained from clear fov's, which can be seen in Figure 1. We also generated retrieval RMS differences based on collocated radiosondes. Figure 9 show the RMS differences between the collacated radiosones, both from the AIRS retrievals and those retrieved using the NESDIS ATOVS system (Reale, 2002). The AIRS retrieval errors are significantly lower than ATOVS, including the systematic bias. The larger errors in the lower tropospheric temperature are probably due to uncertainties arising from collocation temporal and spatial differences. However, the difference between the ATOVS and AIRS retrieval remains large. Previous simulation studies have found that AIRS generally reduces the retrieval error by about 0.5K, and this appears to be holding for this radiosonde comparison. For moisture, the retrieval errors are significantly smaller than ATOVS. The large natural variability of water vapor combined with uncertainties in radiosonde-observed water vapor will prevent demonstrating the 10-15% accuracies often reported in simulated studies.

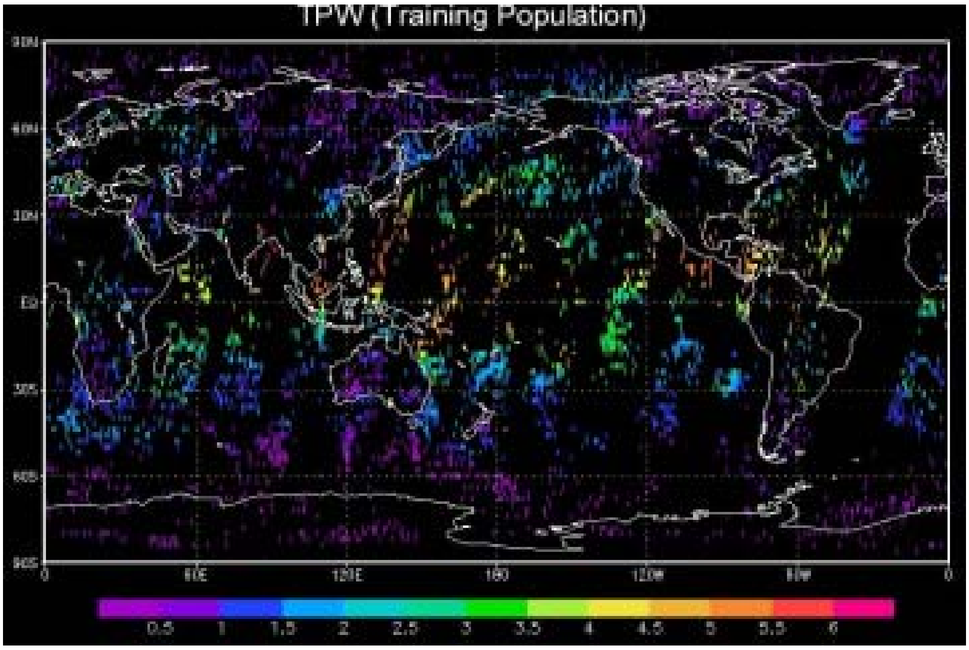


Figure 7: Distribution of collocated AIRS and ECMWF used in generating regression coefficients.

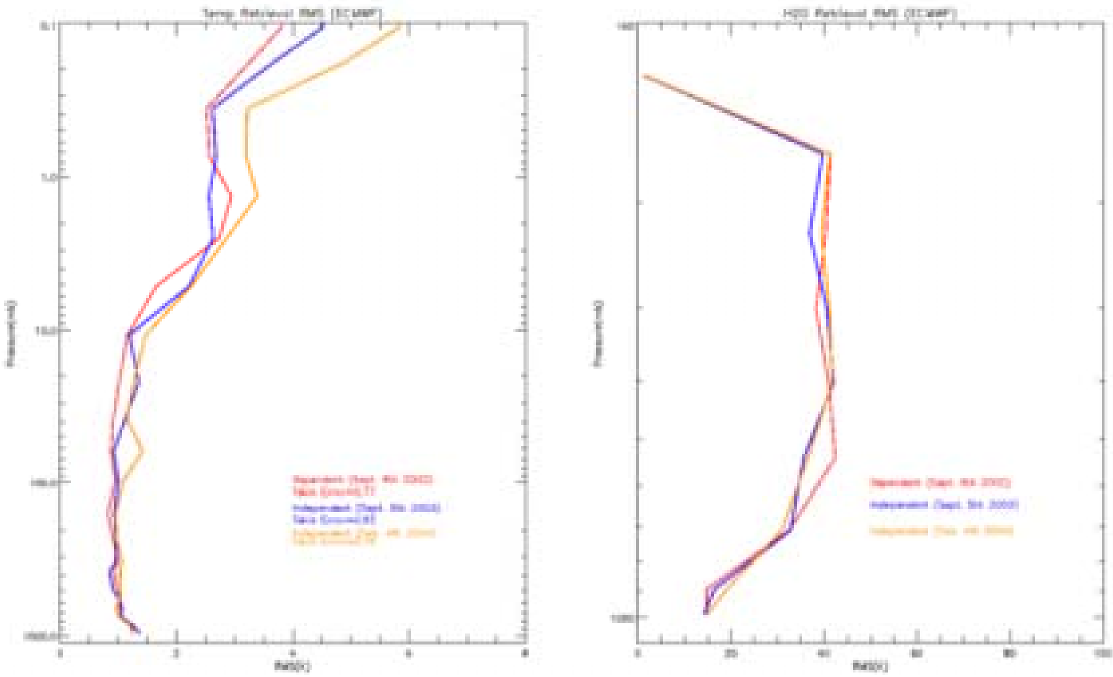
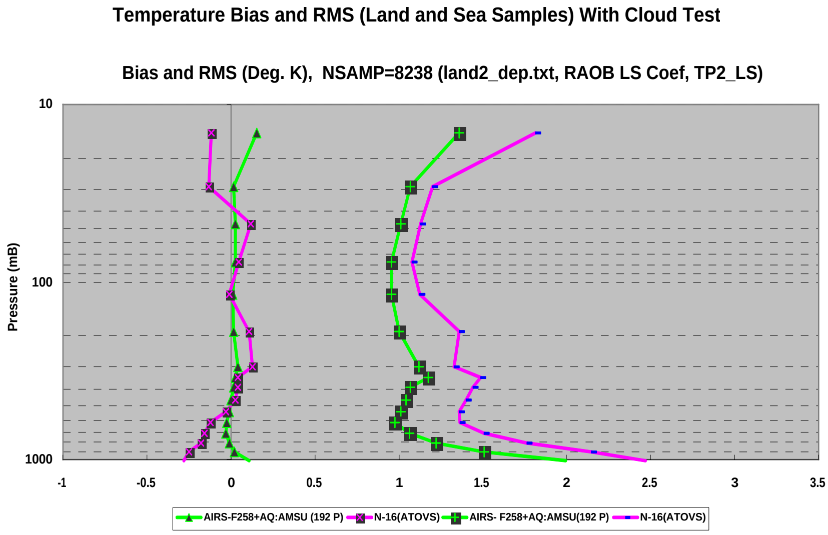


Figure 8: Temperature (in K, left) and water vapor (in %, right) RMS differences between AIRS retrieval and ECMWF.



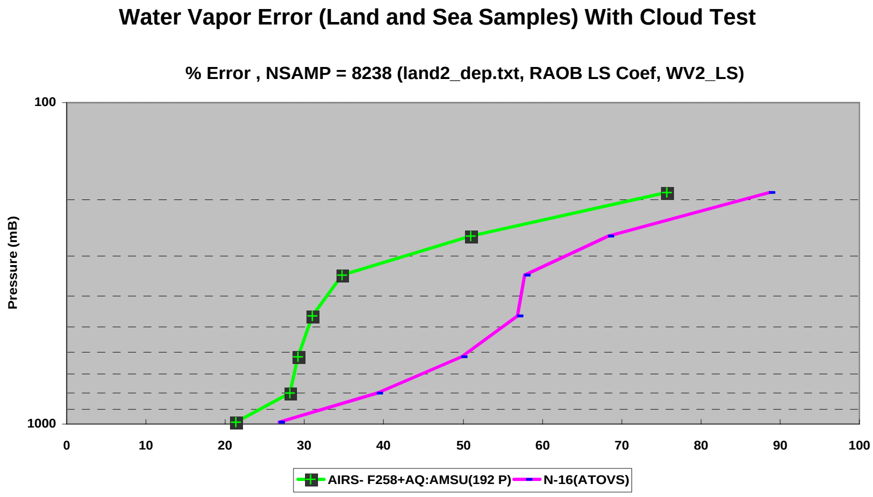


Figure 9: Temperature (in K, top) and moisure (in %, bottom) RMS differences between the regression retrieval and the collocated radiosondes.

Summary

We have demonstrated very good retrieval performance from AIRS in clear, partial cloudiness, and cloud-cleared fov's. The impact in NWP will likely remain small, unless AIRS cloud contaminated or cloud-cleared radiances are assimilated. The challenge for the NWP satellite data assimilation community is to assimilate AIRS data in the presence of clouds, otherwise the full impact of high spectral resolution infrared observations will not be realized. Another option, of course, is to assimilate AIRS retrievals, which are also derived in near real-time. These retrievals have been optimized for the instrument characteristics of the AIRS and AMSU instruments on Aqua and properly account for the spectrally correlated properties of cloud cleared radiances.

References

Goldberg, M.D., Y. Qu, L.M. McMillin, W. Wolf, L. Zhou, and M. Divakarla, 2003: AIRS near-real-time products and algorithms in support of operational numerical weather prediction, *IEEE Trans. Geosci. Remote Sensing*, Vol. **41**, pp 379-389, Feb. 2003

Reale, A.L. 2002. NOAA operational sounding products for advanced-TOVS. *NOAA Technical Report NESDIS 107*. U.S. Dept. of Commerce, Washington DC, 29 pp.

Susskind, J, C. Barnet and J. Blaisdell, Retrieval of atmospheric and surface parameters from AIRS/AMSU/HSB data under cloudy conditions, *IEEE Trans. Geosci. Remote Sensing*, Vol. **41**, pp 390-410, Feb. 2003

Rosenkranz, P.W 2001. Retrieval of temperature and moisture profiles from AMSU-A and AMSU-B measurements. *IEEE Trans. Geosci. Remote Sensing*. Vol. **39**, pp. 2429-2435.

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Towards an Adaptive Observing System

Claude Pastre, consultant for the WMO/WWW
March 2004

Introduction and definition of concepts

Our modern societies have become both more sensitive and less tolerant to the hazards of the environment. There is a distinct tendency from citizen all over the world to consider as an absolute necessity the availability of efficient risk management systems, including prevention, preparedness of authorities, information, early warning, etc… In recognition of this trend, the 6th WMO Long Term Plan identifies as one of the strategic goals the need for better prediction of severe weather events and for improved warning systems.

High impact weather events such as tropical cyclones trajectories, big winter storms, critically heavy rainfall, etc. prove difficult to predict. There are a number of scientific and technical reasons for this situation, among which the uncertainties in the knowledge of the initial state of the atmosphere is recognised as a prominent one. A very active research in the past decade on the way Numerical Weather Prediction models handle the analysis errors has shown that there is no spatial homogeneity in the size and growth rate of errors : for each weather situation there are different areas of particular sensitivity to errors in the initial state. This implies that meteorological observations will have a variable value for NWP depending on the time and place where they are performed. The analysis would be better if observations could be made on a particular day at the locations were the day's forecast is more sensitive errors in the analysis.

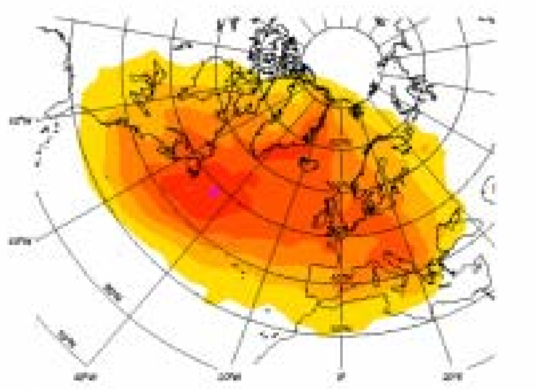
The 6th WMO Long Term Plan identifies as another strategic goal the "improvement of the effectiveness, efficiency and flexibility of the practices of WMO". The improvement of the design and operations of the Global Observing System has to be a major contributor to this goal. An optimised observing system adapted in flexible ways to meteorological circumstances could provide more value (information content) for the same expenditure.

Consequently, for both better performance and better efficiency, the 6th Long Term Plan states as part of the implementation activities that "on a regional basis, observing networks that are adaptable to changing requirements should be developed".

The term "adaptive observation" appeared in the context of what is called "observation targeting", i.e. a technique to predict the areas where specific observations will be particularly useful on a given day and to target specific observing systems on these areas. Adaptive observation is often used a synonym for observation targeting, but it can be used in a more general sense : adaptation serves an optimisation process and the optimisation criteria may be enlarged to include economic considerations such as minimising running expenditure of costly observing systems (e.g. radiosondes or AMDAR). This makes adaptive observation of interest to all NMHSs, even if they are not in a position to implement expensive dedicated observation targeting systems such as research aircraft.

Also, the tools developed for the purpose of observation targeting can be used for climatological studies of sensitivity to errors in the initial state. These studies in turn can contribute to improvement of the design of the GOS (e.g. to decide where the implementation of a specific observing system or station will be most cost-effective). Figure 1 illustrate this process. It shows a result from a climatological study of sensitivity by ECMWF that was used inter alia to plan the EUCOS/ASAP deployment programme for the period 2004-2006.

Figure 1 : climatology of 2-day RMTE key analysis errors
Period 30 Oct 1999 -12UTC to 29 Jan 2000 -12UTC / Target 68/-10/45/35



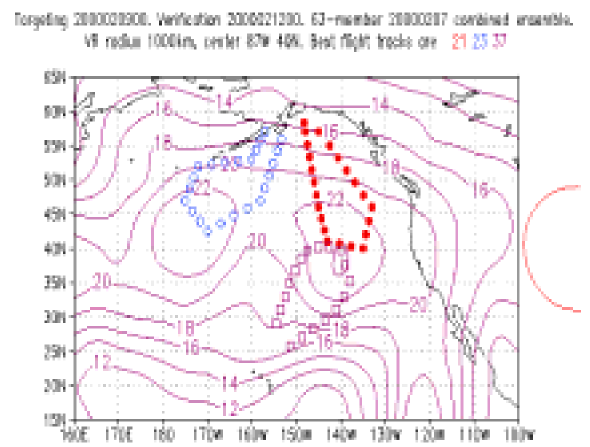
It is important to note that adaptive observation must be handled at regional or sub-regional level. To define the areas of sensitivity one looks for the impact of the errors on a limited geographic region (e.g. the West Coast of Northern America). The sensitive areas are themselves limited in size having typical dimensions of a few thousands of kilometres. Consequently the operation of an adaptive observing system cannot be a global issue. There are however larger scale implications, which require a global perspective to be taken in the WMO framework.

One may also note that it is now recognised that targeting of observations must also take into account the characteristics of the numerical assimilation system that is going to use them. This introduces some complications in regions such as Europe where several NWP systems work in parallel. This should not be taken as a discouraging element, but as an issue to be addressed as part of the design of the adaptive observation programmes.

Relevant past experience and assets

A number of favourable circumstances make possible the development of an operational concept for adaptive observation. There is an active research community on the subject. There is also a wealth of experience acquired in large research experiments and in convincing operational or pre-operational implementations.

Figure 2 : example of targeting for the WSR program (from NOAA/NCEP/EMC)



The half-century old Hurricane Surveillance Program of NOAA is actually an adaptive observation programme even if it is does not make use of the new observation targeting techniques, in the sense that it performs measurements with dedicated aircraft in and around identified threatening cyclones to improve the forecast of their evolution and track. The first experiment of modern techniques for targeting observation was made during FASTEX in 1997 addressing the forecast of winter storms in the Northern Atlantic. Its results were sufficiently positive to convince NOAA to implement the Winter Storm Reconnaissance Program. This programme has run since 1999. Its objective is to improve the forecast of winter storms for the Western Seaboard of North America and of cold outbreaks in the North-East by improving the numerical analysis over the North Pacific. It makes use of dedicated aircraft equipped for dropsonde launch, based in Alaska and Hawaii. Figure 2 gives an example of a chart displaying the aircraft trajectories selected for the sensitivity pattern of a specific day.

Adaptive observation is a major element of the THORPEX research programme run under the auspices of WMO/WWRP. Research is needed in particular to improve the efficiency of sensitivity area selection and of the assimilation of targeted observations. These methods are however mature enough to be tested in pre-operational implementation. This was the purpose of the THORPEX NA-TReC 2003 (THORPEX North-Atlantic Regional Campaign) conducted by NOAA and EUMETNET with the support of ECMWF and operational European NMHSs. The most efficient future development of adaptive observation will be achieved through a tight working relationship between research and operational implementation.

A list of basic references on FASTEX, WSR and THORPEX is provided at the end of this document for the interested readers.

Technological assets are also available to perform adaptive observation. The GOES and METEOSAT satellites have a rapid-scan capability which permits more frequent observation of fast developing weather. GOES also has a targeting capability for its sounding instrument. The technology to launch dropsondes from aircraft is mature and has been extensively used on dedicated research aircraft. This tool is certainly the most powerful one to provide targeted observations as demonstrated in FASTEX, WSR, and NA-TreC. It is unfortunately very costly to maintain and run dedicated aircraft. Imaginative collective arrangements will have to be sought by most countries to make a wider operational use of such aircraft. Promising development of less expensive targeting observing systems (driftsonde, drone aircraft, rocketsonde) is ongoing in the THORPEX context. The success of these developments will be crucial for the implementation of wide-spread observation targeting.

Finally, the list of available assets includes the tools and operational practices developed by EUMETNET/EUCOS to optimise the data collection from AMDAR, ASAP and radiosonde stations. These have been through a comprehensive and successful pre-operational test during the Autumn 2003 NA-TreC.

Proposed objectives for the WMO

The following objectives are proposed for the WMO as concerns adaptive observation :

- **To contribute to the improvement on a regional basis of the short range forecast of high-impact weather through regional programmes of adaptive observation, including targeting of additional observations.**
- **To apply the study of the sensitivity of forecast to errors in the initial conditions to the optimal design and to the operation of observing systems with a view to improve their efficiency to cost ratio.**

Some of the regional programmes for adaptive observation will work on daily adaptation (e.g. winter storms or cyclone tracks). Other will find interest in seasonal adaptation provided adaptation is found to be beneficial either in terms of forecast quality or cost savings when applied to a seasonal phenomenon (e.g. monsoon).

A regional programme will target high-impact weather specific to the region and will need clear identification of objective, methods and needed resources. In particular, a mechanism for operational decisions will have to be implemented for the selection of sensitive areas and the decision on an increased observational programme once a risky episode is emerging. A systematic evaluation of the impact of actions taken will also be necessary. All these characteristics imply an international project management structure. Such structures have been used successfully in large international research experiments such as GARP/FGGE, FASTEX, THORPEX/NA-TreC, etc. They are not however a very common practice in international management of operational meteorological observing systems (one notable exception is EUMETNET/EUCOS). The careful definition and implementation of these project management structures at regional or sub-regional level will be critical for the success of adaptive observation programmes.

Optimisation studies should look for possible cost savings in the operation of the regional observing systems in weather situations where no specific meteorological risk is foreseen. On a daily basis this could be worthwhile for systems with significant running expenditure as AMDAR or radiosondes. For instance, should all radiosounding stations operate with the same programme everyday or could the number of radiosondes launched at some stations be reduced on days where the quality of the forecast does not depend significantly on data at that location on that day (e.g. from two to one sonde during the day)? Such savings would provide resources that would on the contrary permit to increase the number of sondes launched on critical days (e.g. from two to four sondes during a day). This sort of optimisation process could most probably also be applied at seasonal time scales where significantly different seasonal weather patterns may require different geographic distributions of observation density.

A strong symbiotic relationship with research and development activities on the subject will be needed as the operational possibilities will develop in parallel to R&D results and vice-versa, as is systematically the case for matters linked to numerical weather prediction. The capabilities for observation targeting techniques need to be extended and demonstrated for other phenomena than the winter storms to which they have been applied so far. Research on observation targeting should be encouraged to address the issues of hurricane track forecast, Mediterranean cyclonic storms, heavy regional rainfall events, onset of monsoon, seasonal observing system adaptation. Studies and experiments on the optimisation of the efficiency of the in-situ observing systems and networks will also be needed.

It may be useful at this point to introduce some notes of caution. Targeting additional information with dedicated systems such as dropsondes from aircraft in specific areas on specific days may be considered a marginal change to the Global Observing System, unlikely to have large scale detrimental effects. The situation may be different when programmes for regional adaptive observation will try to optimise (or minimise) the running cost of systems like radiosounding networks or AMDAR, because this may mean decreasing in some areas the density of observations below their "normal" value. In these circumstances a number of precautions should be taken:

- a network should not be operated below a minimum spatial density to be defined through long duration OSEs. This means for instance that a process to reduce the operating cost is likely to prove not feasible where the GOS is too thin already,
- adaptive observation is exclusively serving the needs of NWP for short or short/medium range prediction. The other applications must not be neglected. In particular the observing programme of GCOS stations should be carefully respected.
- modifications to the GOS in one area may impact further downstream. This is unlikely to be a major difficulty for well designed and well conducted adaptative observation operations. At the minimum, specific studies (OSEs) of downstream impact should be conducted as part of the programme design as well as monitoring of downstream impact during the course of the programme.

Proposed approach

It is suggested that the first step should be for CBS to analyse the issue, develop a strategy and guidance to ensure that the regional implementation of adaptive observation will be coherent with the GOS design at the service of all applications. CBS should take advantage of the knowledge available from the R&D community. An important source for such knowledge will be found in THORPEX. The operational entities most active in THORPEX such as the NMSs of US, UK, France as well as ECMWF and EUMETNET/EUCOS will contribute actively to the necessary linking between research and operations. A close working relationship of CBS with THORPEX will be essential to ensure that coherence is maintained between CBS plans and the THORPEX Implementation Plan. This could be ensured through an ad-hoc joint working group.

The next step should then be taken at the level of Regional Associations with a view to elaborate the regional approach applicable to the phenomena of interest to the Region (tropical cyclones/hurricanes , winter storms, Mediterranean sea cyclones, monsoon, etc.) taking into account the status of the regional observing system. The Regional Association should first conduct a preliminary analysis to identify the potential for adaptive observation in the region and its feasibility. A positive result of this analysis would then lead to an operational implementation.

A regional workshop of experts should be tasked with this preliminary analysis to establish requirements and feasibility. The workshop would benefit from CBS guidance and should involve scientific experts, in particular from THORPEX and its Regional Committees.

The following is proposed as sketch guidelines for the workshop :

- To check requirements:

  The existence in the region of characteristic atmospheric circulations (patterns) with potentially different observation requirements should be ascertained. These might correspond to high impact weather events, in which case the requirement will be to improve forecast quality, possibly using specific systems to add targeted observations for selected cases. Or they might correspond to "standard" weather situations in which case the objective will be to optimise the running cost of the observing system, for instance to decrease the cost without degrading the accuracy of the forecast.
- To check the technical feasibility:

  Several elements are necessary to conduct a programme of adaptive observation. An access is needed to an NWP system that would provide on a regular basis the operational output necessary for identification of sensitive areas. This output might come from a global, regional, national or specialised centre. Such products are not widely available today and are relatively expensive in terms of computing power. One may expect however that they will become routine production for all major NWP centres in a relatively near future. Another necessary element is of course the existence of routine observation networks and systems able to respond in due time to operational management requests for data acquisition changes. This means response times well below one day in the case of short term forecast. The more sophisticated adaptive observation approach, involving observation targeting on a daily basis requires the availability of systems capable of delivering observations on request in void areas. At present, apart from geostationary satellites, only dedicated manned aircraft can be considered able to provide this function on an operational basis.
- To check the institutional feasibility:

  Members participating to the adaptive observation programme will have to agree a collective operational management of their observation systems on a regional or sub-regional basis. This requires a light but well defined project structure with clearly identified objectives and responsibilities. For instance, in EUMETNET/EUCOS, the members delegate the management responsibility to one of themselves, setting clearly defined limits to the delegated authority. The availability of the necessary resources should also be verified. The required operational resources may be relatively modest if only existing systems are used. In this case the main cost will be with the NWP production, plus the staff – a small number – to actually manage the process. The programme cost may become high if additional systems such as dedicated aircraft are to be used. In this case innovative institutional mechanisms will be needed to collect resources from several members and possibly involve partners who could share expensive equipment. Such might be the case for instance of military air forces : these own suitable aircraft and have to fly them anyway if only for training purposes.

The feasibility study produced by the workshop would be used by the Regional Association to decide the next steps. In case of a positive decision, the first of these next steps would likely be the establishment of a small project team to prepare a detailed project definition.

In parallel to this move towards an operational implementation, it will be most important for the WMO Members to continue their active support of THORPEX and as far as possible increase it in line with Resolution 3.3/1 of Congress-XIV. Continuing R&D is needed on many subjects, inter alia on the methods to select locations to be observed, on the applicability of these methods to cases other than those of mid-latitude winter storms for which they have been developed, on the methods to assimilate the observations (adaptive assimilation) and the necessary links between the adaptive observation and the assimilation system(s) that make(s) use of it.

It would also be helpful to have more effort dedicated to the development of systems less expensive than manned aircraft to procure targeted in-situ information, such as drifting balloons carrying dropsondes (e.g. the driftsonde system) or all-weather unmanned aircraft carrying dropsondes that could be developed from existing military drones.

The above considerations will perhaps make the road towards a fully adaptive observing system look long and arduous, but the expected benefits in terms of improvement of the forecast of high impact weather events and better cost efficiency of the observing system deserve a strong collective commitment to this strategic objective.

References

Joly, A. et al., 1999 : Overview of the field phase of of the Fronts and Atlantic Storm-Track Experiment (FASTEX) project. *Quart. J. Roy. Meteor. Soc.*, 125, 3131-3164.

Szunyogh, I. et al., 2002 : Propagation of the Effect of Targeted Observations : The 2000 Winter Storm Reconnaissance Program. *Mon. Wea. Rev.*, 130, 1144-1165.

Shapiro, M.A., A.J. Thorpe, 2003 : THORPEX International Science Plan, Version 2. *Access through* http://www.wmo.ch/web/arep/wwrp/THORPEX/THORPEX.htm