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WORLD WEATHER WATCH

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

Geneva, Switzerland, 19-21 May 2008

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Fourth WMO Workshop on the Impact of Various Observing Systems on NWP
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SUMMARY AND CONCLUSIONS

1. INTRODUCTION

The Extraordinary Session of the Commission for Basic Systems (Seoul, Republic of Korea, November 2006) requested its Open Programme Area Group on Integrated Observing Systems (OPAG-IOS) to interact more closely on observational issues with the Commission on Atmospheric Sciences (CAS) and encouraged Numerical Weather Prediction (NWP) Centres to keep stimulating the studies of observation targeting strategies in coordination with the THORPEX ad hoc working groups and requested the OPAG-IOS and the WMO Secretariat to organize the Fourth Workshop on the Impact of Various Observing Systems on Numerical Weather Prediction.

The fourteenth congress (Cg-XIV) (Geneva, Switzerland, May 2007) noted with satisfaction that the major activities of CBS in the domain of observations were concentrated, among others, on the evolution of the Global Observing System (GOS) and scientific evaluation of Observing System Experiments (OSE) and Observing System Simulation Experiments (OSSE). It appreciated and supported proposals of CBS in the context of the operations and development of the future composite GOS which aimed to contribute markedly to alleviating deficiencies in the surface and upper-air data coverage. Congress reaffirmed that sustainable operation of the GOS has a vital role and highest priority for WMO in providing observational data to meet the requirements of weather forecasts and warnings, climate monitoring and other strategic tasks of the Organization; and that GOS through coordinated efforts of Members should continue its fundamental mission in providing timely, reliable and consistent meteorological data to meet the requirements of various users worldwide and ensure its essential role in the planning and implementation of an integrated WMO global observation system concept. The Congress also encouraged members to keep supporting the studies of observation targeting strategies based on the THORPEX, AMMA and IPY results; and, based on the guidance given in the Implementation Plan for Evolution of Space and Surface-based Sub-systems of the GOS, to pursue, especially in developing countries a wider use of observing systems (satellite, AMDAR and AWSs) that were less dependent on infrastructure, expertise and funding.

The fourth session of the WMO Workshop on the Impact of Various Observing Systems on Numerical Weather Prediction, organized under the auspices of the CBS OPAG-IOS Expert Team on the Evolution of the GOS (ET-EGOS) by the Organizing Committee headed by Drs John Eyre, Ko Koizumi and Jean Pailleux, is considered as another important step forward in the process of a design of the future GOS.

At the three previous workshops, which were held in Geneva (April 1997), Toulouse (March 2000) and Alpbach (March 2004), the global and regional results of Observing System Experiments were presented and significant conclusions were drawn concerning the contributions of the various observing system components to the large scale forecast skill at short and medium range. Since then, significant developments have taken place in the GOS, such as the launching of satellites equipped with newer instruments, for example METOP in 2006 and the COSMIC constellation providing radio-occultation soundings. In particular, global data assimilation systems are being used with these data as well as data derived from high vertical resolution infra-red sounders (AIRS, IASI). Microwave data are increasingly being assimilated operationally and mesoscale assimilation systems can use local observations such as radar reflectivities, radar Doppler winds and data from surface GPS stations. Design studies on satellite missions planned for the present and next decades are currently being conducted. In order to further contribute to these studies, a Joint Observing System Simulation Experiment (Joint OSSE) initiative was launched in 2006 in North America and Europe. Conventional observing systems are also being adapted through regional programmes like the EUMETNET

Composite Observing System (EUCOS), in particular, radiosonde, aircraft and buoy observations. Targeting strategies are being used or considered for increased use through, for example, the THORPEX Programme and the EUCOS/PREVIEW Data Targeting System (DTS).

During this workshop, major NWP Centres presented recent results in the above-mentioned areas in three different sessions dealing with the: (a) Global Forecast Impact Studies; (b) Regional Aspects of Impact Studies; and (c) Sensitivity, Impact Assessment Techniques and Observation Network Design Studies. Forty-four experts representing all major NWPs and other centres active in the area of observing system impact studies, as well as representatives of 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 papers presented at the Workshop, as provided by the authors, are reproduced in the second part of the Proceedings.

Section 2 of this report contains a synthetic summary of the assessment of impacts from various observing systems. Section 3 presents some specific results on the use and impact of various observing systems which led to discussions in the Workshop. Section 3 presents also specific recommendations focused on implementation of evolving user's requirements as had developed under each section of the Workshop. Section 4 lists the major overall conclusions and recommendations from the Workshop.

2. ASSESSMENT OF IMPACTS FROM VARIOUS OBSERVING SYSTEMS

2.1. 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 medium-range and (to a smaller extent) at short range (unit = hour). The gain is assessed by adding the observing system to all others used routinely in the assimilation. For some systems, the impact cannot be measured through an objective score and it can be identified only on case studies. This is obviously due to the increasing diversity of observing systems used operationally: this improves the overall skill of the system but makes it more and more difficult to evaluate the positive impact increment with respect to all the other systems used in NWP. Notes are attached to table 1 with indication of whether the overall contribution to the skill of the NWP systems has increased / decreased as compared with assessments of the Workshop-2004. As an important tendency of the period 2004-2008 has been the appearance of new observing systems (especially from satellites), the individual impact of most individual observing systems has decreased compared to 2004, but the total impact of the combined observing systems has improved, and the GOS is now more robust because of the variety and quality of instruments available.

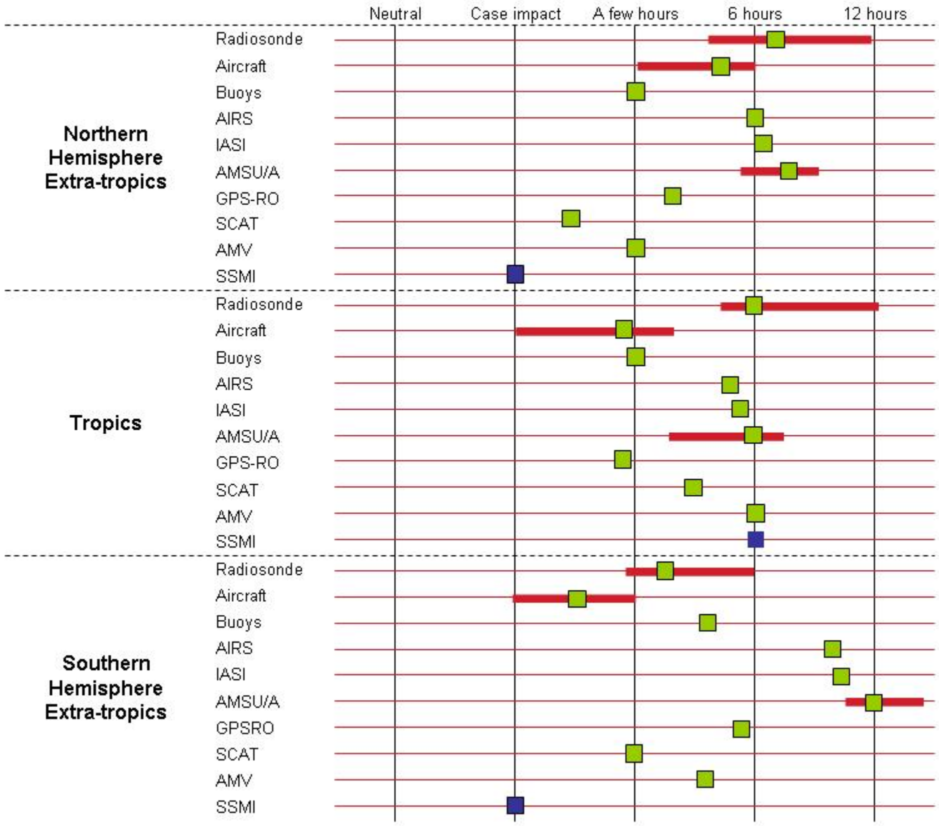

Table 1: Current contributions to some parts of the existing observing system to the large-scale forecast skill at short and medium-range. The green colour means the impact is mainly on the mass and wind field. The blue colour means the impact is mainly on humidity field. The contribution is primarily measured on large-scale upper-air fields. The read horizontal bars give an indication of the spread of results among the different impact studies so far available (for several observing systems the quantity of impact studies is too small and the spread is not quantified).

Notes:

- The table estimates the impact of the total ensemble system appearing on each line. For example the line “AMSU / A” corresponds to the 3 or 4 instruments available on current polar orbiting satellites. It is then compared to one single AIRS or one single IASI instrument, and scores more. One single AMSU/A has been quantified to a slightly smaller value than one AIRS;

- Compared to the situation in 2004, AMSU / A does not dominate any more; AMSU / B is used as well; the new infra-red sounders contribute to the impact with a magnitude similar to micro-wave sounders;

- Micro-wave instruments like SSM / I, SSM / IS and AMSU / B are also very important for large-scale humidity fields, especially in the tropics. Each of them can be rated similarly to SSM / I appearing in table 1;

- MODIS winds are very important for polar caps, and their impact spread quickly to mid-latitude: the impact is always found significant and positive in the southern hemisphere (and in the northern hemisphere, most of the time);

- Global wind profiles remain the more important information to observe, at least relatively to the current GOS where the temperature profiles can be indirectly observed by satellite sounders or GPS radio-occultation (no change with respect to the previous workshop, four years ago); and

- Surface pressure observations are important to anchor the model surface pressure; surface wind observations are less important, but are a very useful complement (provided mainly by scatterometers).

The previous evaluation is mainly based on a synthesis of all known OSEs, including the more recent ones presented at the Workshop. It generally puts more weight on medium-range than on short-range forecasts. Another assessment technique is now used in some NWP Centres. It evaluates the sensitivity of the 24h forecast to each observation through adjoint computations. The use of such an assessment technique is not systematic enough to be summarized in a table. However, some results are documented in the Workshop proceedings (see for example the paper by Gauthier et al.). They confirm the important impact of the radiosonde network and of the satellite sounders (microwave and infra-red).

2.2. Impact of some regional observing systems

- Radiosondes are relatively more important for regional models than for global models; isolated profiles of wind and temperature (from radiosondes, AMDAR…) are crucial for NWP;

- Radiances from geostationary satellites are used in several regional systems with a small positive impact: there is still a lot of potential to improve the use of this type of data;

- Wind profilers have shown neutral impact on average: slightly positive in some impact studies, slightly negative in others. In the workshop of 2004, there were very few results; the impact was marginal but positive. Quality control and screening procedures in data assimilation is an issue which affects the results and should be further studied; and

- Radar data and GPS surface observations have demonstrated their positive impacts on regional assimilation systems, and on some occasions also on global systems.

3. REPORTS FROM THE SESSIONS

3.1 Session 1: Global Forecast Impact Studies (chaired by Lars Peter Riishojgaard and John Eyre)

3.1.1 Summary of results presented in the talks

Here are reported the major results from the global impact studies presented at the workshop.

The summary of OSE and OSSE activities presented by ECMWF includes the impact studies funded by EUCOS and EUMETSAT. These sets of OSEs provide the most comprehensive assessment of the main observing systems to date. A wealth of detailed information can be extracted: (see the extended abstract by E. Andersson et al.) in the proceedings attached to this report. All components of the observing system are giving positive contributions to some aspects of the global analyses and forecasts. The potential for improving the use and the impact of some sub-systems (such as IASI) is still large. Early impacts from Metop data have been positive, and access to Metop data soon after the launch was crucial for early operational use. A short presentation focused on the wind lidar satellite mission ADM-Aeolus showed the type of work needed to prepare the assimilation of a completely new type of observations. It was noted that when radiosonde and aircraft temperature and wind data are used together, they contribute more than the sum of their separate contributions.

At Deutscher WetterDienst (DWD), the operational OI system uses pseudo-TEMPS extracted from the ECMWF analyses every day at 00 UTC - this is a means for them to benefit from the advanced satellite data assimilation at ECMWF. In tests without pseudo-TEMPS, ATOVS data have a large positive impact in both OI and 3DVAR. The 3DVAR system is much better than OI, both with and without ATOVS data. The impact of Metop has been tested, too, and found to be beneficial in southern hemisphere and Europe, but not much in northern hemisphere. GPS Radio-occultations (RO) has demonstrated large impact at 72h, 500 hPa, in the southern hemisphere, and much smaller impact in the northern hemisphere. These OSEs have been run with respect to a conventional-only baseline. The impact was found to be half as big as that of AMSU-A. Atmospheric Motion Vectors (AMVs) have positive impact everywhere, but especially in the tropics at 200 hPa. MODIS winds can now be used in the main run at DWD, as well as in the delayed cut off assimilation. In the northern hemisphere, their impact is small to neutral; it is relatively larger in the southern hemisphere. ASCAT showed relatively neutral impact, apart from one particular case, which was quite dramatic (a low pressure west of Ireland was positioned and deepened correctly by ASCAT).

In global impact studies carried out at Météo-France, GPS-RO data from COSMIC, CHAMP and GRACE showed nice positive impact for geo-potential, temperature and wind. The data are used for both rising and setting occultations, down to 1 km over the Polar Regions, but only down to 6 km in the tropics. A positive impact of IASI was also shown, although the amount of infra-red channels is still limited. The variational technique (called VarBC) to correct the bias in the observation seems very efficient and improves the use and impact of most observing systems. For micro-wave sounders, Météo-France use the radiance observations to retrieve emissivity at the observation point, by inverting the radiative transfer in surface channels (AMSU-A channel 3) and using it in the sounding channels. This improves the distribution of used data over land, e.g. for AMSUA channel 7. This has been studied especially on the African area of the AMMA experiment. A small positive impact of the extra AMMA sondes was detected when verified against satellite sounding channels in the area, and verified against surface data too. Additional bias correction for the radiosondes in this AMMA area, developed at ECMWF, has been applied and has been found to enhance the positive impact of sonde data. For the THORPEX-IPY / CONCORDIASI project in the Antarctic there will be 600 dropsondes released in 2009 from drifting stratospheric balloons. These data and even the flight-level balloon data will be distributed over the GTS.

Data impact experiments carried out in Washington (JCSDA and NCEP/EMC) were presented (see the extended abstract by Lord and Riishojgaard in the proceedings attached to this report). The COSMIC GPS-RO data were put into operations in 2007. It showed positive impact at 500 hPa (geopotential) in both hemispheres, larger in the southern hemisphere. About 1000 COSMIC profiles per day are used. QuikScat impact was tested over four months, with emphasis on tropical cyclones, and with no visible impact in averaged 1000 hPa scores. Then a marginal positive impact in the southern hemisphere was obtained from QuikScat and Windsat used together. Windsat on its own did not show positive impact. A result was found in which MODIS winds degrade the northern hemisphere scores, but was very beneficial in the southern hemisphere. For IASI they will rely on the EUMETSAT channel selection. Initial tests with IASI showed some small positive impact at day 6-7 in the southern hemisphere. IASI is not used operationally yet at NCEP, but will be implemented as soon as possible. A positive impact was also found from SSMI/S data, and it was shown that this positive impact can be enhanced by improving the cloud detection and processing.

A detailed presentation of the joint OSSE project and its status was given. NCEP and JCSDA are collaborating on this project with American, European and Asian partners, and ECMWF has provided the Nature Run. The conventional observations are currently simulated from the Nature Run. Work has started on simulating the radiances and Doppler wind lidar data. There is no secured funding for the core of the OSSE project which could guarantee its existence for several years.

A Met Office presentation was dedicated to the conventional observing systems (at global scale as well as regional scale). The results from the EUCOS study confirm generally the ones found by ECMWF. Radiosonde data are shown to be still very important on the northern hemisphere; major reductions in sonde networks (down to GUAN baseline) can come with substantial degradations in NWP performance. A “subjective targeting” has been evaluated over the USA: the experiment consists first in removing most of the existing radiosonde sites over North America, down to 17 stations, none in the verification area where the forecast impact is checked. Then each day, depending on the meteorological flow, 10 radiosonde observations are picked up in the “sensitive upstream” area. “Upstream data” were shown to be very valuable in this context. Like many other studies presented at the workshop, these targeting experiments demonstrate the benefits of additional profile observations in otherwise data sparse areas. Benefits for global NWP have also been shown through assimilation of more surface level observations.

Another Met Office presentation was dedicated to the use and impact of satellite data. It confirmed a positive impact from most of Metop instruments (shown by ECMWF). It showed the importance of a rapid dissemination in real-time of satellite data from polar orbiting satellites, through specific retransmission systems (RARS, EARS, etc.). In Alpbach, four years ago, it was shown that microwave sounders on three well-spaced polar satellites is close to optimal, and this result is now consolidated. Concerning infra-red sounders, a good early impact from IASI data (clear radiances only) was demonstrated, and strong improvements from the assimilation of cloudy AIRS radiances were shown, with implications for future impacts of other advanced infra-red sounder data. Concerning scatterometer data, it was shown that ASCAT has the highest quality in terms of 10m wind departures “observation – background”, then come Windsat, QuikScat, and ERS scatterometers, which all show smaller departures to the background than buoy and ship wind data. The impact of Windsat is equivalent to the impact of ASCAT, and will become operational soon. Adding ASCAT on top of QuikScat shows a significant positive impact (2 satellites with scatterometer data improve significantly on 1). Concerning GPS-RO observations, 6 COSMIC satellites are currently used at the Met Office, soon the GRACE and CHAMP satellites will be added, and a continuous improvement of the forecast was shown when introducing 4, then 6, and finally 8 satellites (impact saturation does not appear to be reached with 8 satellites).

The results presented by the Canadian Meteorological Service (MSC) were concentrated on observations assimilated over North America and North Pacific. They were performed at two different resolutions (100 and 33 km) and two different assimilation schemes: 3-D and 4-DVAR. It was shown that the low-resolution 4-DVAR has the same quality as the high-resolution 3-DVAR. The impact of Pacific aircraft data (mainly the zone covered by the routes from USA to Hawaii) quickly spread and drifted eastward. Clear impact of satellite data originating in the area to the South-East of this zone was shown for the USA.

The global results coming out from the JMA presentation highlighted the fact that the satellite data coverage is much improved in the early analysis (2h20’ cut-off time) by the Asia-Pacific Regional ATOVS Retransmission Service (AP-RARS), point also mentioned in a Met Office presentation. The impact of AP-RARS is not large but the EARS one is very clear and positive (result consistent with the data volumes). MTSAT-1R clear-sky radiances improve the prediction of cyclone tracks, as well as BUFR-format AMV, especially when a strict screening based on their quality index is performed.

Although the Australian results presented by BoM / CAWCR had mainly regional implications (see section 3.2), it was shown that remote radiosonde observations still show benefits (which are not yet outweighed by the availability of satellite data), and that an increased benefit can be obtained from AMVs by improved processing.

The Chinese (CMA – CAMS) study which was presented does not show the impact of any satellite system as such, but it shows how important a retuning of one parameter (observation error standard deviation) can be for assimilating ATOVS data in the GRAPES Chinese system (3-DVAR assimilation).

3.1.2 Discussion items

From the studies carried out in several global centres, it is clear that all components of the GOS are contributing to some aspects of the performance of NWP. For example, this is true for satellite instruments. The "domination" of microwave sounders (noted in Alpbach in 2004) is not true any more. Nowadays global NWP is dependent on a satellite-based observing system which is a combination of microwave sounders, infra-red sounders, GPS radio-occultation receivers and AMVs, none of these systems being negligible with respect to the others. This is valid for the upper-air analysis; for the surface analysis (pressure, surface winds), the scatterometer data are an important observing system to take into account. The biggest gap at global scale is the need for wind profiles, which explains the interest for the future data of ESA mission ADM-Aeolus.

The current state of the art in global NWP is far from making full use of satellite data. One example is the small percentage of data which is used operationally from AIRS and IASI sounders. Many research and development tasks are carried out in various groups to improve the use of satellite instruments: studies on the surface emissivity and other soil properties, on the bias evaluation, on the data screening, or on the processing of AMV. All these studies are likely to progressively improve the quantitative assessment of the satellite data impact, as it was evaluated in this workshop.

For polar orbiting satellite instruments, the quick availability of data in real-time NWP (including the latest orbit) is important. This was stressed in the discussion, following the results presented by several speakers. This relies on ad hoc telecommunication systems allowing the quick re-transmission of some data, as soon as they "reach the ground" (EARS, RARS).

It may be difficult to draw any concrete action from the result showing that the impact of radiosonde wind and temperature fields is "more than additive" (EUCOS terrestrial study), i.e., that the total impact is greater than the individual impact of temperature and wind data (evaluated separately). It is clear that both fields are needed globally with a good accuracy for the operational analyses, but we do not necessarily need wind and temperature observations at the same point. Also, when a study is carried out in a data sparse context, the first isolated wind and temperature profiles not only act synergetically to improve the forecast but their impact is very big: see Rabier et al. in the workshop proceedings (part dedicated to AMMA) and also Klink et al. (part dedicated to the impact of ASAP). Also, putting aside the humidity field, it is clear that radiosonde and AMDAR have a similar role, a similar impact, and can be interchanged. It is generally easier to increase the AMDAR data coverage than the radiosonde data coverage. Therefore, all the AMDAR opportunities should be used to improve the wind and temperature data coverage, especially in data-poor areas like the intertropical regions. This means to get new wind and temperature profiles at some airports by equipping some aircrafts travelling regularly to these airports, and also to get the data from cruise levels in these regions (which are otherwise data-poor regions). Following the same logic, in Europe, several radiosonde sites, close to busy airports, are likely to be discontinued in the future EUCOS optimisation process.

So far, most of the OSEs have been concentrated on the impact of observations on short or medium ranges forecast (say until day 10). However, the “second week” of forecast range should not be forgotten in terms of observation requirements. It was reminded that the THORPEX programme concentrates on forecast improvements up to day 14, with obvious links with monthly forecasts in terms of numerical tools and observation requirements. This means that in the future some attention should also be given to the impact of analysed surface fields, such as soil moisture, or to the stratospheric fields which are likely to influence the tropospheric weather more at 7-14 day ranges than at short range. For doing this, the current OSE methodology may not be sufficient, as forecasts are currently more dependent on ensemble prediction techniques at ranges of one week or more.

The stratospheric observation requirement is an issue which is not answered completely by the studies presented at the workshop. It is clear that the current rapid increase of the use of GPS-RO is a new factor which contributes to improve very significantly the stratospheric analyses (also the upper tropospheric ones). GPS-RO data are improving directly the stratospheric profiles in temperature (and the wind profiles indirectly outside the tropics). It is clear that the existence of some GPS-RO missions in the future has to be guaranteed for operational use. What is the optimum number of satellites? This question will be addressed for example in the context of the OSSE project, together with the future availability of ADM-Aeolus winds. Then the old question “how many radiosonde sites must observe the stratosphere globally” will have to be addressed again in this new context (without forgetting the GCOS requirements).

3.2 Session 2: Regional aspects of impact studies (chaired by Warren Tennant and Harald Schyberg)

3.2.1 Summary of results presented in the talks

In this section, some of the findings in the regional studies that were presented in the workshop are reviewed. The Met Office reported on experiments with their regional system demonstrating a significant positive impact from radar VAD wind assimilation. They also have performed experiments with moisture related observations such as MOPS derived cloud data and visibility data, demonstrating some positive impact. The Met Office also obtained a small positive effect of ground based GPS data on several parameters.

Regional experiments performed at the Japanese Met Agency (JMA) demonstrated positive impact of radar Doppler winds and retrieved radar precipitation data in their 4-DVAR assimilation. The importance of the thinning strategy for radial winds was pointed out. Positive effects of ground based GPS data on precipitation forecasts were also demonstrated.

The Australian Bureau of Meteorology (BoM) showed results from a regional study of the impacts of the various available radiosondes around the Australian continent. The Canadian Meteorological Service (MSC) presented some studies showing that the availability of some radiosondes at high latitudes is very important in terms of forecast impact, presumably because of the strong air mass variations and of the relatively poorer availability of any other types of observed information in the polar areas.

Several impact studies have been performed in the HIRLAM community regionally with, for instance, MODIS winds, GPS surface data and radar radial winds. Positive impact was found in many, but not in all cases. Regional studies of the various components of the terrestrial part of the observing system were conducted in the framework of EUCOS OSEs, and these show that the relative importance of radiosondes tends to be higher than in global studies, perhaps because the HIRLAM assimilation system does not make use of satellite data as extensively as done in the global systems. The HIRLAM results showed positive impact of ASAPs, although there might be significance issues, as the impact comes from a small number of specific cases, e.g., one Scandinavian storm. No significant impact from adding humidity data and from adding wind profiler data could be demonstrated.

Several impact studies have been performed within the ALADIN community. Results using SEVIRI radiances were positive. Results indicate that the best effect is obtained when also 2m temperatures are assimilated. Results from radial wind assimilation in the AROME setup (2.5km of horizontal resolution) were also presented. It showed the ability of the system to represent the spatial distribution of convergent structures connected to the convective systems. Experiments with reflectivity assimilation are also ongoing. The importance of a proper determination of the background error covariance matrix (especially the vertical correlation), rather than interpolating from matrices on coarser resolution was demonstrated. The ALADIN EUCOS terrestrial studies showed a clear positive impact of both aircraft and radiosonde temperature and wind observations on all the meteorological fields except humidity fields. This positive impact was very significant up to 24 hours range. A positive impact of radiosonde humidity observations was also shown on precipitation forecasts at all ranges, and also on surface pressure forecasts (in the winter period of the study, not the summer period).

An extensive experiment with extra radiosonde launches has been undertaken at the Korean Met Agency (KMA). Positive impact, in particular in convective rainfall events, was demonstrated in their WRF system. The sensitivity of the results to cloud microphysics was also discussed.

South African Weather Service (SAWS) presented a comprehensive demonstration of the positive effect of AMDAR and radiosondes in their regional implementation of the Unified Model. The results support the general idea to prioritize the wind and temperature profile requirements in data sparse areas.

Several impact studies carried out with the COSMO regional system were presented. A positive impact from assimilating precipitation data from the radar network with latent heat nudging was noted up to about 8 hours forecast range. Case studies with ATOVS and SEVIRI radiances used in a 1-D-Var + nudging procedure were presented, showing a slight positive impact. VAD wind assimilation gave mainly neutral results. Assimilation experiments with screen level data have also been undertaken, different setups showing neutral to clearly positive impact. New E-AMDAR humidity measurements have been monitored to assess the possibilities of building up such an observation system in the future. A clear detrimental effect of degrading the radiosonde network over Europe was demonstrated.

Finally, regional studies with the WRF system have been undertaken on Antarctic and Asian domains. In particular, a good effect of COSMIC radio occultation data was found in the troposphere, but revealing model upper boundary problems higher up. Positive impact of AIRS and MODIS data was also demonstrated in the Antarctic domain. On a Korean domain a positive impact of radar, mainly from radial velocities, was shown.

3.2.2 Discussion items

This is an account of some of the main discussion points following the presentations in this session dedicated to regional aspects.

Concern was raised about the variability in the design of regional OSEs and also how sensitive the results were to changes in this design. For example, significant differences between 3-DVAR and 4-DVAR, and the specification of the B-matrix were presented. Notwithstanding, regional

OSE studies are valuable and groups performing such studies were encouraged to place more emphasis on verification relating to the application of their system, for example, air quality or heavy rainfall, as these applications justify the need of high-resolution regional systems. Although it is not possible to standardise verification methods, such scores should be aligned with these application needs and aim to facilitate exchange of results with other centres.

There is a number of observing systems unique to regional NWP, but the group wished to highlight the real-time distribution of such data. Sharing of Doppler Radar wind data should be the start, as these were shown to have positive impacts in a number of systems. Centres producing Radar data need to agree on data pre-processing and transmission standards on the GTS. This should include a channel for users to provide feedback to data producers on the quality and impact of this data in their NWP systems. As a second priority, just after radar data, the GPS surface networks should be exchanged: they have shown their value for regional NWP but also for global NWP models. Although there are problems with observation quality in certain cases, we were also reminded that models have inherent biases, and this will impact negatively on the efficiency of data assimilation. Other improvements in regional observing systems include a new AMDAR humidity instrument that will be tested later in 2008 and will be available for E-AMDAR in due course.

Regional NWP models are currently less dependent on satellite radiances than global NWP models. The main reason is the forecast domain of regional NWP which is often covered mostly by land, and the satellite sounder channels sensitive to the lower troposphere cannot be assimilated properly over land in the current data assimilation systems. Some studies for surface emissivity modelling over land are already available. They are highly required for regional NWP to fully exploit the satellite observations.

There are some links from impact study work to various other programmes, such as the IPY. To enable the community to assess the impact of IPY data, it is important to know which observations types are exchanged in real-time. It is also important to consider which systems will potentially remain in place after IPY. There are also good links to the THORPEX Data Assimilation Working Group and communication is ongoing for example through the intercomparison exercise set up for the THORPEX T-PARC experiment (see section 3.3).

3.3 Session 3: Sensitivity, impact assessment techniques, observation network design studies (chaired by P. Gauthier and J. Caughey)

3.3.1 Summary of results presented in the talks

In this section, the different numerical tools and techniques which can be used to evaluate the impact of observations on NWP, i.e., the OSE methodology (which is the standard one), but also several other techniques are discussed. This section also deals with the benefits which can be drawn from the above tools for network studies on conventional observations and for planning satellite missions. As many of these tools and studies are very dependent on the assimilation system, it is important to intercompare different assimilation systems and to come up with strategies involving several of them.

Several centres (ECMWF, Navy / NRL and GMAO) are now able to run in a quasi-routine mode, diagnostics on the Forecast Impact of Observations (FIO) based on the adjoint of the data assimilation mathematical operators and of the forecast model. The FIO evaluates the impact of any observation subset (down to a single observation datum) on a selected measure of short-range forecast error (at least one particular aspect or norm attached to this short-range forecast). It can be used, displayed and exchanged in a similar way to the DFS (Degrees of Freedom for Signal) which assesses the relative weight of the different observations in the analysis. It was shown (ECMWF) that OSEs and FIO (adjoint techniques) often give the same general message about the impact of one particular observing system. However, the techniques are complementary: with the FIO one can look at the impact of any single observation or of any small ensemble of observations on one parameter measuring the forecast quality; with the traditional OSE it is almost the opposite, as one can measure the impact of one perturbation only (addition or denial of a particular observing system in the assimilation) on all the aspects of the output forecast (any field, any statistical score). Although the new technique requires an adjoint model (not available in all the NWP centres), and is directly applied only to short-range forecasts, the exchange of these FIO diagnostics should be encouraged.

The ECMWF results showed that FIO information can be used to pinpoint and explain why observations can have a negative impact. For instance, it was found in one example that wind profilers over North America had a negative impact that could be explained by problems with the instrument when the local wind variability is much higher than the climatological mean. Negative impact of low-level U-component of AMV winds was noted in some sub-tropical areas and attributed to inaccurate height assignment. Overall, the sensitivities with respect to observations measured through adjoint-based methods yields a consistent signal with that obtained from OSEs.

NASA / GMAO results obtained on the observation impact evaluated with the adjoint-based method were also shown. It was pointed out that only slightly more than 50% of the observations have a positive impact but this is consistent with the statistical nature of the assimilation problem. However, a good observation type should yield an overall positive impact. Examples from GMAO's assimilation system showed problems associated with some of the water vapour channels that become more apparent if a localized error norm is used to estimate the forecast error. Adjoint-based methods differ from OSEs in that, by removing observation types, the latter alter the background against which observation impact is measured. The observation impact applied to two OSEs, gave a striking example showing that the removal of AMSU-A radiances significantly enhances the impact of AIRS radiances. On the other hand, the removal of AMVs wind observations decreases the impact of AIRS radiances. This shows again that sensitivities with respect to observations provide a complementary tool to OSEs.

Results obtained at Navy / NRL were presented where observation impact is used on a routine basis to monitor NRL's assimilation and forecast system. The interpretation of observation impact can help to improve the selection and use of observations for numerical weather prediction. Negative forecast impact may suggest quality control issues, while large impacts from small numbers of observations may suggest regions where more observations should be added. An example was shown for a case where observation impact helped to detect problems with AMV wind processing. This was confirmed in OSEs that showed that restricting the use of AMVs in areas on the fringe of the coverage has a positive impact on the forecast. An NRL website has been developed to display observation impact results (currently for 00 UTC data), see: http://www.nrlmry.navy.mil/obsens/.

The EUMETNET composite observing system, EUCOS, over Europe, which includes ASAP, AMDAR, BUOYS, RAOBs and SYNOP, was presented to the workshop. The main effort is directed towards the future design and coordination of the evolution of ground based EUMETNET observing systems. A studies programme has been put in place to provide guidance on the evolution of EUCOS. Impact studies and new approaches are required to plan for changes in the observing network that would take into account the changes in data assimilation at the regional and global scales. The value of the ground based segment needs to be evaluated in relation to the rapidly developing satellite component. The components of EUCOS have developed strongly in recent years (particularly the AMDAR data coverage) and data assimilation systems are now able to assimilate data with high time resolution. Scientific evidence is required to get the approval of EUMETNET council for further network changes and modifications. The presentation showed that it is possible to design changes to an operational radiosonde network, basing the decisions on scientific analyses coming out from impact studies. More specifically, the results stressed the importance of isolated radiosondes such as Atlantic ASAPs and indicated the possibility to evolve the European continental network towards a better synergy (or less redundancy) between radiosonde and aircraft data.

In Europe, an experiment consisting in deploying targeted observations of radiosondes and AMDAR was presented also by EUCOS and is ongoing until the end of 2008. The main targeting tool (called DTS: Data Targeting System) consists in a web tool developed at ECMWF and used by the Met Office for the decision process (to deploy or not to deploy an extra observation).

A presentation by MGO (Russian Federation) discussed the situation of the current upper-air network in Siberia. The network now comprises 22 stations but only 19 are reporting regularly. The objective of this study was to configure an 'optimal' network design based on information content, in view of making proposals in Russia to upgrade the current network. In practice, several RAOBs stations have been added in Siberia but most are now in the Southern part which deviates from the optimal configuration. This is considered to be insufficient to provide the accuracy needed for winds and temperature. A case study was also presented on the RA-I African network. Missing data areas with respect to operational RAOB station list for RA-I are very significant. Only 46 from nominal 262 sites carried out measurements in January-April, 2004. A scenario for existing operational RAOB network has been proposed to extend from 46 to 59 stations by recovering measurements at 13 stations, which provide a substantial reduction of error fields for all meteorological variables in missing data areas. The studies performed by MGO showed that in Siberia and Africa, it was possible to plan improvements to the upper-air network through simple network studies based on the estimation theory.

EUMETSAT has an operational mandate to plan for the future operational meteorological satellites and related services. The EUMETSAT presentation emphasized the importance of preparing for new instruments so that observations can be used shortly after launch to maximise the cost benefit ratio of the missions. The OSEs / OSSEs and impact studies help to demonstrate the usefulness of the data by measuring the impact or expected impact of observations from satellite measurements. Regarding METEOSAT Third Generation (MTG), the priorities of the infra-red hyperspectral sounder will be to focus on the time evolution of vertically resolved water vapour structures. It will provide atmospheric dynamic variables with high vertical resolution (e.g., water vapour flux, wind profile, transport of pollutant gases). As for the post-EPS, the highest priority has been given to high-resolution infra-red sounder, microwave sounding, scatterometry and VIS / IR imaging. An OSE has been carried out to measure the impact of 'losing' METOP on current NWP systems. This experiment was useful to confirm the choice in priority for a future EPS. The following more general issues were also raised in the EUMETSAT presentation:

- A need is felt for a framework in order to organize better design studies (OSSEs or simpler studies) when a new satellite mission or instrument is emerging, and also to guide the studies assessing the potential impact during the development phase;

- The full utilization of a new satellite instrument requires a rather long learning process; this type of effort for a better use of satellite data should be carried out independently of the operational ground segment, as it involves different scientific and technical tasks; and

- The satellite community is expecting impact studies which help the choice of the compromise they have to make between "diversity of observed parameters" and "data coverage quality". As an example, a train of satellites (like Aqua-Train) gives a high priority to the availability of various parameters at the same observation point and at the same time (and a low priority to the improvement of the data coverage).

The assessment of the impact of observations depends on the characteristics and components of the assimilation method (e.g., error statistics), the nature and volume of assimilated observations, and the NWP model. To make firm statements about the value of observations, it becomes important to examine if different centres get similar conclusions when the systems are configured to be as close as possible. To address this question, the THORPEX Data Assimilation and Observing Strategies Working group (THORPEX DAOS-WG) is conducting intercomparison experiments using a common method to evaluate the observation impact.

A number of centres took part in a first intercomparison exercise for January 2007, using a common set of observations assimilated by all the centres, and using the same adjoint-based technique. As mentioned before, results were presented to the workshop by the NRL, NASA-GMAO and ECMWF. ECMWF is using a 12-h 4DVAR while NRL and GMAO use 3DVAR with a 6-h assimilation window. The results agree on several elements: AMSU-A radiances and aircraft data are found to have an important impact for example. However, significant differences still persist. The AMVs have more impact at NRL than ECMWF and GMAO while ECMWF's 4-DVAR provides a larger impact for surface and ship data and QuikScat surface winds may have a negative impact. (For additional details, see the paper by Gauthier et al. in these workshop proceedings). The conclusion to be drawn is to acknowledge that the value of observations does depend on the assimilation and forecast system and on other elements (e.g., flow regimes). The observation impact intercomparison experiment will be pursued and interested groups were invited to contact the THORPEX DAOS-WG. The objective will also be to use these tools to evaluate the value of observations deployed during the 2008-2009 THORPEX Pacific-Asia Regional Campaign (or T-PARC). Various observing strategies will be used to deploy observations during the different stages of the lifecycle of Tropical cyclones from genesis, to landfall and the recurvature phase, the Extra-Tropical transition and finally, when they move north in the extra-Tropics. It will be interesting to compare different methods to evaluate the impact of observations some being based on adjoint models while ensemble based methods are also proposed. This exercise is important to assess the robustness of the impact evaluation itself.

3.3.2 Discussion items

With respect to the traditional OSEs, the measurement of the impact through an adjoint technique appears as a new and promising technique which should be recommended.

The FIO computed by an adjoint technique will also be very useful to assess some data targeting strategies like the ones which are currently tested within the EUCOS / PREVIEW DTS Project. It will take time before an optimal targeting strategy can be worked out. Whether it is better to add extra targeted observations every now and then, or to target intensively some particular weather episodes for several days in a row, is still an open question. To answer such a question, studies like the current DTS project are needed, but also studies using existing data, especially satellite data. The discussion on the verification and validation of targeting strategies led also to the following points: (i) the verification and validation must not be limited to the averaged scores measuring the overall impact of targeted data; (ii) some tests must be made to check if targeted data are more valuable than non-targeted data; and (iii) targeting of special meteorological events (cases of high impact) must continue to be supported.

In order to improve the conventional upper-air observing network in the different WMO Regions, the discussion recognized the need for a simple statistical tool, maybe limited to the handling of a radiosonde network at the regional scale, which could provide simple guidelines on the priorities for (re)activating upper-air stations, or for closing existing ones. The mathematical tool could follow the method presented by MGO at the workshop: see paper by Oleg Pokrovsky in the proceedings attached to this report. It should however provide an estimate of the more/less informative radiosonde sites with respect to a background which is as realistic as possible in the context of NWP. Statistics on the background error coming from an advanced NWP centre (which assimilates many satellite data) could provide this proper reference. One can foresee simple and flexible software which could be used for different WMO Regions, implemented on a PC and portable, introducing every now and then updated background information from a NWP centre. However, the utility, the efficiency and the complexity of the design of such a tool was not completely assessed in the workshop; this has to be done before deciding the development. If developed, such a tool should be designed in a way that can be used to optimize not only the upper-air observing stations but also, if possible, the Regional Basic Synoptic Networks (RBSN) as a whole. Still, the priority should be put on the upper-air design (radiosonde) to start.

The discussion about the standardization of the OSE methodology and experimentation recognized the fact that guidelines for OSE already exist in different WMO documents (including the preceding workshops similar to this one). In addition, it was noted that there are two different families of OSEs: (i) The “OSEs of opportunities”, which are carried out regularly by NWP centres for their own purposes, most of the time for validating the addition of an extra observing system to their operational data assimilation system; and (ii) The “coordinated OSEs” (like the EUCOS ones in this workshop), where the standardization on the data, the period used, the verification techniques, etc. are pushed very far. Then one should aim at a better exchange of the information, between the different centres, but one should not try to push much further the OSE coordination.

Concerning OSSEs and future observing systems, an improved coordination is still felt desirable by the people planning future satellite missions. An OSSE framework has been built in the US with the help of ECMWF. It can be used for several purposes, but the main concern is to fund the effort in the long term. Although no precise recommendation could be formulated by the workshop, it seems such a coordinated framework would require the joint support of several satellite agencies and NWP centres. Firstly, it is essential to establish a calibrated baseline OSSE, and this must be a centralized effort. Thereafter, the work on a range of OSSE activities can be distributed, and a variety of funding sources can be pursued.

4. WORKSHOP CONCLUSIONS AND RECOMMENDATIONS

The discussions on the workshop presentations and results took also into account the reports from the preceding workshops and the latest comments made by ET-EGOS-4 (Geneva, Switzerland, 7-11 July 2008). They led to the following conclusions and recommendations.

Almost all centres were able to identify positive impacts on forecast skill of practically all parts of the observing system. This is a testament both to the quality of the Global Observing System and to the increasing level of maturity of the models and assimilation systems used to ingest the information for numerical weather prediction. A tremendous activity is now evident in regional NWP using variational assimilation systems to explore new data types. The methodology has converged, and rapid progress is being made in many countries

Several studies seemed to indicate that the impact of simultaneous use of mass (temperature) and wind observations exceeded the sum of the individual impacts in experiments where the two types of information were used separately, especially in the tropical regions. This will have implications for the requirements of the observing system of the future as far as the balance between observations pertaining to the different model variables is concerned.

4.1. Interaction between NWP centres, data providers and data users

a) Some regional observation data sets appear to be more and more useful for regional NWP and will soon be useful also for global NWP. It is recommended to implement a global exchange of these data sets, starting by: (i) Radar data radial wind and reflectivities as the highest priority; and (ii) GPS surface networks as second priority; and

b) For polar orbiting satellite instruments, the quick availability of data in real-time, NWP is important for operational NWP (global and regional). It is then recommended to develop and maintain ad hoc telecommunication means allowing the quick re-transmission of some data (like the existing systems EARS and AP-RARS).

4.2. Observational data requirements

a) Because of the lack of profile-type observations in the polar latitudes, every effort should be made to maintain the existing radiosonde sites, and / or find new systems to observe the vertical structure of the atmosphere (wind, temperature, humidity) in the polar areas. The IPY year is an opportunity to have new systems deployed (e.g., drifting balloons and unmanned aerial vehicles). An exhaustive list of these IPY-specific observations should be made available to all NWP users, and the extension of some of these systems beyond the IPY should be considered;

b) One of the highest priorities in terms of observation requirements is to add more profile observations in many data-poor areas. Thus, all the AMDAR opportunities should be used to improve the wind and temperature data coverage, especially in data-poor areas like the inter-tropical regions or Central and South Africa. This implies collecting new wind and temperature profiles at certain airports by equipping some aircraft flying regularly to these airports, and also to get the data from cruise levels in these regions (which are otherwise data-poor regions); and

c) Remote radiosonde stations are still of exceptional value (as shown with isolated islands, ASAP observations and AMMA radiosonde observations). They are essential and should not be closed although they are the most expensive. We have not yet reached the point of satellite utilisation that makes it possible to close down such stations.

4.3. Proposals for future studies

a) The use of the adjoint technique to compute a FIO is highly recommended to complement OSEs and DFS, to all the centres which can afford it (the adjoint of a forecast model is needed). A somewhat systematic exchange of results between some centres (as is currently done for monitoring of observation availability and quality) is also desirable;

b) For studying rapidly and objectively the optimization of stations of the Regional Basic Synoptic Network (RBSNs) in the WMO Regions (especially radiosondes to start with), it is recommended to study the design of a simple mathematical tool, in the form of a portable software, based on the optimal estimation theory. If assessed feasible and potentially useful, the design could be pursued along the lines of Oleg Pokrovsky, in the present proceedings, but using appropriate NWP background statistics rather than climatology, and taking into account the cost of each individual station);

c) More attention should be given to the forecasts at ranges from 7 to 14 days, in some future impact studies. In this context, some studies should address the requirements in surface variables such as soil moisture, SST and sea-ice and also the observation requirements in the stratosphere. Ensemble prediction systems could be a helpful tool for these future studies;

d) Concerning the stratosphere, the requirements for conventional observations will have to be studied again in the new context where GPS-RO has started to play a major role, and when ADM-AEOLUS wind data are likely to be available within few years. The current Joint OSSE project provides a test-bed for studies to answer the general question of observation requirements in the stratosphere; and

e) Studies related to surface emissivity over land are highly required for regional NWP in order to fully exploit the satellite observations. Some are already available, but the efforts should be increased.

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Böttger, Horst, Paul Menzel and Jean Pailleux (Ed.), 2004: Proceedings of the Third WMO Workshop on the Impact of Various Observing Systems on Numerical Weather Prediction. Alpbach, Austria, 9-12 March 2004, WMO TD No. 1228.

Fourth WMO Workshop
On the Impact of Various Observing Systems
On Numerical Weather Predictions

Geneva, Switzerland
19-21 May 2008

PROGRAMME

MONDAY, 19 MAY 2008

Welcome and Opening Remarks

10:00	Welcome by the WMO Secretary-General or Representative; expectations for the evolution of the GOS by John Eyre; summary of Alpbach Workshop and introduction of the workshop format by Jean Pailleux, and practical aspects by Miroslav Ondráš
Session 1a:	***Global forecast impact studies (Chair: Erik Andersson)***
10:30	Erik Andersson (ECMWF) A summary of OSE and OSSE activities at ECMWF
11:00	Alexander Cress (DWD) Global impact studies at Deutscher Wetterdienst
11:30	Florence Rabier (Météo-France) Global impact studies at Météo-France
12:00	Steve Lord (NCEP) Data impact experiments in JCSDA and NCEP/EMC
12:30	Lunch
Session 1b:	***Global forecast impact studies with some regional aspects (Chair: Steve Lord)***
13:45	Lars Peter Riishojgaard (JCSDA) Observing System Simulation Experiments in JCSDA
14:15	Richard Dumelow (Met Office) Impact studies using the Met Office global and regional model
14:45	Stéphane Laroche and Real Sarrazin (Meteorological Service of Canada) Impact studies with observations assimilated over North America and North Pacific
15:15	Break

15:45 Ko Koizumi (JMA)
Global and regional OSEs at JMA

16:15 Peter Steinle (BoM/BMRC)
Global and regional OSEs in Australia

16:45 John Eyre and Stephan English (Met Office)
Impact studies with satellite observations at the Met Office

17:15 Zhang Hua and Chen Dehui (CMA - CAMS)
Adaptive estimation and tuning of satellite observation error in assimilation cycle with GRAPES

18:00 Cocktail

TUESDAY, 20 MAY 2008

Session 1c: ***Global forecast impact studies (Co-chairs: John Eyre and Lars-Peter Riishojgaard)***

08:30 Erik Andersson (ECMWF)
Short presentation on ADM: AEOLUS: an example of a future global observing system and related preparation studies

08:35 Summary and discussion of Sessions 1a and 1b (global aspects only)

Session 2a: ***Regional aspects of impact studies (Chair: Ko Koizumi)***

09:30 Nils Gustafsson (SMHI)
An overview of observation impact studies performed in the HIRLAM community

10:00 Claude Fischer (Météo-France)
An overview of observation impact studies performed in the ALADIN community

10:30 Break

11:00 Hee-Sang Lee (KMA)
Impact of ProbeX-IOP observations on the predictive skill of heavy rainfall in the middle part of Korea

11:30 Warren Tennant (South African Weather Service)
The impact of AMDAR and radiosonde observations on a regional model forecast system in southern Africa

12:00 Alexander Cress (DWD)
Regional impact studies performed in the COSMO community

12:30 Dale Barker (NCAR)
Regional data impact studies in NCAR and JCSDA

13:00 Lunch

Session 2b: Regional aspects of impact studies (Co-chairs: Nils Gustafsson and Warren Tennant)

14:15 Summary and discussion of Session 2a and regional aspects of Session 1b

Session 3a: Sensitivity, impact assessment techniques, observation network design studies (Chair: Florence Rabier)

15:15 Carla Cardinali (ECMWF)
A complementary approach to OSE to monitor the observing system contribution to the forecast error

15:45 Break

16:15 Ron Gelaro (NASA/GMAO)
Examination of observation impacts derived from OSEs and adjoint models

16:45 Rolf Langland (Navy/NRL)
Applications of adjoint-based observation impact monitoring at NRL-Monterey

17:15 Jochen Dibbern and Stefan Klink (EUMETNET/EUCOS)
Relevance of impact studies for EUCOS and EUCOS requirements in future studies

17:45 Johannes Schmetz (EUMETSAT)
Relevance of NWP impact studies for future satellite programmes

18:15 Adjourn

WEDNESDAY, 21 MAY 2008

08:30 Oleg Pokrovsky (MGO, Russia)
Optimising a regional radiosonde network

09:00 Pierre Gauthier (UQAM)
Intercomparison of sensitivity to observations in the context of THORPEX and T-PARC

Session 3b: Sensitivity, impact assessment techniques, observation network design studies (Co-chairs: Pierre Gauthier and Jim Caughey)

09:30 Stefan Klink (DWD/EUCOS)
Short presentation of the EUCOS/PREVIEW Data Targeting System (DTS)

09:35 Summary and discussion of Session 3a

10:30 Break

Session 4: Workshop Conclusions and Recommendations
(Co-chairs: Erik Andersson and Jean Pailleux)

11:00 Discussion and Recommendations

12:30 Lunch

13:45 Conclusions and wrap-up

15:30 Closure of the workshop

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Fourth WMO Workshop
On the Impact of Various Observing Systems
On Numerical Weather Predictions

Geneva, Switzerland
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Session 1

Global Forecast Impact Studies

Session 2

Regional Aspects of Impact Studies

Session 3

Sensitivity, Impact Assessment Techniques, Observation Network Design Studies

Evaluation of the impact of the main terrestrial and space-based components of the Global Observing System

By Erik Andersson, Graeme Kelly and Jean-Noël Thépaut

As many more satellite instruments (both active and passive) have become operational, the challenge has been how best to assimilate these space-based measurements together with the available conventional terrestrial measurements. Operators of terrestrial observing networks ask the question: what is the most effective combination of surface-based observing technologies given the increased capability of the space-based observing systems?

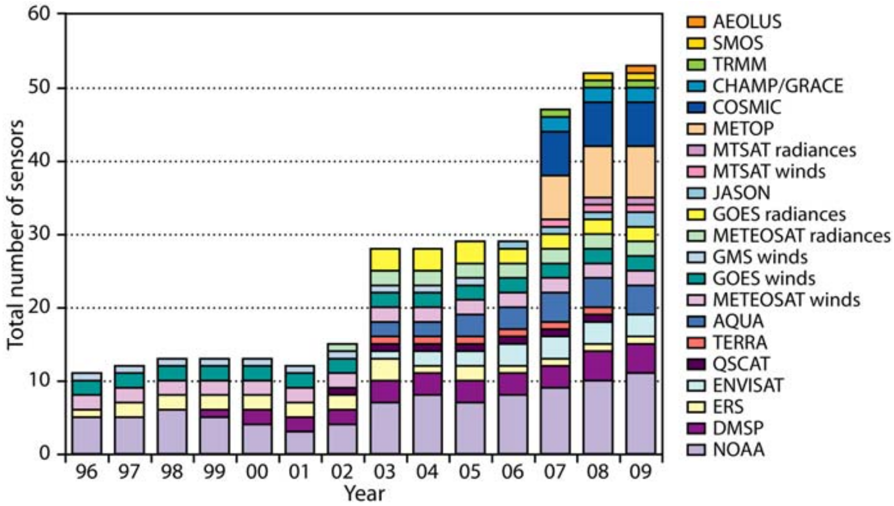

Figure 1 Evolution of the number of satellite sensors (instruments) from 1996 to 2008 (actual) and 2009 (projection) that are being used (or soon to be used) in global numerical weather prediction.

Figure 1 shows the 1996 to 2009 actual and near-future satellite sensors used (or soon to be used) in global Numerical Weather Prediction. Compared to the period before 2001 the number of assimilated satellite sensors has increased by a factor of four and is now reaching 50 sensors in total. The number of observations of each of the main terrestrial and space-based observation types is listed in the table below. The numbers reflect the counts of used data in the ECMWF 4D-Var data assimilation system during a typical 12-hour period. We can see that the current data counts are dominated by radiances (76.5 %) measured from satellites.

	Assimilated data	Percentage
Surface weather stations (SYNOP)	64,000	1.9
Aircraft reports	247,000	7.5
Drifting buoys	6,000	0.2
Radiosondes (TEMP)	75,000	2.3
Wind-profilers and PILOT	57,000	1.75
Atmospheric Motion Vectors	131,000	4.0
Radiances data	2,508,000	76.5
Scatterometer winds	118,000	3.6
GPS radio occultation	73,000	2.2
TOTAL	**3,280,000**	**100.0**

Table 1 Observation data count for a typical 12-hour 4D-Var cycle for 0900–2100 UTC on 24 April 2007, indicating the amount of data used at ECMWF through assimilation.

Recently two comprehensive impact assessment studies sponsored by EUMETSAT and EUCOS, respectively, have been carried out at ECMWF (Kelly and Thépaut, 2007; Thépaut and Kelly 2007). The two studies have been carried out to evaluate the impact of the space-based and terrestrial components of the Global Observing System (GOS) through Observing System Experiments (OSEs). It is found that all the main observing systems generally contribute in a positive way to the overall performance of the ECMWF forecast system. This in itself is an important result, indicating on the one hand that modern assimilation systems can derive benefit from a heterogeneous mixture of in-situ and remotely-sensed observational information, and on the other that the operational observing systems generally are of good quality.

Requirements for Observing System Studies

At its meeting at ECMWF on 3 May 2003, the EUCOS Scientific Advisory Team discussed the need to investigate the interdependencies between the space-based and terrestrial components of the observing system. It was suggested that such an investigation could be based on a set of carefully designed OSEs. These studies would be designed to provide guidance on the future development of the terrestrial observing system in view of the increasing capabilities of the satellite observing systems provided by the meteorological space agencies.

In recent years, several NWP centres have demonstrated substantial benefit from the assimilation of, for example, ATOVS radiances and scatterometer winds (referred to hereafter as SCAT). Since 2003 data has become available second-generation radiometers (AIRS on Aqua in 2003 and IASI on MetOp in 2007) providing significantly enhanced temperature and humidity sounding capabilities – to be followed (in the five to ten year time frame) by similar instruments on the operational NPOESS series of satellites.

It was agreed that, as far as EUCOS is concerned, the primary issues were:

- What are the relative contributions of various components of the terrestrial observing system within the current overall composite observing system?
- How should the terrestrial systems evolve over the next five to ten years and beyond to complement the projected evolution of the space-based observing systems?

This led to a proposal by Andersson et al. (2004) to carry out a set of OSEs specifically designed to evaluate the role of the terrestrial component of the GOS. Several global and regional OSEs were conducted within this framework, and these are reported elsewhere within the current workshop proceedings and in formal reports to EUCOS (Available from the EUCOS management team).

Following a number of discussions between EUMETSAT, ECMWF and EUCOS, it was agreed that specific OSEs dedicated to examining the various contributions of the different components of the space observing system were necessary to complement the original proposal about the terrestrial components. Taking this approach would provide a comprehensive assessment of the space/terrestrial links. It was also agreed that the robustness of this combined assessment would be strengthened by the adoption of similar strategies for experimentation and validation of the two studies.

These studies also take onboard one of the recommendations of the Third WMO Workshop on the Impact of Various Observing Systems on NWP (held in Alpbach 2004). This suggested that, due to a large degree of redundancy of the GOS, performing impact studies by removing one element of the GOS can show very limited impact and does not necessarily highlight the intrinsic benefit of the element in question. It was therefore decided that the scenarios in which the contributions of different elements of the GOS are investigated would be based on adding datasets or combination of datasets to a suitably degraded reference scenario.

Main characteristics of the data assimilation system

The configuration of the ECMWF forecast system used here involves the forecast model at T511 spectral resolution with 60 model levels. The 4D-Var assimilation scheme was run with a 12-hour window and the analysis inner and outer loop resolutions were T95/T159 and T511, respectively.

The conventional observations currently assimilated in the system include:

- TEMP, PILOT and PROFILER reports
- SYNOP, SHIP, METAR and BUOY (moored and drifters) reports
- Aircraft (AMDAR, AIREP, ACARS) including ascent/descent reports

The satellite observations assimilated in the system for the atmospheric analysis were at that time for the winter run:

- Atmospheric Motion Vectors from GEO (Meteosat-5/7, GOES-9/10/12) and LEO (MODIS Terra and Aqua) platforms
- Clear-sky water vapour radiances from GEO (Meteosat-5/8, GOES-9/10/12)
- Level 1c infrared radiances from NOAA-14/17 (HIRS) and Aqua (AIRS)
- Level 1c microwave radiances from NOAA-15 (AMSU-A), NOAA-16 (AMSU-A and AMSU-B), NOAA-17 (AMSU-B), Aqua (AMSU-A) and DMSP 13/14/15 (SSM/I)
- Sea surface winds from scatterometers QuikScat and ERS-2
- Ozone products from NOAA-16 (SBUV) and ENVISAT (SCIAMACHY).

As this study has been spread over two years, different model cycles have been used for the two scenarios.

- **Period 1.** IFS model cycles Cy29r1 (winter) and Cy29r2 (summer) have been used, differing mainly by the inclusion of NOAA-18 level-1c radiances from AMSU-A and MHS and the blacklisting of NOAA-14 HIRS radiances that had become too noisy. AMV(REF) was used as a reference for Period 1. Winter period is from 4 December 2004 until 25 January 2005 and summer from 17 July to 15 September 2005. For this period, the OSEs were based on AMV(REF) as a reference (see below).
- **Period 2.** IFS model cycle Cy31r1 has been used for both winter and summer. AMSUA(REF) was used as a reference for Period 2. Winter period is from 5 December 2006 to 14 Feb-ruary 2007 and summer from 1 June to 18 August 2006. For this period, the OSEs were based on AMSUA(REF) as a reference.

All forecasts were run from 00 UTC.

Terrestrial observing system studies (EUCOS)

The set of terrestrial observing system studies coordinated by EUCOS has been completed following the guidelines indicated in Andersson et al. (2004). These impact studies aimed at examining the various components of the terrestrial observing system, in the presence of the current satellite-based observing system. The experiments (detailed in Figure 2) have been run using the same first winter and summer period used for the space observing system studies with the identical assimilation setup to enable a direct comparison with the space studies. The total number of cases remains probably too short to provide statistical robustness to the findings (especially over relatively small verification areas such as Europe), but it is reassuring that the impact of the various components of the terrestrial observing system remains similar to the first order between the two assessed periods.

The main findings of the winter impact studies indicate a large impact of the radiosondes (wind and temperature) and aircraft (wind and temperature), a marginal impact of radiosonde humidity information, and a neutral impact from the wind profilers. Sole wind or temperature information from radiosondes is not sufficient to impact noticeably on the forecast skill. In contrast, coupled temperature/wind information from radiosondes seems to provide a large and significant improvement in the forecasts well into the medium-range. The experiments demonstrate that observations from aircraft and radiosondes are complementary: each observing system improves the forecast skill even in the presence of the other.

The summer impact studies confirm most of the findings from the winter experiments, although the impact of the various assessed components of the GOS is smaller, both in absolute and relative terms (Thépaut & Kelly, 2007).

1: The Space-Terrestrial Study
Initiated and funded by EUCOS.

i. **BASELINE: all satellite observations currently used in NWP (radiances, cloud-drift winds, scatt winds) + GUAN R/S + GSN surface land data + buoys (no ship data)**
ii. **BASELINE + aircraft data**
iii. **BASELINE + non-GUAN R/S wind profiles**
iv. **BASELINE + non-GUAN R/S wind and temp profiles**
v. **BASELINE + wind-profiler data**
vi. **(iv) + aircraft data**
vii. **BASELINE + non-GUAN R/S wind, temp and humidity profiles**
viii. **CONTROL: the combined observing system**
ix. ***BASELINE + non-GUAN R/S temperature profiles (winter)***
x. ***BASELINE + aircraft temperature data (winter)***

Figure 2 Definition of the various OSEs conducted within the EUCOS-funded study.

Space-based observing system studies (EUMETSAT)

This study considered the relative contributions of the various space-based observing systems (infrared temperature soundings, microwave temperature soundings, imagers, scatterometers, etc.) within the context of ECMWF's data assimilation system. We have assumed in this study that the current conventional observing system is maintained (thereafter called the BASELINE system), and the main focus is to evaluate how specific satellite systems contribute individually to the robustness of the GOS, in addition to this degraded observing network.

The evaluation of satellite sensors is best done in the tropics and southern hemisphere, but the quality of the BASELINE system (equivalent to NOSAT referred to earlier) is so poor outside the northern hemisphere that it was not considered suitable as a reference by itself. Instead, two special reference systems have been designed to ensure a reasonable quality of the atmospheric analyses and forecasts in the tropics and southern hemisphere. These special reference systems are:

- AMV(REF): BASELINE plus the Atmospheric Motion Vectors (AMVs).
- AMSUA(REF): BASELINE plus data from one AMSU-A instrument.

Two sets of assimilation were performed.

- AMV(REF) as reference for Period 1. The observational scenarios tested with AMVs as reference (i.e. AMV(REF)) are described in Figure 3 (left). These experiments are based on the winter and summer forming Period 1. The first ten days of each assimilation scenario are excluded from the verification to ensure a reasonable warm-up phase. No real difference in the impact was found between summer and winter so the mean scores are combined to give a sample of 89 days for each experiment. All experiments are validated using the operational analysis.
- AMSUA(REF) as reference for Period 2. The observational scenarios tested with one AMSU-A as reference (i.e. AMSUA(REF)) are described in Figure 3 (right). These experiments are based on the winter and summer forming Period 2. These experiments were delayed as long as possible in order to make use of the AMSU-A and MHS instruments from the EUMETSAT MetOp satellite. The first two weeks are excluded from the verification to ensure a reasonable warm-up phase for each assimilation scenario. For Period 2, the Variational Bias Correction for satellite radiances was operational and therefore activated during the warm-up phase of the experiments (bias correction coefficients are then kept constant for the remaining of the assimilation period). No real difference in the impact was found between summer and winter so the mean scores are combined to give a sample of 117 days for each experiment. All experiments are validated using the operational analysis.

2a: Assessment of the space component of the GOS Initiated and funded by EUMETSAT

Winter period: 20041204-20050125, Summer period: 20050715-20050915 (cycle 29r1)

- BASELINE **all conventional observations used in NWP (radiosonde + aircraft + profiler network + surface land data + buoy observations + ship data)**
- REFERENCE= BASELINE + AMVs from GEO+MODIS
- REFERENCE + HIRS radiances
- REFERENCE + AMSUA radiances
- REFERENCE + AMSUB radiances
- REFERENCE + SSMI radiances
- REFERENCE + GEO Clear Sky Radiances (CSRs)
- REFERENCE + AIRS radiances
- REFERENCE + SCAT winds
- BASELINE + GEO AMVs (no MODIS)

2b: Assessment of the space component of the GOS Initiated and funded by EUMETSAT

Winter period: 20061205-20070214 (31r1), Summer period: 20060601-20060815 (31r2)

i. BASELINE all conventional observations used in NWP (radiosonde + aircraft + profiler network + surface land data + buoy observations + ship data)
ii. REFERENCE= BASELINE + AMSUA Noaa 16
iii. REFERENCE + AMVs from GEO+MODIS
iv. REFERENCE + AMSUA radiances
v. REFERENCE + AMSUB radiances
vi. REFERENCE + GEO Clear Sky Radiances (CSRs)
vii. REFERENCE + AIRS radiances
viii. REFERENCE + SCAT winds
ix. CONTROL full operational system (all above observations)

Figure 3 Definition of the various OSEs conducted within the EUMETSAT-funded study.

During the course of the study two additional sets of experiments using AMV(REF) and AMSUA(REF) have been carried out to specifically assess the impact of MODIS and AVHRR AMVs, the impact of various AIRS channel combinations (as a scientific preparation for the assimilation of IASI), and finally the respective contribution of clear and cloud/rain effected SSMI radiances. For details and results of these additional studies, see Kelly and Thépaut (2007).

As we have seen, there are two sets of OSEs based on AMV(REF) and AMSUA(REF), respectively. There is also a variety of variables and levels used for evaluation: 500 hPa geopotential height, relative humidity at 850, 500 and 200 hPa, and wind at 1000 and 200 hPa. The results have here been condensed into a few bar graphs which can represent only a small subset of all the results available.

Generally all sensors benefit some verification parameters but some sensors have a neutral or slightly negative impact on others. The small negative impact, mostly noticed on the 500 hPa geopotential height parameter and when using AMV(REF) as a reference, may be due to the fact that the accuracy of the AMV(REF) temperature field is still not quite good enough to assimilate radiances that are mostly sensitive to moisture. This negative impact of some sensors is not generally found when AMSUA(REF) is used as a reference instead.

500 hPa geopotential height

The accuracy of the 500 hPa geopotential height forecast is an important and classical measure of forecast skill. Our main results are:

- OSEs based on AMV(REF). Figure 4 shows the forecast performance at days 2, 5 and 7. The largest impact can be seen in the southern hemisphere and is maintained throughout the forecast range. Clearly the most important sensors are AMSU-A and AIRS followed by HIRS. All other sensors have a relatively small impact; some sensors even show a small negative impact relative to AMV(REF) for this particular parameter. However, other scores are improved by these sensors (this is for example the case for the clear-sky radiances (CSRs) which improve the humidity scores). The impact in the northern hemisphere is similar to that in the southern hemisphere but smaller in magnitude.
- OSEs based on AMSUA(REF). The performance at days 2, 5 and 7 is shown in Figure 5. First of all, it is worth noticing that the relative difference between AMSUA(REF) and CONTROL compared to that of AMV(REF) and its CONTROL is smaller, and therefore gives less margin to measure quantitatively the impact of individual sensors. However, the largest sensor impacts can still be seen in the southern hemisphere and these are maintained throughout the full forecast range. Clearly the most important sensors are AIRS and the AMSU-A/B combination. All other sensors have a relatively small impact. In the northern hemisphere the impact of the sensors is similar but smaller in magnitude.

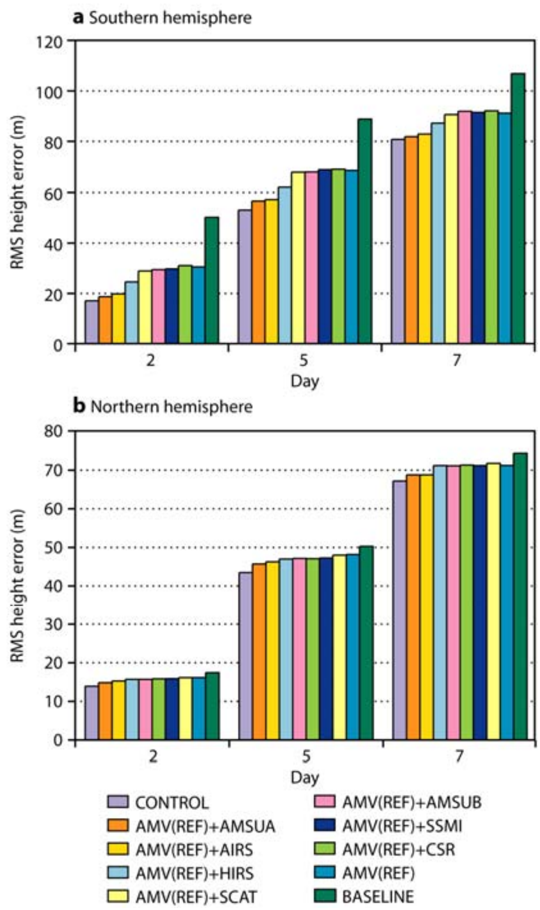

Figure 4 Impact of all sensors (based on AMV(REF)) on 500 hPa geopotential height for (a) southern hemisphere (20–90°S) and (b) northern hemisphere (20–90°N).

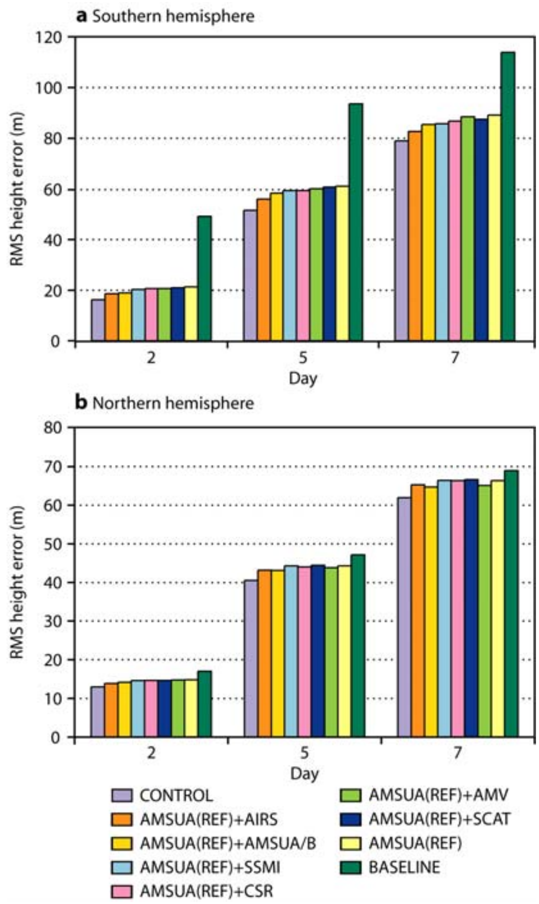

Figure 5 Impact of all sensors (based on AMSUA(REF)) on 500 hPa geopotential height for (a) southern hemisphere (20–90°S) and (b) northern hemisphere (20–90°N).

850 hPa relative humidity

Moisture forecasts, particularly in the tropics, tend to be less accurate than forecasts of mid-latitude geopotential height. After day 4, the moisture forecast becomes less dependent on the initial moisture conditions and the model moisture processes dominate. For this reason all the moisture validations are presented for days 1 to 3.

- OSEs based on AMV(REF).

Figure 6(a) shows the performance of all the OSEs as described in Table 2 for the tropics. SSMI is the most important sensor at day 1 but by day 3 the impact is reduced and overtaken by that of AIRS. However the gap between the CONTROL and the AMV(REF)+SSMI at day 1 is much larger than the difference between AMV(REF)+SSMI and AMV(REF) suggesting it is the combination of all sensors that is important rather than a single sensor. The impact in the northern hemisphere and southern hemisphere is similar to that in the tropics but smaller.

- OSEs based on AMSUA(REF).

Figure 6(b) shows the performance of all the OSEs as described in Table 3 for the tropics where the impacts are the largest. In this set, AMSUA(REF)+SSMI now includes both clear-sky and rain/cloud affected radiances and SSMI is the most important sensor for low level humidity. How-ever there is still a gap between the CONTROL and AMSUA(REF)+SSMI, which again suggests that it is the combination of all sensors that is important for improving the moisture analysis and forecasts rather than a single sensor. The impact in the northern hemisphere and southern hemisphere is similar but smaller in magnitude than in the tropics.

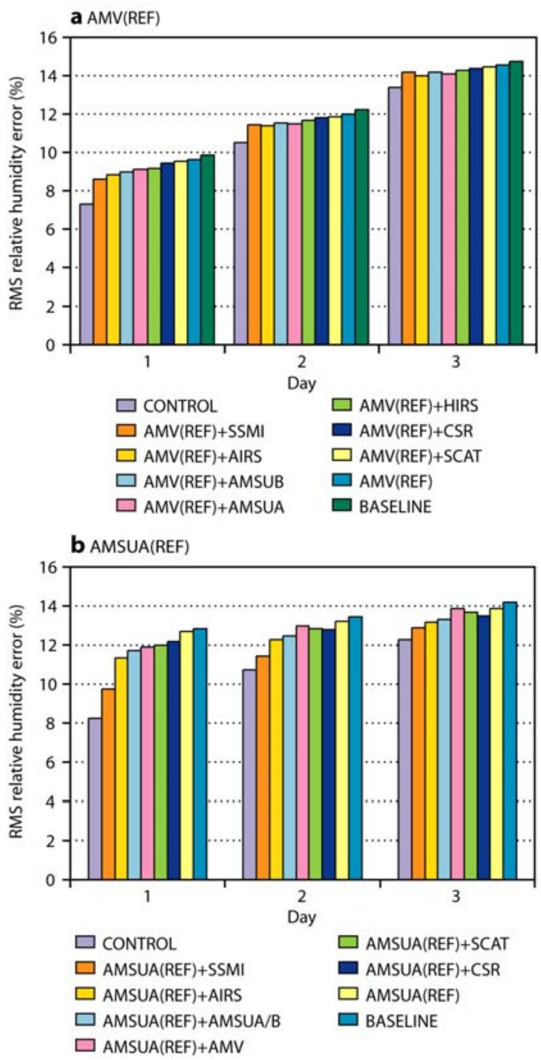

Figure 6 Impact of all sensors on 850 hPa relative humidity for the tropics based on (a) AMV(REF) and (b) AMSUA(REF).

1000 hPa wind

Wind forecasts in the tropics tend to be less accurate than in mid latitudes. In the tropics after day 4 the model wind forecast becomes less dependent on the initial conditions. Therefore all the wind validations presented here are for days 1, 2 and 3.

- OSEs based on AMV(REF).

Figure 7(a) shows the performance of all the OSEs as described in Table 2. In the tropics SSMI is the most important sensor. However the gap between the AMV(REF)+SSMI and CONTROL at day 1 is much larger than the difference between AMV(REF)+SSMI and AMV(REF) suggesting again that it is the combination of all sensors that is important. The impact in the northern hemisphere and southern hemisphere is similar to that in the tropics but smaller in magnitude.

- OSEs based on AMSUA(REF).

Figure 7(b) shows the performance all the OSEs as described in Table 3. In the tropics SSMI is the most important sensor, though SCAT winds are also important in the early part of the forecast. However the gap between the CONTROL and AMSUA(REF)+SSMI suggests it is the combination of all sensors that is important. The impact in the northern hemisphere and southern hemisphere is similar but smaller in magnitude to that in the tropics.

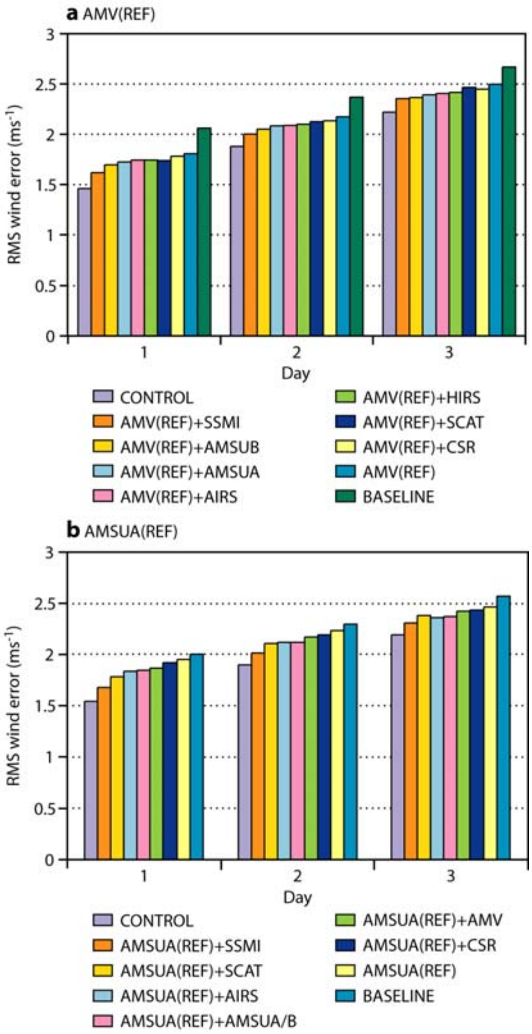

Figure 7 Impact of all sensors on 1000 hPa vector wind for the tropics based on (a) AMV(REF) and (b) AMSUA(REF).

Overall assessment and further prospects

The main findings of the winter impact studies indicate a large impact of the radiosondes (wind and temperature) and aircraft (wind and temperature), a marginal impact of radiosonde humidity information, and a neutral impact from the wind profilers. Sole wind or temperature information from radiosondes is not sufficient to impact noticeably on the forecast skill. In contrast, coupled temperature/wind information from radiosondes seems to provide a large and significant improvement in the forecasts well into the medium-range. The experiments demonstrate that observations from aircraft and radiosondes are complementary: each observing system improves the forecast skill even in the presence of the other.

All the tested space-based sensors provide benefit to the overall performance of the ECMWF forecast system. Sensors like AMSU-A, AIRS and HIRS are clearly the most important for mass and wind forecasts. However the accuracy of the humidity forecast relies on AMSU-B/MHS, GEO CSRs and SSMI. The positive impact of AMVs (GEO and MODIS) and SCAT on the forecast is also clearly demonstrated.

At present, there are no plans to fly an instrument with MODIS-like water vapour channels on future polar satellites. This is a concern as the positive impact of MODIS AMVs in Polar Regions and mid-latitudes has been clearly demonstrated.

The studies also show that AIRS is the sensor that has the most impact on the mass field and experiments indicate that most of the impact comes from its 15-micron spectral band. SSMI is vital for humidity analysis.

These experiments confirm the crucial impact of satellite data on the performance of the ECMWF NWP forecast system. Since the completion of the OSEs, the importance of satellite data has further increased with, for example, the implementation of GPS radio-occultation observations or more recently the introduction of IASI. On the scientific side, further changes are expected in the near future that include the use of more infrared and microwave radiances in cloudy and rainy conditions, and an improved use of all types of satellite radiances over land and sea-ice.

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Global Impact Studies at the German Weather Service (DWD)

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Abstract

This presentation will give a summary of recent progress in assimilation of satellite sounding data, satellite winds and other satellite and in-situ data at DWD, along with an outlook of future developments. In all cases, the quality and usage of new observations were tested by observation system experiments (OSE) and led to a better understanding of the role of the data within the global observation system and a deeper insight into the used assimilation scheme.

The greatest impact on forecast quality could be derived from the use of satellite sounding data, retrieved from TOVS radiances on board various satellite systems (NOAA 15/16/18, Aqua, Metop-A). Recent work on the use of AMV wind data has been focussed on replacing Meteosat 5/7 data by the new wind products derived from the Meteosat Second Generation satellites Meteosat 8/9 and the inclusion of AMV winds from MTSAT-1R, provided by JMA. Further tests are being carried out with Bufr formatted MODIS winds, to take advantage of the included quality information. The quality and usage of scatterometer wind data (QuikScat, ASCAT) in our data assimilation system is a further topic which will be addressed. Additionally, some outlook of further developments in the global observing system such as the use of radio occultation data or the use of the IASI instrument on board of Metop-A will be given.

Introduction

For its global model GME, DWD still uses the method of intermittent data assimilation for its routine data assimilation scheme. This method is based on a very short-range forecast of 3 hours which serves as a first guess for the subsequent analysis of the current state of the atmosphere. Whenever the observations available give indications of an error in this first guess, it will be corrected. The procedure used for correcting is called 'Optimum Interpolation' although in a strict sense, it is not an optimal procedure since the required statistics on the input information (i.e. on the first guess and the observations) are based on numerous simplifications. The resulting analysed current state is used as initial value for another 3-hour forecast, which again is used as a first guess for the following analysis, and so on. A more sophisticated 3D-VAR system is currently under development and will be make routinely available mid 2008. Thereby, a cost function containing penalty terms for deviances of the analysis state, both from the background and the observations, is minimized as a function of the analysis. This minimisation step is performed in observation space. This has the advantage, that it reduces the size of the numerical problem, as the number of model grid points generally outnumbers the number of observations and the transition from model to observation space allows to consider observations which depend on the model background data in a highly nonlinear way, such as satellite radiances or radio occultations. The observations used operationally are land stations and ships (synops), buoys, radiosondes and pilots, aircrafts, vertical sounders on polar-orbiting satellites and Atmospheric Motion Vector (AMV) wind vectors from geostationary satellites. In the following, an overview of recent progress in assimilation of satellite and in-situ data at DWD will be given. The experiments presented, are partly based on the old OI assimilation scheme and partly on the new 3D-VAR system.

Use of vertical sounding data (AMSU-A radiances)

From measurements in different spectral channels of infrared and microwave radiometers onboard of polar-orbiting satellites, information on the vertical distribution of temperature, humidity and ozone in the atmosphere can be deduced. To derive vertical profiles of temperature (or humidity or ozone) which can be used in data assimilation, however, supplementary information has to be included as the vertical resolution of the satellite data is significantly lower than required by the models. Since the beginning of 2006, some of the radiance data from the microwave sensors (AMSU) of the polar-orbiting satellites NOAA 15/16/18 and Aqua are converted into temperature and humidity profiles by means of a one-dimensional variational scheme at DWD. This method uses the current state of the weather forecast model itself as supplementary information. It produces vertical profiles which are good adapted to the particular structure of the model and which can be assimilated like conventional observations in a second step.

Several impact trials were conducted for summer and winter periods, in which mainly temperature profiles retrieved from ATOVS data from NOAA 15/16/18 and Aqua using a 1D-VAR method were assimilated into the operational global OI system and in the new 3D-VAR assimilation system of the DWD. The direct use of the radiances data in the GME data assimilation scheme results in a clear improvement of the large scale numerical weather prediction. This applies particularly to regions where conventional observations e.g. from radiosondes are sparse, as is the case in the southern hemisphere. There, the satellite radiances are almost the only source of information on temperature and humidity. As Fig. 1 illustrates, the use of ATOVS data, on top of the conventional data (radiosondes, aircraft, pilots, synops, buoys and atmospheric vector winds), improves the forecast quality considerably, leading to an increase of forecast benefit of up to 12 hours on the Northern Hemisphere and up to 24 hours on the Southern Hemisphere for both, the OI and the 3D-VAR assimilation system.

In October 2006, the first of three European polar-orbiting satellites (Metop-A) was launched in orbit and a few months later first radiance data from the ATOVS instruments onboard arrived in the data base of DWD. After implementing a new bias correction scheme for AMSU-A data from Metop-A, several impact studies were conducted using AMSU-A radiance data of Metop-A in addition to the radiance data from NOAA15-18 and Aqua in the operation data assimilation scheme at DWD. Since Metop-A operates in a mid morning orbit, a major gap in data coverage of AMSU-A data at 00 and 12 UTC of the Atlantic Ocean can be filled, which is very important for NWP centres in Europe. Using the AMSU-A radiance data results in a consistent improvement of forecast quality for both, Northern and Southern Hemisphere and Europe, especially for the 00 UTC forecasts, leading to a forecast benefit of up to 6 hours for Europe (Fig. 2).

Applying the variational scheme is a major step forward in the NWP at DWD and forms the basis for further development. It is a prerequisite for the assimilation of data from a new generation of infrared sounders such as AIRS and in particular IASI onboard the first European polar-orbiting satellite Metop. Instead of at most 40 channels, this new instrument has thousands of channels and promise a higher vertical resolution and improved data quality. With a currently developed three-dimensional variational data assimilation scheme, which will be operational mid 2008, the satellite radiance data will not be processed anymore single handed but with all other observations together at once. This allows for a consistent treatment of all data and is expected to bring a further clear forecast improvement.

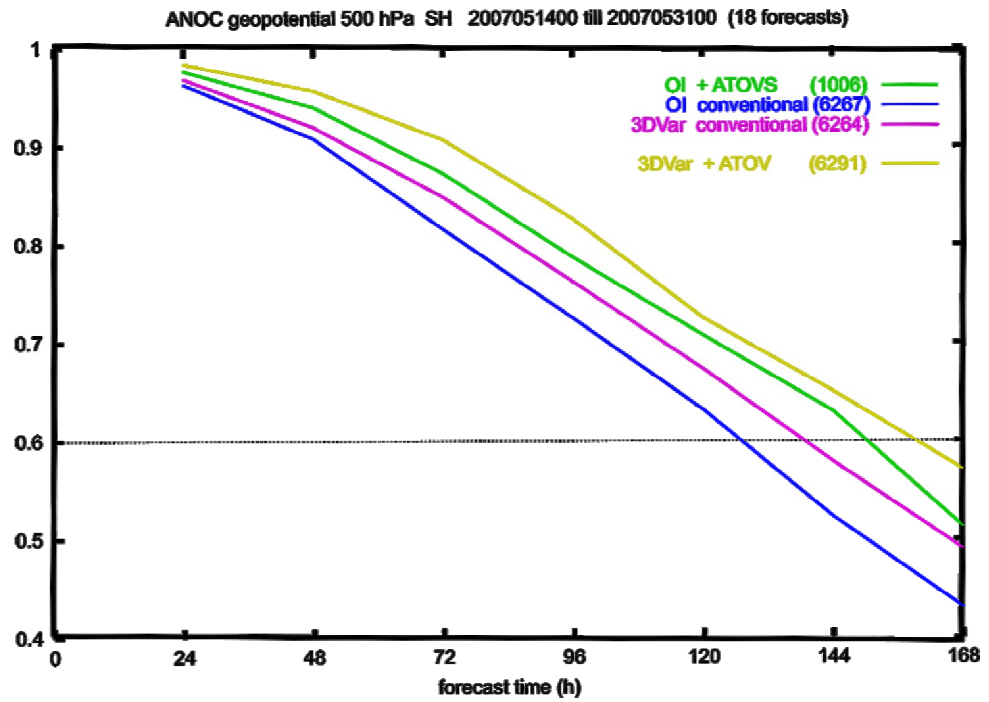

Figure 1: Mean anomaly correlation coefficient for the geopotential height at 500 hPa comparing four experiments (operational OI system using only conventional data (blue), OI using conventional data and ATOVS radiances (green), 3D-VAR using only conventional data (red) and 3D-VAR using conventional data and ATOVS radiances (light brown) for a period in May 2007 (18 forecasts).

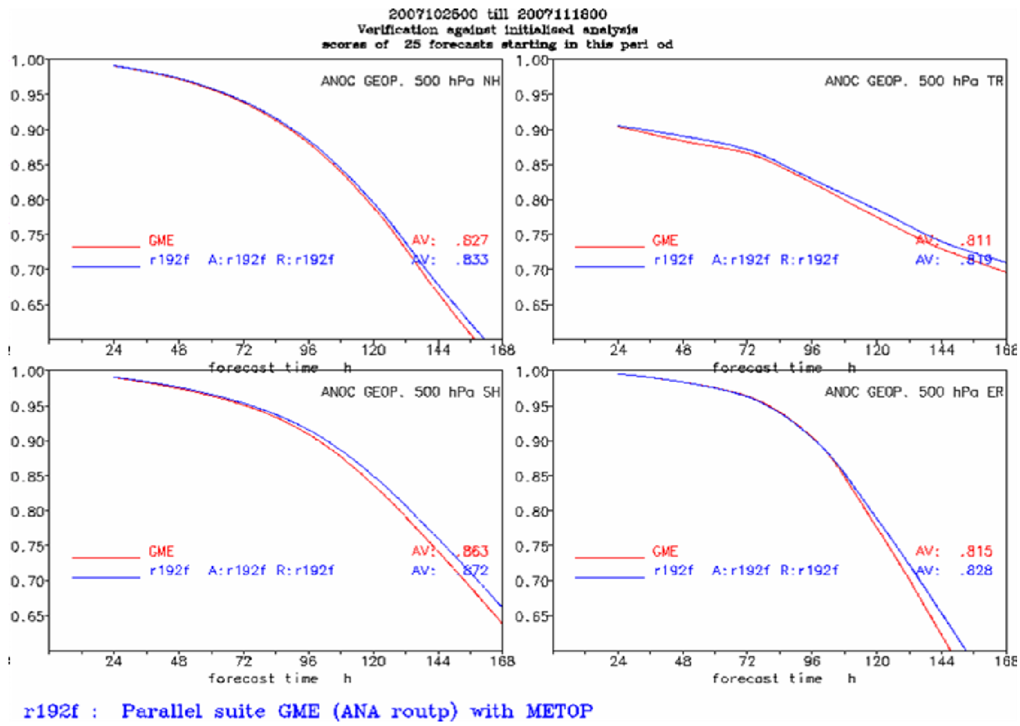

Figure 2: Anomaly correlation coefficient of the 500 hPa geopotential height versus forecast time comparing a Control run and an experiment using additionally AMSU-A radiance data from Metop-A for 25 forecasts in October and November 2007.

Use of GPS Radio Occultation observations

The Radio Occultation (RO) technique has been developed at the Jet Propulsion Laboratory and the Stanford University in the early 1960‚s as a method to sound the atmospheric structure of the planet. The development of the global satellite-based positioning system (GPS) allowed the application of the radio occultation technique for active soundings of the Earth‚s atmosphere. The Global Positioning System/Meteorology (GPS/MET) mission in 1995 was the first experiment to examine the earth atmosphere with help of the new technique.

A GPS radio occultation event occurs when a GPS satellite, transmitting the GPS signal, a low earth orbit (LEO) satellite, which receives the signal, and the earth have a certain relative geometry: The GPS satellite, as viewed from the LEO satellite, sets or rises behind the earth‚s limb an event that typically takes 1-2 minutes. When passing close to the Earth, the electro-magnetic signal is delayed due to the presence of free electrons in the ionosphere and the (neutral) refractivity of the atmosphere. The ionospheric contribution is frequency-dependent and thus can be eliminated by combined use of the two GPS frequencies L1 and L2. The neutral contribution to the delay is of meteorological interest, as the refraction is directly linked to horizontal and vertical variations of temperature, pressure and water vapour. The refraction of the GPS signal corresponds to a shift in its phase, which is recorded at the receiving LEO satellite with help of a reference clock signal. In addition, the signal path undergoes a bending when the refractivity gradient has a component transversal to the direction of propagation (which is generally the case for limb soundings of the atmosphere), resulting in a bending angle. For the retrieval of the bending angle profile from the measured phase delay time series, basically two methods are in use: The geometrical optics approximation, assuming the propagation of the signal in a single ray, and the wave optics (canonical transform) approach, which reconstructs the wave field of the received signal and can take into account also multi-path propagation of the signal.

As the relative geometry of the GPS and LEO satellite and the Earth changes during the occultation event, the signal path intersects the atmosphere vertically, thus providing a vertical profile of the bending angle as a function of the so-called impact parameter p. The profile typically starts a 60-100 km altitude and ends near the Earths surface. An approximation for the observation error can be derived from the SNR of the amplitude of the signal. At DWD, profiles of the bending angle serve as observed quantity to be assimilated by the 3D-VAR system. In addition to the bending angle, profiles of the refractivity itself can be derived and assimilated via Abel transformation, assuming spherically symmetric atmospheric fields of temperature, humidity and pressure and absence of horizontal gradients.

The benefits of the GPS radio occultation bending angle observations are their high vertical resolution, the independence on cloud conditions (contrary ro radiance data), the lack of fundamental biases and their nearly uniform global coverage (Fig. 3).

An increasing number of satellites are equipped with GPS receivers for detecting radio occultation events. Among them, CHAMP (launched 2000), Grace-A and Grace-B (launched 2002) satellites are designed predominantly as non-operational research platforms. But in the meantime and by effort of the GeoForschungsZentrum Potsdam near real time occultation data apt for operational weather forecasting service is available from Champ and Grace. A joint satellite project COSMIC/FORMOSAT-3 by the USA and Taiwan operates six special purpose satellites (launched 2006) exclusively designed for observation of GPS radio occultation events. The occultation data are provided in near real time. Radio occultation data are also available form the Metop-A satellite (EUMETSAT/ESA launched in 2006).

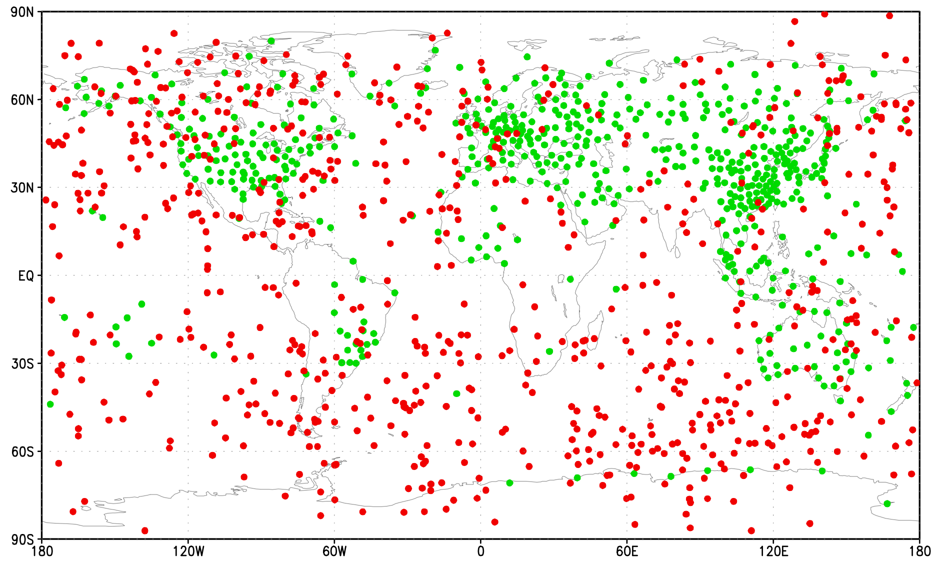

Figure 3: Global distribution of radiosonde (green) and radio occultation (red) measurements

At DWD, monitoring of near real time occultation data separated for each of the above mentioned Satellites is performed. A setup for the so-called forward operator to calculate bending angle profiles from atmospheric model quantities has been established. First assimilation experiments reviled a positive impact of GPS radio occultation bending angle profiles on the forecast quality in the Southern Hemisphere and a neutral impact on the Northern Hemisphere. As Fig. 4 depicts, half of the impact of AMSU-A radiance data can be achieved by using radio occultation data form Champ, Grace and the six COSMIC/FORMOSAT-3 satellites. At present time, tuning operations of the forward operator and the quality control mechanism for bending angle profiles are performed and tested in experiments. The introduction of this new observation quantity into operational assimilation is planned to coincide with the operational start of the new 3-DVAR assimilation scheme of the DWD in mid 2008.

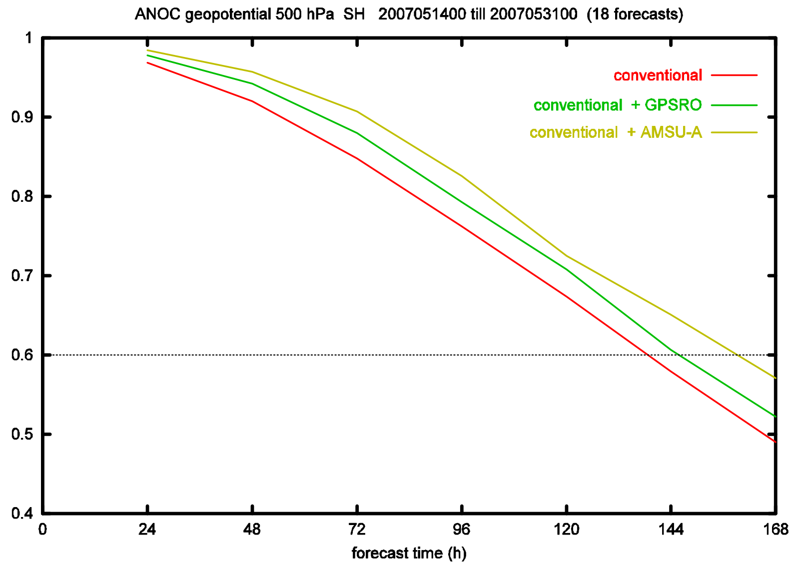

Figure 4: 500 hPa geopotential height anomaly correlation coefficient of experiments using only conventional data (red line), conventional data plus radio occultation data (green) and conventional data plus AMSU A data for 18 forecasts in June 2006.

Assimilation of satellite wind data

Global wind measurements are essential to improve our knowledge of atmospheric dynamics and to describe atmospheric transport processes of energy, water, airbourne particles and trace elements. Atmospheric motion vector (AMV) winds derived from tracking clouds and water vapour image sequences are the only global tropospheric wind information for numerical weather prediction models and therefore make an important contribution to the global observing system, particularly over the oceans and in polar areas, were there are either no other or only very few conventional wind data. Additionally, space-borne scatterometer data provide near surface wind observations over the global oceans with high temporal and spatial resolution under most weather conditions. The German weather service, DWD, has been using AMVs operationally in its global data assimilation system since 1990s, with consistently positive impacts. Recent work has been focused on the replacement of Meteosat-7 data by the new wind products of Meteosat-8 and Meteosat-9, the switch from GOES 10 to GOES 11 and from Meteosat-5 to Meteosat-7 and the successfully inclusion of AMV's from the MTSAT-1R satellite derived by the Meteorological Satellite Center of JMA. Further impact studies have been carried out with Bufr formatted MODIS winds derived by NOAA/NESDIS.

Results of different impact studies demonstrate the positive benefit of using AMV wind products in the NWP system of the DWD. Fig. 5 compares the impact on forecast quality of an experiment not using any AMV wind vectors in the assimilation to control forecasts using all available observations. The No-AMV experiment shows a small, but fairly consistent degradation in forecast quality for the tropical atmosphere and on the Southern Hemisphere, whereas the forecast impact is much smaller on the Northern Hemisphere, due to a better observation density of, especially conventional (radiosonde, aircraft, synops, buoys) data on the Northern Hemisphere which mask the potential benefit of AMV wind vectors considerably. In the absence of other satellite data, the AMV wind vectors show a much bigger benefit. After extensive monitoring and careful QI selection, the winds from Meteosat-8/9 show a slightly positive impact on both hemispheres and Europe. No substantial negative impact results from replacing GOES 10 and Meteosat-5 winds by AMV winds derived from GOES 11 and Meteosat-7, respectively. After the implantation of an improved height assignment scheme, the quality and impact of winds from MTSAT-1R improved substantially. Using quality information in the selection process of MODIS winds lead to a substantial improvement of the polar analysis and increased forecast quality over both hemispheres. Additionally, direct broadcast winds have the potential to increase forecast quality even further. First results indicate a higher forecast quality over the Southern Hemisphere

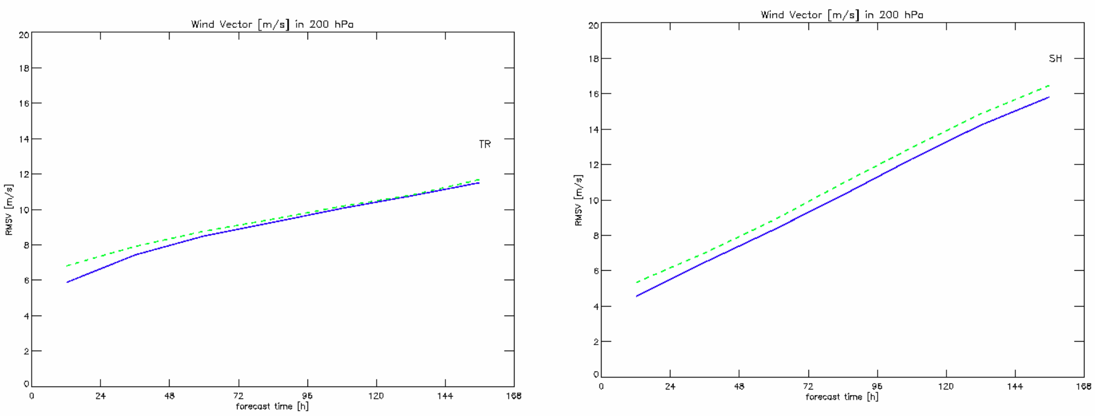

Figure: 5 Mean RMS wind vector scores for the Tropics (left) and the Southern Hemisphere (right) at 200 hPa for the Control run (blue) and an experiment denying all AMV wind vector observations (green) for the period 12 Dec. 2007 _ 12 Jan. 2008.

The assimilation of scatterometer wind data requires careful data selection with regard to rain and ice contamination and in case of data from QuikScat scatterometer a bias correction is needed. At the DWD, 10 meter wind observations from the Seawinds scatterometer aboard the QuikScat satellite and from the ASCAT scatterometer aboard the Metop satellite were tested.

In the following, quality control and forecast results will be focussed on experiments using the newer ASCAT scatterometer 10 meter wind data derived by the OSI SAF facilities at KNMI. As the assimilation scheme at DWD currently can only handle one wind solution, we select the most likely wind vector solution from the two ambiguity wind solutions of the ASCAT scatterometer. Since the ASCAT scatterometer operates in C-band frequencies, there is no sensitivity to rain contamination and the data can be used in all weather situations. Only a careful elimination of winds over land/ice has to implemented. As Fig. 6 illustrates, the quality of ASCAT derived wind vectors compared to collocated model wind vectors is very good. Using the quality flags, developed by the OSI SAF team at KNMI and inherit in the Bufr coded winds, the quality of the ASCAT wind vectors increases substantially (Fig. 6; right) leaving a small positive bias of up to 0.2 m/s, which is comparable to wind measurements from buoys. Obviously, high scatterometer winds at the upper left part of the scatter plot, which do not correspond to corresponding model winds can be successfully eliminated by using the wind vector cell quality flag.

The assimilation of 10 meter wind vectors derived from ASCAT has a positive impact on the analyses and forecast performance of the numerical prediction system at DWD (the same is valid for using QSCAT wind data) mainly on the Southern Hemisphere and for deep baroclinc systems (tropical storms, deep low pressure system), where small positive corrections in position and intensity can be obtained. As an example, Fig. 7 shows a time series of anomaly correlation coefficients for Europe for the Control run and an experiment using additionally ASCAT wind vectors for a 3-day forecast. The time dependent anomaly correlations for both, the Control and the experiment exhibit strong similarities except for the 29^{th} of Jun 2007, where a substantial increase of the anomaly correlation can be found in case of the experiment including ASCAT wind vectors, caused by a better forecast of a strong low pressure system off the coast of Ireland (both position and intensity).

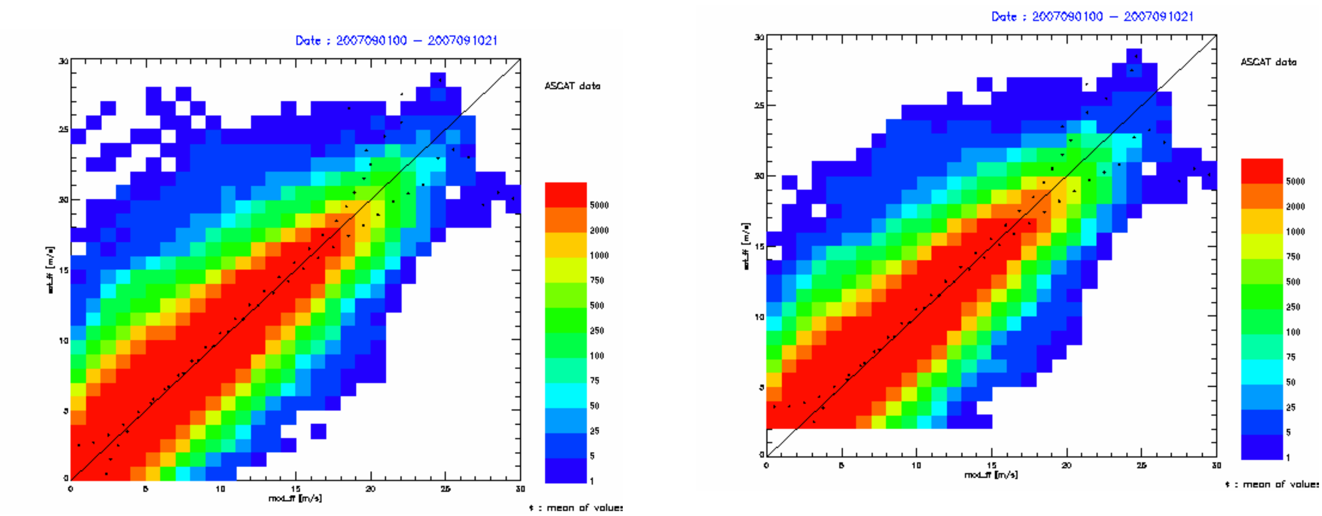

Figure 6: Scatter plot between ASCAT wind speed observations and collocated GME first guess wind speeds for all data (left) and data after using the wind vector cell quality flag (right) for a ten day period in September 2007

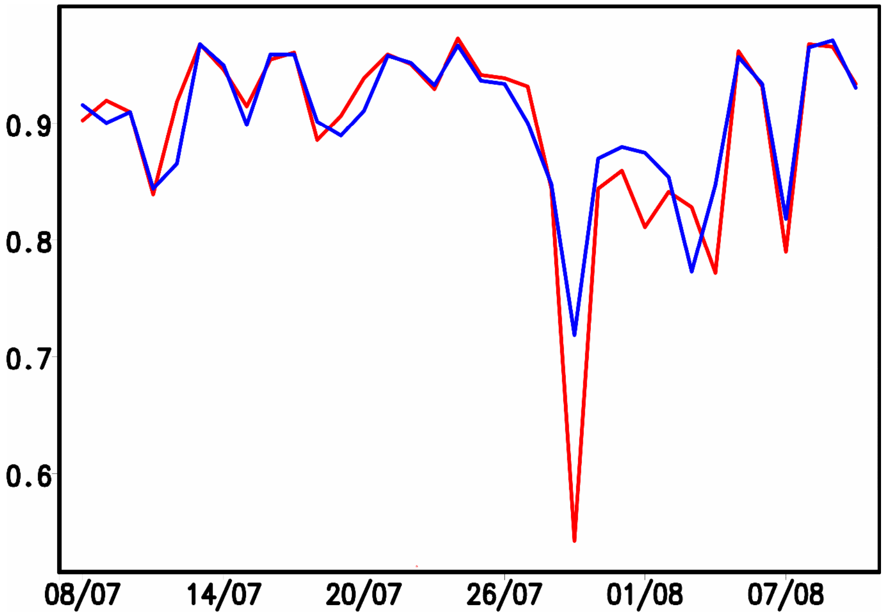

Figure 7: Time series of anomaly correlation coefficients for 72 hour forecast of sea level pressure over Europe for the Control run (red) and an experiment including ASCAT wind vector measurements (blue) for the time period 9th July _ 9th August 2007.

Global Impact Studies at Météo-France

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1. Introduction

Data impact studies are presented for the French global model ARPEGE. The resolution of the model is T538 in spectral triangular truncation. It has a stretched coordinate with a stretching factor of 2.4, the maximum resolution becoming 2.4 times better over the pole of interest (Western Europe), and 2.4 times worse at the antipodes (South Pacific area). The maximum resolution is 15km at best over Western Europe. In the vertical, the model has 60 levels in hybrid coordinate, from the surface to 0.1hPa. The analysis is a four-dimensional variational analysis, with two minimisation loops at T107 and T224 (unstretched). The code is developed in collaboration with ECMWF. The analysis uses all types of observations: conventional observations, satellite winds, satellite radiances and GPS data (both ground-based and radio-occultation). These observations are also used in the limited-area model ALADIN, coupled with ARPEGE, together with extra observations as described in Fischer (same volume). In the past few years, several data impact studies were performed. In particular, we started assimilating Atmospheric Motion vectors (AMV) in BUFR format, using the Quality Indicator (QI) to choose the most accurate data; MODIS polar winds from the Aqua and Terra satellites; SSM/I radiances from F13 and 14; AIRS radiances (54 channels currently); Ground-based GPS data over Europe (in the context of the E-GVAP programme); scatterometer winds from QuikSCAT, ERS and ASCAT; ATOVS from MetOp; MSG Clear-Sky Radiances (CSR); GPS radio-occultation data from COSMIC, CHAMP and GRACE-A; IASI radiances (50 channels). Impact studies also dealt with improvement in our assimilation of data: increase in the AIREP density, Variational Bias Correction (VarBC) for radiances, new emissivity parametrisation over land for micro-wave data. A few of these improvements are presented in this paper, namely the assimilation of GPS radio-occultation, of IASI radiances, the impact of Variational Bias Correction for radiances and of an emissivity parametrisation for micro-wave radiances over land. The impact of data over specific areas is also investigated, usually linked with field experiments. We describe first results obtained over Africa in the context of AMMA and give information in the preparation for a future field experiment over Antarctica (Concordiasi).

2. Assimilation of GPS – Radio Occultation data and of IASI radiances

The operational assimilation of **GPS - Radio Occultation** data took place in September 2007. The assimilated data are bending angles (using the 1D observation operator and its tangent-linear and adjoint versions from GRAS-SAF). CHAMP and GRACE-A data are received from GFZ *via* GTS and FORMOSAT-3/COSMIC 1—6, data from UCAR *via* GTS. We use both rising and setting occultations, up to 25 km altitude, down to altitudes ranging from 6 km (in the tropics) to 1 km (over the poles). The vertical thinning is 1 datum per model vertical layer. An elaborate quality control was introduced in order to select the most relevant data; bending angle data are retained only if the corresponding refractivity (N) meets the following criteria

–$0.01\ km^{-1} > dN/dz$
–dN/dz at all levels above > $-50\ km^{-1}$
–$| d^2N/dz^2 |$ at all levels above < $100\ km^{-2}$
–Occultations extend down to 10 km altitude or below.

This data selection algorithm was devised to avoid radio propagation problems, independently from background check. More details can be found in Poli et al, 2008. The impact on the forecast is shown in Figure 1, representing scores with respect to analyses over a 21-day period from 6 to 30 September 2007. One can see a global significant positive impact for all parameters (wind not shown), with a maximum impact around 100hPa.

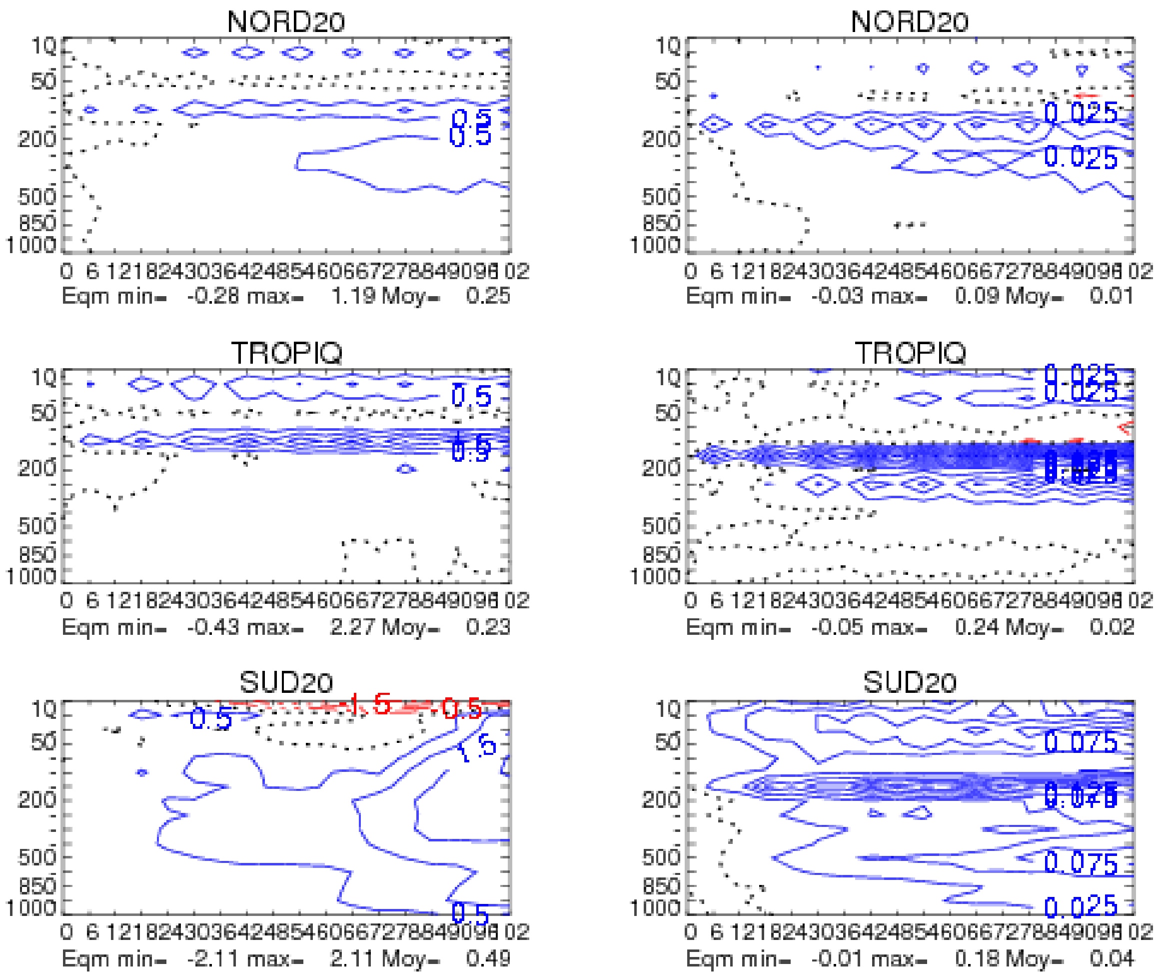

Figure 1: Score differences between forecasts from analyses having used GPS-RO data and forecasts from analyses without GPS-RO data. Root-mean-square errors (RMSE) are computed with respect to analyses over a 21day period from 6 to 30 September 2007. The score differences are for geopotential height (left panels) and temperature (right panels). The contour spacing is 0.5m for the geopotential and 0.025 K for the temperature. The vertical coordinate is the level in hPa, and the horizontal coordinate is the forecast range, from 0 to 102 hours. The top panels are scores over the Northern Hemisphere, the middle panels over the Tropics and the lower panels over the Southern Hemisphere. The blue (respectively red) colour indicates that GPS-RO data have improved (resp. degraded) the forecasts.

Another important addition to our operational system has been the assimilation of **IASI radiances** (operational 1st July 2008). The general features are given below. Level 1C radiances are received *via* EumetCast in Toulouse (whole BUFR including 8461 channels). A subset of 314 channels is monitored (commonly chosen with other NWP centres). 50 channels are actively assimilated, only over sea (sensing temperature in the 15 micron band, peaking between 100 hPa and 620 hPa). Radiances are bias corrected using a Variational Bias Correction (see next section) and the cloud detection is based on a channel ranking method (McNally & Watts, 2003). Pre-operational tests showed a positive impact (esp. in the Southern Hemisphere), both in winter (see Figure 2) and in summer.

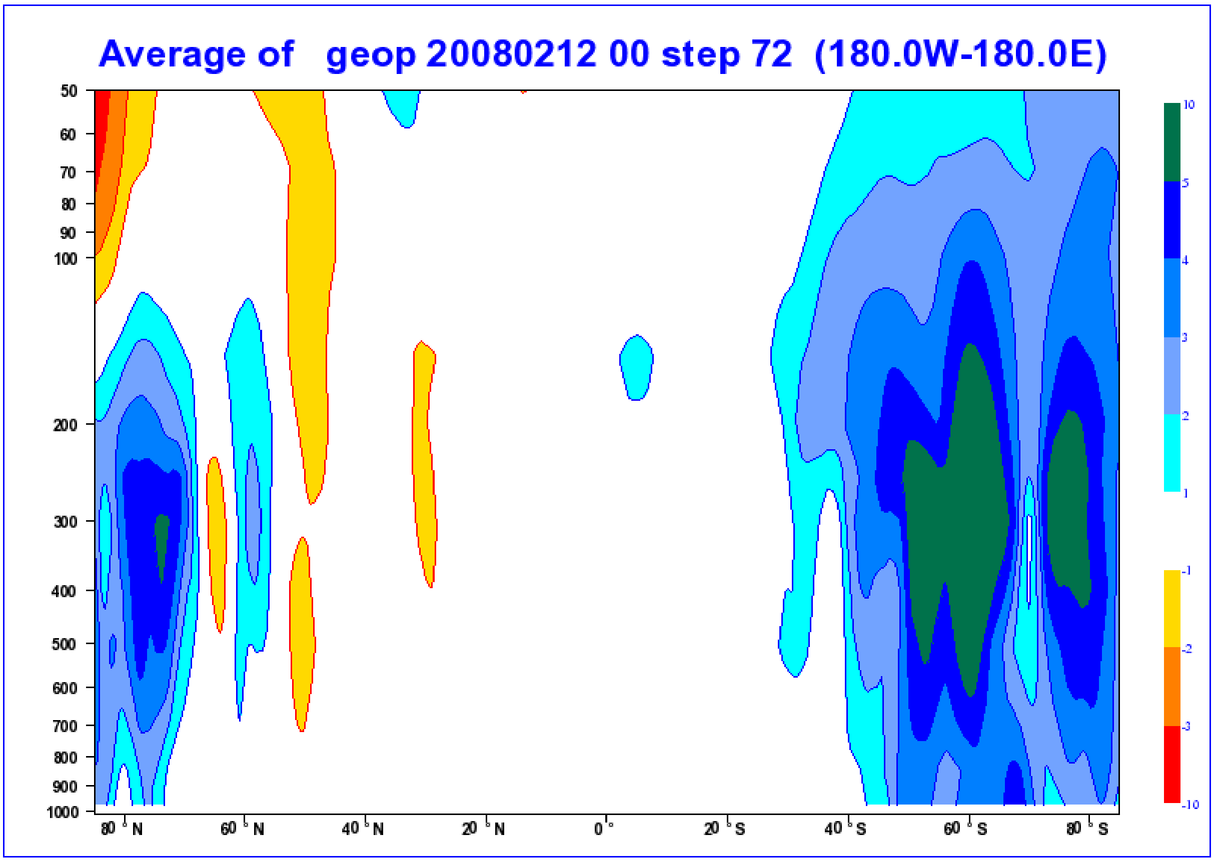

Figure 2: Zonally averaged score differences between 72-hour forecasts from analyses having used IASI data and forecasts from analyses without IASI data. Scores were computed with respect to analyses over a 21day period from 6 to 30 September 2007. The score differences are for geopotential. The vertical coordinate is the level in hPa, and the horizontal coordinate is latitude from 90N to 90S. The blue (respectively red) colours indicates that IASI data have improved (resp. degraded) the forecasts.

3. Variational Bias Correction and emissivity parametrisation

Although a lot of work is dedicated to the assimilation of new types of data, the optimisation of the use of currently assimilated observations is also highly beneficial to the assimilation. Two examples are presented in this section. The first one illustrates the impact of an alternative bias correction. It is well known that satellite radiance data have systematic biases that can depend on the scan angle (geometry) and on the flow. They can be explained by predictors such as the scan angle, thicknesses of some layers of the atmosphere, skin temperature, etc., by a multiple linear regression (Harris and Kelly, 2001).

Commonly, the coefficients of this regression are computed off-line, on a relatively long period (a few weeks) before being applied. They are not updated on a regular basis, although this is necessary in certain occasions, such as the introduction of new instruments, whenever some channels are drifting, or when calibration is changed at the producer level for instance. In the **Variational Bias Correction (VarBC)** scheme, coefficients of the regression are dynamically adapted at each analysis time. They are included in the control variable of the assimilation, and they use other "conventional" data (such as radiosondes or aircraft data) as a constraint to adjust these coefficients for satellite radiances (Auligné et al, 2007). The impact over a 43-day period of July-August 2007 is presented in Figure 3. It shows the impact of VarBC for AMSU-A/B, MHS, SSM/I, HIRS & AIRS, versus a static bias correction. The results are strikingly positive. The VarBC scheme was introduced in operations at Météo-France in February 2008.

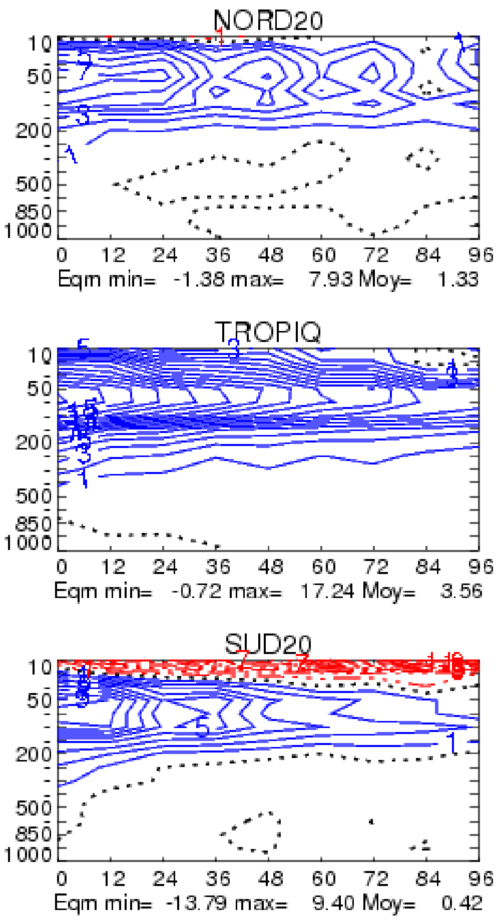

Figure 3: Scores illustrating the impact of VarBC for AMSU-A/B, MHS, SSM/I, HIRS & AIRS, versus a static bias correction over a 43-day period of July-August 2007. Differences in RMSE wrt radiosonde for geopotential height. The contour spacing is 1 m. The vertical coordinate is the level in hPa, and the horizontal coordinate is the forecast range, from 0 to 96 hours. The top panels are scores over the Northern Hemisphere, the middle panels over the Tropics and the lower panels over the Southern Hemisphere. The blue (respectively red) colour indicates that VarBC has improved (resp. degraded) the forecasts.

The second optimisation performed operationally has been the use of an **emissivity parametrisation over land for AMSU microwave observations**. Satellite microwave measurements have large atmospheric and surface information contents and are known to be very useful for Numerical Weather Prediction. However these observations are still not fully used over land because of non negligible uncertainties about land emissivity and surface temperature. Recent developments have been carried out at Météo-France in order to propose new methods for land emissivity and surface temperature modelling anchored on satellite microwave observations. The methods, fully described in Karbou et al. (2006), have been interfaced with the RTTOV model. (1) The first method is based on the use of averaged emissivity estimates calculated within the assimilation system two weeks prior to the assimilation period; (2) the second one uses a dynamically varying emissivities derived at each pixel using one surface channel or a selection of surface channels, and (3) finally the third method combines the two previous ones since it uses averaged emissivities and dynamically estimated skin temperature at each pixel using observations from one surface channel. The relevance of the use of the new methods to assimilate microwave observations over land has been investigated using AMSU-A, AMSU-B and SSM/I observations. The performances of the three methods have been studied in terms of (a) observation departures from first guess and from the analysis and also in terms of analysis and forecast impacts. So far periods of test have been chosen around the August-September 2005 and 2006 AMMA periods (African Monsoon Multidisplinary Analyses, Redelsperger et al., 2006). The results show that an important amount of data is assimilated when the land surface emissivity and/or the surface temperature is updated. Even sounding channels that receive a lesser contribution from the surface take advantage of this modification (see Figure 4). A preliminary version of these developments was implemented operationally 1st July 2008. It consists in using a dynamically-estimated emissivity for AMSU-A and B over land, without assimilating extra sounding channels. In addition, the assimilation of surface sensitive channels over land with improved land surface characteristics modelling appears to have a strong impact on the hydrological cycle both in analysis/first guess and short to medium range forecast and is globally beneficial to our analysis and forecast system. Preliminary results from a assimilation experiments using low-peaking channels over land are quite promising.

4. Field experiments: AMMA and Concordiasi

Field experiments provide a framework in which to investigate more thoroughly various aspects of data impact. In particular, Météo-France is involved in evaluating the impact of the radiosonde network set-up for the **AMMA** experiment which took place in 2006 (Parker et al., 2008). Some radiosonde data were available in real time on the GTS, and were used operationally. Others were only collected at a later time. A data impact study compares the assimilation of RS data received operationally to the assimilation of all available RS data (received later, or even replacing some which were received operationally by higher resolution profiles received at a later date). This study was made possible thanks to the AMMA database and the pre-processing of the data performed at ECMWF. The control experiment also uses more microwave data over land thanks to the recent developments on microwave emissivity (see previous section). This first data impact study was set-up without any special bias correction, whereas we know that this is an important issue. Another data impact study was then performed using a radiosonde bias correction developed at ECMWF. Figure 5 shows the forecast improvement with respect to Synop when using more RS data and when using an appropriate bias correction. The short-range forecasts are improved for most parameters (here, mean sea-level pressure and relative humidity). An improvement to the background fit of high-level peaking channels (AMSU-A 10 to 13) was also noticed.

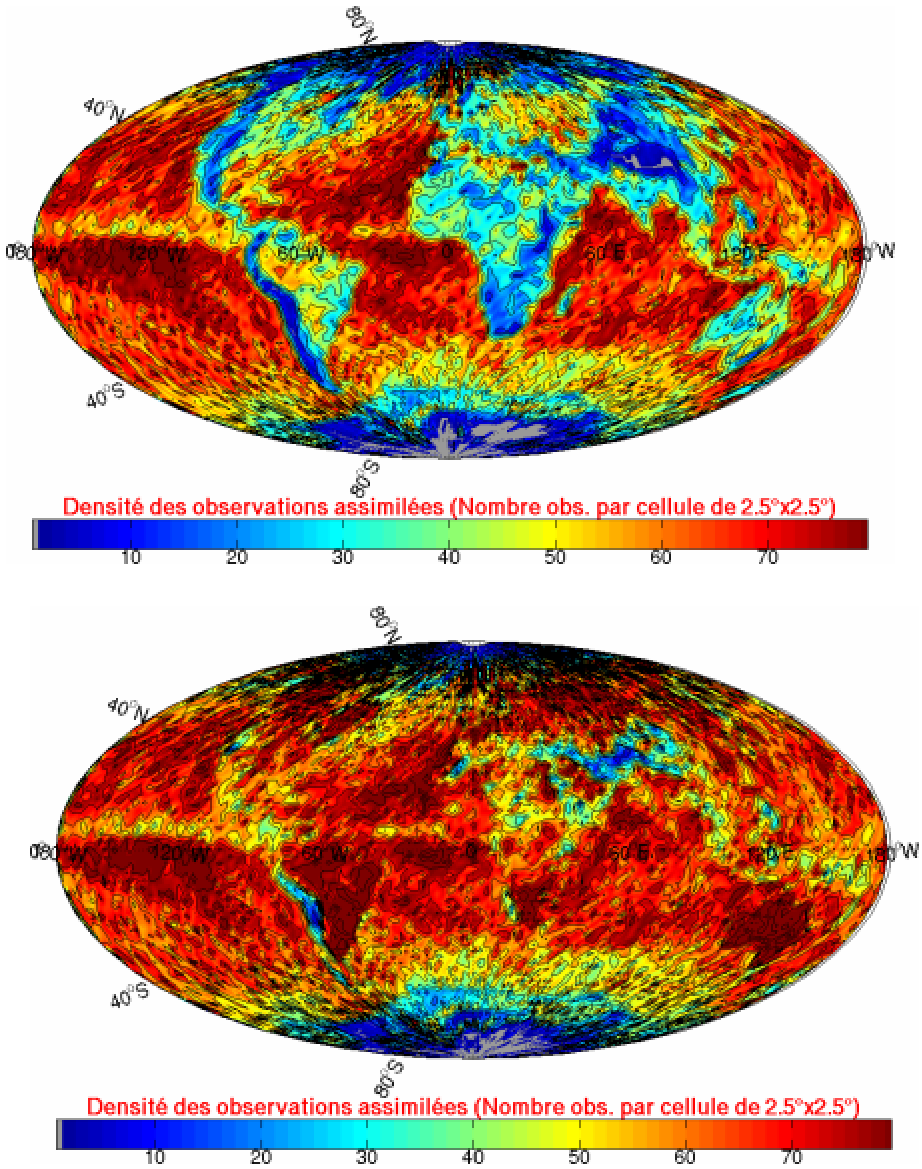

Figure 4**:** Density of assimilated observations (number of assimilated observations over a 2°x2° grid) from AMSU-A channel 7 and over August 2006. Results are given for (a) the control and for (b) an experiment that uses dynamically varying emissivities derived at AMSU-A channel 3.

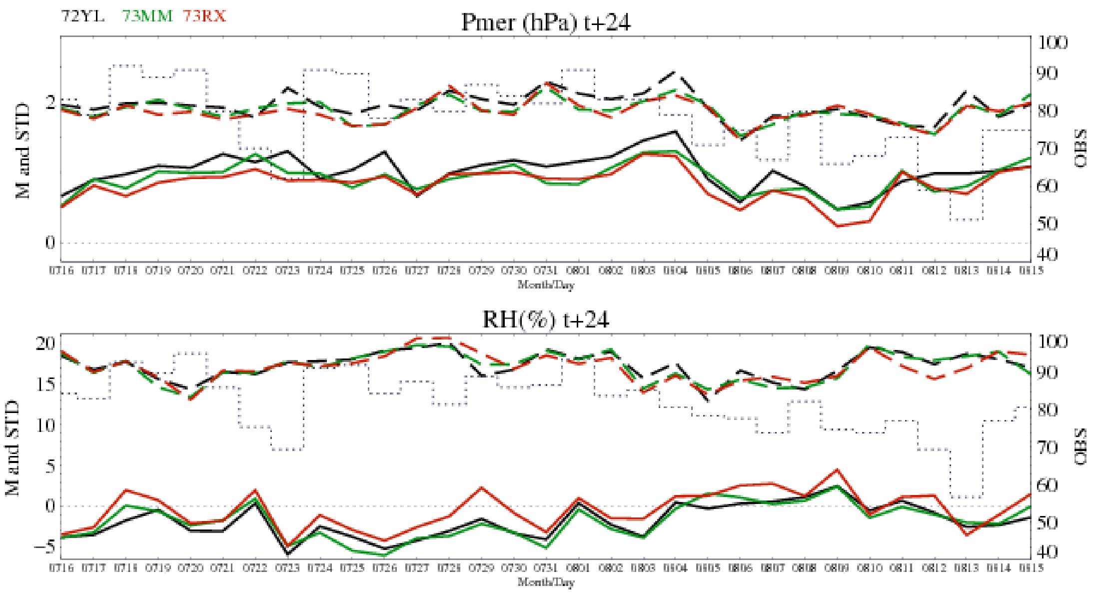

Figure 5: Errors in 24h range forecast for mean sea-level pressure (top panel) and relative humidity (bottom panel) over Northern Africa (latitudes greater than 0°) with respect to SYNOP stations from 15 July 2006 to 15 August 2006. The black lines correspond to the forecasts using GTS data only, the green lines the forecasts using all available AMMA RS data without bias correction and the red lines the forecasts using all available AMMA RS data with bias correction. Standard deviations are shown by dashed lines, and biases by solid lines.

Another field experiment of interest is **Concordiasi**. It is an international project, currently supported by the following agencies: Météo-France, CNES, IPEV, PNRA, CNRS/INSU, NSF, NCAR, Concordia consortium, University of Wyoming and Purdue University. ECMWF also contributes to the project through computer resources and support, and scientific expertise. Concordiasi is part of the THORPEX-IPY cluster within the International Polar Year effort (http://www.cnrm.meteo.fr/concordiasi/, Rabier et al., 2007). One of the main goals of this experiment is to improve the polar assimilation of IASI radiances. IASI is an advanced infrared sounder on board the European Polar orbiting satellite MetOp. From September 2008, additional conventional observations will be operated over Antarctica such as radiosoundings at the Concordia and Dumont d'Urville stations. Moreover, 600 dropsoundings will be dropped by twelve stratospheric pressurised balloons (SPB) in 2009. These SPBs will be deployed from McMurdo station during two months similarly to the VORCORE campaign (Hertzog et al 2007). Figure 6 shows the trajectory of one balloon during VORCORE. During the experiment, both flight-level data (pressure, winds and temperature at 60hPa) and dropsonde data will be made available in real-time.

A daily trial will decide the deployments of sondes. Each dropsonde launch will be predicted as a function of IASI's swath, and/or the predicted meteorological sensitive area valid for that day. Figure 6 also shows an example of the track of IASI over Antarctica the 7th October 2007. As a preliminary work, the meteorological French model ARPEGE has been changed in order to have a better accuracy over the south polar area. As already explained, it is a spectral model with a variable resolution on a stretched grid. The centre of this model has been moved southward to the Dome C station (75,12S; 123,37 E). The current resolution is then maximum over Antarctica. An impact of this modification has been tested by estimating the difference of the observations and the guess of the model over fifteen days of simulation. A positive impact has been noted for the temperature and zonal wind profiles when compared with radiosounding observations. Present and future work focuses on the polar assimilation of the infrared and micro-wave sensors using an improved emissivity parametrisation for snow-covered areas.

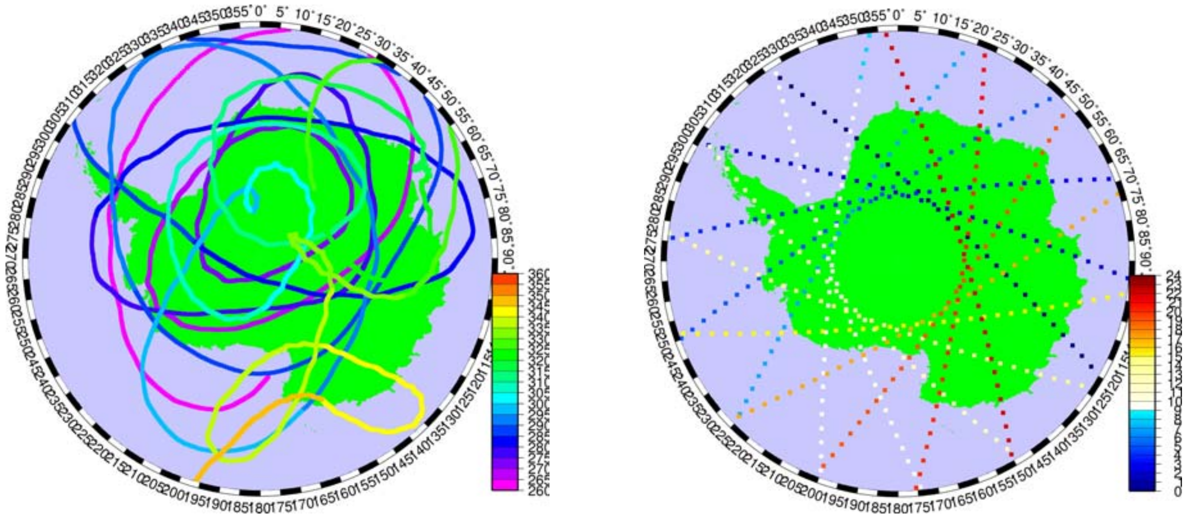

Figure 6: Left panel: Trajectory of the 17th balloon during VORCORE from September to December 2005. The colour shows the trajectory for one day. Right panel: Track of IASI the 7th October 2007. The colour gives the hour of the passage.

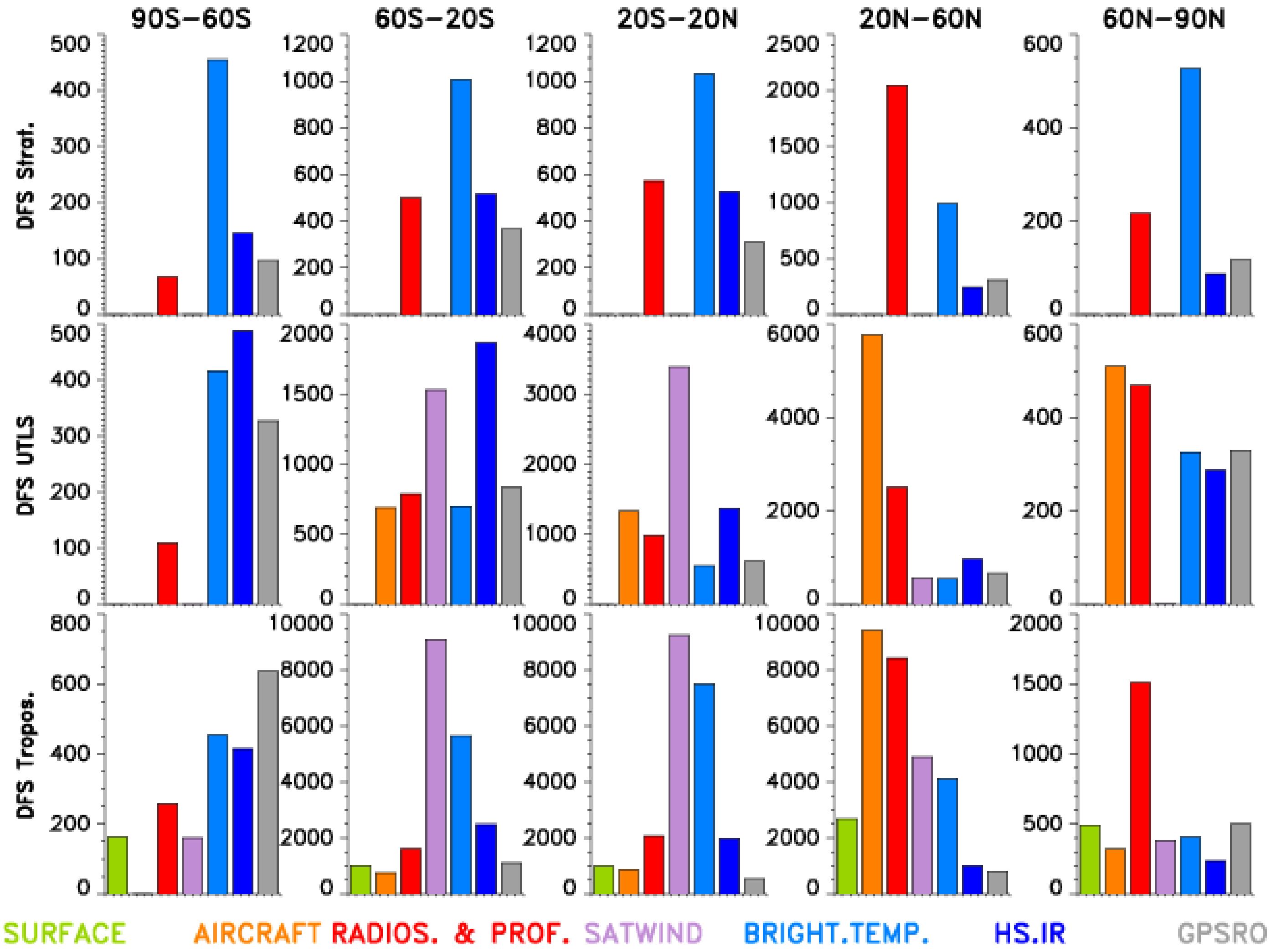

Figure 7: The numbers of degrees of freedom for signal (DFS) in the Météo-France 4DVAR analysis, as a function of observation data-type for five zonal regions and for three altitude bands (below 9 km altitude, between 9-16 km altitude, and above 16 km altitude). Note the different scales. Surface data from SYNOP, SHIP, Buoys and GPS Zenith total delays are in green, AIRCRAFT data are in orange, radiosonde and profiler data are in red, satellite winds from geostationary satellites, scatterometers and polar MODIS winds are in purple, radiance brightness temperatures from ATOVS, SSM/I and SEVIRI instruments are in light blue, those from hyperspectral instruments AIRS and IASI are in dark blue, GPS radio-occultation data are in grey.

5. Current data impact in the system

In summary, operational data impact studies at the global scale at Météo-France have shown a positive impact of GPS-RO and IASI data. It also illustrated a large impact of radiance Variational Bias Correction and an encouraging impact of using microwave radiances over land with an improved emissivity parametrisation. All these developments are now operational. Figure 7 shows the weights of the various data-types in constraining the global analysis in the current model version. The degrees of freedom for signal (DFS) indicate the importance of each observing system in the various regions. As expected the Northern mid-latitude troposphere is well covered by conventional observations (radiosondes and aircraft), while the stratospheric analysis relies primarily on brightness temperatures collected by satellite sounders, with a large impact of hyperspectral sounders in the upper troposphere and lower stratosphere. Figure 7 also illustrates the importance of GPS radio-occultation measurements in constraining the analysis in the high southern latitudes where very few other observations with high vertical resolution are available.

In research mode, the impact of the RS network over Africa is investigated in the AMMA context, and we are also focusing over satellite data assimilation over the poles in the context of the Concordiasi Field experiment over Antarctica in 2008-2009.

6. Acknowledgements

Anna Agusti-Panareda, from ECMWF, is warmly thanked for her help with the AMMA experiments (processing of the observations and bias corrections).

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Data Impact Experiments at the JCSDA and NCEP/EMC

S. Lord and L. P. Riishojgaard

1. Introduction

In the course of preparing new observations for inclusion in NCEP's operational global data assimilation system, a thorough set of assessments of observational quality and impact on the data assimilation and forecasts must be made. In such cases, the emphasis and circumstances are somewhat different from the data denial experiments often considered as part of evaluations of the existing observing system. First, the emphasis is to ensure a non-negative impact on operations so that a conservative implementation approach is often taken by, e.g., using a low resolution observation data set. Second, the observations are typically new, as is the quality control and associated science, and their use has not matured over an extended period of several years. Accordingly, any positive impact from a particular data type is most likely underestimated compared to any estimate later in its life cycle.

Most of the studies reported here were done in the course of the operational implementation of the new observations. The studies covered the following observation types:

- COSMIC (GPS Radio Occultation soundings)
- QuikSCAT and Windsat (surface wind retrievals)
- MODIS (wind retrievals)
- IASI (advanced IR sounder)
- SSM/IS (advanced MW imager and sounder)
- ASCAT (surface wind retrievals)

2. Experimental setup

Although the time periods for each of the above studies differ, they were all conducted with a version of the NCEP Global Data Assimilation System (GDAS) that became operational in May 2007, and some of the studies were made with extensions of that system developed over the period May-November 2007. These extensions did not substantially improve the system's performance, however. The GDAS consists of the Gridpoint Statistical Interpolation (GSI) system, cycled at 6 hour intervals with a background field provided by the NCEP Global (spectral) Forecast System (GFS) model. All studies were performed at the 2007 operational resolution of T382 (~35 km) and 64 levels, with the top level at 0.2 hPa. In addition, the studies were generally performed over two months of cycled data assimilation, and summary statistics were calculated over the last 30 days in most cases. Such a procedure allows the satellite bias correction, quality control and model atmosphere to adjust to the new observations and produce a more statistically reliable result.

3. Results

A. COSMIC observations

COSMIC data were assimilated using refractivity as the observed quantity. Figure 1 shows the customary "die off" curves of NH and SH 500 hPa anomaly correlation from the COSMIC data impact experiment. Scores were averaged over 1-30 November 2006. At 5-6 forecast days, there is noticeable improvement in score with the COSMIC data. In addition, 48 h Root-mean-square (RMS) wind errors COSMIC data were implemented operationally at NCEP on 1 May 2007.

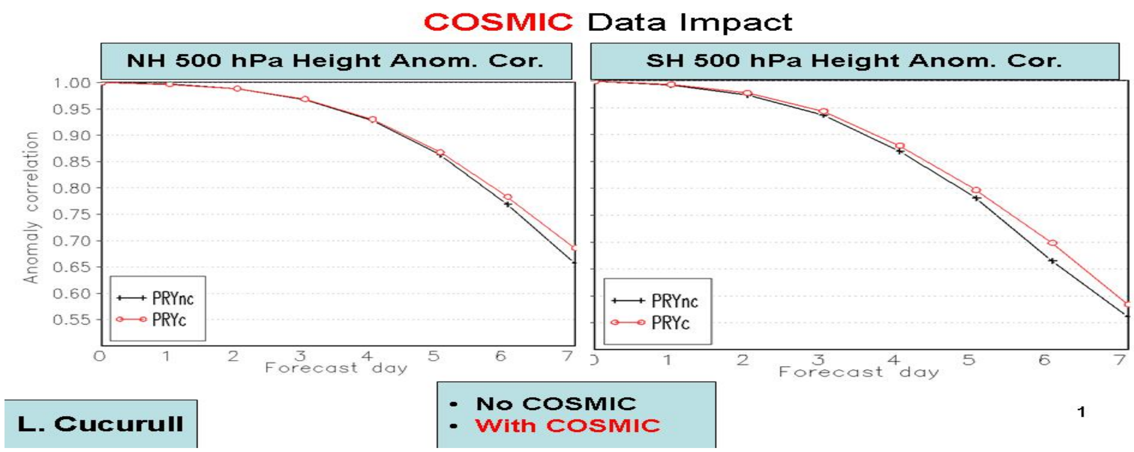

Figure 1. Impact of COSMIC data on 500 hPa anomaly correlation for November 2006.

B. QuikSCAT and WindSat observations

An extensive study of the impact of QuikSCAT was commissioned by National Weather Service Headquarters in the summer of 2007. Three runs were made over the period 5 July-25 October 2005:

1. Operational (since 2002) QuikSCAT data
2. No QuikSCAT data (denial)
3. Improved QuikSCAT (2007) retrievals

RMS wind scores at 1000 hPa are shown in Fig. 2. There is no discernable difference in low level wind scores due to the presence, absence or improved quality of QuikSCAT winds. As part of this study, NCEP was requested to include an evaluation of hurricane track forecast errors vis-à-vis inclusion of QuikSCAT winds. This study included a total of 65 cases of 5 day hurricane forecasts with the GFS. A previous study, with 34 cases (at 1 day, and fewer at 5 days) in the North Atlantic basin, had suggested some positive impact on hurricane forecast tracks due to various observations, including QuikSCAT. Fig. 3 shows little, if any, forecast hurricane track sensitivity. This lack of forecast sensitivity was also found in a small sample of 2006 cases, also in the North Atlantic basin (not shown).

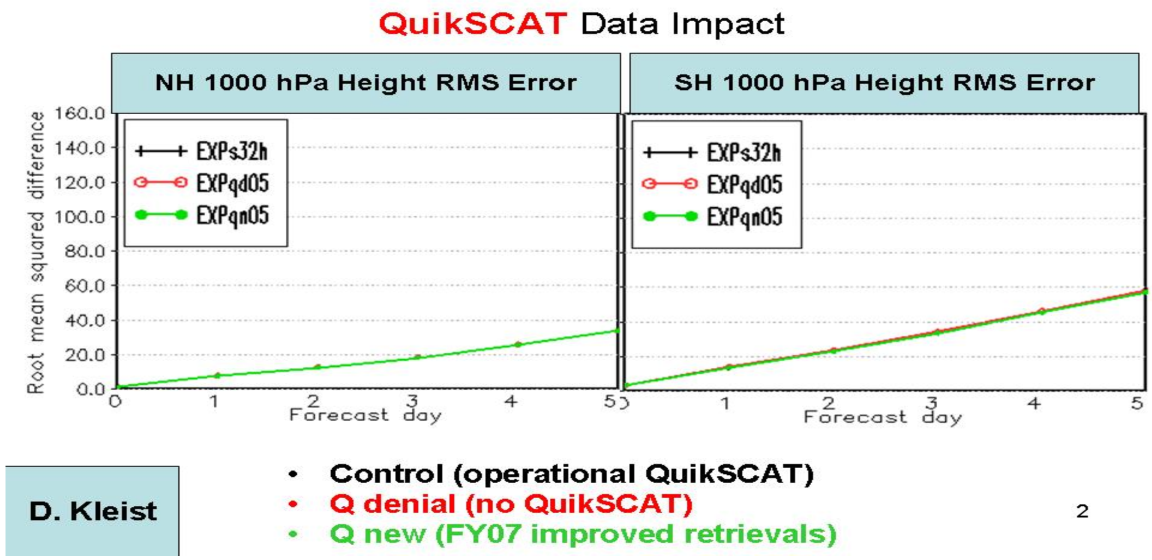

Fig. 2. Impact of QuikSCAT data on 1000 hPa RMS error.

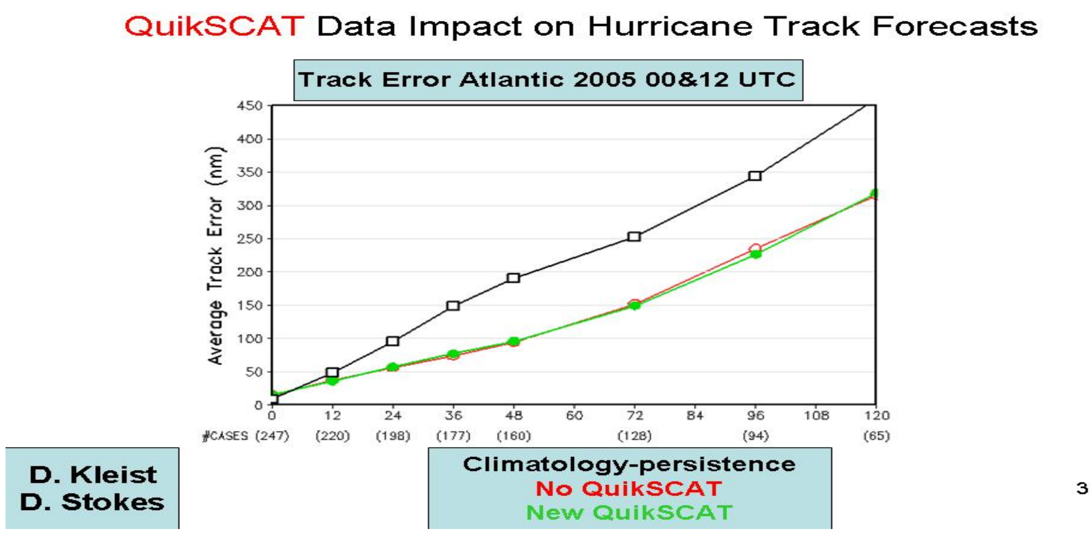

Fig. 3. Impact of QuikSCAT data on hurricane track forecasts.

Four experimental configurations for different combinations of WindSat and QuikSCAT data were run over the period 25 April - 8 June:

1. Control (operational QuikSCAT)
2. WindSat included (with QuikSCAT)
3. WindSat only (no QuikSCAT)

4. No WindSat and no QuikSCAT

Scores of 1000 hPa RMS height error (Fig. 4) are indistinguishable, except possibly in the SH where the combined WindSat and QuikSCAT data give a smaller error at 5 days.

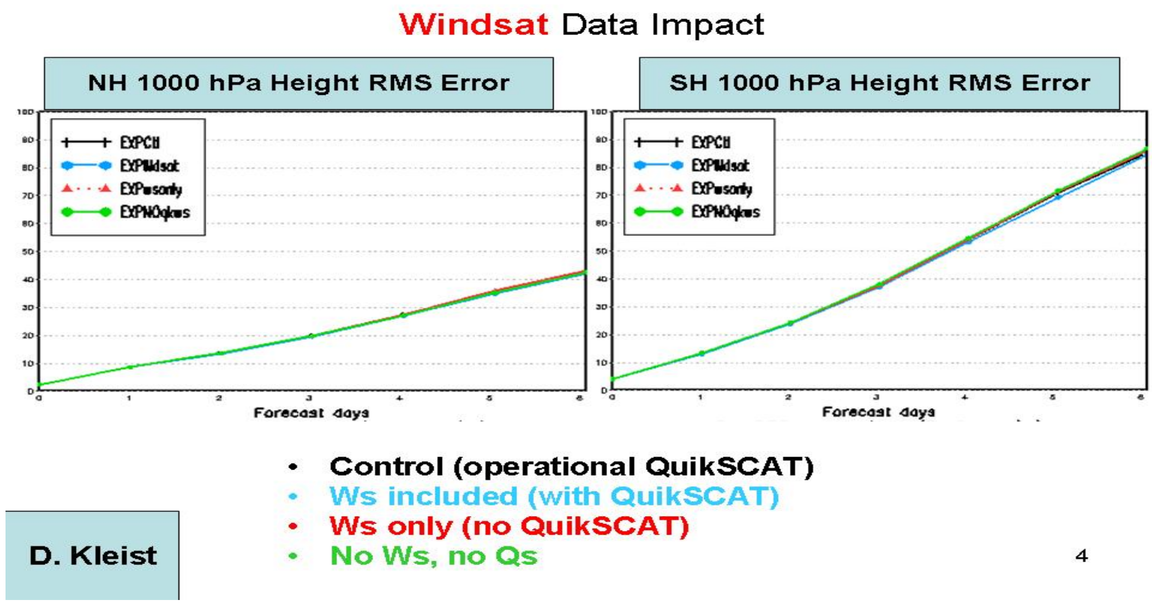

Fig. 4. Impact of WindSat data on 1000 hPa height errors.

C. MODIS Wind Retrievals

Experiments were run with MODIS IR and WV wind retrievals over February and July 2007. Fig. 5 shows monthly mean die-off curves for 500 hPa anomaly correlation. Results are mixed. In February, MODIS winds appear to have a small negative impact in the NH at days 3-6, but noticeable positive impact in the SH. In July, no impact was found either positive or negative.

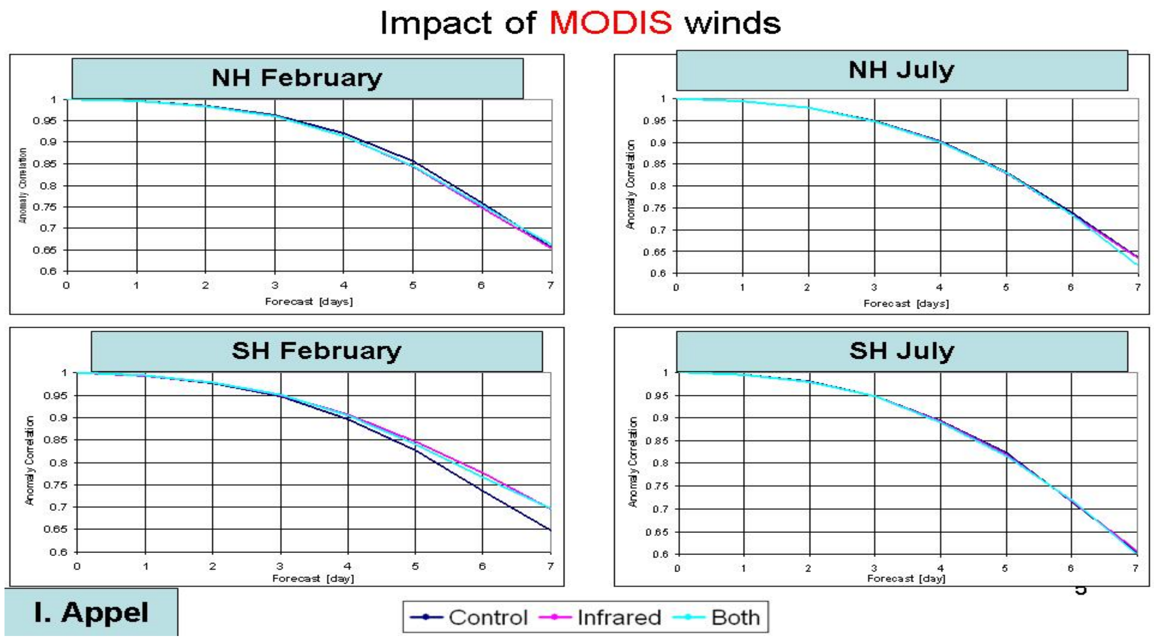

Fig. 5. Impact of MODIS winds on 500 hPa anomaly correlation.

D. METOP IASI radiances

The first JCSDA data assimilation experiment with METOP IASI radiances is reported here. Both summer (1-31 August 2007) and winter (16 December 2007 -15 January 2008) cases were done. The EUMETSAT selection of long wave channels was used. Fig. 6 shows mainly positive impact, particularly in the SH beyond 4 days. It is expected that impacts will be greater in the future as quality control and data selection are improved.

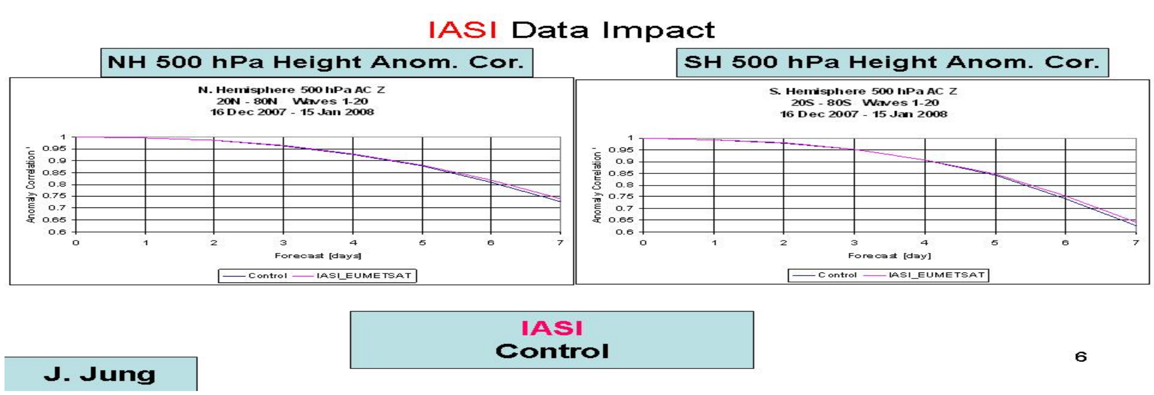

Fig. 6. Impact of IASI data on Winter 500 hPa anomaly correlation scores.

E. SSM/IS

The JCSDA has been testing SSM/IS Unified Pre-Processor (UPP, NRL-Monterey and the UK Met Office) observations as well as those processed by NESDIS. Greater impacts from these observations have been achieved through improved cloud detection (Fig. 7a), surface snow and sea ice emissivity simulations (Fig. 7b), and by adding water vapor channels (not shown).

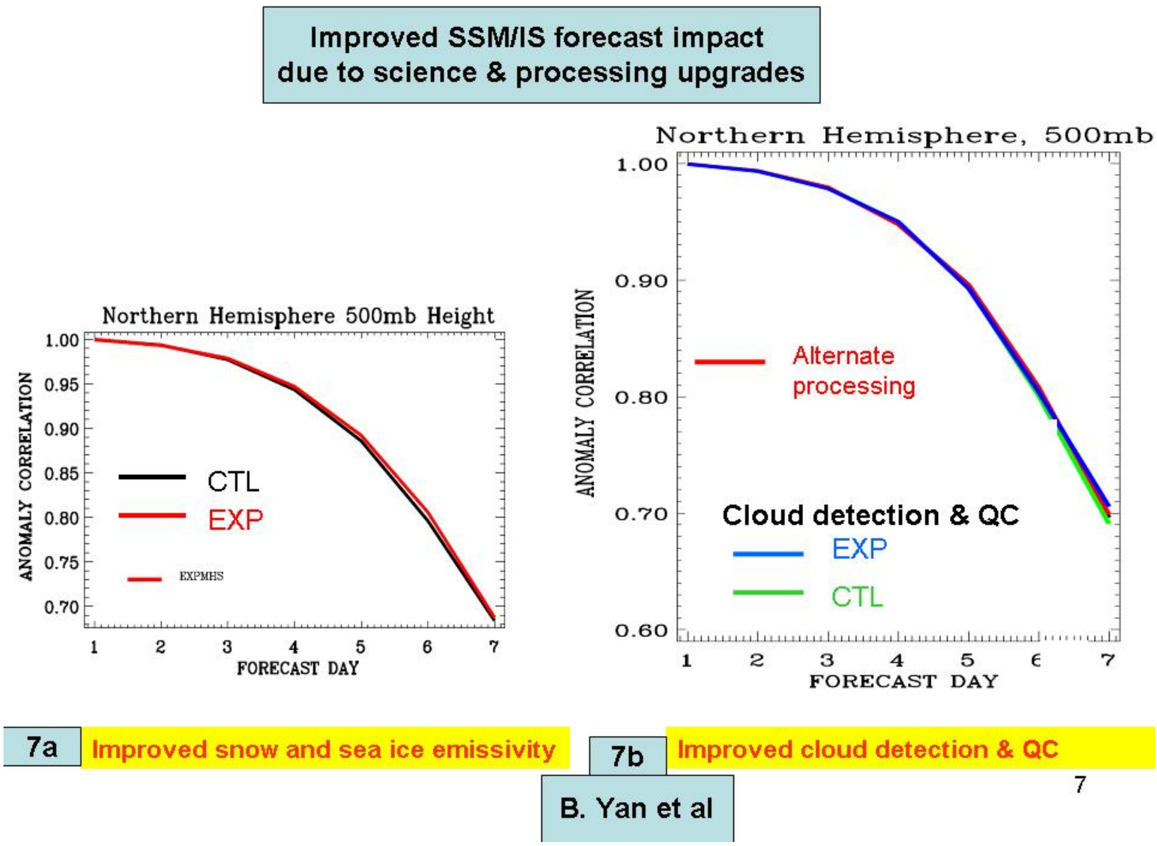

Fig. 7. Impact of improved snow and sea ice emissivity (a) and cloud detection and quality control (b) on 500 hPa anomaly correlation.

F. METOP ASCAT

Like IASI observations, the JCSDA has completed its first set of experiments. A conservative data thinning of 100 km was used. Impacts are neutral in both the NH and SH (Fig. 8); improved results are expected in future experiments with higher density data and better quality control.

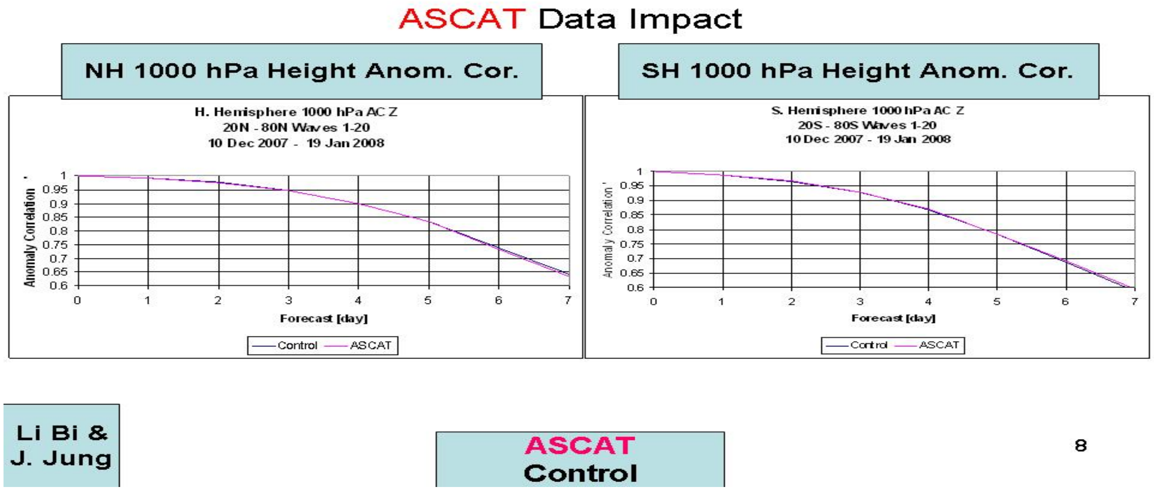

Fig. 8. Impact of ASCAT data on 1000 hPa anomaly correlation scores.

4. Summary and Conclusions

Data impact experiments for seven instruments (COSMIC, QuikSCAT, WindSat, MODIS (winds), IASI, SSM/IS and ASCAT) have been performed at operational resolution using NCEP's global data assimilation and forecast system. All instrument give non-negative impact despite some of them being added to the GDAS for the first time. In particular, the positive impacts from COSMIC are very encouraging. Notable positive impacts from SSM/IS are due to improvements in surface emissivity and cloud detection. As with results from some other weather prediction centers, a negative impact for assimilating water vapor channels on the advanced IR sounders (IASI and AIRS), which requires more investigation.

5. Acknowledgements

The authors appreciate the major contributions of L. Cucurull, J. Jung, L. Bi, D. Kleist, B. Yan and I. Appel in setting up and running this series of data impact studies and for generously providing their results.

Observation System Simulation Experiments in the Joint Center for Satellite Data Assimilation

Lars Peter Riishojgaard, JCSDA, and Michiko Masutani, NCEP/EMC

Introduction

One of the most important and most difficult problems facing funding agencies responsible for the development and deployment of new space-borne sensors and missions for earth observations is the assessment of often disparate claims concerning the expected impact on applications and science of the proposed new system. Over the last 10 to 15 years, Observing System Simulation Experiments (OSSE; e.g. Arnold and Dey, 1986, Atlas, 1997, Masutani et al., 2006) have become widely accepted as the de facto standard for assessing the impact on numerical weather prediction (NWP) applications of new candidate systems. Even though the primary focus of this note is impact assessment for future observing systems, it should be pointed out that OSSEs have applications also in other areas, e.g. research and development in data assimilation methodology (Errico et al., 2007)

The fact that they are widely used and relied upon does not mean that OSSE systems – or the experimental results created by them – are free of controversy. Because of the wide-ranging consequences of decisions on major space systems, any material on which these decisions are based will have to withstand intense scrutiny and criticism. In recognition of this fact, a broad collaboration involving several organizations inside and outside the US has developed over the last couple of years, with the aim of creating a modern OSSE capability of which both the ownership and oversight is shared among a broad group of stakeholders in future observing systems.

The main ingredients in a full OSSE system are:

- A validated set of simulated atmospheric states (“nature run”).
- A set of observations taken from the nature run in simulating the way the Global Observing System samples the real atmosphere (“reference observations”).
- Calibrated error models for the reference observations.
- A set of observations taken from the nature run simulating measurements from one or more candidate observing systems to be studied (“perturbation observations”).
- One or more state of the art data assimilation systems for executing the experiments.
- Diagnostic capabilities similar to what is used in operational NWP practice.

As one may discern from this list, the nature run is in some sense the nucleus around which the rest of the OSSE is revolving. The nature run is to the OSSE what the real atmosphere is to operational numerical weather prediction. Typically the nature run is performed using a high-quality atmospheric model at a relatively high resolution in free running “climate mode”, i.e. with no data assimilation included. The nature run model should be different from the model(s) used for the subsequent data assimilation experiments. This to a certain extents mimics the difference between the real atmosphere and the forecast models used for routine operational data assimilation.

To many newcomers to OSSEs, this use of a nature run initially seems to be a disturbing and unnecessary complication of matters. Why not base the experiment on real data and real atmospheric states? The short answer to this question is that since the OSSEs are aimed at assessing the impact of observations that do not yet exist, we have no way of measuring what they might have contributed to our knowledge of the atmosphere had they in fact existed. Our imperfect knowledge of the real atmospheric state at any given time is built from all the observational data that are available, and therefore by definition we cannot improve on it further by adding simulated observations. In fact, we do not even have an unequivocal way of assessing whether or not an arbitrary change in state would effectively be an improvement. The standard accepted way to get around this problem is to base the whole OSSE framework on simulated atmospheric states over which we have full control and of which we have full knowledge. It goes without saying that the nature run must be well validated, and that the meteorological features and phenomena targeted by the observing system(s) to be studied must be accurately represented in the nature run.

A very substantial part of the OSSE effort is devoted to simulation of the observations. Not only the data from the new systems subject to assessment must be simulate; the entire existing or projected observing system must be simulated as well in order for us to be able to reasonably accurately gauge the impact of the new data in the context of everything else that is or will be available.

Another very important aspect is the modeling the error of the simulated observation. In a well-calibrated OSSE system, the withholding of a certain type of observations – e.g. aircraft winds – will lead to a decrease in forecast skill that closely parallels what is seen in operational practice in the real world. This is achieved by tuning the simulated observation error accordingly.

A Joint OSSE capability as a national US resource

Space-borne observing systems are expensive to design, develop, deploy and operate, and typically a considerable amount of effort goes into promoting and assessing the merits of a proposed new system. In the United States, NASA is the main agency responsible for space-based systems for civilian earth remote sensing, and the agency therefore has an inherent interest in having at its disposal high-quality objective methodologies and tools for evaluating proposed systems and sensors. One might reasonably argue that the agency should not fund and fly any new mission that has not proved its merit through an OSSE or equivalent assessment tool.

Even though NASA is the main development agency for civilian remote sensing from space, it is not the only federal agency with an interest in earth remote sensing. The group of key stakeholders includes organizations such as the National Oceanic and Atmospheric Administration, the Department for Homeland Security, the US Geological Survey, the Department of Energy as well as groups involved in non-classified missions for the Department of Defense.

NOAA/NESDIS in particular operates the civilian operational meteorological satellites in the US, and together with DoD be responsible for the next-generation National Polar-orbiting Operational Environmental Satellite System, NPOESS.

It is therefore in the best interest of NASA and NOAA to collaborate not only on data from past and current missions but also on developing and using the right processes and tools for making informed decisions on future missions.
With a "small" research satellite mission costing on the order of $300M and a major operational satellite program running closer to $10B, it is not surprising that many individuals and organizations have vested interests both in the actual outcome of the decision-making process and in the tools that are used to support it. The scientific merit of the system is only one of the concerns that need to be addressed, there are often important technical, political and financial issues to take into consideration as well.

Because of the high stakes involved, it is of critical importance that the assessment tools on which these decisions are based be decoupled from advocacy groups or organizations developing specific missions or systems to as large an extent as possible. An OSSE capability that is wholly owned and operated by one institution – e.g. a NASA field center or a NOAA Lab – with a vested interest in mission opportunities would necessarily be viewed with suspicion by parts of the community, irrespective of the quality of the work it might produce. It should be recognized that with a limited pool of relevant scientific and technical expertise available, it is not always possible to maintain absolute firewalls between mission development and mission assessment. Precisely for this reason it is important to build a high degree of community oversight and community ownership into such a capability.

This fact is well recognized in the NWP area, and over the course of the last few years, an informal "Joint OSSE" working group involving groups from Goddard, NOAA/NCEP, NOAA/NESDIS, NOAA/ESRL and DoD has taken shape. The Joint OSSE work is being coordinated through the Joint Center for Satellite Data Assimilation with the intent of sharing many of the tasks involved in building a state of the art national OSSE capability for weather-related systems. The primary aims of the working group are:

- To collaborate on commissioning, evaluating and calibrating an OSSE nature run intended to serve as a basis for all OSSE efforts carried out by the members of the group over the next several years
- To coordinate and share the work involved in simulating the entire reference observing system, including biases and error covariances
- To define a set of "best practices" for designing, calibrating, executing and evaluating OSSEs
- To maintain a joint OSSE capability using (at least) two distinct major global data assimilation systems in order to estimate robustness of results.

At the present time (July 2008), the Joint OSSE group has no formal status, no official mandate and no dedicated funding stream. Its primary support comes from individuals and their line managers in the participating organizations, but additional support in terms of dedicated funds to study the impact of specific observing systems is becoming available shortly. It is the hope that as the work of the group matures and its visibility increases, this situation will change and that the respective agencies will adopt the group and eventually constitute a proper steering group with a clear mandate and clearly defined responsibilities vis-a-vis the broader community.

The current status of the work is that a nature run has been commissioned and validated and the simulation of the first complete set of observations for calibration runs is expected to be completed by late summer 2008. The nature run has been contributed to the effort by ECMWF, and the use of this run is consistent with the notion of taking as “nature” output from a high quality model that is unrelated to the model(s) subsequently used in the assimilation experiments. The requirements for the nature run were set by the Joint OSSE group and ECMWF in collaboration, and they went through several iterations involving all partners before being finalized. As a result a 13-month long run at a horizontal resolution of T-511 with complete data dumps every 3 hours was executed. Embedded in the 13-month run are two separate runs at a higher horizontal resolution of T-799 for five weeks each, both with data dumps every hour. The simulation periods of the high-resolution runs were chosen to include the peaks in severe weather over the US during the spring season and in the Atlantic hurricane season, respectively.

An extensive validation of several aspects of the nature run is currently being carried, and some of this work has already been published (Reale et al., 2007). Once the calibration experiments are completed, hopefully toward the end of 2008, the first actual OSSEs can be undertaken. Among the many proposed future systems waiting to be assessed through OSSEs, some of the likely candidates for the first experiments are:

- GPS Radio Occultation – how many satellites are needed and in what orbit?
- Hyperspectral IR sounding from GEO – what is the value for NWP?
- Microwave sounding from GEO – what is the value for NWP?
- Wind Lidar – optimal instrument configuration and data acquisition

Toward an international OSSE collaboration

In the previous section, the emerging Joint OSSE capability in the US was briefly described. However, it should be pointed out that certain aspects of this work are well suited for an even broader, international collaboration. The observational problem of numerical weather prediction transcends national borders, as do many observing systems – including essentially all space-based observing systems. NOAA/NESDIS and EUMETSAT are collaborating on operational meteorological satellite observations from their respective polar orbiters through the Initial Joint Polar System, and NASA and ESA are making attempts to improve the coordination between their respective research satellite programs. All of these agencies – as well as their counterparts in other countries – share the need for objective assessment and assessment tools to study the impact of proposed future missions and systems. Given the cost of setting up and tuning an OSSE system, it is therefore reasonable to explore whether at least some of this burden could be shared internationally.

Some aspects of the existing Joint OSSE collaboration are already now being developed in international partnership. As noted in the previous section, the nature run was contributed by ECMWF. Also KNMI is actively involved in the Joint OSSE group, mainly though discussions on how to simulate observations from future space-borne Doppler Wind Lidar systems, a type of observations that is drawing increased interest on both sides of the Atlantic. In terms of future plans for a more formal international collaboration, discussions are ongoing with both ESA and EUMETSAT about funding European groups to become more closely involved in the OSSE and to study observing systems that are of particular interest to those agencies.

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Impact experiments using the Met Office global and regional models

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Space-terrestrial link (Richard Dumelow)

An Observing System Experiment was carried out to investigate the impact of conventional observations on NWP forecasts. The experiment was run over two-month periods in both winter and summer. The impact was measured by adding in conventional observations to a baseline network comprising all satellite data plus data from the land stations from the GCOS network and all buoy data. The observations added to baseline were radiosonde temperature and wind observations, radiosonde wind observations only, and aircraft temperature and wind observations. The experiment used the Met Office global and limited area (NAE) models run in a configuration that was operational at the time of the experiment. For each experimental run the boundary conditions for the NAE model were taken from the corresponding global run. Global model forecasts were verified against the analyses from the ‘all data’ run and the NAE forecasts against European radiosondes.

Using the baseline network only results in degradation of forecast quality in the northern hemisphere and Europe of between 5 and 30% depending on level and time range compared to the run using all observations. Most of the differences in the objective verification scores are statistically significant at the 90% level (Figure1). In addition to a significant reduction in the mean skill, running forecasts using the baseline network of observations only is likely to increase the probability of very poor forecasts. Much smaller differences in the quality of forecasts produced from the baseline and full system are seen in the tropics and southern hemisphere where there are less conventional observations.

For the global model forecasts, the most effective way of recovering forecast skill is to add radiosonde wind and temperature observations to the baseline. Next most effective method is to add in radiosonde wind observations only and the least effective method is to add in aircraft temperature and wind measurements (Figure 2). Adding in radiosonde data to the baseline is thought to be the most effective strategy since these observations add profile information over a wide geographical area and frequently in time.

For NAE model forecasts verified against European radiosondes the results are more variable most probably due to the smaller geographical area (sample size) used when calculating the statistics. For the winter period, there is no statistically significant difference in the objective verification scores for the observation use scenarios that add observations to the baseline. For the summer period, adding in aircraft observations appears to be the best strategy for improving on the skill of forecasts using the baseline network only and gives a similar result to using all observations.

For both global and NAE models and for winter and summer periods, none of the observation networks tested completely recover the forecast skill obtained when using all observations in the GOS.

The results obtained by an OSE such as this are influenced by the NWP system used as well as observation usage. In particular it should be noted that 3D-Var was used in the NAE model and thus the results for the NAE model might have been different if 4D-Var was used. For example, a notable advantage of 4D-Var over 3D-Var is its greater ability at using information from sparse observation networks. A comparison of verification results from the global and NAE model forecasts verified against European radiosondes indicates that the two sets of runs do not always give similar results over Europe.

The general conclusion from this study is that the conventional observation network still adds value to the quality of NWP forecasts and any re-design of it must include a comprehensive coverage of conventional profile observations (Dumelow, 2008).

Global data denial experiment (Richard Dumelow)

An Observing System Experiment was run in which whole observing systems were excluded from assimilation. The experiment included the following runs:

1. All data
2. All data – all satellite
3. All data – all radiosonde
4. All data – all aircraft
5. All data – all surface
6. All data – all conventional (satellite only)
7. All data – European wind profilers

The Met Office NWP system, which uses 4D-Var, was run at full operational resolution using observations from the one month period from 24th May to 24th June. Forecasts up to 6 days were run from 12UTC and standard fields were verified against observations and the ‘All data’ run analysis. Initial analysis of the results confirms that satellite is the predominant data source in the southern hemisphere and the most important for height forecasts in the northern hemisphere. However, using satellite data only significantly degrades forecast skill in the northern hemisphere (Figure 3).

Targeting Experiments (Keir Bovis, Gareth Dow, Richard Dumelow)

Comparison of upstream, downstream and verification region targeting

An Observing System Experiment (OSE) was run to investigate the impact of radiosonde observations on the Met Office operational CAMM model forecasts. The area over which impact was assessed was chosen to be North America where there is a widespread network of radiosonde observations and surface observations. Runs were made in which additional radiosonde observations were assimilated by the Met Office NWP system on top of a baseline network of observations comprising a sparse network of radiosonde and surface reports plus all satellite observations. The quality of the forecasts was measured through standard verification scores over a fixed verification region.

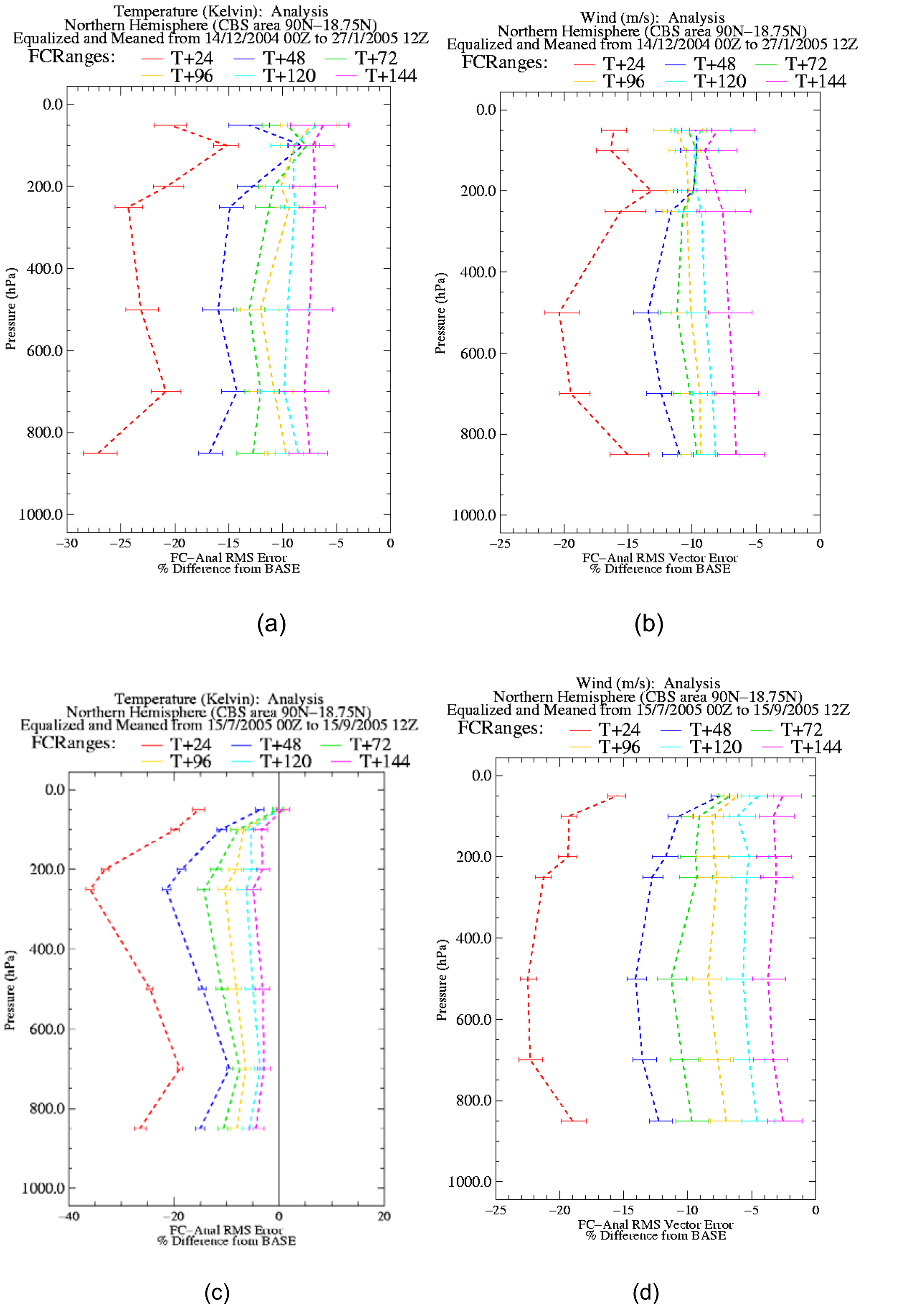


Figure 1. Differences in normalised RMS forecast error with pressure between the BASE and COMB runs for the global model. Errors calculated against the COMB analysis, normalised by BASE run values and averaged over the northern hemisphere. (a) temperature for winter; (b) vector wind for winter; (c) temperature for summer; (d) vector wind for summer. Error bars give statistical significance at the 90% level.

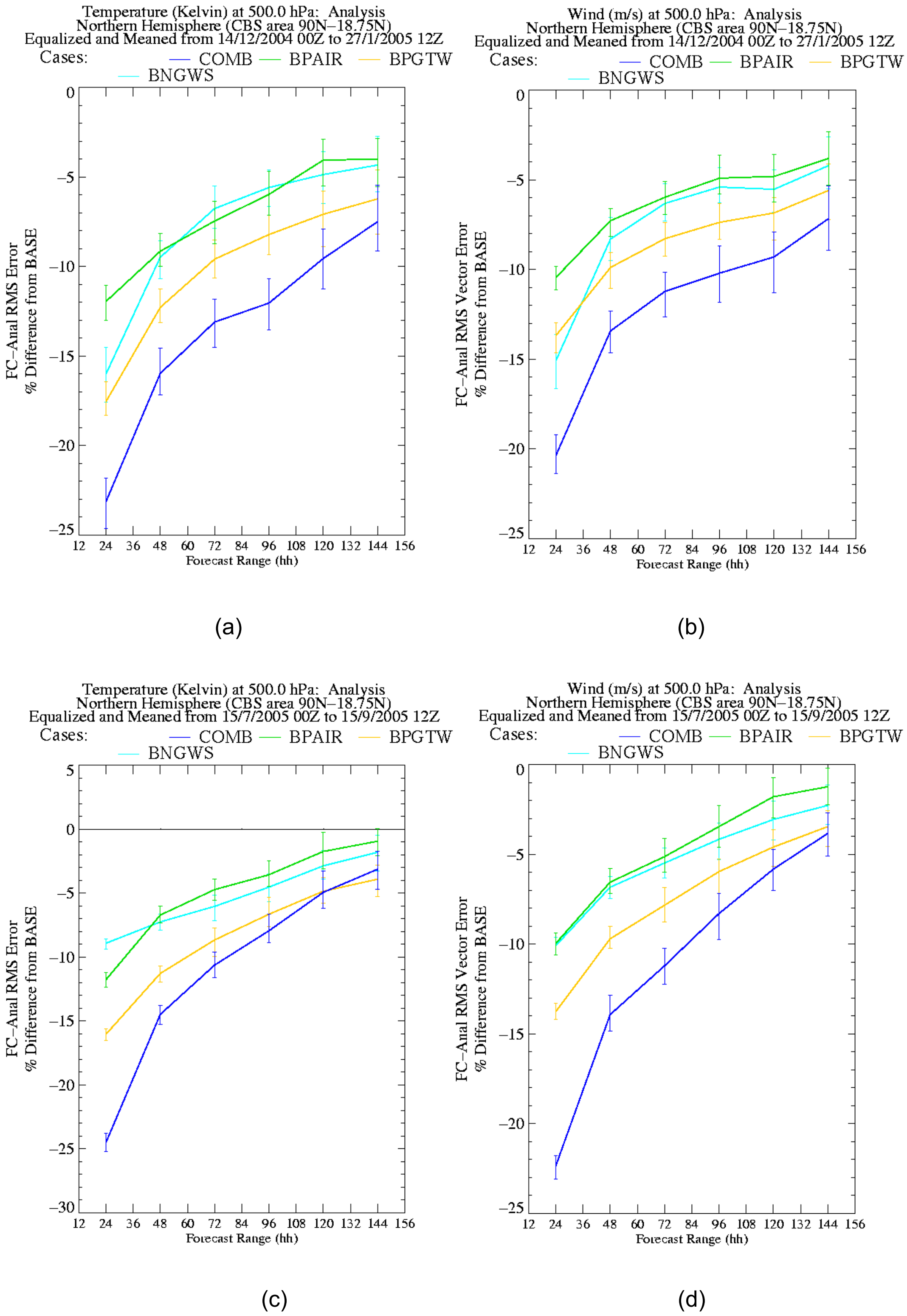


Figure 2. Differences in normalised RMS forecast error at 500hPa between the BASE and other runs for the global model. Errors calculated against the COMB analysis, normalised by BASE run values and averaged over the northern hemisphere. (a) temperature for winter; (b) vector wind for winter; (c) temperature for summer; (d) vector wind for summer. Error bars give statistical significance at the 90% level.

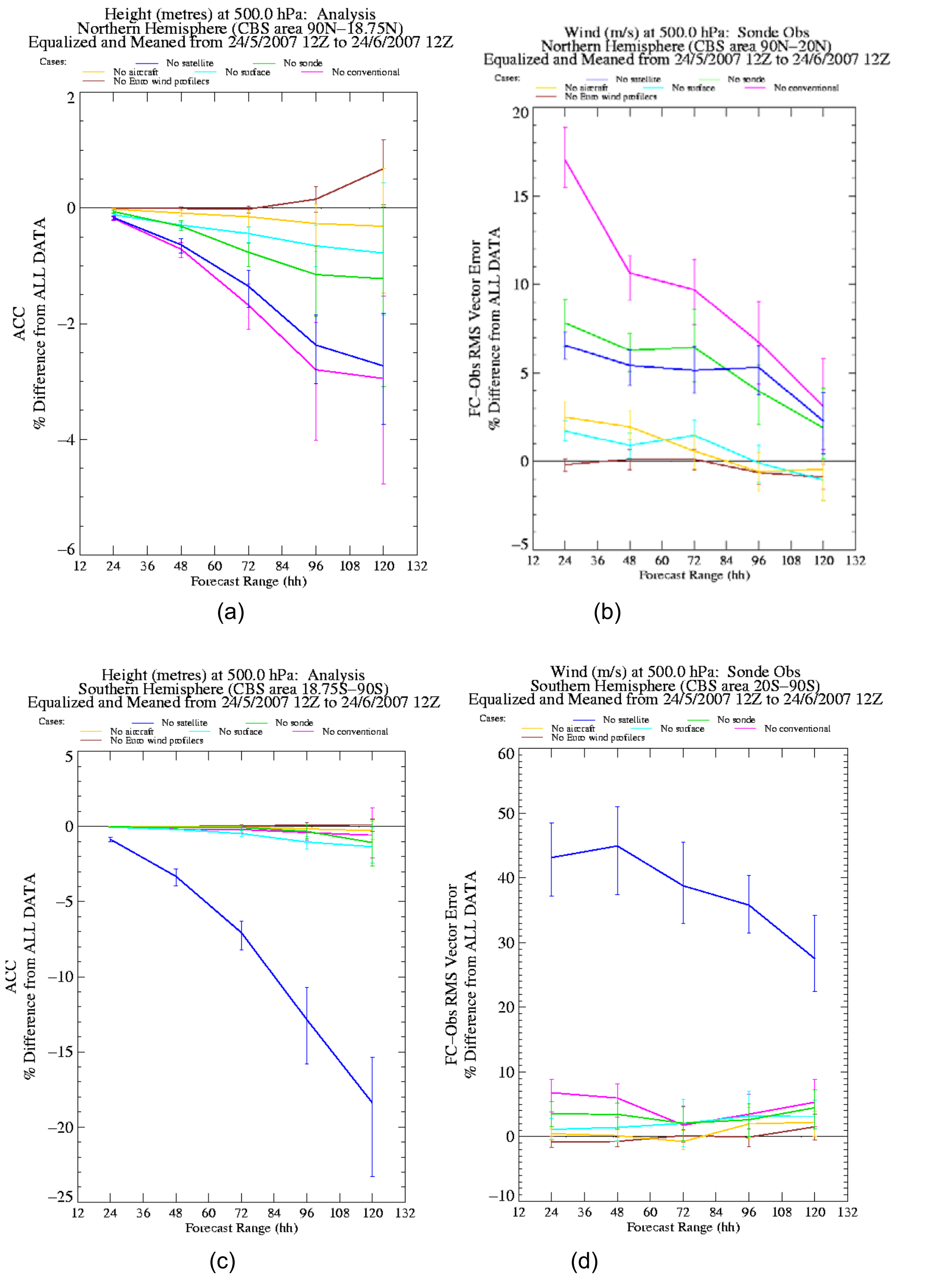


Figure 3. Differences in normalised RMS forecast error at 500hPa between the ALL DATA and other runs for the global model. Errors calculated against the ALL DATA analysis for height and radiosonde observations for wind. Values normalised by ALL DATA run values and averaged over a hemisphere. Anomaly correlation coefficient for height (a) and RMS vector wind error (b) averaged over the northern hemisphere. (c), (d) corresponding values for the southern hemisphere. Error bars give statistical significance at the 90% level.

‘Upstream’ and ‘downstream’ areas were selected by looking at the 500hPa wind flow at 00UTC and 12UTC on each day of the experiment. For these times, observations were selected subjectively in ‘upstream’ and ‘downstream’ regions.

An example of the impact of these subjective targeting strategies is given in figure 4.

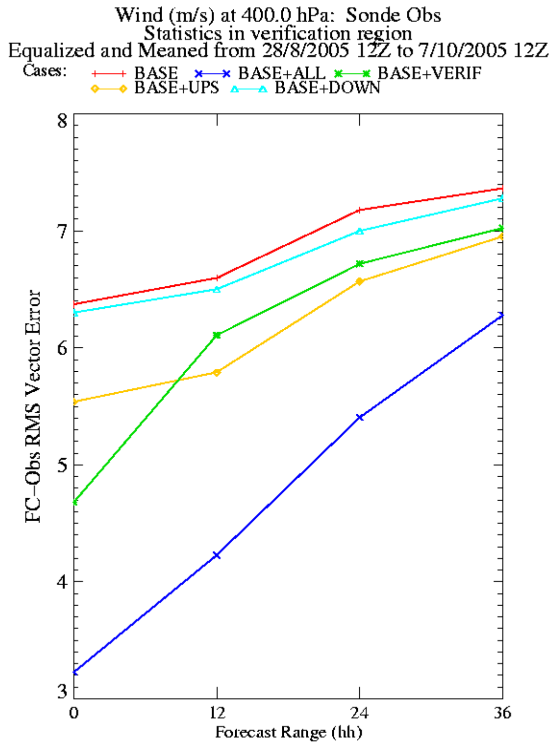


Figure 4. RMS vector wind error at 400hPa for forecast times up to 36 hours.

The overall conclusions of this study are as follows. Given the observational data coverage assumed to be in the baseline network, additional profile observations such as those obtained from radiosondes, are very important for the production of accurate NWP forecasts.

- Downstream deployment has positive benefit on NWP forecast accuracy but is the least effective strategy.
- Short-range NWP forecasts of up to 12 hours are likely to benefit most from local area deployment although upstream deployment also benefits short-range forecasts.
- For general NWP forecasts, upstream deployment is likely to be more effective at longer time scales (e.g. T+24) but the overall effectiveness of upstream deployment is likely to depend on deployment strategy.
- In-situ profile observations, such as those provided by radiosondes, can have a very positive impact on the forecasting of significant weather events.

Objective targeting using the Ensemble Transform Kalman Filter (ETKF)

The benefits of deploying a supplemental observational network to complement the routine have been well known by Met centres for some time. The previous results demonstrated that deployment of an additional network upstream of the verification region in areas subjectively identified by trained forecast staff leads a to smaller forecast error at the target forecast range. We now proceed to evaluate objective methods of targeting radiosonde observations motivated for the following reasons: i) subjective targeting requires valuable forecaster time; ii) subjective targeting takes no account of the routine network ; iii) identification of targeting areas is subject to much variability in the presence of many trained forecast staff.

In this study targeting regions or Sensitive Area Predictions (SAPs) are identified using the Met Office's implementation of the Ensemble Transform Kalman Filter (ETKF) (Bishop et. al., 2001). This seeks a deployment of additional observations in the presence of a routine network that will minimise the forecast error in a pre-defined verification region at a pre-defined forecast range.

Four OSEs corresponding to different targeting strategies were evaluated using the CAMM model described in the previous section. Two OSEs based on a subjective targeting strategy, base+ups and base+T36 identified targeting regions using a T+0 and T+36 500 hPa flow analysis respectively. These are compared with two objective targeting strategies, ETKF(24) and ETKF(48) where SAPs are generated using the ETKF with a 24 and 48 hour lead time respectively. Targeting in all cases aims to improve 36 hour forecasts.

The results in Figure 5 show that at the target forecast range of 36 hours each objective targeting strategy based on the ETKF SAPs matches or improves the RMS error obtained using a subjective approach. A more detailed account of this study can be found in Bovis et. al., 2008.

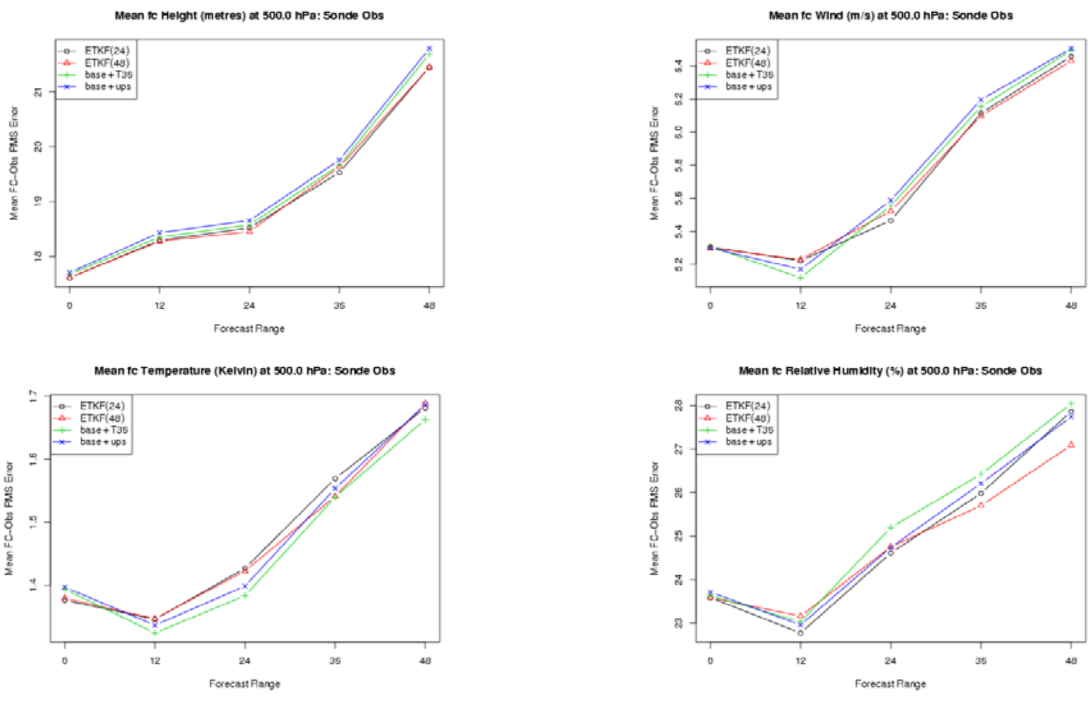


Figure 5. Mean forecast minus sonde observations verifying within the verification region over all forecast cycles at different forecast ranges.

The Greenland Flow Distortion Experiment (GFDex)

The developed Met Office targeting capability has recently been utilised operationally during the observation targeting component of the Greenland Flow Distortion experiment (GFDex) (Renfrew et al., 2008). An important aim of this campaign is to investigate Greenland's role in atmospheric flow predictability. One approach to quantify this is by deploying additional upstream observations and then investigating the sensitivity of the downstream flow to the detail of the upstream flow. Of primary importance is the impact on subsequent NWP forecasts over Europe.

During the three-week long campaign, guidance was provided for the deployment of dropsondes from the FAAM aircraft for two verification regions at different target forecast ranges and lead times. The Met Office and ECMWF supplied SAPs using the ETKF initialised from the 15 day Met Office ensemble and a singular vector method respectively. The resulting impact realised 24 and 48 hours after deployment by operational NWP forecasts is quantified by running a series of OSEs.

Headline verification of operational forecasts compared with OSEs without targeted observations show mixed improvements in the first verification region over Northern Europe but a positive impact in the second over Scandinavia.

Improved use of *in situ* surface data (Bruce Ingleby)

Until recently the global forecasting system at the Met Office (in common with most other global NWP systems) only assimilated pressure data from land surface stations (SYNOPs); pressure and wind information was assimilated from ships and moored buoys. From 1 April 2008 the global system has been assimilating pressure, temperature, humidity and wind from most land and marine stations (pressure only from drifting buoys). The changes bring the global and regional NWP systems much closer in terms of surface data usage and forecast performance for surface variables. Improvements to model resolution and the modelling of (near-) surface conditions have provided a necessary foundation for this advance. An extensive series of 3D-Var trials were performed before final 4D-Var testing. It was found necessary to exclude SYNOP winds from islands and headlands not resolved in the forecast model. All tropical SYNOP winds are also excluded, they are generally weaker than the forecast winds – both model and observation error may be involved.

Other details of the changes included: a 6-hour extraction window for SYNOPs (previously 3-hours for historical reasons), height adjustment for humidity and wind speed (Ingleby, 2008, in preparation) and use of soil temperature nudging. Further changes planned for 2008 include: updated metadata for some stations, improved pressure and humidity processing, improved height adjustment of ship winds and processing of mobile SYNOP data.

Trials

Initial testing was performed for June 2006 using 3D-Var at N216 resolution and only one SYNOP report per six-hour window. Assimilation of SYNOP temperature and humidity (T/RH) gave a clear improvement, use of SYNOP winds was found to be more problematic – resulting in the exclusion of island and tropical winds mentioned above. Initially T/RH/wind were used if the station height and model height were within 200m – later changed to 500m (modified slightly at night) with a modest improvement. Use of hourly SYNOPs (where available) gave neutral results in 3D-Var. Based on monitoring results some stations are rejected, either for selected variables or in total. There was marked sensitivity to this “rejection-list” and the criteria were tightened for wind. Overall, the 3D-Var improvement for June 2006 was about 1 point on the Met Office NWP Index, measured either against observations or analyses with improvements particularly marked in the northern hemisphere at short range (Figure 6). Disappointingly, 3D-Var trials for December 2006 gave a neutral impact in the northern hemisphere and a negative impact in the southern hemisphere. In both June and December use of island T/RH gave a modest benefit. This was the motivation for introducing use of ship/buoy T/RH which gave a neutral impact.

The surface assimilation changes were combined with improvements to soil properties and minor changes to radiosonde RH processing and GPSRO selection in the “PS18” package. This underwent 4D-Var trials for June 2007 and March 2008, both showed an overall improvement. The June 2007 trials showed some improvement from the use of hourly SYNOP data (Figure 7): as expected 4D-Var can make better use of asynoptic data than 3D-Var. Forecasts of screen variables were improved due to both the assimilation of in situ surface data and the improved soil properties. For screen temperature and humidity there was generally a 6-12 hour improvement in prediction skill; at longer range this mainly comes from the improved soil properties.

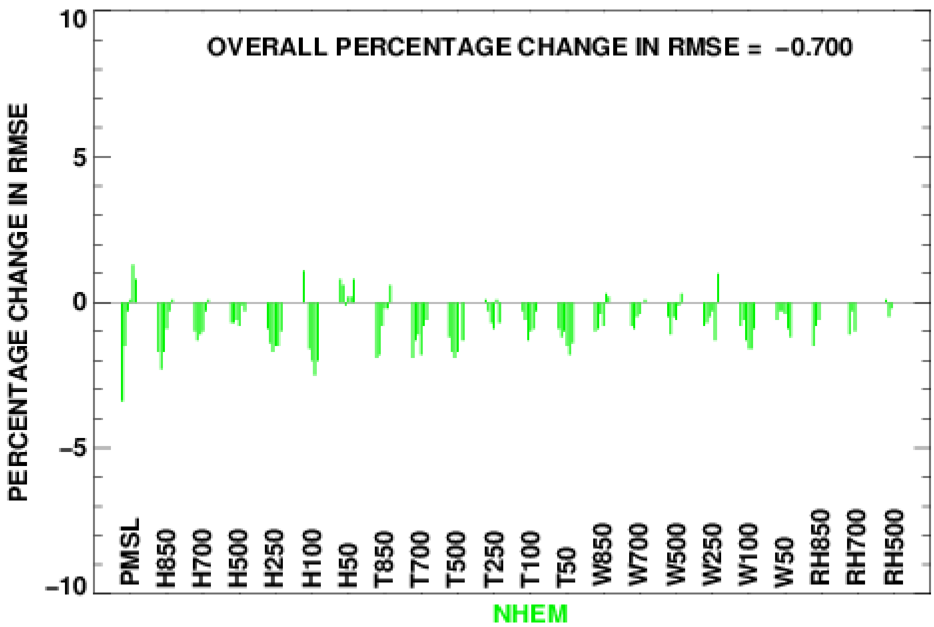


Figure 6. Percentage change in northern hemisphere RMS measured against observations for June 2006 3D-Var trial assimilating screen T/RH/wind as described in the text. Both control and trial only used one Synop from each station per six-hour window. The bars for each variable are for 24, 48, 72, 96, 120 and 144 hour forecasts. Thus Pmsl is improved by over 3% at T+24, but slightly worse at long range. It is notable that variables at all levels of the atmosphere are improved. Results for the southern hemisphere are more mixed whilst the tropics are generally improved (not shown).

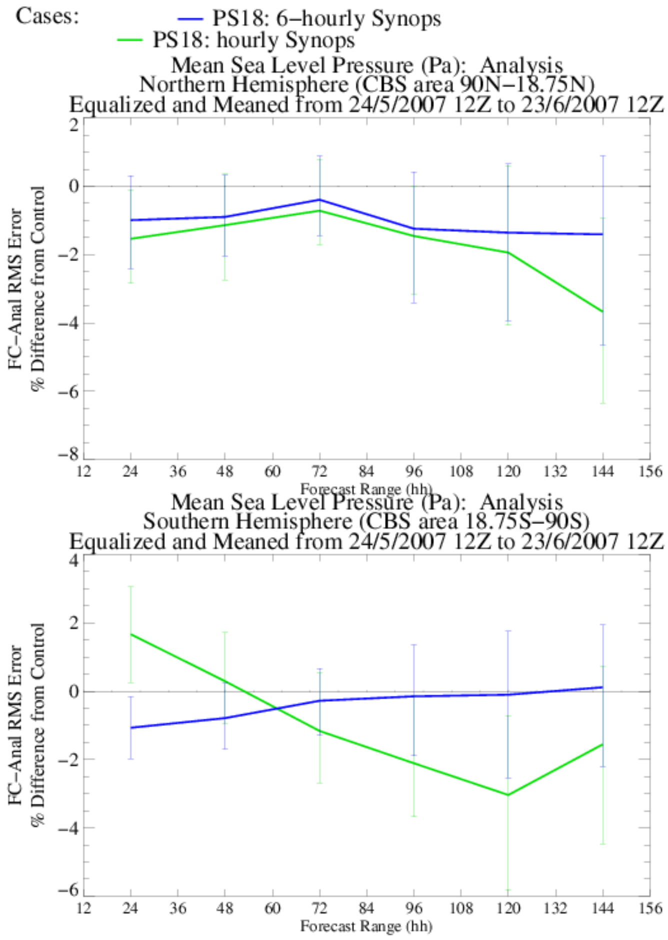
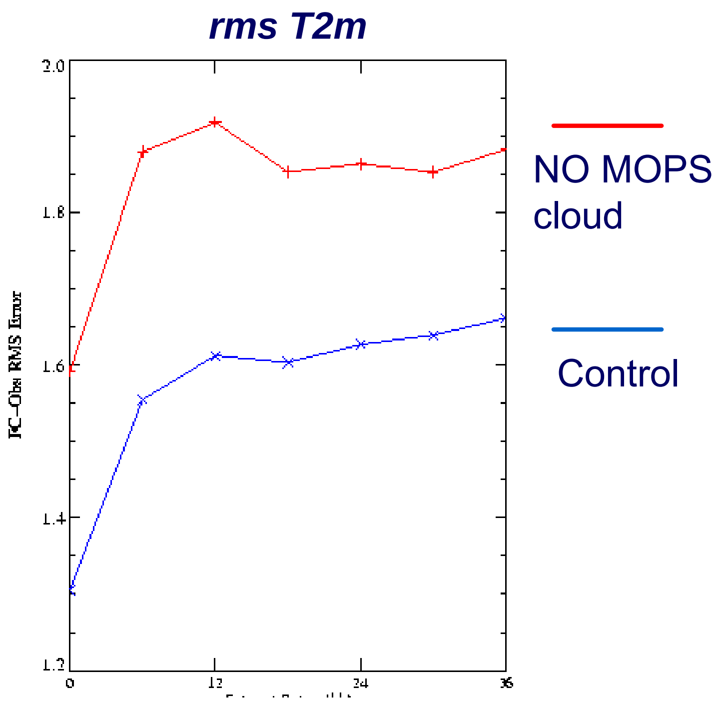


Figure 7. Northern hemisphere (top) and southern hemisphere (bottom) differences in RMS for Pmsl measured against analyses for June 2007 4D-Var trials: PS18 package as described in the text. Option 1 (blue line) only used one Synop from each station per six-hour window, option 2 (green line) used hourly Synop data where available. Use of hourly Synop data appears beneficial except at short-range in the southern hemisphere (the larger RMS there is probably an artefact from larger analysis increments), against observations the impact of hourly Synops was largely neutral.

Observation impact experiments in the regional models (Bruce MacPherson)

The UK Met Office assimilates VAD wind profiles from weather radars into its global and regional (North Atlantic & European) models. Information on which data are assimilated is available at:
http://www.metoffice.gov.uk/corporate/interproj/cwinde/wradar/index.html
In a 3-week observation impact study run in autumn 2006, a parallel assimilation cycle was run without VAD winds in the North Atlantic and European Model. Results showed a slight benefit of VAD winds in reducing mean sea-level pressure errors, and the difference was judged to be statistically significant.

The UK Met Office assimilates a 3-dimensional cloud fraction analysis into its regional models. The cloud data are prepared by the Moisture Observation Processing System (MOPS) from satellite cloud top information and surface cloud cover reports. MOPS data can be very beneficial for improving cloud and temperature forecasts in stratocumulus episodes. Results for such a week in February 2006 are shown in the figure below, where MOPS data lower the rms screen temperature errors by around 15%.



The Met Office regional models also assimilate observations of screen-level visibility. Within the variational analysis, these give rise to increments in aerosol content, humidity and temperature. An impact experiment was run for 16 days in March 2005 with visibility observations withdrawn and the signal was assessed with reference to the Equitable Threat Score (ETS) for visibility at thresholds of 200m, 1000m, and 5000m. At the 200m threshold, visibility assimilation gave benefit for 12-18 hours, while at the 5km threshold, benefit was detected up to 36 hours into the forecast.

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Impact study with observations assimilated over North America and the North Pacific Ocean at MSC

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Environment Canada

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ABSTRACT

A series of observing system experiments for the two-month period of January-February 2007 have been carried out to assess the impact of radiosonde and aircraft data available over North America, as well as the impact of satellite data available over the North Pacific Ocean. The impact of these subcomponents of the global observing system on the accuracy of forecasts over the North American continent is not uniform. The quality of the forecasts over the Canadian Arctic heavily relies on the radiosonde network. The primary source of forecast improvements over the western United States and Canada is provided by the North Pacific satellite data. Over the eastern part of the North American continent, the radiosonde and aircraft data are the main contributors to the forecast skill at short forecast ranges. The effect of the weather regime that prevailed during the evaluation period is discussed, as well as the robustness of the conclusions drawn with respect to the analysis scheme (3D-Var vs 4D-Var) used and to the horizontal resolution of the forecast model selected. It is found that the results are closer to each other when changing the horizontal resolution of the forecast model than they are when changing the analysis scheme.

1. Introduction

With the increasing volume of satellite observations available for operational Numerical Weather Prediction (NWP) systems and the advances in data assimilation, it is relevant to periodically evaluate the value of both conventional and satellite data and their role in the short to medium range forecasts. It is also important to examine the impact of the conventional observing network to provide objective guidance for rationalization purposes and for a better use of these sources of data. The most accepted approach for such an investigation consists of Observing System Experiments (OSEs).

Many observation impact studies have been performed in several meteorological centers to assess the contribution of each data type to the improvement of numerical weather forecasts. The series of OSEs carried out at the European Centre for Medium-range Weather Forecasts (ECMWF) has demonstrated the increasing importance of satellite observations over the years (Kelly, 1997; Bouttier and Kelly 2001; Kelly et al., 2004; Kelly and Thépaut, 2007). They also showed that since the beginning of this century, the impact of satellite data in the Northern Hemisphere has become as important as the impact of in situ data, especially for longer forecast ranges. A recent study at NCEP confirmed this trend in their global data assimilation and forecast systems (Zapotocny 2007).

Most observation impact studies have been conducted using the same data assimilation scheme and forecast model configuration for all the experiments. One exception is the recent work by Kelly et al. (2007) in which the impact of excluding all data over the North Pacific using 3D-Var and 4D-Var analysis schemes are compared. One important conclusion of this work is that 4D-Var is more effective to propagate information from data-rich to data-poor regions, which means that 4D-Var is more robust to the problems caused by data gaps than is 3D-Var. Such a change in the analysis behavior may have an effect on the relative value of the various observing networks. Other components of the data assimilation and forecast systems may also have an indirect effect on the impact results, such as the horizontal resolution of the forecast model, the bias correction scheme and background error statistics.

At the Meteorological Service of Canada (MSC), we have recently conducted OSEs to assess the relative value of radiosonde and aircraft data over North America, as well as the impact of satellite observations over the North Pacific Ocean, on the short to medium range MSC forecasts. Most experiments were run with a lower (100 km) resolution version of the operational global forecast model. We paid particular attention to the propagation of the impact and to the role that the weather regime may play. Several data denial experiments were conducted with both 3D-Var and 4D-Var schemes to assess the sensitivity of the results to the choice of the analysis method. In order to verify if the conclusions obtained at lower resolution are similar to those from the operational high resolution (33 km) model, we also ran a few experiments at high resolution. This later exercise is of interest to confirm whether results from previous OSEs conducted with former lower-resolution models are still valid, given that higher resolution models are now in use.

Usually, OSEs are performed over extended periods during winter and summer seasons. Although the impact in the warm and cold seasons can be different for some data types, especially those related to humidity and precipitation, the relative impact of most observation types on the forecast skill is generally the same in both seasons. The magnitude of the impacts is however greater in the boreal winter season in the troposphere (Zapotocny, 2007 Thépaut and Kelly, 2007). For these reasons, our study focuses only on one winter season (i.e. January and February 2007).

2. Methodology

2.1 Experimental design

All the OSEs presented in this study were carried out with the MSC operational variational data assimilation and global forecast systems (Gauthier et al., 2006; Laroche et al. 2006; Bélair et al. 2005). The data assimilation system includes 4D-Var and 3D-Var analysis schemes. The horizontal resolution of the analysis increment in the inner loop is T108. A summary of the observations assimilated during the winter 2006-2007 is given in Table 1. The same set of observations is assimilated in both analysis schemes. Since the background check and the variational quality control are activated in each experiment, the number of observations may slightly differ from one experiment to another. The MSC global forecast system was designed to fully use the computational resources available. The current horizontal resolution of the global model is 33 km over central North America. As a result, it would be computationally prohibitive to carry out all the experiments presented in this study with the high-resolution model version. This is the reason why most of the experiments were run at a lower 100 km resolution, which corresponds to the resolution of the previous operational model version in use before October 2006.

The main features and nomenclature of the experiments presented in this study are summarized in Table 2. The first four experiments were run with the 4D-Var scheme (4D) and the 100 km resolution forecast model (LO). In the first experiment (RA), radiosonde (TEMP, PILOT and dropsondes) and wind profiler data are denied over North America (NA). Although the radiosonde stations and the NOAA wind profilers are distinct networks, we grouped them because the value of the wind profiler network in the MSC forecast systems have recently been evaluated (St-James and Laroche, 2005). It was shown that wind profilers, mainly located in the central United States, provide only a slight improvement. In the next two OSEs, aircraft data are denied over North America. All aircraft reports are removed in the second experiment (AI) while in third experiment (AD) only those below 350 hPa are denied. The 350 hPa level is a good choice to discriminate data at flight levels from those in ascent and descent (AD) observing phases (Cardinali et al., 2002). These two experiments will thus enable us to assess the relative value of aircraft measurement profiles located over major airports in North America. In the fourth OSE, all satellite observations over the North Pacific Ocean, including ATOVS, GOES imager radiances and AMVs, are omitted. This experiment was designed to assess the current value of upstream satellite observations in comparison with in situ data over North America.

The sensitivity of two aspects of the data assimilation and forecast systems was examined: the analysis scheme (3D-Var (3D) vs 4D-Var (4D)) and the horizontal resolution of the forecast model (100 km (LO) vs 33 km (HI)). The impact of the worldwide (WD) radiosonde network on forecasts over North America is also assessed.

Since all the data assimilation cycles were started from the same operational analysis, they were initiated 11 days before the 2-month verification period (i.e. 1 January to 28 February 2007). This 11 days warm-up phase is a minimum period to erase memory of the first and common analysis, making the results of the various OSEs independent (Fisher, 2005).

2.2 Verification method

All the verifications shown in this study were made against analyses from the latest upgrade of the MSC data assimilation scheme that was operationally implemented in 2008. In addition to the observations assimilated in the control runs (Table 1), AIRS, SSM/I (clear sky radiances) and QuikScat data are now assimilated. Moreover, the number of ATOVS and AMVs observations assimilated was increased in the new system. These verifying analyses are thus of better quality over the oceans and are independent of all the experiments presented in this study.

The choice of impact diagnostics depends on weather elements and features that are investigated. We decided to show a limited number of scores because of the numerous experiments carried out. Since this study focuses on a particular winter season over North America, where synoptic-scale weather systems are dominant, the root-mean-square forecast error (RMSE) of 500-hPa geopotential height (Z500) and 250-hPa zonal wind speed (U250) are used to assess the impact of the various data denial experiments.

Another useful diagnostic score is the Forecast Impact (FI) proposed by Zapotochy et al. (2002), which is the normalized RMSE difference between the data-denial and control experiments over a region of interest. This can be interpreted as the improvement in percent when the denied data set is assimilated.

Even though the experiments are run over a 2-month period (118 forecasts), the forecast impact patterns are difficult to follow beyond day 3. Also irrelevant error patterns grow in time, hiding the impact at longer forecast ranges as will be shown in the 72h-verifications. Consequently, only the results for the first 3 days are presented in this study. For these forecast ranges, we verified that most differences in the results are statistically significant so that confidence intervals are not plotted in the various figures for clarity.

Fig. 1 shows the RMSE of the control experiments against reference analyses for Z500 over North America in January and February 2007. Also shown is the RMSE from the latest upgrade of the global analysis-forecast system (in black). This comparison provides an objective evaluation of the advances introduced into the MSC data assimilation and forecast systems over the recent years. Both the 4D-Var analysis procedure and the increase in horizontal resolution of the forecast model significantly improved the forecast skill. The impact of the last set of observations recently implemented at MSC (i.e. AIRS, QuikScat, SSM/I) is also noticeable. Overall, the improvement between forecasts from the high-resolution 4D-Var (CT.4D.HI) and the low-resolution 3D-Var (CT.3D.LO) experiments is nearly constant at 16% from 24h to 72h. Moreover, the predictability gain at day 3 is nearly 12h between the latest upgrade and the low-resolution 3D-Var experiment. It is therefore important to assess how the changes made in the data assimilation and forecast systems affect the results and conclusions drawn from OSEs performed with a single system.

3. Impact of the observing systems on forecast error over North America

Figs. 2 to 4 show the propagation (from 0h to 72h forecast every 24h) of Z500 impacts for the RA.NA.4D.LO, AI.NA.4D.LO and ST.PA.4D.LO experiments respectively. The impact shown is the average RMSE differences over the two-month period between data-denial and control experiments. A positive RMSE difference in the Z500 means that the data set improves the forecast. It is important to note that the color scales are not the same for the 3 experiments (i.e. between -0.5 to 0.5 dam for AI.NA.4D.LO, -1.0 to 1.0 dam for RA.NA.4D.LO and -1.5 to 1.5 dam for ST.PA.4D.LO). This facilitates tracking the impact patterns. At the initial forecast time (Figs. 2a, 3a and 4a), the impacts of each data type are quite complementary, the most detrimental impact of removing radiosonde data is located over northern Canada, while it is located over the northeast United States and over the Canadian prairies for the aircraft data and over the whole North Pacific Ocean for the satellite data. The relatively weak impact of the radiosonde network over the United States is explained by its collocation with profiling aircraft data.

Essentially, the initial impacts move with the large-scale westerly circulation, especially for the satellite and aircraft denial experiments. The propagation of the impact for the RA.NA.4D.LO experiment is more difficult to follow, since it is located near the upper trough over northern Québec. Thus the main impact tends to remain quasi-stationary nearby this trough. However, errors due to the removal of radiosonde data over the United States grow in time and propagate over the northeastern United States at 48h and over the Atlantic Ocean at 72h (see Fig. 2c-d). For the AI.NA.4D.LO experiment, the impact over the Canadian Prairies moves over the Great Lakes by 24h and then over the Atlantic Ocean. The impact over the northeastern United States moves rapidly over the Atlantic Ocean and reaches Europe after day 2. Part of the forecast error induced by removing the aircraft data is wrapping around the upper through, leading to a large detrimental impact over the Hudson Bay by 72h. Noteworthy at 72h and beyond (not shown), the impact patterns from the omitted data are mixed with other sources of differences between the data-denial experiment and corresponding control. These differences grow in time as seen in Figs. 3b-3d over the Pacific Ocean. This is partly due to the limited number of samples (118 forecasts) in the calculation of the RMSEs, which should be increased for longer forecast range.

The evolution of impact for the ST.PA.4D.LO experiment for U250 is shown in Fig. 5. At the initial forecast time, the impact over the North Pacific Ocean is divided in two distinct areas: north and south of the air corridor between Hawaii and California. The aircraft data over the Pacific Ocean were assimilated in this experiment, which explains why the initial impact is very small in this corridor. Interestingly, most of the impact that spreads over the continental United States at this level (i.e. 250 hPa) is coming from the southern part of the North Pacific Ocean, as shown in Figs. 5b and 5c.

Fig. 6 shows the Z500 FI over parts of North America and over the North Atlantic Ocean for the three data-denial experiments examined so far. Also shown is the impact when only ascent/descent aircraft reports are removed over North America (i.e. AD.NA.4D.LO experiment). For short-range forecasts, the impact of radiosonde data over Canada is important, being greater than 30% over the Canadian Arctic region. The impact of radiosonde data decreases rapidly in time but remains significant in the medium-range over Canada. The greatest impact of ST.PA.4D.LO experiment is over the continental United States, peaking at 48h. The impact from satellite data over North Pacific Ocean is more important than from radiosonde and aircraft data over the whole United States. The short-term impact of aircraft data, for the same region, is two to three times larger than the impact of radiosonde data during day 1. However, the impact of aircraft data profiles from ascent/descent reports is smaller than when all the aircraft data are denied especially at short forecast ranges. The impact does not vanish as rapidly over eastern North America so that both AI and AD impacts are similar by 72h. The satellite data set over the North Pacific Ocean is the main source of improvement over the western part of the continent, especially in the short-range forecast, while it becomes the main source of improvement later in the medium-range over the eastern regions. Both radiosonde and aircraft data remain however the main source of improvement at 24h over Eastern North America and North Atlantic regions.

The FI for U250 are shown in Fig. 7. The results for this field are complementary to those for Z500. The eastward propagation of the impact from the denied satellite data over North Pacific can be seen in Fig. 7d, 7e and 7f. Radiosonde data are still the main source of improvement over the Canadian Arctic region but with weaker amplitudes. In contrast, the magnitude of the FI for the ST.PA.4D.LO experiment over the United States is enhanced. Also, the U250 forecast impact of aircraft data becomes greater than the one of radiosonde data, especially at shorter term over eastern North America (Fig. 7e).

Fig. 8 summarizes the impact on Z500 forecast at 24h and 72h for the experiments in which radiosonde data are omitted over North America (Fig. 8a and 8c) and over the globe (Fig. 8b and 8d). At 24h, the impact patterns are similar over the North American continent, which means that the short-range impact is largely dominated by the nearby observing system. Overall, the magnitude of the impact is a few percent greater and there are some visible areas of deterioration over both the Pacific and Atlantic Oceans when all radiosondes are omitted (Fig. 8b). This reflects the short-term contribution of the information carried by the background. At 72h, the impact of the missing radiosonde over Asia has already spread all over the Pacific Ocean and over western North America (Fig. 8d).

4. Sensitivity to the analysis scheme

Data assimilation systems in operational meteorological centers are continually improving and are becoming more effective in extracting information from observations distributed in space and time. One important difference between 3D-Var and 4D-Var schemes is the use of the tangent linear model and its adjoint in 4D-Var to propagate the information over the assimilation window, leading to a better fit of the innovation vector.

The experiments presented in section 3 were repeated but using the 3D-Var scheme, except for experiment AD.NA.4D.LO. Fig. 9 shows the forecast impact score (FI) for both 3D-Var and 4D-Var experiments over the Canadian Arctic, Canada and the United States. Overall, the results for 3D-Var experiments are in good agreement with those for 4D-Var, especially over Canada. The main differences between 3D-Var and 4D-Var results are the following: for the short forecast ranges, the impact of radiosonde data is 10 to 15 % greater over the Canadian Arctic; the impact of North Pacific satellite data is 5 to 10 % greater over Canada, but 5 to 10% smaller over the United States up to 48h. Thus, the impacts with 3D-Var are not systematically larger than those with 4D-Var. We found that the initial impact over the southwestern part of the North Pacific Ocean (Fig. 4a for Z500 and Fig. 5a for U250) is more important when using the 4D-Var scheme. However, we verified that the RMSEs for 4D-Var experiments with and without satellite data over the North Pacific Ocean remain smaller than those for 3D-Var experiments over both Canada and the United States.

A data assimilation cycle is a continuous process in which a background field and current observations are optimally blended to produce an analysis from which a short-range forecast is run to serve as background field to the next analysis cycle. Hence, useful information from past observations is carried foreword through the background field. Fisher (2005) showed that memory of past observations can persist up to 10 days in the ECMWF data assimilation system. This means that all radiosonde data outside North America may contribute to the forecast skill over North America by the advection of information from the global observing network in the mean circulation.

A comparison of FI obtained with both 3D-Var and 4D-Var schemes when radiosonde data are omitted over North America and over the world, is depicted in Fig. 10. Over the Canadian Arctic, the impact is much greater in the 3D-Var context and it is more than 30% higher at very short forecast range when all radiosonde data are denied compared to when only North America data are denied. Therefore, the impact of the radiosonde network over the Arctic as well as over the world is more important in 3D-Var than in 4D-Var. This is explained by the fact that the acquisition time of radiosonde data is at the center (synoptic time) of the 6-h assimilation time window. The 3D-Var scheme does not take into account the acquisition time of the observation in the analysis process, which introduces representativeness errors for asynoptic data. 4D-Var relaxes the stationarity assumption implicit in 3D-Var, which means that the asynoptic data are better assimilated and thus limit the detrimental impact of removing data that are located to the center of the assimilation time window. Consequently, observations assimilated at the central time are the most beneficial (for a given data type) in the 3D-Var context and this would enhance the forecast error when they are omitted. This effect is even more important when radiosonde data are globally denied.

Kernel density estimates of Z500 24h RMSE over the North American regions for the 3D-Var and 4D-Var experiments are plotted in Fig. 11. The vertical dashed lines are the mean RMSE for each experiments displayed. With such graphs, it is possible to determine if the mean impact is either explained by a general day to day degradation, or by a few forecast busts, or both. The results for the Canadian Arctic are particularly relevant. For all experiments, the tail towards positive RMSE is longer than those for Canada and United States, which indicates that the frequency of forecast busts is higher in the Canadian Arctic when the radiosonde data are omitted. Moreover, the RMSE distribution for the 3D-Var experiment in which radiosonde data over the globe are denied is shifted towards higher values and is much broader than the corresponding 4D-Var experiment. Finally, the density estimates are much tighter and the means are smaller over the United States than over the northern regions.

5. Sensitivity to the horizontal resolution of the forecast model

To verify how the horizontal resolution may affect the results presented so far, two experiments (i.e. one 3D-Var and one 4D-Var) were performed with the high-resolution (33 km) operational model, along with their control runs. These experiments correspond to those at lower resolution (100 km) in which aircraft data over North America are denied. The impacts from these observations are generally smaller than those from satellite and radiosonde data. Hence, the removal of this dataset provides a more challenging test to verify if the impact results are sensitive to the model configuration.

The 24h Z500 impacts for the experiments without aircraft data over North America are presented in Fig.12. The two upper panels show the 4D-Var and 3D-Var results using the low-resolution forecast model, while the two lower panels show the corresponding results from the high-resolution forecast model. The impacts for U250 are depicted in Fig.13. The locations of the largest impact, over the Great Lakes and offshore the Canadian Atlantic provinces, are about the same for all experiments in Fig. 12. However, some differences over western North America and over the North Pacific are visible. For instance, an area of greater forecast error over western United States appears in the low-resolution/4D-Var experiment (Fig. 12b) where there is none in the high-resolution/4D-Var experiment (Fig. 12d). Smaller scale structures in the impact patterns can be seen in the experiments conducted with the high-resolution model, especially for the U250 field (Fig. 13). Again the propagation of the impact over North Atlantic is about the same for all experiments. It is however easier to assess the variability of the results by looking at the mean forecast impacts over the regions of North America and the North Atlantic, as shown in Fig. 14 for Z500 and Fig.15 for U250. As already mentioned in section 3 for the aircraft data-denial experiment, the impact vanishes quickly in time over North America whereas it persists throughout the 3-day forecast over the North Atlantic Ocean. The largest impact is found in the very short-range forecast over eastern North America, in all the experiments. For the 12h forecast range, the impact in the 4D-Var experiments is smaller by about 5% with respect to the 3D-Var experiments for Z500, while it is the opposite for U250. Overall, the results are closer to each other when changing the horizontal resolution of the forecast model scheme than they are when changing the data assimilation scheme.

6. Sensitivity to the weather regime

The propagation of the impacts of an observing network depends to some extent on the weather regime that prevails during the evaluation period (Szunyogh et al., 2002). It is thus important to examine the atmospheric flow over the regions of interest during January and February 2007. To assess the effect of the large-scale flow on the impacts, we examined the results for January and February separately.

Fig. 16 shows Z500 anomaly for January and February 2007. The mean large-scale flow during these two months is quite different although the climatological means for January and February (black contours in Figs. 16a and 16b) are similar. We found that the circulation was particularly complex during the second half of January and the beginning of February. Firstly, two blocking events took place over the west coast of North America and over the eastern North Atlantic Ocean during the last two weeks of January, explaining the Z500 anomaly dipoles in the mean flow over Europe and Scandinavia and over the eastern North Pacific Ocean in January (Fig. 16a). Secondly, a very intense cutoff low remained quasi-stationary over the eastern Canada during the first week of February 2007, which is the origin of the strong negative anomaly seen in Fig. 16b over that region.

The 48h forecast impacts of satellite data over the North Pacific Ocean for the two months of interest are shown in Fig 17. In January, the mean flow was very strong over the western part of North America and adjacent Pacific Ocean which favors a fast propagation of the impact over the continental United States. On the other hand, the presence of the cutoff low in February tends to limit the transport of the impact over the northwestern part of the continent.

Fig. 18 shows the FI over western and eastern North America and over the North Atlantic Ocean for both months individually. The impact of the satellite data over the whole North America is more significant in January than in February for forecast ranges up to 72h. However, the forecast impact from the radiosonde and aircraft data are similar in all the verification regions, except over the western North Atlantic where the impact of aircraft data is greater in February than in January. Although the weather circulation during these two months was different, the relative forecast impacts are generally similar.

7. Conclusions

The impact of subsets of the global observing system that are the most significant for the quality of weather forecasts over North America has been evaluated for January and February 2007. For the observing networks examined in this study, that is the radiosonde and aircraft data over North America and all satellite observations over the North Pacific Ocean, the forecast impacts are not homogeneous. The quality of the forecast over the Canadian Arctic heavily relies on the radiosonde network. Even though the radiosonde network over northern Canada has a lower resolution, its impact is much more important than over the continental United States and southern Canada where the mean distance between adjacent stations is three times shorter. This is due to the collocation of radiosonde and aircraft data over these regions. The primary source of forecast improvements over the western United States and Canada is provided by the satellite data over the North Pacific Ocean. Over the eastern part of the North American continent, the radiosonde and aircraft data are still the main contributors to the forecast skill at short forecast ranges, but beyond 48h, the impact of satellite data over the North Pacific Ocean may become greater, depending on the weather regime. The short-range impact of aircraft data over the United States is about three times larger than the impact of radiosonde data. The impact of aircraft ascent/descent reports alone is similar to the impact of radiosonde data over that region.

The results from OSEs run with 3D-Var are generally in good agreement with those using 4D-Var. However the impact of the radiosonde network over northern Canada is more important in the 3D-Var context, especially for short forecast ranges. 4D-Var seems superior to 3D-Var to exploit the fewer number of observations available over that region (i.e. surface stations, MODIS winds and upper peaking satellite radiance channels) and also to fill-in data-void (or data-sparse) areas as explained by Kelly et al. (2007). However, for the experiments in which the satellite data over the North Pacific Ocean are omitted, the impact with 3D-Var is not systematically larger than with 4D-Var. The short-range forecast impact over the United States is more important in the 4D-Var context.

A few experiments using the high-horizontal resolution (33 km) forecast model were also run to verify the robustness of the conclusions drawn from the OSEs at 100 km resolution. In particular, the impacts of the aircraft data over North America in both 3D-Var and 4D-Var context using the high-resolution forecast model were examined. In general, the impacts are similar for all the experiments in which aircraft data were omitted. However, there are noticeable differences in a few regions such as over the western United States where, in the 4D-Var context, the short-range impact obtained with the high-resolution model is much smaller than with the low-resolution model. We also found that the short-range impact is smaller in 4D-Var than in 3D-Var for Z500, but it is the opposite for U250. This is true for both low-resolution and high-resolution experiments. Therefore, the impact results are less sensitive to the horizontal resolution of the forecast model than they are to the data assimilation scheme employed. Further work is needed to explain why the impact variations are not the same for Z500 and U250 when comparing 4D-Var and 3D-Var results.

The weather regime that prevails during the period under investigation (i.e. January and February 2007) had a noticeable effect on the propagation of the impacts, especially from the satellite data over the North Pacific Ocean. The intense cutoff low that developed during the first week of February prevents the impact from the satellite data to spread over eastern Canada. This cutoff low also tends to trap the impact of the radiosonde and part of the aircraft data over Canada for the shorter forecast ranges. Consequently, this particular regime may have enhanced the importance of the radiosonde network in Northern Canada since no other source of information could easily spread over that region.

As indicated by the variability of the results from the various sensitivity tests, the forecast impact over a given region may change by 5% to 15% depending on the analysis scheme, the forecast resolution, or the weather regime that prevails during the period investigated.

More details about the experiments presented in this paper will be reported in two articles in preparation by Laroche and Sarrazin (2008a, b). Additional experiments in which both radiosonde and aircraft data over North America are denied will also be presented. The objective of these experiments is to examine the complementarity and redundancy of the two observing networks and their joint impact in the short-range forecast over Canada and the United States.

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TABLE 1: List of observations assimilated during winter 2006-2007 and in the control experiments.

<table>
<tr><th>Observing Network</th><th colspan="3">Variables</th><th>Thinning</th></tr>
<tr><td>radiosonde/dropsonde</td><td colspan="3">U, V, T, (T-Td), ps</td><td>28 levels</td></tr>
<tr><td>Surface report
(SYNOPS, SHIPS, BUOYS)</td><td colspan="3">T, (T-Td), ps, (U, V over water)</td><td>1 report/6h</td></tr>
<tr><td>Aircraft
(BUFR, AIREP,
AMDAR, ADS)</td><td colspan="3">U, V, T</td><td>1^{o} x 1^{o} x 50 hPa</td></tr>
<tr><td rowspan="3">ATOVS
(NOAA 15-16-17-18, AQUA)</td><td></td><td>Ocean</td><td>Land</td><td rowspan="3">250 km x 250 km</td></tr>
<tr><td>AMSU-A</td><td>Ch. 3-10</td><td>Ch. 6-10</td></tr>
<tr><td>AMSU-B</td><td>Ch. 2-5</td><td>Ch. 3-4</td></tr>
<tr><td>Water vapor channel
GOES 11-12</td><td colspan="3">IM3
(6.7 µm)</td><td>2^{o} x 2^{o}</td></tr>
<tr><td>AMV
(Meteosat 5-7-8, GOES 11-12,
MTSAT-1R)</td><td colspan="3">U, V
(IR, WV, VI channels)</td><td>1.5^{o} x 1.5^{o}</td></tr>
<tr><td>MODIS
(Aqua, Terra)</td><td colspan="3">U, V</td><td>1.5^{o} x 1.5^{o}</td></tr>
<tr><td>Wind Profiler
(NOAA Network)</td><td colspan="3">U, V</td><td>(750 m) Vertical</td></tr>
</table>

TABLE 2: Summary of the OSEs conducted in this study.

Nomenclature	Data type denied	Region where data are denied	Data assimilation scheme	Horizontal resolution of the forecast model
AI.NA.4D.LO	Aircraft	North America	4D-Var	100 km
AD.NA.4D.LO	Ascent/Descent AI	North America	4D-Var	100 km
RA.NA.4D.LO	Radiosonde	North America	4D-Var	100 km
ST.PA.4D.LO	Satellite	North Pacific	4D-Var	100 km
CT.4D.LO	None	-	4D-Var	100 km
AI.NA.3D.LO	Aircraft	North America	3D-Var	100 km
RA.NA.3D.LO	Radiosonde	North America	3D-Var	100 km
ST.PA.3D.LO	Satellite	North Pacific	3D-Var	100 km
CT.3D.LO	None	-	3D-Var	100 km
RA.WD.4D.LO	Radiosonde	World	4D-Var	100 km
RA.WD.3D.LO	Radiosonde	World	3D-Var	100 km
AI.NA.4D.HI	Aircraft	North America	4D-Var	33 km
AI.NA.3D.HI	Aircraft	North America	3D-Var	33 km
CT.4D.HI	None	-	4D-Var	33 km
CT.3D.HI	None	-	3D-Var	33 km

CT : Control
AI : Aircraft (AMDARS, ACARS, AIREPS reports) data are denied
AD : Ascent/Descent aircraft reports are denied
RA : Radiosonde (TEMP, PILOT, dropsondes) and wind profiler data are denied
ST : All satellite (ATOVS, AMV, GOES radiances) data are denied

NA : North America
PA : North Pacific
WD : World

3D : 3D-Var
4D : 4D-Var

LO : 100 km horizontal resolution of the forecast model
HI : 33 km horizontal resolution of the forecast model

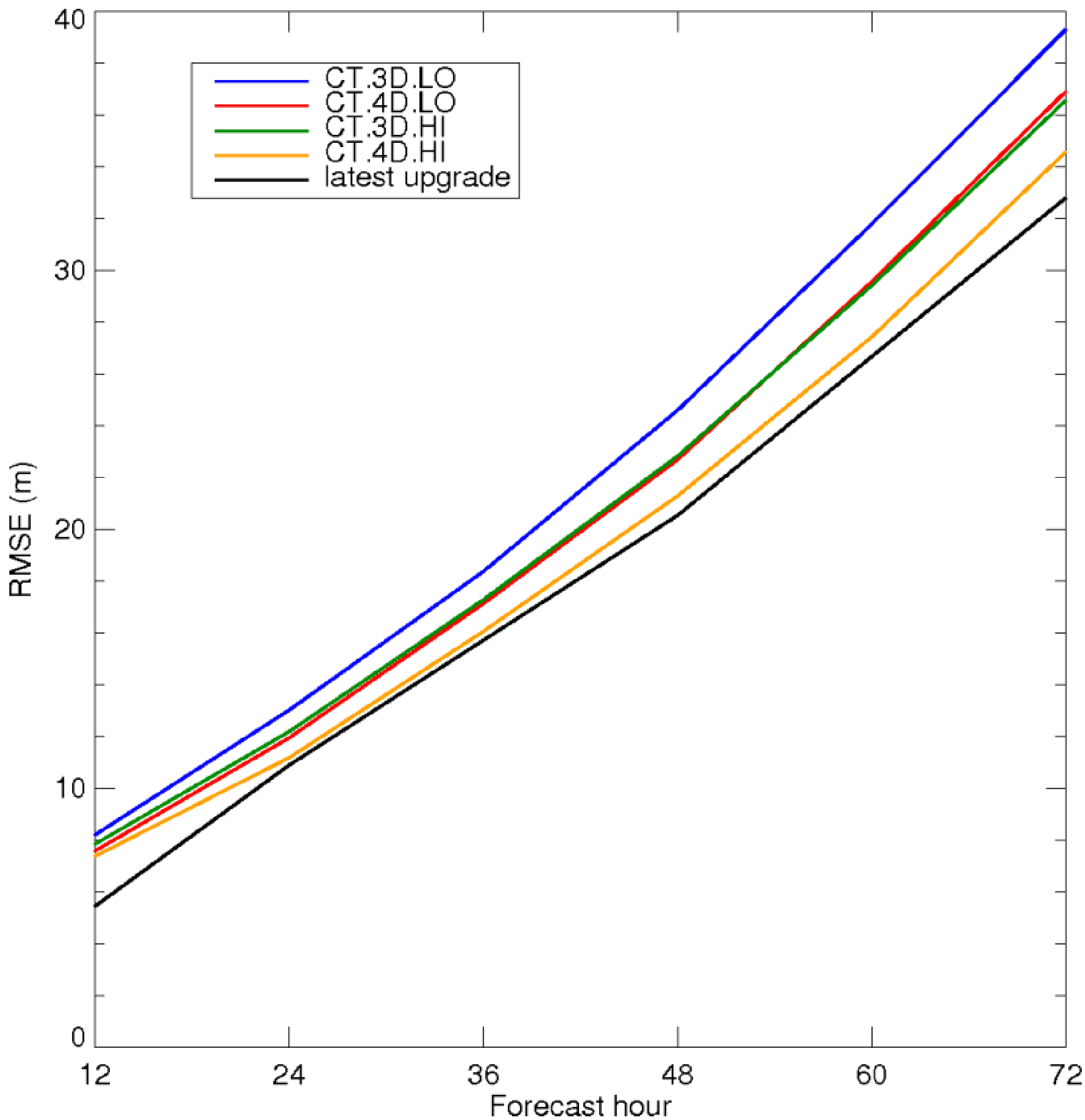

Fig. 1: RMSE against analyses (from the latest upgrade of the MSC global forecast system) for Z500 over North America for January and February 2007.

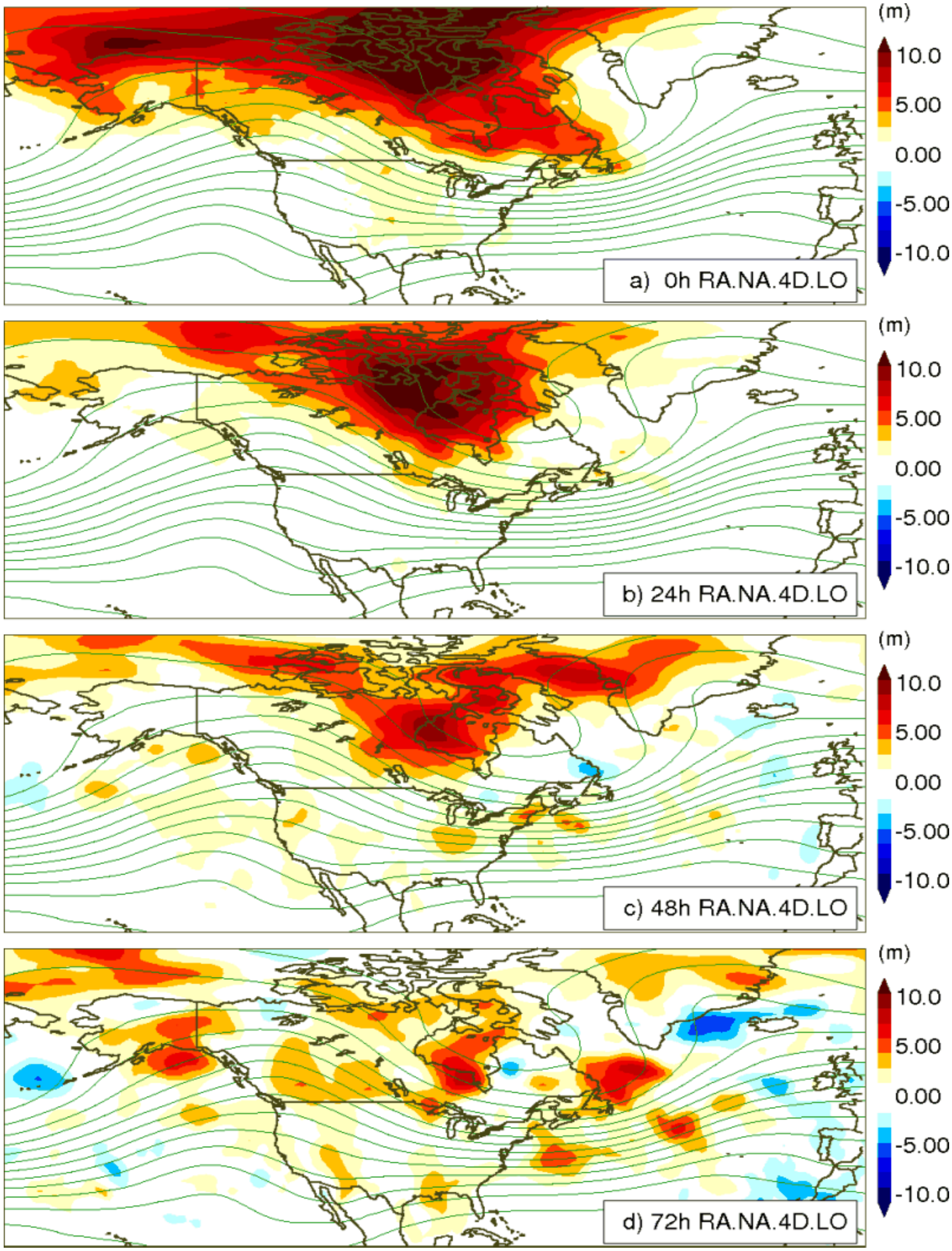

Fig. 2: RMSE differences between RA.NA.4D.LO and CT.4D.LO Panels (a) to (d) show the forecast error for 0h, 24h, 48h and 72h respectively. Also shown in green contours is the time-mean Z500 analysis from the control experiment. The contour interval is 40 m.

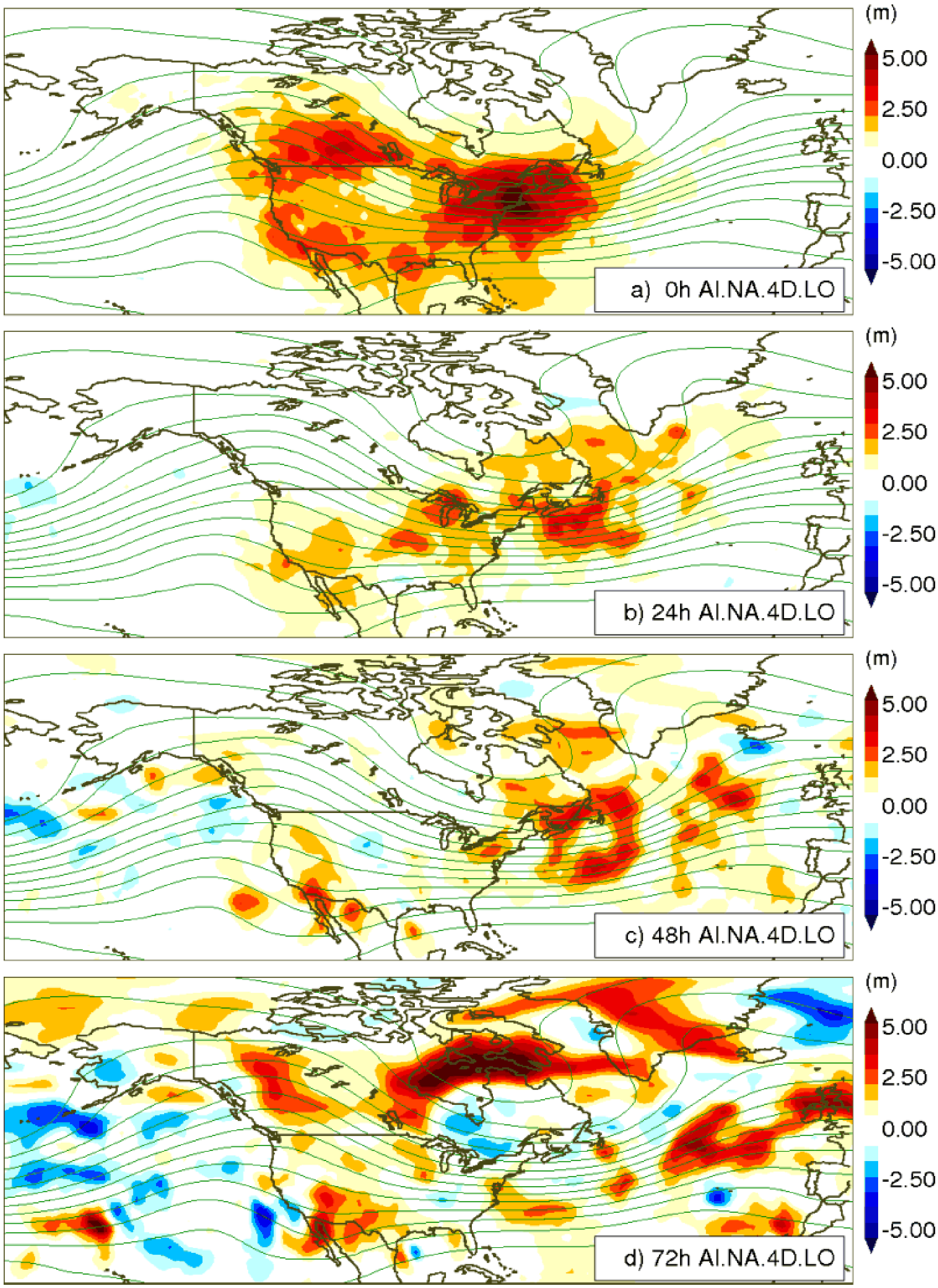

Fig. 3: As Fig. 2 but for AI.NA.4D.LO.

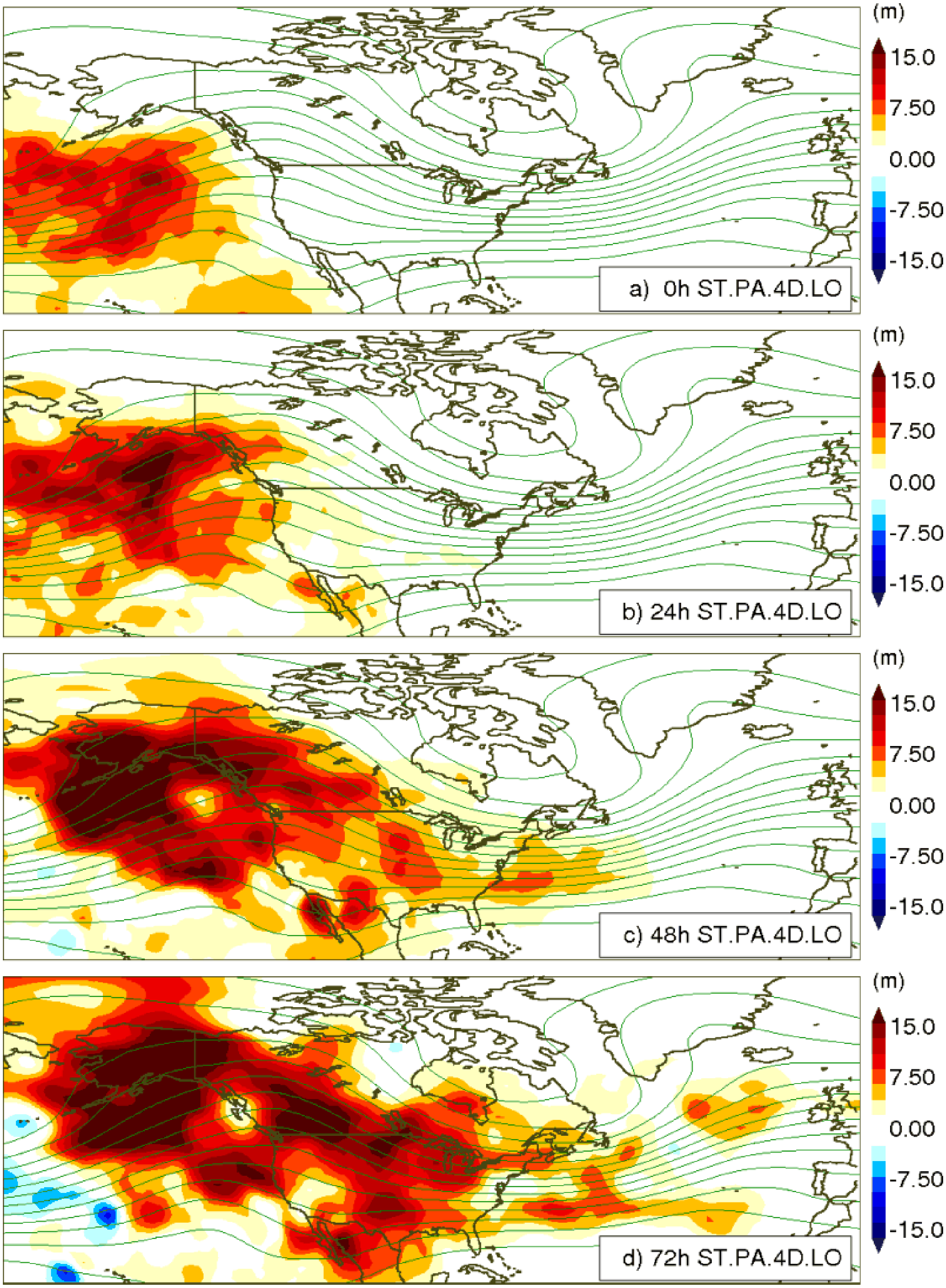

Fig. 4: As Fig. 2 but for ST.PA.4D.LO.

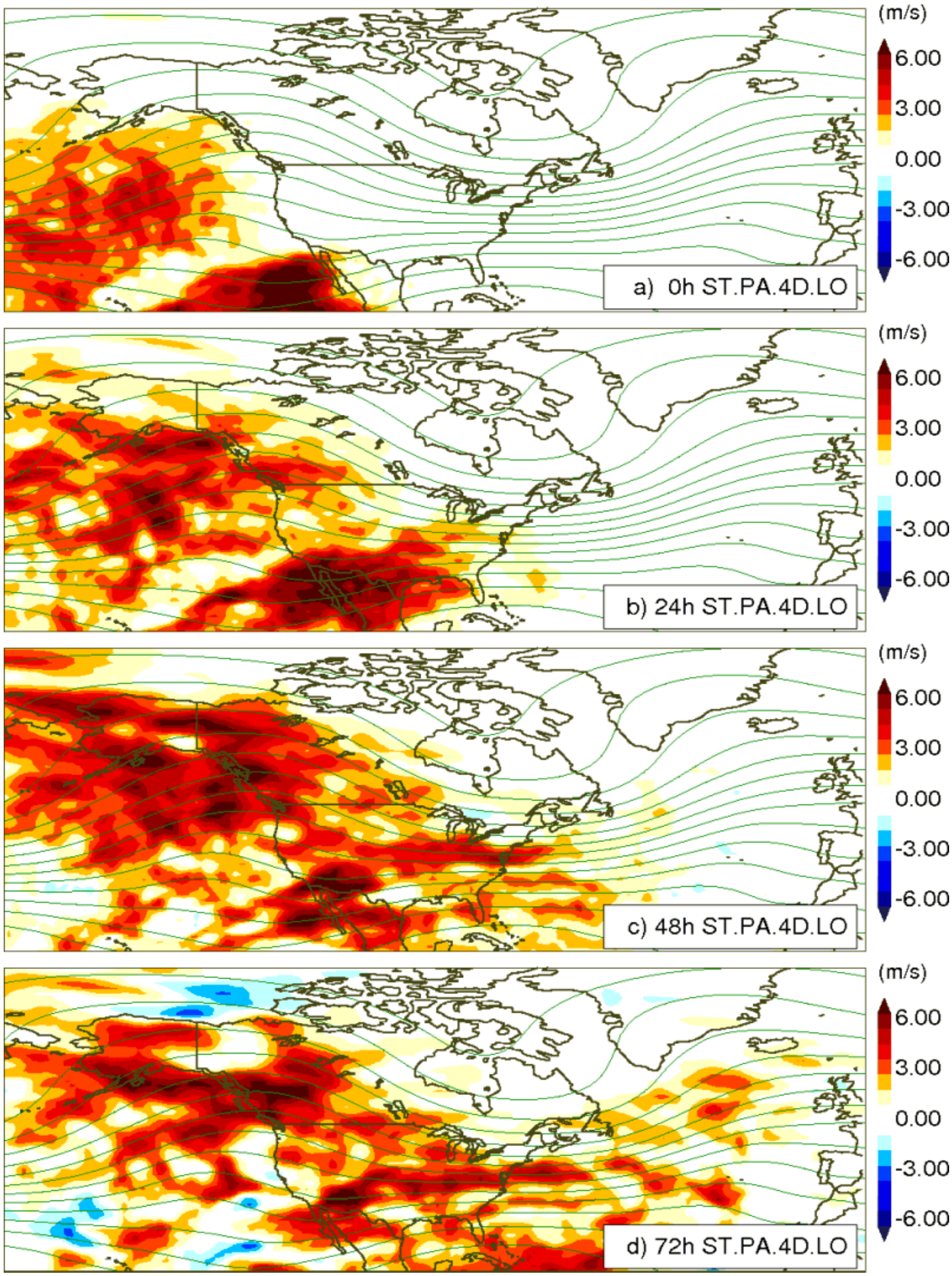

Fig. 5: As Fig. 4 but for U250.

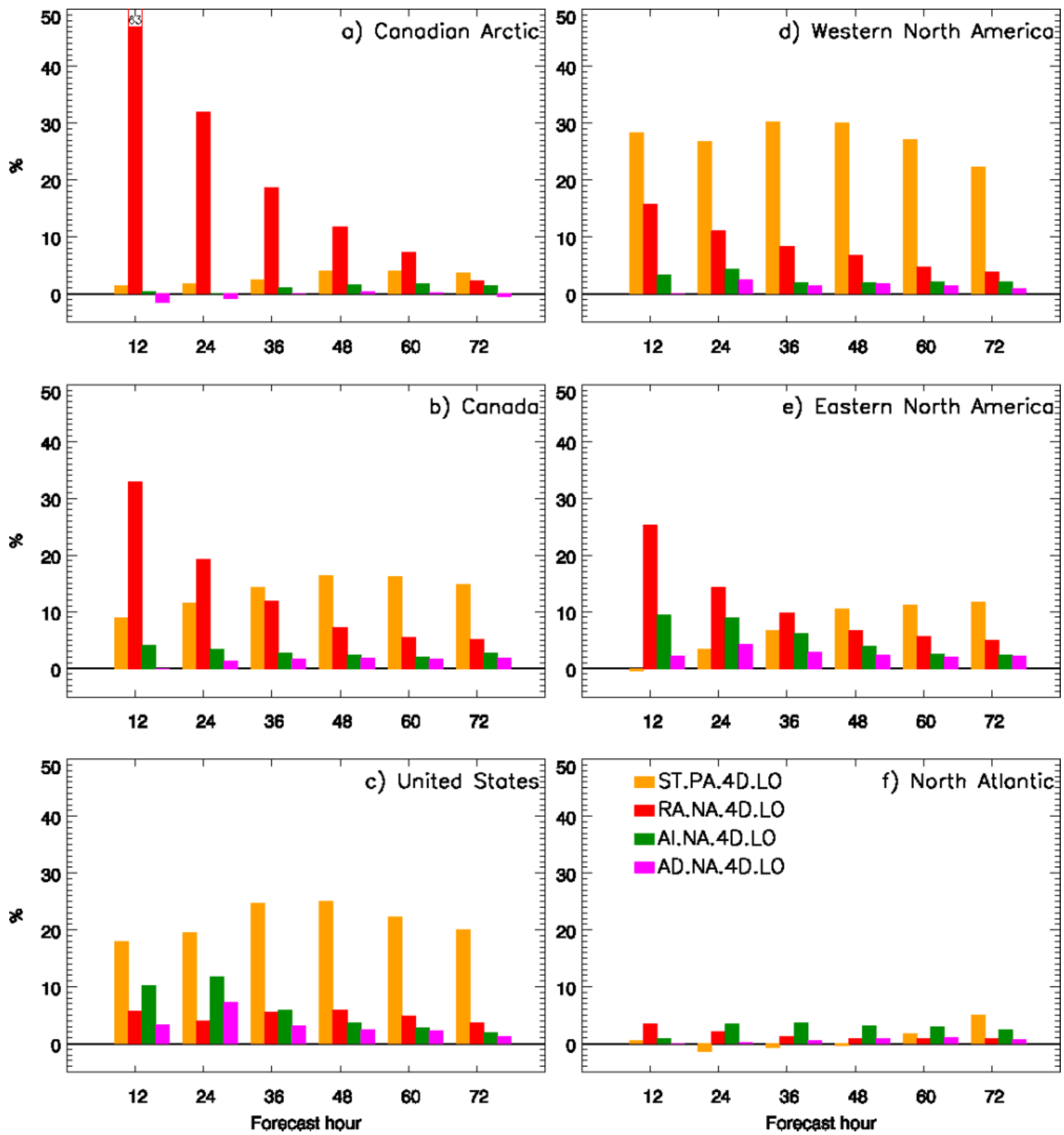

Fig. 6: FI (in percent) of Z500 over (a) Canadian Arctic, (b) Canada, (c) continental United States, (d) western North America, (e) eastern North America and (f) North Atlantic for the experiments in which satellite data over the North Pacific are denied (yellow), radiosonde data over North America are denied (red), aircraft data over North America are denied (green) and when only ascent/descent aircraft reports are denied (magenta). The left panels show the north to south progression of the FI while the right panels show the west to east evolution. The FI value is indicated over the bar if it exceeds 50%.

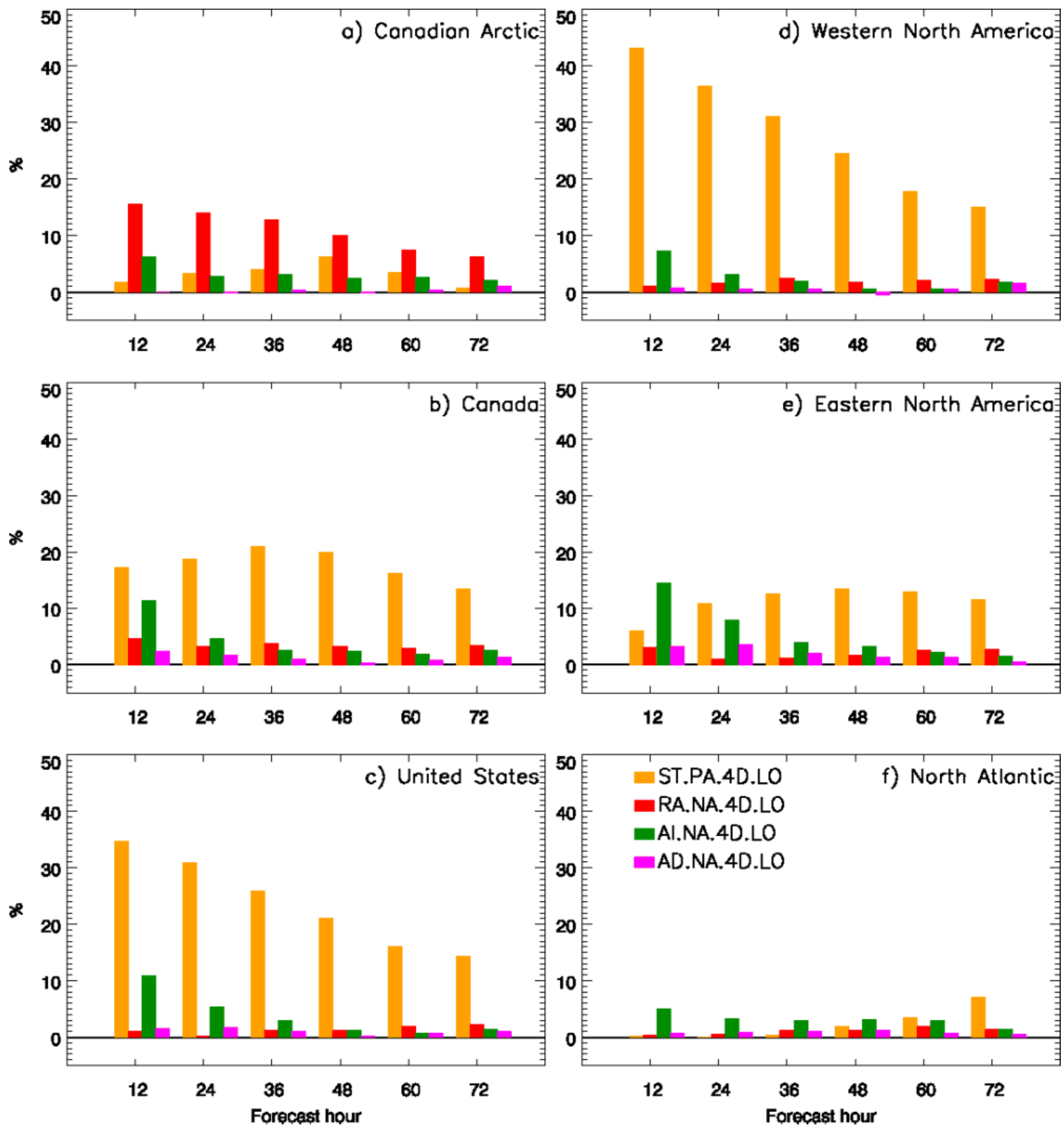

Fig. 7: As Fig.6 but for U250.

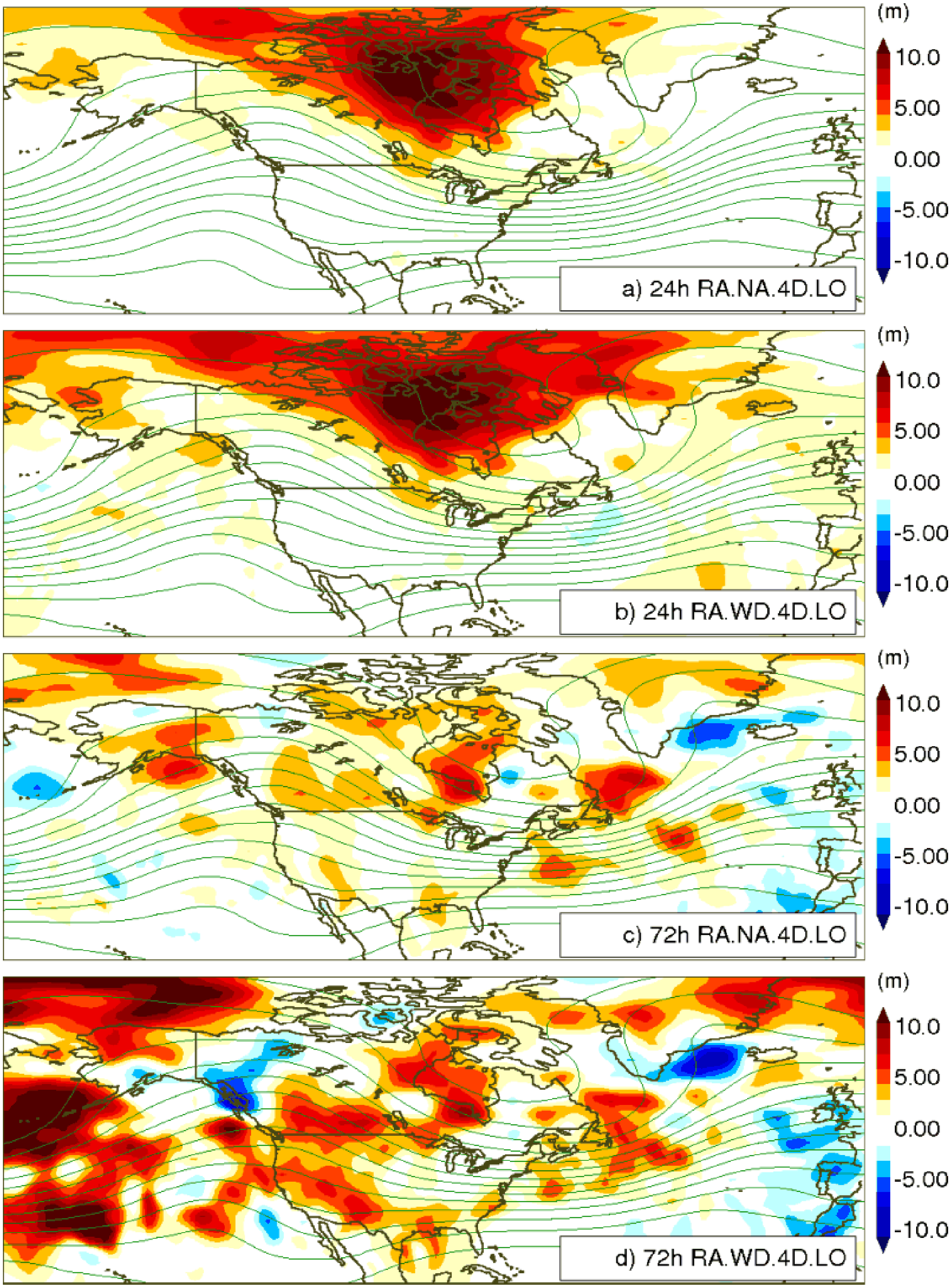

Fig. 8: RMSE differences for Z500 for RA.NA.4D.LO at (a) 24h and (c) 72h, as well as for RA.WD.4D.LO at (b) 24h and (d) 72h.

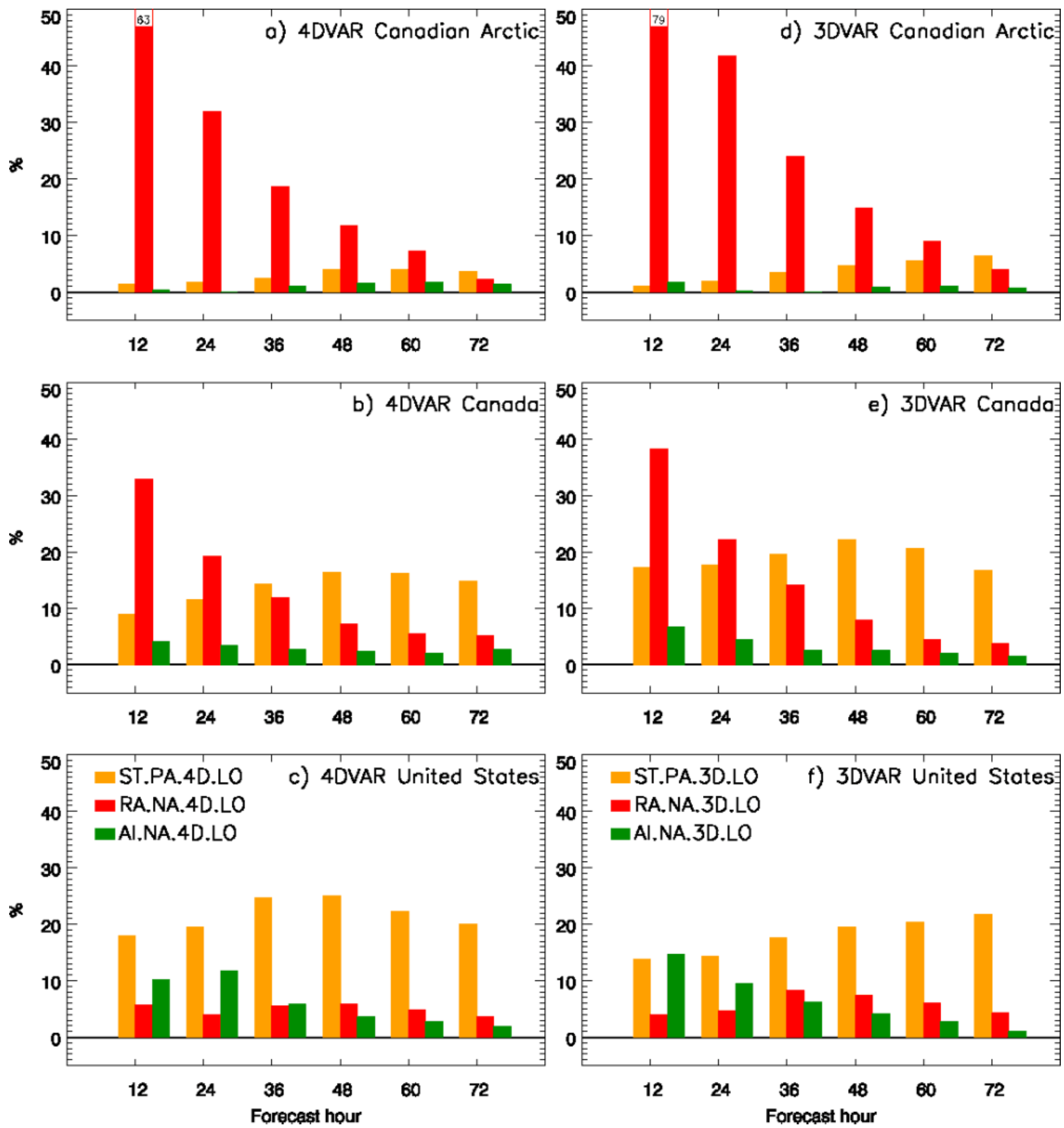

Fig. 9: FI (in percent) of Z500 for the experiments in which satellite data over North Pacific are denied (yellow), radiosonde data over North America are denied (red) and aircraft data over North America are denied (green). Displayed are the FI over: (a, d) Canadian Arctic, (b, e) Canada, (c, f) United States. The left panels show the experiments using 4D-Var while the right panels show those using 3D-Var. The FI value is indicated over the bar if it exceeds 50%.

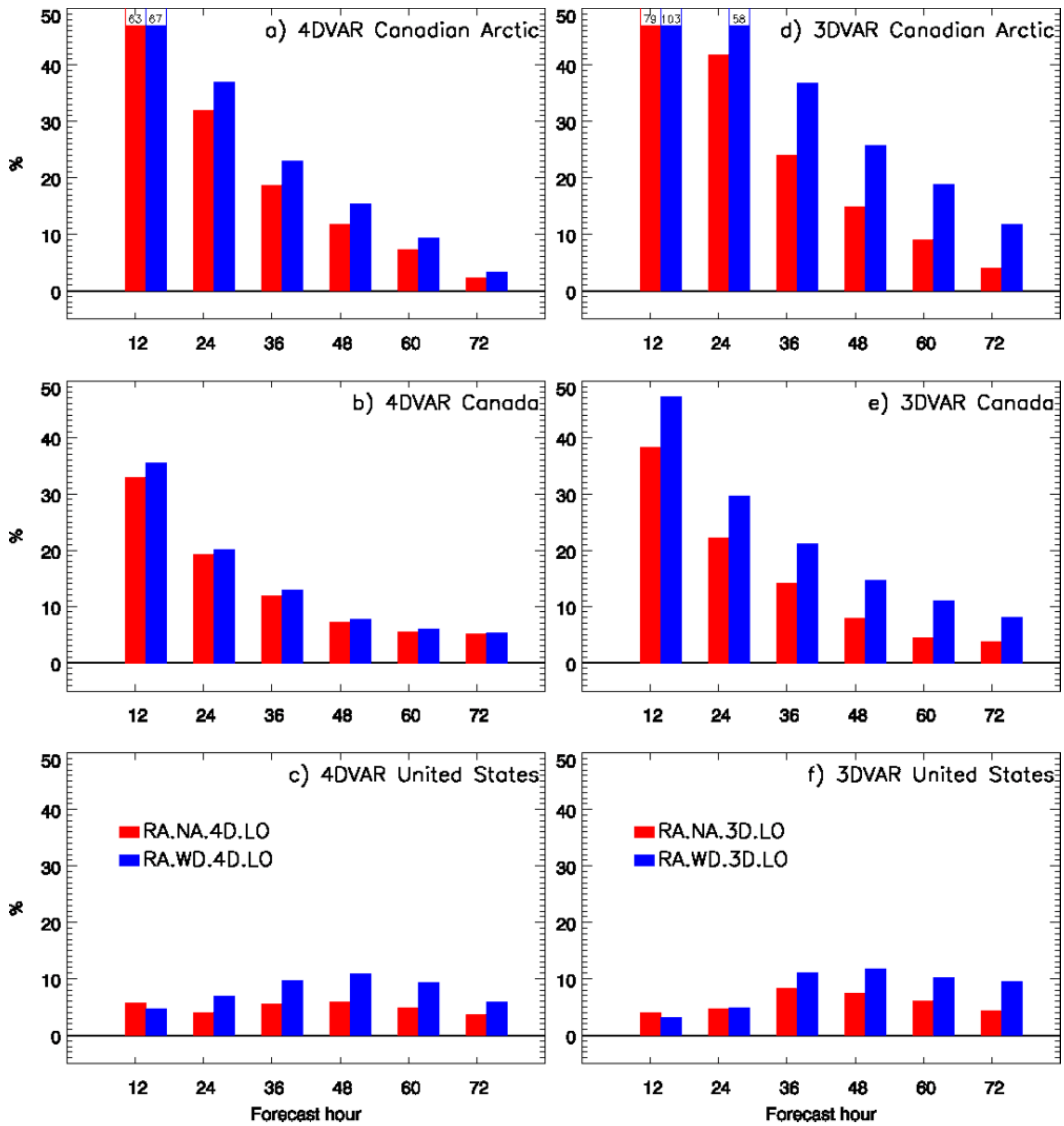

Fig. 10: As Fig. 9 but for the experiments in which radiosonde data over North America are denied (red) and radiosonde data over the world are denied (blue).

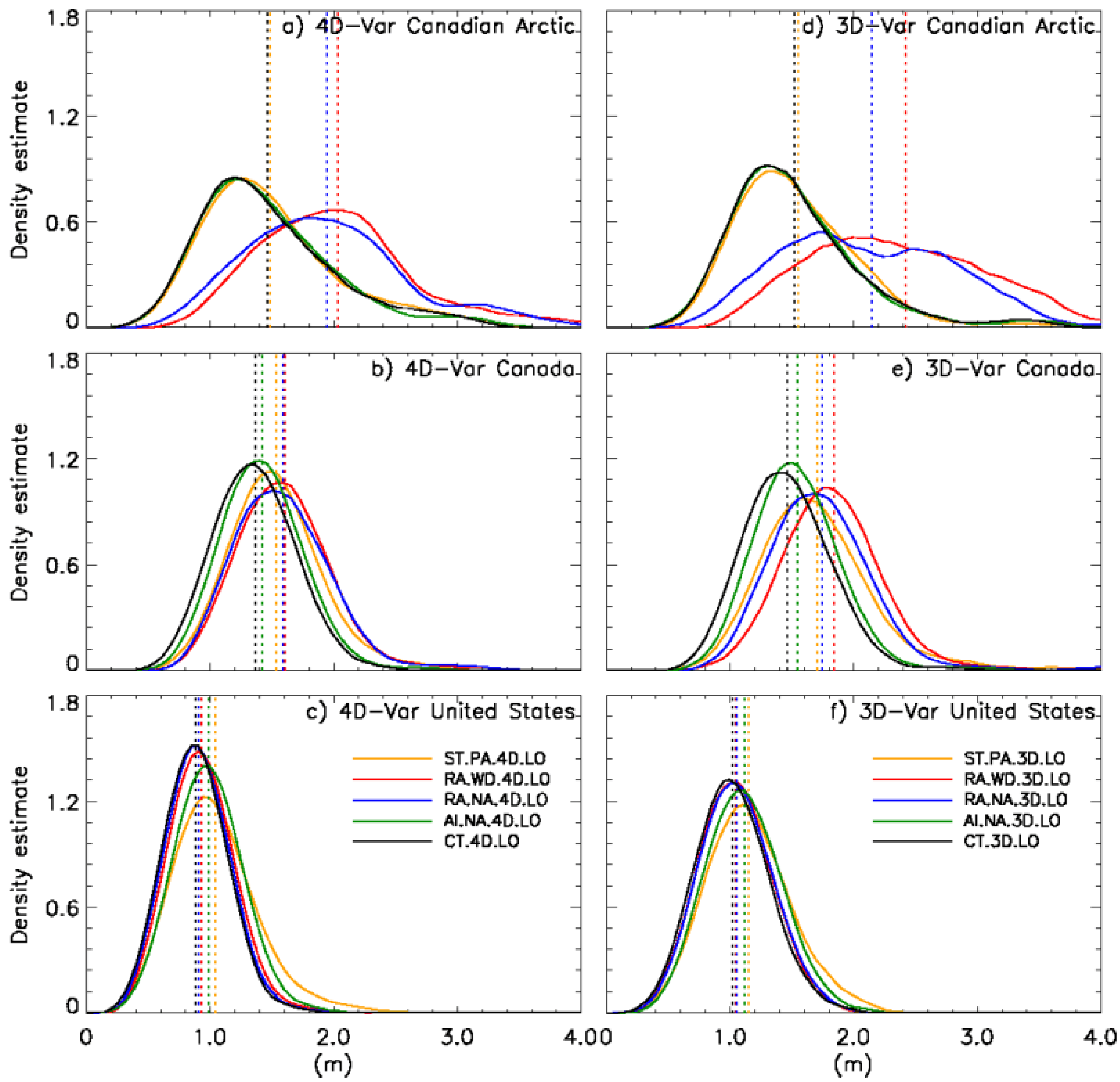

Fig. 11: Kernel density estimates of 24h RMSE for Z500 over (a, d) Canadian Arctic, (b, e) Canada, (c, f) United States for various experiments. These estimates are calculated from the 2-month RMSE distributions using a triangular kernel. The left panels show the experiments using 4D-Var while the right panels show those using 3D-Var. The dashed lines are the mean RMSE for each experiment.

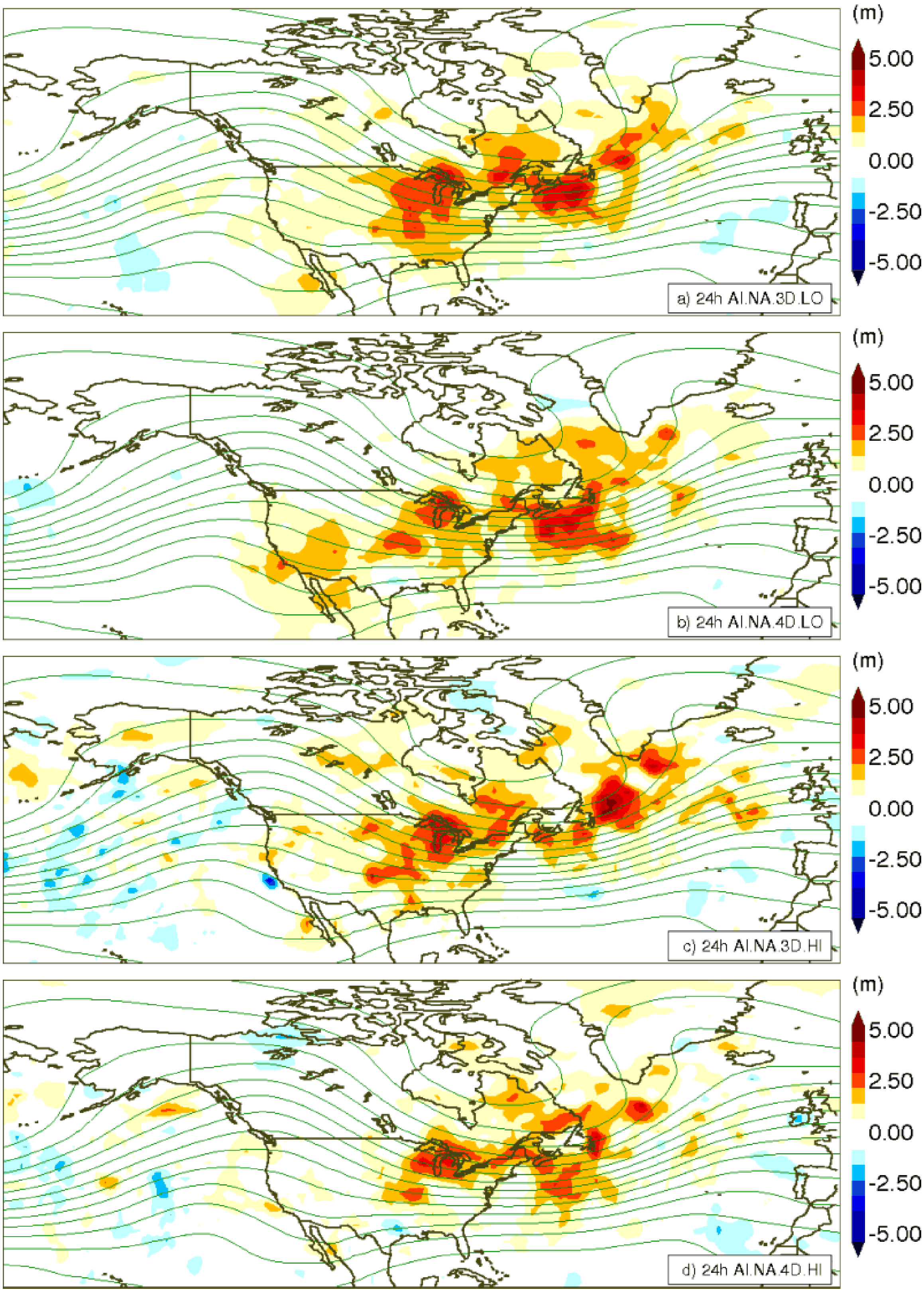

Fig. 12: 24h RMSE differences for Z500 for (a) AI.NA.3D.LO, (b) AI.NA.4D.LO, (c) AI.NA.3D.HI and (d) AI.NA.4D.HI.

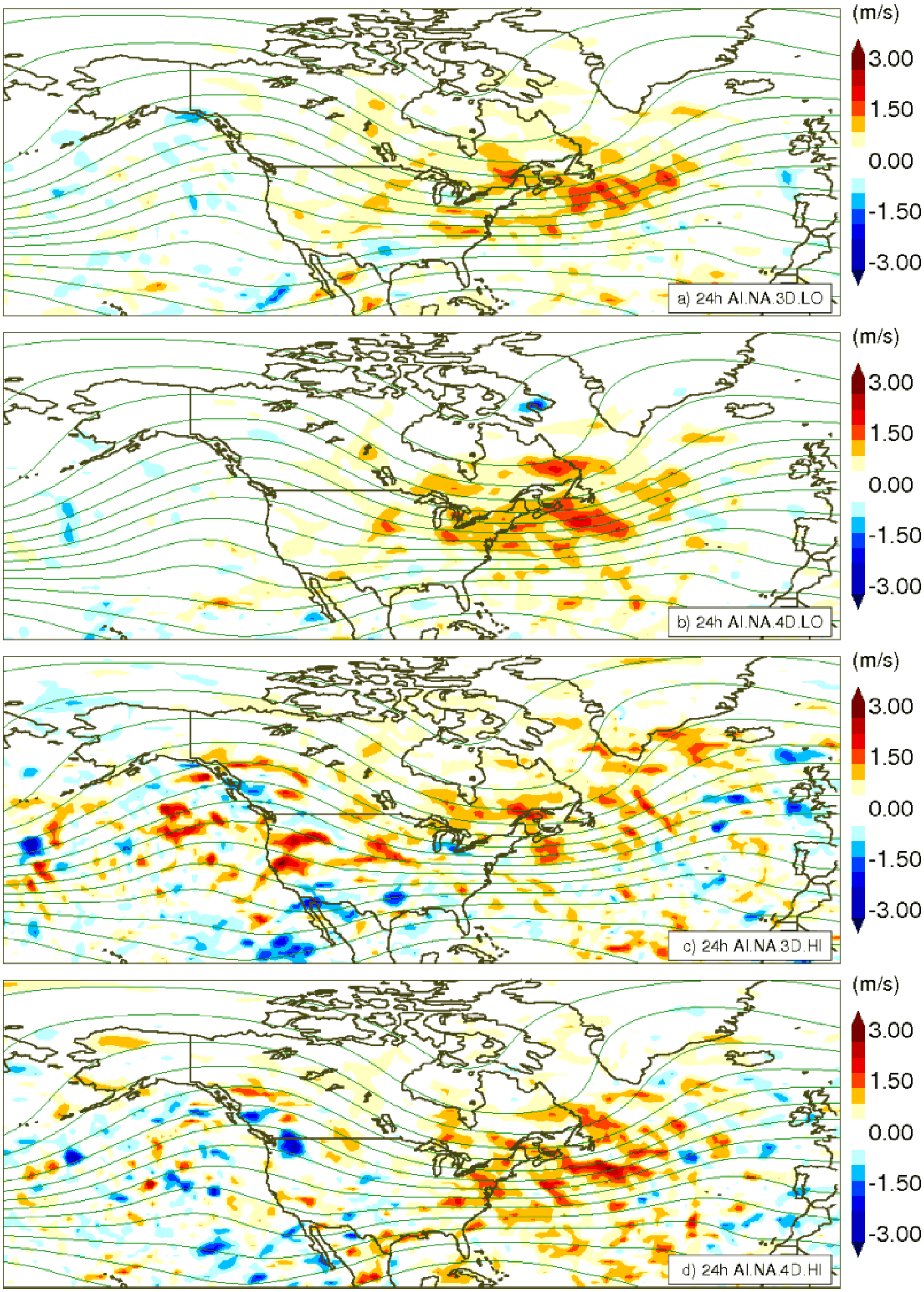

Fig. 13: As Fig.12 but for U250.

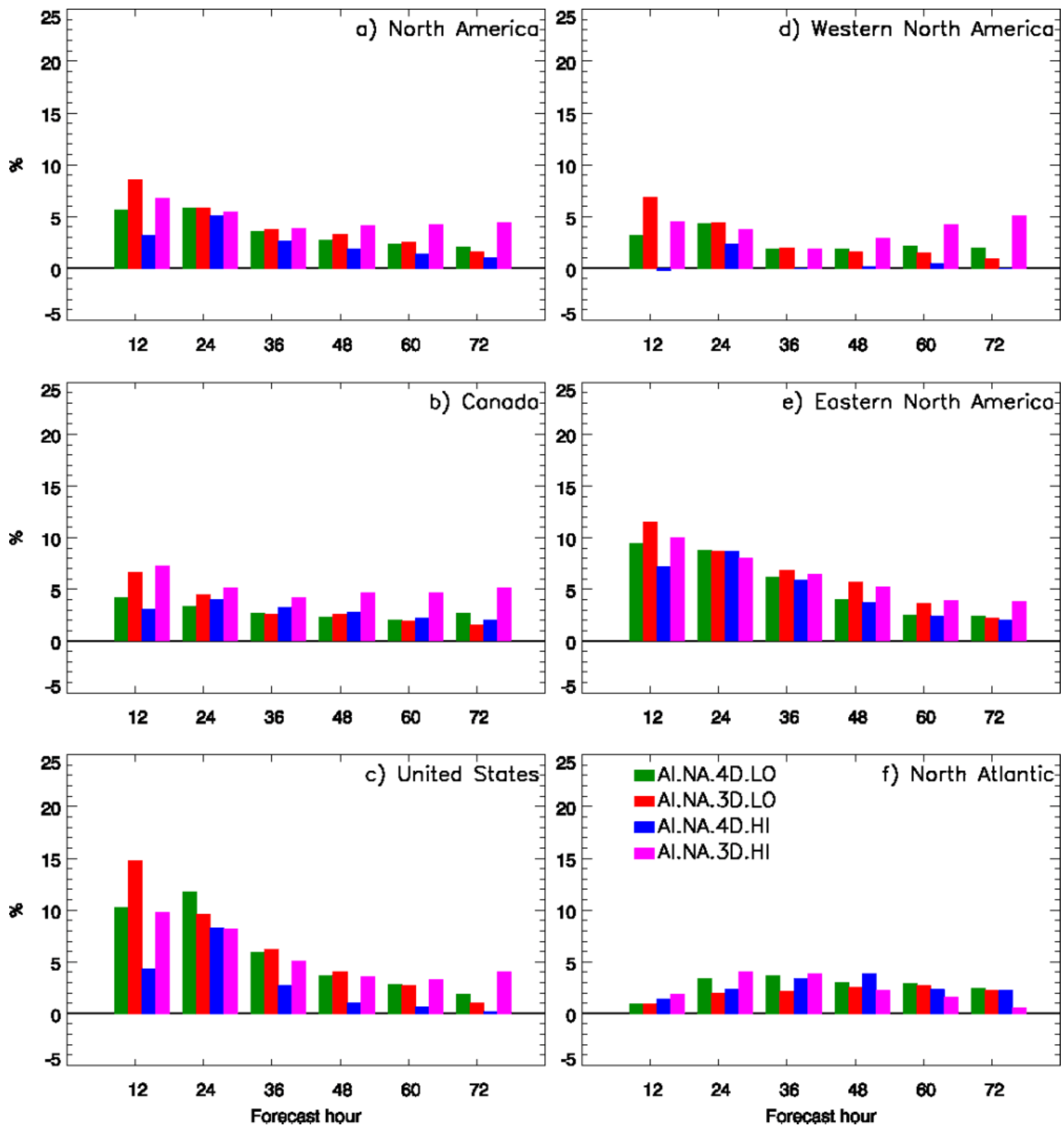

Fig. 14: FI (in percent) of Z500 for the experiments in which aircraft data over North America are denied. Displayed is the impact for 4D-Var/100 km (green), 3D-Var/100 km (red), 4D-Var/33 km (blue) and 3D-Var/33 km (magenta) over: (a) North America, (b) Canada, (c) United States, (d) western North America, (e) eastern North America and (f) North Atlantic.

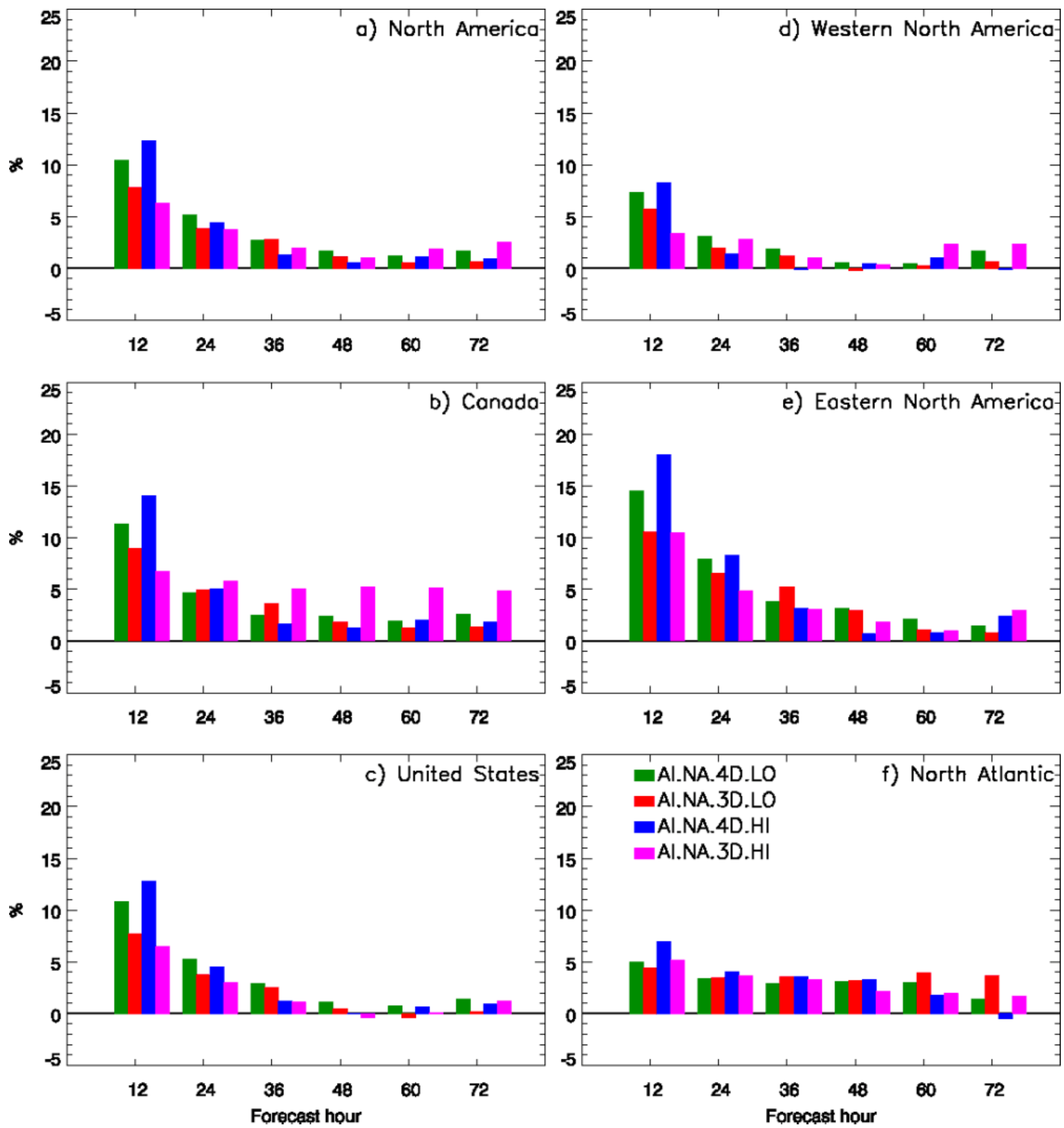

Fig. 15 Same as Fig.14 but for U250.

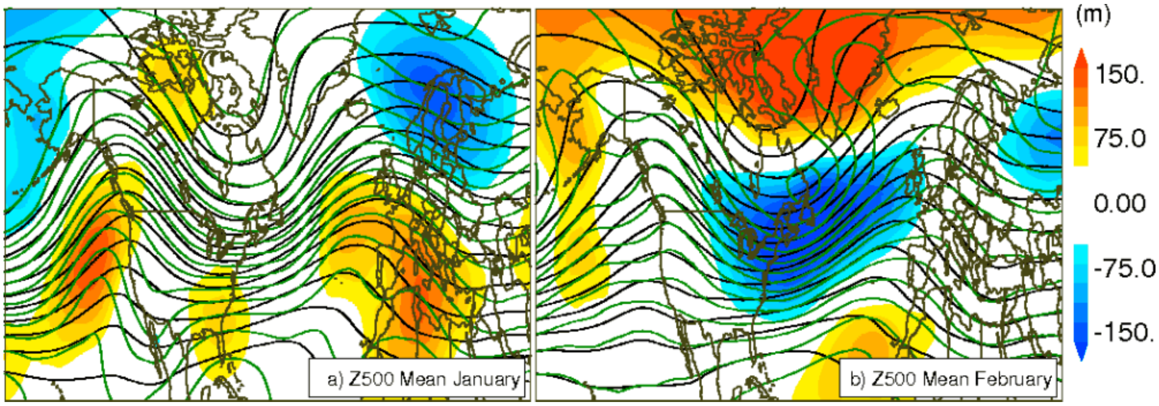

Fig. 16: Z500 anomaly for (a) January 2007 and (b) February 2007. Also shown are the climatological mean Z500 for January and February over 1979-2004 from the Japanese reanalysis (black contours) and time-mean Z500 analysis from the control experiment (green contours). The anomaly is the difference between these two fields. The contour interval is 40 m.

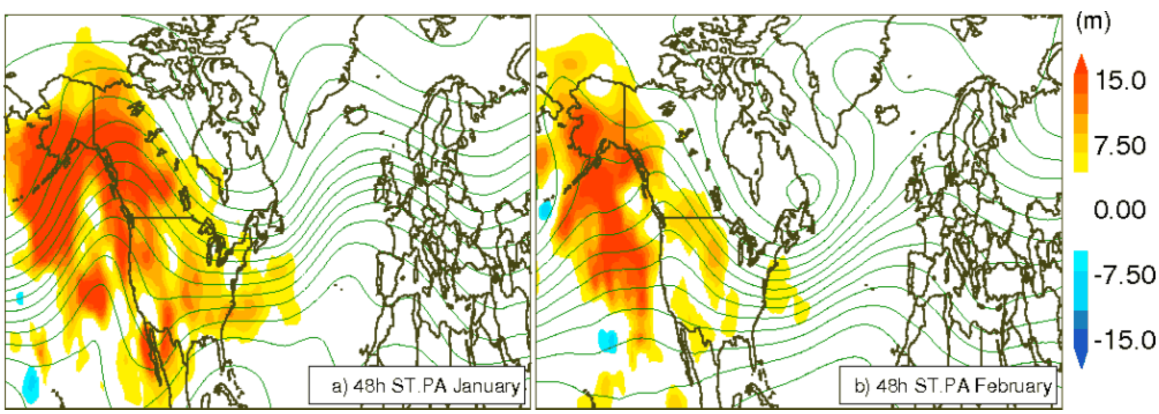

Fig. 17: 48h RMSE differences between ST.PA.4D.LO and CT.4D.LO for (a) January 2007 and (b) February 2007. Also shown in green contours is the time-mean Z500 analysis from the control experiment. The contour interval is 40 m.

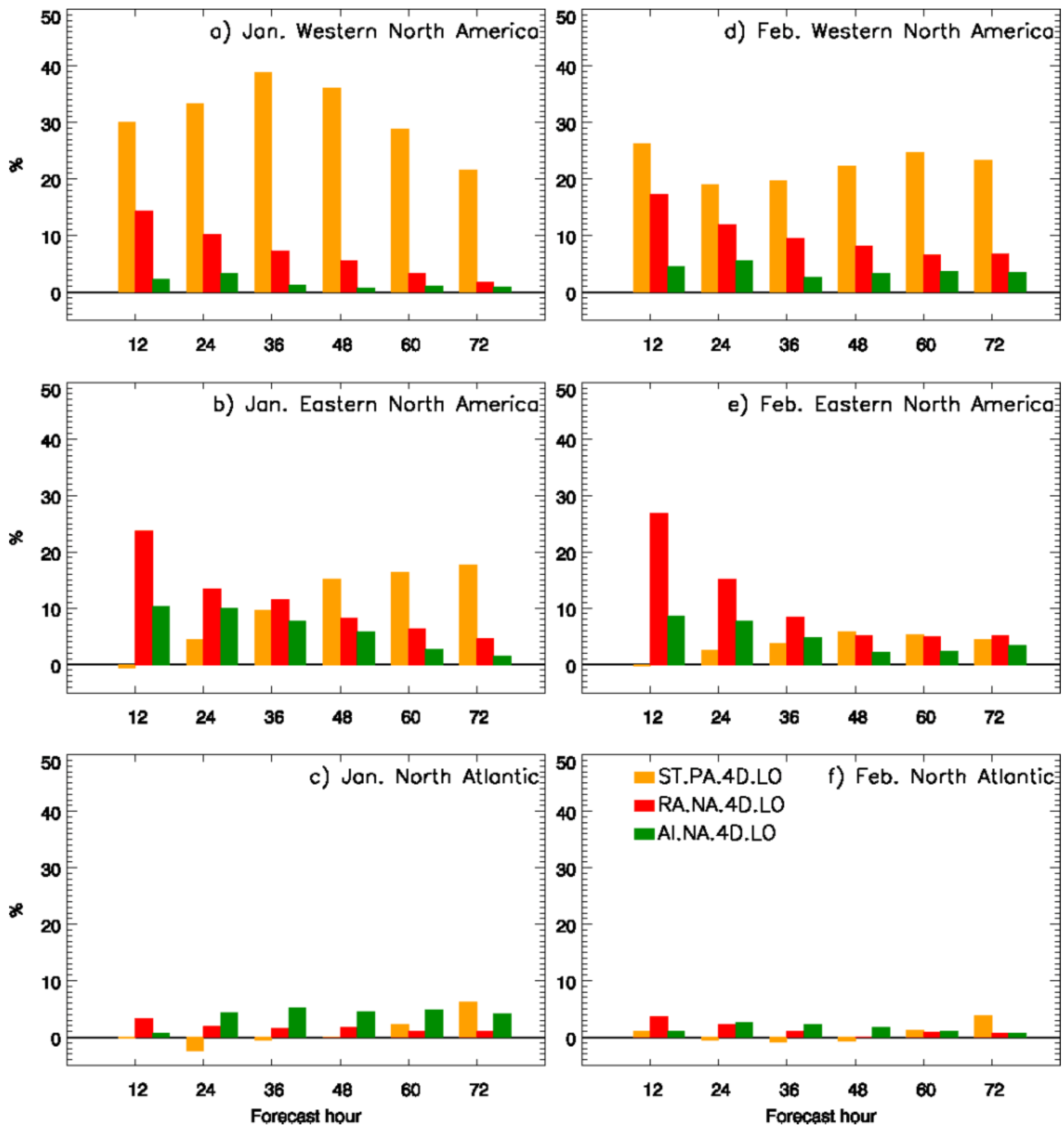

Fig. 18: FI (in percent) of Z500 for the experiments in which satellite data over North Pacific are denied (yellow), radiosonde data over North America are denied (red) and aircraft data over North America are denied (green). Displayed are the FI over: (a, d) western North America, (b, e) eastern North America, (c, f) North Atlantic. The left panels show the FI for January 2007 while the right panels show those for February 2007.

Global and regional OSEs at JMA *

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Abstract OSEs performed at JMA since the last workshop are reviewed.
First, impacts of AP-RARS (Asia-Pacific Regional ATOVS Retransmission Service) data were investigated and it was confirmed that the data improved "the Early analysis". A comparison with the impacts of EARS (EUMETSAT Advanced Retransmission Service) data showed that EARS data had larger impacts because of the larger amount of data.
Clear-sky radiance data from MTSAT-1R were shown to improve the quality of analysis in the upper troposphere and to have small but positive impacts on the global model forecasts in the middle-level and lower troposphere.
Atmospheric Motion Vectors (AMVs) reported in BUFR format are larger in amount (including hourly AMVs of MTSAT-1R) than those reported in SATOB format and are attached Quality Indicator, which enables "a strict data selection from a large amount of candidates". It appeared that the increase of data did not directly lead to the improvement of forecasts but an application of new (more strict) data selection strategies was required to get positive impacts.
The impacts of radial velocity data of Doppler radars and precipitable water data of ground-based GPS observation were investigated with regional OSEs. The impacts of Doppler velocity were positive on moderate precipitation forecasts but they were sensitive to the choice of thinning methods. GPS precipitable water also improved forecasts in heavy rain cases, but the data often suppressed precipitation in early stage of forecasts, which suggests that the vertical distribution of humidity was not properly retrieved from integrated observables such as precipitable water.

1. Global OSEs

1.1. Model and assimilation system

The model used in the global experiments was the Global Spectral Model (GSM) of the Japan Meteorological Agency (JMA) with horizontal resolution of TL319 and 40 vertical levels.

Data assimilation was made with a four-dimensional variational method with six-hour assimilation window where iterative calculation was made with linear and adjoint model of GSM whose horizontal resolution was T106. The iterative calculation was executed 70 times, first half of which was performed with simple physics and latter half is with more complicated ones.

Data assimilation cycle was six-hourly and 216 hour-forecasts were made once a day at 12 UTC throughout the experiment period.

1.2. RARS data

It is without doubt that ATOVS data are among the most important information source for a global analysis, and quick delivery of the data is crucial to the quality of "Early analysis" that provides an initial condition for the operational global forecast with a short data cut-off time. In this context, RARS (Regional ATOVS Retransmission Service) was expected to contribute to the improvement of the operational forecasts.

Asia-Pacific RARS (A-P RARS) data, which are directly received at stations in Japan, Australia, China and Korea, and are distributed via GTS, have become available in June 2006.

Statistical scores of one-month OSE in September 2006 showed no apparent improvement in the forecasts of troposphere (fig. 1), but in some cases forecast errors were reduced in the

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stratosphere by using A-P RARS data and the Early analyses became closer to the "Cycle analyses" whose data cut-off time are much longer than the Early analyses (fig. 2).

As for EUMETSAT Advanced Retransmission Service (EARS) data, another one-month experiment was performed, showing some positive impact on forecasts of troposphere (fig. 3).

The difference of impacts between A-P RARS and EARS data seem to be caused by the difference of data amount, e.g. the amount of EARS data for one analysis is three times larger than A-P RARS data.

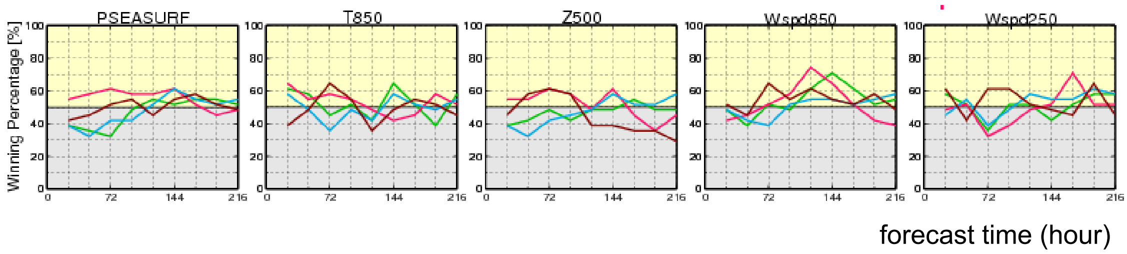

Fig. 1 Ratio (%) of the forecasts with AP-RARS data among 30 forecasts in September 2006, which have smaller RMSE than those without AP-RARS. The forecast elements are (left to right): sea-level pressure, temperature at 850hPa, height at 500hPa, wind speed at 850hPa and wind speed at 250hPa. Blown lines are for the Northern Hemisphere, red for the Tropics, cyan for the Southern Hemisphere and green for all over the globe.

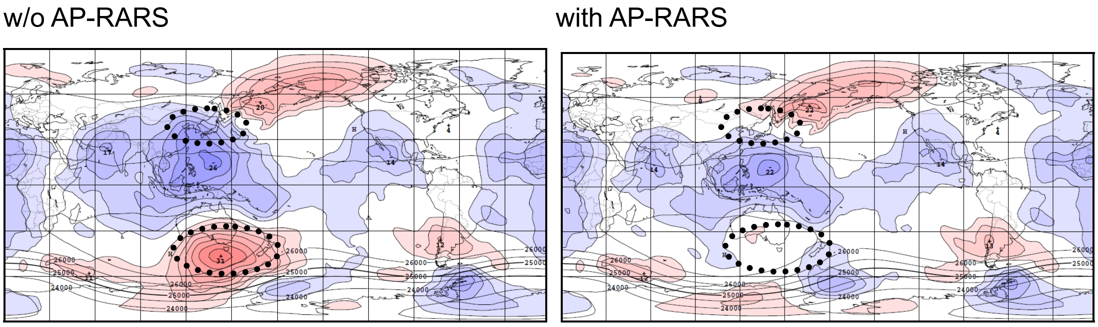

Fig. 2 Difference of the Early Analysis of 20hPa height from Cycle Analysis at 06 UTC 25 September 2006. Left panel is without AP-RARS data and right one is with them. Data from Beijing and Crib Point in AP-RARS reduce the difference of two analyses.

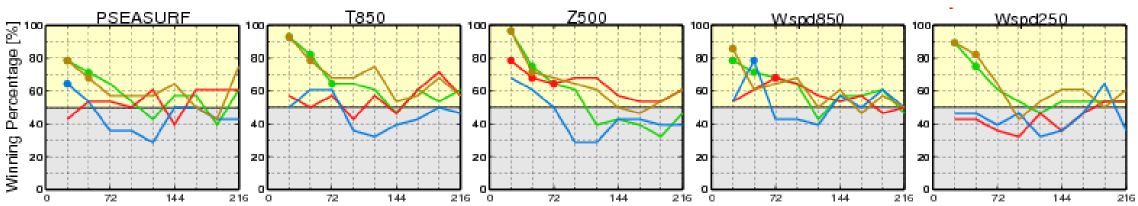

Fig. 3 Same as fig. 1 except that the data are from EARS and the experiment period is June 2007.

1.3. Clear-Sky Radiance of MTSAT-1R

Impacts of radiance data of 6.8µm channel of MTSAT-1R in clear-sky regions were evaluated. The data have sensitivity to moisture in the middle and upper troposphere.

One-month experiments in August 2006 and January 2007 show that the data ameliorated dry biases of the model in the mid troposphere in the Tropics and Southern hemisphere and cold biases at 850hPa level all over the globe. The RMSE of 500hPa height was reduced by the use of the data (fig. 4) and typhoon track forecasts were also improved.

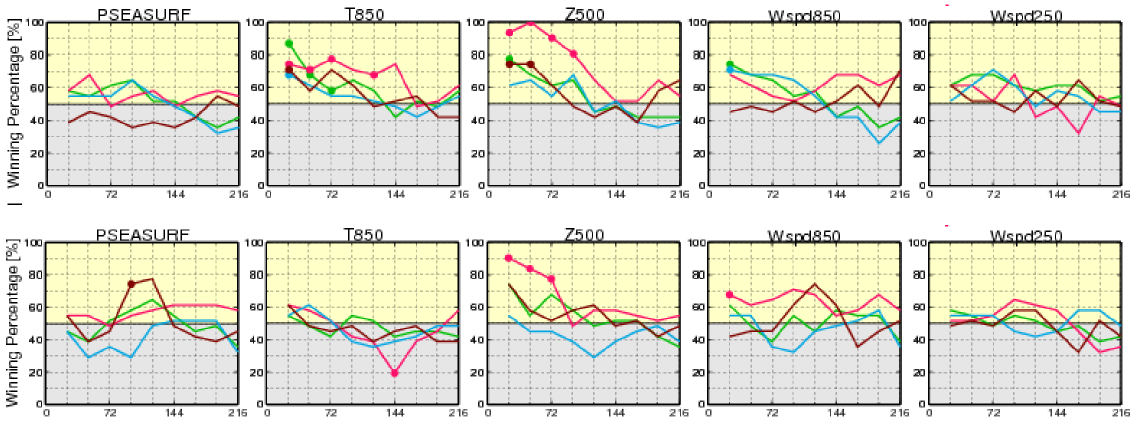

Fig. 4 Same as fig. 1 except that the evaluated data are the clear-sky radiance of 6.8μm channel of MTSAT-1R and the experiment periods are August 2006 (top) and January 2007 (bottom).

1.4. BUFR AMV

Atmospheric Motion Vectors (AMV) in the BUFR encoded dataset (BUFR AMV) are now available from all geostationary satellites. BUFR AMVs have an advantage over previously-used SATOB AMVs in the high density distribution and the availability of quality information called QI (Quality Indicator). Hourly reports of AMVs of MTSAT-1R are also available in BUFR format.

One-month experiments were performed to compare impacts of BUFR AMVs with those of SATOB AMVs in September 2005 and January 2006, showing that improvements in Z500 forecasts were achieved only after employing a strict data selection strategy based on QI value (table 1). It seemed to be favorable for the forecast improvement to select a few good data from a larger amount of candidates. BUFR AMV with the new data selection strategy also improved Typhoon track forecasts (fig.5).

Table 1 Threshold values of QI for each category of AMV with which positive impacts on the forecasts were attained

		extratropics(NH/SH)			tropics		
		HL	ML	LL	HL	ML	LL
Meteosat-7	IR	94/94	94/94	86/85	84	88	85
	VIS	-/-	-/-	-/88	-	-	84
	WV	95/95	-/-	-/-	88	-	-
Meteosat-9	IR	94/90	90/90	80/80	82	88	85
	VIS	-/-	-/-	82/82	-	-	82
	WV	94/94	-/-	-/-	84	-	-
GOES-11/12	IR	60/60	60/60	60/60	60	60	60
	VIS	-/-	-/-	60/60	-	-	60
	WV	60/60	-/-	-/-	60	-	-
MTSAT-1R	IR	98/96	96/94	84/84	84	84	85
	VIS	-/-	-/-	84/84	-	-	84
	WV	95/90	-/-	-/-	88	-	-

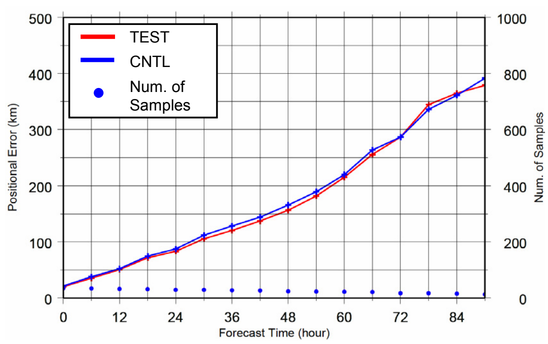

Fig. 5 Typhoon center position errors with BUFR AMVs (red) and without them (blue). Blue circles show the number of samples (right scale). The experiment period is September 2005 (forecasts of T0514 – T0519 were evaluated).

2. Regional OSEs

2.1. Model and assimilation system

The model used in the regional experiments (except for 2.4) was the MesoScale Model (MSM) of JMA, which was a non-hydrostatic grid model of 5 km grid distance.

Data assimilation was made with a four-dimensional variational method with six-hour assimilation window. The assimilation system was based on a hydrostatic spectral model, which had been the former operational mesoscale model. Iterative calculation of the 4D-Var was executed with non-linear full-physics forward model and reduced-physics adjoint model of 20 km grid distance.

Data assimilation cycle was three-hourly and 33 hour-forecasts were made four times a day at 03, 09, 15 and 21 UTC throughout the experiment period. Though the assimilation windows had three-hour overlaps, the same data were not used twice.

In the experiments described in this section, the experiment periods were around one to two weeks. Precipitation forecast skill was our main concern in the evaluation of experiments.

2.2. BUFR AMV

BUFR AMV data, mentioned in section 1.4, were tested also with the regional system. While almost same data selection strategy was applied as in the global experiment, two different chronological thinning methods were also tested: one datum per one hour or one datum per six hours in a 200km x 200km thinning box.

The results showed that again it was preferable to the improvement of forecasts that more candidate data were available and data selection was more strictly applied. Thinning to one per six hours gave better scores than one per an hour, which seemed to suggest that the observation errors might be chronologically correlated.

2.3. Doppler-radar radial velocities

The positive impacts of Doppler-radar radial velocities had already been reported in the last workshop. In this experiment, the thinning method was reconsidered.

Previously, one datum was selected in a 20km x 20km box on the surface of a cone determined by a fixed elevation angle of the radar beam (2-D thinning). The method is relatively easy to implement because it considers only two-dimensional distribution of the data. However, the thinned data by this method are apparently still too dense in the adjacent area of the radar.

The new method, which was tested in the experiment, thinned the data three-dimensionally (3-D thinning). The result shows that the forecasts were improved with the new thinning method (fig. 6), which suggests that a proper thinning is indispensable to exploit the value of observational data.

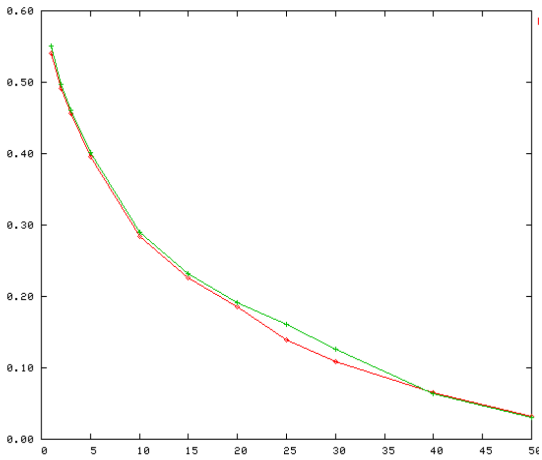

Fig. 6 Threat scores of 3-hour precipitation forecasts with 2-D thinning of Doppler velocities (red) and 3-D thinning of them (green). The experiment was made during 8 to 17 June 2006.

2.4. Ground-based GPS data

Zenith Total Delay (ZTD) data, which are calculated from GPS signals of ground-fixed receivers, contain information about integrated amount of water vapor above the receivers. Precipitable water (PW) can be easily derived from ZTD.

Since the Geographical Survey Institute of Japan has a country-wide network of GPS receivers, several researches had been made to evaluate the impact of the ZTD calculated from them on MesoScale Model forecasts (Nakamura et al., 2004, Koizumi and Sato, 2004). However, as these researches had used the precise orbit data of GPS satellites to get ZTD, their results might not go for an operational application of the data, which must be delivered in a short time from observation while the precise orbit data are not yet available.

Recently, a system to calculate ZTD and PW in near real-time basis has been installed in JMA, providing good quality PW data (fig. 7). Hence, an impact study in the operational settings has now become possible. The experiment in this section was performed with the hydrostatic spectral version of MesoScale Model (the former operational one) of 10km horizontal grid distance. The assimilation system was the same as in the other experiments except that the assimilation window was 3 hours.

An experiment was made for 1 to 13 September 2006, showing positive impacts on precipitation forecasts at 9 hour and after (fig. 8). While the impacts on precipitation forecasts were generally positive, forecast precipitation was sometimes suppressed at early hours. The reason is still obscure but one suggestion is that the vertical distribution of humidity in the initial field was distorted by the assimilation of GPS PW. Fig. 9 shows statistics of analysis increments of specific humidity where GPS PW was greater than a background value. The analysis increments were mainly put to the mid-troposphere (3-5km), while lower troposphere (below 2km) seems to have had insufficient increments.

Considering that the distribution of increments of integrated observables (e.g. PW) depends on the assimilation system configuration (background error covariances etc.), some modification in the assimilation system might be necessary to fully exploit the GPS PW data.

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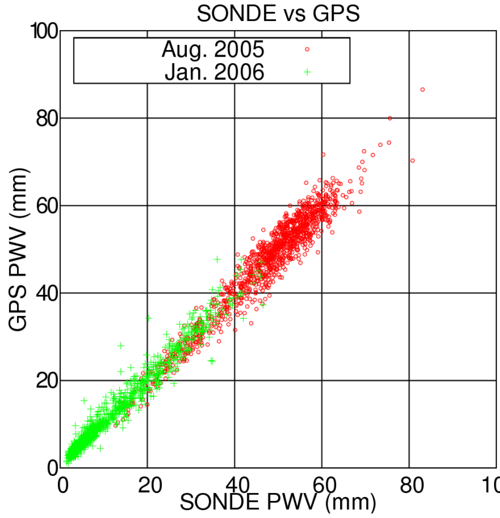

Fig. 7 Scattergram of GPS-derived PW (vertical axis) and radiosonde observation (horizontal axis). Data in August 2005 and January 2006 are plotted.

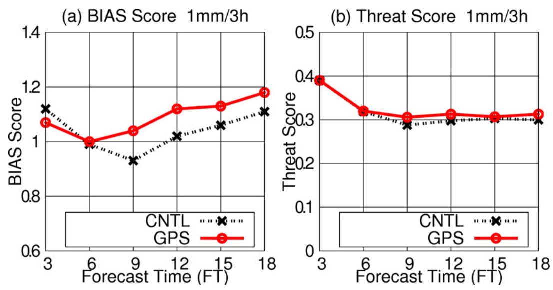

Fig. 8 Bias scores (left) and threat scores (right) of 3-hour precipitation forecasts. The threshold value is 1mm/3hour. The experiment period is 1 to 13 September 2006. Red lines with circles are for forecasts with GPS PW and black lines with crosses are for those without GPS PW.

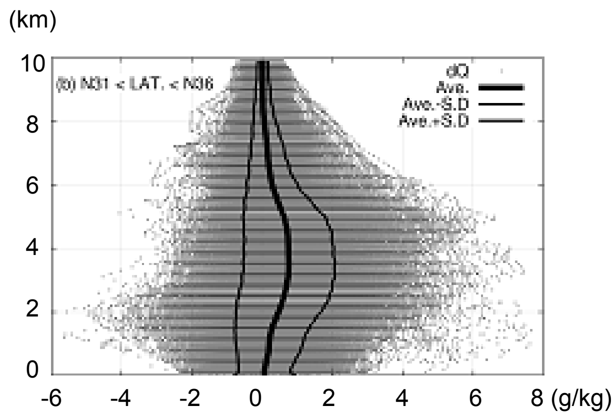

Fig. 9 Analysis increments of specific humidity at each level with the average (thick line) and the single standard deviation range (thin lines). Positive departure points only (e.g. GPS PW is greater than background value) are shown.

Impact of observations on Australian Bureau of Meteorology NWP systems

Peter Steinle, Robert Seaman, J.LeMarshall and Yi Xiao

1. The relative importance of Australian radiosonde stations

The Australian Bureau of Meteorology has routinely estimated the impact of rawinsonde and surface data on the analyses for the operational global NWP system. The impact of any given sounding is defined as the difference at the observation location between an analysis with the observation and another without the observations. This can be calculated quite efficiently within the currently operational systems, as described in Seaman (1994). The impact of an observation depends on the assimilation system, the forecast model, the accuracy and distribution of the rest of the observing system and the atmospheric conditions. The study by Seaman (2007) accounted for changes in assimilation systems, forecast models and observing systems by examining the ranking of each station's impact rather than the actual values. Variations due to transient atmospheric conditions were removed by considering averaged monthly impacts over the extended period from 1994 to 2007.

The Australian rawinsonde network consists of 42 stations, and the stations are ranked according to their monthly averaged impact on 500hPa and 200hPa wind analyses. Each station was then rated by how often it appeared amongst the most influential quartile, i.e. the top 10 highest impacts. The results were quite stable, with the only significant changes in relative performance being due to major changes in station observing schedules, i.e. stations starting or ceasing observations.

It must be stressed that this study only investigates the relative importance of the different stations. This is quite different to the more commonly studied problem of what would be forecast impact of reducing observation coverage. The main points to come from the study are:

- Tropical stations are relatively most influential
- Stations near the sub tropical jet are relatively very influential at upper levels
- Stations along the south coast became less influential with advances in satellite data usage
- The relative influence of stations near major airports is very low.
- Some wind only stations never have significant relative impact.

The reasons for these results are fairly clear. In the first case the tropical stations are in the more remote areas of the nation, and being tropical there is less influence on wind analyses from satellite soundings. It should also be noted that a major retuning of the background error variances was related to an increased influence of the tropical stations. This retuning also provided a significantly more accurate fit between forecast fields and both satellite and in situ observations. The importance of satellite data was also seen in the significant decrease in the impact of mid-latitude stations along the southern coasts of Australia following a major increase in the amount of satellite data used within the assimilation system.

It was also notable that most of the rarely or never influential stations were located in the south east of Australia. This is as expected as it is where both the rawinsonde and aircraft observing networks are most dense. This area is also generally downstream of the rest of the observing network. The relatively minor impact of some wind-only stations was also noted.

2. Value of atmospheric motion vectors from geostationary satellites

The value of atmospheric motion vectors from geostationary satellites has been demonstrated in numerous studies, such as Le Marshall et al. (2004, 2007). Similar experiments are being repeated as the Bureau of Meteorology is in the process of introducing the Australian Community Climate and Earth System Simulator (ACCESS). The ACCESS atmospheric model and assimilation system consists of the UK Met Office Unified Model and 4dVAR system for both global and regional domains.

Experiments have been conducted over the Australian region using the full real-time database which includes local continuous (hourly) error characterized AMVs. Recently these high density hourly visible and infrared image-based winds (see Figure 1) have been used in a series of experiments examining the motion of tropical cyclone Nicholas which developed off the NW coast of Australia during February 2008. The forecasts shown here were undertaken using the ACCESS model at 37.5km resolution employing 4dVAR with a six hour time window. A sample forecast is seen in Figures 2 and 3. The track of tropical cyclone Nicholas from 12 UTC on the 14 February 2008 is shown in Figure 2 in 12 hour steps. Also shown is the track using the operational data base (including local AMVs at synoptic times) and the track resulting from the use of the operational data base plus continuous local (hourly) AMVs with 4D-VAR.

The 15 and 24 hour forecasts for the developing tropical cyclone Nicholas from 12UTC on the 14 February 2008 are also shown in Figure 3. The quality of the forecasts using continuous (hourly) AMVs represents high standard operational guidance for what was a difficult forecast case associated with poor numerical guidance. The result is consistent with earlier studies. Further work continues with these and other regional and global studies and results indicate the potential for significant improvement in operational guidance on implementation of the new system.

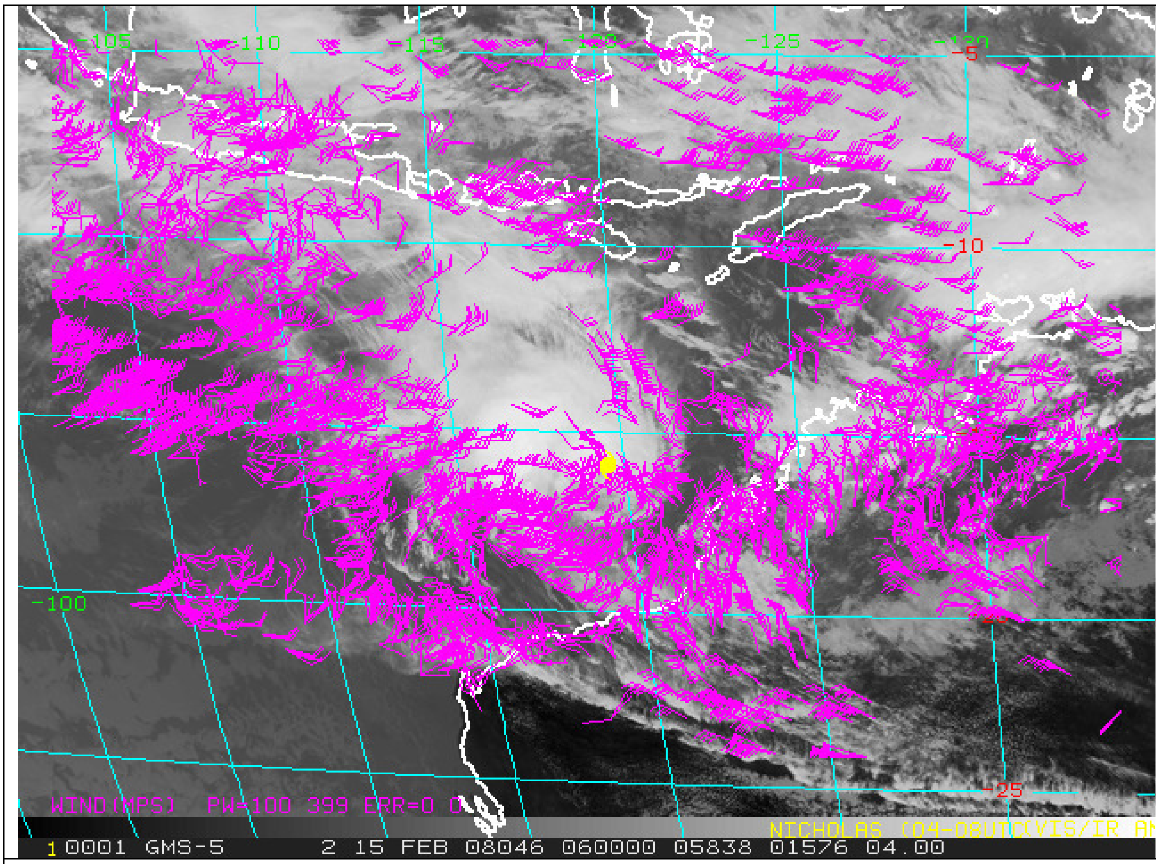

Figure 1. Visible and infrared image-based hourly AMVs for the period 9 - 15 UTC on 15 February 2008.

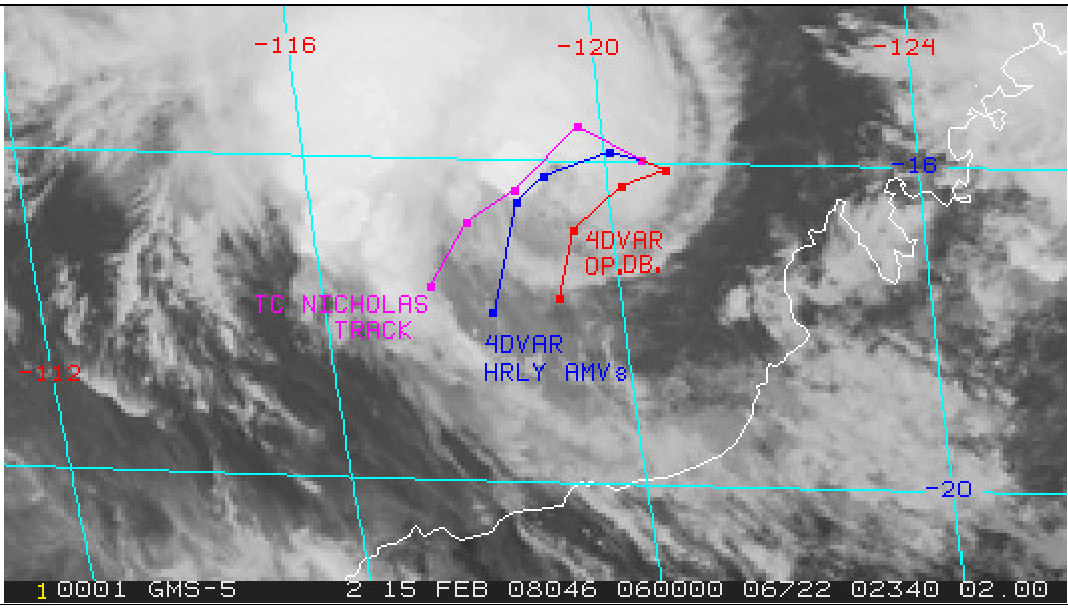

Figure 2. The track for TC Nicholas starting 12 UTC on 14 February 2008, the forecast with the operational database (OP.DB.) and the forecast with the operational database plus hourly AMVs.

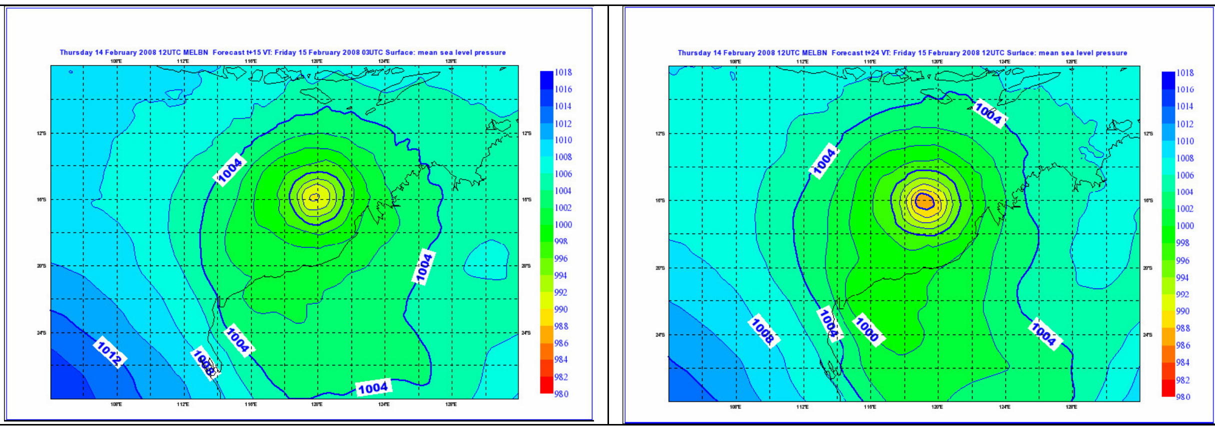

Figure 3. The 15 and 24hour 4DVAR forecasts from ACCESS starting 12 UTC on 14 February 2008 using the operational database plus hourly AMVs.

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Impact studies with satellite observations at the Met Office

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Adrian Jupp, Simon Keogh, Ed Pavelin and Michael Rennie

Met Office, Exeter, UK

ABSTRACT

In the last 4 years, the Met Office has conducted many impact studies using satellite observations, as part of the process of improving the use of satellite data in operational NWP and of bringing newly available observations into operational use. In this talk we summarise results obtained during this period, focussing on those with most implications for the design of the Global Observing System. These include the impact of: multiple microwave sounders; data from the Regional ATOVS Retransmission Service (RARS); observations from MetOp - ATOVS, IASI and ASCAT; cloudy AIRS radiances; GPS radio occultation (RO) data, particularly from the COSMIC constellation; atmospheric motion vectors (AMVs); and ground-based GPS measurements of zenith total delay.

Results with implications for design of the GOS are: microwave sounders of AMSU class in 3 well-space orbits are close to optimal; the RARS is delivering improved timeliness for ATOVS data, with beneficial impact on global NWP; the early availability of MetOp ATOVS data was an excellent example of service to the NWP user community; MetOp IASI data have already delivered substantial impact on global NWP performance from cloud-free radiances; a method for assimilating cloudy radiances has been successfully demonstrated with AIRS data, showing that much greater operational impact can be expected from AIRS and IASI data; MetOp ASCAT retrieved winds have been shown to be of very high quality, and positive impact on NWP performance has been demonstrated; Windsat wind vectors have been shown to give impacts on global NWP of the same order as scatterometers, although the latter have given more impact on short-range forecasts; substantial impact has been demonstrated from RO data from 6 COSMIC satellites, and increased impact has been shown with data from more than 6 RO receivers; AMVs are delivering useful impact within the global NWP system, but quality control and error characterisation problems remain; ground-based GPS observations of zenith total delay are delivering small positive impacts on forecast for the UK using the regional NWP system.

1. INTRODUCTION

Over the last four years, the Met Office has completed many studies of the impact of satellite data on NWP performance. Most of these have been conducted in the process of bringing new satellite data into operational use, or of improving the impact of satellite data already used through changes to their processing or assimilation. However, other studies have been conducted retrospectively, to investigate the current impact of data types already in use. All of these can be considered as Observing System Experiments (OSEs) mainly of the data-denial type.

In this paper, we provide only a summary of results, and we focus primarily on those studies for which the results have implications for design of the Global Observing System (GOS).

Most of the results here concern the impact of various satellite data types within the Met Office's global NWP system, using the 4D-Var data assimilation system (Rawlins et al, 2007), with the version that was operational at the time of the experiment. The impact experiments had a resolution of N216L50 (about 60 km horizontal, 50 vertical levels) except where stated otherwise. In section 2.10, we report on the impact of ground-based GPS measurements of zenith total delay on forecasts over the UK from the Met Office's North Atlantic and European regional NWP model, again using 4D-Var.

2. IMPACT STUDIES

2.1 Microwave sounding data from multiple satellites

At the third workshop in this series, we reported on the impact of assimilating microwave sounding data – AMSU data from the NOAA satellites – from one, two or three instruments (English et al, 2004). The conclusions of this work have been fully supported by similar, more recent experiments. We summarise these results and conclusions again here, because of the implications they have for the design of the GOS.

Results were available from ten experiments in all (at various times and with various resolutions), from which the impact on global NWP performance of AMSU data from one or more satellites could be compared. Impact was assessed mainly in terms of:
- analysis accuracy, assessed by comparing the r.m.s. fit of a subsequent 6-hour forecast to observations from a range of observing systems,
- forecast accuracy, for a range of domains, variables, and forecast ranges, by verification against both observations and analyses.

Results of forecast impact were summarized as follows: if 100% represents the impact of AMSU data from 3 satellites (compared with experiments in which no AMSU data were assimilated), then:
- the 1st satellite provides 75% of the impact, with 45% of the data coverage,
- the addition of a 2nd satellite raises the impact to 95% and the data coverage to 85%,
- the addition of a 3rd satellite provides, by definition, 100% of the impact with 100% of the data coverage.

Based on these results, we conclude that:
- the 1st and 2nd AMSUs are very important for the maintenance of current levels of global NWP performance,
- the 3rd satellite has positive impact overall, but its main role is to provide robustness in case of instrument failure and to mitigate the effects of data delays,
- complete global coverage is very important; more data improve forecasts if they fill gaps in data coverage,
- a small but significant impact of a 4th satellite has been demonstrated with 4D-Var,
- when adding additional instruments to the total system, it is most important to fill gaps in coverage.

2.2 RARS

Data from the EUMETSAT ATOVS Retransmission Service (EARS) became available operationally in 2004. Data from other parts of the WMO Regional ATOVS Retransmission Service (RARS), which is still expanding, started to become available in 2006. The role of this service is to make ATOVS data (and potentially other satellite data) available to NWP centres faster than they are available from the central global data processing service of NOAA. This allows more data to meet the cut-off times that operational centres have to impose. The cut-off time for the main run of the Met Office global NWP model is T+2.75 hours.

We have conducted experiments in which ATOVS data are assimilated:
- using only data available before the cut-off time from the global processing centre,

- using all data received, regardless of timeliness,
- using all data received before the cut-off, from global processing and from RARS.

Results demonstrated a substantial impact of the data from the global processing centre that do not meet the cut-off; r.m.s. errors in forecast surface pressure at forecast ranges from 1 to 5 days were reduced by ~1% in the Northern Hemisphere and ~3% in the Southern Hemisphere, with significant impacts on analysed fields, particularly in the North Pacific and the southern oceans.

The effect of the RARS data (available in December 2007) was to capture about ~20% of the potential impact of the "late" global data. This demonstrates a significant impact from the RARS data already and also the potential for greater impact if the RARS system were extended to cover a greater proportion of the world (Candy and Atkinson, 2008).

2.3 ATOVS on MetOp

ATOVS data from MetOp-A were introduced into operations as soon as possible after the launch on 19 October 2006; near-real time global data became available from EUMETSAT in December 2007 and were introduced into the Met Office global NWP system on 17 January 2007, only 90 days after launch. For a new satellite and a new ground segment, this represents a remarkable achievement, and it is an excellent example of the value to users of rapid access to new data types.

As a result of limitations on the processing capacity of the Met Office NWP system at the time, MetOp-A ATOVS data could only be introduced as a replacement for NOAA-15 ATOVS data (not as an addition). The impact of this change was tested. The benefit of MetOp data relative to NOAA-15 data was measured in one 14-day assimilation trial as +0.6 on Met Office global NWP index. (This index, which is used as a primary measure of forecast impact here and in subsequent sections, is described in Annex 1). This improvement reflects mainly the superior performance of the new MetOp instruments compared with the rather aged NOAA-15 instruments. For further details, see Candy et al. (2008)

2.4 IASI on MetOp

IASI data were introduced into operations in November 2007, following an intensive period of system development, testing and tuning. The processing and assimilation system and the pre-operational testing are described by Hilton and Atkinson (2008).

In summary, various combinations of channel selection, cloud detection, observation errors and model resolution were tested, and a preferred configuration was chosen for the initial operational implementation. This included the assimilation of 138 selected IASI channels in 4D-Var using observation errors of 0.5K, 1.0K and 4.0K for the 15μm CO_2 channels, the 11μm window channels and the 6μm H_2O channels respectively.

Impact trials were conducted using several configurations for the period 24 May to 24 June 2007. Using the preferred configuration at N216L50 resolution, the global NWP index was increased by +1.2 when verified against observations and +0.8 against analyses, giving an impact of +1.0 overall. This is a very encouraging result for an initial implementation, noting that the impact is within a system that already includes data from 3 ATOVS instruments on NOAA platforms, ATOVS on MetOp-A, AIRS on Aqua and SSMIS on DMSP F-16. Moreover, initial use of IASI data is rather cautious; only cloud-free fields of view over sea are used (except for stratospheric channels, which are also used over land), only a restricted channel set is used, and observation errors are set quite high. Also, we tested the impact of AIRS on the global NWP index for the same period; results were: +0.6 against observations and +0.1 against analysis, giving +0.4 overall. We have found more impact than this from AIRS in other periods (Hilton et al., 2005).

We are therefore confident that there is much more impact to be expected from IASI data as a result of future improvements in processing and assimilation.

2.5 Cloudy AIRS radiances

In our current operational assimilation of AIRS and IASI data, cloud-affected observations are rejected, and so only a small proportion of observations are retained. We have recently developed (Pavelin et al, 2008) a new scheme for assimilating cloud-affected AIRS radiances directly into 4D-Var. Using a simple radiative transfer model for cloudy radiances, we first retrieve the cloud-top pressure and effective fractional cloud-coverage simultaneously with the temperature and humidity profiles, using a 1D-Var scheme. We then use the retrieved cloud values within the radiative transfer calculations as we assimilate these radiances in the 4D-Var system. This is found to be successful as long as only those channels with weighting functions peaking above the retrieved cloud-top are assimilated.

In this way, the amount of AIRS data assimilated is doubled, and the coverage of assimilated data is extended into more meteorologically active areas. The new system was tested for the period December 2006 to January 2007. It gave an improvement of +0.9 on global NWP index. This is equivalent to doubling the overall impact of AIRS data. We plan to make this system operational soon and then to extend its use also to IASI data.

2.6 ASCAT on MetOp

Data from the C-band scatterometer ASCAT on MetOp-A were also introduced in operations in November 2007, following a period of system development, testing and tuning. Raw ASCAT data are processed by the EUMETSAT Ocean and Sea-Ice Satellite Applications Facility (OSI SAF) (see OSI SAF, 2008) and products are delivered to NWP centres as ambiguous wind vectors. We assimilate these in 4D-Var using an observation operator developed for other scatterometers (Candy, 2001).

ASCAT retrieved wind vectors are of very good quality; when compared with forecast background fields, they have a r.m.s. wind speed difference of 1.15 m/s, which compares favourably with equivalent statistics for Quikscat Seawinds and ERS-2 AMI: 1.33 and 1.40 m/s respectively. The C-band ASCAT also has far less rain-contaminated data than the Ku-band Seawinds. This allows ASCAT to provide good data closer to the centre of tropical storms.

In an assimilation trial for the period 24 May – 24 June 2007, addition of ASCAT data improved the global NWP index by +0.35 against observations. Performance was neutral when verified against analysis. These impacts were in the presence of QuikSCAT and ERS-2 data.

Systematic trials of the impacts of scatterometer data have been performed for the same period and are summarised in Table 1.

	Change in global NWP index verified against observations	**Change in global NWP index verified against anaysis**
All scatterometers	+0.97	-0.07
ASCAT only	+0.61	+0.29
QuikSCAT only	+0.66	-0.08

Table 1. Changes in global NWP index for trials compared with a control containing no scatterometer data.

Neutral/negative impacts found in two experiments when verifying against analyses came mainly from 850 hPa tropical winds and are not fully understood. However, such results are not uncommon when new observations are introduced in areas that are otherwise data-sparse and the performance measure is weighted heavily towards short-range forecasts.

In summary, ASCAT data are giving an overall impact similar to Seawinds. These experiments also indicate that a system of two scatterometers providing global coverage provides significantly more benefit to NWP than a system with only one. For further results, see Keogh and Candy (2008).

2.7 Windsat wind vectors

We have been receiving Windsat wind vector retrievals since September 2006. Data are processed by the Naval Research Laboratory, USA (Bettenhausen et al., 2006). We have developed WindSat-specific quality control procedures. In particular, low wind speeds are rejected because of their low information content on wind direction.

We have performed information content studies (English et al., 2006) and assimilation trials in which ambiguous wind vectors are assimilated in a manner similar to Quikscat (Candy et al., 2008). Windsat and Quikscat winds are found to be similar both in their data coverage and in the distribution and magnitude of the analysis increments they produce. A one-month impact trial was conducted for data in August 2005 at resolution N216L38. Overall, the impacts on forecast skill from Windsat and Quikscat data were of the same order, with Quikscat providing more impact on short-range scores and Windsat a little more on medium-range scores.

2.8 GPS radio occultation (RO)

The Met Office first assimilated RO data operationally in September 2006 in the form of refractivity profiles from CHAMP and GRACE-A (Buontempo et al, 2008). However, these data had to be withdrawn in November 2006 as a result of quality control problems at the producing centre (which have subsequently been corrected). In May 2007, we started to assimilate refractivity profiles from the data of 4 COSMIC satellites, and this was extended to 6 COSMIC satellites in November 2007, when improvements to our data processing and assimilation methods were also made (Rennie, 2008).

In April 2008, the vertical range over which data are assimilated was increased from 4-27 km to 0-40 km, following demonstration of small beneficial impacts of the extended vertical range - on extra-tropical humidities, on low level winds and on the temperature bias in lower stratosphere.

Recent experiments have demonstrated that increasing the number of satellites – from 4 to 6 COSMIC satellites, or from 4 COSMIC satellites to 6 COSMIC plus CHAMP and GRACE-A – produce significant performance improvements. It is planned to re-introduce CHAMP and GRACE-A data soon.

The impacts of RO data within the global NWP system are, in summary:

- large impacts on S.Hemisphere forecasts at all ranges for temperature, height and winds, with improvements of >6% in r.m.s. temperature errors verified against sondes at 100 and 250 hPa,
- useful improvements in Tropics in same fields: ~3% in r.m.s. temperature errors at 50, 100 and 250 hPa,
- small but positive impacts in the N.Hemisphere,
- small improvements in humidity analyses.

In the current assimilation system, data from 6 COSMIC satellites provide improvements on the global NWP index of +1.3 against observations and +0.8 against analysis.

2.9 Atmospheric motion vectors (AMVs)

The impact of AMVs within the global NWP system has been tested in two seasons:

For the period 12 December 2005 to 11 January 2006, the following experiments were run:
- control (all observations used operationally in March 2006),
- all AMV data removed,
- all satellite data removed,
- AMVs added to a baseline containing no satellite data.

Removal of AMVs from the full system degraded the global NWP index by 1.8, whereas removing all the satellite data degraded it by 18.8. Introducing AMVs with no other satellite data, then gave an improvement of 8.6. Therefore it is clear that AMVs improve forecasts significantly but that their impact is modest compared to that of satellite sounding radiance data. For more details, see Forsythe (2007).

For the period 12 December 2007 to 12 January 2008, the following experiments were run:
- control (all observations used operationally in November 2007),
- all AMV data removed.

In this period, the impact of removing AMVs was -0.9 on the global NWP index (cf. -1.8 for the first experiment).

Smaller impacts in the second season may be attributable to improvements in the NWP model and the observation usage (e.g. IASI, RO) but may also be caused by meteorological differences between the two periods. When looking at the impact on different forecast domains, variables and ranges, similar patterns of impacts were seen in the two periods. A positive impact of AMVs was found on most fields. Negative impacts were found on tropical surface pressures and tropical height fields. In general, significant problems with quality control and error characterisation of these data are known to remain (Forsythe and Saunders, 2006).

Improvements were observed in the 500 hPa height fields over the polar Northern Hemisphere when the AMVs were assimilated, consistent with patterns seen in MODIS polar wind impact experiments (Forsythe, 2006).

2.10 Ground-based GPS zenith total delay (ZTD)

GPS observations of ZTD are obtained in near real-time from the European E-GVAP GPS network. These data are available at high time resolution, often several per hour, which can potentially be exploited within 4D-Var. Uncertainties in ZTD are related mainly to uncertainties in total column water vapour but also to those in temperature and pressure.

We have been assimilating these data operationally since March 2007. They are used in the North Atlantic and European regional NWP model (12 km grid length, 38 levels) and in the UK area NWP model (4 km grid length). Observations are currently assimilated at a temporal density of one per hour in 4D-Var. Small positive impacts on forecasts of cloud, surface temperature, visibility and precipitation over the UK have been found with the regional NWP system (Jupp, 2006).

3. SUMMARY

We have conducted many experiments demonstrating the impact of a range of satellite data on NWP performance. Results with implications for design of the GOS are:

- Microwave sounders of AMSU class in 3 well-space orbits are close to optimal.
- The Regional ATOVS Retransmission Service is delivering improved timeliness for ATOVS data, with beneficial impact on global NWP.
- The early availability from EUMETSAT of MetOp ATOVS data was an excellent example of service to the NWP user community.
- MetOp IASI data have already delivered substantial impact on global NWP performance from cloud-free radiances.
- A method for assimilating cloudy radiances has been successfully demonstrated with AIRS data, showing that much greater operational impact can be expected from AIRS and IASI data.
- MetOp ASCAT retrieved winds have been shown to be of very high quality, and positive impact on NWP performance has been demonstrated.
- Windsat wind vectors have been shown to give impacts on global NWP of the same order as scatterometers, although the latter have given more impact on short-range forecasts.
- Substantial impact has been demonstrated from GPS-RO data from 6 COSMIC satellites, and increased impact has been shown with data from more than 6 RO receivers.
- AMVs are delivering useful impact within the global NWP system; quality control and error characterisation problems remain.
- Ground-based GPS observations of zenith total data are delivering small positive impacts on UK forecasts from the regional NWP system.

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ANNEX 1. The Met Office global NWP index.

The Met Office global NWP index combines in one measure the overall performance of the system, using skill scores for a number of forecast domains, variables and ranges. Each skill score is calculated as:

$$S = 1 - r_f^2/r_p^2$$

where r_f = r.m.s. forecast error and r_p = r.m.s. persistence error.

The separate skills scores are combined to form a weighted mean, S_{mean}, with the weights given in Table A.1.

		Forecast period				
		T+24	T+48	T+72	T+96	T+120
N.Hem	PMSL	10	8	6	4	4
	H500	6	4	2		
	W250	12				
Tropics	W850	5	3	2		
	W250	6				
S.Hem	PMSL	5	4	3	2	2
	H500	3	2	1		
	W250	6				

Table A.1. Weights used in the Met Office global NWP index

The weights are intended to represent the relative importance of these fields to the Met Office's main customers. They reflect the fact the Met Office global NWP system is focused on short-range forecasts and that most of the customers are in the N. Hemisphere. However, they also reflect the global responsibilities of some of the Met Office's services, including its role as a World Aviation Forecast Centre.

The mean skill score is converted to an index:

$$N = (1 - S_{mean})^{-½} .$$

This index is then normalized:

$$\text{Global NWP Index} = 100 . N / N_0,$$

where N_0 = value of N at 31 March 2000.

The index is computed separately using forecasts verified against observations and against analysed. The combined index is the average of the two. This index stood at 130 on 31 March 2008.

As an aid to interpretation of this index: if r.m.s. forecast errors are reduced by 1% in all fields in Table A.1, then the index increases by 1%.

Adaptive Estimation and Tuning of Satellite Observation Error in Assimilation Cycle with GRAPES

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ABSTRACT

The observation error which is useful for data assimilation is best estimated within an assimilation cycle. In most of today's 3D-var or 4D-var operational assimilation systems, however, the observation error are prescribed. An improper characterization of the observation error statistics will lead to a suboptimal assimilation scheme. Desroziers et al (2005) developed a method to tune observation error using the diagnosis computed from analysis residuals in observation space. In this work we proposed a new implementation of the tuning algorithm and applied it to the estimation and tuning of satellite observation (ATOVS from the NOAA satellites and FY2C cloud motion winds) error in the 3D-Var assimilation system of Chinese Meteorological Administration (CMA) new generation of NWP system GRAPES (Global/Regional Assimilation PrEdiction System). The method is shown to be feasible in a practical tuning of background and observation error for operational variational assimilation. The iteration process converges very rapidly and the results are reasonable . The impacts of the tuning of error on analyses and forecasts in both global and meso-scale configuration are shown and discussed. The latest development of GRAPES is also introduced in the paper. These results are very promising.

Keywords: Adaptive tuning, error estimation, satellite radiances, variational assimilation, AMSU, QPF

1. INTRODUCTION

The fundamental idea of data assimilation method is to find the closest solution between the effective observation and background field (the first guess) in the given periods under the meaning of the least square method by adjusting the first guess. Therefore, accurate estimation of the observation and background error statistics is of vital importance in data assimilation as they determine, at analysis time, the weight and spatial influence function of observations and possibly the impact on other variables. The background error and observation error which is useful for data assimilation is best estimated within an assimilation cycle. In most of today's 3D-var or 4D-var operational assimilation systems, however, the observation error and background error are prescribed. An improper characterization of the observation and background error statistics will lead to a suboptimal assimilation scheme. Desrosies et al(2005) developed a method to tune observation and background error using the diagnosis computed from analysis residuals.

In this work we proposed a new implementation of the tuning algorithm apply it to the 3D-Var assimilation system of Chinese Meteorological Administration (CMA) new generation of NWP system

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GRAPES (Global/Regional Assimilation PrEdiction System). GRAPES 3D-Var is an incremental analysis system that is currently used by both our global and regional models with very little modifications. We use the objective method to tune the background and satellite radiances observation error.

2. DIAGNOSIS OF VARIATIONAL ASSIMILATION AND TUNING APPROACH

2.1 Notation and definition

Let $\mathbf{x}^t$ be the n-dimensionally discretized unknown true state of the atmosphere to be estimated. The information available at a certain analysis time is prior information (or background) $\mathbf{x}^b$, generally provided by a short-term forecast with errors $\boldsymbol{\varepsilon}^b = \mathbf{x}^b - \mathbf{x}^t$, and an observation vector $\mathbf{y}^o$ with dimension p associated with errors $\boldsymbol{\varepsilon}^o = \mathbf{y}^o - H\left(\mathbf{x}^t\right)$, where H is the observation operator mapping the state space onto the observation space. For instance, H is a fast radiative transfer model (RTM) for satellite radiances assimilation. The observation error includes both a relatively well-known instrument error and a somewhat more imprecise error of representative-ness. Both error vectors are assumed to be unbiased; it must be stressed that the issue of bias is very important and that it should be considered before any attempt is made to evaluate covariance matrices especially for satellite radiances. Furthermore, it is assumed that observation and background errors are uncorrelated, which, denoting E the expectation operator, reads $E\left(\boldsymbol{\varepsilon}^b \boldsymbol{\varepsilon}^{oT}\right) = 0$. The analysis $\mathbf{x}^a$ is produced as a linear combination of the background and of the observations using a gain matrix $\mathbf{K}$:

$$\mathbf{x}^a = \mathbf{x}^b + \delta \mathbf{x}^a = \mathbf{x}^b + \mathbf{K}\mathbf{d}_b^o \tag{1}$$

The innovation vector $\mathbf{d}_b^o = \mathbf{y}^o - H\left(\mathbf{x}^b\right)$ is the difference between observation $\mathbf{y}^o$ and their background counterparts $H\left(\mathbf{x}^b\right)$. In statistical linear estimation theory, this estimate is optimal (i.e. the variance of its error $\boldsymbol{\varepsilon}^a = \mathbf{x}^a - \mathbf{x}^t$ is a minimum) when $\mathbf{K}$ takes the form of the Kalman gain(Talagrand,1997):

$$\mathbf{K} = \mathbf{B}\mathbf{H}^T\left(\mathbf{H}\mathbf{B}\mathbf{H}^T + \mathbf{R}\right)^{-1} \tag{2}$$

where $\mathbf{B} = E\left(\boldsymbol{\varepsilon}^b \boldsymbol{\varepsilon}^{bT}\right)$ is the covariance matrix of background errors , $\mathbf{R} = E\left(\boldsymbol{\varepsilon}^o \boldsymbol{\varepsilon}^{oT}\right)$ is the covariance matrix of observation errors and $\mathbf{H}$ the linearized version of H .

2.2 χ^2 diagnostic

The χ^2 test is a way of testing whether a particular random vector belongs to a given Gaussian distribution and the χ^2diagnostic is a measure of consistency between the variances of random variables. This diagnostic has been used in many applications such as as geophysics (Tarantola,1987), atmospheric retrievals (Rodgers,2000) and data assimilation (Talagrand,1999) where the random variable is a residual or innovation. In 3D and 4D-Var, the value of χ^2can be obtained directly from the value of the cost function at the minimum as follows(Bennett et al.,1993)

$$J_{\min} = J\left(\mathbf{x}_a\right) = \frac{1}{2}\mathbf{d}^T\mathbf{D}^{-1}\mathbf{d} \tag{3}$$

where $\mathbf{D} = \mathbf{R} + \mathbf{HBH}^T$, is the prescribed innovation covariance. The expected value of χ^2 is given as

$$E\left(\chi^2\right) = E\left(\mathbf{d}^T\mathbf{D}^{-1}\mathbf{d}\right) = Tr\left(\mathbf{D}^{-1}\overline{\mathbf{D}}\right) \tag{4}$$

where $\overline{\mathbf{D}} = E\left(\mathbf{d}_a^o\mathbf{d}_b^{oT}\right)$,is the sample covariance of the innovations. If the sample covariance of the innovation matches the given or prescribed innovation covariance, i.e. $\mathbf{D} = \overline{\mathbf{D}}$, then

$$E\left(J_{\min}\right) = \frac{1}{2}E\left(\chi^2\right) = \frac{p}{2} \tag{5}$$

where p is the dimension of the observation space or the number of observations. Equation (5) is the necessary optimality criterion to meet the χ^2 diagnostic.

2.3 Consistency diagnostic on innovations, background errors and observation errors

From the definition of the innovation vector, the following sequences of relations can be derived(Desrosies et al.,2005):

$$\mathbf{d}_b^o = \mathbf{y}^o - H\left(\mathbf{x}^b\right) = \mathbf{y}^o - H\left(\mathbf{x}^t\right) + H\left(\mathbf{x}^t\right) - H\left(\mathbf{x}^b\right) \approx \boldsymbol{\varepsilon}^o - \mathbf{H}\boldsymbol{\varepsilon}^b \tag{6}$$

Similarly, the analysis residual $\mathbf{d}_a^o$ and analysis increments in observation space $\mathbf{d}_b^a$ can be written

$$\mathbf{d}_a^o = \mathbf{y}^o - H\left(\mathbf{x}^a\right) \approx \mathbf{y}^o - H\left(\mathbf{x}^b\right) - \mathbf{HKd}_b^o = \left(\mathbf{I} - \mathbf{HK}\right)\mathbf{d}_b^o \tag{7}$$

$$\mathbf{d}_b^a = H\left(\mathbf{x}^a\right) - H\left(\mathbf{x}^b\right) \approx \mathbf{H}\delta\mathbf{x}^a = \mathbf{HKd}_b^o \tag{8}$$

Then, the covariance of innovation is

$$E\left(\mathbf{d}_b^o\mathbf{d}_b^{oT}\right) \approx E\left(\boldsymbol{\varepsilon}^o\boldsymbol{\varepsilon}^{oT}\right) + \mathbf{H}E\left(\boldsymbol{\varepsilon}^b\boldsymbol{\varepsilon}^{bT}\right)\mathbf{H}^T = \mathbf{R} + \mathbf{HBH}^T \tag{9}$$

using the linearity of the statistical expectation operator E and assuming that observation error and background error are uncorrelated. If the convariance of observation error $\mathbf{R}$ and the covariance of background errors in observation space $\mathbf{HBH}^T$ are correctly specified in the analysis, then $\mathbf{D} = \overline{\mathbf{D}}$.This is a classical result that provides a global check on the specification of those covariances.

Furthermore, the cross-product between $\mathbf{d}_b^o$ and $\mathbf{d}_a^o$ is

$$E\left(\mathbf{d}_a^o\mathbf{d}_b^{oT}\right) = \mathbf{R}\left(\mathbf{R} + \mathbf{HBH}^T\right)^{-1}E\left(\mathbf{d}_b^o\mathbf{d}_b^{oT}\right) = \mathbf{RD}^{-1}\overline{\mathbf{D}} \tag{10}$$

the cross-product between $\mathbf{d}_b^a$ and $\mathbf{d}_b^o$ is

$$E\left(\mathbf{d}_b^a\mathbf{d}_b^{oT}\right) = \mathbf{HBH}^T\left(\mathbf{R} + \mathbf{HBH}^T\right)^{-1}E\left(\mathbf{d}_b^o\mathbf{d}_b^{oT}\right) = \mathbf{HBH}^T\mathbf{D}^{-1}\overline{\mathbf{D}} \tag{11}$$

If the covariances of observation error and the background errors are correctly specified in the analysis, then

$$E\left(\mathbf{d}_a^o\mathbf{d}_b^{oT}\right)=\mathbf{R} \tag{12}$$

$$E\left(\mathbf{d}_b^a\mathbf{d}_b^{oT}\right)=\mathbf{HBH}^T \tag{13}$$

These diagnostics, (10) and (11) provide separate consistency checks on observation error covariances and the background errors covariance respectively. Furthermore, (10) and (11) are defined in observation space which can be directly computed from the innovations and analysis residuals, without extra computations. In the case that the prescribed error statistics are incorrect, (10) and (11) can be can be used to tune the background and observation error in observation space. This is a nonlinear problem since the $\mathbf{d}_b^a$ and $\mathbf{d}_b^o$ depend themselves on $\mathbf{R}$ and $\mathbf{HBH}^T$. The form of those nonlinear equations suggests the use of an iterative fixed-point method to solve this tuning problem(Desroziers and Ivanov ,2001). The diagnostics of equations (5),(12) and (13) potentially provide information on the minimum cost function and the full covariances of observation and background in observation space.

2.4 Adaptive tuning of background and observation error with the estimation of $\mathbf{D}^{-1}\overline{\mathbf{D}}$

Desroziers et al. (2005) use the diagnostics (12) and (13) to tune observation and background error variances(i.e. the diagonal element of the covariance matrix) by (12) and (13) which implies that $\mathbf{D}^{-1}\overline{\mathbf{D}}\approx\mathbf{I}$ at each iteration. As a consequence, if the observation and background error are all overestimated at the beginning, $\mathbf{R}$ and $\mathbf{HBH}^T$ will be underestimated at the first iteration, and then will be overestimated at the second iteration. Although the iteration scheme will always converge, it can be converge more rapidly if $\mathbf{D}^{-1}\overline{\mathbf{D}}$ are properly estimated. In order to this, we use the relation that

$$\mathbf{D}^{-1}\overline{\mathbf{D}}=\left[E\left(\mathbf{d}_b^a\mathbf{d}_b^{oT}\right)+E\left(\mathbf{d}_a^o\mathbf{d}_b^{oT}\right)\right]^{-1}E\left(\mathbf{d}_a^o\mathbf{d}_b^{oT}\right) \tag{14}$$

The optimal criterion becomes: the tuning observation and background error are those for which Eqs. (5),(12) and (13) are exactly satisfied. The algorithm is based on the realization that Eqs. (10) and (11) can be understood as a fixed-point relation that can be written symbolically as $\mathbf{s}=\mathbf{F}(\mathbf{s})$.The solution can be obtained iteratively: if $\mathbf{R}_k$ and $\mathbf{B}_k$ are the convariance matrix at step of the algorithm, k+1is computed from with this estimation, the procedure for tuning of background and observation error is as follows:

$$\begin{cases}\mathbf{P}=\left[E\left(\mathbf{d}_b^a\left(\mathbf{R}_k,\mathbf{B}_k\right)\mathbf{d}_b^{oT}\right)+E\left(\mathbf{d}_a^o\left(\mathbf{R}_k,\mathbf{B}_k\right)\mathbf{d}_b^{oT}\right)\right]^{-1}E\left(\mathbf{d}_b^o\left(\mathbf{R}_k,\mathbf{B}_k\right)\mathbf{d}_b^{oT}\right)\\ \mathbf{R}_{k+1}=E\left[\mathbf{d}_a^o\left(\mathbf{R}_k,\mathbf{B}_k\right)\mathbf{d}_b^{oT}\right]\mathbf{P}\\ \mathbf{HB}_{k+1}\mathbf{H}^T=E\left[\mathbf{d}_b^a\left(\mathbf{R}_k,\mathbf{B}_k\right)\mathbf{d}_b^{oT}\right]\mathbf{P}\end{cases} \tag{15}$$

3. APPLICATION OF THE METHOD TO GRAPES 3DVAR

We have tuned the background and radiosonde observation error firstly and then started to use the temperature sensitive radiances from the AMSU-A (Microwave Sounding Unit A) instruments and the water sensitive radiances from the AMSU-B(Microwave Sounding Unit B) instruments onboard NOAA-16, and NOAA-17. The tuning was performed following the approach proposed in Section 2. The experiment domain is East Asia region(55E~145E,5N~65N), on which the regional-meso version of GRAPES produce 72h forecast every day operationally at National Meteorological Center(NMC) of CMA. The tuning 3D-Var experiments are performed each day at 00 UTC from 1 June to 14 June 2007 for radiosonde observation and AMSU-B, while at 06 UTC from 1 June to 14 June 2007 for AMSU-A because of the availability of observation in this region. For each of radiosonde observation types, an independent tuning was performed at each of the following pressure levels: 1000, 925, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20 and 10 hPa. For satellite radiances, an independent tuning was performed at each channel, the covariances between channels are not considered in the present study.

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3.1 Tuning of background and radiosonde observation error variances

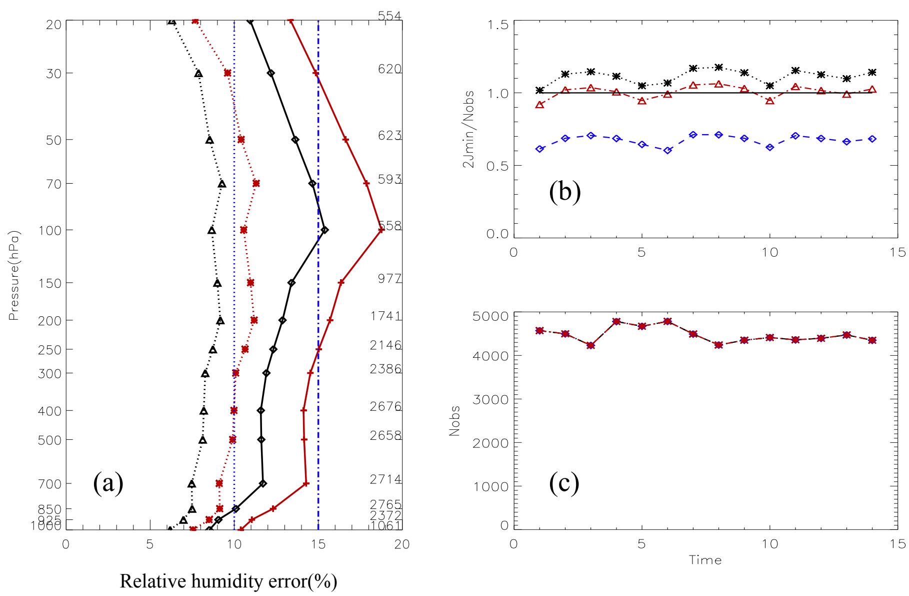


Fig. 1. (a)Vertical profiles of tuned square roots of background relative humidity error(solid with plus sign) and observation (dotted with asterisk) error variances for radiosonde observations in the East Asia region(55E~145E,5N~65N) during the period after the first iteration defined by (17), compared with the corresponding tuned profiles for background profile(solid with diamond) and observation(dotted with triangle)after the first iteration defined by (12) and (13), the corresponding profiles for prescribed background(dash-dotted) and observation errors (dotted) are also shown. All values are in %. The numbers of observations used to compute statistics at every pressure level are shown in figure. (b) The ratio of the cost function minimum and the half of the observation number:min2/*Jp*, with prescribed background and observation error(dashed with diamond), after 1 iteration defined by (12) and (13) (dotted with asterisk) and after 1 iteration defined by (17) (dash-dot with triangle) .(c) The number of used radiosonde relative humidity observations at every 3D-Var assimilation for the prescribed error(dashed with diamond), 1st iteration defined by (12) and (13) (dotted with asterisk) ,1st iteration defined by (17) (dash-dot with triangle).

Figure 1 shows the evolution of one iteration of the tuning profiles for radiosonde relative humidity error. The prescribed background and observation error are 15% and 10% respectively at every pressure level. With the estimation of **P** proposed in section 2(Equation 14), first iteration is shown to be a better approximation than the that without the estimation of **P**, as shown in Figure 1b, the minimum of cost function meets the χ^2 diagnostic(Equation 5) after 1st iteration. In this experiment, both the prescribed background and observation error are overestimated, the background and observation error are underestimated at the first iteration without the estimation of **P** as stated in section 2. The observation number at each pressure levels to compute the statistics are also shown in figure 1(a) and the numbers of used radiosonde relative humidity observations in iterations at every 3D-Var assimilation are shown in figure 1(c), the numbers of observations with different observation error profile are nearly the same, which is different from AMSU radiances assimilation due to the first guess check in quality control as shown in section 3.2. Other error of radiosonde observations are all tuned similarly which is not shown here, and the similar results has been obtained. It also indicated a nice property of the algorithm that the first iteration of the fixed point used here converges very quickly.

3.2 Tuning of satellite radiances observation error

One of the advantages of variational data assimilation is its ability to assimilate indirect observations such as satellite radiances. With the help of RTM , most Numerical Weather Prediction(NWP) Centers are now able to directly assimilate radiance data and these have produced significant gains in the quality of operational analyses and forecasts. It is tempting to use this algorithm with satellite radiances whose observation operator is nonlinear, though linearized in an incremental scheme for which the standard deviation is poorly known. The radiances observation error is often estimated based on some ad hoc approaches, such as Chouinard and Hallé (1999), which assumes that observation error variance is equal to 2/3 of the innovation variance (the remaining error variance represents background error variance). In this section, the results obtained with satellite radiances are presented.

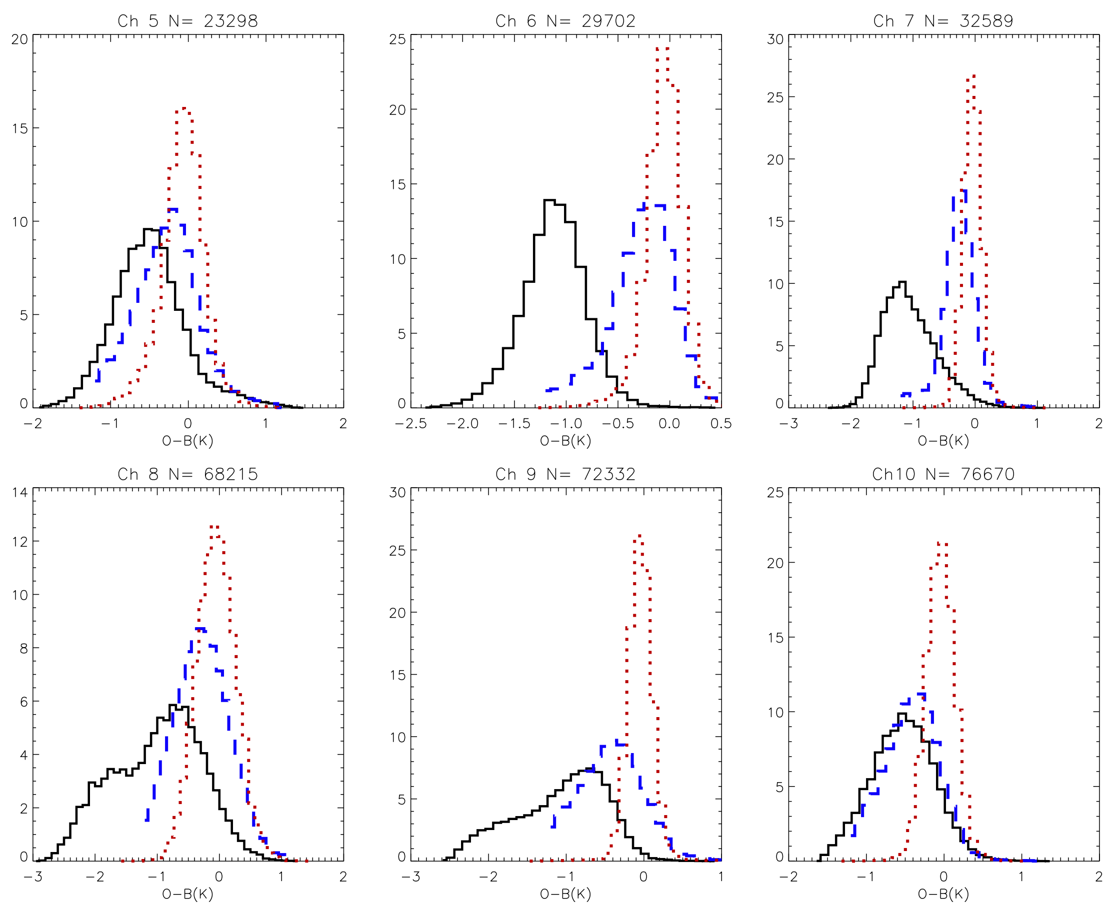
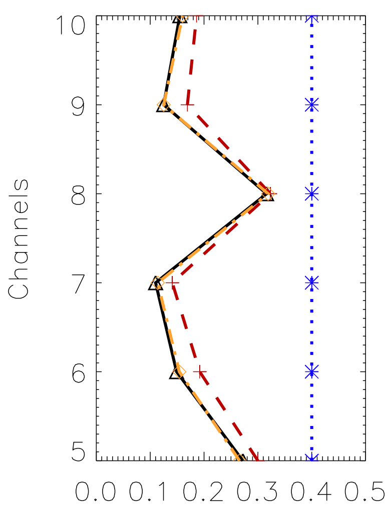


Fig. 2. Frequency histograms of innovations(observation minus backgroud) before (solid lines) , after (dashed lines) bias correction and residual(dotted line) for NOAA-16 AMSUA(Channe5—Channel0,). They are from all data which pass QC with the observation error of operational setting from NOAA-16 AMSUA for 14 days in June 2007,from June 1st 2007 to June 14th 2007 on every 00UTC in the 6h time window. The numbers on each figure title denote the observation numbers for each channel . The units for vertical axis are percent and the units for innovations and residuals are K.

The observations are satellite radiances from the available channels of NOAA* satellites: NOAA-16 and 17 for experiments carried out at every 06 UTC for AMSU-A and 00 UTC for AMSU-B from 1 June to 14 June 2007 due to the availability of the observation. Satellite radiances may be spatially correlated, however a 'thinning' procedure (retaining only one set of radiances in a 100 km box) was used. It is therefore assumed that the possible correlation between observation errors is too small to modify the results. Furthermore, an air-mass and scan bias correction was also used (W.Han et al,2006) to make sure that observation error are to be unbiased, as shown in figure 2 for NOAA-16 AMSU-A. The experiments presented here only deal with the following 10 channels: AMSUA 5–10 which are operationally assimilated in GRAPES 3D-Var. In the experiments that were carried out, the tuning was computed only for these channels. A particular feature of the implementation of the algorithm for the tuning of radiances is that the background error is not tuned which has been tuned together with radiosonde data. As was seen in section 2, this should not qualitatively modify the results if the background error has been well tuned.



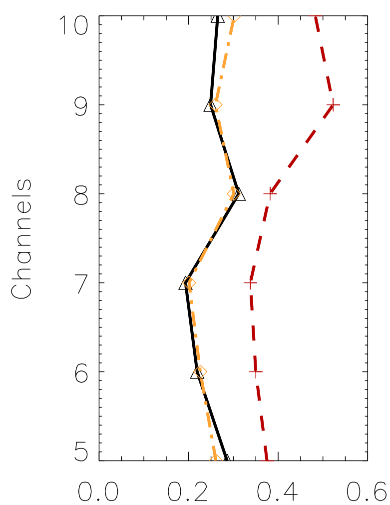


Fig. 3. Tuning results of observation error of NOAA16 AMSUA (a), and the corresponding background error projected on the observation space for AMSUA of NOAA16 (b) . The units are K. The dotted line with asterisk sign in (a) is the operational setting before tuning, while the dashed line with plus sign , solid line with triangle sign and dash-dotted line with diamond are for 1st,2nd and 3rd iteration results respectively. The dashed line with plus sign , solid line with triangle sign and dash-dotted line with diamond in (b) are for 1st,2nd and 3rd iteration results for corresponding background error projected on the observation space for AMSUA of NOAA16 .

The evolution of three iterations of the tuning are shown in figure 3, for NOAA-16 AMSUB (a) and NOAA-17 AMSUB (b).These tuned errors are also listed in Table 1 and Table 2. The corresponding background error projected on the observation space are also shown in figure 3 for AMSUB of NOAA-16(c) and NOAA-17(d). It shows that the convergence of the proposed iterative algorithm for satellite radiances observation error tuning is a bit slower than that for radiosonde observation as shown in figure 3 and 4. One of the reason is probably the interaction between the observation error tuning and the quality control(QC) for radiance assimilation which consists of a background check, only those whose innovation $\left|\mathbf{d}_b^a\right| = \left|\mathbf{y}^o - H\left(\mathbf{x}^b\right)\right| \le \alpha\sigma_o$ can pass the background check, where α a positive real number and σ_o the observation error. It is obvious that number of observations which passed QC in the original setting is greater than that for the first and second iterations as shown in figure 4(b) since the observation error are overestimated in the original setting(figure 4).

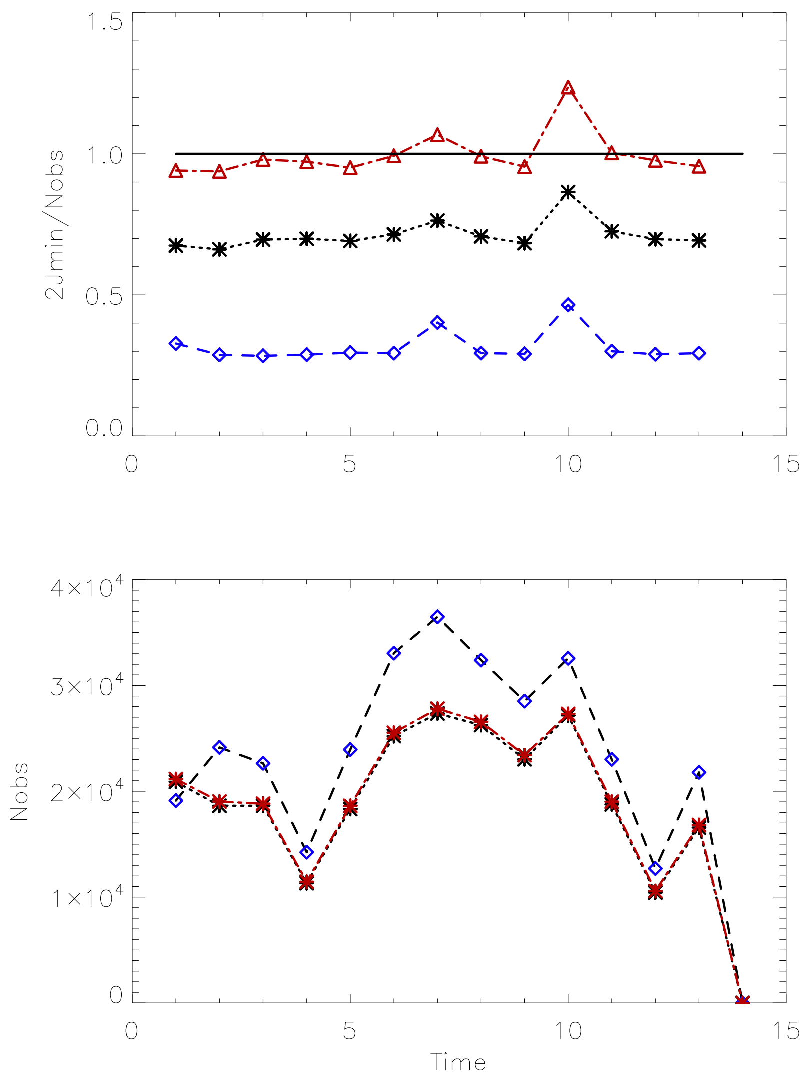


Fig. 4. (a) The ratio of the cost function minimum and the half of the observation number:min2/*Jp*, with prescribed AMSU-A observation error(dashed with diamond), after 1 iteration (dotted with asterisk) and after 2 iteration (dash-dot with triangle) .(b) The number of used AMSU-A observations at every 3D-Var assimilation from June 1st 2007 to June 14th 2007 on every 00UTC in the 6h time window, with prescribed AMSU-A observation error(dashed with diamond), after 1 iteration (dotted with asterisk) and after 2 iteration (dash-dot with triangle).

4. IMPACT ON ANALYSIS AND FORECAST

In order to evaluate the impact of the AMSU-A radiances and the observation error tuning, we prepare Observation System Experiments (OSE) without and with AMSU-A data assigning different observation error to measure their impact in a full analysis/forecast system. It is generally accepted that to get a clear signal, the OSE should cover a period of at least 1 month. In the present study, we have performed two months OSE experiment, one month for summer and one month for winter. Due to the pages limitation, only a 2-week period experiment results in this summer (1-14 June,2007) are shown in this paper.

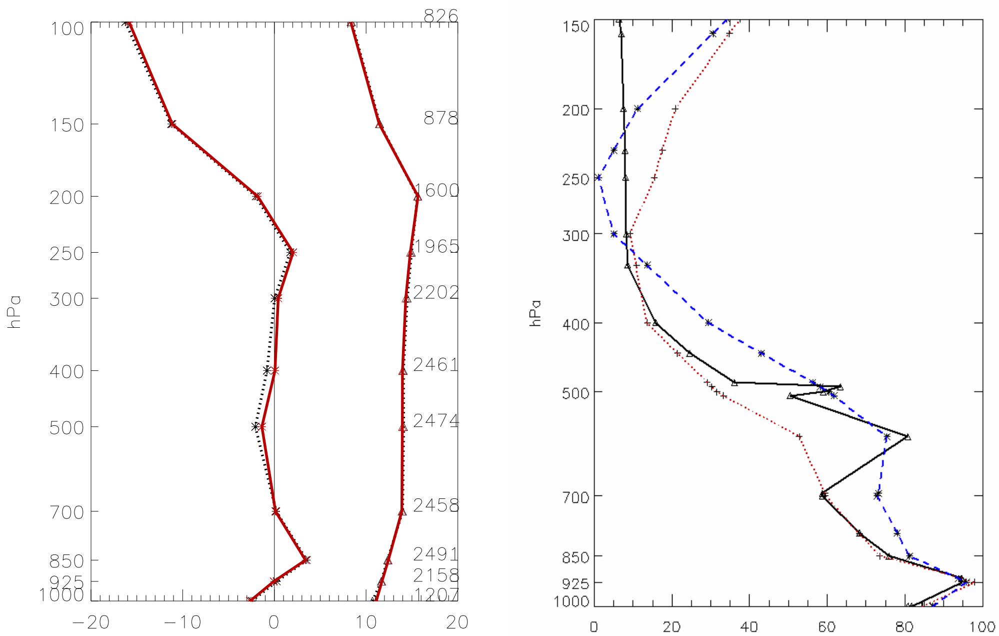


Fig. 5. Analysis biases and standard deviations (std) against radiosonde relative humidity observation. (a) The the 2-week averaged verification of “control” and “test” against radiosonde relative humidity observation, bias of “control”(dotted with asterisk), bias of “test”(solid with asterisk), std of “control”(dotted with triangle) and std of “test”(solid with triangle), the numbers of observations used to compute statistics at every pressure level are also shown. (b) The verification at Nanjing station on 00 UTC 9th June,2007.The background relative humidity (dotted with plus), radiosonde observation of relative humidity(solid with triangle), analysis after assimilation of AMSU-B with tuned observation error(short dashed with asterisk).

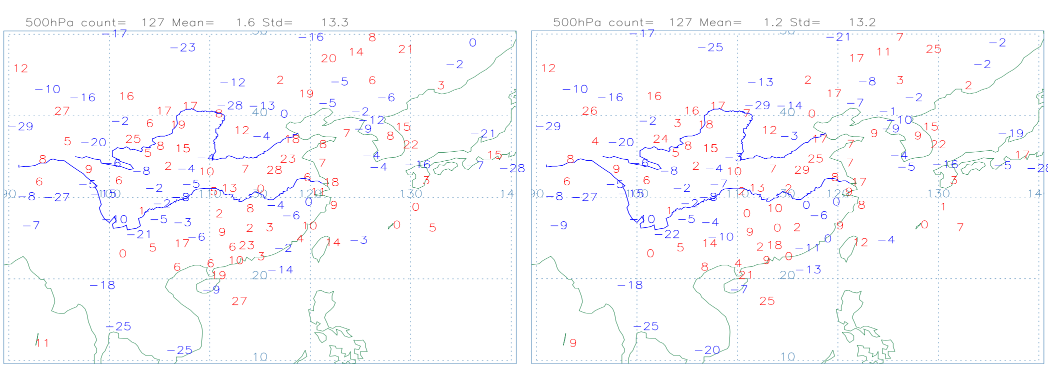


Fig. 6. Departure of relative humidity. (a) “reference”. (b) “test”, against radiosonde at the pressure level of 500hPa on 00 UTC 9th June 2007.

Figure 5 and Figure 6 show the impacts of AMSU-B and the observation error tuning on analysis. The verification is against the radiosonde data for the “control”(background without assimilation any observation), “reference”(assimilation with AMSU-B data with the operational error assignment) and the “test”(assimilation with AMSU-B data with the tuned error assignment). In figure 5(a), the 2-week averaged verification shows that the assimilation of AMSU-B slightly improve the humidity analysis for the middle troposphere(700hPa-400hPa), where the background is more drier than the radiosonde observation. Figure 5(b) shows the verification comparisons on 00 UTC 9th June 2007, and the results at a radiosonde station are also shown. In figure 6(a), the background has dry bias in the South China, after assimilation of AMSU-B data, the analyses of humidity are improved. From the verification, it is clear that the assimilation AMSU-B with the tuned observation error produced a proper response in GRAPES 3D-Var system.

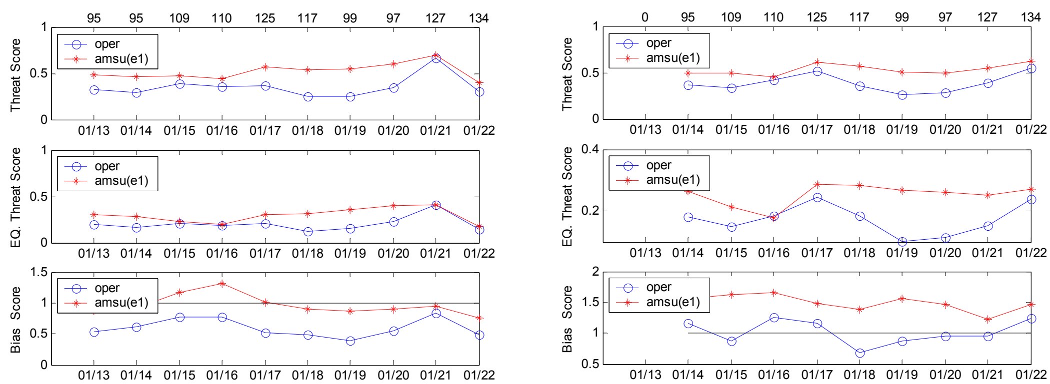


Fig. 7. The impacts of AMSU-B observation error tuning on 24h (left) and 48h (right) QPF scores. “Oper” is for “reference” and “tuned”for “test”.

We performed the verification at five levels of accumulated rainfall in 24 hours: level I(>0.1mm), II(>10mm), III(>25mm), IV(>50mm), V(>100mm). Figure 7 shows 24h and 48h threat scores, equitable threat scores and bias scores for level I accumulated rainfall verification every day, and It is obvious that the tuned AMSU observation error has a positive impact on the 24h and QPF scores, except a slightly negative impact on level I threat score of 48h QPF.

5. Latest development in the global assimilation/prediction experiment：2008

Besides adaptive tuning of satellite observation error, we have also improved GRAPES as following:

- SEMI-Bias Correction in background
- Modify the QC of satellite radiances
- Introduce NOAA-15
- Improve the surface albedo
- Introduce the diagnostic cloud ref. ECMWF
- Introduce the new O3 data
- Daily SST

Two experiments are performed, Exp2008 with Modification as above, Exp2007 without Modification. Observation data set in the experiment is listed on table 1. Figure 8 shows anomaly correlations of 500hPa geopotential height verified against NCEP analyses. We note that

GRAPES has a similar performance with NCEP in the Northern Hemisphere, The new experiment (Exp2008) improved the analyses significantly in the Southern Hemisphere although does not finish yet.

Table 1: *Observation data set in the experiment from 12 UTC 1 Jan 2006 to 30 Nov 2007. H, RH, u and v stand for Geopotential height, relative humidity, and u and v wind components.*

Type of Data	**Description**
AMSU	NOAA15,16,17 microwave radiances
TEMP	Radiosondes H, RH , u and v
SYNOP	Surface Observations from land stations: measuring H, RH , u and v
SHIPS	Surface Observations from ship stations: measuring H, RH , u and v
AIREP	Aircraft measurements of T, u and v
SATOB	Atmospheric Motion Vectors derived from satellite cloud imagery

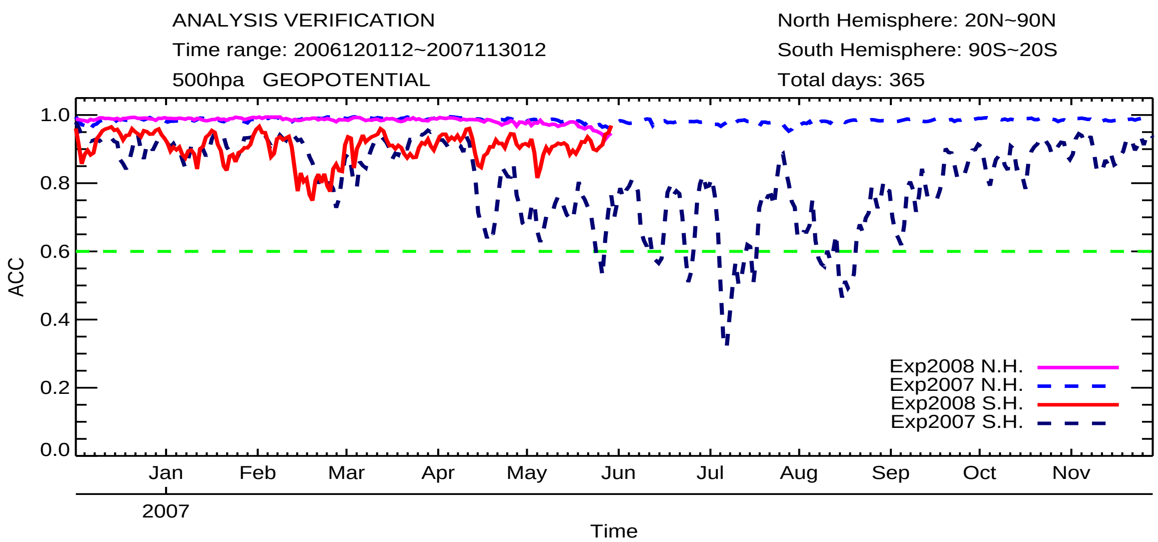


Fig.8 500hPa geopotential height anomaly correlations, verified against NCEP analyses

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Overview of observation impact studies within the HIRLAM community

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Harald Schyberg, Norwegian Meteorological Institute

1. Introduction

The HIRLAM program is established between the weather services in Denmark, Finland, Ireland, Netherlands, Norway, Spain and Sweden for development of short range weather forecasting systems. The present phase of HIRLAM, the “HIRLAM-A” program, has three general targets: (1) An improved synoptic scale forecasting system (grid resolution around 10 km); (2) A mesoscale forecasting system (grid resolution a few km); (3) A probabilistic forecasting system, in the first instance intended for the synoptic scales. For the development of the mesoscale forecasting system, collaboration has been established with the ALADIN community, including Meteo-France. It is intended that the mesoscale forecasting system, based on the Integrated Forecasting System (IFS) of the ECMWF, will replace also the HIRLAM synoptic scale forecasting system after a few years.

Experimentation with the goal to measure the impact of various observation types is an integrated part of the development of numerical weather prediction systems. Many efforts within the HIRLAM community have been devoted to the development of observation operators for various new satellite and radar data, in general made possible through external funding. Much smaller efforts have been devoted to general data impact studies with the objective to improve the overall performance of the HIRLAM forecasting system. One exception is the participation of HIRLAM in EUMETNET/EUCOS data network studies (Amstrup, 2006a, 2006b, Thyness and Schyberg, 2007) and the recently initiated Comprehensive Impact Studies (CIS). This report provides an overview of data impact studies within the HIRLAM community.

2. The HIRLAM synoptic scale forecasting system

The HIRLAM synoptic scale forecasting system is intended for a 10 – 20 km horizontal resolution, and it consists of the grid-point hydrostatic, semi-Lagrangian and semi-implicit forecast model and a variational data assimilation, applied in 3D-Var (Gustafsson et al., 2001, Lindskog et al., 2001) or 4D-Var (Huang et al., 2002) mode. Most HIRLAM participants apply 3D-Var operationally, 4D-Var was recently (January 2008) implemented operationally at the Swedish Meteorological and Hydrological Institute.

The HIRLAM variational data assimilation is based on an incremental formulation closely following Courtier et al. (1994) and a statistical balance background error constraint formulated in spectral space, closely following Berre (2000). The tangent-linear and adjoint models of HIRLAM 4D-Var are based on the spectral HIRLAM (Gustafsson and Huang 1996) with an efficient and stable semi-Lagrangian time integration (Hortal, 2002). 3D-Var is mostly applied together with an incremental Digital Filter Initialization (Lynch and Huang, 1992), while with 4D-Var it has proven satisfactory to apply a weak digital filter constraint (Gustafsson, 1991) within the 4D-Var minimization. The simplified physics package of Janiskova et al. (1997) is applied in HIRLAM 4D-Var.

3. HIRLAM impact studies in connection with development of observation operators

The main aim of the HIRLAM collaboration is operational weather forecasting, and this of course also includes development and implementation of techniques for utilization of satellite and other remote sensing observations. The internally financed resources for this development work at the weather services have been quite small, however. In order to achieve something, external funding has to a large extent been utilized. This has resulted in an impressive list of observation operators available in the HIRLAM variational data assimilation code and the corresponding scientific papers and research reports. Examples are AMSU-A radiances over sea (Schyberg et al., 2003), AMSU-A radiances over sea ice (Thyness et al., 2005), radar radial wind vectors (Lindskog et al., 2004), GPS ground-based zenith delay data (Gustafsson, 2001, Huang and Vedel, 2004), wind profiler data, MODIS water vapor retrievals and EUMETSAT SEVIRI radiances (Geijo and Amstrup, 2005). Due to various reasons, most of these development efforts never went as far as being implemented into the reference HIRLAM system, and only some of them are being applied operationally by participating weather services.

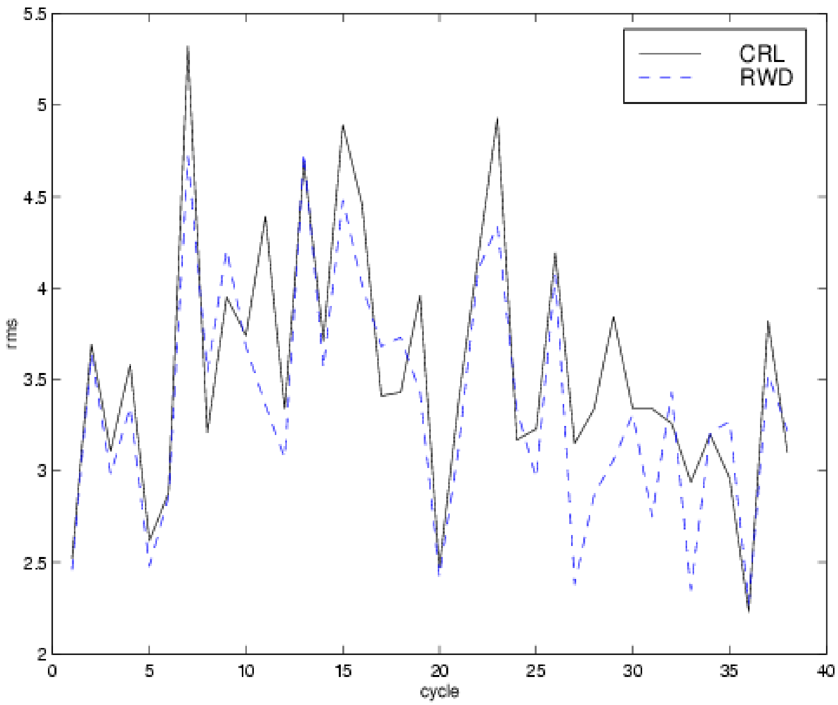

Figure 1: RMS forecast verification scores for 700 hPa wind speed, verified against radiosonde data, from experiment with (RWD) and without (CRL) radar radial wind super-observations. The data period is 1 – 10 December 1999.

One example of a pioneering HIRLAM development was in the use of radar radial wind vectors (Lindskog et al., 2004). The raw radial wind vectors are subject to an efficient de-aliasing algorithm and pre-processed to super-observations based on spatial averaging. The observation operator is quite comprehensive taking account of the radar beam bending due to refractivity processes as well as the vertical spread of the radar beam, modeled by a Gaussian PDF. An early example of the impact of radar radial wind vectors on HIRLAM forecast quality is given in Figure 1.

4. HIRLAM impact studies for EUCOS at the Norwegian Meteorological Institute

In the EUCOS Space-Terrestrial study a series of Observing System Experiments (OSEs) was carried out to establish the impact, in the European context, of selected terrestrial observation data of varying density, over and above what we get from current space-based data. There was also a space component of the studies, described in Kelly and Thepaut, 2007. The terrestrial part of the studies was done by sequentially adding conventional observations from e.g. aircraft, radiosonde (including ASAP) and surface data onto a “Baseline” system, where a full set of space-based observations, but a minimum set of conventional terrestrial observations was used (see Andersson et al, 2004 for a more detailed description and motivation for the observation scenarios). A study group was established by EUCOS to assess the impacts in various operational global and regional NWP systems. From the HIRLAM consortium the Danish (Amstrup, 2006a, 2006b) and Norwegian Meteorological institutes participated. Here we present some results from the Norwegian studies (Thyness and Schyberg, 2007). The observation scenarios specified from Andersson et al, 2004, were investigated in parallel suites within two periods: December 2004-January 2005 (a period with several severe storms passing Northern Europe) and August 2005. The Norwegian experiments were run with 6 hours cycling of the HIRLAM 3D-Var using conventional data according to the various scenarios, and also using AMSU-A data, scatterometer winds and Meteosat Atmospheric Motion Vectors (AMVs) in all experiments.

The quality of the suites was assessed by validation statistics against the EWGLAM list of surface and radiosonde stations. It was demonstrated that the conventional upper-air observations have a large positive effect on the forecast quality in the operational setup at the Norwegian Meteorological Institute, and radiosondes are still a major contributor to the forecast quality. The “Control” experiment with the full combined observing system verifies significantly better than the minimum system used in the Baseline scenario, using a few radiosondes only, even in the presence of all available satellite data. Wind and temperature from radiosondes are equally important, while radiosonde humidity gives little added effect. The gain in quality from new satellite data sources and fast delivery systems such as the Eumetsat Advanced Retransmission System, can not outweigh the loss from receiving fewer radiosondes as defined in the “Baseline” scenario at present.

The results from two of the simulated scenarios show that AMDARs and AIREPs profiles complement the radiosondes and further improve the forecast skill of the HIRLAM model. This is clearest for the winter period, whereas for the summer it seems that the added impact of these observations is much smaller.

Some cases of extreme wind in Northern Europe were studied in more detail. These case studies generally confirmed the results concerning the overall merits of the various scenarios found in the EWGLAM verification statistics. From the case studies, some cases of storm developments over ocean gave a particularly good influence of added E-ASAP data.

The results from the scenario adding the E-ASAP network show that even the very limited number of radiosondes located in data sparse regions in the oceans can have a significant impact on the forecasts. This signal is clearest for the summer period, whereas for the winter period as a whole the impact of the E-ASAP network is neutral. However, during the period with large synoptic activity in January they seem to contribute in a positive way, and also, with the inclusion of the sondes on the North Sea platform EKOFISK and ocean weather ship MIKE, the E-ASAP network has an overall positive impact.

The study clearly shows the benefit of the various observation types supported by EUCOS in the regional model used at the Norwegian Meteorological Institute. The quantification of the various impacts given here can, together with cost assessments for the various components, assist the development of a future cost-effective observing system for regional weather forecasting.

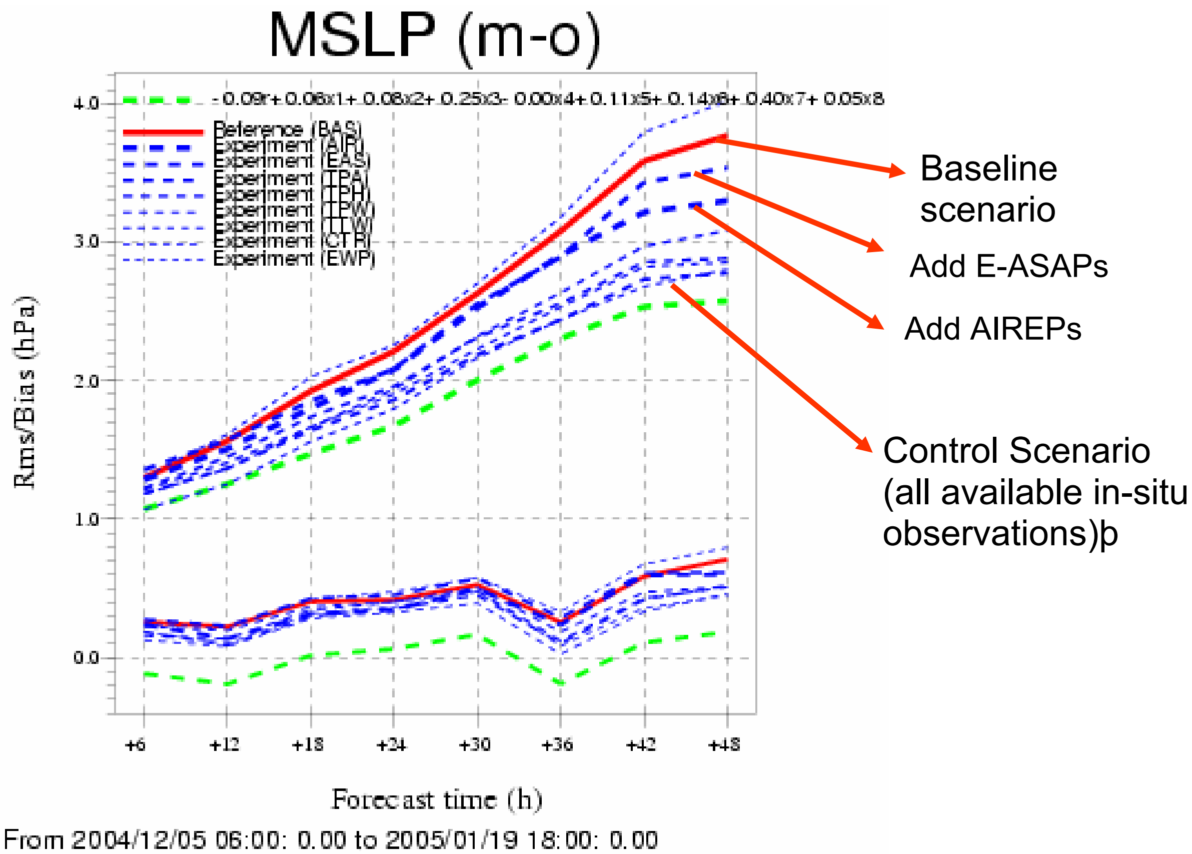

Figure 2: Time series of root mean square error and bias compared to EWGLAM surface observations for Mean Sea Level Pressure against forecast range. Results from the winter experimental period.

5. HIRLAM Comprehensive Impact Studies (CIS)

The synoptic scale forecast verification scores for HIRLAM have for years been lagging behind those of competing forecasting centers for the same forecast range. One main reason is the very limited use of satellite and other remote sensing data in the operational HIRLAM implementations. Another reason is the inherent difficulty of limited area data assimilation schemes to utilize large-scale information, for example provided by observations outside the model domain.

In an attempt to improve the situation with regard to the use of observations in HIRLAM, the concept of Comprehensive Impact Studies (CIS) was established during autumn 2007. The basic idea of CIS is to try to advance through a few coordinated “Great Leaps” with participation from several HIRLAM countries. Each CIS should, and this is important, also include all the necessary preparations for operational introduction of the new data types at the participating weather services, for example data transmission procedures, data pre-processing, data calibrations, bias corrections, quality control algorithms and easy-to-use instruction manuals.

Two series of CIS have so far been planned for the synoptic scale HIRLAM. The Atlantic scale CIS concentrates on data assimilation for weather disturbance coming in from the Northern Atlantic and from the Arctic. These experiments are carried out with 4D-Var, with a grid resolution of 15 km, with 60 vertical levels and over a rather large domain covering Europe, Northern America and the Arctic. Important new observation types for this CIS are AMSU radiances, AMVs from geostationary satellites as well as from the MODIS instrument and Seawind scatterometer winds. A second CIS will be devoted to forecasting of summertime convection with the synoptic scale HIRLAM at 5-10 km grid resolution over an area coving the continental parts of Europe. One may argue that the initial wind and moisture fields will be crucial with regard to this forecasting task. Thus, the impact of radar radial winds, ground-based GPS measurements of zenith delay and EUMETSAT SEVIRI water vapor radiance measurements will be tested in this summer time convection CIS.

6. Some results from the HIRLAM Atlantic scale CIS

The HIRLAM Atlantic scale CIS has been carried for one summer period 25 July – 24 August 2006 and one winter period 1 – 28 February 2007. The following experiments have been done so far:

Conventional: Radiosonde, SYNOP, SHIP, DRIBU, AIREP and AMDAR observations

Baseline: Conventional + AMSU-A radiances over sea (as in the HIRLAM reference system)

Allinclusive: Conventional + AMSU-A over sea, sea ice and land + AMSU-B over sea + SEAWINDS scatterometer winds + Air moiton vectors from geostationary satellites and MODIS

No AMSU: Allinclusive – AMSU A and B radiances

No AMSU-B: Allinclusive – AMSU B radiances

No AMV MODIS: Allinclusive – AMV MODIS

No AMV GEO: Allinclusive – AMV geostationary satellites

No Seawinds: Allinclusive – Seawinds scatterometer winds

Forecast verification scores for the winter period indicate a clear total positive impact of the new observation types tested in the HIRLAM Atlantic scale CIS for the winter period, while the results for the summer period indicate a more neutral impact. As one example, the surface pressure verification scores, verifying mean sea level pressure against SYNOP observations, are presented in Figure 3.

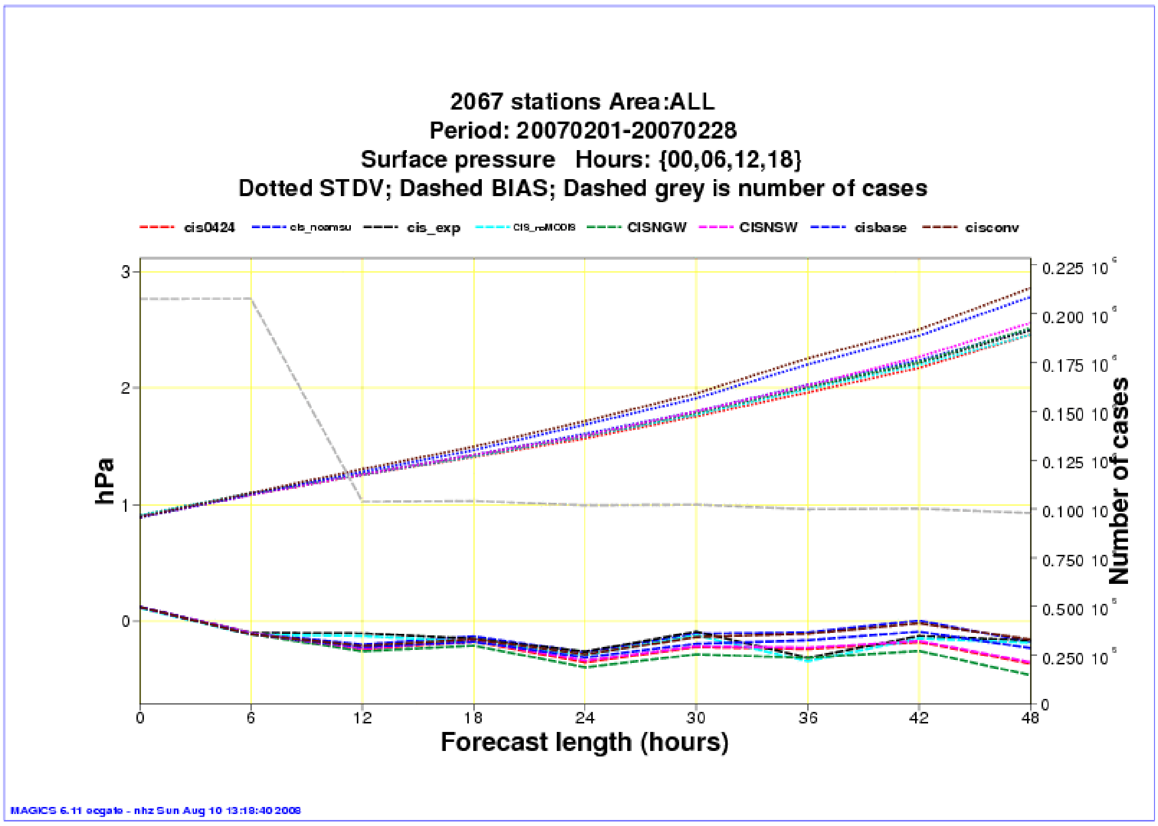

Figure 3: Bias and Standard deviation forecast verification scores for the Atlantic scale CIS with HIRLAM 4D-Var. Time period 2-28 February 2007. cis0424 = Allinclusive, cis_noamsu = No AMSU, cis_exp = No AMSU-B, cis_nomodis = No AMV MODIS, CISNSV = No AMV GEO, cisbase= Baseline and cisconv= Conventional.

The results indicate significantly reduced standard deviation forecast verification scores when the **Allinclusive** experiment is compared with the **Conventional** and **Baseline** experiments. Inspecting the time-series of the verification scores (not shown here), it is evident that the positive impact originates from a single event, the 3-day period 7-9 February 2007. The large influence of a single event on the time averaged verification score in Figure3 tells us that a one month period is far too short to avoid the influence due the chaotic character of the atmosphere (a quality control decision influenced by some small differences in background model states or the availability of supporting observations may well explain the large impact during the 3 day period – this hypothesis needs to be confirmed by more investigations).

The results of data denial experiments furthermore indicate that it is no single additional data source that provides the good impact. So, either the positive impact originates from the combination of several instruments and/or the positive impact has a more occasional explanation (as discussed above).

7. Concluding remarks

HIRLAM efforts have been quite advanced in the development of observation operators for new types of remote sensing data and in impact studies with these data. However, operational HIRLAM applications have not yet had sufficient benefit from these research and development efforts.

Two HIRLAM coutries participated in the comprehensive observation network studies initiated by EUCOS for assessing the components of the conventional terrestrial observation network. These studies showed that conventional observations still is a backbone of the HIRLAM assimilation system and gave valuable information about the relative contributions of the various conventional components of the observing system.

Recently, a series of Comprehensive Impact Studies (CIS) have been initiated within the HIRLAM community with particular emphasis on satellite data usage. The first CIS is devoted to the Atlantic scale short range forecasting and the results have not yet been fully analyzed. A preliminary analysis indicates a significantly positive impact of adding several new sources of data. On the other hand, the results also indicate that a one month period is far too short for obtaining reliable impact results, and also that the positive impact may originate from a combination of the new types of observations added.

The HIRLAM community is on the move to use the ALADIN forecasting system based on the ECMWF IFS model code. One main motivation is the advanced use of remote sensing data at ECMWF, and the benefit of a lower threshold for use of such new observations within a system integrated with IFS.

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An overview of observation impact studies performed in the ALADIN community

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Abstract:

The International Aladin NWP consortium develops a mesoscale limited area data assimilation system which aims at operating on a wide range of horizontal resolutions (from 10 km down to about 2.5 km so far). In this report, we do not address in detail the aspect of surface data assimilation, but concentrate on experiments of atmospheric observation impact studies performed in the frame of the atmospheric 3D-VAR system. We discuss the benefits and possible difficulties found when assimilating extra radiosonde and/or aircraft data, satellite raw radiances (with a focus on MSG/SEVIRI data), screen-level observations. We also give some hints on the preparations for assimilating radar Doppler winds and reflectivities.

OSE impact studies often are undertaken in the frame of specific calls for tender, or preparation for new observational platforms (satellites). However, experience from pre-operational test suites also can give some clues on the delicate interaction between new observations, model improvements and statistical specifications within the data analysis scheme.

1. Introduction

ALADIN is an international Numerical Weather Prediction (NWP) consortium encompassing 15 members in the Euro-Mediterranean area (see at http://www.cnrm.meteo.fr/aladin/). The general purpose of the project is to develop NWP systems providing state-of-the art weather forecasts from the mesoscale (resolution of about 10 km) down to the convective scale (kilometric and sub-kilometric scales). Efforts are put on all aspects of NWP: dynamical core, physics parametrizations, surface processes, data assimilation, system aspects. At present and in the near future, the two most prominent NWP systems within the ALADIN consortium will be the “old” hydrostatic Aladin model (resolution down to 8 km) and the non-hydrostatic version Arome (resolution of 2.5 km or slightly less). Other, intermediate resolution (7.5 to 3 km), model versions also are under development.

As concerns data assimilation, the consortium focuses on 3D-and 4D-VAR limited area systems for the atmospheric fields, and optimal interpolation (to be extended towards a simplified EnKF) for surface fields. Efforts mostly go in the following directions: for R&D, improve the initialization of fields informative for the frontal and convective scales; for operations, rationalize the system and the share of work in order to ease local implementations. Observation impact studies, in the wide sense, therefore fall into both types of work. Indeed, most of the experience gained recently on OSE studies has been obtained by either focused R&D (MSG/SEVIRI radiances, radar data) or pre-operational testing of observations already assimilated in a global system (ATOVS, aircraft, 10 m winds).

In the sequel of this abstract, we provide a comprehensive overview on recent impact studies, which address both the issue of satellite radiances and the merits of more conventional, terrestrial observational networks. These impact studies all have been carried out with the hydrostatic Aladin model, at Météo-France or at the Hungarian Met. Service. We furthermore give a short insight into the convective-scale efforts for the Arome system.

2. The numerical model and its 3D-VAR

The Aladin model (Horányi etal., 2006) is the limited area, plane geometry, adaptation of the global Arpège forecast system (Courtier etal., 1991). On the side of the forecast model, Aladin-France operates with a Semi-Lagrangian Semi-Implicit advection scheme using the set of hydrostatic primitive equations at a horizontal resolution of 9.5 km and 46 vertical hybrid levels (at the time of these studies). Aladin-Hungary is a quite similar version, operating at 8 km resolution with 49 levels. The physics parametrizations are shared with the global model Arpège, and encompass representations of gravity wave drag, large scale precipitations, sub-grid convection, vertical turbulent mixing, radiation. On the side of assimilation, both versions of Aladin use a 3D-VAR (non-FGAT) cycled analysis system, able to assimilate potentially all conventional and satellite radiance data available on the Global Telecommunications System (GTS) or on national networks. As we discuss in the sequel, efforts are ongoing in order to add radar data as a crucial extra observational source of information into these regional (and local) assimilation systems.

In parallel to the improvements and maintenance of the original Aladin system, Météo-France and its Aladin Project partners are developing a convective-scale NWP facility, Arome (Ducrocq etal., 2005), whose target resolution is 2.5 km. This system will have its own 3D-VAR assimilation, derived from the Aladin version. Arome shall become the leading tool for the short-term (about 30 h) forecast of heavy precipitations and local dynamical adaptation and data assimilation of meteorological fields.

3. Various impact studies

As concerns satellite observations, the initial Aladin 3D-VAR systems have been using ATOVS AMSU-A/B radiances, in a similar way to the global system Arpège for channel selection, bias correction, density of pixels (Fischer etal., 2005, Bölöni, 2006, Randriamampianina, 2006). These data proved to be very useful information over the big data void areas such as oceans and seas. The first very focused impact study and implementation of regional-model oriented satellite data has been performed with MSG/SEVIRI raw radiances. We mostly refer to Montmerle etal. (2007) for a detailed presentation of this work. The major outcomes have been to prove the usefulness of these data for the Aladin-France 3D-VAR assimilation, after a very careful monitoring, bias correction computation and data selection. Figure 1 shows an example of the data coverage for one given SEVIRI channel after extraction, thinning and quality control (first guess check) of the data.

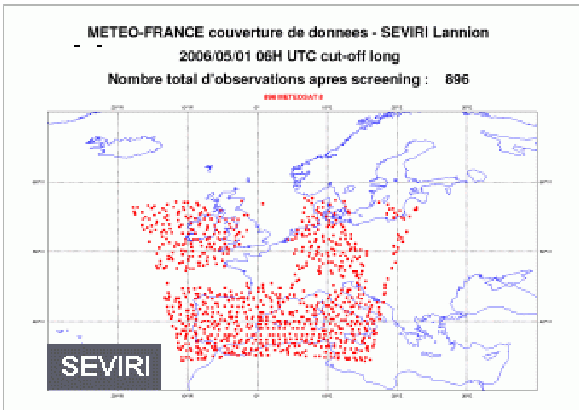

Fig.1: SEVIRI radiance pixel coverage, after removal of cloudy pixels, quality control and thinning. For the channel displayed here, 896 pixels eventually have entered the analysis.

Over cloud-free areas, these radiances provide a dense supply of information to the analysis, which comes as a significant statistical additional information as can be seen in Figure 2, which shows the sensitivity of the final analysis to various types of observations. In Fig. 2, we display the Degree of Freedom of the Signal (DFS), which is a measure of the sensitivity of the analysis solution to a given subset of observations:

$$DFS = Tr\left(\frac{\partial Hx^a}{\partial y}\right)$$

3 experiments are displayed: “OPER” (usual ATOVS coverage with 1 pixel every 125 km, SEVIRI about every 70 km), “moreATOVS” (ATOVS every 80 km, SEVIRI density as in OPER), “noSEV” (usual ATOVS, no SEVIRI). One notices slight variations of DFS for conventional types of observations, depending on the settings for satellite radiances. However, at first order, both radiosonde (TEMP), aircraft and surface mesoscale station data (SYNOP) do bring information (in the sense of the DFS) into the analysis. So do also satellite radiances. When doubling the density for ATOVS, their DFS increases significantly, while the influence of SEVIRI radiances diminishes: the new information of denser ATOVS pixels decreases the role of the SEVIRI data. When SEVIRI is completely switched off, then the DFS of HIRS and AMSU-B increases by a factor of about 2. Thus, some compensatory effects can be seen on humidity-sensitive sensors. One also can estimate the relative impact of one observational datum by computing the ratio of the DFS divided by the number of observations per observation type, p. The study of plots of DFS/p indicates that the relative impact of one ATOVS datum decreases when doubling the density of these radiances. Conversely, when SEVIRI data are discarded, then the relative influence of other satellite radiances increases clearly (not shown in this report).

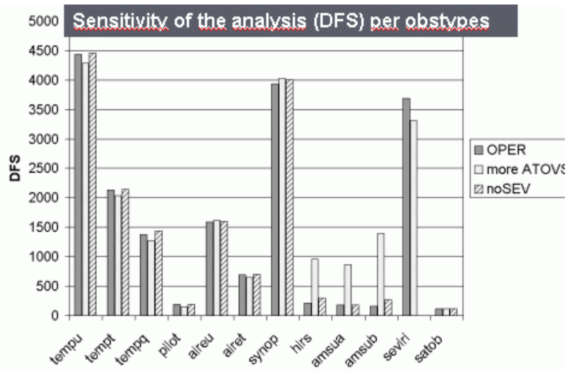

Fig. 2: DFS for various observation types, and for 3 different OSE experiments.

Supplementary experiments have shown that the satellite data, especially the humidity-sensitive SEVIRI channels, are best assimilated in conjunction with screen-level 2m temperature and relative humidity. The reason for this combination is that the very dense SEVIRI data in the troposphere also have an influence on the analysis of the planetary boundary layer (PBL) via the vertical correlation functions in 3D-VAR. However, the temperature and humidity profiles can be fairly decoupled between the free troposphere and the PBL, so that the SEVIRI information can have a significant detrimental impact on the lowest analysis levels. While changing the representation of vertical correlation functions could probably have been one (non trivial) way for reducing such interaction, the use of additional, low level observations was found to be an acceptable alternative in our operations (Aladin-France model). These findings have also been confirmed by sensitivity experiments performed within the LACE (Limited Area Central Europe) group of ALADIN (Alena Trojáková and Gergely Bölöni, personal communication).

Further OSE studies have been conducted at the Hungarian Met. Service, in the frame of the EUCOS/PB-OBS Program for assessing the relative impact of the main observational networks over Europe. The study has been performed with the Hungarian installation of the Aladin 3D-VAR (Boloni, 2006) and a very comprehensive list of assimilation experiments was performed (Randriamampianina etal., 2007):

- EU01/ES01- baseline (GSN surface and GUAN radiosonde + AMV + ATOVS radiances)
- EU02/ES02- baseline + aircraft
- EU03/ES03- baseline + radiosonde wind
- EU04/ES04- baseline + radiosonde wind and temperature
- EU05/ES05- baseline + wind profilers
- EU06/ES06- baseline + radiosonde wind and temperature + aircraft
- EU07/ES07- baseline + radiosonde wind, temperature and humidity
- EU08/ES08- full observation (radiosonde + aircraft + wind profiler)

Both a winter and a summer period were tested. As concerns the impact of aircraft data, the following conclusions were drawn:

- Comparison against ECMWF analyses: a clear positive impact on the temperature, geopotential, wind speed and humidity fields was found for all the forecast ranges
- Comparison against observations: the impact concerned mostly the analysis and forecasts up to 24-hours
- A bigger positive impact of the aircraft observation was observed for the summer period than for the winter period
- Positive impact of the aircraft data on the forecast of humidity fields was observed for the summer period, while negative impact was found for the winter period
- Positive impact of the aircraft data on the forecast of precipitation was observed for the summer period, while neutral (for 00UTC) and negative (for 12 UTC) impact was observed for the winter period

The OSE on radiosonde data lead to the following conclusions:

- In the troposphere, clear positive impact of the radiosonde wind observation on the analysis and short-range forecasts was observed
- A positive impact of the radiosonde temperature on the analysis and on the forecasts up to (mostly) 24-hours was observed
- Clear positive impact of the radiosonde temperature data on the analysis and on the forecasts of the mean sea level pressure up to 24-hours was observed for the summer, while neutral impact was found for the winter period
- Neutral impact of the radiosonde humidity on the mean sea level pressure was observed for the summer period, while clear positive impact was observed for the winter period
- Bigger positive impact of the radiosonde temperature on the geopotential was observed in the summer study than for the winter study
- Large positive impact of the radiosonde humidity was observed for all forecast ranges of precipitation

Fig. 3 shows the example of the impact of radiosonde wind data on the root mean square error for 850 hPa temperature from the same radiosonde network and for the summer period.

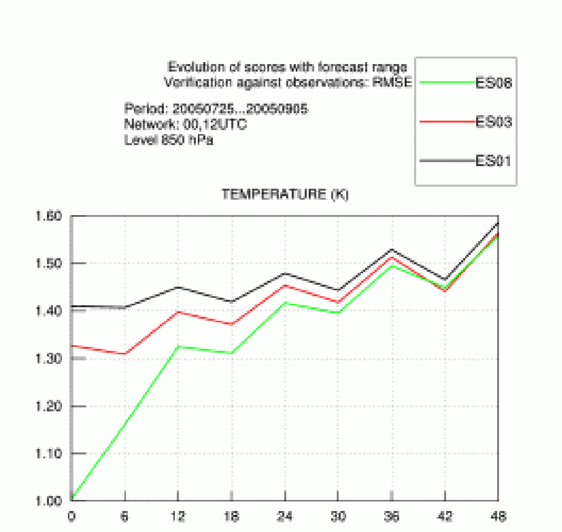

Fig. 3: Evolution of root mean square error for 3 OSE's (ES01, black; ES03, red; ES08, green) as a function of forecast lead time. RMSE are computed with respect to radiosonde 850 hPa temperature.

Eventually, the impact of adding the aircraft wind and temperature data on top of the radiosonde data also was assessed:

- Comparing ES01, ES02 and ES04 (summer study), we found that the impact of the aircraft (wind & temp.) observations was a bit larger than what we found during the winter study (- half of that of the radiosonde (wind & temp.) data)
- For the summer period, a small improvement in the scores was observed when comparing the impact of the aircraft data on top of the radiosonde wind and temperature data (ES04 vs ES06), while a small deterioration was observed in the winter study

In the course of the general, routine evaluation and improvement of the Aladin 3D-VAR operational suite at Météo-France, the 10 m wind observations from the mesoscale national network, along with those from the GTS SYNOP network, have also been proven ripe for assimilation. Their usage in 3D-VAR has been switched on in July 2007. The 10 m wind observations provide a fairly dense information on the very low level flow, though their testing showed rather neutral overall scores when compared with global analyses or radiosonde observations. These data seem most useful in individual cases, and they also have slightly improved the Quantitative Precipitation Forecast scores of Aladin-France. About 2600 stations can enter the analysis, after quality control checks.

A further increase of the observational data is expected by radar wind and reflectivity. The primary target system for these data is the 2.5 km resolution Arome system, using for both winds and reflectivities 3D volume data sets. There is ongoing work at Météo-France in order to prepare for the assimilation of radar radial winds in the very first operational version of Arome, scheduled for about October 2008, using the output from the national Doppler radars. Focus is put on the optimal choice for data thinning (between 25 and 70 km) and for the radius of relevance of each radar scan (between 100 and 200 km, multiple scanning heights for a given radar are possible). Radar radial winds are also filtered horizontally and quality controlled with respect to VAD-derived winds (especially to spot bias error). For reflectivities, which also should be assimilated as 3D data (as opposed to rain rate aggregates), a reflectivity simulator has been developed and implemented in the Aladin/Arome code. The simulator takes into account a fairly simple beam geometry (standard refraction only) but it recognizes the Arome-derived hydrometeors and microphysical fields (rain, snow, graupel, cloud liquid and ice water). Work is still ahead in order to add ground blocking effects for beam propagation (due to orography, see in Haase etal., 2007) and data quality control. These developments are undertaken within the Aladin/Hirlam collaboration. For the assimilation of reflectivity in 3D-VAR, a first method has been proposed by Caumont (2007) based on a Bayesian retrieval method in which synthetic profiles of relative humidity are first obtained from observed reflectivity profiles by using consistent profiles of model relative humidity and reflectivity. The retrieved profiles of relative humidity are then assimilated in 3D-VAR. Fig. 4 shows the radar simulator's geometry.

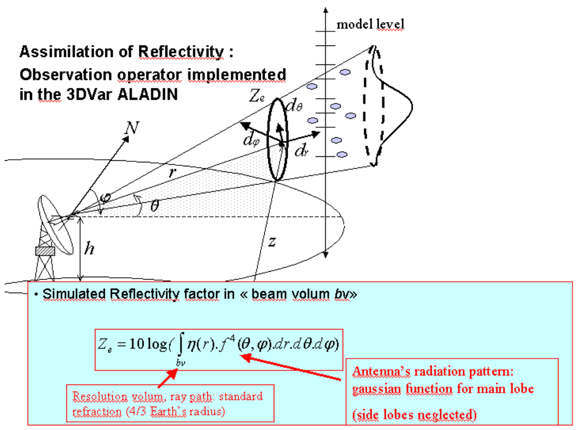

Fig. 4: Radar simulator geometry. Side lobes are ignored (only the primary lobe is modeled, with a presumed Gaussian distribution of the backscattered power). A simple beam propagation is assumed (4/3 of the Earth radius for refraction of the emitted signal).

4. Summary

The following main lessons can be drawn from the work on new observations in the regional Aladin data assimilation systems:

- Confirmation that conventional observations (TEMP, Surface) continue to play an important role in regional and local-scale data assimilation, as compared with aircraft and/or satellite data
- Aircraft data as well provides some innovative information to the analysis, compared with either conventional or satellite observations
- Satellite raw radiances are a useful extra source of information for the troposphere and low stratosphere and over otherwise data void areas, in regional systems. At the present state of the art, a careful bias correction and a removal of almost all cloudy pixels remains mandatory
- satellite radiance pixel density mostly is optimized with respect to the typical lengthscale of the specified background error correlations (more than by the actual grid mesh of the analysis grid)
- at convective-scale, preliminary R&D work performed with the Arome system indicates the beneficial impact of radar data, especially for depicting fine scale structures of active big convective or frontal systems (low level wind convergence or shear)
- the precise statistical (but probably as well case-by-case) impact of a new observational data set can depend on other specifications of the assimilation system. Typically, the background error covariances (the "B matrix"), which act as the final filter of the analyzed increment on the analysis grid, can have a significant detrimental effect due to a lack of physical robustness (too poor vertical correlations, for any reason, for instance)

Observation impact studies within the ALADIN consortium mostly will be continued via the routine evaluation of new observational data in pre-operational assimilation suites. This strategy will essentially be applied for observations which already are prepared for the global Arpège system, or for transfer and inter-comparison of know-how between Aladin-France and other Aladin assimilation systems (like at HMS). R&D observation impact studies will concentrate on convective-scale OSE (and field campaign re-analyses, occasionally), and on the further evaluation of the benefit of radar data.

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Impact of ProbeX-IOP (KEOP) observations on the predictive skill of heavy rainfall in the middle part of Korea

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1. Introduction

Heavy precipitation over the middle part of Korea occasionally results from individual mesoscale convective storms embedded in synoptic disturbances along the Changma front. The mechanism causing heavy rainfall over the Korean peninsula has been explored in many numerical studies (Lee and Hong, 1989; Lee et al., 1993; Sun and Lee, 2002). Hong and Lee (1994) shows that strong convective storms and relevant heavy rainfall can be reproduced well in the numerical simulation with the high-resolution model by using the conventional observation data.

A heavy rainfall event occurred over the middle part of Korea in the early morning on 4 July 2007 while a synoptic-scale low system passes over the southern part of Korea along the Changma front, and it results in heavy precipitation over the southern coastal area of Korea. In the early morning over the southern part of Gyeonggi province in the middle of Korea peninsula, a mesoscale convective storm cell was rapidly developed. The precipitating event was mostly concentrated during the six hours from 0500 LST 4 July to 1100 LST 4 July 2007, and the maximum rainfall amount was recorded 148.5mm at Mungyong, and 104mm at Anyang station.

In this study, we examined the impact of intensive observations on improvement of precipitation forecast skill in the numerical model experiment. Also we investigate the clue of poor forecast skill to predict the heavy rainfall event in the present study.

2. Numerical model and data

The KWRF10 (KMA Weather Research and Forecasting model with the horizontal resolution of 10km) based on WRF model version 2.1.2 was employed in this study. The KWRF10 uses a unified 3DVAR for the global data assimilation and digital filters for the initialization. A nested grid system included two model domains of 10 km for the coarser grid and 3.3km for the finer grid in the horizontal grid spacing with 30 vertical sigma levels. The updated Kain-Fritsch scheme was adopted for cumulus parameterization and the WRF Single Moment 6 Class (WSM6) microphysics for explicit moisture process. The Yonsei University PBL scheme was used for the planetary boundary layer physics. The initial and boundary conditions provided by the KMA operational global model (T426) directly to the KWRF10 model domain for the cold start run simulation. In this study, the first guess fields in the 3DVAR data assimilation were derived from the previous 6-h forecast of the KWRF10 model itself in the KWRF cycling run system. We investigated the sensitivity of the assimilation of intense observations to the simulation of a heavy rainfall event over Korea.

The Forecast Research Laboratory of National Institute of Meteorological Research has been conducting a Korea Enhanced Observing Program (KEOP) to advance the understanding of the dynamical structure and evolution of high impact weather during the Changma period. Field experiments with increasing spatial and temporal resolution of upper air observations at three more sites in space, and 6 hours interval in time were conducted in 2007. We implemented the numerical experiments which test the impact of enhanced rawinsonde observations at initial state by the assimilation using the KMA unified 3DVAR system. Experimental designs of the assimilation of

Table 1. Experimental designs for the sensitivity to the KEOP-2007 data assimilation.

Experiment ID	Assimilated observation data	Remarks
CTL	All available observations without KEOP-2007 soundings	Operational
ALL	All available observations including KEOP-2007 soundings	1249
KOP	KEOP-2007 soundings only	2
KAL	AMDAR including KAL reports only	451

KEOP-2007 and AMDAR (Aircraft Meteorological Data Relay) data are summarized in Table 1.

3. Results

The observed 12-h accumulated rainfall amount and the simulated ones by the RDAPS (Regional Data Analysis and Prediction System; operational regional model of KMA) and by the KWRF at 12 LST on 4 July 2007 are shown in Fig. 2. Three RDAPS models with different horizontal resolution simulates well rain bands associated with low-system along the Changma front over southern part of the Korean peninsula, which is almost close to the AWS observations, but they failed to capture the heavy precipitation over the middle part of Korea. On the other hand, two KWRF model simulates moderate rainfall in the area of middle part of Korea. Moreover, it is obviously seen that the simulated rainfall amount and pattern were well agreed with the AWS observation as the horizontal resolution increases from 10 km to 3.3 km in the KWRF model. However, the location of rain bands were shifted toward northeast in both KWRF model simulations.

Figure 3 shows the simulated 12-h accumulated rainfall amount in the numerical experiment of conventional and enhanced KEOP data assimilation with the background from the KWRF cycle run. The

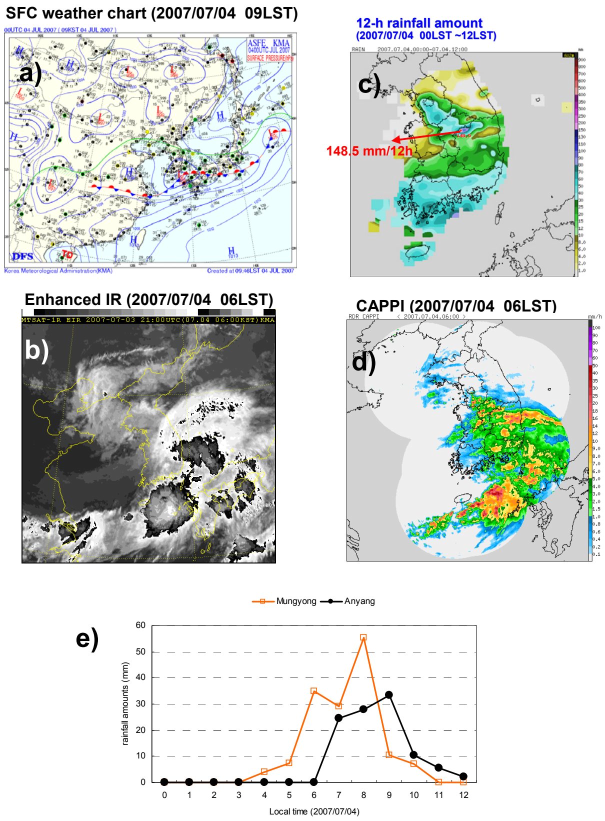

Fig. 1. a) Surface weather chart at 09LST 4 July 2007, b) enhanced IR, c) observed 12-h accumulated rainfall amount from 00LST to 12 LST, d) reflectivity at 06 LST 4 July 2007, and e) time series of hourly rainfall amounts at Mungyong and Anyang station.

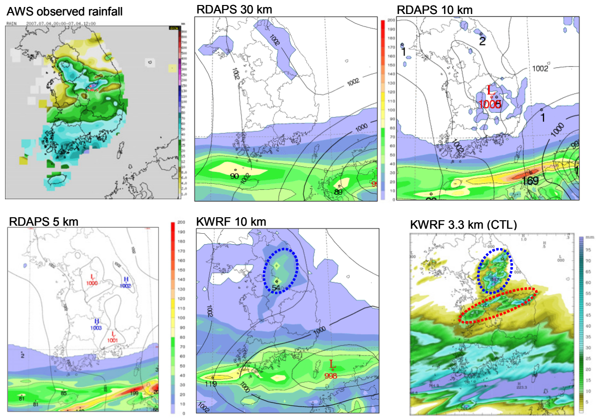

Fig. 2. Precipitation amounts for for AWS observation, and operational RDAPS and KWRF model.

KWRF 3.3 km model simulated well the heavy precipitation over the middle part of Korea in terms of the beginning time and the rainfall amounts (figure not shown). As shown in Fig. 2, however, the maximum location of the heavy precipitation area was shifted northeastward. In the experiment of KEOP data added to the conventional data for the 3DVAR, the simulated maximum rainfall area over the south of Gyeonggi province got closer to the observation and it presented higher forecast skill score than the CTL experiment. In the KOP experiment which assimilates only KEOP-2007 data using 3DVAR, the simulated rainband positioned back to the west so that it has better agreement with the observed one. Although the simulated rainfall amount was smaller than the observed one, the location of the maximum rainfall area was largely improved in the KAL experiment. Since the reports from the Korea Airlines concentrated over the middle part of Korea near Inchon airport in KWRF 3.3 km model domain, enhancement of vertical structure by the assimilation of AMDAR data resulted in the improvement of predictive skill of heavy rainfall over the middle part of Korea noting that the AMDAR data provide only dynamical structure of temperature and wind field.

Fig. 4 shows equitable threat scores for the 12-h forecast of precipitation as a function of threshold value. The predictive skill drops rapidly as the threshold value increases for the CTL experiment, and it reveals negative score at a larger threshold value over 5 mm. The ALL experiment which assimilates KEOP-2007 data added to CTL experiment showed major improvement near 5 mm threshold, and the skill score falls as the threshold value increases up to 7 mm. The impact of IOP data on the accuracy in the simulation of heavy rainfall was more distinct in the KOP experiment which assimilates with KEOP-2007 sounding data only. The skill score shows much larger value at the threshold value from 1 to 10 mm in the KOP experiment. It is obvious that the threat score increases over 10 mm threshold value in the KAL experiment which

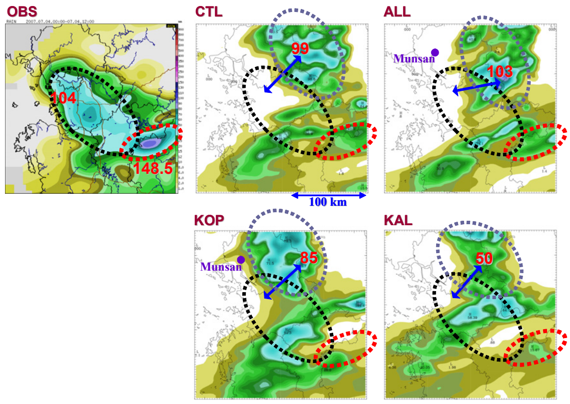

Fig. 3. Observed and simulated 12-h accumulated rainfall amount for the sensitivity experiment to KEOP-2007 data.

assimilates temperature and wind data from AMDAR including the Korea Airlines report around the center of the maximum precipitation area over the middle part of Korea. It supports that improvement in quality of initial data by the assimilation of enhanced observation data contributes to increase the predictive skill in simulation of heavy rainfall.

4. Summary

In this study, we investigated a heavy rainfall event on 4 July 2007 which one failed to capture in the real-time forecast in the area of middle part of Korea by using the operational RDAPS models of KMA. We have drawn the conclusion that one major reason for failure is insufficiency of spin-up at initial time. The RDAPS model uses the initial background from the GDAPS of KMA while the KWRF model uses a previous forecast field as an initial background by cycling run. In this study, initial mesoscale features should be captured because the heavy precipitation developed rapidly over the middle part of Korea, Thus, note that the cycling process in KWRF model to provide the background to the initial condition plays an important role in the spin-up process of precipitation over the middle part of Korea.

The assimilation of the intensive observations (KEOP-2007) showed positive potential in improvement of the predictive skill of the heavy rainfall event using the KWRF 3.3 km model. Despite soundings at a single site (Munsan) near the center of heavy rainfall, an improvement in the initial field by the assimilation of humidity sounding brought in the increase of predictive skill in heavy rainfall simulation. The result shows an agreement to some extent with the result of Kato et al. (2003) which shows the importance of spatially and temporally dense sounding observation in the simulation of heavy precipitation developed around Baiu frontal zone over Japan.

Although the simulated rainfall amounts were much smaller than the observation, the assimilation of temperature and wind data of AMDAR can contribute to improve the performance of

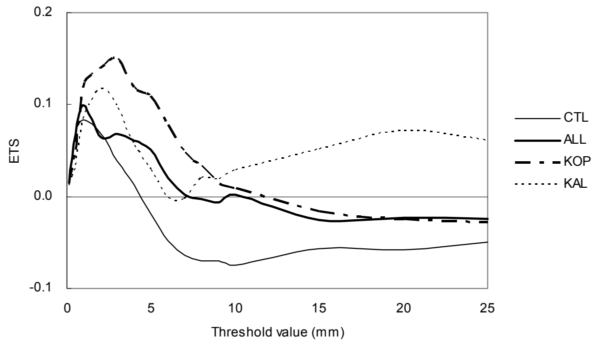

Fig. 4. The equitable threat scores with respect to the threshold values of 12-h accumulated rainfall amount for the experiment of assimilation of KEOP and AMDAR data.

precipitation forecast in the KAL experiment. It suggests that the improvement of accuracy in dynamical structure of initial condition can contribute to improve the predictive skill of heavy rainfall as much as in the improvement of initial lower-level humidity field, because mesoscale dynamical fields can be reproduced more realistically by the assimilation of dense vertical temperature and wind profile data.

Acknowledgements

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The Impact of AMDAR and Rawindsonde Observations on a 3dvar Regional Model Forecast System in Southern Africa

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1. Introduction

The problem of inadequate atmospheric observations in Africa has been acknowledged for some time (e.g. Bruce, 1994, Schulze, 2007). Only a small fraction of the minimum required rawindsonde stations have been implemented, but in reality the situation is even worse as many of the implemented stations do not function reliably in real-time. Equatorial Africa is largely a data void in terms of rawindsonde soundings. Arguably, the need for more in-situ observations in this region is higher than elsewhere. With the development of AMDAR programme and the relatively cheaper cost of these in-situ observations, South Africa started a regional AMDAR Project in 2000 (Stickland, 2004), collecting data from long-haul and later regional aircraft carriers. Currently, on any given day there are between 50 and 800 AMDAR reports per 10^{o} x 10^{o} grid-box over all of southern Africa. *(source: http://collaboration.cmc.ec.gc.ca/cmc/data_monitoring)*

Earlier work done at the South African Weather Service (SAWS) using the Eta regional modelling system (Riphagen, 2004) showed a convincing positive impact of AMDAR reports, especially at higher levels, with a general decrease in impact with forecast lead-time. This study is an extension of that work, but with the following changes. This study employs a new modelling system, *viz.* the Met Office Unified Model (UM) SA12 configuration run at the SAWS. Furthermore there has been a significant increase in the quantity of AMDAR reports since 2004, especially on regional routes. The Eta data assimilation system did not include satellite data, which accounts for the majority of observation data ingested into the UM by volume. Although both modelling systems used a 3dvar analysis technique, the UM followed a continuous 6-hourly cycling approach, while the Eta system used a cold-start 12-hour assimilation process, cycling 3-hourly. The results from this study are intended to build on the earlier findings.

The objective of this paper is to determine the impact of in-situ rawindsonde and AMDAR observations on the forecasts generated from a regional model data assimilation system in southern Africa.

2. Experiment design

The South African Weather Service (SAWS) runs a 12km resolution, 38 level limited area version (SA12) of the Met Office Unified Model (UM) for operational forecasting purposes. The model domain covers southern Africa south of the equator to 44^{o}S and 10^{o}W to 56^{o}E. The SA12 is configured to produce daily 48-hour forecasts from 00Z using two initial condition sources. The first is an interpolated Met Office global model 6-hour forecast from their 18Z cycle, and the second, a 6-hourly continuous 3dvar cycle run at the SAWS that acquires observation input from the Met Office MetDB system in real-time with a cut-off time of 3-hours.

Two periods were chosen for this denial experiment, a summer case from 24 October 2006 to 10 January 2007, and a winter case from 1 May 2007 to 10 July 2007. The control experiment included all observations that were available to the operational run and the experiment denied all AMDAR and rawindsonde observations. A caveat for experiments using limited area models is that the denied observations will still indirectly filter into the model domain through the 3-hourly lateral boundary condition updates, but owing to the large size of the domain this effect is not expected to alter the results dramatically, especially during the day one of the forecast period as air masses travel relatively slowly in the tropics and sub-tropics.

3. Results

On average about 50 reports from about a dozen rawindsonde stations and 2200-2500 AMDAR reports were received daily over the Unified Model (UM) SA12km domain for duration of this study. During winter, the dry season in southern Africa except in the south-western Cape, the South African rawindsonde stations are reduced to half of their capacity to save costs. Overall the rawindsonde reports make up only a tiny fraction of the total observation data ingested into the model and should not account for much forecast impact in the presence of the copious satellite data ingested. Unfortunately the only possible in-situ verification in the vertical over southern Africa can be done using the few rawindsonde reports from South Africa. The remaining verification statistics need to rely on model analyses. To broaden this base, the analysis from the Met Office global 4dVAR system is also used for comparison. Generally results from the summer and winter cases were similar, so the discussion will concentrate on one case and show significant differences between the seasons.

The 2-D Zapotocny geographical Forecast Impact (FI) diagnostic (Zapotocny et al., 2008) was used to plot the change in RMSE of the experiment relative to the control forecast. Positive values (reds) indicate that the control has lower errors than the experiment.

Using this diagnostic it is clear that the rawindsonde/AMDAR observations have a strong positive impact on the vector wind forecasts, especially over the tropical regions of the domain (Fig. 1). Interestingly, the impact is negative in winter at higher level winds over South Africa at forecast hour 48. Temperatures don't show the same impact though. In the summer case there is only a slight negative impact on the wind at 48-hours.

One possible explanation for this is that the denial of rawindsonde observations over South Africa may create a discontinuity between the locally generated regional model first guess field and the LBC fields generated from the Global 4dvar runs at the Met Office. The stronger westerlies, especially during winter over the southern part of the regional model domain, may be transporting this signal into the centre of the domain. Further indication of impact signal advection can be seen with the maximum forecast impact over the South Atlantic, i.e. west of the AMDAR observations (Fig. 2), being propagated by the tropical easterly winds.

Similar findings are seen with the correlation of model forecasts with rawindsonde time-series (Fig. 3). The control wind-speed forecast matches significantly better to observations than the experiment at 24-hours, but less so at 48-hours. Again at higher levels the 250hPa level forecasts at 48-hours are slightly worse. In this case, the forecasts from the interpolated global model 4dvar initial conditions fare best out of the three - note that the same LBCs are used in all SA12 runs. This suggests that the global 4dvar outperforms the regional 3dvar for these forecast variables, but a comparison of regional 3dvar vs 4dvar remains to be tested rigorously on this domain.

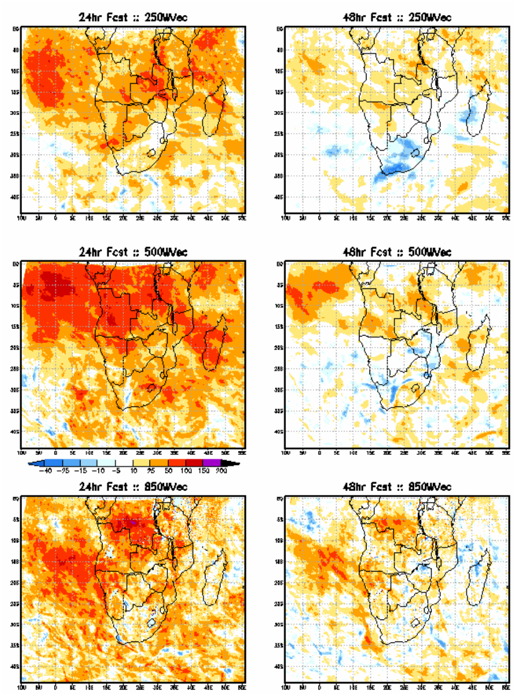

Figure 1: Geographical distribution of the Forecast Impact of on the Vector Wind from the denial of AMDAR/Rawindsonde for May-Jun-Jul 2007 at the levels and forecast hours as shown.

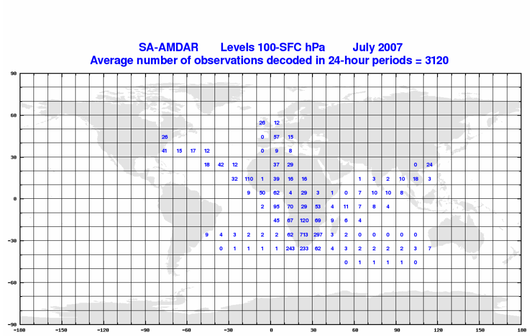

Figure 2: Monthly summary of AMDAR reports for July 2007 as monitored by CMC/Environment Canada.

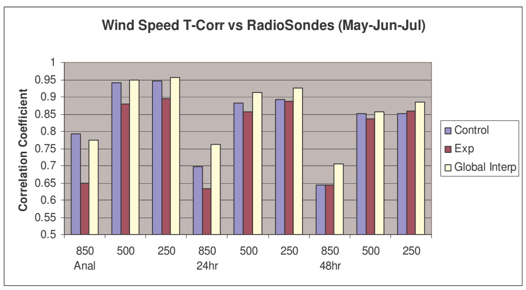

Figure 3: Average temporal correlation of Control (Control), Denial Experiment (Exp) and No-data assimilation (Global Interp) wind-speed forecasts against Rawindsonde Stations in South Africa for levels and forecast lead-time as indicated.

Notwithstanding, the value of local data assimilation becomes evident when rainfall forecasts are verified. The percentage of absolute errors in forecast rain-days is higher for the global 4dvar initial conditions, except for the highest threshold of 50mm (Fig. 4) for both day-1 and day-2 forecasts.

Normalised RMSE values show a small impact of AMDAR/RS on day-1 rainfall amounts and even negative impacts for heavy rainfall (Fig. 5). However, on day-2 these observations have a clear positive impact for all thresholds. As with rain-day errors, this statistic shows better scores for runs using data assimilation compared to the global interpolated run. This was found for both the winter and summer cases.

Rainfall forecasts have a relatively large systematic error, especially in regions where convective rainfall dominates, so this may affect the impact results as the change could be attributed to various factors other than data assimilation alone.

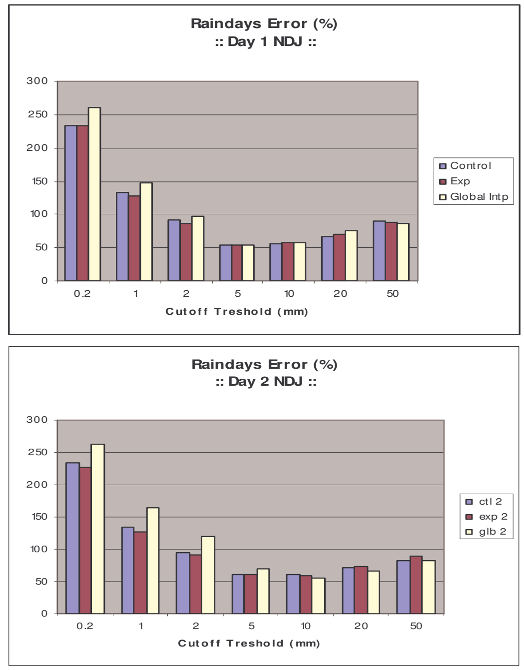

Figure 4: Area-average summer forecast day-1 (top) and day-2 (bottom) rain-day error against rainfall stations in South Africa expressed as percentage of the observed number of rain-days above the given thresholds.

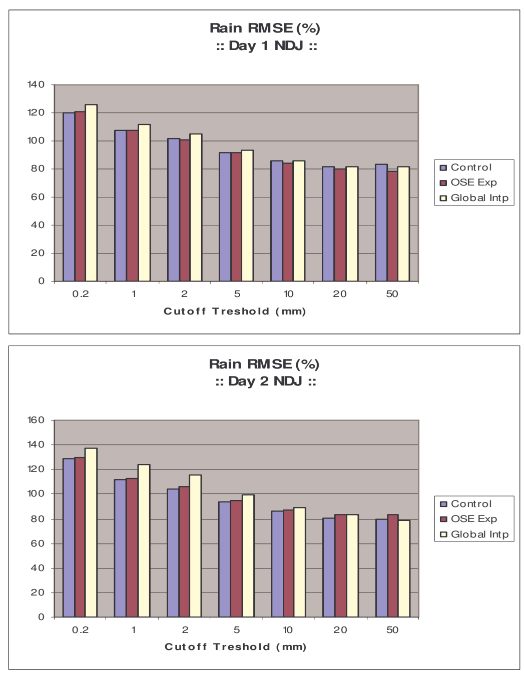

Figure 5: Area-average RMSE of day-1 (top) and day-2 (bottom) summer forecast rainfall normalised by observed rainfall amount against rainfall stations in South Africa for the given thresholds.

Spatial correlation statistics are perhaps more subjective than the previous verification scores in that they favour the model whose analysis is used for comparison, but these results still indicate that the control wind-speed forecast is better than the experiment at all times and levels when using either the control or global 4dvar analysis fields as truth (Fig. 6). Similar results were found for temperature and geopotential height forecasts for both seasons.

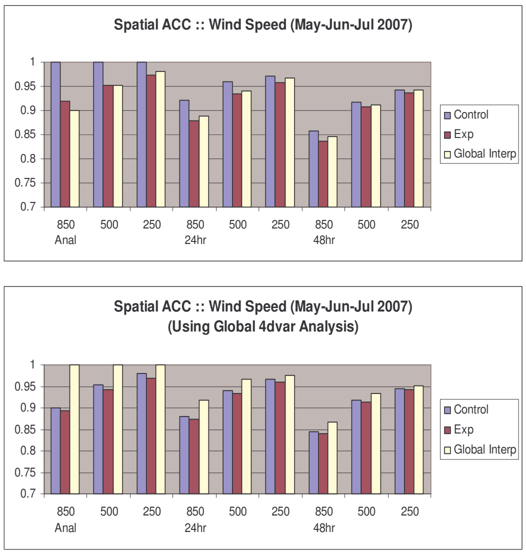

Figure 6: Average spatial Anomaly Correlation Coefficient comparison of Control (Control), Denial Experiment (Exp) and No-data assimilation (Global Interp) wind-speed forecasts against the control analysis (top) and Global 4dvar analysis (bottom) for levels and forecast lead-time as indicated.

The impact is similar at all levels, although the 850hPa level tends to show the highest impact. Note that over Africa this level is close to the surface and will reflect the more complex structures near the boundary layer which would certainly benefit from data assimilation at regional model resolution.

4. Conclusions

Although results are mixed in some cases, there is good evidence that the UM SA12 3dVAR system forecasts are degraded when the AMDAR and rawindsonde observations are removed. It is anticipated that the same results would be obtained if the rawindsonde were retained, with possibly less dramatic impact where forecasts are verified against rawindsonde observations.

Impact of AMDAR and rawindsonde observations (and indeed data assimilation in general for this limited area domain) on rainfall forecasts is also generally positive, but owing to the relatively larger model errors with rainfall, especially convective rainfall, these particular results are sometimes mixed.

Given the caveats mentioned in this document about LBCs containing the full observing system information and the lack of in situ verification data, it is still sensible to conclude that the AMDAR and limited rawindsonde observations available in the southern Africa region have a positive impact on the forecasts made from a limited area NWP system.

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Regional impact studies performed in the COSMO community

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Abstract

The principle objective of COSMO is the creation of a meso-scale prediction and simulation model system. It is intended to be used as a flexible tool for specific tasks of weather services as well as for various scientific applications on a broad range of spatial scales. Two application of the COSMO model system the regional model COSMO-EU and the convection-resolving model COSMO-DE together with the global model GME form the Numerical Weather Prediction (NWP) model chain at DWD. The COSMO-EU covers the Eastern Atlantic and Europe with 40 vertical layers and a grid resolution of seven km. The COSMO-DE covers Germany, Switzerland and Austria and has a grid resolution of 2.8 km and 50 vertical layers.

The data assimilation scheme for the COSMO models is based on the "nudging technique", in which the model state is gently relaxed towards the observed values. During the assimilation sequence, the model forecast is corrected using observations at every time step, thus allowing the use of observations made at non-synoptical time scales. At present, only conventional observations are used operationally in both COMSO-EU and COSMO-DE. For COSMO-DE, the operational use of radar-derived rain rates is also included.

Due to technological progress in satellite- and ground-based remote sensing methods, the DWD is intensifying its efforts to use more remote sensing data in its local data assimilation scheme. This presentation will give a summary of recent progress in assimilation of radar-derived rain rates, VAD wind profiles, vertical integrated water vapour content of the atmosphere, derived from GPS signals, and wind profiles derived from the European wind profiler network. In addition, the results of using satellite sounding data and scatterometer wind vectors at 10m height will be shown.

One major finding is, that the use of radar-derived rain rates exert a high impact on the forecast quality of precipitation in the first three to six hours. Thereafter, the impact decreases gradually. Using data from wind profilers and VAD estimates depict a small positive impact on the forecast quality of the COSMO models, whereas the use of scatterometer winds have an overall neutral impact, but in cases of intense low pressure systems over the Atlantic a substantial positive impact on the analysis and forecast of the position and intensity of these lows is obvious.

1. Introduction

Limited area models with variable resolutions from 14 km down to 2 km and less are developed to simulate smaller scale structures in space and time as e.g. detailed convection processes or orographical-induced precipitation. Sophisticated physical packages are used and there are fewer constraints at small scales as hydrostacy and geostrophy. In general, the quality of forecasts is less depend on initial conditions and the predictability of simulated phenomena is more limited compared to large scale modeling. There is a high interest in using asynchronous and high frequent observations (satellite and radar data), especially over land, where limited area models are mainly located.

At the German Weather Service (DWD) two applications of a meso-scale prediction and simulation model system, the regional model COSMO-EU and the convection-resolving model COSMO-DE together with the global model GME, form the operational NWP model chain. The COSMO-EU covers the Eastern Atlantic and Europe with 40 vertical layers and a grid resolution of 7 km. The COSMO-DE covers Germany, Switzerland and Austria and has a grid resolution of 2.8 km and 50 vertical layers.

The data assimilation scheme for the COSMO models is based on the Newtonian relaxation technique or Nudging Analysis and is operationally applied at the DWD since 2000. Nudging can use straight forward asynchronous observations and deal with any complexity of physics and unsteady solutions, since it does not require tangent linear or adjoint modules. Thereby, the model state is gently relaxed towards the observed values. The most predominate backdraw of Nudging is that remote sensing observations with nonlinear observation operators cannot be assimilated directly. At present, only conventional observations are used operational in both COSMO-EU and COSMO-DE. In order to analyse meso-γ-scale structures the introduction of radar data into the assimilation system of COSMO-DE is essential.

In the following some examples of recent progress in assimilation of asynchronous, high frequent observations (radar data, satellite radiances and scatterometer wind observations) into the regional and local limited area models, COSMO-EU and COSMO-DE will be given.

2. Assimilation of radar observations into the COSMO-DE

DWD operates a radar network of 16 doppler radars covering most parts of Germany. A scan containing near-surface reflectivity is available very 5 minutes with a spatial resolution of 1 km in range and 1^{o} in azimuth. As the radar reflectivity data can be contaminated with manifold non-rain echoes an efficient quality control mechanism for every single scan has been implemented to detect spurious features such as positive and negative spokes and circles, speckles duet to ground clutter, anomalous propagation or bright band effects. After flagging the pixels depending on quality control, the reflectivity values are then converted to precipitation rates by using empirical Z-R relationships.

In order to assimilate radar derived rain rates into the COSMO-DE assimilation nudging scheme a technique called “latent heat nudging (LHN)” is chosen partly motivated by the need for high time efficiency in an operational environment. It is based on the fact that any kind of precipitation production is related to phase changes and thus will be linked to release of latent heat. In the concept of LHN, the rain rate at the surface of a grid point is simply proportional to the vertical integral of latent heat release in the column above this point and the idea of LHN is to scale the current modeled latent heat profile (by scaling the temperature and humidity profile of the model) according to the ratio of observed and simulated rain rates. The model would then be expected to respond to the adapted heat release by producing a rain rate closer the observed one. A revision of the conventional LHN scheme is accomplished to take into account the spatial and temporal structure of the prognostic cloud scheme used in the operational COSMO models.

The ability of the revised LHN scheme to assimilated radar reflectivity observations into the COSMO-DE model will be demonstrated for a two month summer period in 2006 (15 June to 15 August (60 days)). Thereby, the LHN experiment, consisting of a COSMO-DE data assimilation cycle including LHN and following free forecasts, is compared to a control experiment not using LHN during the data assimilation. The weather conditions during that period were characterized by summer-like conditions with high temperatures and some heavy convective events (thunderstorms, squall lines accompanied by heavy precipitation) and a two weeks period in August were low pressure systems predominate causing cool conditions with both stratiform and convective precipitation. The forecast skill of the COSMO-

DE precipitation is verified against radar observations. Figure 1 illustrates equitable threat score (ETS) and frequency bias (FBI) for the thresholds 0.1 mm/h and 1.0 mm/h for both assimilation and free forecast. During assimilation a significant benefit of LHN can be deduced, both the ETS as well as the FBI (closer to one) of the LHN experiment is much higher than for the control run. During the free forecast, the positive impact of LHN on ETS starts at a high level and decreases rapidly during the first 4 to 6 hours but a small benefit remains throughout the forecast while for higher thresholds (not shown, the impact is neutral after 6 hours. The positive benefit of using radar reflectivity measurements during LHN is also verifiable with the FBI score. Here, the experiment with LHN remains around the desired

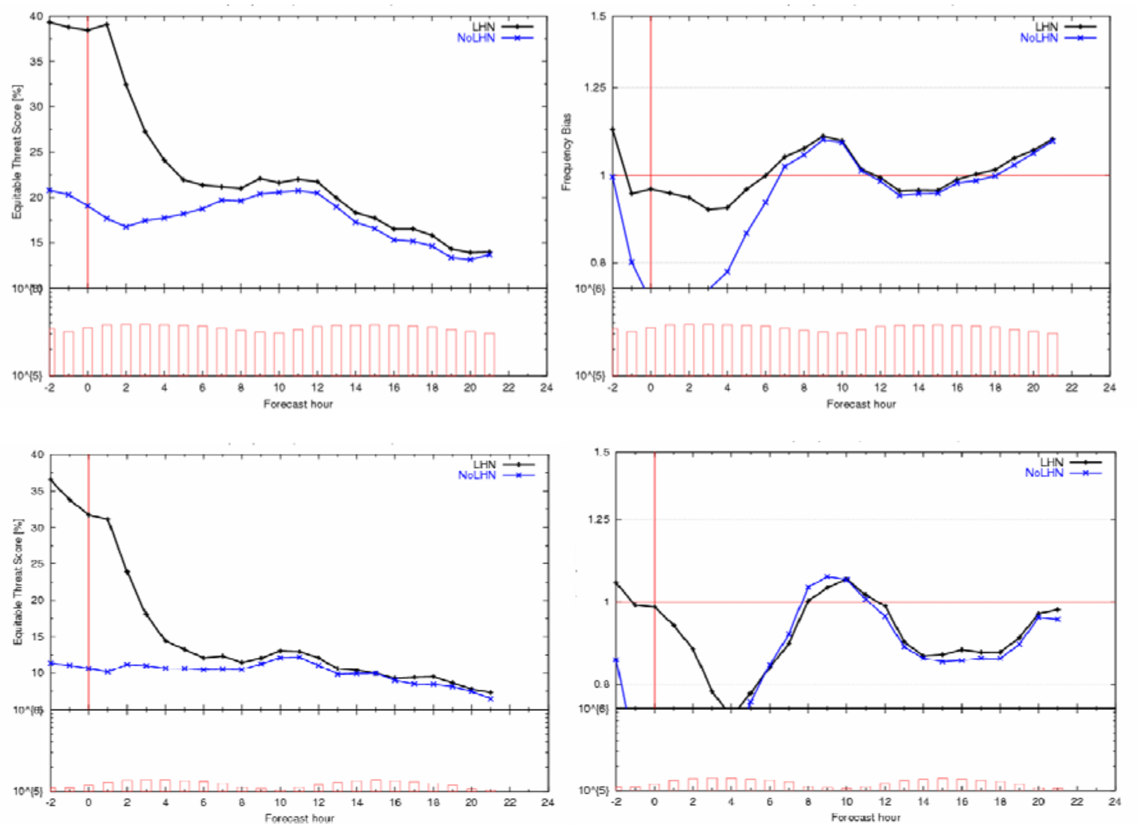

Figure1: Statistical verification against radar observations of assimilation cycle and free forecasts for a 60 day summer period in 2006. Equitable threat score (left) and frequency bias (right) of hourly precipitation for thresholds 0.1 mm/h (upper) and 1.0 mm/h (lower) for COSMO-DE with LHN (LHN, blue) and COSMO-DE without LHN (noLHN, black). The boxes at the bottom of each panel show the number of radar observations.

FBI value of 1.0 during the free forecast, whereas the control run is far under 1.0 during the first 9 hours forecast time. Afterwards, both the experiment and the control remain almost on the same level. The LHN scheme also has a positive impact om screen level parameters and on the longer term climatology of the model (not shown). Extending the positive temporal impact of the radar observations further into the free forecast will be a focus of future research.

3. Use of satellite radiances in the COSMO-EU

Satellite sounding data retrieved from TOVS radiances on board various satellite systems are are the most important data sources for global data assimilation. The increasing resolution of satellite sounding instruments in space and time and also spectrally provide more and more wealthy information also for limited area models. Some specialties and complications exist when using satellite radiances for limited area models compared to global models. Among them are bias correction, the prescription of temperature profiles above model top for the radiative transfer simulation and the specification of background errors. The latter express errors of the background that include small scale features of the simulation and also errors introduced from the boundaries with much larger error structures. There are less constraints (hydrostacy, geostrophy) on smaller scales and interest in adaptive, flow dependent background errors increase for limited area models.

Concerning the bias correction, the sample size is not found exceptionally critical, even not for scan line correction of AMSU-A. In case of COSMO-EU about two weeks were sufficient

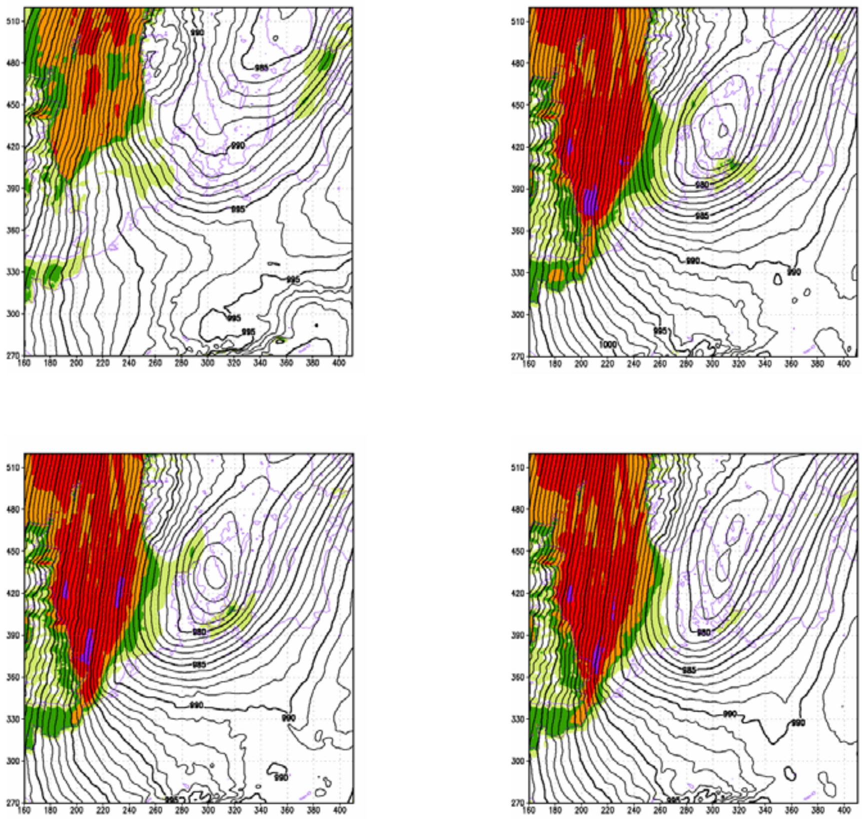

Figure 2: Mean sea level pressure (lines) and 10m wind gusts (shaded) of COSMO-EU for analysis (upper left), control forecast (upper right), a forecast with 1D-Var and Nudging and every second observation is active after thinning (lower left) and a forecast with 1D-Var and Nudging and every third observation is active after thinning. Valid date of analysis and forecasts is 20 March 2007, 00 UTC and a forecast length of 48 hours.

to provide reliable estimations of the scan line biases for most relevant tropospheric channels. The forecast quality of limited area models depends essentially on boundary values and the forecast quality of the models itself. In general less improvements can be expected for limited area models when assimilation satellite radiances compared to global models. In order to test the impact of satellite radiances in a limited area environment an experiment of COSMO-EU with 1D-Var for AMSU-A and Nudging was conducted for 20 March 2007, 00 UTC. Thereby, the satellites NOAA-15, 16 and 18 were used, that altogether deliver at least some reasonable data coverage for the COSMO-EU area within every three hours. Microwave radiances contaminated by rain are detected by the surface type classification scheme of Kelly and Bauer 2000. The reference forecast shows a too intense low pressure system over the Baltic Sea with strong wind gusts of over 30 m/s in northern Germany. The low was generated within the model domain of COSMO-EU and is not driven by the boundary conditions. Two studies with different thinning options show slightly better results if compared to the reference analysis. The improvement is small, however encouraging. More improvements are expected by a better tuning of the 1D-Var scheme and the nudging coefficients. Most prominent challenges for a improved assimilation of radiances is to enhance the data coverage, i.e. the use of microwave data over land and the use of infrared data in case of clouds, since only 5% of all infrared data is cloud free.

4. Assimilation of scatterometer wind data into COSMO-EU

Space-borne scatterometer data provide accurate near surface wind observations (both wind speed and direction) over the global oceans with high temporal and spatial resolution under most weather conditions. The high temporal and spatial resolution makes this data source also an interesting observation system for limited area models with an integration domain

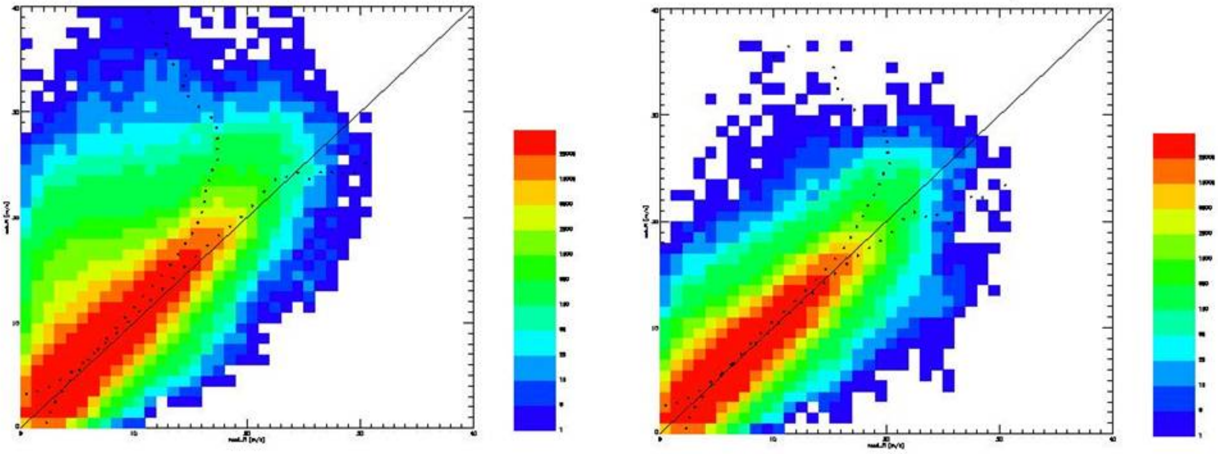

Figure 3: Scatter plot between QuikScat wind speeds and collocated GME first guess wind speeds [m/s] for all data (left) and for data that were not rejected due to rain land/ice contamination and bias corrected (right)

partly of oceanic areas. The assimilation of scatterometer wind data requires careful data selection with respect to rain and ice contamination. Therefore a new processing chain at DWD is established taking into account a rain-flagging algorithm developed at KNMI, a careful elimination of land or sea ice contaminated wind vectors and, in case of scatterometer winds from QuikScat, a bias correction for observed wind speeds. As an example, Figure 3 shows the beneficial impact of quality control and bias correction on the data quality of scatterometer wind data from QuikScat for a period in Summer 2007. In that case, the correlation of wind speed data with collocated first guess wind speeds enhanced from 0.66 for all data to 0.82 for quality controlled data.

In order to use scatterometer data in the COSMO-EU nudging scheme one single wind vector has to be selected out of the up to four wind vectors supplied by the data producers. All quality control and bias correction steps developed for use in the global model GME were also taking into account in the COSMO-EU assimilation environment. In several idealized test case studies the 10-m wind vector information provided by the scatterometer data are widely rejected by the COSMO-EU unless the mass field is explicitly balanced. Therefore a new COSMO-EU version was developed, were starting from 10-m wind analysis corrections surface pressure corrections are derived witch are in geostrophic balance with 10-m wind analysis increments. After the implementation, the new model system now accepts the scatterometer data largely. A first real case study were computed for the 19th June 2007 (Figure 4). A strong low pressure system southwest off Ireland was not captured very well by the routine COSMO-EU (without QuikScat data) analysis due to a lack of conventional observations (buoys, synop-ships) in this area. Using QuikScat scatterometer 10-m wind vectors the mean sea level pressure in the center of the low is reduced by more than 3 hPa shifting the position of the low more towards the observed position. This is an encouraging result and the impact of scatterometer data is noe being tested in a longer trail.

Most prominent challenges for the improved assimilation of scatterometer data is the enhance data coverage by using additional scatterometer data from the ASCAT instrument onboard Metop and the adjustment of the Nudging coefficient, horizontally and vertically, for the use of scatterometer data.

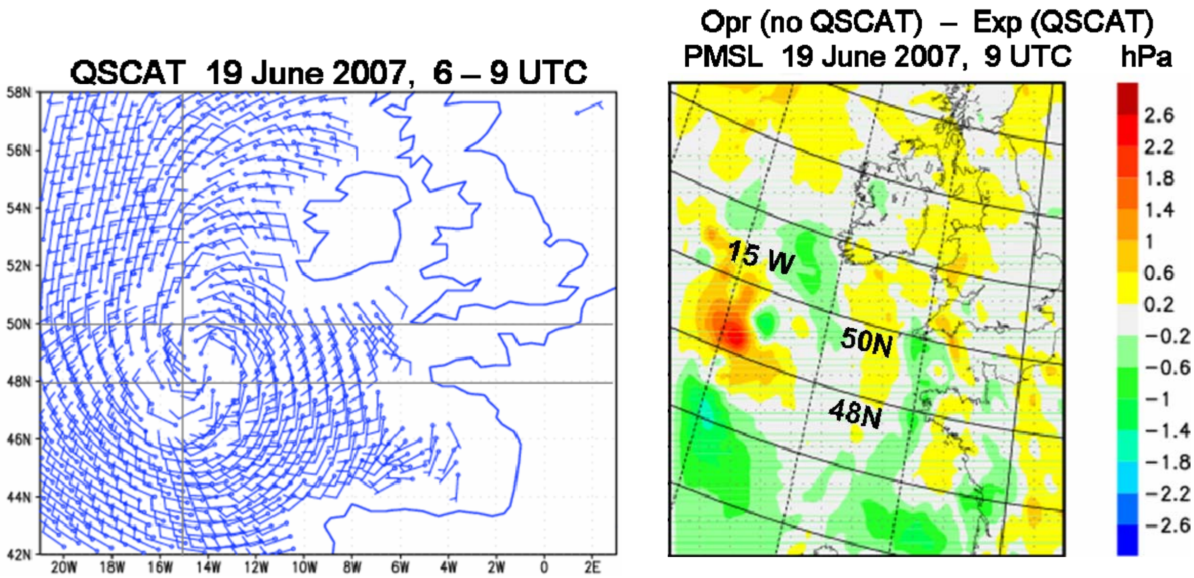

Figure 4: QuikScat wind vector observations (left) and mean a sea level pressure analysis difference [hPa] for 19th June 2007 between a routine COSMO-EU analysis (no use of QuikScat wind data) and a COSMO-EU analysis using QuikScat wind vector observations.

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Regional Data Impact Studies at NCAR and the JCSDA

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1. Introduction

The Weather Research and Forecasting (WRF) modeling effort is a joint NCAR, NOAA, DoD, FAA, and university community effort to build a state of the art NWP modeling system suitable for both operational and academic research applications. The WRF-Var system is a three/four dimensional variational (3/4D-Var) and hybrid variational/ensemble data assimilation system developed by MMM Division of NCAR. The WRF-Var system is a model-space, incremental formulation of the varational data assimilation algorithm and is based on the 3D-Var system built for the MM5 model (Barker et al., 2003, 2004). The WRF-Var system is the operational data assimilation system of the US Air Force Weather Agency (AFWA), and runs in their worldwide theaters of operation (see Fig. 1). The WRF-Var system is also implemented in numerous other real-time applications running over the US, Taiwan, China, S. Korea, India, the middle-East, and Antarctica.

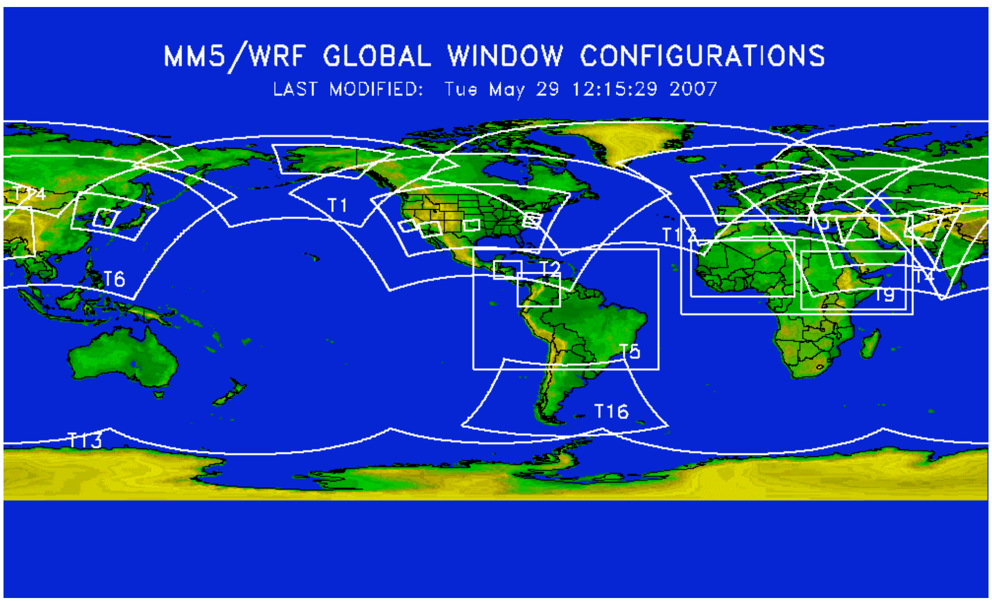

Figure 1: AFWA Worldwide theaters of operation as of May 29th 2007.

2. WRF-Var Regional Data Impact Studies

a. Antarctica

The traditionally data-sparse Antarctic/Southern Ocean has been a focus for remotely-sensed observation impact studies with WRF-Var in recent years. Antarctic studies are performed in the multi-nested (60/20/6.6 km resolution) domains of the Antarctic Mesoscale Prediction System(AMPS) – Powers et al. 2003). Initial observation impact studies have focused on the 60km domain shown in Fig. 2, although more localized studies (e.g. impact of MODIS winds, AIRS retrievals, COSMIC) confined to higher-resolution over the Antarctic continent are also underway.

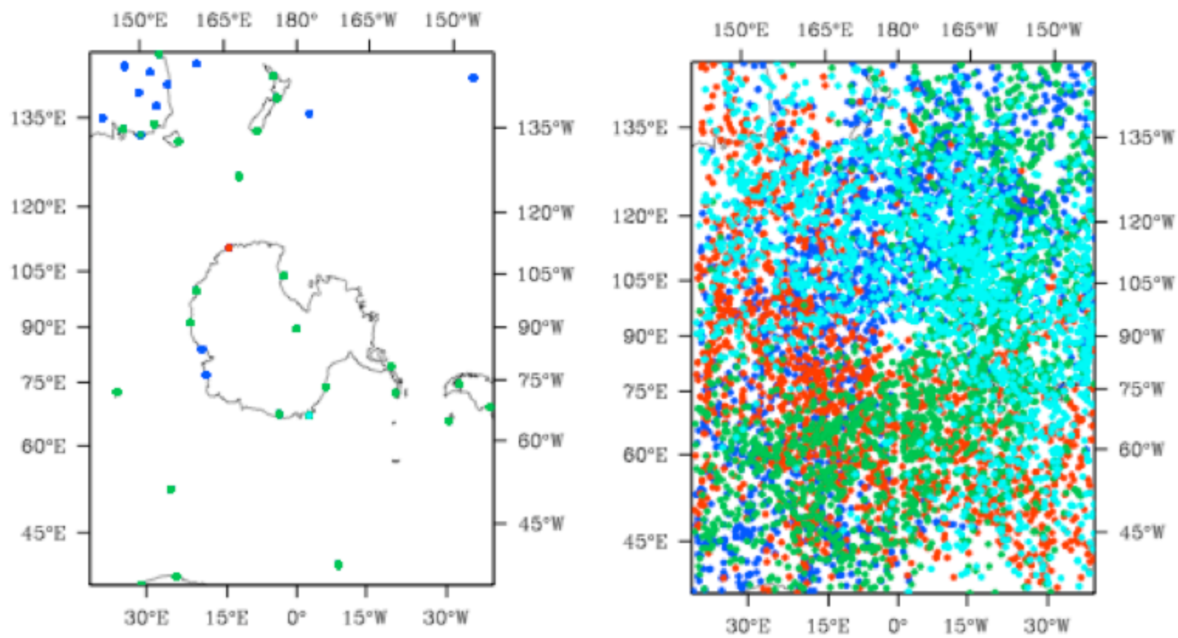

Figure 2: Domain 1 of the Antarctic Mesoscale Prediction System (AMPS). Radiosonde (left) and COSMIC radio occultation data coverage for a 24hr period (1 October 2006) shown.

The impact of COSMIC data on T+36 temperature forecast error (against radiosondes) is shown in Fig. 3 for a month long (October 2006) test period. A statistically-significant positive impact is seen in the troposphere and lower-stratosphere. The origin of the negative impact of COSMIC above 70hPa is under investigation, and is believed related to problems near the model top (currently 10hPa in AMPS). The COSMIC trials shown above were performed without the inclusion of AIRS radiance observations. Initial studies have been performed using an initial conservative subset of the AIRS data (e.g. over sea, thinned to 120km, etc). Results will be presented in a future paper.

b. Impact of AMSU radiances in AFWA's E. Asia Theater

Initial AFWA radiance impact trials have focused on their E. Asia (Korea/Japan) and tropical Atlantic domains. The impact of AMSU-A observations in the 15km "T46" E. Asia domain has been assessed during a month-long trial performed in the summer of 2007. The domain and sample distribution of observations is show in Fig. 4. The WRF-Var system is used not only for the assimilation of observations, but also as an observation verification tool (observation minus forecast differences). This feature enables the user to verify WRF forecasts against all the observations that WRF-Var is capable of monitoring/assimilating. Fig. 5 illustrates this for the AMSU impact assessment, with forecasts verified against a number of non-traditional datasets. These preliminary results indicate a generally positive impact from the assimilation of AMSU-A radiances in a regional E. Asian application of WRF.

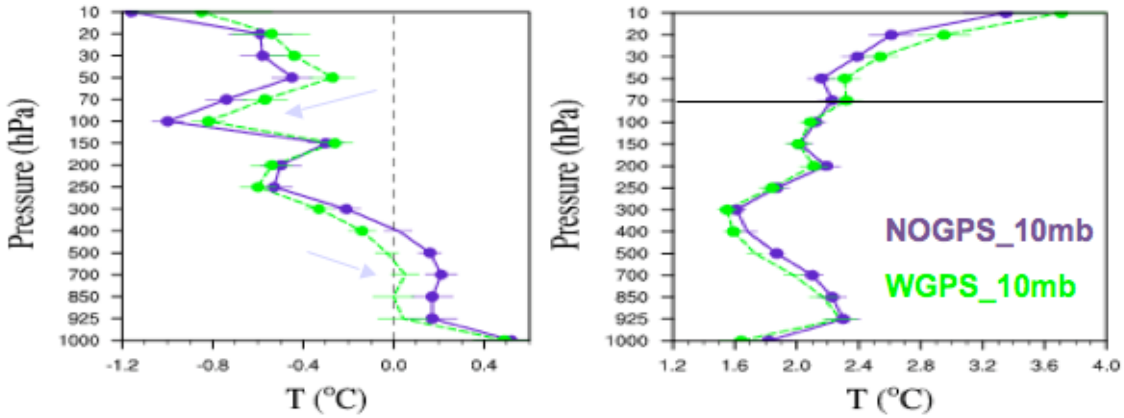

Figure 3: Mean (left) and RMS (right) T+36 temperature forecast error (v.s. sondes) for WRF forecasts during the October 2006 test period. With (green) and without (blue) COSMIC refractivity observations assimilated.

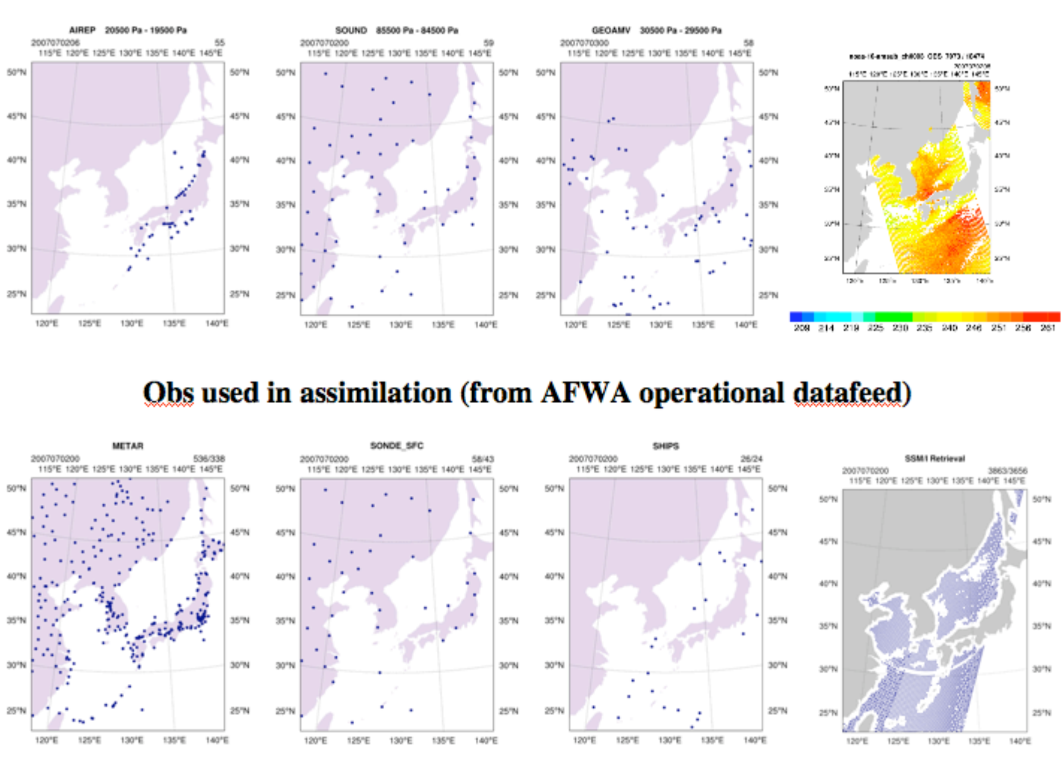

Figure 4: AFWA operational datafeed for 00 UTC 3 July 2007.

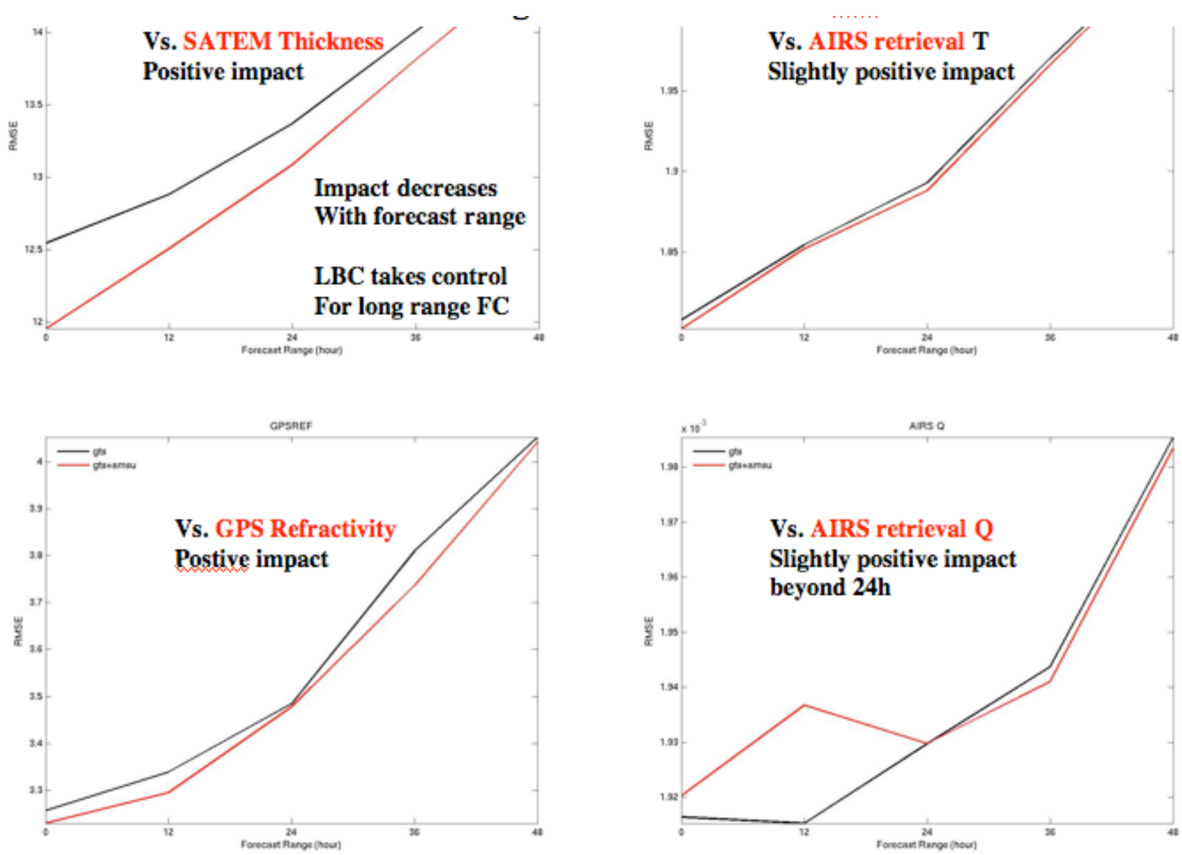

Figure 5: WRF forecast verification with/without AMSU radiance assimilation for AFWA's E. Asian domain during July 2007. Verification datasets (not assimilated): a) SATEM thicknesses, b) AIRS temperature retrievals, c) GPS RO temperature retrievals, d) AIRS humidity retrievals.

3. Summary

The WRF-Var data assimilation system is being increasingly used for observation impact studies in a variety of worldwide applications. Results from sample applications presented here indicate a generally positive impact of COSMIC refractivities in Antarctica and AMSU-A radiances in E. Asia. Further details of these studies and other ongoing work will be presented in a number of future papers.

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Short-range forecast impact of observations at ECMWF

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SUMMARY

Over the past years, Observation System Experiments (OSEs) have been used to show the observation ability in improving weather forecast. OSE can be quite costly if one wants to perform a fine analysis of the various contributions of the elements of the Global Observing System (GOS). Recently a diagnostic tool was developed based on the sensitivity equation of 4D-Var assimilation system. The tool provides a complete analysis of the observations performance in the short range forecast, 24 to 48 hour, being able to zoom on different subsets that can represent the impact of observations from different data types, specific vertical or horizontal domains or particular meteorological measured variables. The potential of the Forecast Sensitivity to Observation (FSO) diagnostic tool on the contribution of the observing system to the numerical weather forecast error is presented in comparison with the OSE tool.

INTRODUCTION

Over the last years, data assimilation schemes have evolved towards very complicated systems, such as the four-dimensional variational system (4D-Var) (Rabier *et al.* 2000) that operates at the European Centre for Medium-Range Weather Forecasts (ECMWF). The scheme handles a large variety of both space and surface-based meteorological observations. It combines the observations with prior (or background) information on the atmospheric state and uses a comprehensive (linearized) forecast model to ensure that the observations are given a dynamically realistic, as well as statistically likely response in the analysis. Effective performance monitoring of such a complex system, with an order of 10^7 degrees of freedom and more than 10^6 observations per 12-hour assimilation cycle, is a necessity. Adjoint-based observation sensitivity techniques are now used to characterize the data impact on the forecast (Baker and Daley 2000, Langland and Baker 2004, Cardinali and Buizza, 2004, Zhu and Gelaro 2008), in particular the impact of the observations on a scalar function of the short-range forecast error. In general, the adjoint methodology can be used to estimate the sensitivity measure with respect to any parameter (Daescu 2008) of importance of the assimilation system. Over the past year, Observing System Experiments (OSEs) have been the traditional tool for estimating data impact in a forecasting system (Bouttier and Kelly, 2001 English *et al*., 2004 and Lord *et al*., 2004, Kelly 2007). Usually, OSEs are performed by removing subsets of observation from the assimilation system and the forecasts are compared against a *control* experiment that includes all observations. The value of observations in the forecast is assessed by comparing forecast skill using different statistical measures. Several independent experiments need to be performed for some months, being hence quite expensive if a full investigation of the different components of the GOS (Global Observing System) is accomplished. The aim of this paper is to illustrate the type of investigation and diagnostics that can be carried out with the adjoint-based observation sensitivity in an operational context. To this respect the adjoint tool is based on the forecast error of the *control* experiment of those OSEs that have recently been performed at ECMWF (Kelly 2007). In this paper, the potential of estimating forecast sensitivity to observations as a diagnostic tool to investigate the sources of short-range forecast errors is shown and qualitatively contrasted with an Observing System Experiment data impact tool. In section 2, forecast sensitivity equation and measure impact is introduced together with a summary of the OSE used in the investigation. Results are illustrated in section 3 and conclusions are given in section 4.

OBSERVATION IMPACT ON THE FORECAST

(a) Observation impact measure

Data assimilation systems for numerical weather prediction (NWP) provide estimates of the atmospheric state $\mathbf{x}$ by combining meteorological observations $\mathbf{y}$ with prior (or background) information $\mathbf{x}_b$. A simple Bayesian normal model provides the solution as the posterior expectation for $\mathbf{x}$, given $\mathbf{y}$ and $\mathbf{x}_b$. The same solution can be achieved from a classical *frequentist* approach, based on a statistical linear analysis scheme providing the Best Linear Unbiased Estimate (Talagrand 1997) of $\mathbf{x}$, given $\mathbf{y}$ and $\mathbf{x}_b$. Let be $\mathbf{x}_a$ the optimal general least square solution to the analysis problem (see Lorenc 1986). The vector $\mathbf{x}_a$ is called the 'analysis'.

Baker and Daley (2000) derived the forecast sensitivity equation with respect to the observations in the context of variational data assimilation. Let us consider a scalar J-function of the forecast error. Then, the sensitivity of J with respect to the observations can be written using a simple derivative chain as:

$$\frac{\partial J}{\partial \mathbf{y}} = \frac{\partial J}{\partial \mathbf{x}_a}\frac{\partial \mathbf{x}_a}{\partial \mathbf{y}}$$

where $\partial J/\partial \mathbf{x}_a$ is the sensitivity of the forecast error to the initial condition (Rabier *et al.* 1996, Gelaro *et al.*, 1998) and $\partial \mathbf{x}_a/\partial \mathbf{y}$ is the analysis sensitivity to the observation. Once the forecast sensitivity is computed (see Cardinali 2008 for details on the equation and solution), the variation δJ of the forecast error expressed by J can be found by using the adjoint property for the linear operator:

$$\delta J = \left\langle \frac{\partial J}{\partial \mathbf{x}_a}, \delta \mathbf{x}_a \right\rangle = \left\langle \frac{\partial J}{\partial \mathbf{x}_a}, \mathbf{K}(\mathbf{y} - \mathbf{H}\mathbf{x}_b) \right\rangle = \left\langle \mathbf{K}^T \frac{\partial J}{\partial \mathbf{x}_a}, \mathbf{y} - \mathbf{H}\mathbf{x}_b \right\rangle = \left\langle \mathbf{K}^T \frac{\partial J}{\partial \mathbf{x}_a}, \delta \mathbf{y} \right\rangle = \left\langle \frac{\partial J}{\partial \mathbf{y}}, \delta \mathbf{y} \right\rangle$$

where $\delta \mathbf{x}_a = \mathbf{x}_a - \mathbf{x}_b$ are the analysis increments and $\delta \mathbf{y} = \mathbf{y} - \mathbf{H}\mathbf{x}_b$ is the innovation vector and **K** is Kalman gain matrix. This is the first time that δJ has been computed for a full 4D-Var system; the sensitivity gradient $\partial J/\partial \mathbf{x}_a$ is valid at the starting time of the 4D-Var window (09 and 21 UTC). As for **K**, the adjoint, $\mathbf{K}^T$, incorporates the temporal dimension, and the δ**y** innovations are distributed over the 12-hour window. The forecast error contribution can be gathered over different subsets that can represent a specific observation type, a specific vertical or horizontal domain, or a particular meteorological variable.

(b) Observation System Experiment

A traditional way of estimating data impact in a forecasting system is to perform OSEs such as those illustrated by Bouttier and Kelly (2001) or Kelly (2007) (for other weather centers see also English *et al.* 2004 and Lord *et al.* 2004). OSEs can be performed in two ways: in one way, the performance of a baseline

Table 1: Operational data set in the OSE control experiment for summer 2006 and winter 2007 (Kelly 2007). T, H, RH, p, u and v stand for temperature, humidity, relative humidity, pressure and u and v wind components.

Type of Data	Description
OZONE	Satellite ozone retrieval
GOES	Geostationary satellite infrared sounder radiances
METEOSAT	Geostationary satellite infrared sounder radiances
AMSU-B	Satellite microwave sounder radiances related to H
SSMI-TCWV	Satellite microwave imager radiances related to clouds and precipitation
SSMI	Satellite microwave imager radiances related to Hand surface wind speed
AIRS	Satellite infrared sounder radiances related to H and T
AMSU-A	Satellite microwave sounder radiances related to T
HIRS	Satellite infrared radiances
ERS-QuikSCAT	Satellite microwave scatterometer
AMVs	Atmospheric Motion Vectors derived from satellite cloud imagery
GPS-RO	Satellite GPS radio occultation
PILOT	Sondes and American, European and Japanese Wind profiler (u,v)
TEMP	Radiosondes from land and ship measuring p_s, T, RH , u and v
AIREP	Aircraft measurements of T, u and v
DRIBU	Drifting buoy measuring p_s, T, RH, u and v
SYNOP	Surface Observations from land and ship stations: measuring p_s, RH , u and v

(reference) experiment which uses a minimum amount of observation types is compared with experiments that add at least one more observation type (Kelly 2007). The other way consists of removing one particular or various datasets from the full system over a long assimilation period and to then compare the performance with respect to the control experiment, which assimilates the available observations from the global network. In any case, it is clear that removing observations from the assimilation system will generate a different

Kalman matrix. Therefore, every experiment in the OSEs will employ a different dataset and consequently produce a different gain matrix.

Table 2: List of OSEs.

Name	**Observations assimilated**
Reference	Conventional, AMSU-A from NOAA-16.
AMV	Reference + AMVs
SCAT	Reference + ERS scatterometer+ QuickSCAT
Control	All data without GPS-RO
GPSRO	All data with GPS-RO

The assessment of the observation value with respect the forecast skill through OSEs is performed by comparing the root mean square forecast error (also anomaly correlation) obtained with and without the subset of interest. This usually involves several independent experiments over a few months. Therefore, OSEs can be quite costly if one wants to perform a comprehensive investigation of the various contributions of the elements of the GOS. The 10-day forecast is computed starting either from the 00 or 12 UTC analyses, both are rarely performed together, given the heavy computational cost. In Table 1 and Table 2, the observations assimilated in the control experiment and the list of the OSEs used in the investigation, are summarized, respectively. Here, the forecasts have been computed from the 00 UTC analysis fields only.

RESULTS

The forecast sensitivity to the observation (FSO) has been computed for two periods, namely a winter and a summer period, and related to the forecast error calculated for the control experiment of the OSEs performed at ECMWF (Kelly 2007). The FSO calculation has been carried out on 60 model levels and with a horizontal truncation of T159 to match with the OSE analysis resolution and has been based on the 00 and 12 UTC forecasts. As for the OSE, the observation departures were computed at T511 (model trajectory resolution, Rabier *et al*. 2000).

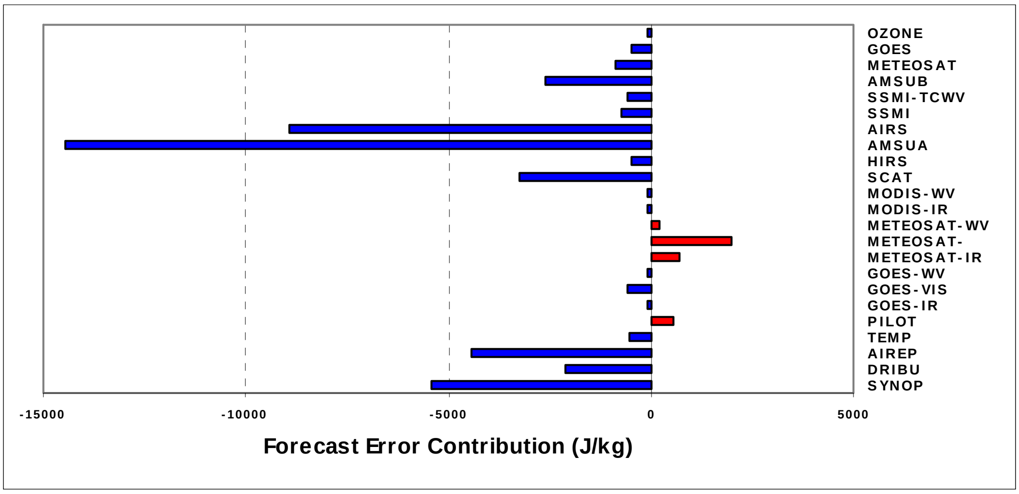

Figure 1: 24-hour forecast error contribution in J/kg of the components (types) of the observing system in summer 2006. Negative (positive) values correspond to a decrease (increase) in the energy norm of forecast error.

The first order sensitivity gradients were computed at the same T159 resolution based on a global square dry energy norm diagnostic function $J = 1/2\langle \mathbf{e}_t, \mathbf{C}\mathbf{e}_t \rangle$ (Rabier *et al*. 1996) where the forecast error **e** was either computed at t=24 or t=48 hours and where **C** is a diagonal matrix whose elements are weighting factors such that J represents the system's total energy. The sensitivity to the humidity initial condition is obtained as a secondary effect due to the adjoint of the linearized moist physical processes used in the sensitivity gradient calculation (Lopez and Moreau 2005, Tompkins and Janisková 2004) which accounts for the dependency of the forecast error at the verification time due to the humidity errors in the initial conditions. The energy norm diagnostic function was computed with the OSE control (using all available observations) experiment forecast error.

(c) (a) Summer

The impact of the operational data set on the 24 hour forecast error has been investigated from the 15 June to 15 July 2006 at 00 and 12 UTC (summer 2006). The forecast error on which the FSO is based, is computed from the control experiment of the OSEs (see Table 1 and Table 2). The global observation performance over this month is summarized in Fig.1. Negative (positive) values correspond to a decrease (increase) of forecast error due to a specific observation type. The largest error decrease is due to AMSU-A (four satellites) and AIRS radiances followed by SYNOP (mainly surface pressure) and AIREP conventional observations. Good error reduction is also due to SCAT (Quickscat and ERS scatterometer), AMSU-B radiances and DRIBU (mainly surface pressure) observations. An increase of forecast error is caused by AMVs (Atmospheric Motion Vector) obtained from geostationary satellites, in particular from METEOSAT. Some degradation is also due to PILOT observations.A more detailed diagnostic of the forecast error contribution from AMVs is shown in Fig.2. The contribution to the forecast error of the observed u-wind component is grouped by pressure levels, geostationary satellite types, such as GOES (G, two satellites GOES-8 and 9), METEOSAT (M, two satellite METEOSAT-7 and 8) and MODIS (MO, two satellites MODIS Terra and Aqua), and by frequency bands: infrared (IR), visible (V) and water vapour (WV). The largest degradation is due to the visible and infrared frequency band at levels below 700 hPa, (mainly at 850 hPa) from METEOSAT (to a larger extent) and from the GOES satellites.

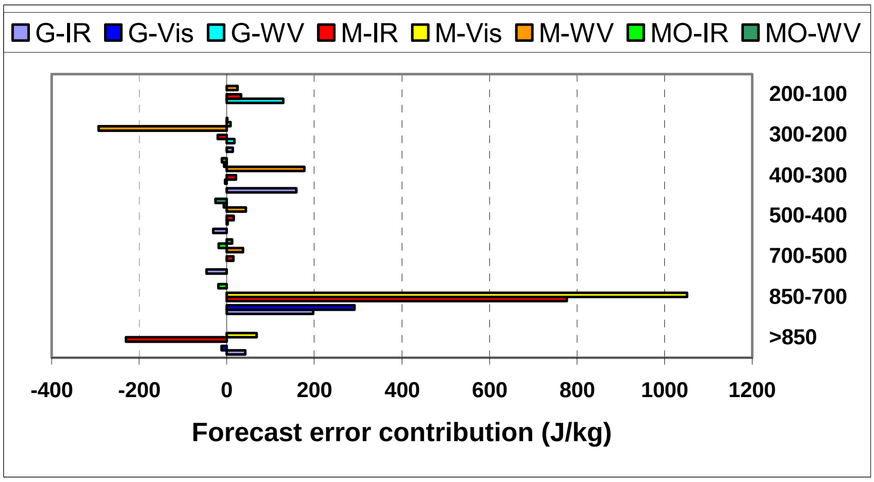

Figure 2 Forecast error contribution of the observed u-component of the wind on pressure levels and grouped by geostationary satellite types: GOES (G, two satellites GOES-8 and 9), METEOSAT (M, two satellite METEOSAT-7 and 8) and MODIS (MO, two satellites: Terra and Aqua) and by frequency bands: infrared (IR), visible (V) and water vapour (WV). Negative (positive) values correspond to a decrease (increase) of forecast error

The geographical locations of the degradation are shown in Fig 3 which displays the 00 UTC forecast error contribution of the visible and infrared bands between 1000 and 700 hPa accumulated over the summer month. The largest degradation is found over the southern equatorial band, in particular over the Atlantic and Indian ocean where the METEOSAT satellites are located, followed by the one over the West Pacific where GOES is operated. The causes of the degradations are still under investigation. The impact of AMVs on the forecast has also been assessed trough the OSE. Among the different OSEs performed at ECMWF, one in particular was performed to measure the impact of assimilated AMVs by comparing a Reference with AMV experiment (AMV's are added on top of the Reference, see Table 2). Figure 4 shows the *rmse* (root mean square error) differences between Reference and AMV experiments for the 24-hour forecast starting at 00 UTC for the 850 hPa u-wind component. The degradations appear in the same locations of Fig 3. Figure 1 shows also a forecast error increase due to PILOT observations (Table 1). The geographical display of the forecast error for PILOT observations (not shown) indicates that the degradation was coming from the America wind profilers. Problems with the American wind profilers at lower levels (below 700 hPa) were known during spring due to bird migration contamination (Wilczak *et al*. 1995). Some meteorological situations also produce profiler measurement contamination (Ackley *et al*. 1998), one of which is the limitation of the local horizontal atmospheric uniformity assumption that must be satisfied to have a correct mean wind measure. Meteorological conditions in which short spatial and temporal scales of variability have amplitudes as large as the mean, as in the presence of a CBL (Convective Boundary Layer) and severe storms, limit the use of profilers for measuring wind profiles of horizontal wind. It was in fact found that the

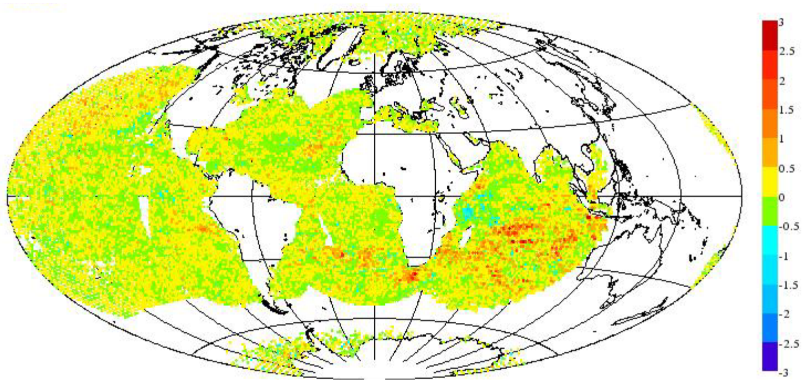

Figure 3 00 UTC forecast error contribution (J/kg) of the observed u-component of the wind between 700 and 1000 hPa from GOES and METEOSAT visible wavelength bands accumulated over one month in summer 2006. Negative (positive) values correspond to a decrease (increase) of forecast error.

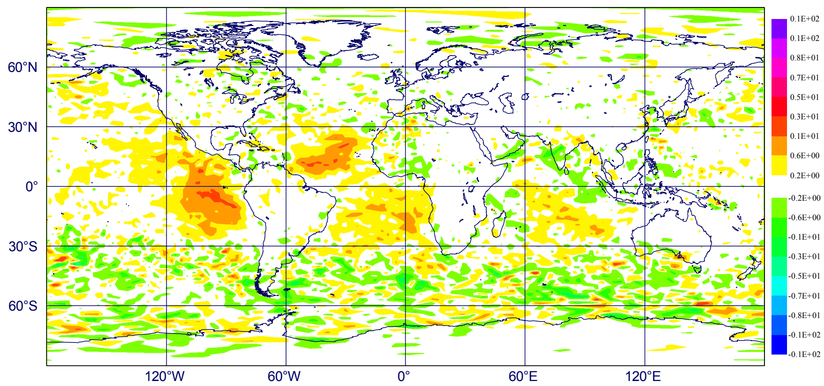

Figure 4: rmse differences between AMV and Reference OSEs of the 24 hour forecast starting at 00UTC for the u-component of the wind at 850 hpa (m/s). Positive (negative) contours indicate AMV errors are larger (smaller) than Reference errors.

CBL-activity was rather high for this period as can be see from the large height of the boundary layer at the station locations, averaged among all profiler stations (not shown). It was also found that both CAPE and TCWV compared with the ERA climatology indicated larger CAPE and humidity advection from the Golf of Mexico in areas where wind profilers are located (not shown). Together, high TCWV and CAPE also provide triggering conditions for convection. Forecast impact of wind profiler can change quite a lot during different meteorological situations, therefore monitoring their impact on forecast skill would allow screening for contaminated measurements.

(b) Winter

The winter period examined ranges from the 5 of January to the 12 of February 2007. On the 24-hour forecast error the global observation performance (not shown) is very similar to the summer one shown in Fig. 1. Again some forecast skill deteriorations are produced by METEOSAT and GOES AMVs obtained from the visible and infrared band, GPS-RO (Global Positioning System satellite Radio Occultation) and a slightly negative impact from GOES-radiances. Impact studies on the use of GPS-RO observations had shown a positive impact in the forecast (Healy and Thépaut 2006) at different ranges with the exception of the 24-hour forecast range (Fig. 5). The OSE was performed by removing the GPS-RO observations (GPSRO experiment) from the operational data set (Table 2). Figure 5 shows the *rmse* of the temperature field at 50 hPa (about 20 km) in the tropical band for GPSRO (solid line) and control (dashed line) experiment (assimilating the full operational observation set) for the same winter period. On the 24-hour forecast the impact of GPS-RO data is negative (Fig. 5) becoming positive only past the 48-hour forecast range. A different FSO experiment based on the 48-hour forecast error was therefore performed to be compared with the 24-hour FSO experiment. Forecast error contribution of GPS-RO measurements at different vertical levels (distance in km from the surface) for the 24 and 48-hour range indicates that the large detrimental effect on the 24 hour forecast accuracy from 100 hPa upwards (above 17 km) is noticeably reduced in the 48-hour forecast (Fig 6).

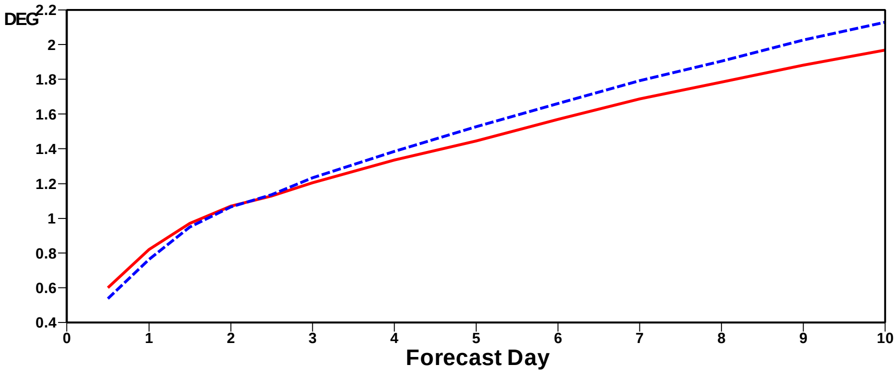

Figure 5: 50 hPa rmse of temperature field at 50 hPa in the tropics for GPSRO (solid line) and Control (dashed line) experiments versus forecast length.

The comparisons with the OSE clearly indicates that, already at the first screening, the FSO diagnostic highlights the major problems and gives a similar qualitative picture than what observing system experiments provide at higher computational cost and with less direct approach for the identification of regions and the level of the problem. According to the OSE, GPSRO performs better than control only after day 2, and the improvement increases with forecast range (up to 0.3 degree in temperature at day 10).

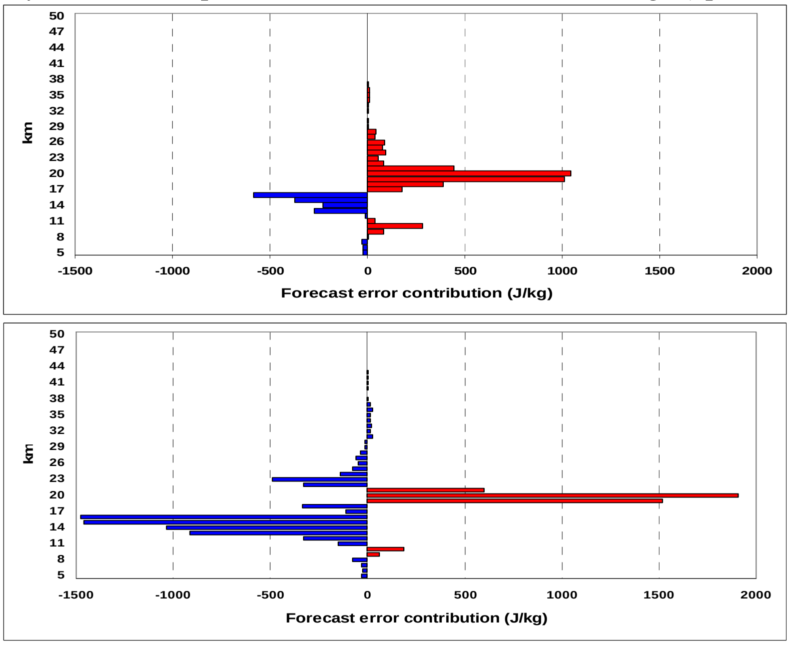

Figure 6 Forecast error contribution of GPS-RO at different vertical levels, from 5 km to the surface up to 50 km: (a) 24 hour forecast range; (b) 48-hour forecast range.

Comparing the results between 24 and 48-hour FSO, the other emerging difference is the impact of SYNOP pressure observations. On the 24-hour forecast range, SYNOPs were globally decreasing the forecast error whilst on the 48-hour range the error increased. Further investigation showed that a group of land stations over Germany and France that were already degrading the forecast at 24 hours, had larger negative impact at 48 hours thus affecting the global monthly forecast error result. The last difference between the 24 and 48-hour forecast errors based FSO, FSO_{24} and FSO_{48} respectively, is also noticed for scatterometer observations. In particular for the whole globe, the impact went from slightly positive (24 hours) to slightly negative (48 hours), being the largest increase of error in the Tropics and Southern Hemisphere whilst in the Northern Hemisphere a global error reduction is noticed (Fig. 8) for the forecasts initialized at 00 UTC. The 48-hour *rmse* differences (normalized with respect to the reference run) were computed between SCAT and Reference experiments (Table 2) initialized at 00 UTC. They indicate a similar skill degradation for latitudes below 30 degrees (4-5 % worse than reference) and a slightly positive impact of scatterometer observations in the Northern Hemisphere (~1% better than reference, Fig. 8) either at 24 (not shown) or 48-hour forecast ranges.

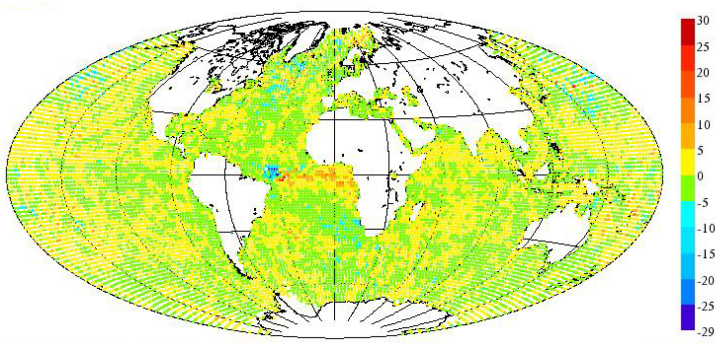

Figure 7: Forecast error contribution at 00 UTC (J/kg) of the observed v-component of the wind from ERS and Quikscat scatterometers. Negative (positive) values correspond to a decrease (increase) of forecast error.

The areas of degradation match quite well with the ones obtained with FSO_{48} (Fig 7). It is only at day 3 that SCAT performs better than the reference experiment in tropical and southern regions.

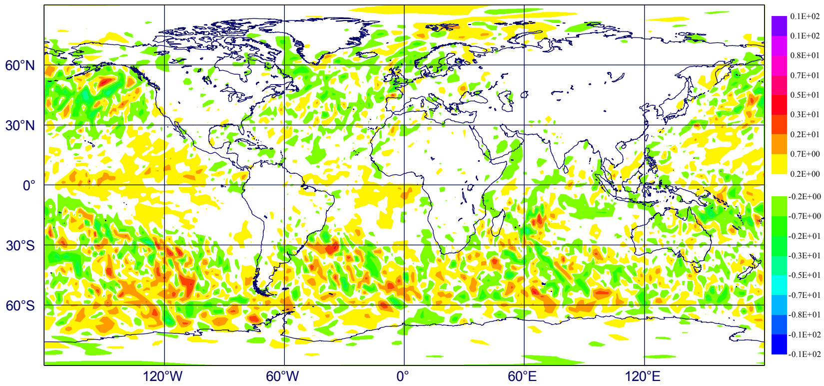

Figure 8 Normalized with respect to Reference, rmse differences between SCAT and Reference OSEs of the 48-hour forecast starting at 00 UTC for the v-component of the wind at 925 hPa (in m/s). Positive (negative) contours indicate SCAT error larger (smaller) than reference error.

In the observation impact monitoring performed so far, the forecast error diagnostic obtained for the 48-hour range (FSO_{48}) provides more information than the FSO_{24} diagnostic. Similar results are obtained with FSO when third-order sensitivity gradients are used (Langland and Baker, 2004 and Errico, 2007). Results are not shown.

CONCLUSIONS

Over the last few years, the potential of using derived adjoint-based diagnostic tools has been largely exploited. This paper illustrates the use of the forecast sensitivity with respect to time-distributed observational data, first time in a 4D-Var assimilation system, as a diagnostic tool to monitor the observation performance in the short-range forecast. Here, the forecast sensitivity to the observation has been based on the forecast error of the control experiment from the observing system experiments that have recently been performed at ECMWF with the intention of comparing the performance of the two diagnostic tools. The assessment of the value of observations for forecast error reduction trough the OSEs is performed by comparing the root mean square error forecast skill obtained with and without the subset of data of interest. This usually involves large numbers of independent experiments over several months and is therefore quite expensive to perform and prohibitive if a detailed investigation of operational observing systems must be obtained. Also, any variation in the observation set that is assimilated through data addition or denial modifies the Kalman gain matrix, therefore producing different solutions in the minimization. However, observation forecast impact on the medium and long-range can also be investigated. Forecast sensitivity to observations can only be used to diagnose the impact on the short-range forecast, namely 24 to 48 hours, given the use of the adjoint of the data assimilation system and the implied linearity assumption. On the other hand, the use of FSO quickly allows the identification of potential problems and directing further investigation. It was demonstrated that a very similar qualitative picture is provided by FSO and OSE on the short-range forecast. The forecast degradation that was observed at certain pressure levels and a number of areas in the OSE due to some observation type, matches well with the FSO forecast error contribution maps for the same observation type. Clearly, the two tools have different meanings of use. Whilst OSEs are more indicated for evaluating the longer term forecast impact of data, FSO should be used to investigate the reasons of short-range forecast impact from the observations. Form the results of this paper, it is concluded that 48-hour forecast error analysis is preferable. Over the two months period, the global impact of observations was found to be positive and the forecast errors decrease for almost all data type. Problems have been noticed with Atmospheric Motion Vectors mainly derived from visible and infrared wavelength bands (and for low-level winds). Problems with conventional observations, wind profilers in summer and SYNOP Metar surface pressure observations in winter, was mainly due, for different reasons, to the local synoptic situation. Wind profiler measurements were corrupted by the presence of strong convection activity in the boundary layer, while large surface pressure variability that characterized the entire winter month at the surface over a limited domain (eastern France and Germany) was not correctly solved in the minimization. Given the dependency of some observation types on the meteorological situation, it is suggested to run the forecast sensitivity to the observation diagnostic tool on an operational basis and in relation to the operational suite error. A constant monitoring of the performance of the model forecast would allow the use of the observation network in an adaptive way where observations with negative impact can be investigated and potentially denied in real time.

Acknowledgements: The author thanks ECMWF data assimilation section for the support on the FSO tool development

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Examination of observation impacts derived from OSEs and adjoint models

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1. Introduction

Until recently, assessing the impact of observations on numerical weather forecasts has been done mainly through observing system experiments (OSEs), in which subsets of observations are removed from a data assimilation system and the resulting forecasts compared against a control set that includes all observations. OSEs are performed intermittently at most operational centers but, because of their expense (multiple executions of the data assimilation system are required), usually involve a relatively small number of independent experiments, each considering relatively large subsets of observations. Nevertheless, OSEs have been extremely useful for quantifying the relative "importance" of the various components of the observing system and have made clear, for example, the increasing benefit from satellite observations.

During the last few years, the adjoint of a data assimilation system has also emerged as an accurate and efficient tool for estimating observation impacts on short-range weather forecasts (Baker and Daley 2000, Langland and Baker 2004). The impacts of any or all observations can be computed simultaneously based on a single execution of the adjoint system. In addition, the results can be easily aggregated by data type, location, channel, etc. making this technique especially attractive for regular, even near-real time, monitoring of the entire observing system.

Comparisons between OSEs and adjoint estimates of observation impact have been mostly anecdotal up to now. This is due in part to the much more limited use of the latter at present, but also because of fundamental differences in the way observation impact is measured in the two approaches. These differences relate to whether observations are included versus removed as a means of measuring their impact, and the treatment of information in the background state. In this study, we compare observation impacts derived from OSEs and the adjoint of the GEOS-5 atmospheric data assimilation system developed at the NASA Global Modeling and Assimilation Office (GMAO).

2. Methodology

a. Estimation of observation impact

We consider the impact of observations on a measure of forecast error defined as

$$e = (\mathbf{x}^f - \mathbf{x}^t)^{\mathrm{T}}\mathbf{C}\,(\mathbf{x}^f - \mathbf{x}^t)\,, \tag{1}$$

where $\mathbf{x}^f$ is a forecast state, $\mathbf{x}^t$ is a verification state and $\mathbf{C}$ is a matrix defined such that (1) measures the forecast error in terms of dry static energy from the surface to approximately 140 hPa. The forecast is produced by a nonlinear model integration from an initial state $\mathbf{x}^0$. Both $\mathbf{x}^0$ and $\mathbf{x}^t$ are based on atmospheric analyses, $\mathbf{x}_a$, produced by a cycling data assimilation system that optimally combines observations $\mathbf{y}$ with a background forecast $\mathbf{x}_b$ in the form

$$\delta\mathbf{x}^0 = \mathbf{x}_a - \mathbf{x}_b = \mathbf{K}\delta\mathbf{y}, \tag{2}$$

where $\delta\mathbf{x}^0$ is the analysis increment, $\mathbf{K}$ is a matrix that determines the scalar weight given to each observation and $\delta\mathbf{y}$ are the innovations (observation minus background departures). Changes in e due to changes in $\mathbf{x}^0$ may be expressed in terms of a Taylor series approximation

$$\delta e = \sum_i \delta x_i^0 \Bigg(\frac{\partial e}{\partial x_i^0} + \frac{1}{2}\sum_j \frac{\partial^2 e}{\partial x_i^0 \partial x_j^0}\,\delta x_j^0 + \frac{1}{6}\sum_{j,k}\frac{\partial^3 e}{\partial x_i^0\partial x_j^0\partial x_k^0}\,\delta x_k^0\,\delta x_j^0 + \dots \Bigg). \tag{3}$$

With the transformation (2), various-order approximations of δe can be expressed in terms of the innovations $\delta\mathbf{y}$ (Errico 2007). In this study, we use the third-order approximation

$$\delta e \approx (\delta\mathbf{y})^{\mathrm{T}}\mathbf{K}^{\mathrm{T}}\left[\mathbf{M}_b^{\mathrm{T}}\mathbf{C}\,(\mathbf{x}_b^f - \mathbf{x}^t) + \mathbf{M}_a^{\mathrm{T}}\mathbf{C}\,(\mathbf{x}_a^f - \mathbf{x}^t)\right], \tag{4}$$

where $\mathbf{x}_b^f$ and $\mathbf{x}_a^f$ are forecasts initialized from $\mathbf{x}_b$ and $\mathbf{x}_a$, $\mathbf{M}_b^{\mathrm{T}}$ and $\mathbf{M}_a^{\mathrm{T}}$ represent the adjoint of the forecast model evaluated along those trajectories and $\mathbf{K}^{\mathrm{T}}$ is the adjoint of the data assimilation system. This expression is equivalent to the impact measure derived originally by Langland and Baker (2004) using an alternative approach. It provides an estimate of the change, typically a reduction, in the error of $\mathbf{x}_a^f$ compared with that of $\mathbf{x}_b^f$ resulting from assimilation of the complete set of observations. The impact of any or all observations may be determined, therefore, from a single (control) data assimilation experiment that includes all observations assimilated routinely.

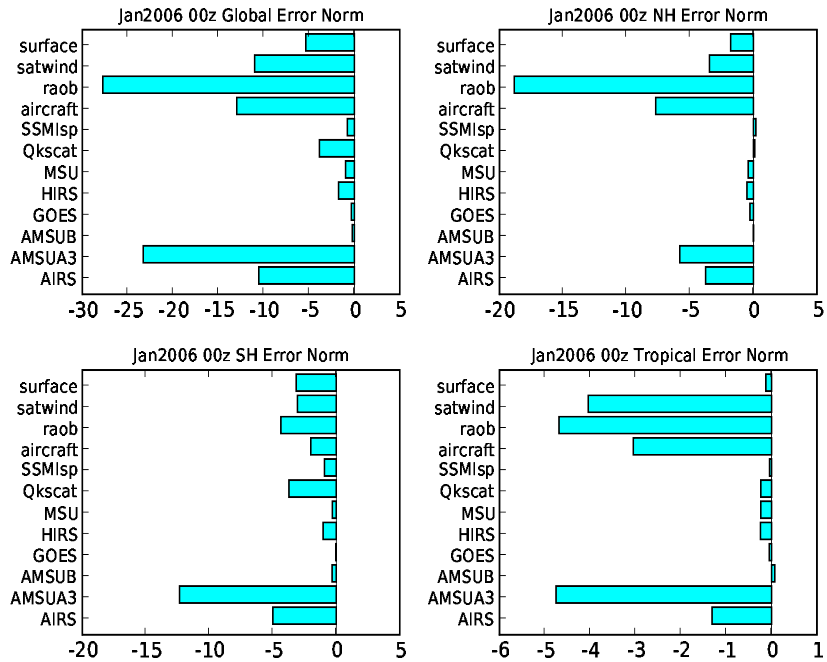

Figure 1: Adjoint-based accumulated 24-h forecast error reduction δe due to various observing systems assimilated in GEOS-5 during January 2006, using response functions for the globe (upper left), NH (upper right), SH (lower left) and tropics (lower right). The units are Jkg^{-1}.

The impact of observations on (1) can also be assessed using OSEs, by simply computing differences in e between the control forecasts and forecasts in which selected observations have been removed from the data assimilation system. Differences in e computed this way provide a measure of the change, typically an *increase*, in forecast error resulting from the *removal* of observations from the system. The removal of observations changes the scalar weights of the remaining observations, so that the assimilation systems for the perturbed members of the OSES differ from the control as well as from one another. OSEs reflect the removal of observational information from both the background and analysis in a cumulative manner, whereas (4) measures the impact of observations in each analysis cycle separately and the background contains all previous information from the complete observing system.

b. Experiments

The impacts of observations on 24-hour forecasts from 00 UTC were examined for the months of January 2006 and July 2005 using forward and adjoint versions of GEOS-5 (Rienecker et al. 2007, Zhu and Gelaro 2008). Analyses were produced at 0.5-degree horizontal resolution with 72 vertical levels using a 6-hour assimilation cycle that included all observations assimilated operationally. To evaluate (4), 24-h forecast trajectories were produced at 1.0-degree horizontal resolution with 72 vertical levels and full physics from the 00 UTC analysis and corresponding background state for each day of the study period. Adjoint forecasts along these trajectories were produced at the same resolution but with simplified dry physics. Separate response functions were used to measure e over the globe, Northern Hemisphere (NH, 20-80N), Southern Hemisphere (SH, 20-80S) and tropics (20S-20N). For comparison with the adjoint results, a set of eight OSEs were conducted for the same months in which the following observation sets were individually excluded from the data assimilation system:

- all AMSU-A radiances from a single satellite (NOAA-16): *no amsua1*
- all AMSU-A radiances from two satellites (NOAA-15, NOAA-16): *no amsua2*
- all AMSU-A radiances from three satellites (NOAA-15, NOAA-16, Aqua): *no amsua3*
- all AIRS radiances: *no airs*
- all rawinsonde observations: *no raob*
- all satellite winds: *no satwind*
- all aircraft observations: *no aircraft*

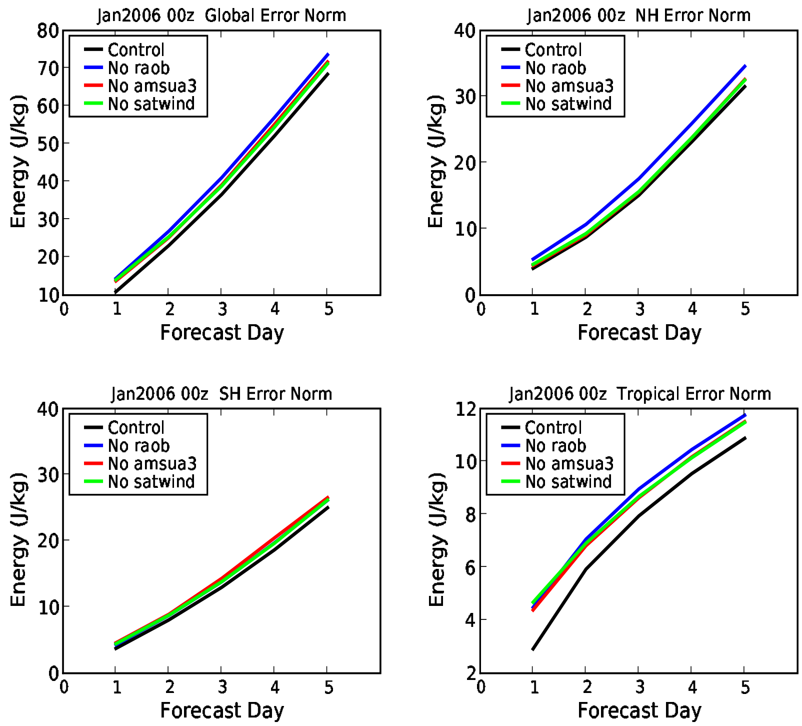

Figure 2: Growth of e over the globe (upper left), NH (upper right), SH (lower left) and tropics (lower right) for various OSEs during January 2006. The units are Jkg^{-1}.

- all scatterometer winds from QuikSCAT: *no qkscat*

Forecasts were produced from the 00 UTC analysis each day and values of e were computed over the same verification domains used to define the adjoint response functions. The control analysis containing all observations was used for the verification state in all cases. For brevity, we focus mostly on results for January 2006.

3. Observation impact results

Fig. 1 shows the adjoint-based accumulated impacts of the major observing systems assimilated in GEOS-5 during January 2006 for the four response functions. With few exceptions, the observing systems shown have an accumulated beneficial impact ($\delta e < 0$) on the 24-h forecast. The contributions from the various observing systems vary significantly depending on the verification region. Globally, both rawinsondes and AMSU-A have the largest beneficial impacts, with smaller, but still significant, contributions from AIRS, aircraft observations and satellite winds. The rawinsondes dominate the impact in the NH while AMSU-A has the largest impact in the SH. In the tropics, the relative impacts of the various observing systems are similar to the impacts globally, although the magnitude of the error reduction is smaller.

Fig. 2 shows examples of the OSE results for January 2006. For clarity, results are shown only for the *no raob*, *no amsua3* and *no satwind* experiments, in addition to the control. Each panel shows the growth of e as a function of time for forecast days 1–5 for each verification region. As expected, the magnitudes and growth rates of the errors vary regionally. The removal of rawinsondes has the dominant impact both globally and in the NH, while the removal AMSU-A has the largest impact in the SH. These results agree qualitatively with the adjoint-based ones for these instruments (Fig. 1). The picture differs in the tropics. The forecast errors are smaller and grow in a manner that more closely resembles a square root, as opposed to exponential, function of time. At the same time, the relative impacts of the various observing systems change markedly as a function of time. There appear to be larger qualitative differences between the OSEs and adjoint results, even at day one.

4. Direct comparison of OSE and adjoint results

Quantitative comparisons between the OSEs and adjoint results are restricted to the 24-h forecast since this is the time at which the latter are formerly valid in this study. Even so, comparisons between the OSE and adjoint results are

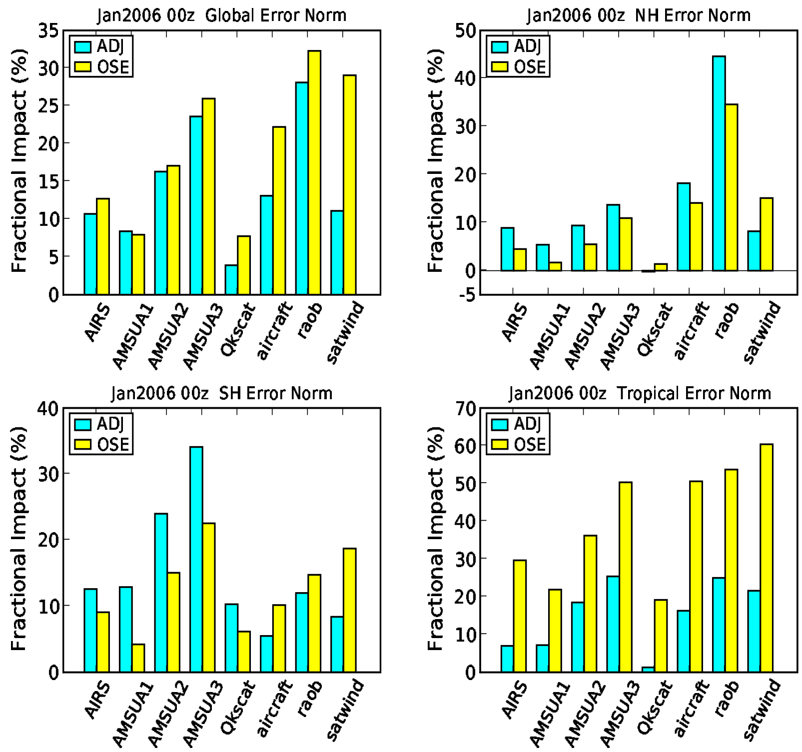

Figure 3: Adjoint- and OSE-based fractional impacts of various observing systems on the change in 24-h forecast error over the globe (upper left), NH (upper right), SH (lower left) and tropics (lower right) during January 2006.

complicated by the fact that changes in e based on evaluation of (1) in the OSE context are not directly comparable to values of δe based on (4) in the adjoint context. We can, however, define for each approach a measure of the fractional impact of an observing system, j, on the total change in e as measured by that approach. In the adjoint context, an obvious choice for this measure is

$$F_j(\mathrm{ADJ}) = \delta e_j / \delta e\,, \tag{5}$$

where δe_j represents the partial sum over only the elements in (4) involving observing system j. Note that for any partitioning of the complete observing system into j components, we have $\sum_j F_j(\mathrm{ADJ}) = 1$, since the impact of any or all observations in the adjoint context is assessed within a single experiment. The choice of measure is less obvious for OSEs, since changes in e resulting from the removal of observations in these experiments can be measured with respect to forecasts from either the background or analyzed states. Since OSEs typically involve comparisons with respect to the latter, we define the fractional impact of a given observing system in the OSE context as

$$F_j(\mathrm{OSE}) = (e_{j*} - e_{ctl})/e_{ctl}\,, \tag{6}$$

where e_{j*} is the error measure of the 24-h forecast from the analyzed state *without* observing system j and e_{ctl} is the error measure of the 24-h forecast from the analyzed control state. Unlike $F_j(\mathrm{ADJ})$, there is no expectation that for a given partitioning of the observing system the sum of $F_j(\mathrm{OSE})$ will equal one since the contribution of each observing system is determined from a separate experiment and different permutation of the data assimilation system. If, for example, the forecast is highly sensitive to the removal of one or more types of observations, then the sum of the contributions may be much larger than one. In that case, direct comparisons between $F_j(\mathrm{ADJ})$ and $F_j(\mathrm{OSE})$ become more difficult.

Fig. 3 compares the values of $F_j(\mathrm{ADJ})$ and $F_j(\mathrm{OSE})$ for January 2006 for the eight observing systems tested in the OSEs. Over the globe and extratropics, we see fairly good quantitative agreement between the two measures for most observing systems, with the exception of the satellite winds globally. In the NH there is good agreement for all observing systems. In the SH we see somewhat larger impacts for AMSU-A in the adjoint results, as well as the larger impact of satellite winds in the OSE results seen globally.

In the tropics, there is greater disagreement overall between $F_j(\mathrm{ADJ})$ and $F_j(\mathrm{OSE})$. Values of $F_j(\mathrm{OSE})$ are much larger than those of $F_j(\mathrm{ADJ})$ for all observing systems, with

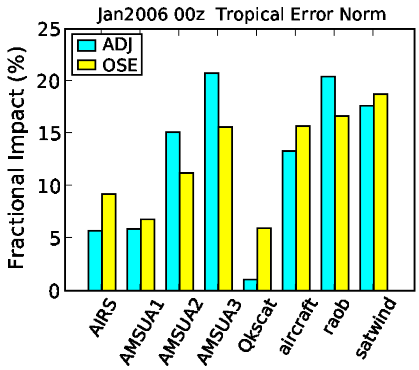

Figure 4: Normalized adjoint- and OSE-based fractional impacts of various observing systems on the change in 24-h forecast error over the tropics during January 2006.

the former exceeding 50% for several observing systems. In the adjoint results, it is impossible to have such large fractional contributions from several observing systems simultaneously. Nonetheless, the relative magnitudes of the various observing system contributions are consistent in the two sets of results. This can be seen more clearly in Fig. 4, in which the values of $F_j(\mathrm{ADJ})$ and $F_j(\mathrm{OSE})$ in the tropics have been normalized such that they sum to one for the eight experiments shown. Only the contribution from QuikSCAT remains disproportionately larger in the OSEs after normalization, but it is among the smallest impacts overall.

5. Combined use of adjoints and OSEs

The results presented thus far provide little insight into the behavior of the data assimilation system, including likely dependencies and redundancies between observing system impacts as observations are added or removed from the system. Such information is implicitly available in an OSE in terms of the responses of the *remaining* observations when a given set of observations is removed. These responses can be measured through the combined use of OSEs and the adjoint by applying the latter to the perturbed OSE members and comparing the impacts of the remaining observing systems with those in the control experiment.

As an example, Fig. 5 compares the fractional impacts in the control experiment with those in the *no amsua3*, *no raob* and *no satwind* experiments during July 2005. In this case, we show contributions from observations in the tropics to the reduction of the global error norm. There are large variations in the impacts of several observing systems. Removal of the satellite winds increases the impact of rawinsondes by more than two thirds compared with the control, from 28% to 47%. There is a reciprocal response in the impact of satellite winds to the removal of rawinsondes, which more than doubles with respect to the control experiment, increasing from 15% to more than 30%.

The response of AIRS is more complex. The removal of AMSU-A radiances nearly doubles the fractional impact of AIRS from 19% to 37% with respect to the control. In sharp contrast to this, however, the removal of the satellite winds erases the benefit of AIRS entirely such that the impact is in fact slightly detrimental to the forecast in terms of this metric. This result may point to a deficiency in the wind-mass relationship imposed through the background error covariances used in the analysis system. While AIRS provides substantial benefit to the forecast in the tropics when assimilated in conjunction with sufficient observations of the winds, the results here suggest that the wind increments induced by AIRS through the balance relationship alone are detrimental at these latitudes.

6. Conclusions

Despite fundamental differences in their underlying assumptions and methodologies, OSEs and adjoint measures of observation impact appear to provide comparable estimates of the overall "importance" of most of the major observing systems assimilated in the GEOS-5 atmospheric data assimilation system, at least in terms of their contribution to an energy-based metric of 24-h forecast error. Outside the tropics, the fractional impacts of most observing systems were found to be in reasonable to good quantitative agreement with only a few exceptions. Within the tropics, the OSEs yielded fractional impacts that, while larger in absolute magnitude than those measured by the adjoint, were similar overall in terms of the relative contributions of the various observing systems to the quality of the forecast in that region.

Differences should be expected in the results produced by the two methods, and do not necessarily point to shortcomings in one or the other. Information gleaned from OSEs and adjoints should be viewed as complementary since both address relevant questions about how observations influence the quality of weather forecasts. Specifically, it is important to keep in mind that the adjoint measures the impact of observations in each analysis cycle separately and against the control background containing all previous information, while the OSEs measure the impact of removing observational information from both the background and analysis in a cumulative manner. This distinction can be significant, especially if an observing system contributes disproportionately to the quality of the analysis and subsequent background state.

The *combined* use of OSEs and adjoints provides insights into how (changes in) the mix of observations in a

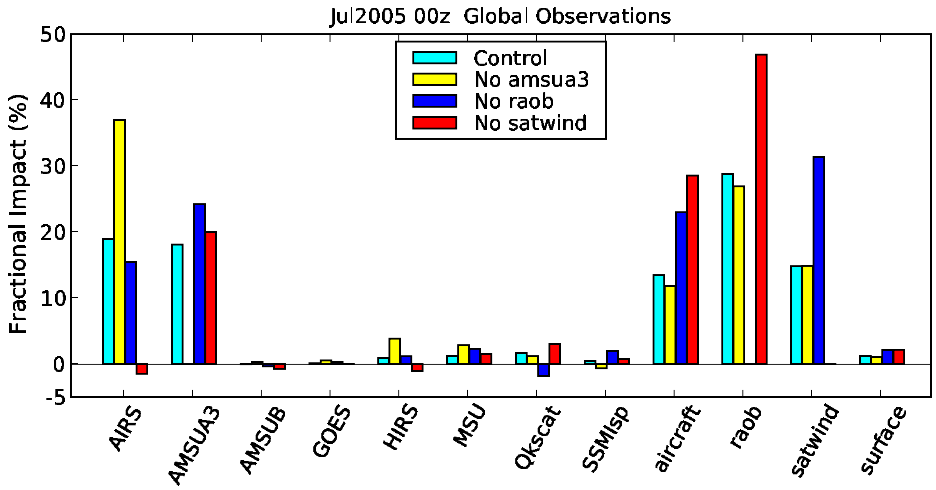

Figure 5: Adjoint-based fractional impacts of various observing systems on the change in 24-h forecast error during July 2005 for different OSEs. Results include only contributions from observations in the tropics to the reduction in global forecast error.

data assimilation system affects their impacts. Examples of these calculations in the present study showed significant compensatory effects between observing systems, as well as a possible deficiency in the assimilation system. Information about these dependencies may be useful for making intelligent data selection decisions and possibly identifying needs for future observation types.

Acknowledgments

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Adjoint-based observation impact monitoring at NRL-Monterey

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1. Introduction

In numerical weather prediction (NWP) there is an increasing need to develop and apply methods for monitoring the impact and value provided by atmospheric observations used in operational data assimilation. Significant investments have been made to obtain observations from satellite observing systems (AMSU, AIRS, HIRS, SSM/I, etc.) and the efforts to use these data to improve NWP involves considerable research and computational expense. It is recognized that larger amounts of satellite observations benefits NWP, yet it can be difficult to quantify the relative value of the many types of data that are assimilated. For example, when 300 channels of an infrared sounder are assimilated, what is the relative benefit provided by each of these channels? The adjoint-based observation impact monitoring system developed at NRL can answer these types of questions, by providing the capability to quantify and visualize with graphics the forecast impact of every observation assimilated in an operational NWP system.

2. Methodology

The essential steps involved in adjoint-based observation impact estimates are described by Langland and Baker (2004), LB04 hereafter. The measure of observation impact is defined as the *difference* between forecast errors on an analysis and a background trajectory, whose initial conditions are separated by six hours. For example, we can obtain an adjoint-based estimate of e_{24} - e_{30}, the difference between the 24h error of a forecast started from 0000UTC (the start of the analysis trajectory) and the 30h error of a forecast started from the prior 1800UTC (the start of the background trajectory). Here e_{24} and e_{30} are norms defining moist total energy-weighted forecast error in the global domain.

The effect of observations that are assimilated at 0000UTC is to move the forecast from the 1800UTC background trajectory to the new analysis trajectory, which produces a different forecast error. The difference of forecast errors on these two trajectories is due solely to the assimilation of the observations, and the separate forecast impact of *every assimilated observation* can be quantified using this approach. For each observation, the "observation impact" δe_{24}^{30} is obtained as a scalar product of the observation innovation and the sensitivity of forecast error to the innovation, in observation-space

$$\delta e_{24}^{30} = \left\langle (\mathbf{y} - \mathbf{H}\mathbf{x}_b), \mathbf{K}^{\mathrm{T}} \left(\frac{\partial e_{24}}{\partial \mathbf{x}_a} + \frac{\partial e_{30}}{\partial \mathbf{x}_b} \right) \right\rangle \quad (1)$$

When (1) is summed over the entire set of assimilated observations it provides an approximation of the difference between the nonlinear forecast error norms for the global domain

$$\sum^{all\ obs} \delta e_{24}^{30} \cong e_{24} - e_{30} \quad (2)$$

If $\delta e_{24}^{30} < 0$ then the assimilation of that observation (or set of observations) has made the analysis trajectory more accurate than the background trajectory in terms of the selected forecast error norms.

This calculation requires adjoint versions of the forecast model and the data assimilation procedure and, as described by LB04, we use the forecast model adjoint to compute sensitivity gradients on both the analysis and background trajectories to obtain higher accuracy. It has been shown in Gelaro et al. (2007) that (1) is essentially equivalent to a third-order approximation of the change in the quadratic measure of energy-weighted forecast error. The computational cost of producing the observation impact information using the adjoint system is about the same as one run of the regular analysis and forecast model. Note that this method evaluates the impact with *all observation data included*, in contrast to conventional data-denial sensitivity studies that estimate the forecast impact when observations are withheld from, or added to, the analysis.

3. Observation Impact Monitor

We have developed a web-based user-interactive system to monitor the impact of observations assimilated in the operational and beta-runs of NAVDAS [1] -NOGAPS [2] at NRL-Fleet Numerical

[1] NAVDAS – NRL Atmospheric Variational Data Assimilation System

Meteorology and Oceanography Center.
Currently, the monitoring page is updated once per-day, using observations assimilated at 0000UTC and a global 24h forecast moist total energy-weighted error norm integrated from the surface to 350 hPa as a costfunction.

The NRL observation impact monitoring web page is available for public access at: www.nrlmry.navy.mil/ob_sens/ Information is provided in several formats, including histograms, time series, and maps of observation impact. Menus (see supplemental figure) allow users to select and generate graphics for specific instrument types, observation variables (temperature, u or v-wind component, humidity, etc.), vertical levels, satellite platform and data-provider, and satellite channel.

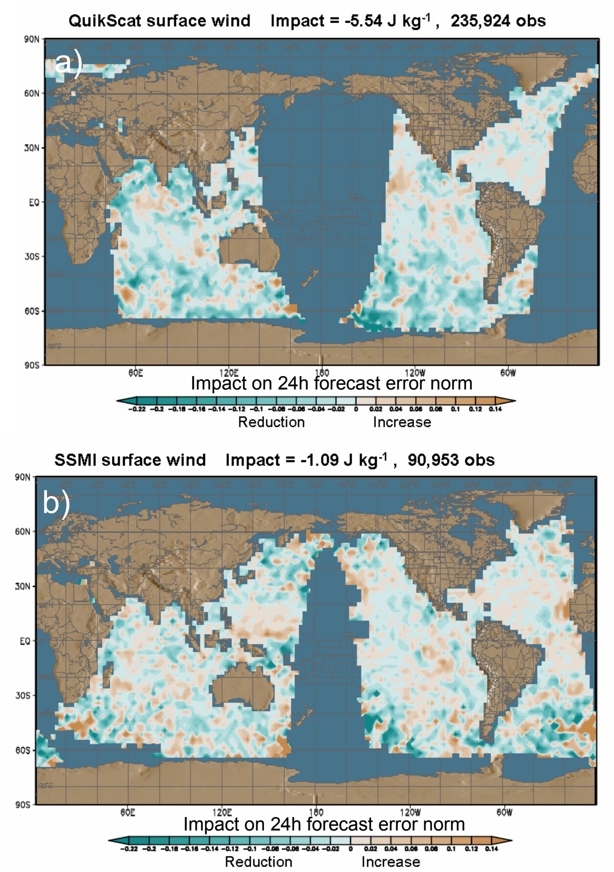

Fig. 1: 30-day cumulative impact of observations δe_{24}^{30} for: a) Quikscat surface wind component observations, b) SSMI surface wind speed observations assimilated in NAVDAS at 0000 UTC during 29Mar – 27Apr 2008. The impacts are plotted as sums within 2.5º x 2.5º latitude-longitude boxes. Negative (positive) values indicate forecast error reduction (increase) on analysis vs. background trajectory.

Maps of observation impact are displayed as 30-day sums, which filters out short-term variability in the results. It has been found that assessments of observation impact should in general be based on results accumulated over at least 2-3 weeks to obtain a representative sample.

Fig. 1 illustrates the 30-day cumulative impact of a) QuikScat u- and v- surface wind observations, and b) SSMI surface wind speed observations. While in terms of the global sum, both observation types reduce e_{24}-e_{30}, the total impact of QuikScat is about 5x larger, and is about 2x larger per assimilated observation. Note that there are areas where observations are beneficial (e.g, their assimilation reduces forecast error) and in other areas observations are non-beneficial (e.g. their assimilation increases forecast error). In general, about 50-55% of assimilated observations in a given set are beneficial. This result is essentially explained by the inability to provide precise specifications of observation and background error statistics in a data assimilation procedure. The assumptions made about error statistics allow successful assimilation of large sets of observations, but they are not accurate for all observations in all regions at all times. For example, areas where surface wind observations did not improve 24h forecast skill are shown with red shading in Fig. 1.

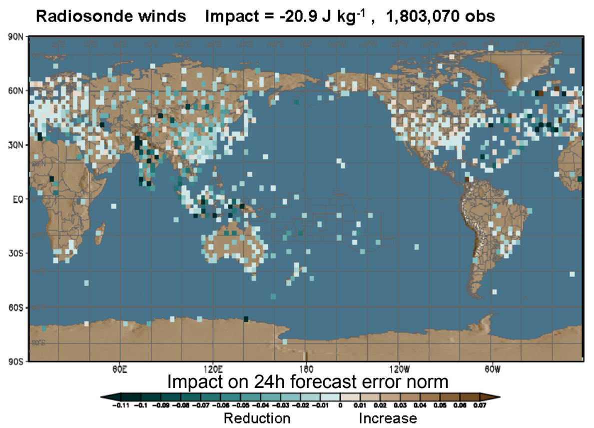

Fig. 2: As in Fig. 1, for radiosonde wind component observations at all levels.

For comparison, Fig. 2 illustrates the 30-day cumulative impact of wind observations from radiosonde profiles. Note the number of radiosonsde wind observations and their impact is much larger than is obtained from the surface winds shown in Fig. 1. In a 30-day summary, the great majority of land-based radiosonde stations are beneficial. The large forecast error reductions provided by radiosonde observations (Table 1) are due to their number and the accuracy of the data. Note that ship-launched radiosondes profiles in the north Atlantic also have large impact, although they are single profiles, not the sum of 30 separate daily profiles, as are the regular land-based radiosonde stations.

The impact of radiosondes over North America,

[2] NOGAPS- Navy Operational Global Atmospheric Prediction System

China and Europe is reduced somewhat due to large amounts of wind observations from commercial aircraft, especially MDCRS (Fig. 3a) and AMDAR (Fig. 3b). Although there are about twice as many MDCRS wind observations, the AMDAR winds (Fig. 3b) have larger forecast impact, because many AMDAR winds are provided in areas where other in-situ upper-air wind observations (e.g., from radiosondes) are sparse, such as Africa, the southern Indian ocean, and northern Canada and Greenland.

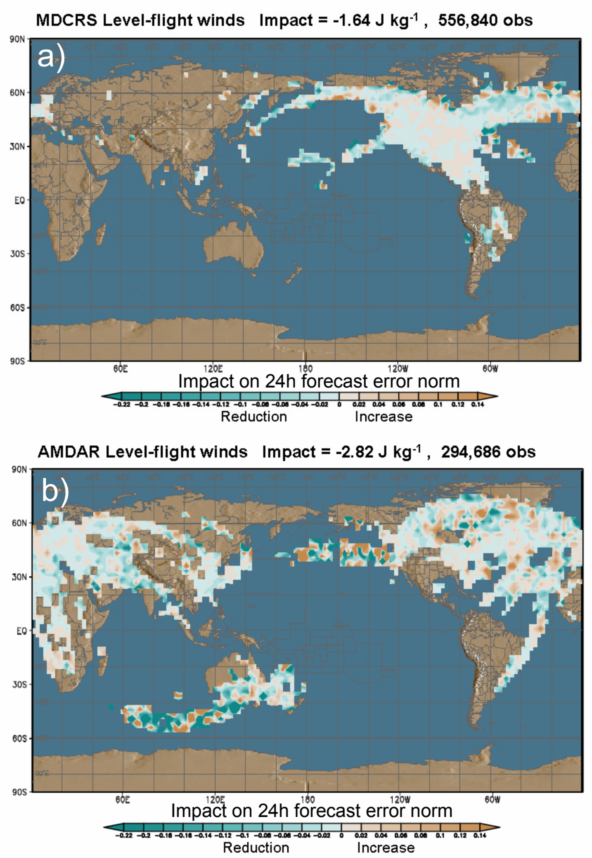

Fig. 3: As in Fig. 1, for: a) MDCRS level-flight wind obsevations, and b) AMDAR level-flight observations.

Fig 4 shows time series of impact of radiance observations provided by NOAA-16 and NOAA-18 AMSU-A, Ch. 4, during 2006-2007. Both satellites provide about the same number of observations, but the impact of NOAA-18, Ch. 4 is about twice as large. This is evidence of a documented instrument quality problem with NOAA-16, Ch. 4 that caused the channel to be turned off in late Jan 2007.
Table 1 summarizes the 30-day cumulative impact of observations assimilated in NAVDAS. The largest impacts on 24h forecast error are provided by radiosondes, geostationary AMVS, and AMSU-A radiances.

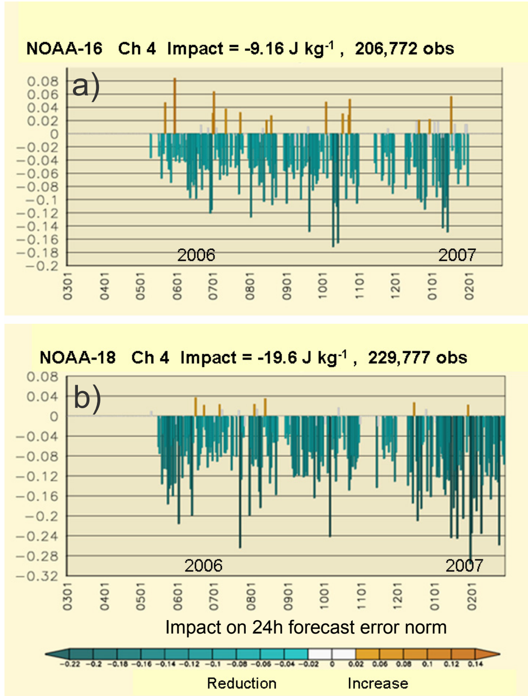

Fig. 4: Daily impact of AMSU-A radiance observations δe_{24}^{30} assimilated at 0000 UTC for: a) NOAA-16, Ch. 4, and b) NOAA-18, Ch. 4.

Type	*Impact*	*# of obs*
Radiosondes	-44.9	2,848,105
Geosat AMVs	-44.2	2,887,156
AMSUA	-31.8	2,666,174
Aircraft	-14.0	1,950,766
Sat water vapor	-13.8	3,406,700
MODIS	-6.1	204,074
Scat sfc winds	-5.9	254,694
Ship surface	-4.9	143,862
Land surface	-4.6	482,197
Windsat sfc wind	-1.7	166,624
SSMI sfc wind	-1.5	119,098

Table 1: Cumulative impact δe_{24}^{30} (J kg^{-1}) and number of observations assimilated in NAVDAS at 0000UTC during 29 Mar to 27 Apr 2008. Includes all observed variables (temperature, wind, humidity, etc.) for each observation type, and all vertical levels where applicable.

4. Summary

An adjoint-based observation impact monitoring system, including a user-interactive web page, has been developed at NRL-Monterey to provide diagnostic information in near real-time. The system currently uses observations assimilated at 0000UTC for the operational NAVDAS-NOGAPS forecast. A parallel system will be provided for the NAVDAS-AR (4D-Var, Xu and Langland 2006). The observation impact algorithm is also being used at Environment Canada (Morneau et al. 2006) and NASA-GMAO (Gelaro et al. 2007). Observation impact monitoring is a research priority in the THORPEX program (Rabier et al. 2008).

Examination of results over the past several years confirms that the adjoint-based observation impact information can identify specific observations with data quality problems - for example, individual radiosonde, land, or ship data that provide non-beneficial impact due to instrument problems, inaccurate metadata, or other issues. Adjoint-based observation impact information can be used to make decisions for quality control and to help decide which features of the data assimilation procedures may need improvement – for example, the observation error statistics or bias correction. The information can also be partitioned for each observation variable so that a station can be blacklisted for just temperature, humidity, or wind observations. In one such case, observation impact information was used to detect a data processing problem that affected the quality of geostationary satellite wind observations over a particular region of the southern hemisphere – the data-provider was notified and the problem was corrected. Another application of the observation impact information being explored at NRL is satellite channel selection (Ruston et al. 2006).

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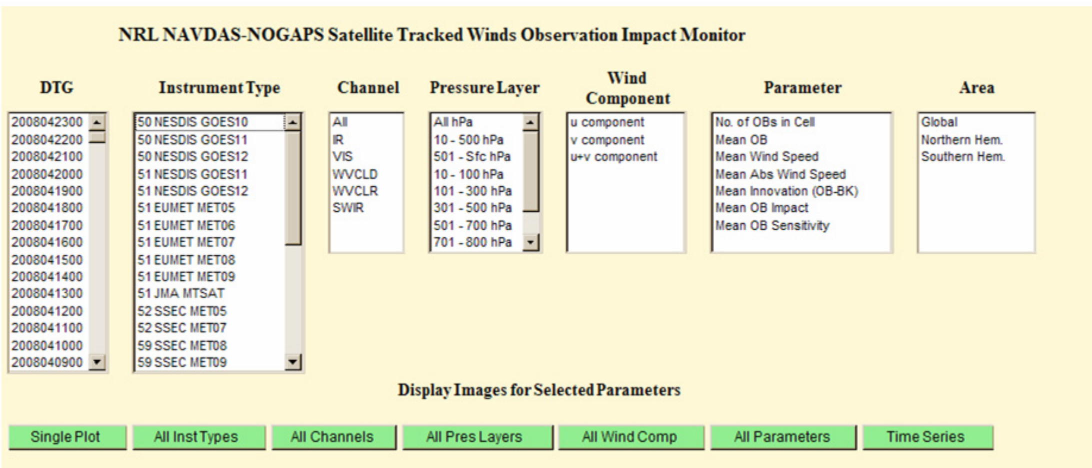

Supplemental Figure: Menu for plots of satellite wind observation impact in NAVDAS-NOGAPS. Web users can select from this and other menus to generate maps, time-series and other graphics upon-request. www.nrlmry.navy.mil/ob_sens/

Relevance of impact studies for EUCOS and EUCOS requirements in future studies

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Abstract

EUCOS, which stands for EUMETNET Composite Observing System, is a EUMETNET programme whose main objective is the central management of surface based operational observations on a European-wide scale serving the needs of regional scale NWP. The management tasks of EUCOS include the co-ordination of the integrated programmes E-AMDAR, E-ASAP, E-SURFMAR and WINPROF and parts of the operational territorial observing networks, furthermore a redesign of the existing networks with the aim to better meet changing requirements, and a centralised monitoring of all these networks. For the current EUCOS phase it is envisaged to redesign the EUCOS upper-air network, whose configuration and setting should be based on scientific analyses. Therefore the so called Space-Terrestrial study was initiated in the previous programme phase. This study consisted of a set of observation system experiments (OSE) – assessing the impact of different observing systems. We are going to present the recommendations derived from the study's results and we will also talk about requirements for future studies. Further tasks for EUCOS are the support of research on targeted observations, setting of new objectives for the programme components and an extension of quality monitoring activities. For an assessment of data targeting activities an evaluation by OSEs would be highly appreciated. An example for new programme objectives is the introduction of a humidity sensor on commercial aircraft within the E-AMDAR programme.

1. About EUMETNET and EUCOS

EUMETNET is a network grouping of 24 European National Meteorological Services. EUMETNET provides a framework to organise co-operative programmes between the Members in the various fields of basic meteorological activities such as observing systems, data processing, basic forecasting products, research and development, training. Through EUMETNET Programmes, the Members intend to develop their collective capability to serve environment management and climate monitoring and to bring all European users the best available quality of meteorological information. They will use EUMETNET to make more efficient the management of their collective resources.

The EUCOS Operational Programme aims to establish and operate a truly European observing network under the auspices of EUMETNET, to deliver increased efficiency, leading to better quality numerical and general forecasts, initially on a European scale. The EUCOS management team works under the guidance of the programme board for observations (PB-OBS). The EUMETNET Co-ordination office monitors EUCOS on behalf of EUMETNET Council and PB-OBS.

During the last five years the EUMETNET Composite Observing System (EUCOS) was being developed from the planning phase to an operational programme as an integrated terrestrial observing system for Europe serving the needs of regional numerical weather prediction. EUCOS has evolved rapidly by the active co-operation and support of all the members of EUMETNET. In the coming years additional ground based observing systems will be integrated into the programme, and the terrestrial observing system will continue to be coordinated with the space based observing system.

2. EUCOS objectives

The objectives of the EUCOS Programme are to:

- Design and coordinate the evolution of the ground based EUMETNET composite observing system to be optimized at European scale with a view to improve short range forecast over Europe without increasing the overall cost, in line with the EUCOS strategy defined by the Council
- Monitor and control EUCOS performance
- Ensure integrated management for agreed components such as E-ASAP, E-AMDAR and E-SURFMAR

- Support the evolution of EUCOS through a studies programme.

3. The current EUCOS network

The EUCOS network design has broadly been fully implemented during the 2002-2006 operational phase. In 2007 no major changes have been made.

Table 1 summarises the 2007 EUCOS Network. The radiosonde station Zagreb of the new member Croatia and the radiosonde station De Bilt have been added to the station list. The surface station list has been updated and 209 stations instead of 195 stations (in 2006) were monitored by the EUCOS team. All other networks had no increases in station number. A preoperational test of observation targeting started in 2008 (PREVIEW DTS trial).

EUCOS 2007		
Oceanic segment	Ocean platforms	OWS "M" (4 RW/day) and Ekofisk oil rig (2 RW/day) 2,028 TEMPs in 2007
	ASAP units	16 units operated by E-ASAP producing 4,032 TEMPSHIPs in 2007
	Data Buoys	89 Drifting Buoys operated by E-SURFMAR
	Moored Buoys	4 moored buoys operated primarily for satellite calibration purposes by E-SURFMAR
	Ships	On average 408 conventional VOS ships providing 301 daily observations and 69 automated VOS providing 799 daily observations operated by E-SURFMAR
Aeronautic segment	AMDAR units	12,750,000 AMDAR observations. On average 753 daily profiles from 112 European Airports and 389 aircraft.
Territorial segment (under revision)	Radiosonde stations	52 stations selected based on a 500 km spacing, providing 2 RW/day 34,967 TEMP in 2007
	Surface stations	209 surface synoptic stations selected according to a 250 km spacing, providing hourly or 3 hourly reports 1,329,069 SYNOPs in 2007
Observation Targeting	ASAP, AMDAR	Season and area variable deployment and activation
	Other systems	To be defined according to the results from the studies programme

Table 1: 2007 EUCOS Network.

4. Motivation for impact studies

In order to fulfil the EUCOS objective to design and coordinate the evolution of the ground based EUMETNET composite observing system a periodic review of user requirements and external drivers and developments becomes necessary. As an external driver can be considered the fact that the different observing networks evolve differently (e.g. regarding availability, accuracy, cost, etc.). Another external development is the ongoing improvement of data assimilation algorithms, which can make use of more and more observational data. A potential outcome of the review process could be that a modification of the meteorological observing network becomes necessary.

When aiming for changes in the observing network EUCOS needs approval from PB-OBS and EUMETNET Council respectively. In order to get the 24 Members convinced of such changes it was decided to base them on scientific analyses. A favourite means is to run observation system experiments (OSE) or impact studies and to derive general design principles from the outcomes of these experiments.

5. Space-Terrestrial Study and recommendations derived from it

During the EUCOS programme phase 2002-2006 the EUCOS management proposed to run a so-called Space-Terrestrial Study. The motivation was to assess and clarify several findings and conclusions like the fact that historically the planning of the space and terrestrial components of the composite observing system had proceeded largely independently and that the timescales for implementation of these programmes vary enormously ranging from decades for the space component to months or even a few weeks for some elements of the terrestrial component. Furthermore there was the feeling that there is a need to better understand the relative contribution of both components so that the total system may be progressively optimised and that there was also a need in particular to define the impact of the additional data from the EUCOS Programme at that point of implementation in 2005.

When setting-up the study the approach taken had been to seek co-ordinated studies sponsored by both EUMETSAT and EUMETNET (EUCOS) in order to achieve a comprehensive set of results. Both EUMETNET and EUMETSAT Councils had approved the programme of work and the associated initial funding. EUMETSAT was funding ECWMF to consider the space contribution and EUCOS was funding ECMWF, Met Office, DMI, met.no and OMSZ to study the terrestrial components. Thereby the varying assimilation schemes models etc were regarded as strength. The differing approaches reflected the need to understand the contribution of the elements of the space component when added progressively to the total terrestrial component and vice versa. Finally, it was hoped that most of the results would be available during 2006 to guide the further evolution of EUCOS in the timescale 2007-2011 and space programmes in the longer term.

The five NWP centres: ECMWF, Met Office, DMI, met.no and OMSZ, which carried out the S-T study, agreed on common OSE scenarios, time periods, verification procedures and presentation styles.
The experimental set-up for the OSEs was as follows. Two periods were selected: Winter, 14th December 2004 to 27th January 2005 (44 days) and Summer: 15th July 2005 to 15th September 2005 (63 days). Forecast runs were started at 00UTC and 12UTC. The following scenarios were defined:

- Baseline: all current satellite observations used in NWP (radiances, cloud-drift winds, scatt winds) + GUAN radiosonde network + hourly GSN surface land data + hourly buoys (no ship data);
- Control: full combined observing system;
- And different additions to the Baseline (radiosondes, wind profiler, aircraft measurements).

After a presentation of results a discussion within the EUCOS Scientific Advisory Team (E-SAT) in May 2007 lead to the following general recommendations, thereby keeping in mind that the individual results vary depending on season (winter or summer), type of assimilation scheme and numerical model:

- Compared to Baseline all additional ground based observing systems have a positive impact on the forecast skill. On top of the additional available satellite data further improvements of the ground based observing system are important.

- The radiosonde network is still the most important component of the ground based upper-air observing network. Any further reductions of the current radiosonde network should be evaluated by an OSE.

- NMSs are encouraged to move to BUFR for Radiosonde messages and make full use of increased vertical resolution profile data.

- E-ASAP shows a positive impact on the forecast. A compilation of studies made 10 years ago showed that a minimum of 10-15 systems are needed in the Atlantic Ocean to show any significant impact in NWP. E-SAT proposes reactivating of the existing 2 French and 1 Danish units.

- The 6 remote island radiosonde stations (Heraklion (Crete), Lajes (Azores), Funchal (Madeira), Tenerife, Jan Mayen and Torshavn (Faroe Islands)) are seen as important part of the EUCOS radiosonde network, as long as no 3-hourly aircraft measurements are available at those locations.

- The impact of aircraft measurements is significant and second largest. The E-AMDAR optimisation systems should be developed further to get a more homogenous distribution of profiles in space and time. More airlines should be incorporated to get 3-hourly observations from more European airports.

- AMDAR humidity is seen as a high priority project.

- Having now more than 15 wind profiler systems being assimilated in NWP models the impact on regional forecast models should be evaluated again.

- Weather Radar Wind Profiles are available from more than 80 sites. NWP centres are encouraged to monitor the data and work towards operational assimilation.

6. EUCOS upper-air network redesign

The original EUCOS upper-air network design was prepared in 2000 in order to define a set of stations serving the common general NWP requirement. Additional considerations were to make it possible to supply a common set of performance standards across the territory of EUMETNET Members and to ensure that the radiosonde network interleaved with AMDAR airports.

The EUCOS upper-air network now requires a redesign because of several reasons. There is a need to take into account the significant evolution of the AMDAR network. Member states were not able to install the proposed EUCOS radiosonde network design with 4 ascents per day at most of the sites. The results from the Space-Terrestrial Study are available with recommendations for the network design. Data assimilation of NWP models has improved significantly with advanced capability to make use of high time resolution data. A subset of the wind profiler network has achieved operational status and the data are used operationally in the different NWP models. Wind measurements from Doppler weather radars are available which are used in the data assimilation of the Met Office numerical model, and monitored at other NWP centers. Water vapour measurements from the GPS networks are available.

The main objective for the proposed study is the definition of a European-wide network of ground-based upper-air observing systems whose configuration and setting is based on scientific analyses rather than on a simple merging of historically grown national networks. The S-T study has shown that despite of all the additional new satellite observations, the degrading of the current terrestrial observing system to a basic (GUAN+GSN) network would have a significant negative impact on the forecast skill.

The expected result from the envisaged OSE is to find an optimum setting of upper-air measurements in space and time which maintains forecast skill. The WMO user requirements for regional NWP are a good basis to start from. Thus, a natural idea could be to configure a set of different networks (in different wording: scenarios), each realising a specific setting of horizontal and/or vertical spacings of observations.

Furthermore, when setting-up the different OSE scenarios the following constraints have to be considered. The experimental set-up should start with the baseline, as specified in the Space-Terrestrial Study to have the connection with this study. The control run should be the full combined operational system. The S-T study has shown that the radiosonde network is still the most important component of the ground based upper-air observing network. In addition the study demonstrated that the impact of aircraft measurements is significant and second largest. Therefore, at sites where 3-hourly AMDAR profile measurements are available with a collocated radiosonde (having a spacing less than 20 km), the radiosonde station will not be included in the upper-air design. The 6 remote island radiosonde stations (Heraklion (Crete), Lajes (Azores), Funchal (Madeira), Tenerife, Jan Mayen and Torshavn (Faroe Islands)) are seen as important part of the EUCOS upper-air network, as long as no 3-hourly aircraft measurements are available at those locations. The marine upper-air observing network is below or near the threshold to show an impact on the forecast skill. Therefore all ASAP measurements together with the radiosonde profiles from weather ship Mike and the Ekofisk platform will be included in all experiments. The main application of Doppler weather radar is in the area of nowcasting for the management and issuing of warnings. The wind profiles are a by-product delivering a contribution to the upper-air network. It can be seen as an enhancement of observations in high impact weather situations.

The following OSE scenarios are agreed:

Scenario no 1: Baseline:
All current satellite observations used in NWP (radiances, cloud-drift winds, scatt winds) + GUAN radiosonde network + GSN + hourly buoys (no ship data);

Scenario no 2: Control run:
All currently available data in the EUCOS area.

Scenario no 3a:
Experiment with horizontal spacing of 100 km for profiles.
Baseline + terrestrial RaSo stations with 100 km

horizontal spacing, thereby excluding RaSo stations if 3 hourly AMDAR measurements are available at those locations + AMDAR data with 100 km horizontal spacing, SHIP, BUOY, ASAP, WRWP, WP data

Scenario no 3b:
The same as for 3a but keeping 0 UTC radiosonde ascents at those sites which are excluded in scenario 3a because of the vicinity to an airport

Scenario no 4:
Experiment with horizontal spacing of 250 km for profiles from radiosondes and aircraft.

Scenario no 5:
Experiment with horizontal spacing of 500 km for profiles from radiosondes and aircraft.

Several NWP centres assured their participation in the proposed study and they agreed again on common time periods, verification procedures and presentation styles.

As agreed with E-SAT the upper-air network redesign OSE will be conducted until end of June 2009 and the proposals for a revised EUCOS upper-air network will be co-ordinated with relevant bodies before being recommended for implementation.

7. Future plans for OSEs

EUCOS currently plans to run further OSEs during the current programme phase 2007-2011. These are an E-SURFMAR network design study (to be run in 2008/2009), an evaluation of the EUCOS/PREVIEW Data Targeting System Trial Phase by running data denial studies (to be carried out in 2009) and a second Space-Terrestrial Study investigating the benefit of the additional satellite data from METOP (to be conducted in 2009-2010).

Relevance of NWP Impact Studies for Future Satellite Programmes

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1. Introduction

Informed decisions on candidate missions to be flown on future operational meteorological satellites must be based on careful analyses and trade-offs considering continuity of services, the necessary evolution of services and the different observing system scenarios that would meet requirements for the future services. A proven way, though not always straightforward, is to perform impact studies with an NWP system. OSE (Observing System Experiments) are good for studying the issues related to continuity of services. Novel observations from space call for Observing System Simulation Experiments (OSSE). The presentation did discuss with examples the relevance of impact studies in support of the future follow-on EUMETSAT Programmes Meteosat Third Generation (MTG) and Post-EPS (EUMETSAT Polar System). Furthermore the presentation asked questions and provided suggestions that would make NWP impact studies a part of a development of future meteorological satellite programmes. This extended abstract summarises the salient points of the presentation.

2. Continuity of Services

An important requirement of future operational satellite missions is the continuation of successful established services resulting from specific observations. At the same time it is relevant to ask whether services can be provided by different means or whether the relative importance of observations diminished. An established way to demonstrate the usefulness of existing observations is through impact studies (OSE) with an NWP assimilation and forecasting system. Recent OSEs at ECMWF (Kelly and Thépaut, 2007) demonstrate this in a comprehensive and systematic way, whereby a wide range of combinations of observations were used to demonstrate the relative usefulness of an observation. An important message of the work of Kelly and Thépaut (2007) is that satellite observations have become a key part the Global Observing System (GOS) for numerical weather prediction.

In a way OSEs can also cast light on the ‘evolution of services’ as OSEs are able to address the question ‘how many of a kind are enough’ provided a sufficient number of observations of a kind are available.

For the assessment of re-launch criteria for the current Metop series in the case of instrument failure and also in preparation for the development of the EUMETSAT Post-EPS Programme a study is being conducted by ECMWF on ‘Observing System Experiments for the evaluation of degraded EPS/Post-EPS instrument scenarios. While the prime purpose of this currently ongoing study is the assessment of detrimental impact on NWP skill due to loosing Metop instruments, this OSE study will also:

- substantiate a priority ranking for future satellite missions on the basis of the existing observing system
- evaluate the robustness of the operational satellite observing system; i.e. it will identify the observations that are unique and where there is little redundancy.

2.1 Learning how to Use the Data

In a presentation at the Annual Meeting of the American Meteorological Society in 2007 Uccellini discussed various contributions to improvements in NWP due to satellite data. He explained that improvement is due to a balance among i) observations, ii) data assimilation and modeling and iii) computing resources. The interesting point is that an estimated 30 - 40% of improvement comes from observations (principally global polar satellite data) and 60 - 70% from data assimilation and modeling techniques and computing resources. This suggests that Research and Development toward advanced operational utilization of future satellite missions should commence early, i.e. well before launch. This activity should be clearly separated from the development of an operational ground segment and it is suggested to make it an integral part of the satellite development with a dedicated budget line. While it may appear as 'common sense' to do so because it paves the way toward a full operational utilization of the satellite mission, the realization would indeed constitute a novelty in satellite development programmes.

3. Evolution of Services through Novel Observations

The evolution of weather forecasting and the related improvement of services on the basis of new instruments do require Observing System Simulation Experiments (OSSE). The difficulties of such studies are well-known and presumably better explained by experts (see other papers in these proceedings). From the perspective of satellite mission development the situation can be summarised as follows:

- there is a clear need to demonstrate the usefulness and the better services that will emerge from a new satellite mission
- this need is aggravated by the high cost of a new observing system
- on the other hand it is not trivial to demonstrate the usefulness in unequivocal way because it requires adequate simulation of non-existing observations and it uses the observation in-spe in way that merely reflects current knowledge, particularly current assimilation techniques and forecast models; one cannot draw on a learning experience yet (see 2.1).

A current example for EUMETSAT is the demonstration of the usefulness of the hyperspectral sounding mission (IRS: Infrared Sounder) foreseen as candidate mission on Meteosat Third Generation (MTG). Observations with the IRS mission provide i) atmospheric dynamics variables with high vertical resolution (e.g. water vapour flux, wind profile), ii) more frequent information on temperature and humidity profiles for NWP (regional and global), iii) monitoring of instability / early warning of convective intensity etc. An OSSE conducted by H. Huang et al. (2007) tries to document the added value of observations derived from a hyperspectral infrared sounding instrument in a geostationary satellite for regional forecasting. Simulated IRS measurements and subsequent temperature and humidity retrievals are used in a high resolution meso-scale model. It is shown that realistic mesoscale details in the moisture field are important for forecasting convective events. Current results include:

- Three storms are simulated and well reproduced in a five day nature run.
- The calibration experiment shows that the real and simulated observations have similar impacts on the analysis increments and forecast differences,
- AND: The forecast skill is improved when MTG-IRS temperature and humidity retrieved profiles are assimilated.

While the results are encouraging and corroborate the usefulness of OSSEs we also see the difficulty and resulting reservations at NWP centers to perform such supporting impact studies. We conclude and suggest that world-wide concerted activities, presumably under the lead and coordination of WMO would be a great step toward creating an environment that is more conducive to performing OSSEs in support of new satellite missions. A call for support through such OSSEs would be part of a satellite development programme.

3.1 Evolution of Model Physics

A corollary to the need to improve assimilation and use of the satellite data is the need to improve the capability of the model to retain and exploit new observations for an improved forecast. The MTG IRS study does recall the known fact that improved humidity measurements will only result in improved precipitation forecasts if the model contains the adequate physics parameterisations. Therefore we offer for discussion as a corollary thought that 'it could be an advantage to fly new research satellite missions in foreseen in polar orbits as near simultaneous observations in a train with the operational instruments'. It would offer the advantage that the operational observations are augmented by the potential for new process studies. The resulting research could advance NWP model physics; for instance, it is widely agreed that adequate consideration is necessary of the physical processes governing the water cycle. An example is the successful satellite formation in the A-train (Stephens et al., 2002). This suggestion calls for detailed studies addressing concrete cases and weighing the benefits against the costs (e.g. maintaining the orbits).

4. Conclusions and Suggestions

The salient points of the presentation are summarised as follows:

- OSEs are a good tool to provide guidance on priorities of future missions and to investigate the robustness of the Global Observing System (GOS). We should continue to perform those regularly as part of studies on the evolution of the GOS.
- WMO should support and coordinate concerted efforts on performing OSSEs in support of future satellite missions. The benefit will be an increased weight of the anticipated observation and a very important element in support of the planning and coordination of a future GOS.
- Work toward the 'full exploitation' of new instruments of a satellite observing system should be part of the respective satellite programme development, i.e. the development of 'new science' for the full utilisation of a satellite mission should be part of a satellite development. This ought to be different from the development of the operational ground segment. Benefit will be that the optimum use of observations is reached quicker, resulting in higher return on investment.
- Another point raised was: In case they are complementary, it would be useful to fly future polar research and operational satellite missions as 'trains'. This would help understanding physical processes and advance parameterisations in the model physics.

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THE OPTIMISING OF REGIONAL RADIOSONDE NETWORKS

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1. Introduction

The global meteorological observing system is extremely expensive and in the present economical situation some conventional observations such as RAOB (radiosondes) begin to be severely reduced. But in some regions with high spatial and temporal variability of major meteorological variables a priority role of RAOB still remains. Measurements at the Siberian radiosonde observation (RAOB) network were substantially reduced after financial crisis of 1998. Recently, a problem of an optimal location of new or reopened RAOB stations re-appeared in the Asian part of Russia. Nonetheless, it still does not achieve pre-crisis level. Moreover, some RAOB stations located in synoptically important areas, such 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 Kamchatka Peninsulas, Sakhalin and Kuryl Islands, were provided only by sparse and irregular (in time) measurements. Significant part of RA I (Africa) is located within ITZC (intra-tropical zone of convergence). Therefore, air mass field, air temperature, humidity and geopotential fields, in contrast to those in the moderate and high latitudes, have smaller scales of horizontal disturbances. Thus, here a role of the wind velocity components in numerical weather prediction (NWP) is a more significant than in other latitude belts. On other hand ITZC has an advantage in satellite data availability. Geo-stationary platforms (GMS, METEOSAT, MSG) provide a more detailed (in time and in space) information on all meteorological variables than outside of the ITZC area. But, there is some uncertainty in simultaneous acquisition of height and wind fields in ITZC. Wind field components are retrieved from cloudiness movement tracing by instruments boarding at GMS and other satellites. However, cloudiness in the field of radiometer view limits accuracy of the temperature and humidity profile retrievals. It is known that radiances coming from surface-atmosphere system to satellite radiometer are contaminated by cloudiness impact even in microwave domain. That is a cause of degrading in accuracy of height profile retrieval. Vice versa, wind by satellite is not available in cloudless conditions. Thus, RAOB data in this area cannot be replaced by satellite information in full extent.

Current state of RAOB network in RA I might be characterized as partly satisfactory because of non-uniform coverage of Africa by RAOB stations. Some regions (North, North-West and South Africa) are sufficiently provided by RAOB data. But there are many missing ranges in some others. The aim of this study is to define some statistically homogeneous ranges within RA I, estimate information weights of existing stations with respect to major meteorological variables H500, T500, U700, V700, Q850 used in NWP models and to determine the priority synoptic sites, which might be used to extend our RAOB network.

2. Information content estimation

Theoretical background. Shannon information theory and its generalization (Anderson, 1958) to the case of multidimensional fields are implemented to quantitatively evaluate the measured data.

Information model of observing system. This model was developed to establish a relationship between measured data and estimated variables (meteorological fields) by means of operator, which depends on observing system parameters – control variables: number and site locations, measurement error statistics: magnitudes and correlation features.

Regionalization. Spatial range allocated for the analysis and the forecast of meteorological fields should be split into a set of statistically homogeneous areas (SHA) in such a way that within each of them usual assumptions on stationary and isotropy of meteorological fields are approximately valid.

Optimization problem for observational system. To state this problem it is necessary to select a quantitative criterion and develop some search technique to minimize related cost function. We applied a criterion of minimum of the root mean square approximation of meteorological fields by set of measurements delivered by observing system. As the information model is a regression equation with coefficients depending on a network configuration our task is to minimize the residual, which is composed of a cost function. To minimize the cost functional we implied Boolean function minimization technique, which requires several tens of iterations to achieve an optimal solution instead of several thousands of iteration when any direct minimum search is applied.

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 the linear trend, calculated on each grid after an annual cycle removal is related either to artificial factors (measurement errors) or to a variability having large time scale (equivalent or larger than a century), which is not relevant to a predictive problem concerned here. The amplitude of the linear trend is very small. However, it may give rise to a trajectory shifting in a phase space and thus affect the selection of nearest fuzzy set activated in a nonlinear model. Therefore, this filtering procedure might be considered as a necessary step in the present context.

4. Siberia

This paper is focused on the development of an optimal scenario to redesign an existed network by redistribution of stations and network extension in order to maximize the information content of observing data with account to height and wind fields (H500, U700 and V700). An objective classification of wind and height re-analysis fields for the North Asia by fuzzy logic tools permit us to reveal major regimes of atmospheric circulation and acquire statistical samples responded to each of corresponding classes. The information model of the combined Siberian land surface and satellite (NOAA/ATOVS/SATW) observing systems based on the Kalman filter methodology was developed and applied to determine corresponding information content function. Implementation of numerical optimal search algorithms leads us to an acquisition of consecutive sequence of optimal designs for RAOB network with various numbers of stations when remote sensing data contribution was taken into account within the information model. These numbers should lies between 14 and 42 (see Fig.1).

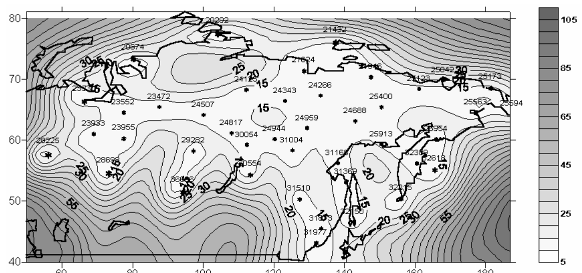

Figure 1. Optimal interpolation H500 RMS error field (m): suggested optimal RAOB network included 42 stations.

Former is designed as minimal network, latter – as sufficient one. Each of scenarios assumes a recovering of currently closed RAOB stations located in the North and the North-Eastern

Siberia. RMS (root mean square) error fields for major meteorological variables describe an efficiency of a network design. Heavy clouds occur most part of the year in these areas. Therefore, the remote sensing data accuracies in these areas are lower than in other regions. Impact experiments were carried out with a simplified forecasting model under conditions of various atmospheric circulation regimes. These experiments demonstrated a priority of the RAOB sites located along Arctic and Pacific Ocean coasts. It was also found that most meteorological parameters have largest variance just in these regions. The North and the North-Eastern Siberia also provide the most important low oscillation patterns: the East and the West Pacific oscillations, the Polar-Euro-Asian oscillation and others. Latter regulate not only the airflow over the Asia, but also over the North Pacific and the Western coast of the North America. Unfortunately, actual development of the Siberian RAOB network has been carried out in a "voluntary" way, which was far away from above recommendations. Most new stations were located in the southern part of Siberia (see fig.2). A corresponding error field demonstrates anomaly high analysis error magnitudes in areas located to the north of 60° N.

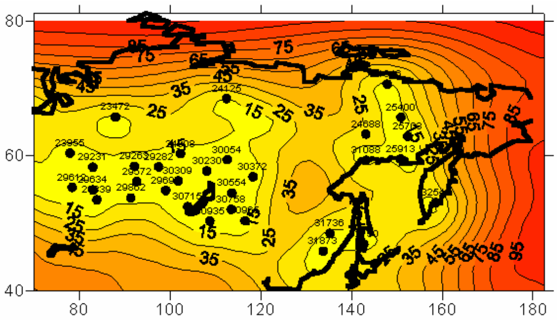

Figure 2. Optimal interpolation H500 RMS error field (m) responded to Jan-March, 2007RAOB network configuration.

Digital error magnitudes presented in Table 1 permits to come to a conclusion that an optimal network of 42 sites (Fig.1) provides comparable analysis RMS in both high and middle latitude belts. Meanwhile, the actual RAOB network (Fig.2) having the same number of stations could not give uniform error fields. Mean errors in high latitudes are two times higher than those responded to optimal network (Fig.1).

5. Africa

Missing data areas with respect to operational RAOB station list for RA-I are very significant. Only 46 from nominal 262 sites carried out measurements in January-April 2004. Therefore, error fields corresponding to major meteorological variables reveal many gap regions, where the relative errors of meteorological field representation reach 0.7-0.8 levels. Highest errors are achieved in an objective analysis of a wind velocity component fields (Fig.3). Similarly, it is valid for GUAN network. Only 12 from nominal 17 GUAN stations provide measurement data in RA-I.

Search of statistically homogeneous areas (SHA) in RA-I, useful for optimal interpolation, permits to find several of them, which are not supported by any of the operational RAOB stations. A methodology of SHA, considered as homogeneous random fields, allows us to find SHA and geographic areas, which are now missing data and should be provided with RAOB data to reduce uncertainty in the grid fields used in NWP. This step might be considered as a search of hints to determine an optimal RAOB network configuration.

An error field performance is an important step in order to estimate an impact of missing data areas on input data accuracy for NWP. Our finding proofs that many regions of Central Africa are provided by low quality data on wind and height fields if only operational RAOB data are used. This is because a network is degrading in these areas.

Information weights of particular sites give a helpful estimate of BSRN RAOB station contribution in reduction of the meteorological field uncertainty. These values permit to find out that the most informative stations are located in regions with lowest site density, at ocean islands and at coast areas.

A search algorithm allows us to develop a scenario for the existing operational RAOB network extension from 46 to 59 stations by recover measurements at 13 stations, which provide a substantial improvement of error fields for all meteorological variables in missing data areas (see Fig.4). An analysis of information weights showed that the recovering stations have maximal contribution in a reduction of the error fields with respect to many of other sites, which belong to both, existing and nominal WMO networks.

Existing GUAN network has some gaps in the Central Africa, which are a reason of anomaly in objective analysis error fields. An alternative set of ten GUAN sites provides more uniform information coverage of Africa with respect to monthly fields. Maximal error magnitudes are decreased at 15-20%.

6. Conclusion

Our study showed that the existing RAOB network configuration is far away from being optimal. That is happened by objective reasons. Firstly, it appeared because of urgent necessity to reduce the number of sites due to the unavailability of consumables (balloons, sondes) in short-term (after financial crisis). Secondly, it happened because of an absence of any theoretical background for rational network design.

Early conceptions were based on network configuration close to uniform distribution of observing sites. RAOB configuration in time of Soviet planned economy finally responded to such a concept. Authorities in Roshydromet were not prepared for substantial network reduction. A decision on this subject was 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 air companies, network 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 a numerical weather forecasting requirements. Therefore, RAOB optimal design problem solution is very urgent. We made first attempt to solve this problem. There are several advantages of our approach, such as generality, universality, and relative simplicity. This method implementation permits us to formulate general recommendation for a number of RAOB sites and their spatial distribution. This is relevant not only to weather forecasting, but to climate monitoring as well.

There are several problems, which have yet 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, an approach area extension to the European part of Russia, the South-Eastern Asia in the Eastern Hemisphere and to the Western coast of the North America in the Western Hemisphere. Another challenge region is the RAOB sparse area in the South America.

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Table 1. Comparison of the optimal and operational RAOB network configurations in Siberia with account for Z500 objective analysis error (m).

Contribution of measurement data in covariance matrix reduction	RAOB -40	RAOB-34 (Jan-Mar, 0Z&12Z, 2007)	RAOB-42 (Optimal design)
N (eig vector)	STD (m)		
1	48.7076	48.8542	49.2377
2	14.2048	14.1605	14.7831
3	12.0032	12.3051	13.0346
4	11.7356	11.7050	12.0969
5	6.8689	6.2936	7.9364
Mean STD	51.0	52.6	34.74
Mean STD (60-80 N)	58.7	57.6532	27.8442
Mean STD (40-60 N)	42.3	46.9253	42.5138

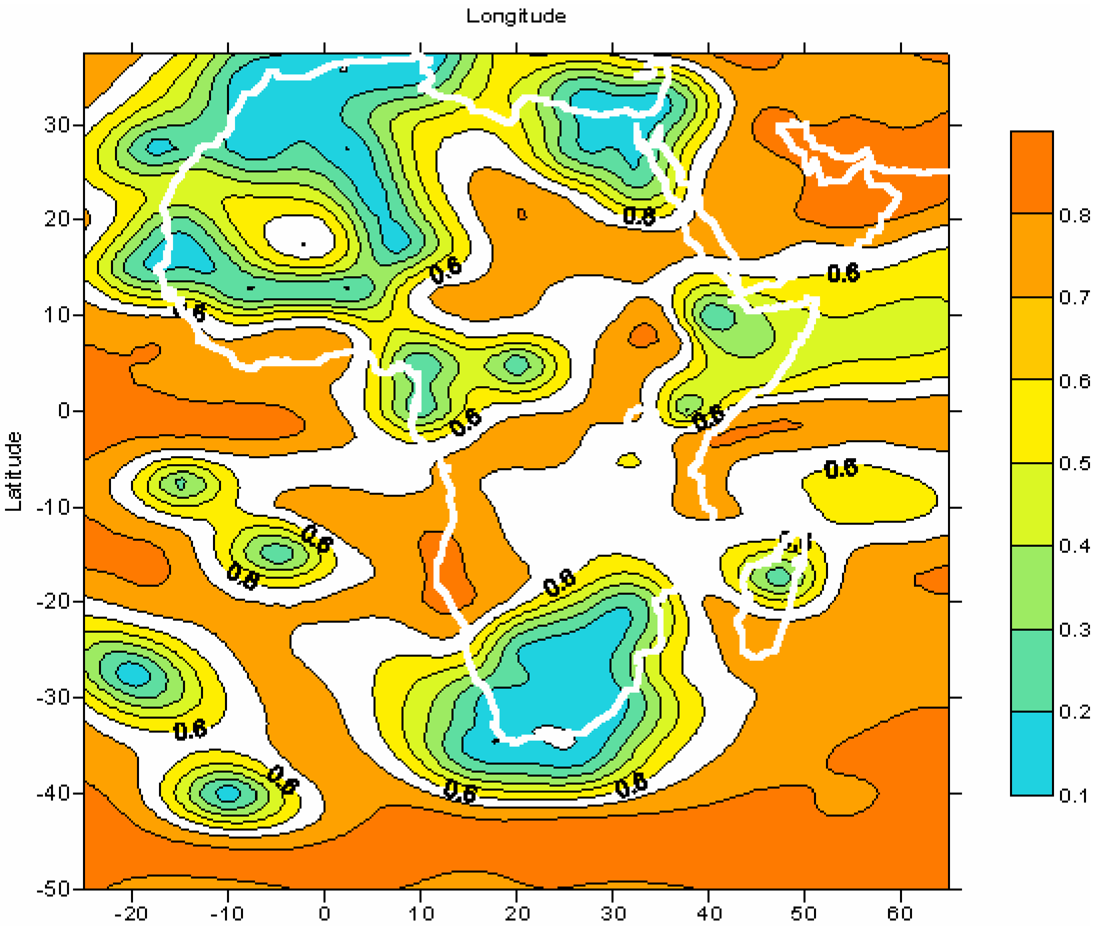

Figure 3. Optimal interpolation relative error for zonal wind field U700 responded to operational 46 stations in RA-I.

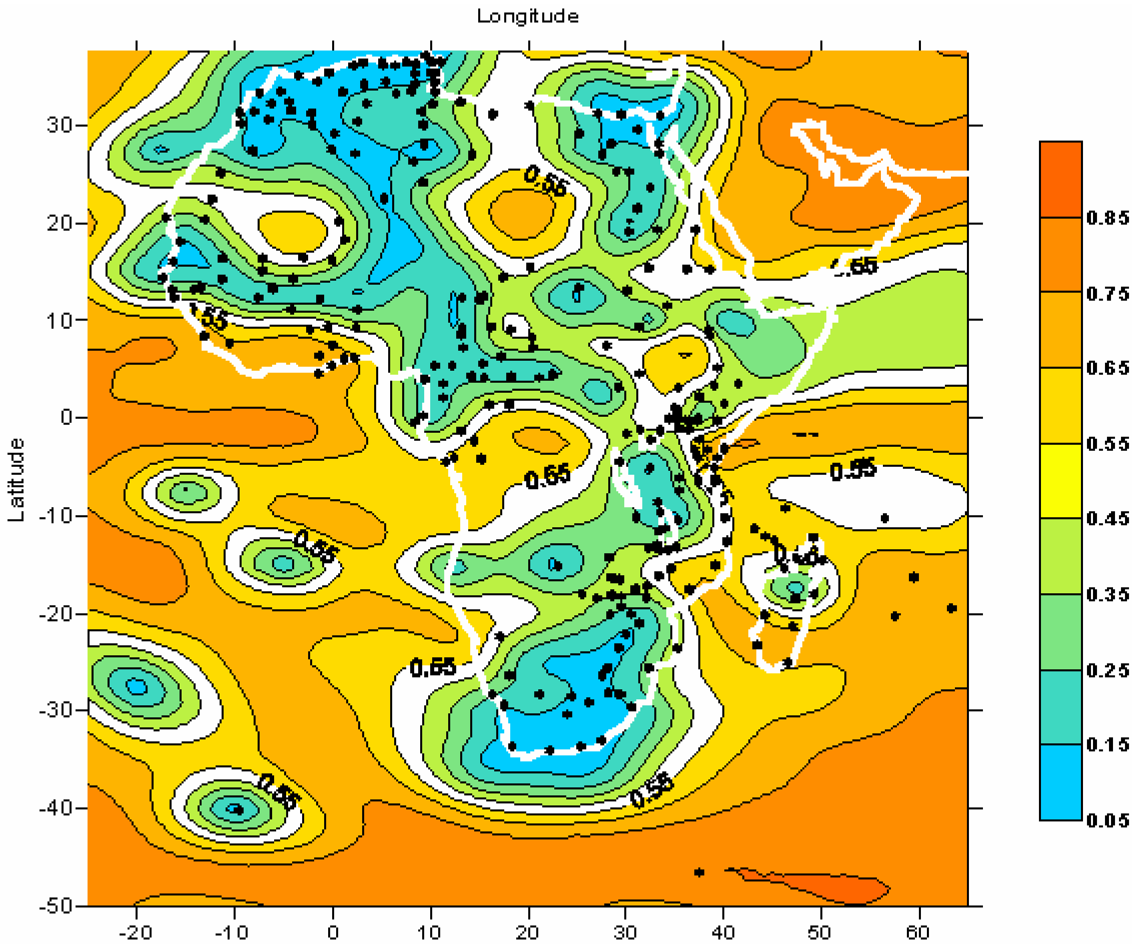

Figure 4. Optimal interpolation relative error for zonal wind field U700 responded to suggested (extended) RAOB 46+13 stations in RA-I.

Intercomparison of sensitivity to observations in the context of THORPEX and the THORPEX Pacific-Asia regional campaign (T-PARC)

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ABSTRACT

An intercomparison experiment is being performed to evaluate the impact of observations in current forecast systems for a recent winter period. Preliminary results from NRL (Langland), NASA-GMAO (Gelaro and Todling), and ECMWF (Cardinali) have been individually presented at this workshop by the authors. The objective is to assess the extent to which these systems provide a robust assessment of the impact of the current global observing network, which would serve as a baseline for subsequent experiments on the placement of additional observations for an observation campaign like T-PARC. This presentation will focus on the objectives of this intercomparison experiment to foster discussion on the next steps to be taken to support WMO activities on the evaluation of the Global Observing System.

1. INTRODUCTION

The THORPEX Pacific Asian Regional Campaign (T-PARC) is a major international THORPEX field campaign developed as an outcome of the North American and Asian THORPEX planning process. The T-PARC field phase will take place in two phases from August to October 2008 (TCS-08, Tropical Cyclone Structure - 2008) and from January to March 2009 (Winter T-PARC) and will focus on advancing knowledge, improving prediction and society's response to i) western Pacific and Asian typhoons from genesis to extra-Tropical transition and decay, and ii) downstream high-impact weather events over North America, the Arctic and other locations whose dynamical roots and predictability are driven by aspects of the lifecycle of typhoons and other intense cyclogenesis events over east Asia and the western Pacific (Parsons *et al.*, 2007).

The winter component of T-PARC will take place January to March 2009. During this phase, enhanced observational resources, both in-situ and remotely sensed, will be deployed in a selected locations over Asia and the North Pacific as part of the THORPEX strategy for achieving objective (ii) above. This document describes a proposed set of experiments to be conducted in preparation for winter T-PARC that will help maximize the scientific and societal benefits derived from the deployment of these resources. The ultimate objective is to identify regions where observation coverage would be supplemented for an extended period of time (as opposed to identifying only targets of the day), as may be demonstrated during T-PARC.

The value of observations used in a data assimilation system varies with respect to a number of factors that characterize the system. In numerical weather prediction, the value of observations is measured by the impact they have on the analysis and the subsequent forecasts made from these analyses. Typically, the method employed is to perform Observing System Experiments (OSEs) in which the value of an observation type is measured by removing from (or adding to) this type in the assimilation and measuring the impact on the forecast error. This approach provides a bulk measure of the impact of a given type of observations on the forecasts at different lead times. In recent years, new approaches have been introduced based on adjoint sensitivities with respect to observations and ensemble-based methods that provide more details about the impact of observations which may be useful to pinpoint problems with the observation itself or the way it is being assimilated (Langland and Baker 2004; hereafter LB04).

As a starting point, an intercomparison experiment has been proposed to evaluate the impact of observations in current forecast systems for a recent winter period. The objective is to produce a robust assessment of the impact of the current global observing network, which would serve as a baseline for subsequent experiments on the placement of additional observations. This paper presents the design of the intercomparison experiment in which the participants used the method described in LB04, based on adjoint sensitivities with respect to observations, as the basis for computing observation impact. A particular effort was made to minimize the differences between the respective data assimilation systems, although some differences remained. Preliminary results were produced at NRL, ECMWF and NASA/GMAO and are briefly presented here.

2. BASELINE EVALUATION OF THE CURRENT OBSERVING NETWORK

The evaluation of targeted observation has been the object of recent studies associated with the 2003 THORPEX Atlantic Regional Campaign (Rabier *et al*, 2008; Kelly *et al.*, 2007; Buizza *et al*., 2007; Cardinali *et al.*, 2007; Langland, 2005). Although observations deployed in targeted areas have a small but positive impact, the number of cases leading to significant forecast errors is usually very small and it is therefore difficult to reach statistically significant conclusions. Moreover, the results vary from one centre to another due to differences in the forecast and assimilation systems, the observations used in the assimilation, and in the metrics used to measure the impact of the observations.

Intercomparison experiments are meant to bring different data assimilation systems to a common ground to assess the robustness of the results and conclusions obtained from numerical simulations. This is done for climate studies (Atmospheric Model Intercomparison Project, AMIP) to estimate the variability of the results by comparing different climate models. This is done also in numerical weather prediction to compare NWP models to better understand the impact of changes in resolution, physical parameterizations, etc. on the subsequent forecast. In data assimilation, the task is more complex as the differences lie with the NWP model itself, the assimilation methodology, and the observations used in the assimilation. Ballard *et al.* (1999) presented a first attempt that was carried out to compare the structure functions implicitly used by different assimilation systems. This could be achieved by performing a single observation experiment with fixed value for the innovation.

The objective of the proposed experiment is to see if different centres have similar impact of observations on forecasts within their forecast-assimilation system. The design of the experiment thus required that the participants agree on several points. The initial discussions took place at NRL in Monterey and were extended later through Email. The participating centres were NRL, NASA/GMAO, ECMWF, and Environment Canada.

a) Methodology

The adjoint-based observation impact procedure described by LB04 was chosen as the primary tool used for this phase of the evaluation. However, studies based on other methods (e.g, OSEs) conducted under similar experimental conditions would be a welcome complement to the adjoint-based techniques used here. In a broader perspective, the conclusions reached can be compared with ensemble based methods (e.g., Kalman filter sensitivities, ensemble transform methods) and methods based on information content (e.g., DFS). Three centres managed to obtain preliminary results in time for this workshop. All three (NRL, ECMWF, NASA/GMAO) used the LB04 methodology.

b) Period

As this work was in preparation for winter T-PARC, it was agreed that all centres perform an evaluation for January 2007, preceded by a suitable spin-up period . Since this is a recent period, observation types currently assimilated in operational systems were part of the study.

c) Definition of sensitivities

The LB04 method requires that the adjoint model be used to map the forecast error back to the initial time (Rabier *et al*., 1996). A dry total energy norm is used in the global domain with vertical extent from the surface to approximately 150 hPa. The configuration of the adjoint model was chosen to include only simple dry physics, as not all centres had moist physical processes in their adjoint systems. The time length for the computation of sensitivities is 24-h. The horizontal resolution was set to be the same by all, namely in the vicinity of 1°. The vertical resolution however was kept as in the respective operational systems. It would have been too complicated to reconfigure the vertical resolution which involved changes in the background-error statistics, the observation operators and other elements of the NWP model.

d) Assimilation component

To the extent possible, it would be beneficial if all centres were able to use a common assimilation method and the same observation types. However, given the existing unique operational environments within which each system has evolved, this goal was not fully achievable in practice. All centres agreed to restrict themselves to a common set of observations assimilated by all (Table 2-1), but used their own model, error statistics and observation operators. It is acknowledged that quality control has to be performed by all centres

TABLE 2-1 OBSERVATIONS USED IN THE BASELINE EXPERIMENT

Radiosondes (all data except humidity)	AMV from geostationary satellites (no rapid-scan winds)
Dropsondes (all data except humidity)	MODIS winds
Land surface stations (all data except winds and humidity)	AMSU-A radiances
Ship surface (all data except winds and humidity)	QuikScat retrievals
Aircraft (all data except humidity)	

	NRL	GMAO	ECMWF
ANALYSIS	T239 L30 6-h 3DVAR	0.5º×0.67º L72 6-h 3DVAR	T255 L60 12-h 4DVAR
FORECAST	T239 L30 spectral	0.5º×0.67º L72 finite volume	T255 L60 spectral

Table 2-2. Characteristics of the analysis expressed in terms of horizontal resolution and vertical resolution of the increments. The assimilation is done with a 3D-Var at NRL and GMAO but ECMWF is using 4D-Var with a 12-h assimilation window.

and that this will result in some differences in the observations used in the different assimilation systems; this could not be avoided. It is also important to stress that any data assimilation system is tuned for optimality in the presence of a reference data set that includes all observations assimilated in the operational configuration. To obtain optimal results with a subset of these observations would require recalibration of the error statistics but, for sake of simplicity, this was not done.

A critical component of any assimilation system is the NWP model that drives the assimilation cycle. The horizontal resolution of each system is close to 0.5°, although the discretization methods differ. Table 2-2 summarizes the resolution used for the analysis increments and the resolution of the forecast (corresponding to the background state used in the analysis). As indicated, NRL and GMAO are both using a 3D-Var over a 6-h assimilation window while ECMWF is using its 4D-Var with a 12-h assimilation window.

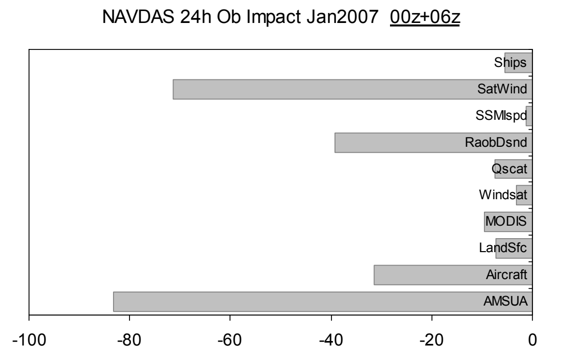
3. RESULTS

The observation impact was evaluated in terms of total impact taking into account all observations of a given type that were assimilated. Figure 3-1 shows the results from NRL, ECMWF and GMAO. Total impact reflects the large volume of data assimilated during the entire month-long study period based on 12-h windows centered at 00 UTC in the case of ECMWF and on the combined 6-h windows centered at 00 UTC and 06 UTC in the case of NRL and GMAO.

AMSU-A and aircraft data have a significant impact for all centres of similar magnitudes. SATWIND wind measurements derived from geostationary imagery also show a significant impact in all three systems, but especially the NRL system. It is also observed that radiosonde data have more impact in 3D-Var assimilation systems than in 4D-Var, suggesting that more information is extracted from satellite data in 4D-Var than in 3D-Var. It also shows that the impact of observations may vary according to the observation coverage (see Gelaro, 2008, this volume). The most significant differences are seen in the impact of ships and surface data, which are more important in the ECMWF system than in the NRL and GMAO systems. This is consistent with the argument presented in Järvinen *et al.* (1999), showing that timeseries of surface pressure data provide tendency information in 4D-Var that cannot be obtained in 3D-Var. Ship data are particularly beneficial as they tend to be located in regions where other in-situ data are sparse.

Total impact includes the contribution from all data and therefore depends on the volume of data of a given type that is included in the assimilation. The impact per-observation puts things

-A-



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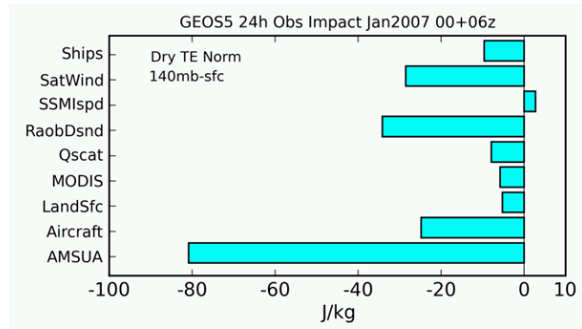
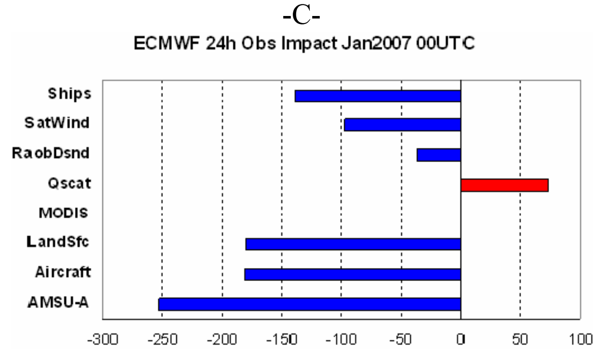


Figure 3-1: Total observation impact per observation types for a) NRL, b) NASA-GMAO, and c) ECMWF. Results are shown at 00UTC and averaged over January 2007. Units are in Jkg^{-1}.

-C-



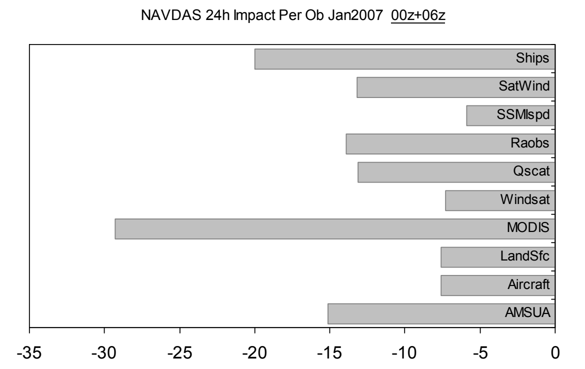
in perspective regarding the impact of individual observations in the different systems. This is shown in Fig.3-2. It is worth noticing that ECMWF exhibits a large impact from both ship and surface data. All other types of data show much smaller impact per-observation. The NRL and GMAO systems also measure an important impact from ship and land surface data that is however commensurate with that of the other data types. Note that small impact per-observation can produce large total impact when the number of assimilated data is large, as with satellite observations.

The comparison between NRL and GMAO shows a significant difference on the impact of MODIS winds which are more important for NRL than GMAO. SATWIND measurements also have a more significant impact in NRL's system than at GMAO. NRL assimilates more SATWIND data, which largely explains why the total impact of this observation type is greater in their results. On the other hand, GMAO assimilates a larger number of MODIS winds, but NRL appears to obtain larger impact per-observation. The reasons for these differences will be examined in future work.

Interestingly, only ECMWF shows a negative impact of QuikSCAT surface winds, which have a small but positive impact in the NRL and GMAO systems. This would merit further investigation as this seems to be contrary to results obtained by Isaksen and Stoffelen (2000) which indicated that 4D-Var was better suited to extract useful dynamical information from surface winds than 3D-Var in cases of Tropical cyclones where scatterometer winds have the most significant impact.

The similarities are greater between the results obtained with systems based on similar assimilation methods (NRL and GMAO). This suggests that a baseline intercomparison

-A-



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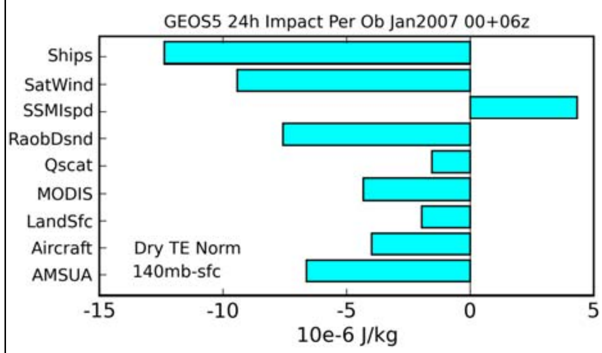
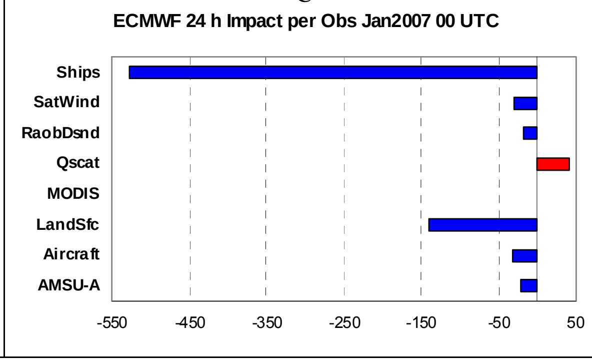


Figure 3-2: Observation impact per observation for a) NRL, b) NASA-GMAO, and c) ECMWF. Results are shown at 00UTC and averaged over January 2007. Units are in 10^{-6} Jkg^{-1}.

-C-



experiment should try to bring the systems closer to one another by sharing the same assimilation method if possible. Comparing NRL's and GMAO's results shows that differences in observation impact may be associated with the forecast models, observation counts, or details of the data assimilation procedures used by the different centres. If that is the case, the evaluation of the impact of changes in individual components may be better evaluated within an individual system to get a signal that would not be "contaminated" by differences in the NWP model or the components of the assimilation.

4. FUTURE OBJECTIVES AND CONCLUSION

During T-PARC, various types of observations will be deployed based on targeting information obtained with singular vectors or the ensemble transform Kalman filter (ETKF) method. As the emphasis will be on changes in the short to medium-range, the metric used to define the sensitivities of forecasts will be defined as a measure over a regional domain (e.g., North America). As discussed in Buizza et al. (2008), Cardinali et al. (2008) and Langland (2005), it is difficult to make definitive statements on the value of targeted observations given that the number of cases during a measurement campaign is very low. Data denial experiments enable experiments to be carried out over longer period of times but one can question the fact that sensitive areas may not be optimally sampled as one has to do such experiments with existing observations that may not provide adequate coverage. Results based on ATReC 2003 observations and on data denial experiments indicate that, on average, targeted data have a small but positive impact. The sensitivities with respect to observations may be used (as in Langland, 2005) to get a more detailed view of the value of targeted data. The signal being weak, it may be interesting to set up an intercomparison experiment to at least establish a common ground to evaluate the impact of such observations. The results presented in this paper are a first step toward this goal.

Given these preliminary results, it would be interesting to use other methods to evaluate the value of observations. For example, it would be interesting to see if ensemble based methods and information content approaches lead to the same conclusions. Further thinking on the value of an intercomparison experiment needs to be pursued. The results presented in this paper show that substantial differences persist between different data assimilation systems, some of which may explain differences in the results obtained (e.g., 3D-Var and 4D-Var). The difficulties in establishing a common ground are numerous. For instance, any data assimilation system requires a careful calibration of components like quality control, bias estimation and correction of observation errors, specification of background-error statistics, flow dependency (e.g,, the meteorological situation at hand), numerical prediction model used, etc. Assessments of the value of observations made by different NWP centres should try to at least determine a common ground for those parameters that can be easily set. For practical reasons, results on OSEs presented by the participants at the workshop were often based on evaluation over different periods, meaning that the evaluation was carried out during different flow regimes. Other elements were intended to be similar in the intercomparison experiment presented here, but were more difficult to constrain. Having all centres use a common set of observations implies that, in this configuration, the assimilation system may not meet optimality criteria used to calibrate the error statistics.

If one wants to look at the impact of changing a single component, another approach could be to evaluate, say, the impact of going from 3D to 4D-Var in several systems. Preliminary results produced by NRL and Environment Canada indicate that similar conclusions are obtained. This will be an object of future research.

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