OBSERVATIONS FROM THE GLOBAL AMDAR PROGRAMME

Author: J. J. Stickland
WMO AMDAR Panel
Bureau of Meteorology
P.O. Box 1289K, GPO Melbourne,
Victoria 3001, Australia
Tel: (+)613 9669 4255 Fax: (+)613 9669 4168
E-mail: j.Stickland@bom.gov.au

Co-author: A.T.F Grooters
WMO AMDAR Panel
Royal Netherlands Meteorological Institute
P.O. Box 201, 3730 AE De Bilt
The Netherlands
Tel: (+)3130 220 6691 Fax: (+)3130 221 0407
E-mail: frank.grooters@knmi.nl

ABSTRACT

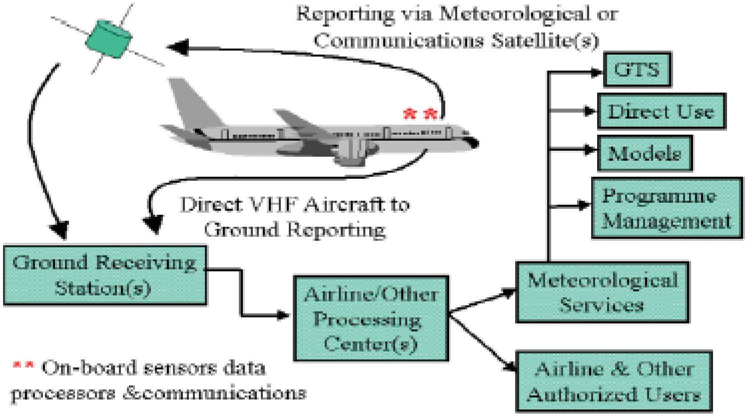
The global AMDAR programme provides a relatively new upper air observing system that has expanded rapidly over the past 10 years. It is a very cost effective system that is automatically producing daily more than 170,000 high quality observations of wind and temperature from the surface to 40,000 ft from regular passenger and freight aircraft. The programme is coordinated by the WMO AMDAR Panel that comprises a group of 21 Members and other interested organizations. The programme has 2 main goals - firstly, to provide timely, low cost observations in data sparse areas of the world in support of the WMO World Weather Watch Programme through integration in the Global Observing System. Secondly, to provide such observations to supplement data from existing conventional observing systems as part of a more complete integrated upper air programme. The AMDAR Panel has undertaken a priority project to meet the fundamental requirement for high quality observations of humidity/water vapour for operational use. There are also requirements for observations of turbulence and icing to support the aviation industry. This paper presents an outline of the status of the programme and presents information on data quality and progress in developing and implementing new types of observations.

Introduction

Since the beginning of flight, weather observations taken from aircraft have made an important contribution towards understanding the current state of the atmosphere so that better weather forecasts can be made. The value of automated reporting of meteorological observations from aircraft was established in the 1970s during the First Global Atmosphere Research Program Global Experiment (FGGE). A number of long-haul wide-bodied passenger jet aircraft were fitted with specially built **A**ircraft to **S**atellite **Da**ta **R**elay (ASDAR) systems that provided valuable observations of temperature, wind and pressure over data sparse land and oceanic areas of the world. High quality data were transmitted via geostationary meteorological satellites to national meteorological services and exchanged globally on the WMO GTS. Today, the Aircraft Meteorological Data Relay (AMDAR) system facilitates the fully automated collection and transmission of weather observations on commercial aircraft around the world. AMDAR has been adopted as the generic name for automated meteorological reporting systems from aircraft. The first operational AMDAR program commenced in 1986 with 5 aircraft producing less than 1000 observations per day, but the program has grown rapidly since then with more than 2300 aircraft worldwide contributing approximately 180,000 observations per day. Further more, various AMDAR programs undertaking operational trials are producing more than 20,000 observations per day. AMDAR data are used operationally to support a wide range of meteorological applications and are considered by WMO to be an essential source of basic upper air information.

The AMDAR System

AMDAR takes advantage of existing systems and infrastructure onboard aircraft as well as those established by airlines for routine operations. Onboard sensors, computers and communications systems obtain, process, format and transmit data to ground via the aviation industry standard Aircraft Communication Addressing and Reporting System (ACARS) that consists of Very High Frequency (VHF) and satellite elements to provide communications coverage for much of the world. Once on the ground, the data are relayed to the global network of national meteorological services (NMS) and other authorised users as shown in the figure. Data are received at the data acquisition system of the NMS where they undergo basic quality checks and control before being reformatted to the relevant Text FM42 or BUFR FM94 AMDAR code for distribution for internal use and via the GTS to other NMSs.



Data Flow through an AMDAR System

An essential element of the AMDAR system is the routine data quality monitoring undertaken by global and regional centres. Reports are provided on a daily basis by some centres to assist program managers make decisions on maintaining high quality data. Other centres provide monthly reports that also assist with careful program management. Of equal importance is the 2-way feedback path between the NMS and airlines to ensure relevant remedial actions are taken to remove the source of poor quality data. This is one of the main reasons for the proportion of poor quality AMDAR data being less than 1%.

Other essential elements include the ability to target observations in time and space to help fill data sparse regions of the world and to optimise local operations to maintain tight control over data coverage to meet operational and financial constraints.

AMDAR Data

National meteorological services have shown these cost-effective high quality AMDAR observations contribute to improved short to medium term numerical weather forecasts and provide a valuable tool to real-time forecasters for a wide range of operational services including severe weather, aviation, defence, marine, public weather and environmental monitoring. Since AMDAR observations are used for a wide variety of operational functions, they are considered to be basic data and can provide valuable asynoptic in-situ information in data sparse areas that otherwise would not be available. AMDAR has shown that it can form an important component of national, regional and global composite observing systems.

Evaluation of AMDAR data over many years has shown the observations to be of high quality comparable to operational radiosonde data. Requirements for the desirable horizontal spatial and temporal density of vertical profiles of wind, temperature and humidity have become more stringent over recent years. Currently, the requirements for Europe and the US respectively are one profile on a 250 km grid at 3-hourly intervals and a 100 km grid at 30 min. intervals.

The primary (basic) data set from each aircraft participating in the AMDAR program includes position in time and space, wind speed and direction and ambient temperature that are available directly from the aircraft avionics system. A secondary additional data set contains derived observations that require further onboard processing of other basic observations form the aircraft data bus. Details are given in the following tables.

BASIC Data

Element	Unit	Range	Output resolution	Desired accuracy
Pressure Altitude	Foot (ft)	-1000 to 50000	10	100$^{(1)}$
Static Air Temperature	°C	-99 to 99	0.1	0.5$^{(2)}$
Wind Direction	^{O} from true N	1 to 360	1	Note (2,3)
Wind Speed	Knot (kt)	0 to 800	1	Note (2,3)
Latitude	Degree:minute	90:00S to 90:00N	1.0min	Note (4)
Longitude	Degree:minute	180:00E to 180:00W	1.0min	Note (4)
Time (UTC)	Hour:Minute:Second	00:00:00 to 23:59:59	1 min	1s

Notes:

(1) required to preserve temperature accuracy
(2) WMO requirement for NWP in troposphere
(3) 2ms^{-1} (4kt) vector error
(4) 5Nm equivalent (specified for ASDAR)

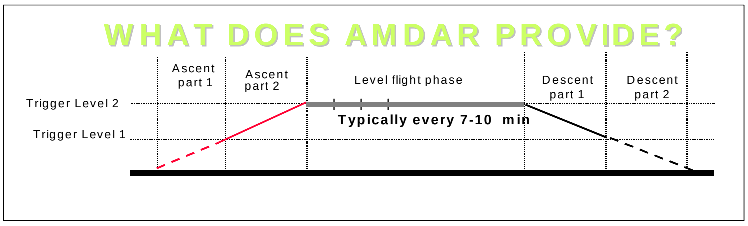
ADDITIONAL DATA

Element	Unit		Output resolution	Desired accuracy
Maximum wind	kt	0 to 800	1	4
Turbulence (g)	g $^{(4)}$	-3 to 6	0.1	0.15$^{(1)}$
Turbulence(DEVG)	m s^{-1}	0 to 20	0.25	0.5$^{(1)}$
Turbulence(EDR)	m$^{2/3}$s^{-1}	0 to 1	0.05	0.1$^{(1)}$
Humidity(RH)	%	0 to 100	1	5$^{(2)}$
Humidity (dew pt)	°C	-99 to +49	0.1	Note 5
Humidity(mixing ratio)	gram/kg	0 to 100	0.001	1:10^{3} (measurement)$^{(3)}$

Notes:
(1) Determined by output categories required
(2) WMO requirement for NWP in troposphere
(3) To meet stratospheric humidity requirement
(4) Acceleration due to gravity. 'Zero' reference on aircraft is usually +1.
(5) Equivalent to 5% RH error.

Profiles and Cruise Level Data

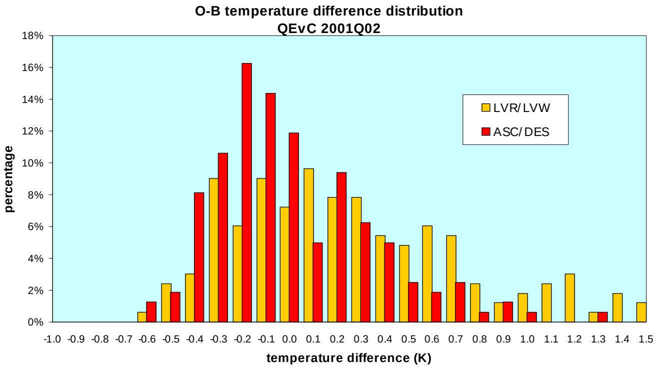
AMDAR provides data profiles during ascent and descent phases of flight and routine observations at given time intervals at cruise level as shown in the diagram. Profiles are divided into 2 stages and may be triggered according to preset pressure levels (preferred) or time intervals. Sampling rates can be varied as required to meet operational requirements and budgetary constraints.

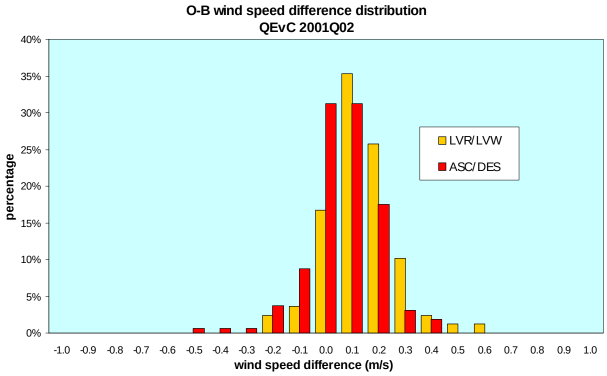


	Pressure Based Triggering	Time Based Triggering
Ascent Part 1:	5 or 10 hPa intervals for first 100 hPa	3 to 20 second intervals (default 6) for 30 to 200 seconds (default 90)
Ascent Part 2:	25 or 50 hPa intervals above first 100 hPa	20 to 60 second intervals (default 20) for 490 to 1050 seconds (default 510)
Enroute:		1 to 60 minute intervals (default 7)
Descent Part 1:	25 or 50 hPa intervals from TOD to last 100 hPa	20 to 300 second intervals (default 40) from top of descent to surface.
Descent Part 2:	5 or 10 hPa intervals for last 100 hPa	

Data Quality

The general quality of automated aircraft observations is consistently high across the 2300 participating aircraft around the world. Mean temperature bias and uncertainty respectively are typically less than 0.5 and 1.3 deg. C . The equivalent numbers for wind observations are 0.6 and 4.0 m/s. The figures below provided by the E-AMDAR monitoring centre at KNMI show the results of monitoring about 300 aircraft over a 3-month period and are typical of all fleets.





Centres monitoring AMDAR data include the National Centers for Environmental Prediction, ECMWF, UK Met Office, KNMI, Canadian Met. Centre, Meteo France, Deutscher Wetterdienst, Bur. of Met. and JMA most of whom make the data available ether on a daily basis for local and regional use or monthly for global use. A number of other centres including those from Saudi Arabia and China also monitor their own data. The results are generally quite consistent across the centres and poor performing aircraft are readily identified. WMO has produced a standard set of monitoring criteria that are being implemented across all centres. Monitoring is achieved by comparing observations with the model first guess field, however in at least one case, 2 additional techniques are employed. AMDAR data are routinely compared with radiosonde data as well as as against other aircraft. This latter technique is very sensitive and removes contributions from the reference monitoring systems. Some 94% of data are available on the GTS within 60 minutes and more than 99% are available within 120 minutes.

As previously stated, critical elements of the AMDAR system are the free exchange of data-quality information between monitoring centres and the respective participating NMSs together with the excellent collaborative relationship most AMDAR operators have with their participating airlines. Apart from providing the airlines with a very sensitive and accurate calibration service of the temperature and wind sensors onboard their aircraft, the various national and regional AMDAR focal points alert the airlines when sensor biases approach 2 deg.C. As soon as the bias consistently goes beyond this value, data from the aircraft are withdrawn from distribution and local operational use and the airline is requested to take remedial action. Initially airlines were reluctant to consider such drastic steps until the bias reached 5 deg. or more but they now recognise the importance that accurate temperature observations have on aircraft engine performance. This of course converts to money saved on fuel burned and engine wear. Similarly, the airlines appreciate the improved wind forecasts, particularly for long-haul routes.

To the left is a picture of an insect taken from an aircraft temperature probe. Errors were first noticed when a large jump in temperature bias was detected by the national AMDAR monitoring centre. This coincided exactly with the airline detecting an increase in fuel burn on the same aircraft. Engine performance returned to normal after the probe was replaced.

Participating Countries and the AMDAR Panel

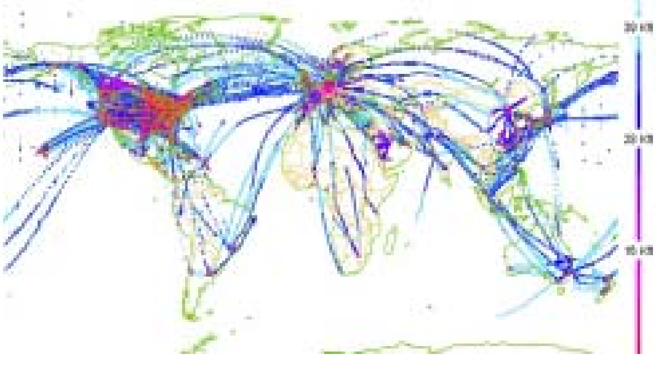
AMDAR programs are now operated by 14 countries including Australia, New Zealand, Japan, China, Hong Kong China, Saudi Arabia, South Africa, US, Canada, The Netherlands, UK, France, Sweden and Germany (the latter group of 5 operating as a European regional program under EUMETNET). Programs are under development in Finland, Chile, Argentina, The Republic of Korea and the United Arab Emirates. A number of other countries are either planning or exploring the feasibility of developing programs including the Russian Federation, Romania, Poland, Hungary, the Ukraine, Austria, Spain, Iceland, Ireland, Morocco, Brazil, India and Pakistan.

AMDAR is an internationally coordinated program with the core aim of collecting and globally distributing high quality meteorological/environmental data obtained automatically from appropriately equipped aircraft. Stakeholders include aircraft operators, national meteorological services, research institutions and other national and international agencies. In recognition of its importance and value as a reliable source of high quality upper air data, AMDAR is being integrated into the World Weather Watch Global Observing System under the World Meteorological Organization. AMDAR will also form an important component of the Global Earth Observing System of Systems that will be supported by WMO and countries committed to providing and using AMDAR data.

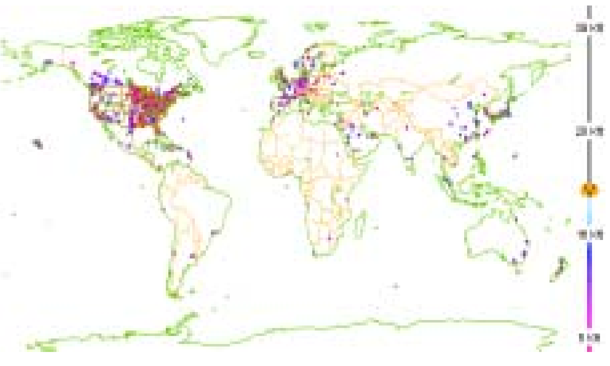
The AMDAR Panel was formed in 1998 and consists of representatives from WMO Member countries that participate directly in the AMDAR program and who provide the funding for its activities. Panel meetings and workshops are coordinated by the AMDAR Panel with organizations and groups actively involved in the development, collection and use of observations from aircraft. Observers currently include international agencies representing airline operators and providers of air traffic safety. Other bodies with direct interest include providers of airline communications, aircraft avionics and sensors and research institutes. The AMDAR Panel is the executive manager for the International AMDAR program.

Data Coverage and Growth

The following two figures show the global enroute AMDAR coverage and the locations where AMDAR profiles were generated on 15 February 2005. The second figure in particular clearly reveals the data sparse areas where no profiles are available. At the moment these sites tend to correlate with the sparsity of upper data from conventional observing systems. The CBS Expert Team on Data Requirements and Redesign of the Global Observing System has identified a number of regions that urgently in need of upper air data that generally match the second figure. One of the main aims of the AMDAR Panel is to increase AMDAR coverage using a variety of techniques to help reduce these data sparse areas. The principle means of achieving this is through the provision of targeted data by existing AMDAR providers through collaborative programs with countries in the data sparse regions. This system is further explained below.



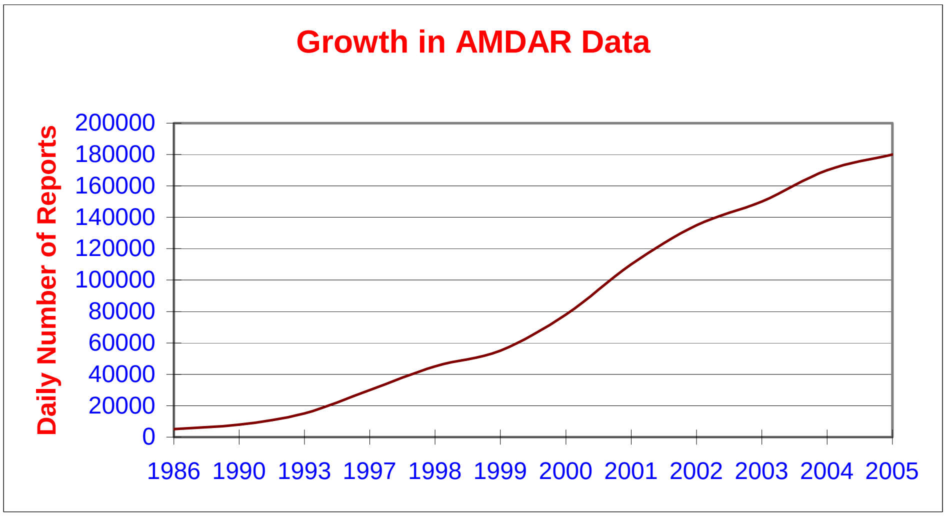
Global AMDAR Coverage 15/2/05



AMDAR Profile sites

Figures provided Courtesy of NOAA Forecast Systems Laboratory

The number of AMDAR observations exchanged daily on the GTS has grown from less than a thousand in 1986 to over 180,000 currently as shown in the accompanying figure. It is anticipated that the number will nearly double over the coming 5 years as existing programs expand, new observation types are introduced and new national and regional programs come on line.



Data Constraints

The production of AMDAR observations is subject to a number of constraints:

- Data profiles are confined to airports where AMDAR configured aircraft operate;
- Cruise-level data are confined to normally well defined aircraft routes;
- Maximum altitude reports are limited to aircraft cruise levels, typically between 20,000 and 40,000 feet;
- The time of observations are constrained to scheduled flight time tables;
- The number of reporting aircraft, area coverage and sampling frequency including vertical profile density are governed by budgetary constraints of the responsible national weather service;
- Observed elements have been limited to pressure, temperature and wind with a small number of turbulence observations. Moisture content, icing and more extensive coverage of turbulence will be gradually phased in over the next few years;

New Types of Observations

One of the major limitations of automated observations from aircraft has been the lack of a reliable humidity/water vapour sensor. Although trials of a prototype sensor occurred several years ago, no aircraft are routinely reporting water vapour content. Work on a new water vapour sensor (WVSSII) in the US has been completed and a 6-month evaluation trial using 30 sensors mounted on B757 freighter aircraft will take place later in 2005. A number of countries including the E-AMDAR group, Australia, South Africa and New Zealand are planning operational evaluation trials in 2006 on the Airbus A320 family of aircraft using a small number of sensors. Once proven, the number of sensors will grow slowly because all purchase, installation and operational costs are paid by the participating weather service. However, additional countries have indicated their intension to install and operate a limited number of sensors to help supplement radiosonde soundings in carefully planned integrated upper air observing systems.

Although an aircraft independent observation of turbulence in the form of Derived Equivalent Vertical Gust Velocity (DEVG), has been reported automatically by some aircraft since 1986, there has not been a strong demand for this type of observation. Data were used mostly for forecast verification and the location of jet streams and gust fronts. More recently however, as awareness has grown of the potential operational use of this observed element particularly in the aviation industry where the safety of passengers and aircraft has become a major issue, new implementation programs have commenced reporting turbulence in the form of Eddy Dissipation Rate. The US FAA has a number of programs to develop services based on these data.

Another type of observation that is not of great interest or value for routine forecasting but is of special interest to the aviation industry is the detection of icing conditions. In flight icing potential and the rate of ice accretion on aircraft flight control surfaces is of value to the industry for a number of operational and safety reasons. Tests are being undertaken to determine the most appropriate way to report and use the on/off signal of automated de-icing systems found on many modern aircraft. A number of icing sensors are being developed to report icing conditions. Information relating to the existence of super cooled water droplets is currently considered to be the preferred type of data needed.

Data Targeting and Optimisation

It is now technically feasible to control the time and location of observations on appropriately configured AMDAR aircraft operating anywhere in the world. This can be achieved by a number of techniques including manually initiated commands from a control centre eg. NWS, or automatically either by onboard software controls or via uplinking commands from a ground-based control system via the aircraft communications system. This gives national weather services 2 very valuable tools:

(i) The ability to optimise its operational AMDAR program to meet requirements for data while still meeting financial constraints; and
(ii) The ability to target the generation of data in data sparse regions of the world in collaboration with NMSs in these regions with a basic very cost effective upper air program. This same tool can be used to target the collection of upper-air data in locations and at times of special meteorological interest.

The European E-AMDAR program has developed a range of optimisation systems that provide very effective cost control on a daily basis while attempting to meet the basic operational need for a profile at 3-hourly intervals at most airports. In some cases, vertical sampling density is increased together with more frequent profiles to meet specific operational needs of very busy airports. Data are used to better control approach and landing times of aircraft either to improve airport efficiency while still maintaining safety standards or to conduct research for example on aircraft wake vortices. Australia and New Zealand also operate limited optimisation systems through onboard software to help control expenditure on data.

A number of data targeting programs have been implemented by NMSs to data sparse regions. E-AMDAR is providing targeted data for Eastern Europe, the Middle East, Africa, the Central Atlantic Ocean, Caribbean countries and South America. The group is developing an ambitious program in collaboration with the ASECNA organisation to provide profiles for 14 countries in Central and West Africa and Madagascar. In the latter case the agency will meet the operational costs to operate the program. South Africa provides data over Africa up to the equator. Australia provides profile data for New Zealand, Hong Kong and South Africa and enroute data over many countries in Asia, Pacific Islands, the Middle East and Eastern Europe. The US is providing data over Asia, Canada and South America. Development of further collaborative programs with countries that can contribute to their operational cost, are also envisaged.

Benefits and Impacts

AMDAR observation profiles and enroute data provide benefits to operational forecasters, numerical weather prediction products, climatology and atmospheric quality monitoring. More detailed knowledge of vertical profile temperature and wind structure provides significant improvements to:

(i) Short to medium term Public Weather and Marine Weather forecasts:
  - Surface wind and temperature;
  - Detection of height and strength of inversion;
  - Cloud development;

- Onset and dissipation of fog and sea breeze;
- Timing and strength of warm and cold fronts; and
- Eddy circulation systems and other local meteorological phenomena.

(ii) Severe Weather forecasts

- Improved timing of weather fronts, strong winds, dust sqalls etc.;
- Improved in-situ information, particularly upper winds near tropical cyclones;
- Validating satellite-based cloud drift and water vapour winds;
- Vertical stability, helicity (convection, wind shear, thunderstorms, hail, turbulence, wind squalls, etc.);
- Fire-weather (high temperatures, low humidity, strong winds, wind changes);
- Better understanding of the impacts of topgography.

(iii) Now-Casting

- The close-to-real-time nature of AMDAR data provides a very useful data source in most now-casting situations, eg. monitoring current situations and updating NWP forecast information.

(iv) Climatology

- AMDAR provides the ability to develop vertical wind and temperature climatologies for general application throughout the year, eg. to provide basic meteorological information for air quality and other numerous applications.

(v) Impact Studies

- Impact studies show benefits to NWP regional analyses and forecasts;
  - Improved accuracy of jet stream location and depth;
  - Improved analysis and forecasts of wind in the mid to upper troposphere;
  - Improved accuracy in short and medium range analyses and forecasts out to 6 days;
  - Improved forecasts of rainfall accumulation, particularly at the higher rainfall thresholds (even without the availability of AMDAR humidity observations);

(vi) Aviation

- AMDAR data provide a number of important direct meteorological forecast benefits to airlines, air traffic control service providers and airport operators:
  - Improved surface and low level temperature and wind data (for ARFOR and TAF);
  - Cloud development, type, bases, tops;
  - Observed freezing level;
  - Boundary layer stability, severe weather (strong winds, dust, rain, freezing rain, hail, convection etc.
  - Vertical wind shear, turbulence, mountain wave activity and winds for middle level steering mechanisms;
  - Onset and dissipation of fog, sea breeze and other relevant phenomena governing the safety and control of airport operations;
  - Enroute winds, turbulence, jet stream location, structure and intensity, severe weather, icing conditions, etc.;
  - Support for balloonists and glider pilots;
  - Investigations into air-safety incidents;
  - Routine quality monitoring of AMDAR data provides a very effective quality check on aircraft sensing and data management systems.

The Results of Some Impact Studies

A number of studies have been undertaken by NWP centres including ECMWF, UK Met Office, DWD, NCEP CMC, Hong China, JMA,, CMA and SAWS. A sample of the results of studies reported by ECMWF and NCEP together show strong positive impact of AMDAR from hours to more than 6 days. Two examples of the many available are given below.

Example of Short-Term Impact (Courtesy of Dr. Ralph Petersen, University of Wisconsin)

The most extreme test of the impact of the aircraft data was conducted by the Forecast Systems Laboratory (personal communication, 2004) in which aircraft observations were excluded from the RUC analyses at all levels and all times during a multi-week wintertime test period in 2002. The results in figure 3 show very clearly that, when averaged over the entire contiguous United States area, the inclusion of aircraft data adds more than 1.5 knots to the accuracy of the 3 hr forecasts. At specific locations, the improvements can be much greater, reaching as high as 10-15 knots in some instances – much larger than the two kt threshold for ‘significant’ differences designated by aviation users. Stated in another way, the net effect of including aircraft observations at all levels and times in the hourly RUC analysis and forecast updates consistently reduces the error in standard 12 hr forecasts by as much as 20 %, even though other ‘off-time’ data sets are available over the U.S.

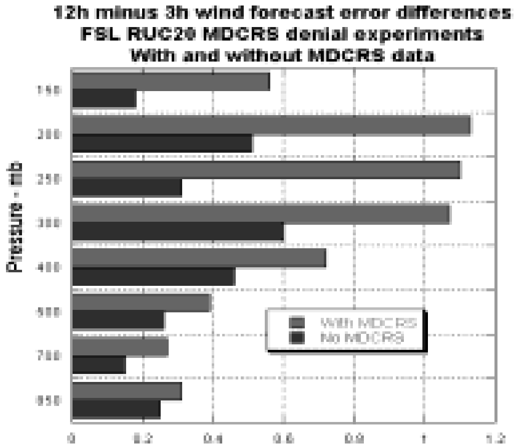


Figure 1a: Differences between 12hr and 3 hr forecasts with and without aircraft (labeled MDCRS) data. Difference in RMSV Error shown in m s^{-1}, where 1 m s^{-1} equals approximately 2 knots.

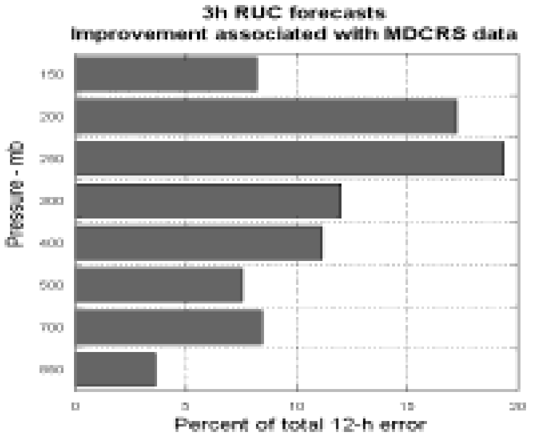
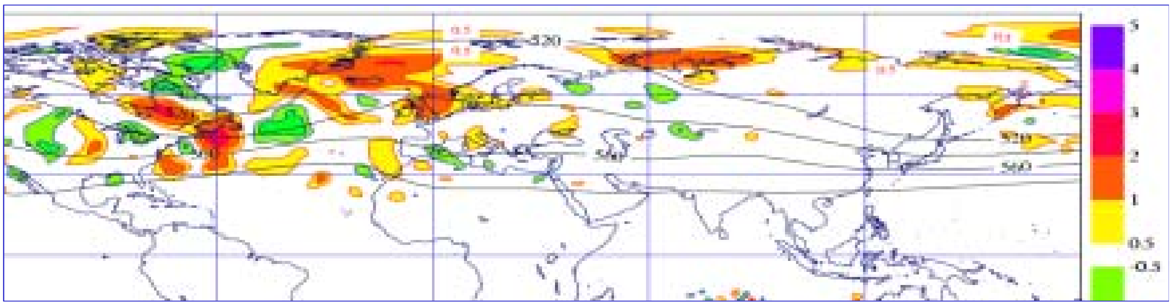


Figure 3b: Percentage of 3hr forecast improvement due to aircraft (MDCRS) data.

Examples of Medium Term Impact (Courtesy Erik Andersson, ECMWF)

Diff in RMS of 120 Hr Forecast Error: Exp-Control
500 hPa, 20010102-0131, Valid 12 UTC

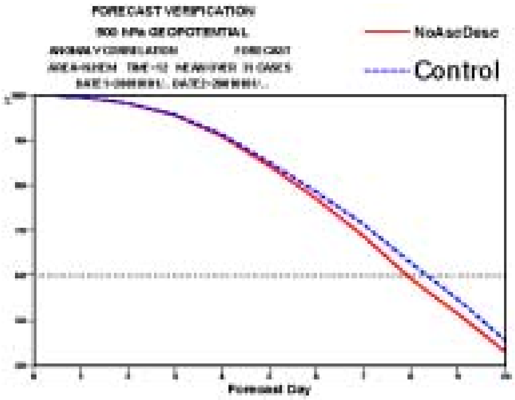
- **Exp: Denied ascending and descending aircraft, p>350 hPa**
- **Positive Values indicate ascent/descent data added value**



Eur: 3.02m, N.Atl: 2.90m, N.Amer: 0.31m N.Hem: 1.35m

Exp: Forecast impact

- **Exp: Denied ascending and descending aircraft, p>350 hPa**
- **Higher Values** *(Dashed)* **indicate ascent/descent data added value**



The Ascent/Descent data add ~0.4 days of forecast skill at day 8 –
a 5% improvement in forecast skill - - this is significant