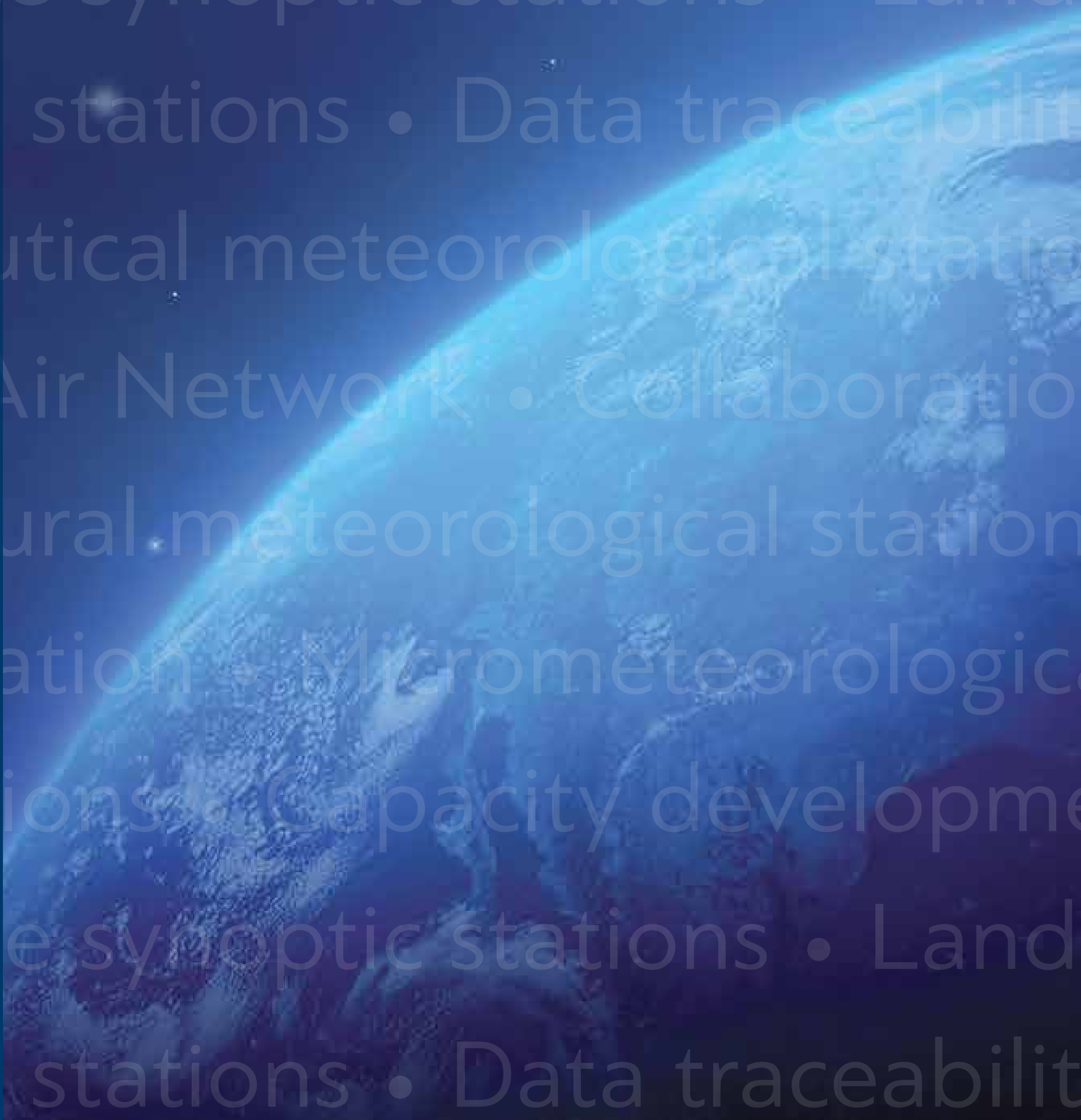
TECHNICAL REPORT
No. 2018-01

WIGOS

WMO Integrated Global Observing System

Benefits to the Environment and Society from the Availability and Use of AMDAR Data



WMO

TECHNICAL REPORT
No. 2018-01

WIGOS

WMO Integrated Global Observing System

Benefits to the Environment and Society from the Availability and Use of AMDAR Data

WMO

Chair, Publications Board
World Meteorological Organization (WMO)
7 bis, avenue de la Paix
P.O. Box 2300
CH-1211 Geneva 2, Switzerland

Tel.: +41 (0) 22 730 8403
Fax: +41 (0) 22 730 8040
E-mail: Publications@wmo.int

CONTENTS

ACKNOWLEDGEMENTS

This report is prepared by Mr. Ercument Avsar, Consultant to the World Meteorological Organization (WMO) and Engineer at the Turkish State Meteorological Services, under the supervision of Mr. Dean Lockett, Scientific Officer in the Observing Systems Division, Observing and Information Systems Department at the WMO based on guidance provided by the Commission for Basic Systems (CBS) Expert Team on Aircraft-Based Observing systems.

The report benefited from the comments and suggestions of Mr. Dean Lockett (WMO Scientific Officer, Aircraft-Based Observations), Mr. Curtis Marshall (Chair of the WMO Expert Team on Aircraft-Based Observing Systems), Mr. Frank Grooters (Core-Member Expert Team on Aircraft-Based Observations), Mr. Carl Weiss (WMO AMDAR Observing System Newsletter editor), Mr. Stewart Taylor (UK MetOffice, WMO AMDAR Development Officer, E-AMDAR Technical Coordinator), Mr. Greg Brock (WMO Scientific Officer, Aeronautical Meteorology Division).

1. INTRODUCTION

Observations of temperature, wind, and humidity are crucial for examining the current state of the atmosphere, short-term forecasting, assimilation into numerical models, and understanding the climate. The World Meteorological Organization (WMO) Aircraft Meteorological DAta Relay (AMDAR) observing system provides an automated measurement of atmospheric conditions from the surface to around 40,000 feet using commercial aircraft as a platform. It uses mainly existing aircraft on-board sensors, computers and communications systems to collect, process, format and transmit meteorological data to ground stations via satellite or radio links. After relay to the ground, the data is processed, quality controlled and transmitted on the WMO Global Telecommunications System (GTS) by National Meteorological and Hydrological Services (NMHSs).[1]

As with all high quality upper-air observations, AMDAR data are used in many meteorological and aviation applications. Table 1 shows upper-air weather parameters measured or derived from AMDAR such as air temperature (static air temperature), wind speed and direction, pressure altitude (derived from barometric pressure), turbulence (EDR - Eddy Dissipation Rate or DEVG - Derived Equivalent Vertical Gust) and water vapour.

Table 1. AMDAR measurements and deliverables

METEOROLOGICAL PARAMETERS	NON- METEOROLOGICAL PARAMETERS
Air temperature (static air temperature)	Departure and destination airport & Time
Wind speed and direction	Icing indication (accreting or not accreting)
Pressure altitude (barometric pressure)	Latitude Position / Longitude
Turbulence (EDR or DEVG, if it is installed)	Flight or Aircraft Identifier
Water vapour (Operationally in the U.S. and Europe)	Aircraft roll angle

Source: Reproduced by the author using WMO AMDAR website and the WMO CIMO Guide[2].

The AMDAR observing system provides *in situ* observations with higher accuracy compared to remote-sensed data sources (e.g. satellites) and with higher resolution (time and space) than the traditional sources of *in situ* data (i.e. radiosondes). For aviation forecasting, AMDAR has the advantage of providing observations in exactly the areas and at the altitudes that aircraft operate. Moreover, AMDAR data provides the required upper air observations at a relatively low cost as it requires only the implementation of software without additional on-board equipment.[3] AMDAR data complements other sources of upper-air meteorological

[1] http://www.wmo.int/pages/prog/www/GOS/ABO/AMDAR/About.html
[2] http://www.wmo.int/pages/prog/www/IMOP/CIMO-Guide.html (Part 2, Chapter 3, Aircraft Observations).
[3] The measurement of moisture (water vapour) and the detection of Eddy Dissipation Rate (EDR) do, however, require the supplementary installation of a water vapour sensing system and implementation of a specific metric, respectively.

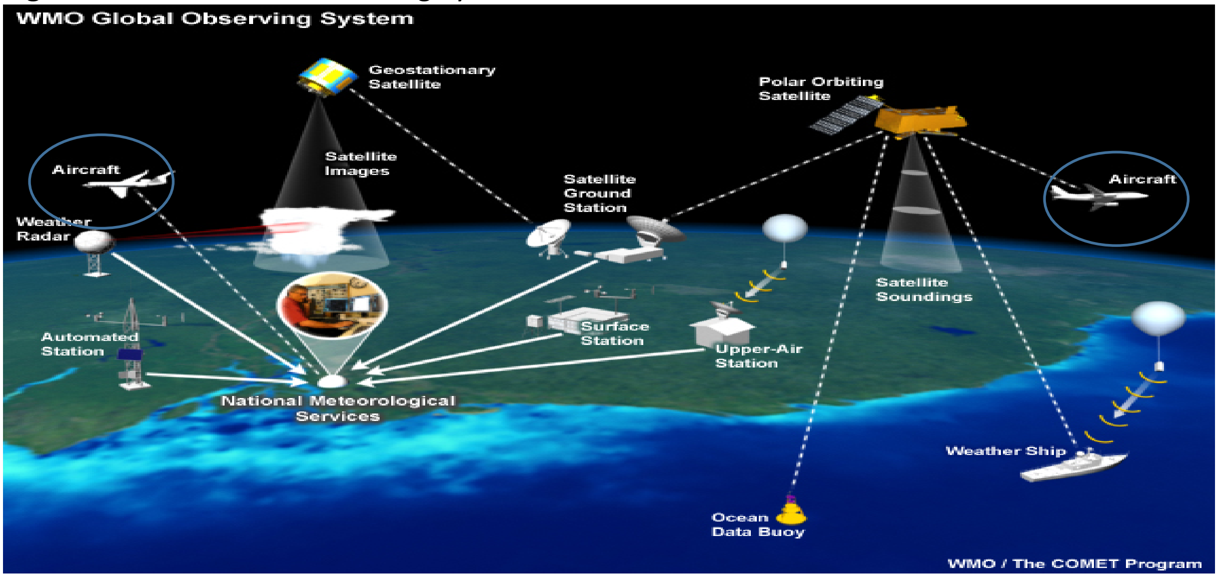
data, resulting in broader coverage and more accurate predictions at a relatively lower cost than almost all other observing systems.

The range of uses and benefits of AMDAR data have been acknowledged in various studies, particularly its use in meteorological applications[4] which, through the resulting improvements made to forecast accuracy and service products for aviation, have led to documented benefits and efficiencies to airlines and the wider aviation industry.[5] However, the resulting benefits of the use of AMDAR data to understand and study environmental issues and to support climate research appear to have been discussed and documented to a lesser extent. This report presents an updated summary of AMDAR data usage and the resulting impacts and benefits to meteorological forecasting and the aviation industry. It then provides a presentation of the environmental and climate applications and studies that also benefit from the use of AMDAR data, as a result, bringing benefits to the environment and wider society. These areas of societal benefits include weather, transportation, energy, disaster reduction, health, climate and agriculture.

1.1. An Overview of the AMDAR Observing System

The WMO AMDAR observing system currently provides arguably the best source of *in situ* tropospheric data at a relatively low cost compared to other meteorological observing systems. Yet, it has the potential to be expanded and enhanced significantly to provide a much more comprehensive global coverage and deliver additional important measureable parameters. AMDAR is an integrated component of the WMO Global Observing System (GOS), and supports the World Weather Watch Programme of WMO (Figure 1).

Figure 1. WMO Global Observing System



Source: WMO/The COMET Program website.

[4] WMO. 2015. *Impact and Benefits of AMDAR Temperature, Wind and Moisture Observations in Operational Weather Forecasting*, WIGOS Technical Report No. 2015-01, Geneva: WMO.

[5] WMO. 2014. *WMO Integrated Global Observing System, The Benefits of AMDAR Data to Meteorology and Aviation*, WIGOS Technical Report No. 2014-01, Geneva: WMO.

WMO and its relevant Technical Commissions and Expert Teams provide central support and coordination of the AMDAR programme through the maintenance of standards and guidance, development of strategy and plans, assistance with implementation at the regional and national levels, development and provision of information, publications, education and training and stakeholder engagement. WMO also maintains a list of Aircraft Based Observations (ABO) national focal points for WMO Members to facilitate the exchange of information and ideas.[6]

WMO, International Civil Aviation Organization (ICAO) and International Air Transport Association (IATA) all play important roles in expanding the coverage of the AMDAR programme. WMO works with regional and global stakeholders in coordinating the AMDAR programme from policy to user oriented and technical aspects. In May 2017, WMO signed a working arrangement with ICAO to work closely towards a joint-approach to operations and further development of ABO. This collaboration would have the general aims to expand and enhance the programme, to improve the management of AMDAR data and to better integrate AMDAR into aviation and air traffic management systems.[7] In July 2017, WMO entered an agreement with IATA that specifically relates to the AMDAR programme. IATA will help to expand and improve the operation of the AMDAR programme, while WMO will help to better secure the aircraft-based data, which is formally owned by the participating airlines.[8]

1.2. AMDAR Data Quality and Impact

It has been demonstrated that commercial aircraft-based data have played a significant role in reducing flight-level wind and temperature forecast errors by nearly 50% over the last three decades.[9] This, in turn, has had a major positive impact on airline operations including fuel savings, improved flight planning and improved passenger comfort and safety.[10] Automated aircraft reports are over five times more cost effective than other major observing systems providing the most cost effective data source for Numerical Weather Prediction (NWP). AMDAR also offers an economical data source for tropospheric profiles. Moisture observations are becoming increasingly available as more AMDAR aircraft are being equipped with humidity sensing systems.[9]

There has been and continues to be an increasing demand from aviation customers for higher quality meteorological products, which necessitates an ever-increasing demand for higher frequency and improved resolution of observations. Development and creation of

---

[6] http://www.wmo.int/pages/prog/www/GOS/ABO/ABOWorkTeams.html

[7] https://public.wmo.int/en/media/news/wmo-and-international-civil-aviation-organization-strengthen-cooperation

[8] https://public.wmo.int/en/media/news/wmo-works-air-transport-industry-data-gathering-system

[9] Petersen. 2016. On the Impact and Benefits of AMDAR Observations in Operational Forecasting—Part I: A Review of the Impact of Automated Aircraft Wind and Temperature Reports, *Bulletin of the American Meteorological Society*, 97(4): 586-602.

[10] WMO. 2016. *WMO Integrated Global Observing System, AMDAR Benefits to the Air Transport Industry*, WIGOS Technical Report No. 2016-01, Geneva: WMO.

such products require resources which can place additional financial burdens on NMHSs, especially hitting hard in developing countries. The AMDAR programme provides a very reliable source of high quality but low-cost upper-air data that can be considered supplementary to conventional observational products. The coverage of radiosondes is very low, and even close to zero, in many developing countries; therefore, the AMDAR programme can help developing countries to close this gap by providing upper-air observations.

The quality of observations received from each reporting aircraft is routinely monitored by regional and global centres. The National Oceanic and Atmospheric Association's (NOAA) National Centres for Environmental Prediction (NCEP) is the WMO designated lead centre for monitoring aircraft observations. The quality of AMDAR observations is in accordance with the WMO requirements for upper air data. The calculated uncertainties for basic AMDAR data parameters are given in Table 2. In summary, it is well established that AMDAR observations have equal, if not better, degree measurement accuracy as radiosondes.

Having been in operation for more than three decades, the long history of AMDAR data, combined with its high quality, makes it increasingly suitable for use in many applications, including climate.

Table 2. AMDAR data expected uncertainties

AMDAR Variable	Uncertainty
Temperature	+/- 1.0 C
Wind vector	+/- 2-3 m/s
Pressure altitude	+/- 4 hPa

Source: WMO WIGOS TR No. 2014-01.

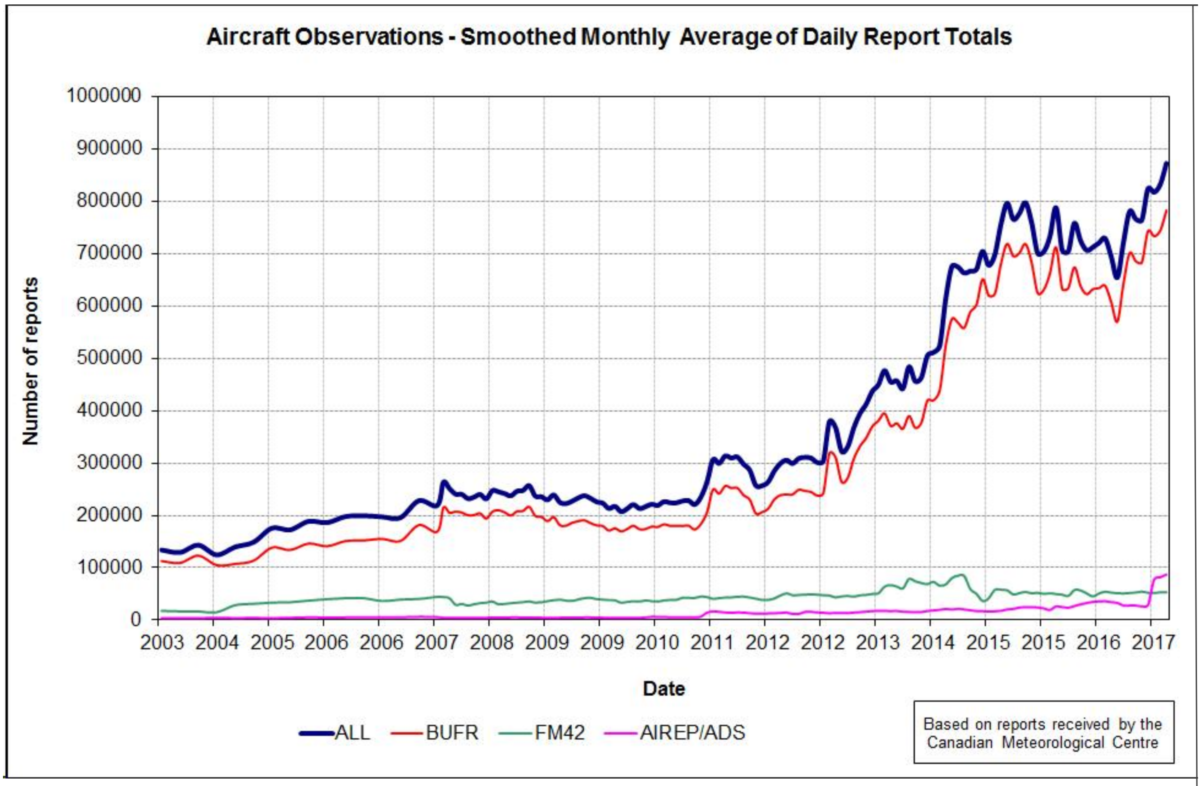
1.3. Airline Participation in AMDAR

AMDAR has expanded significantly over the past two decades by increasing the number of countries and their partner airlines participating in the programme. This has been achieved predominantly through capacity building activities such as regional workshops, which engage both the NMHSs and national and international aviation communities, as well as the development, implementation and maintenance of WMO AMDAR-related standards.

Figure 2 shows the levels and rapid growth of AMDAR observations available on the WMO GTS over the period from January 2003 to June 2017.

As of July 2017, the system was comprised of 12 national and regional AMDAR programmes with more than 4500 aircraft from 40 participating airlines contributing around 800,000 temperature and wind observations per day.

Figure 2. Evolution of AMDAR data reports over time



Source: WMO AMDAR website (https://www.wmo.int/pages/prog/www/GOS/ABO/data/ABO_Data_Statistics.html).

2. APPLICATIONS & BENEFITS

This section introduces the utilisation of AMDAR data in a range of applications including meteorological forecasting, climate and air quality monitoring and prediction, agricultural studies and air traffic control and flight operations. As a result of the positive impacts that AMDAR data has on such applications, there are resulting benefits to the users (consumers) and downstream stakeholders of such applications that will be identified, analysed and, in some cases, quantified later in the document. The use of AMDAR data in meteorological forecasting is only briefly reviewed, as it is already covered in detail in other WMO reports.[4] This report instead emphasizes areas of AMDAR data use related to the environment and climate.

As the coverage of the AMDAR programme has expanded over time and the historical record of AMDAR data has been extended, new areas of application have emerged for the use of the data.

The environmental impact of aviation has become increasingly important in recent decades, particularly given the pressing issue of global warming related to the burning of fossil fuels. For this reason, the ICAO Committee on Aviation Environmental Protection (CAEP) prepares environmental trends projections as the basis for their decision-making on environmental-related matters and has agreed on a comprehensive set of environmental aircraft design standards covering aircraft noise, pollutants that affect local air quality, and CO_2 emissions to protect the global climate.[11]

The use of AMDAR data in a range of applications provides both direct and indirect benefits to the environment and society depending on the specific area of use. Following are a variety of applications for which the use of AMDAR data results in direct and indirect benefits to the environment and society. Each sub-section introduces the current applications and their benefits and then discusses potential benefits for the future.

2.1. Meteorological Forecasting

The various areas of weather forecasting are clearly the main areas where AMDAR data are utilised and provide their greatest positive impact. Vertical profiles of temperature, moisture, wind and pressure are vital inputs for many application areas of atmospheric science and are especially critical input to NWP systems. With radiosonde stations relatively sparse and decreasing in number in many areas, and satellite-based data, while global in coverage, lacking the quality of *in situ* observing systems, AMDAR data is able to take on a very critical role in the WMO Global Observing System, by providing high quality and high resolution *in situ* data at a very low cost.[12] A recent study comparing the cost-benefit of observing systems found that aircraft-based observations have the highest impact per unit cost among all observing system categories.[13] Through its use in meteorological forecast applications, AMDAR data improves the quality and accuracy of weather forecasts and also plays an important role in their verification and validation process. By virtue of their more frequent availability in comparison to radiosonde vertical profiles, AMDAR data also allows forecasters the opportunity to regularly update or verify NWP and other forecasts and products.

It has been demonstrated through data denial experiments and other tests by numerous NWP centres over 25 years, that high-quality and high-frequency AMDAR temperature and wind observations improve skill for both short and medium range forecasts on both regional and global scales. Aircraft observations rank third[14] in importance at the global scale, contributing around 10-15% of the error reduction attributable to all observing systems over the 24-hour forecast period. Their impact on forecast improvement extends to 48-hours and beyond. In shorter-range, high-resolution NWP applications, especially those using moisture data, aircraft observations have been shown to become the single-most important source of data for forecasters.[9] AMDAR high resolution wind and temperature data at the tropopause level is also used for nowcasting (next 0-2 hours) and very short-range forecasting (VSRF, 2-

[11] ICAO. 2016a. *Environmental Report 2016: Aviation and Climate Change*, Montreal: ICAO.

[12] Cronce & Petersen. 2011. *Meteorological Impacts and Benefits of AMDAR Data*, AMDAR Regional Science and Technology Workshop, 9 November 2011, Mexico City, Mexico.

[13] Eyre & Reid. 2014. *Cost-benefit studies for observing systems*, Met Office Forecasting Research Technical Report No: 593, August 2014.

[14] Microwave satellite observations rank the first and rawinsonde observations rank the second [WIGOS TR No. 2015-01].

12 hours), which use frequently updated fields of a three-dimensional (3D) winds and temperatures.[15]

Other meteorological forecasting applications for which AMDAR observations provide valuable and reliable data input include cloud base height determination and icing forecasts. A recent study[16] showed that AMDAR temperature and moisture data can be used to produce icing potential forecasts that are consistent with verifications against other observing platforms such as pilot reports (PIREPs) or aircraft reports (AIREPs) and meteorological satellites. Cloud base height determinations using AMDAR data also were consistent with observations from meteorological reports at aerodromes (METAR). The study also showed that AMDAR Water Vapour Sensing System (WVSS-II) relative humidity measurements can be used in forecasts to verify regions where ceilings (i.e. cloud bases) and icing can be expected. The assimilation of humidity measurements from the AMDAR WVSS-II into the U.S. Global Data Assimilation System (GDAS) also was shown to have a statistically significant positive impact on the warm season moisture and precipitation forecasts at a range of 12-36 h.[17] As a result, aircraft moisture observations are now being assimilated in the operational GDAS.

The use of AMDAR data in meteorological applications has a very direct benefit through its demonstrated and documented improvement to accuracy in many forecast areas and has been quantified many times, in particular for its impact on error reduction in NWP systems as discussed above. These improvements in forecasts by the use of AMDAR data have direct benefits for aviation, health, agriculture, and disaster risk reduction as well as indirect benefits to the environment and society. For example, the improved accuracy of forecasts for upper-air winds and temperatures results in real benefits and, therefore, cost savings for airline flight operations, Air Traffic Management (ATM), terminal operations, flight planners and other aviation stakeholders. The improved efficiency of aircraft operations in turn has indirect benefits to the environment from the resulting reduction in fuel consumption.

Through its use in both NWP and as a source of upper-air data used directly by meteorologists to monitor and predict severe weather events and systems, the use of AMDAR data in meteorological forecasting has a direct benefit for disaster risk reduction associated with severe weather events such as thunderstorms, severe tropical storms and hurricanes, and fire weather events. It also has direct benefits to health through its use and positive impact on air pollution forecasting and to agricultural productivity through climate studies.

By expanding the coverage of the AMDAR observing system and the use of AMDAR data in meteorological forecasts, these benefits can extend to more applications and a wider user community around the world.

---

[15] WMO. 2015. *Statement of Guidance for Nowcasting and Very Short Range Forecasting (VSRF)*, Geneva.
[16] Wandishin et al. 2017. *The Use of AMDAR Observations for Verifying Cloud Ceiling and Icing Forecasts*, 18th Conference on Aviation, Range, and Aerospace Meteorology, 23-26 January 2017, Seattle, WA, USA.
[17] Hoover et al. 2017. Forecast Impact of Assimilating Aircraft WVSS-II Water Vapor Mixing Ratio Observations in the Global Data Assimilation System (GDAS), *Weather and Forecasting,* 32(4): 1603–1611.

2.2. Air Traffic Management, Air Traffic Control and Flight Operations

Aeronautical meteorology is a central component of ATM, contributing to flight safety, efficiency, economy and environmental protection aspects. The AMDAR programme plays a key role in many aspects of aeronautical meteorology. For example, meteorological conditions are often significant factors in the analysis and understanding of aviation incidents and accidents at airports and in the air.

The benefits of AMDAR to aviation, particularly focusing on those derived from the improvements made to weather forecast services and products, are described in detail in the WMO - WMO Integrated Global Observing System (WIGOS) Technical Report 2014-01, *The Benefits of AMDAR Data to Meteorology and Aviation*. In summary, the following benefits are described:

- Improved forecasting ability and resulting improvement in the quality of NMHSs services and products provided to the aviation industry.
- Improved flight operations resulting from better forecast services and products (for example, better route planning, optimal flight level selection, avoidance of severe weather and turbulence, optimized fuel usage planning, improved planning for passenger notifications and crew scheduling).
- Improved safety of passengers and crew as a result of more accurate severe weather warning and resulting increase in customer satisfaction.
- Improved fuel efficiency and aircraft management and resulting operational cost savings.
- Use of AMDAR data for aircraft sensor and system monitoring and feedback on the quality of data being produced by aircraft sensors.

In particular, AMDAR data contributes to improvements in the following meteorological forecast products for air traffic management, control and flight operations:[18] surface and low level temperature and wind information; cloud formation (amount and type); freezing level; boundary layer stability and severe weather; vertical wind shear and en route winds, turbulence, and mountain wave activity; fog and sea breeze; jet stream location (structure and intensity), and icing conditions.

This report therefore focuses on the additional and resulting environmental benefits that either are or might be realised from the use of AMDAR data for air traffic management, control and flight operations. AMDAR has great potential to help airlines and ATM systems in reaching their sustainability goals in the context of green aviation.

2.2.1. Air Traffic Management

Air Traffic Management refers to the regulation of air traffic within an air space over the long term.[10] ATM systems use weather information, services and products through the operations of the units that contracting states establish in accordance with Annex 3 to

[18] Stickland & Grooters. 2005. Observations from the Global AMDAR Programme. TECO 2005 Paper.

ICAO's Convention on International Civil Aviation. The World Area Forecast System (WAFS) aims to supply meteorological authorities and other users with global aeronautical meteorological en route forecasts in digital form through a comprehensive, integrated and worldwide system. Within the framework of the WAFS, the contracting states agree to establish the following units: World Area Forecast Centres (WAFCs), the Aerodrome Meteorological Offices, the Meteorological Watch Offices (MWOs), the Volcanic Ash Advisory Centres (VAACs), the State Volcano Observatories, and the Tropical Cyclone Advisory Centres (TCACs).[19]

WAFCs and MWOs are the two main units that utilize aircraft-based data (including AMDAR data in their weather information, services, and products. Further details will be given on their operations and how they use AMDAR data in their products and services. Within the framework of WAFS, WAFCs are responsible for:[19]

- Preparing gridded global forecasts of upper winds, upper-air temperatures and humidity, geopotential altitude of flight levels, flight levels and temperature of tropopause, direction, speed and flight level of maximum winds, cumulonimbus clouds, icing, and turbulence,
- Preparing global forecasts of significant weather (SIGWX) phenomena,
- Issuing these forecasts in digital form to meteorological authorities and other users,
- Receiving information concerning the release of radioactive materials into the atmosphere from its associated WMO regional specialized meteorological centre (RSMC).
- Being in contact with VAACs for the exchange of information on volcanic activity to be included in SIGWX forecasts.

MWOs are in charge of:[19]

- Continuously watching meteorological conditions affecting flight operations in their areas of responsibility,
- Preparing and supplying SIGMETs to air traffic services units and disseminating other information,
- Preparing, supplying and disseminating AIRMET information to air traffic services units,
- Supplying information received on pre-eruption volcanic activity and on the release of radioactive materials into the atmosphere to their associated area control centre (ACC)/flight information centre (FIC).

The AMDAR observing system helps in achieving high accuracy in forecast products and services of WAFCs and MWOs by providing high resolution upper air wind, temperature, pressure and humidity data during ascent, en route and descent flight phases. Better forecast products and services result in improved flight planning, less flight diversions,

[19] ICAO. 2016b. Annex 3 to the Convention on International Civil Aviation - Meteorological Service for International Air Navigation, 19the edition, July 2016.

alterations and delays, less forced alternate landings due to interaction with severe weather and fuel miscalculations, optimized runway selection, and less reactive changes to flight plans and routes. AMDAR also can help mitigate the (negative) effects of (or the risks resulting from) low-level wind shear and turbulence, and low visibility operations. All of these improvements in flight planning mean cost savings due to lower levels of fuel consumption and increased passenger and aircraft safety. In this regard, wider coverage of AMDAR wind data would further contribute to fuel burning efficiency and the resulting positive implications for the environment.

Besides their direct economical benefits for airlines, optimal flight planning also contributes to their sustainability goals in the context of green aviation. One of the main environmental benefits from the use of AMDAR data is mitigation of global warming through the reduction in the emission of greenhouse gases (GHGs) by its contribution to more efficient aircraft operations. CO_2 and water vapour (H_2O) form the main greenhouse gases emitted by aviation. These contribute 2% of anthropogenic CO_2 emissions, according to the Intergovernmental Panel on Climate Change (IPCC).[20] ICAO introduced a set of measures to reduce international aviation CO_2 emissions through Resolution A38-18 of the ICAO Assembly in 2013. It also introduced the global aspirational goals of annual fuel efficiency improvement by 2%, and stabilization of the sector's global CO_2 emissions at 2020 levels (carbon neutral growth after 2020). Accordingly, ICAO introduced a range of mitigation measures, which are grouped under advancements in aircraft technology, operational improvements, sustainable alternative fuels, and market-based measures.[11] With the expansion of AMDAR data coverage and its contribution to climate-friendly aircraft operations, these benefits to the environment can be increased and extended in the future.

In addition to the current economical and environmental benefits from the use of conventional AMDAR wind and temperature data in weather forecast products and services, the AMDAR WVSS-II relative humidity measurements potentially could improve airline operations and have environmental benefits through applications such as water vapour contrail avoidance, possible icing warnings and fuel efficiency improvements. Above the cost savings and environmental benefits, these AMDAR-induced improvements in weather forecast products and services potentially could further improve flight safety.

2.2.2. Air Traffic Control and Terminal Operations

Air Traffic Control (ATC) uses information on current and projected traffic and atmospheric conditions to control and adjust aircraft routing in a dynamic way. The use of AMDAR data in aviation forecasting, in addition to traditional sources of meteorological data, results in direct benefits for ATC and optimal flight routing as a result of improved and more accurate weather forecasts and services.

Improvements in ATC derived from more accurate aviation forecasting, also lead to improvements in the efficiency of terminal operations. These operations include scheduling

[20] IPCC Fourth Assessment Report, 2004.

of departure and arrival times, allocation of gates and runway management in relation to wind strength and shear, fog conditions, etc. Improvements in ATC management, which require accurate temperature and wind data, help avoid holdings and re-routing. As discussed in more detail in section 2.2.5, the use of AMDAR data in continuous descent approach (CDA) applications contribute to ATC by improving arrival management at the airports.

These benefits realized in ATC and terminal operations potentially can be increased in the future through the expansion of AMDAR humidity measurements. Most of the flight disruptions result from snow, freezing rain, fog and thunderstorms. Forecasts of these elements would be significantly improved in the future through the progressive inclusion of AMDAR (WVSS-II measurements.[10] Dispatchers can use AMDAR data to optimize flight plans by detecting turbulent weather and areas with thunder storms.

Although it is not easy to quantify, improvements in ATC and flight routing achieved especially through increased accuracy in the prediction of turbulence and other potentially dangerous weather phenomena also lead to increased flight safety as a core benefit to aviation industry.

2.2.3. Reduction in Emissions of Greenhouse Gases (GHGs).

AMDAR data helps improve the efficiency of airline operations and reduces fuel consumption and emissions through more efficient flight operations and routing. Increased wind and temperature forecast accuracy, as a result of the use of AMDAR data in forecast products, improves fuel burn prediction and hence contributes in optimizing the pre-flight fuel load. This, in turn, results in significant savings in fuel burn once the aircraft takes off.

The benefits from the use of updated, high-accuracy forecast products during flight are more difficult to assess. However, updated forecasts and weather observations (particularly en route winds) achieved through AMDAR validation and correction during the flight make it possible for pilots to optimise their flying parameters. This is particularly true for flights longer than 6 hours and for trans-oceanic or routes with limited traffic. It is estimated that a typical large airline participating in the AMDAR program potentially can realize fuel savings of up to $10M per annum.[10] This estimate is based on the calculation of additional fuel burn resulting from carrying unnecessary fuel due to wind forecast inaccuracies.

Reduction of fuel consumption through increased wind forecast accuracy by the use of AMDAR data has direct environmental implications besides the cost savings it generates to airlines. Environmental monitoring and impact minimisation programmes are likely to expand in the near future as a result of expected increases in incentives for airlines to participate. Airlines are also likely to be in a better position within the Emission Trading Scheme (ETS) markets when they are in a position to more effectively manage and reduce CO_2 emissions and contrail production with the increased utilisation of high frequency and high quality AMDAR data, as discussed further in section 2.2.5.

ICAO also emphasizes on three environmental goals:

- reducing GHGs emissions released by the air transport industry and avoiding contrail formations as the main non-CO_2 source of global warming caused by aircraft,
- improving local air quality, and
- reducing noise pollution.

A recent study simulated a climate-optimized routing strategy for all trans-Atlantic flights on five typical winter and three typical summer days. According to the findings of this study, even small changes in routing reduces the climate impact of aviation by 10% while increasing the operations costs by only 1%.[21] These findings show that the use of AMDAR data in aviation forecasting can make a significant contribution to reducing the carbon footprint of the aviation industry by means of more efficient climb, en route and descent operations. Besides the gains through efficient flight operations and the resulting reduction of aircraft emissions, AMDAR also contributes to reducing the global warming effect through its use in continuous descent approach (CDA) applications, as discussed in section 2.2.5.

Besides the CO_2 emissions from fuel use, aviation also contributes to climate change in other ways. Atmospheric ozone and methane concentrations and contrail formation are two such aspects of aviation from a climate change perspective. Non-CO_2 impacts of aviation depend significantly on the location and timing of emissions. Therefore, an air traffic routing system that avoids regions where emissions lead to the highest impact would reduce the climate impact of aviation. The AMDAR programme can be part of such collaboration for green aviation and mitigation of climate change effects on the global scale. This is particularly important as climate-friendly routing would reduce the impact of aviation without making costly changes to aircraft, their engines and airports.[22]

2.2.4. Reducing the Climate Impact of Contrails

The aviation industry contributes to global warming mainly though aircraft emissions and contrail formation. Contrails reflect outgoing long wave radiation toward the surface which, in turn, leads to warming of the troposphere. This warming is increasing in significance as the air transport system expands.[23] A combination of low temperatures and super saturation leads to contrail production. Contrails have the same effect as cirrus type cloud coverage. Through the use of AMDAR upper-air temperature, humidity and wind data, flight levels can be optimally assigned to minimize contrail formation.

---

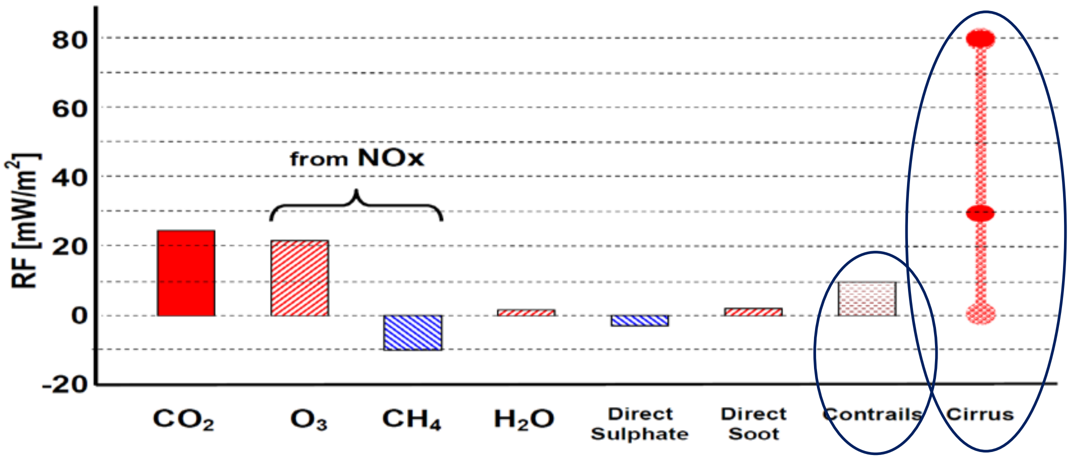
[21] Grewe et al. 2017. Feasibility of climate-optimized air traffic routing for trans-Atlantic flights, *Environmental Research Letters*, 12 034003.

[22] Airlines could reduce climate impact by 10% by making these small changes to flights:
March 2, 2017 accessed at https://phys.org/news/2017-03-airlines-climate-impact-small-flights.html

[23] The International Air Transport Association (IATA) forecasts that the number of air travellers will almost double by 2035 increasing from 3.8 billion air travellers in 2016 to 7.2 billion air travellers in 2035 according to the press release no. 59 issued on 18 October 2016 (http://www.iata.org/pressroom/pr/Pages/2016-10-18-02.aspx).

Figure 3 shows the various components of aircraft emissions contributing to radiative forcing. Aircraft emissions are the main source of climate impact by aviation, and contrails have the third highest impact in terms of radiative forcing.

Figure 3. Aircraft Radiative Forcing



Source: This graph is produced by Brooker (2008) based on an adaptation from Sausen et al (2005). The shadings indicate the reduced confidence in the estimate going from left to right. The 'blobbed' cirrus values are a 'mean' and an upper bound'.

A real case clearly illustrating the effects of contrails on temperatures is the cancellation of all flights across the U.S. for three days following the "9/11" attacks in 2001. An anomalous increase was recorded for the average diurnal temperature range (DTR) for the period 11–14 September 2001, which was partly attributed to the absence of contrails during this period of aircraft grounding in the U.S. This is because contrails reduce the DTR by reducing the transfer of both incoming solar and outgoing infrared (long wave) radiation.[24]

The production of contrails by aircraft influences climate by increasing the solar albedo (cooling) and trapping thermal infrared radiation (warming). A combination of low temperatures and super saturation in the upper troposphere causes the "favourable" condition for contrail production, which is then initiated by the engine exhaust forming ice crystals. As a result of the cooling effect being diminished at night, the radiative balance overall is a positive or warming impact leading to higher overnight minimum temperatures and a lower diurnal range.

Although there is currently no practical way of preventing contrails, there are possible ways of reducing their formation or avoiding them. In order to minimize contrail formation, air traffic controllers could be advised to re-assign flight levels through the use of AMDAR upper-air humidity and temperature data. Regions where ice-supersaturated regions (ISSRs) occur are conducive to contrail formation and they dissolve quickly in dry air. In ISSRs, where

[24] Travis et al. 2002. Contrails reduce daily temperature range, *Nature*, Volume 418, 8 August 2002.

there is sufficiently moist air, contrails form contrail cirrus by using ambient water vapour. Knowing the potential for contrail formation can aid flight planning operations in avoiding these areas. In this way, AMDAR can significantly contribute towards reducing the global warming effects of aviation.

A study has shown that flying below ISSRs was likely to give the best results for contrail reduction compared to flying around or above such regions.[25] An aircraft must cruise at about 6,000 feet below the ISSR to reduce contrail production. However, this can result in increased fuel burn by about 5%, underscoring the need to establish more sophisticated flight planning and management systems and tools (such as the production and installation of optimized and efficient engines) that are best able to optimally minimise environmental impacts.[26] Given the fact that AMDAR data are available in areas where aircraft operate and that these data have such a significant positive impact on products that are used for flight planning and management applications, it is obvious that AMDAR itself can play a significant role in reducing the impact of the air transport industry (ATI) on the environment.

Additionally and importantly, with a wider deployment of water vapour sensors within the Aircraft Based Observations Programme (ABOP), AMDAR humidity data can more effectively be used to determine, predict and avoid areas of ISSR through improved and advanced flight planning and management.[27]

2.2.5. Implementation of Continuous Descent Approach (CDA)

Continuous Descent Approach (CDA) applications are becoming important over time to reduce noise and GHG emissions. AMDAR wind data is crucial to the implementation of CDA applications. ICAO Document 9931, the 'Continuous Descent Operations Manual' defines CDA as "an aircraft operating technique aided by appropriate airspace and procedure design and appropriate ATC clearances enabling the execution of a flight profile optimized to the operating capability of the aircraft, with low engine thrust settings and, where possible, a low drag configuration, thereby reducing fuel burn and emissions during descent. The optimum vertical profile takes the form of a continuously descending path, with a minimum of level flight segments only as needed to decelerate and configure the aircraft or to establish on a landing guidance system (e.g. Instrument Landing System (ILS))."[28]

CDA holds significant potential to save fuel in the order of several hundred kilos of Kerosene (and related reduction of CO_2 emissions) and to reduce noise exposure for the communities

[25] Carlier, et al. 2005. *ATM Contrail Mitigation Options - Environmental Study*. Eurocontrol Experimental Centre Report SEE/2005/015.

[26] Brooker. 2009. Aviation and Climate Change, Air Traffic Management and Aviation: Non-CO2 Issues. *Air Traffic Technology International*, 26-30.

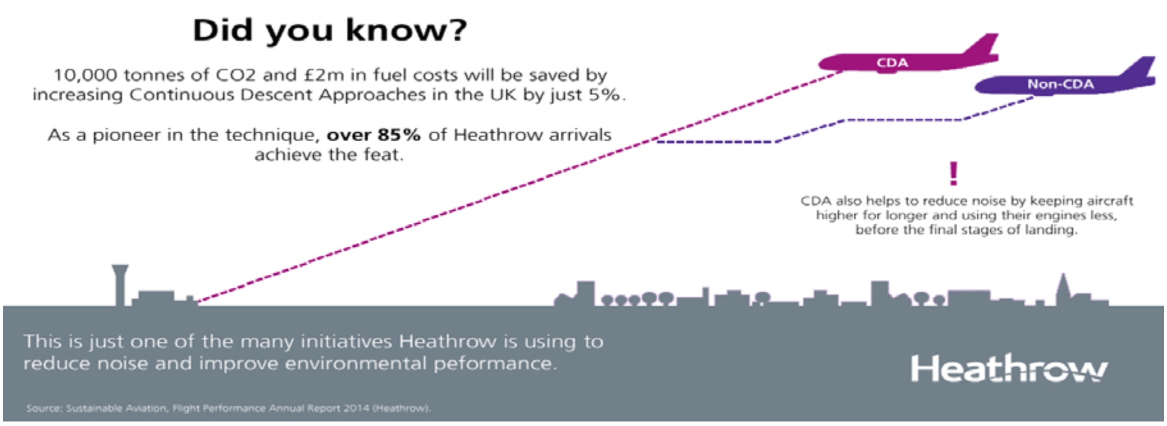
[27] COMET Module.

[28] Eurocontrol. 2011. *Continuous Descent: A guide to implementing Continuous Descent*, European Organisation for the Safety of Air Navigation.

under the approach paths.[29] CDA typically starts from an altitude of 6,000 feet. In order to implement CDA optimally, it is essential to obtain accurate and frequent information about shear and wind components above and below these levels. It is currently possible and practical to gather this required information only from aircraft data with high vertical resolution out to the top of descent. Light Imaging, Detection, And Ranging (LIDAR) winds, for example, will normally only be available along the final path in one direction to about 3000 ft. [29] Other data parameters necessary for CDA implementation include air temperature, atmospheric pressure and icing conditions.[30] AMDAR data can contribute significantly to the implementation and operation of CDA by providing these required data in support of both initial analyses, tests and operational systems. Specifically, AMDAR can be used both to improve the en route wind forecast and also provide the “real wind” conditions the aircraft will encounter during the last phase of the flight.[10]

Recent studies show that AMDAR wind data are increasingly being used in the CDA process. This helps to significantly reduce the noise over residential areas, and increase fuel efficiency. Figure 4 illustrates the benefits of CDA for Heathrow Airport, UK. Increasing CDA in the UK by just 5% leads to a saving of 10,000 tonnes of CO_2 and £2m in fuel costs per day, counted over the 650 daily landings.

Figure 4. CDA vs. Non-CDA Approaching System



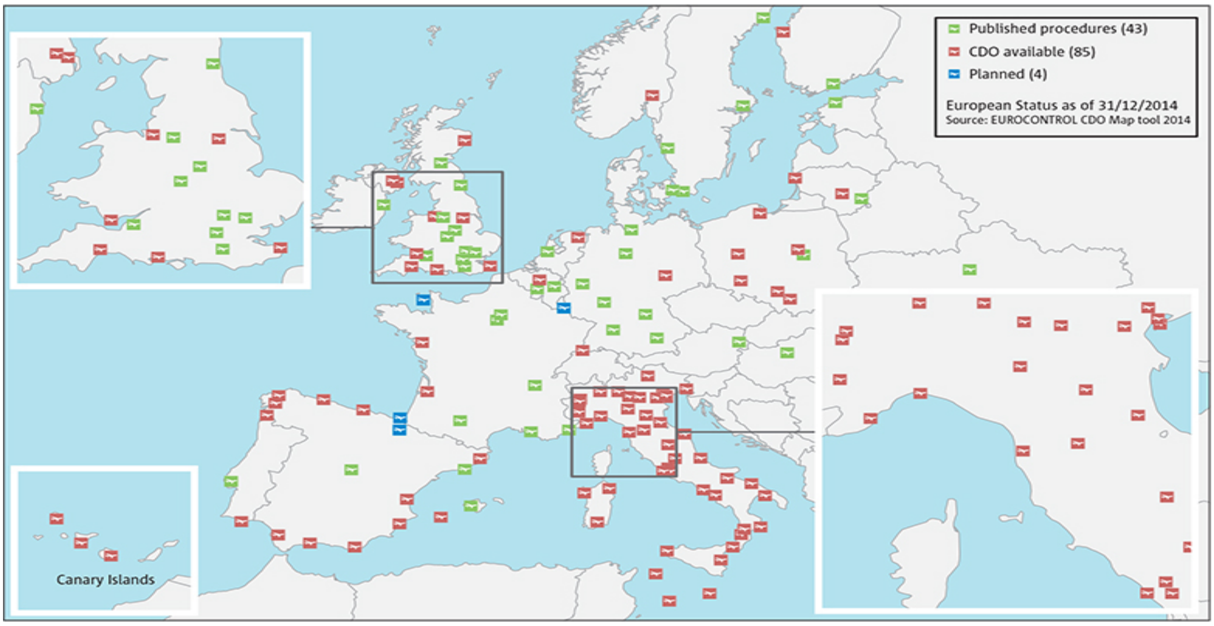
Source: Sustainable Aviation, Flight Performance Annual Report 2014 (Heathrow)[31]

According to a study done at Louisville International Airport in Kentucky, USA, 200 kg of fuel were saved on each landing and the noise was reduced by between 3.9 and 6.5 decibels when using CDA rather than by the traditional approach.[32] AMDAR wind data also are used for nowcasting wind verification in the implementation of CDA. Such a study was conducted

[29] Pumpel. 2016. Evolving Requirements for Accuracy and Reliability of MET information for ATM - In Particular Trajectory Based Operations. *WMO AMDAR Observing System Newsletter*, 11.
[30] Da Silva, “Continuous Descent Operations (CDO)”, Workshop on preparations for ANConf/12 − ASBU methodology, Nairobi, 13-17 August 2012.
[31] http://your.heathrow.com/quieter-arrivals-continue-as-fly-quiet-league-results-released/
[32] Clarke et al. 2004. Continuous Descent Approach - Design and Flight Test for Louisville International Airport, *Journal of Aircraft*. 41(5): 1054- 1066.

for Stockholm Arlanda Airport in Sweden.[33] Similarly, the Reduction Emissions Terminal Areas using Continuous Descent Approaches (RETACDA) project, implemented in Madrid, Spain, compared the CDA and No-CDA flights to determine the average fuel burn and found that, on average, CDA resulted in a 25% savings in fuel consumption during descent, and a 10% reduction during ascent.[34] CDA implementation is expanding over time and ICAO also has emphasized the use of CDA by airlines. Figure 5 illustrates the coverage at airports that have been planning and implementing CDA in Europe in 2017.

Figure 5. Coverage of CDA in Europe



Source: European Aviation Environmental Report, Figure 4.5

Airlines are being encouraged by ICAO to adopt CDA and it will be more widely accepted by additional airports in the near future. In many countries, CDA is being tested or in a pre-operational phase.

2.3. Climate Monitoring and Prediction

Climate monitoring and prediction applications require long term and continuous time series of meteorological observations. The availability of high-quality records of meteorological variables such as temperature, water vapour, wind and atmospheric pressure through much of the depth of the earth's atmosphere is crucial for such applications that attempt to measure, monitor and predict changes and long-term trends in these and other key climate variables.

Radiosonde observations are a very important source of upper-air data for climate change studies. Such studies require that any systematic errors of the observing system measurements be highly stable. However, early radiosonde measurements had large errors

[33] Gill et al., P2.18 Wind Nowcasting to Support Continuous Descent Approaches, accessed on: https://ams.confex.com/ams/pdfpapers/131776.pdf

[34] AIRE. 2009. Delivering green results - A summary of European AIRE project results in 2009.

that were very complex and difficult to correct (especially humidity and pressure data).[35] Moreover, the non-uniform application of radiosondes, due to their high cost, remains an issue, despite the technological improvements in their design. In this respect, AMDAR observations have the potential to provide an important source of upper-air data for climate scientists due to their relatively low degree of error. Table 3 shows the requirements for upper-air temperature observations for six application areas from the WMO Rolling Review of Requirements (RRR) database and the corresponding capabilities from two observing systems (radiosonde and AMDAR). Comparing the various requirements of the application areas with the observing system capabilities, it can be seen that AMDAR fulfils or exceeds most of the requirements at around the "breakthrough" threshold, also often better meeting these conditions than the radiosonde observing system.

Table 3. An Example for Requirements for Upper-air Temperature Observations (Lower Troposphere, LT)

Application Area/ Observing Systems	Horizontal Resolution	Vertical Resolution	Observation Cycle	Time Res. Availability	Uncertainty
Aeronautical Meteorology	50 km	0.15 km	60 min	60 min	2 K
	70 km	0.3 km	90 min	80 min	3 K
	100 km	0.6 km	3 h	2 h	5 K
Global NWP	15 km	0.3 km	60 min	6 min	0.5 K
	100 km	1 km	6 h	30 min	1 K
	500 km	3 km	24 h	6 h	3 K
High Res NWP	0.5 km	0.1 km	15 min	15 min	0.5 K
	2 km	0.25 km	60 min	30 min	1 K
	10 km	1 km	6 h	2 h	3 K
Nowcasting / VSRF	5 km	0.1 km	5 min	5 min	0.5 K
	10 km	0.3 km	10 min	10 min	1 K
	50 km	1 km	60 min	60 min	3 K
Climate	100 km	0.1 km	3 h	3 h	0.5 K
	200 km	0.2 km	4 h	6 h	1 K
	500 km	0.5 km	6 h	12 h	2 K
Synoptic Meterology	20 km	0,1 km	3 h	1 h	0,5 K
	50 km	2 km	6 h	1,5 h	1 K
	200 km	5 km	12 h	3 h	3 K
Radiosonde (RS41)	300 km	0.03km	12 to 24 h	1 h	0.5
AMDAR	200-500 km over land	0.1 km	3 hr ~~-~~, 1 hr~~,~~ and better	~~>~~< 5m for ascent, descent; <30m for en route	0.5-1.0 K

[35] Nash. 2015. Measurement of Upper-Air Pressure, Temperature and Humidity, Instruments and Observing Methods Report No. 121, Geneva: WMO.

Source: WMO Rolling Review of Requirements http://www.wmo.int/pages/prog/www/OSY/GOS-RRR.html
Note: The colouring of the values of requirements for Application Areas in the table correspond to the three levels of observing system capabilities that are specified. The threshold “goal” is marked blue, “breakthrough” green and “threshold” orange. The goal is the value beyond which it is expected that further improvement of the observation capability would not cause any significant improvement in performance for the application in question. The threshold is the value that has to be met to ensure that data are useful. The breakthrough is an intermediate level between threshold and goal which, if achieved, would be expected to result in a significant improvement for the targeted application.

As is the case for meteorological forecasting, AMDAR data provide a number of advantages over traditional sources of meteorological data for climate studies. Radiosonde measurements provide relatively low spatial and temporal coverage with an average 400 km separation over land areas and a cycle of 12 hours or more. Moreover, radiosonde measurements are limited, even in Europe and the USA, due to resource and other constraints in many meteorological services and at some major airports. Satellite measurements have higher resolution horizontally in space and in time but capture the vertical structure of the atmosphere poorly. Satellite data generally also re limited in the lower troposphere and over land areas. There also are issues with the continuity and homogeneity of this data over time.[36] Changes in radiosonde instruments and observing methods make the comparison of upper-air temperature trends difficult. The provision of satellite data from consecutive satellite platforms with differing sensing systems, leads to time-varying biases and in-homogeneities in the satellite data record.

Aircraft-based observations help to fill these gaps globally by providing valuable high quality and higher resolution spatial and temporal coverage per unit cost.[37] AMDAR data also can be considered complementary to traditional upper-air data sources for climate monitoring and prediction studies, as it is the only source of *in situ* observations in some parts of the world.

Given that satellite remote sensing measurement require validation with ground based, observing systems, AMDAR temperature and humidity measurements can also be used for corroboration of satellite water vapour measurements, providing an additional source of reliable ground-based referencing.

Climate change and variability are highly sensitive to variations in water vapour distribution occurring at altitudes of 9-12 km (300 hPa – 200 hPa) - the nominal flight levels of most of today’s commercial aircraft. Measuring water vapour in the upper atmosphere is a difficult task for current sensor technologies used in radiosondes such as Humicap, thin-film capacitive humidity sensor. The availability of AMDAR water vapour observations (using WVSS-II) is becoming more widespread and, given its recent rapid expansion and its

[36] Seidel et al. 2009. Reference Upper-Air Observations for Climate: Rationale, Progress, and Plans, *Bulletin of the American Meteorological Society*, 90(3): 361–369.
[37] Fleming. 1996. The Use of Commercial Aircraft as Platforms for Environmental Measurements, *Bulletin of the American Meteorological Society*, 77(10): 2229-42.

potential to become a sustainable source of high-quality moisture data not readily accessible through other measurement methods, can be used for climate change studies. [38]

For some climate applications, remotely-sensed data cannot fully substitute for *in situ* observations, which often are either limited to radiosonde measurements or unavailable altogether. This is particularly true over ocean areas and sparsely-populated regions of the Southern Hemisphere. AMDAR data, therefore, are significant for both atmospheric and oceanographic applications in these areas. With approximately three decades of data now available, AMDAR provides a relatively long and continuous source of high quality upper-air data.[10] In May, 2017, the WMO Executive Council designated the NOAA's Meteorological Assimilation Data Ingest System (MADIS) as the Global Data Centre for Aircraft-Based Observations. In the future, this will ensure access to a single, centralised and quality-controlled archive of aircraft-based observations to support climate and other applications.

The use of AMDAR data in climate applications is a relatively new development compared to its use in meteorological forecasting and there are currently few climate studies that make use of these data. However, a recent study developed a diurnal climatology of the lower atmosphere in Southern California (for Los Angeles, San Diego, and Ontario) during the spring and the summer, using 14 years of AMDAR profiles between June 2001–2014.[39] The June 2001–14 climatology showed that the deepening of the boundary layer overnight was consistent with a cloud-topped boundary layer. The climatology also revealed that AMDAR is a source of excellent and detailed information when examining the lower atmosphere and can provide an unprecedented set of diurnal data globally even though the information is available only at major airports.

As described in detail in Section 2.2.4, it is likely that the expansion of AMDAR water vapour measurement can significantly help scientists analyse the formation of contrails produced by aircraft. The possible reduction of contrail production through future air traffic flight management practices assisted by AMDAR data, offers an additional significant benefit to both the ATI and the environment.

Current studies on seasonal and climate modelling and climate scenarios often use data from global centres such as Max Planck Institute for Meteorology (MPI-M), Geophysical Fluid Dynamics Laboratory (NOAA-GFDL), Hadley Centre Global Environment Model (HAdGEM), etc. As a long-term strategic goal, it would be useful to engage centres working on global climate models such as MPI, GFDL, HAdGEM and encourage the use of AMDAR data.

The archival of AMDAR data clearly offers a very important source of upper-air information that potentially can be more widely used for climate analyses and reanalyses. For instance, the NCEP Climate Forecast System (CFS) used 10 years (from 2000 to 2010) of AMDAR temperature, humidity and wind data as a source of upper air wind and upper air mass

[38] Boers & van der Meulen. 2011. *AMDAR and Climate*, KNMI, Netherlands.

[39] David A. Rahn, and Christopher J. Mitchell. 2016. Diurnal Climatology of the Boundary Layer in Southern California Using AMDAR Temperature and Wind Profiles, *Journal of Applied Meteorology and Climatology*, Vol. 56, No. 8, 2141–2153.

(uniform temperature and humidAIREPity) input data for the CFS reanalysis.[40] For use in additional climate applications, NCEP aims to perform comprehensive quality control on conventional sources of aircraft-based wind, temperature and, where applicable, moisture observations such as AIREPs, PIREPs, AMDAR, Tropospheric Airborne Meteorological Data Reporting (TAMDAR) and Meteorological Data Collection and Reporting System (MDCRS).[41]

It is clear that AMDAR data has the potential to make an increasing and significant contribution to research on climate change, which will contribute further benefits to the environment and society.

2.4. Air Quality Monitoring and Prediction

Air quality forecasting systems require accurate observations of temperature and wind at high frequency and resolution to adequately analyse and predict atmospheric dispersion of gases and particles. Also critical in such models is the monitoring and prediction of low-level atmospheric stability and the identification of temperature inversions which significantly impact air quality forecasts.

Accurate characterisation of the planetary boundary layer (PBL) is a key component in monitoring and predicting the near-surface air pollutant concentrations. AMDAR can play a role in constructing 4D analyses of the height of the PBL. The height of the well-mixed PBL governs the dispersion of pollutants and it is also a very important player in other meteorological processes, such convective initiation. It is not feasible to forecast the height of the PBL with models and radiosondes are far too far apart to construct 3D maps. Satellites can't resolve the temperature inversion that is the top of the well mixed PBL. Low level temperature and wind information from AMDAR ascent and descent profiles can therefore be an important input to air quality monitoring and prediction systems and applications.

Meteorological parameters can be produced through observation, modelling or a combination of both, depending on the set of dispersion variables needed (such as transport, diffusion, stability, deposition, and plume rise). Table 4 shows the candidate meteorological observing systems for dispersion applications,[42] with aircraft-based observations used as input for transport, stability and plume rise.

---

[40] The atlas is available at http://cfs.ncep.noaa.gov/cfsr/atlas/ and http://cfs.ncep.noaa.gov/pub/raid0/CFSRR/1993/199307/inputm/EMC/obsdist/1993070212/

[41] http://www.emc.ncep.noaa.gov/mmb/data_processing/prepbufr.doc/document.htm

[42] Dabberdt, et al. 2004. Advances in meteorological instrumentation for air quality and emergency response, *Meteorology and Atmospheric Physics*, 87(1–3): 57–88.

Table 4. Candidate meteorological observing systems for dispersion applications

Dispersion Variables	Meteorological variables (not all required; algorithm dependent)	Candidate measurement systems
Transport	Three-dimensional fields of wind speed and wind direction	Profilers; Doppler weather radar; RAOBs; **Aircraft**; Tethersonde; Doppler Lidar
Diffusion	Turbulence; wind speed variance; wind direction variance; stability; lapse rate; mixing height; surface roughness	3D sonic anemometers; Cup & Vane anemometers; RAOBs; Profilers; RASS; Scanning Micro-Wave Radiometer, Tethersonde
Stability	Temperature gradient; heat flux; cloud cover; insolation or net radiation	Towers; Ceilometers; Profiler/RASS; RAOBs; **Aircraft**; Tethersonde; Net Radiometers; Pyranometers; Pyrgemeters
Deposition , wet	Precipitation rate; phase; size distribution	Weather radar (polarimetric); Cloud radar; Profilers
Deposition, dry	Turbulence; surface roughness	Turbulence
Plume rise	Wind speed; temperature profile; mixing height; stability	Profilers/RASS; RAOBs; Lidar; Ceilometer; Tethersonde; **Aircraft**

Source: Dabberdt et al. (2004).

RAOB: Radiosonde Observations, RASS: Radio Acoustic Sounding System

Information on the chemical state of the atmosphere gives valuable data for air quality applications. Another aircraft-based observing system, In-service Aircraft for a Global Observing System (IAGOS) provides *in situ* measurements of atmospheric chemicals such as O3, CO, CO_2, CH4, NOx, NOy, H2O, aerosols and cloud particles.[43] In this regard, AMDAR and IAGOS provide complementary information for the monitoring and prediction of air quality.

Air quality and health agencies increasingly use AMDAR temperature and wind data in their air pollution monitoring and forecasting applications. For example, the Australian Air Quality Forecasting System (AAQFS) uses AMDAR temperature data for comparison and validation.[44] These models utilize AMDAR soundings to determine mixing depth, height and strength of inversions, changes in temperature aloft and ventilation. The model output then is used for forecasting products such as health watches and high pollution advisories.[45]

NOAA's Air Resource Laboratory (ARL) is working towards allowing forecasters to enter AMDAR data into the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) dispersion model. AMDAR has proven to be a valuable input to predict the transport of hazardous airborne chemicals in such models. In this way, AMDAR can contribute to our understanding of air pollution, in particular in the vicinity of airports, and in the development of preventive actions to reduce emissions.

---

[43] http://www.esfri.eu/ri-world-news/iagos-using-commercial-aircraft-monitor-atmosphere and http://iagos.sedoo.fr/

[44] Copea, et al. 2004. The Australian Air Quality Forecasting System. Part I: Project Description and Early Outcomes, *Journal of Applied Meteorology*, 43(5): 649–662.

[45] Moninger et al. 2006. AMDAR Optimization Studies at the Earth System Research Laboratory/Global Systems Division. 10th Symposium on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface (IOAS-AOLS), Atlanta, GA.

In the future, AMDAR data can be expected to be more widely incorporated worldwide into governmental air quality forecasting systems, thereby assisting in the establishment and monitoring of environmental protection regulations.

2.5. Agricultural Studies and Applications

Accurate climate and weather observations are critical to the efficient use of natural resources for sustainable agriculture. Early warning of extreme weather or natural disasters is important for agriculture to reduce crop losses and for better forecasts which assist in more efficient planning for agricultural management. Climate change also poses threats to agriculture and food security by increasing the likelihood of hazardous weather events. Therefore, high quality climate data is needed to assist in developing projections revealing opportunities and threats that may emerge from climate change. In this regard, AMDAR data can be used by NMHSs to support the agricultural sector through their use in medium to long-term forecast models, especially in areas where there is limited or no other meteorological data available for both early warning and long-term climate projections.

The WMO reports that agricultural productivity has increased by 20% through the use of weather information.[46] Improved planning of agricultural production and resulting productivity gains from the use of AMDAR data in agriculture and climate applications would bring indirect benefits to society. These include increased food security, early warning systems for flood and drought events as well as for anomalous season changes.

AMDAR data also can help improve seasonal forecasting which would benefit agricultural investments and lead to higher agricultural productivity. This is particularly important in countries where agriculture is the main sector of economic activity. It is difficult to draw direct links between AMDAR data and its agricultural benefits due to less availability of AMDAR data over parts of the world where agriculture forms the main source of livelihood. However, as AMDAR helps to improve weather forecasts, it indirectly benefits agriculture.

Locust migration is an important case illustrating the role played by better weather information in reducing the adverse effects from such phenomenon. Meteorological parameters such as rainfall, temperature and winds directly influence the behaviour of desert locust and are crucial to understanding locus population dynamics, breeding and migration. The Food and Agriculture Organization of the United Nations (FAO) uses seasonal forecasts from the World Climate Service supplemented with sub-regional forecasts to predict rainfall and temperature anomalies. Trajectory models such as the NOAA HYSPLIT Model can be used to estimate adult and swarm movements, as locusts are passive fliers and drift with the wind.[47] In this regard, AMDAR, if its coverage is expanded, can become a key source of high-frequency wind data in those areas where traditional *in situ* observations (for example, radiosondes) are lacking. This would, in turn, lead to direct benefits for the local communities through early warning of locust migration.

---

[46] WMO. 2015. Supporting the AMDAR Programme – Business Case for Meteorological Services.
[47] WMO & FAO. 2016. *Weather and Desert Locusts*, WMO-No 1175. Geneva: WMO.

3. SUMMARY & CONCLUSIONS

AMDAR data currently provide many well-established benefits to the environment and society through its use in applications for meteorological forecasting, air traffic management, control and flight operations, climate, air quality, and agriculture. It also has great potential for expansion within these areas in the future.

AMDAR observations have many advantages over the traditional and remote-sensed sources of upper-air meteorological data. While radiosonde data provides *in situ* upper air observations, their spatial and temporal coverage is poor. Satellite data provide remotely-sensed, lower quality observations at *in situ* levels globally. AMDAR data fills those gaps in the traditional sources of meteorological data and plays a complementary role by providing high quality and high frequency *in situ* upper air observations. Moreover, aircraft-based observations have the highest impact per unit cost among all observing system categories.

Meteorological input to NWP systems is the most prevalent application for AMDAR data. Improving the quality and accuracy of weather forecasts/watches/warnings and assisting in forecast validation and model output verification also are crucial roles. Improvements in meteorological forecasting through the use of AMDAR data have direct benefits for aviation, health, agriculture and disaster risk reduction, as well as indirect benefits to the environment and society. The expansion of the horizontal and temporal coverage of AMDAR and the growth of water vapour measurement over time would potentially extend these benefits to a wider global population.

In air traffic management and control, better forecast products and services, improved by the use of AMDAR data, contribute to more efficient flight and terminal operations. As a result, airlines reduce fuel consumption and terminal operations are improved and made more efficient resulting in cost savings and other benefits to all parties, including airlines, airport operators and their customers. Besides such direct economic benefits for airlines, the use of AMDAR data in forecasting contributes to reducing emission of GHGs through its indirect contribution to optimal flight planning. Moreover, improved forecasting of severe weather phenomena such as turbulence, icing and convection leads to increased passenger safety.

The use of AMDAR data in aviation forecasting makes a significant contribution to reducing the carbon footprint of the aviation industry through more efficient air traffic operations, reduced fuel use and, therefore, reduced emissions. AMDAR also offers great potential to play a key role in the future reduction of contrail formation by aircraft, an application that likely would be further enhanced by the expansion of AMDAR humidity measurements. The wider availability of AMDAR humidity data also could potentially aid airline operations and has environmental benefits through applications such as icing warnings and fuel efficiency improvements.

AMDAR contributes to reducing the global warming effect through its use in CDA applications, which are expected to greatly expand over the coming years.

Several climate monitoring, prediction and reanalysis studies have clearly demonstrated the benefits and positive impact of AMDAR data use within the climate application areas. While its use within climate studies is relatively new compared to other sources of upper-air observations, AMDAR data already contribute to high quality upper air data records. They, therefore, have great potential to play a vital role within localised, regional and global climate monitoring and forecast applications as well as in future climate change studies. These applications also would benefit further from wider collection of AMDAR water vapour data. The commitment by WMO and NOAA to establish the WMO Global Data Centre for Aircraft-Based Observations in May 2017 was an important step towards more efficient and centralised availability of high-quality aircraft-based observations in support of climate and environmental applications.

The AMDAR observing system is an important source of data for air quality monitoring and prediction systems particularly contributing to the computation of key transport, stability and plume rise variables. Several air quality and health agencies make use of AMDAR data in their air pollution monitoring and forecasting applications. These include the AAQFS and the NOAA's ARL with its HYSPLIT dispersion model. This is another area of AMDAR data use that is expected to expand greatly in the future, ensuring that AMDAR data will make an even greater contribution to the provision of health and environmental benefits for society.

Agriculture is a sector in which the use of AMDAR data can provide real benefits through its use in early warning and long-term climate prediction systems as well as in seasonal forecasting. This will lead to better agricultural management and higher agricultural productivity. The expansion of AMDAR coverage in many currently data-sparse regions of the world clearly has great potential to contribute to the economies of the countries in those regions, in particular those that rely heavily on agriculture.

In conclusion, the use of AMDAR data in many different meteorological, climate and environmental applications extends many direct and indirect benefits to both the environment and society. Given its still not fully global coverage and potential for significant future expansion, AMDAR clearly offers even greater benefits to these areas. Considering that the AMDAR programme, until now, has grown chiefly over developed countries, there is an urgent need for expansion into developing regions. Cooperative means must be undertaken to ensure that AMDAR will reach its potential and deliver these benefits globally. This will necessitate initiatives such as regional infrastructure and cost-sharing as well as policies to assist in the cooperation of airlines and the support of NMHSs and relevant international organisations and authorities.

ABBREVIATIONS

AAQFS	Australian Air Quality Forecasting System
ABO	Aircraft Based Observations
ABOP	Aircraft Based Observations Programme
ACC	Area Control Centre
AIREP	Aircraft Report
AMDAR	Aircraft Meteorological Data Relay
ARL	Air Resource Laboratory
ATC	Air Traffic Control
ATI	Air Transport Industry
ATM	Air Traffic Management
CAEP	Committee on Aviation Environmental Protection
CDA	Continuous Descent Approach
CFS	Climate Forecast System
DEVG	Derived Equivalent Vertical Gust
DTR	Diurnal Temperature Range
EDR	Eddy Dissipation Rate
ETS	Emission Trading Scheme
FAO	Food and Agriculture Organization of the United Nations
FIC	Flight Information Centre
GDAS	Global Data Assimilation System
GDFL	Geophysical Fluid Dynamics Laboratory
GHG	Greenhouse Gas
GOS	Global Observing System
GTS	Global Telecommunications System
HAdGEM	Hadley Centre Global Environment Model
HYSPLIT	Hybrid Single Particle Lagrangian Integrated Trajectory
IAGOS	In-service Aircraft for a Global Observing System
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ILS	Instrument Landing System
IPCC	Intergovernmental Panel on Climate Change
ISSR	Ice-Supersaturated Region
LIDAR	Light Imaging, Detection, And Ranging
LT	Lower Troposphere
MADIS	Meteorological Assimilation Data Ingest System
MDCRS	Meteorological Data Collection and Reporting System
METAR	Meteorological Terminal Air Reports
MPI/M	Max Planck Institute for Meteorology
MWO	Meteorological Watch Offices
NCEP	National Centers for Environmental Prediction
NMHS	National Meteorological and Hydrological Services
NOAA	National Oceanic and Atmospheric Administration
NOAA/GFDL	Geophysical Fluid Dynamics Laboratory
NWP	Numerical Weather Prediction
PIREP	Pilot Report
PBL	Planetary boundary layer
RAOB	Radiosonde Observations,
RASS	Radio Acoustic Sounding System
RETACDA	Reduction Emissions Terminal Areas using Continuous Descent Approaches

RMSC	Regional Specialized Meteorological Centre
RRR	Rolling Review of Requirements
SIGMET	Significant Meteorological Information
SIGWX	Significant Weather
TAMDAR	Tropospheric Airborne Meteorological Data Reporting
TCAC	Tropical Cyclone Advisory Centres
UK	United Kingdom
USA	United States of America
VAAC	Volcanic Ash Advisory Centre
WAFC	World Area Forecast Centre
WAFS	World Area Forecast System
WIGOS	WMO Integrated Global Observing System
WMO	World Meteorological Organization
WVSS-II	Water Vapour Sensor System
WWWP	World Weather Watch Programme

For more information, please contact:

World Meteorological Organization

7 bis, avenue de la Paix – P.O. Box 2300 – CH 1211 Geneva 2 – Switzerland

Communication and Public Affairs Office

Tel.: +41 (0) 22 730 83 14/15 – Fax: +41 (0) 22 730 80 27

Email: cpa@wmo.int

public.wmo.int

JN 181496