WIGOS
WMO Integrated Global Observing System

AMDAR Benefits to the Air Transport Industry
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AMDA benefits to the Air Transport Industry
Abstract

This report describes and documents the benefits that the Air Transport Industry (ATI) gains from increased forecast accuracy achieved through the daily collection of atmospheric data gathered by approximately 4,000 inflight commercial aircraft. The report also outlines the Aircraft Meteorological Data Relay (AMDAR) observing system, the forecast process and describes the importance that AMDAR data plays in numerical weather prediction (NWP).

Measuring the benefits to the ATI requires first to describe and to quantify the improved weather forecast accuracies due solely to the assimilation of the AMDAR data into NWP and its availability to meteorologists. The effects and impacts of the resulting improved forecasts are categorized according to their characteristics (linear¹, threshold, etc.) and in relation with each operational activity performed by each ATI sector and function.

For the airlines, we can clearly quantify the benefits of more accurate wind forecasts especially on the fuel burn calculation and fuel load made prior to flight. The impacts during flights and for the other operational activities are more difficult to model. Statistical data for each operational decision derived from better forecast accuracy would be needed to make such assessments. These ‘relational’ statistics are less likely to be documented and much more complex to evaluate. Indeed complex weather phenomena (like convective storms, icing, fog, etc.) are the primary disruptive sources to ATI operations and their prediction certainly is improved with the availability of AMDAR data. However, we are able to leverage a modeling method which relates the Weather Impact Traffic Index (WITI) and the Forecast Accuracy Index (WITI-FA) to calculate an economic impact accounting for the significant role that AMDAR plays in increasing weather forecast accuracy. For other operational activities and aspects of the ATI, there is considerable and well-justified subjective evidence and testimony of the positive impact and value of AMDAR data.

The report therefore provides strong quantitative and ample qualitative evidence of significant benefits and costs savings to be gained from ATI support and participation in the WMO AMDAR Program.

¹ More information about the terminology in section 10
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<td>4DT</td>
<td>4 Dimensional Trajectories</td>
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<td>AMDAR</td>
<td>Aircraft Meteorological DAta Relay</td>
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<tr>
<td>ATI</td>
<td>Air Transport Industry</td>
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<tr>
<td>ATM</td>
<td>Air Traffic Management</td>
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<tr>
<td>CDA</td>
<td>Continuous Descent Approach</td>
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<tr>
<td>DEVG</td>
<td>Derived Equivalent Vertical Gust</td>
</tr>
<tr>
<td>ECMWF</td>
<td>European Centre for Medium-Range Weather Forecasts</td>
</tr>
<tr>
<td>EDR</td>
<td>Eddy Dissipation Rate</td>
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<tr>
<td>GFS</td>
<td>Global Forecast System</td>
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<tr>
<td>IATA</td>
<td>International Air Transport Association</td>
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<tr>
<td>ICAO</td>
<td>International Civil Aviation Organization</td>
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<tr>
<td>IMC</td>
<td>Instrument Meteorological Conditions (opposite of Visual MC)</td>
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<tr>
<td>ISA</td>
<td>International Standard Atmosphere</td>
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<tr>
<td>NextGen</td>
<td>Next Generation Air Transportation System (USA)</td>
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<tr>
<td>NOAA</td>
<td>National Oceanographic and Atmospheric Administration (USA)</td>
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<tr>
<td>NCEP</td>
<td>National Centers for Environmental Prediction</td>
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<tr>
<td>MDCRS</td>
<td>Meteorological Data Collection and Reporting System</td>
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<tr>
<td>NMHS</td>
<td>National Meteorological and Hydrological Service</td>
</tr>
<tr>
<td>NWP</td>
<td>Numerical Weather Prediction</td>
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<tr>
<td>OSE</td>
<td>Observing System Experiment</td>
</tr>
<tr>
<td>RAOB</td>
<td>RAwinsonde OBservation (RAdiosonde OBservation)</td>
</tr>
<tr>
<td>RIEHW</td>
<td>Route Integrated Equivalent Head Wind</td>
</tr>
<tr>
<td>RMS-RMSE</td>
<td>Root Mean Square – Root Mean Square Error</td>
</tr>
<tr>
<td>RUC/RAP</td>
<td>Rapid Update Cycle / Rapid Refresh</td>
</tr>
<tr>
<td>SESAR</td>
<td>Single European Sky ATM Research</td>
</tr>
<tr>
<td>SITA</td>
<td>Société Internationale de Télécommunications Aéronautiques</td>
</tr>
<tr>
<td>TAMDAR</td>
<td>Tropospheric Airborne Meteorological DAta Reporting (Panasonic Avionics Corporation)</td>
</tr>
<tr>
<td>WITI</td>
<td>Weather Impact Traffic Index</td>
</tr>
<tr>
<td>WITI-FA</td>
<td>Weather Impact Traffic Forecast Accuracy Index</td>
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<tr>
<td>WMO</td>
<td>World Meteorological Organization</td>
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<tr>
<td>WVSS-II</td>
<td>(Atmospheric) Water Vapor Sensing System, version two (SpectraSensors®, Inc.)</td>
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2. Executive Summary

Readers unfamiliar with the Aircraft Meteorological Data Relay (AMDar) Program may want to read first section 4 - Introduction to the AMDAR Program - before reading the executive summary.

This report documents the weather forecast accuracy gained through the addition of AMDAR data and the resulting economic benefits that the ATI derives from this improvement. It focuses more specifically on the airlines, airports and air traffic management sectors.

Collecting in situ atmospheric data remains critical in order to initialize numerical weather prediction (NWP) forecast systems as well as for other applications. The most economically efficient method of collecting high density in situ upper air meteorological observations with the highest impact per cost is by utilizing inflight commercial aircraft to observe winds, temperature, humidity and turbulence\(^2\).

In [Ref 3, Dr. R. Petersen] AMDAR data were shown to be the 3\(^{rd}\) most important data set in terms of their impact on the overall reduction of global NWP model error and resulting forecast improvement, which is consistent with other similar studies. The AMDAR data have the advantage of being collected seamlessly with a high spatial and frequency coverage- especially over oceans and in remote areas where radiosonde data are not readily available. AMDAR is the primary contributor to wind forecast error reduction (50\%) at cruising flight level and has the greatest impact on the accuracy increase for the 3 to 48 hours wind forecasts. This time frame corresponds well with the usual forecast windows used by the ATI for operational purposes (see sections 4 and 6).

For this report (see section 9), the weather forecast parameters are divided into 2 major categories: 1) the physical parameters, such as wind, temperature, pressure and humidity; and 2) the set of disruptive weather phenomena, such as turbulence, thunderstorm, icing, snow, fog and freezing rain. We have listed the type and magnitude of impacts that each weather parameter or phenomenon has on the various functions of the ATI. The impact can be direct, indirect, linear, threshold based or can have a combination of these characteristics. Of course, the realization of the benefits of increased weather forecast accuracy depends upon the operational practices in place in airlines and airports. Airlines can utilize weather forecasts by integrating them into their operational practices to minimize additional costs associated with detrimental or unfavorable weather conditions. Unlike aircraft which can sometimes avoid unfavorable weather conditions, airports can only amend their operational procedures to minimize the disruption caused by bad weather.

Wind forecast accuracy remains the core focus of this study, as it induces a clear and usually linear economic benefit to the airlines. Due to AMDAR data availability, meteorologists already are seeing an average reduction of wind forecast errors in the range of at least 2 knots\(^3\) (kts) (see Annexes 1 and 2). With full worldwide coverage and inclusion of moisture data, it is expected that AMDAR data will contribute to an even greater forecast error reduction and improved prediction of disruptive weather events like convective storms.

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\(^3\) Expressed as a Root Mean Square (RMS) value
Section 12, covers fuel consumption reduction due to the improved accuracy of wind and temperature forecasts because of the availability of AMDAR data. For an airline performing medium to long-haul flights we have calculated a fuel cost saving of $18,000 per aircraft assuming a fuel price of $0.5/kg. The reasoning is relatively simple and based on the fact that flight planning systems rely on wind and temperature forecasts to calculate the optimum route. If the wind forecast is inaccurate, it obliges the aircraft to carry additional fuel which, because of the added weight, causes a fuel consumption increase. The detailed calculation can be found in Annex 3.

However, the average wind error reduction may in fact hide another important aspect of AMDAR’s contribution to forecast accuracy, namely the reduction of extreme wind forecast errors. Airlines must always be prepared to cope with a worst-case scenario. There are numerous examples illustrating where AMDAR data contribute to reduced wind forecast errors of more than 10 to 20 knots. This is significant in terms of optimizing the amount of fuel carried as well as the impact on flight safety. Due to the lack of statistical data on the incidences of such forecast errors, the benefit cannot easily be quantified economically. This is described qualitatively later in section 13 and section 14.

Delays caused by bad weather cost the ATI billions of dollars annually. Of course, here we must make the distinction between costs that are avoidable from those that are unavoidable. In the case of avoidable costs, isolating that portion only attributable to the AMDAR contribution to reducing the weather forecast error is quite challenging and has not been attempted in this study. However, using a correlation analysis between the Weather Impact Traffic Index (WITI) and the Forecast Accuracy Index (WITA-FA), indicates a potential direct cost savings for airlines collectively of around $1B per year through realizable improvement to the accuracy of weather forecasts, thereby reducing the costs of flight delays. Given that the AMDAR program currently contributes at least 10% to the reduction of forecast errors in numerical weather prediction systems (see section 9) and that the program is estimated to be implemented to only 50% of its potential, further expansion and enhancement of the program would clearly be expected to deliver large cost savings to airlines and the wider ATI.

The introduction of Continuous Descent Approaches (CDA) and 4 Dimensional Trajectories (4DT) rely heavily on observed wind information in addition to local and short-term predictions. AMDAR datasets are of prime importance to enable these new operational practices promoted by the European SESAR and US NextGen4 initiatives. These procedures open the door for additional savings of up to hundreds of kilos of fuel per flight and can help saturated airports cope with increasing traffic. Because of the numerous interdependencies of parameters, the proportion of these savings that are directly attributable to AMDAR data could not be quantified for this report but they are likely to be substantial (see section 15).

In conclusion, the tangible cumulative benefits and cost savings to the ATI due to the use of AMDAR data in operational and weather forecasting, is substantial and potentially much greater than currently realized. These quantifiable savings and identified benefits are over and above the additional significant gains in safety, customer satisfaction and environmental protection and are far in excess of the relatively small cost of the AMDAR program’s initialization and operation. Further improvement and additional benefits to the ATI can be achieved through increasing the participation of more airlines, particularly those operating in

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4 https://www.faa.gov/nextgen/
currently data sparse regions of the Pacific, Africa, Asia, and Latin America including the South Atlantic.

3. Objectives and Scope of the Analysis

The benefits to the meteorological community of capturing and transmitting atmospheric data from an aircraft platform are known for many years and widely accepted. The impact and value of these data are well documented in NWP impact studies, articles in meteorological journals and operational case studies.

This report focuses on the benefits to the ATI that arise from these known improvements and impacts on forecast skill. Where possible, it quantifies specific benefits the ATI derives from the improved weather forecast accuracy stemming from the wider use of the data provided by commercial aircraft participating in the World Meteorological Organization’s Aircraft Meteorological DAta Relay (AMDAR) Program. The report complements [Ref 1] The Benefits of AMDAR Data to Meteorology and Aviation - World Meteorological Organization Integrated Global Observing System (WIGOS) - Technical Report 2014-01

This report should be of most interest and relevance to stakeholders and potential beneficiaries of AMDAR within the airline industry, especially those using and depending on meteorological information and forecasts.

In addition to describing and explaining the quantitative and qualitative benefits of AMDAR to ATI stakeholders, the report outlines the calculation methods used and clarifies the rationale for the assumptions used. Whenever possible, industry experts have been enlisted to validate the methodologies and modelling associated with the specific benefits that have been examined and documented herein.

The Executive Summary of the report provided the reader with an overview of the important benefits AMDAR brings to the ATI. The remainder of the report describes in detail the methods and analyses that underpins these results.

4. Introduction to the AMDAR Program

- at the request of the committee that commissioned this report some of this chapter is quoted from: "[Ref 1] The Benefits of AMDAR Data to Meteorology and Aviation - World Meteorological Organization Integrated Global Observing System (WIGOS) - Technical Report 2014-01

Aircraft Meteorological DAta Relay\(^5\) is a system designed for automated measurement and transmission of meteorological data from an aircraft platform according to meteorological specification\(^6\) and predominantly utilizing existing on-board sensors and avionics. A special AMDAR software module is installed in the appropriate aircraft avionics, which facilitates data acquisition, initial data quality checks and formatting. The observations are compiled into a

\(5\) More detailed information on the WMO AMDAR observing system is available from the WMO AMDAR website: http://www.wmo.int/pages/prog/www/GOS/ABO/AMDAR/

\(6\) WMO Specifications and standards for AMDAR are available at: http://www.wmo.int/pages/prog/www/GOS/ABO/AMDAR/resources/index_en.html
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standard message format (in accordance with the AEEC published ARINC 620 Datalink Ground
System Standard and Interface Specification) and transmitted to the partner NMHS in as near
to real-time as possible. More detailed information on the AMDAR observing system is
available from the WMO AMDAR website\(^7\).

The AMDAR observing system now is recognized by WMO as a critical component of the WMO
Global Observing System (GOS\(^8\)), supporting the World Weather Watch Program\(^9\).

4.1. Data Derivatives from an AMDAR Program

The AMDAR program provides the following parameters:

- High resolution\(^10\) vertical profiles during ascent and/or descent of air temperature,
wind speed and direction;
- Regular real-time reports (e.g., every 5-10 minutes) of meteorological variables
whilst the aircraft is en-route at cruise level;
- Accurate measurement of coordinates (time, latitude, longitude and pressure
altitude);
- Measurement and reporting of turbulence, if the aircraft is properly equipped:
  - DEVG (Derived Equivalent Vertical Gust); and/or,
  - EDR (Eddy Dissipation Rate: a meteorological turbulence parameter
  appropriate for direct assimilation into numerical weather prediction
  models); and
- Optionally, water vapor (or humidity) measurement may be included in AMDAR if
  the aircraft is appropriately equipped with a Water Vapor Sensing System.

4.2. Airline Participation in the AMDAR Program

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\(^7\) http://www.wmo.int/pages/prog/www/GOS/ABO/AMDAR/AMDAR_System.html
\(^8\) http://www.wmo.int/pages/prog/www/OSY/GOS.html
\(^9\) http://www.wmo.int/pages/prog/www/index_en.html
\(^10\) Vertical resolution of around 100 meters in the lower troposphere (to 700 hPa) and temporal resolution of up to
around 1 profile per hour depending on fleet size and configuration for reporting and AMDAR fleet traffic at individual
airports.
The World Meteorological Organization (WMO) global AMDAR Observing System builds on many national and international airlines11 working in partnership with a national meteorological and hydrological service (NMHS), national aviation authorities, or regional associations of these or similar agencies. As of February 2015, more than 650,000 AMDAR observations per day are being produced by 39 participating airlines. Participation in the program has increased markedly over the past decade as demonstrated in Figure 2, which shows the number of AMDAR reports per day being exchanged on the WMO Global Telecommunications System (GTS) since 2007. This shows initial acceptance from leading edge airlines to contribute to weather forecast improvement process.

Error! Reference source not found. provides an indication of the data coverage currently provided by the AMDAR observing system, but also demonstrates that the program has considerable potential for expansion over many currently data-sparse areas of the globe.

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11 See: http://www.wmo.int/pages/prog/www/GOS/ABO/AMDAR/AMDAR_Airlines.html
5. The Air Transport Industry Sectors

The primary sectors for which we will assess the qualitative or quantitative benefits are identified below.

5.1. Commercial Airlines

Commercial airlines primarily operate aircraft to transport passengers or freight. Analysis of delay and flight disruption information shows that weather is the most significant cause [Ref 6, A. Klein & S. Kavoussi - 8th ATM Research and Dev. Seminar 2009]. We exclude from this study private aviation, military and governmental fleets.

5.2. Airport Operators

Airport operations incorporate a multitude of functions. They operate the infrastructure that enables aircraft to take-off, land and park. Airports also coordinate the activities of a variety of stakeholders: e.g., airport traffic control, local meteorological offices, ground handlers (including airport baggage handling), checking agents, airline ground staff, security and border control. All these entities are affected by delays and disruptions that are attributable to weather. The optimum performance of their respective roles, duties and functions depends in part on the weather forecast. Many other functions such as modal transportation are not part of this specific study but nevertheless benefit indirectly from accurate weather forecasts.
5.3.  Air Traffic Management and Control

Air Traffic Management (ATM) regulates the traffic within an air space over the long term; while Air Traffic Control (ATC) focuses on controlling and amending air traffic routing dynamically based on current and projected traffic and atmospheric conditions.

5.4.  Aircraft and Engine Manufacturers

The benefits on aircraft and engine manufacturers are not included in this report as they profit indirectly from better weather forecast and operating conditions for their customers, namely the airlines.
6. Introduction to Meteorological Forecast

Weather forecasting is the application of science and technology to predict the state of the atmosphere for a given location. To the ATI the requirements for predicting the state of the atmosphere are much more complex than for most other industrial sectors. Indeed, airlines need to know the predicted weather conditions at various flying levels and along specific routes and usually over quite a short timeframe. In addition and like many other sectors, they must know the forecast in terms of temperature, wind speed and direction, visibility, precipitation and icing conditions at destination airports and within very precise timeframes.

The weather forecasting process can be simplified to 2 major steps: 1) collecting observations to assess the current state of the atmosphere and 2) using the knowledge of atmospheric processes to predict future weather patterns.

This knowledge and modeling capabilities of atmospheric processes have increased tremendously during the last decades mainly for 4 reasons: 1) the exponential increase in computing power; 2) improved coverage of observations; 3) improved accuracy of the observations and 4) improved knowledge of the physical processes at play – e.g. atmosphere-ocean-cryosphere couplings. Satellites and radars also play an increasing role in providing atmospheric data, especially with the improvement of telemetric measurements. Even with these advancements, timely collection of in situ atmospheric observations remains paramount. Figure 4 outlines the variety of measurement methods. The layman is familiar with radiosondes which are launched daily from hundreds of stations scattered across the five continents. For obvious reasons, very few of them travel over oceans which constitute the majority of the earth’s surface. Radiosondes have the advantage of gathering in situ data which are more accurate than data remotely observed from satellites. However, the infrastructure and operation of radiosondes are expensive and the data coverage is limited both in space and time. While coverage of temperature and wind observations has improved due to the increased availability of data from satellite vertical sounders over ocean areas, the amount and location of moisture data are still very inadequate. AMDAR offers an opportunity to improve upon this. These observations are complementary to those from terrestrial sites, which often are at airports, as well as oceanic weather buoys and ships. By their nature, these latter examples are limited to surface observations, although a small number of ships participate in an expensive program in which radiosondes are launched along their ocean routes.

In situ observational data remain critical to numerical weather prediction and other applications. While in situ data have large impacts on the error reduction of NWP assimilation and prediction outcomes, they also are critical to the validation, verification and continuous improvement process of these computer models. The most economical method of obtaining
high density in situ upper air meteorological observations is through the use of inflight commercial aircraft to collect wind, temperature, humidity and turbulence information (see [Ref 14, J.Eyre and R.Reid, 2014]).

7. The Use of Weather Forecast and the Notion of Increased Accuracy

Modern commercial airlines could not operate efficiently and, indeed, could barely exist, without accurate predicted weather information. Few passengers or crew would dare to embark on a non-stop 15-hour flight without a reliable weather forecast for the flight route. The focus of this study is to show how AMDAR data provide a measureable positive impact on the industry as a result of the subsequently improved quality and accuracy of weather forecasts. While the importance of weather forecasts is obvious to everyone, measuring the quantitative impact of the forecast improvement for particular applications is more complex.

The use of weather forecasts and the importance of their accuracy will vary across all the different ATI stakeholders. The flight operations department needs to know the temperature and the prevailing wind direction and speed at different flight levels for the flight duration along all possible routes. In addition to the winds, the cockpit crew will want to know the probability of disruptive phenomena like thunderstorms or snow at their expected arrival time at the destination and alternate airports. The probability and magnitude of en-route turbulence may influence the way the cabin crew will serve meals and therefore impact the comfort of the passengers. [Ref 6, A.Klein and S.Kavoussi] describes many examples of predictive operational tasks based on weather forecasts. For example, a flight dispatcher, aware of the potential closure of the destination airport in 18 hours and possibly preventing the return of the aircraft, might simply cancel the outbound flight. This action would prevent having the aircraft grounded at a distant location for a long duration because the local weather conditions are not expected to improve in the next day or two.

The previous examples show that the concept of predictive accuracy is relevant to each physical atmospheric parameter and phenomenon and its importance and impact will depend on how the forecast is used in various ATI roles and functions. This study will focus on the weather forecast as it is applied to various functions within the ATI. It also will endeavor to measure and assess the importance and impact of forecast accuracy and improvement for each function. When possible, both quantitative and qualitative benefits derived from the forecast accuracy improvement will be identified and assessed.

8. Weather Forecast Improvement due to AMDAR

It is normal practice within meteorological services to measure the change in forecast accuracy when data input changes or when model updates occur. In order to gauge the benefits that AMDAR brings to the forecasts, meteorologists measure the difference between forecasts with and without the AMDAR data. The average difference between the forecasts with and without aircraft observations provides a quantitative measure of the forecast accuracy improvement resulting from AMDAR data inclusion. This type of data denial test is known as an Observing System Experiment (OSE).

All types of meteorological observations together contribute to the quality of a forecast but some have a greater impact on its accuracy. This depends on the physical parameters observed, their accuracy and the temporal and spatial resolution at which they are measured.
As shown in section 4.1, AMDAR observations, measured with high precision and accuracy, provide information about the most important atmospheric physical parameters. These include wind speed and direction, temperature, humidity and turbulence. Another significant advantage of AMDAR data is the dense temporal and spatial coverage as compared to other in situ observations.

The purpose of this report is to exploit the documented positive impacts that AMDAR data have on weather forecasts and to analyze the resulting benefits to the ATI. The reader will find extensive description of the impact of AMDAR data on the weather forecast skill in [Ref 1], [Ref 2], [Ref 3], [Ref 4] and [Ref 9].

Annex 2 provides the background discussion and evidence to support the assumption that AMDAR data contribute to an average wind RMS\textsuperscript{12} error reduction of approximately 2 knots. This information also underpins the fuel burn analysis included in the document. It is important to understand that this is a conservative assumption that has the potential to increase as more airlines participate and provide AMDAR data as well as humidity observations.

It is also important to distinguish between average improvement and the reduction of the frequency and magnitude of major forecast errors. The ATI has great interest in the reduction of large forecast errors because, for safety reasons, the industry must plan for the worst case scenario. This means that the costs associated with “false alarms” and over- or under-prediction can be significant. The impact of AMDAR data on the reduction of the frequency and magnitude of weather forecast accuracy errors remains an area for further investigation and it is therefore difficult to associate a reliable quantitative estimate of the value of this benefit. However, such benefits (see examples in section 14) are real and expected to be significant and it is recommended that a detailed quantitative analysis of this aspect should be undertaken in the future.

9. Weather Forecast Parameters

Table 1 lists the main weather parameters and phenomena, their influence on the ATI operations and if forecast improvement has been realized because of the availability of AMDAR data. The reader will note that AMDAR provides measurement of atmospheric pressure, temperature, wind (speed and direction) and has done so since its inception. Humidity and turbulence measurements, through the inclusion of the Water Vapor Sensing System (WVSS\textsuperscript{13}) and Eddy Dissipation Rate (EDR) applications respectively, are being progressively implemented, having commenced in some programs over the past several years. These 2 additional measured parameters are very important to further improve forecast accuracy, especially for phenomena such as thunderstorms, fog, icing and freezing rain, which are not measured directly by AMDAR. Some advanced US carriers are installing WVSS particularly for fog prediction at destinations where their aircraft are landing early in the morning, when the risk for fog is higher.

\textsuperscript{12} (see Annex 2 for the illustration of RMS)
\textsuperscript{13} http://www.spectrasensors.com/wvss/
### Physical Parameters & Phenomena

**Overview of:**

1. **the importance of collecting these parameters** (either collecting the data, or measuring the parameters) and observing the phenomena to improve weather forecast

2. **the impact of the forecast parameter on the Air Transport Industry**

3. **AM DAR data impact on the forecast improvement of these parameters and phenomena**

<table>
<thead>
<tr>
<th><strong>Air Pressure</strong></th>
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</thead>
<tbody>
<tr>
<td>1. Winds develop anywhere in the atmosphere where there is a pressure difference or gradient, hence the importance of measuring atmospheric pressure to determine the wind that the gradient will generate.</td>
</tr>
<tr>
<td>2. Air pressure is used for a different function by the airlines. For route planning, aircraft use atmospheric pressure as a proxy for determining altitude and as a vertical coordinate. Pressure and temperature are important parameters for maximum take-off weight calculations.</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Temperature</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Temperature and air pressure are critical to the “thickness” or density of the atmosphere and therefore are determinants in calculating flight level. Forecast wind accuracy is therefore also impacted by temperature accuracy. Finally, temperature is critical in determining atmospheric stability and is important in forecasting thunderstorms, clouds, freezing rain, etc.</td>
</tr>
<tr>
<td>2. Air temperature influences both engine and aircraft performance. Flight planning systems utilize temperature forecasts along the different possible routes to optimize aircraft performance.</td>
</tr>
<tr>
<td>3. <strong>AM DAR data denial tests show improvement to temperature forecast by up to 20% for flight levels 300 to 390. The absolute accuracy gained is of the order of 0.1 °K. Temperature information from AM DAR is also used for verification (and correction) of NWP products for the ATI.</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Wind</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Wind is essentially a by-product of pressure and temperature. The wind is measured in terms of speed and direction and the prediction error is quantified by root mean square error (RMSE).</td>
</tr>
<tr>
<td>2. Wind forecast accuracy is the primary concern for flight operations. It is a fundamental determinant for the amount of fuel an aircraft must carry to arrive at its destination. Inaccurate wind forecasts may lead to fuel burn waste or could force a re-routing because of fuel shortage. Wind is a critical parameter for runway operations.</td>
</tr>
<tr>
<td>3. <strong>AM DAR data contribute to reducing upper-level forecast error by up to 20%. Data denial tests have shown cases of forecast improvement of 10 knots or more. See Annexes 2 and 3.</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Humidity</strong></th>
</tr>
</thead>
</table>
| 1. Humidity is an important parameter in the forecasting of key weather phenomena for the ATI including:  
   a. Thunderstorms and related severe weather.  
   b. Precipitation and icing.  
   c. Cloud base and ceiling level.  
   d. Fog and visibility. |
| 2. Cloud formation and visibility have an indirect impact on to the ATI. Under certain temperature & pressure conditions, humidity can create dangerous icing conditions for aircraft (see below). The potential forecasting of thunderstorms development, the duration, the strength and the dissipation are important for flight planning, airport operations and flight safety. |

<table>
<thead>
<tr>
<th><strong>Icing</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Icing is a function of humidity, temperature and pressure, hence the importance to monitor these parameters.</td>
</tr>
<tr>
<td>2. Icing at ground level and on low altitude flights can present a clear danger. It is an extremely important parameter for aircraft operations. It can impact directly the safety of the aircraft and may trigger costly ground de-icing operations.</td>
</tr>
</tbody>
</table>
It could be misleading to consider the forecast accuracy gained separately for each parameter as they are all interdependent. For reference, we will note and assume that AMDAR data contribute around 10% to the overall weather forecast accuracy (see [Ref 1, WIGOS-Tech. Rep. 2014]) through a reduction in forecast error.

14 The inclusion of turbulence into the AMDAR dataset is very important to the NWP models as it helps in their validation and calibration.
10. The Functional Domains Affected in Each ATI Sector

The following summary and Table 2 p. 19 show the type and magnitude of impact that each weather parameter and phenomenon has on each of the various functions of the ATI.

- **direct impact:** The weather parameter or phenomenon has a straightforward influence on the functional domain in terms of forcing a change in operations, which also may affect costs, and the level of safety.

- **indirect impact:** The weather parameter or phenomenon affects some other functional domains directly, which indirectly forces a change in operations and which again also may impact costs of either domain and the level of safety. (See the importance of direct versus indirect impact in section 11)

Example: A thunderstorm forces an aircraft to deviate to an alternate airport:

- This creates a direct impact on the aircraft and everyone aboard. It impacts as well the safety the flight.
- It has an indirect impact on ground handlers and checking agents because the thunderstorm does not directly cause the disruption to them, but rather the aircraft is diverted to a different site. If the aircraft landed at its original destination, the ground personnel would not have been affected by the thunderstorm.

- **impact scale:** Table 2 captures the impact in four categories represented using the following signs; (Not measurable - , Small +, Medium ++, Significant +++).

- **impact type:** The impact must be distinguished as linear or threshold based.

  - Linear (Lin. in abbreviation) impacts are those that vary proportionally with the variation of the weather parameter or phenomenon: e.g., the wind strength influences proportionally the time of arrival and therefore the fuel burn.\(^\text{15}\)
  - Threshold based impacts (Thr. in abbreviation) occur only above a defined measured value of the weather parameter or phenomenon: e.g., light fog or mist does not prevent modern aircraft to land. However below a certain visibility, fog will trigger a delay if it reduces the runway throughput and, in a worst case, prevent aircraft from landing.
  - Some weather parameters or phenomena can create both linear and threshold based impacts: e.g., wind speed and direction can affect runway throughput and above certain criteria, cause runway closure.
  - The accumulation of several weather parameters and phenomena can cause a threshold effect while each individual component has little effect on its own: e.g., a bit of snow or fog or cross wind may not disturb landing operations while the combination of the three may have a disruptive effect.

\(^\text{15}\) As wind speed is usually small compared to jet aircraft speed, one can almost consider its impact on fuel burn to be linear
Table 2: Influence of Weather Parameters and Phenomena on the Air Transport Industry

<table>
<thead>
<tr>
<th>Parameters and Phenomena</th>
<th>Flight Planning</th>
<th>Flight Dispatch</th>
<th>Cockpit Crew</th>
<th>Cabin Crew</th>
<th>Ground Handler</th>
<th>Checking Agents</th>
<th>Airport Mgmt</th>
<th>Air Traffic Mgmt</th>
<th>Air Traffic Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind</td>
<td>Direct ++ Linear</td>
<td>Direct ++</td>
<td>Indirect -</td>
<td>Indirect -</td>
<td>Direct + Lin+Thr</td>
<td>Direct + Lin+Thr</td>
<td>Direct +</td>
<td>Direct +</td>
<td>Direct +</td>
</tr>
<tr>
<td>Temperature</td>
<td>Direct ++ Linear</td>
<td>Direct ++ Thr.</td>
<td>Indirect +</td>
<td>Direct ++ Thr.</td>
<td>Direct + Lin+Thr</td>
<td>Direct + Lin+Thr</td>
<td>Direct ++</td>
<td>Direct ++</td>
<td>Direct ++</td>
</tr>
<tr>
<td>Icing Conditions</td>
<td>Direct ++ Thr.</td>
<td>Direct ++ Thr.</td>
<td>Indirect +</td>
<td>Direct ++ Thr.</td>
<td>Direct + Lin+Thr</td>
<td>Direct + Lin+Thr</td>
<td>Direct ++</td>
<td>Direct ++</td>
<td>Direct ++</td>
</tr>
<tr>
<td>Turbulence - Wind Shear</td>
<td>Direct ++ Thr.</td>
<td>Direct ++ Thr.</td>
<td>Indirect +</td>
<td>Indirect +</td>
<td>Direct ++ Thr.</td>
<td>Direct ++ Thr.</td>
<td>Direct ++</td>
<td>Direct ++</td>
<td>Direct ++</td>
</tr>
<tr>
<td>Convective Areas - Thunderstorms</td>
<td>Direct ++ Lin+Thr</td>
<td>Direct ++ Lin+Thr</td>
<td>Indirect +</td>
<td>Indirect +</td>
<td>Direct ++ Lin+Thr</td>
<td>Direct ++ Lin+Thr</td>
<td>Direct ++</td>
<td>Direct ++</td>
<td>Direct ++</td>
</tr>
<tr>
<td>Fog</td>
<td>Direct ++ Lin+Thr</td>
<td>Direct ++ Lin+Thr</td>
<td>Indirect +</td>
<td>Indirect +</td>
<td>Direct ++ Lin+Thr</td>
<td>Direct ++ Lin+Thr</td>
<td>Direct ++</td>
<td>Direct ++</td>
<td>Direct ++</td>
</tr>
<tr>
<td>IMC&lt;sup&gt;16&lt;/sup&gt;</td>
<td>Direct ++ Lin+Thr</td>
<td>Direct ++ Lin+Thr</td>
<td>Indirect +</td>
<td>Indirect +</td>
<td>Direct ++ Lin+Thr</td>
<td>Direct ++ Lin+Thr</td>
<td>Direct ++</td>
<td>Direct ++</td>
<td>Direct ++</td>
</tr>
</tbody>
</table>

Color Legend Scheme

Green: Functions for which there is potential for cost optimization when the forecast skills improve for the associated weather parameters or phenomena:
Typically, the better the wind and temperature forecast, the better the flight planning system will optimize the flight parameters.

Orange: Functions which incur unavoidable costs except when a forecast gives good indication that the threshold will be exceeded for the associated weather parameters or phenomena:
Typically, when there is icing, turbulence, wind shear and cross winds (which may prevent a safe landing), thunderstorms, fog and low ceilings, most airlines will not amend operations except if defined thresholds are exceeded.

Grey: Functions whose operations are affected by the associated weather parameters or phenomena but without necessarily inducing additional cost. When additional costs do incur, they are unavoidable.
Typically, these weather parameters or phenomena will determine the way these functions perform their operations; but usually they do not create any means to optimize the economic impact. However, they can affect the stress level of the staff, the service delivered and in some cases safety.

White: Functions indirectly affected by the associated weather parameter or phenomenon.

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<sup>16</sup> Low ceiling, Visibility or Heavy rain
11. Importance of the Operational Practices already in Place

In addition to our study of the impact of improved weather forecasting, we also must consider the actual and potential operational reaction of each ATI function when the forecast accuracy improves. Not all the functions listed in Table 2 are able to plan and optimize their operations based on weather forecasts.

Usually when there is a **direct impact**, those responsible for the function make operational adjustments according to the weather forecast: e.g., flight planning and dispatch, airport traffic management. When an **indirect impact** occurs, the operators must interpret the potential consequence the weather will have on the function and stakeholders before amending operations accordingly. One could imagine the difficulty to amend operations because of the suspicion that the function might be affected by the weather. In addition, when the weather parameter or phenomenon has a threshold based impact, it is even more difficult to make operational decisions prior to encountering the actual weather: e.g., light snow may not impact airport procedures while one foot of snow will completely disrupt operations. A baggage handler having a service level agreement with an airline may not risk making staffing decisions before knowing if the customer (the airline) is affected by the weather forecast.

Nevertheless, the ATI is constantly searching for optimization and is utilizing weather forecasts in all of the relevant functions pertaining to the airlines, airport and air traffic management sectors. Furthermore, the use and the importance of weather forecasts are cascading down to more and more stakeholders associated with these sectors.

Overall, the increased benefit of accurate forecasts is occurring simply because more functions integrate these forecasts into their operations to avoid unnecessary costs and to render a better service. As a simple example, passengers can be informed in advance by SMS if an aircraft will not be on time. This then can trigger many levels of potential cost avoidance and will certainly reduce dissatisfaction from passenger inconveniences that cannot easily be assigned as an economic value.

In the following chapters, the monetary and some of the qualitative impacts are illustrated for each function category noted in Table 2.
12. Wind and Temperature Forecast Accuracy Impact on Flight Planning Function (prior to flight)

This section covers the blue frame shown to the left. See Table 2 p. 19 for impact details: [Direct, ++, Linear]

An increase in wind and temperature forecast accuracy has a direct and linear impact on fuel burn prediction and therefore the amount of fuel loaded on an aircraft. It is important to differentiate between avoidable fuel burn due to procedures taken before the flight versus the avoidable fuel burn due to procedures occurring during the flight (see section 13).

Avoided fuel burn as a result of increased wind forecast accuracy due to AMDAR data has been modeled and calculated. The principles are the following:

Fuel load is a calculated element which depends in part on wind forecast accuracy. Part of the extra fuel, or a fuel reserve\(^\text{17}\), is always carried to account for various outcomes such as inaccurately forecast winds. This fuel reserve itself causes extra fuel burn due to the added weight. The more precise the wind forecasts are, the less reserve fuel is required to be carried and the more the excess fuel burn can be reduced.

12.1. Impact of Wind Forecast Accuracy

For the purposes of this study, we have, for a major airline, simulated the annual cost savings resulting from a wind forecast improvement of 2 kts RMS due to the availability of AMDAR data and its use in numerical weather forecast systems to generate predicted wind fields. The computer simulation consisted of calculating the fuel burn differences when running flight plans with and without the statistical effect of the wind forecast error components on the aircraft. A detailed description and technical explanation of the simulation can be found in Annex 3.

The airline used in the simulation to demonstrate and calculate the benefits of AMDAR data, operates a middle-eastern hub with flights servicing destinations in Asia, Europe and the Americas. The fleet consists of 54 double deck aircraft (B747-400ER and A380), 152 large double aisle aircraft (B777-300ER and A340) and 21 double aisle aircraft (A330).

Figure 5 p. 22 represents the potential savings derived from the improved wind forecasts, solely due to the availability of AMDAR data. It translates to:

- fuel burn reduction of approximately 8,400 tons (T) [+/- 25%]. This leads to a 26,500T reduction in CO\(_2\) emission.
- a saving of $4.2M or around $18,000 per aircraft assuming a fuel price of $0.5/kg

\(^{17}\) The regulation imposes carriage of fuel reserves for events like holding time, deviation to an alternate airports, etc
With an average 2 kts wind forecast improvement, this particular airline saves 8,400T of fuel annually which, at an estimated price of $500 per ton (see Annex 5), yields a yearly saving of $4.2M [+/- 25%].

If more commercial aircraft were to participate in the AMDAR program and as a result produce a sufficiently dense spatial and temporal coverage, the additional collected data would further increase weather forecast accuracy resulting in even greater fuel burn savings. For example, a hypothetical wind error forecast reduction of 3 knots, the annual saving for the above airline and its fleet is estimated to be $6.3M [+/- 25%].

12.2. Impact of the Temperature and Pressure Forecast Accuracy

Aircraft performance curves typically are plotted with respect to the International Standard Atmospheric (ISA) temperature for a specific altitude and then corrected to account for observed deviations [Ref 7]. Temperature primarily influences the aircraft’s true airspeed. For example, Table 3 shows a 9 minutes flying time difference with respect to a +20 C and -10 C temperature.

<table>
<thead>
<tr>
<th>Altitude</th>
<th>ISA temperature</th>
<th>ISA+20°C</th>
<th>ISA-10°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>35,000 feet</td>
<td>2h27</td>
<td>2h21</td>
<td>2h30</td>
</tr>
</tbody>
</table>

Table 3: Trip Time for a Typical 1,000 nm Trip at Long Range Cruise [Ref 7]

In Figure 6 we have investigated this impact a bit further by calculating the fuel burn amount for an Airbus A380 flying from Hamburg (Germany) to Cape Town (South Africa) using first the ISA standard conditions and then the actual temperature and pressure forecast.
The difference in fuel burn is 757 kg for this 5,364 nautical mile (nm) long route. For this specific fuel burn calculation, we could not determine the magnitude of the temperature and pressure difference between the ISA and the forecast conditions. This example shows clearly the importance of both parameters for optimizing fuel consumption. Figure 11 and Figure 12 p.34 show the AMDAR impacts on pressure and temperature forecast accuracy at flight cruising levels. The influence appears small. We recommend further investigation into the impact of a 0.1 K absolute forecast accuracy improvement on long flights.

13. Wind, Temperature and Pressure Forecast Accuracy Impact During Flight

Contrary to the flight planning phase which directly benefits from every marginal weather forecast improvement, the impacts once the flight is in process are more difficult to assess. Here, there is a mix of linear and threshold based impacts. Much of the weather an aircraft will encounter en-route is not avoidable and marginal forecast accuracy improvements once the flight has departed will generate limited savings except if that improvement crosses a threshold value that leads to an operational disruption.

However, it is standard practice for flights longer than 6 hours and for trans-oceanic or routes with limited traffic to consider alternate routes based on forecast and observed weather conditions, particularly en-route winds. The crew will request new wind information to be uplinked to the flight management system to calculate alternate routes. When the forecast has changed considerably from that of the original flight plan, an aircraft pilot can use the latest forecast to adjust and gain time along the route. Traffic control will be contacted to request a more favorable flight level to take advantage of winds, temperature and pressure. The flying time gained usually is measured in minutes. It is important to note that a saving of 1 minute of flying time translates into a savings of about 200 kg of fuel burn for a double deck aircraft. The impact that AMDAR data has on improving wind forecasts once the flight has started is certainly measurable and greatly leveraged by airlines flying intercontinental routes. There are many examples of flight saving hundreds of kg of fuel burn.

The reader will note that AMDAR benefit occurs as well when a nearby aircraft broadcasts actual winds and temperatures that can be used directly by other aircraft to improve the flying
conditions. These frequent in situ observations, that only AMDAR can provide, enable NWP to update the model and provide updated forecasts based on very recent observations.


At about 1200 UTC on 6 February 1998 the Miami Centre Weather Service Unit (CWSU) was notified that an airliner had encountered sustained, strong headwinds over the Atlantic that were not taken into account when the plane was fuelled in Italy. The pilot was concerned that they might suffer fuel exhaustion en-route. He needed an altitude that offered substantially smaller headwinds because he was approaching critical fuel. Fortunately recent information collected by AMDAR reporting aircraft showed a flight track over the Bahamas less than one hour old with headwinds 40 knots (21 m s\(^{-1}\)) less than the winds that the airliner was reporting. Controllers immediately assigned the airliner to that altitude and flight path and the aircraft was able to complete the flight without incident. The figure below shows wind reports from three aircraft over the Bahamas for 1500-1659 UTC that day (the aircraft with low fuel did not generate reports).

To the left is a map of MDCRS (US AMDAR) wind data over the Bahamas showing strong and lighter headwinds. (Memrosh et al., 2001)

The above situation resulted in a direct savings of almost 10% of the hourly fuel burn rate by taking advantage of the more favorable headwinds indicated by AMDAR data. Secondly, by avoiding a diversion to an alternate airport, more than $10K was saved. This additional saving would include the cost of descent, climbing, refueling, landing charges and compensation fees paid to passengers for missing their connecting flights, among others.

13.1. Use of AMDAR for CDA

AMDAR wind information is essential to enable Continuous Descent Approach (CDA). It helps increase the en-route wind forecast and provides almost the real wind conditions the aircraft will encounter during the last phase of the flight. Figure 7 below illustrates a services provider combining AMDAR data with a short term weather forecast to optimize the descent of the aircraft, thereby avoiding unnecessary thrust. Fuel savings can be around one hundred kg of fuel in some cases\(^{19}\). The portion attributable to AMDAR is difficult to estimate on an average basis.

14. Wind, Wind Shear, Icing, Convective Areas, Thunderstorm and Fog Impacts on Airlines, Airport and Ground Operations

As shown in Table 2, weather does induce costs, some of which can be avoided if the forecasts are sufficiently accurate and timely to allow stakeholders to adjust their operations accordingly.

For example, whenever there is a risk for weather disruptions at a destination, the aircraft crew will augment the fuel reserves to allow for possible holding or runway delays due to the adverse conditions. Over-forecast of these weather disruptions will cause significant **avoidable fuel burn**. Another instance occurs when a large aircraft has its fuel reserve increased by 4,000kg for a 30-minute hold at its destination because of potential thunderstorms. For a long flight, this 4,000kg additional weight will lead to a fuel burn increase of 1,600kg, or $800.

Another example: Ground level winds can significantly diminish airport capacity especially when a cross wind reduces runway throughput. These conditions affect those particular airports with closely-spaced parallel or crossing runways leading them to operate a suboptimal runway configuration. Thus, the ability to forecast accurately the wind direction and speed is critical to airport operations. For certain wind conditions, the airport will trigger a suite of operational measures to mitigate the impacts of the disruption. For instance, ground staff can be released or augmented as conditions warrant.
The following three sub-paragraphs show examples of a weather forecast being influenced by real time Water Vapor Sensing System (WVSS-II) data, (extracted from [Ref 12]).

14.1. Case 1: Confirmation of UPS Forecast Supports Continuation of Maximum Inbound Flow

On this occasion the UPS Meteorological Operations team forecast conditions at Louisville International Airport (SDF) to stay above minimums, in spite of various indicators that there was a reasonable risk of fog. This was based on a forecast of moisture decreasing with height in the boundary layer, which reduces the risk of dense fog. That forecast resulted in a decision to plan flight operations for arrivals into SDF using both runways. At that time, one runway was undergoing construction and had higher visibility minimums required for operations. Thus if fog were to occur and minimums were reduced for that runway, the planned arrival rate into SDF would not be possible. During the course of early arrivals, observed real-time data from WVSS-II verified that moisture was decreasing with height, validating the forecast made 12 hours earlier by UPS Met Ops. In spite of an otherwise apparent risk of fog, the observations supported the forecast and enabled flight operations to continue at the desired capacity. While flights had already begun to arrive, it would have been too late to change operational plans significantly at that point. If fog had developed, the second runway would be required to cease operation and inbound flow would have been decreased accordingly. Such a late change in plan would cause many aircraft already in the air to be slowed or go into a hold, awaiting clearance for arrival on the one available runway. This event provided a definite boost of confidence in the forecast made by the UPS meteorological staff, and enabled arrivals to continue at the planned flow rate without compromising safety concerns, rather than slowing the arrival flow.

14.2. Case 2: Warm Moist Air Observed Aloft Improves UPS Forecast of Rain to Snow Transition at SDF

On this occasion MDCRS data, including WVSS-II, observed by UPS Met Ops during evening arrivals into SDF indicated warmer and moister air aloft than the models had previously forecast. Based on that information, UPS Met Ops was able to move back their estimated time for the transition of rain to snow by one hour, impacting fewer departing aircraft that night. This improved information helped to increase preparedness and efficiency of the UPS aircraft de-icing operations and UPS pilots.

14.3. Case 3: UPS Benefits to De-Icing Operations at SDF on Nov 18, 2010

While many of the current benefits from WVSS-II are indirect, one small example of how data from WVSS-II was able to directly benefit UPS de-ice operations at SDF was recorded on Nov 18th, 2010. All the models and even the satellite imagery showed clearing conditions approaching SDF from the northwest, therefore the official forecast at SDF was for the low clouds to clear. This clearing led to a forecast of frost, which would require pre-treating all 80+ UPS aircraft with Type IV de-ice fluid. The clearing was expected to reach SDF during the end of the
UPS arrivals, and therefore every departure would be expected to have frost, and require de-icing.

During the arrivals, UPS Meteorological Operations noticed that the AMDAR reported winds at 3,000 ft were turning more to the west and then southwest, and the WVSS-II data showed moisture saturation at that layer. The meteorological model output had indicated this south-westerly turning of the wind would occur later in the night with dry conditions and clear skies prevailing during operations. The WVSS-II observations revealed the reality that the cloud layer was trapped below an inversion and surging in a few hours earlier than forecast, preventing the cloud clearing over SDF. The line of cloud clearing stalled about 30 nm north of SDF, rather than making it through SDF and stalling 30 miles south.

UPS Meteorological Operations noticed this difference from forecast conditions and made the call to the de-icing operations that they could suspend pre-treating the aircraft because it was not going to clear after all, and frost was therefore not expected. This avoided about 30 aircraft from being treated, even though much of the fleet had already been sprayed. This action directly saved UPS operations approximately $4,500 in cost of de-ice fluid, and allowed UPS staff to return to other critical functions, speeding up the UPS operation at SDF that night. While this event led to only a very minor saving, UPS Meteorological Operations will now be on the lookout for similar situations in order to maximize future benefits to operational efficiency at locations within the UPS network.

14.4. Weather Impact Traffic Forecast Accuracy Index

While there are many examples showing weather-related operational decisions being made, it is difficult to assess or quantify the resulting direct and indirect economic impacts and even more difficult to isolate that portion related to improved weather forecast accuracy.

To help solve this intrinsic difficulty, the Weather Impact Traffic Index (WITI) for en-route and airport surface weather is a valuable measurement tool to relate weather and traffic. Even more interesting is the Weather Impact Traffic Forecast Accuracy Index (WITI-FA) which analyses the impact of forecast accuracy on air traffic. Results for both over and under forecasting weather situations have been examined and their estimated economic impacts have been described by Alexander Klein and Sadegh Kavoussi, see [Ref 6].

From [Ref 6]:  "An over-forecast may, and often does, lead to excessive cancellations, ground delay programs and traffic reroutes that, in retrospect, wouldn’t have been necessary. An under-forecast may cause last-minute traffic flow management actions as the players scramble.”

Figure 8 shows delays that the ATI encounters and the accuracy of the forecast represented by the delta WITA-FA curve (in black). For both an over forecast or an under forecast, there is a direct link with the delays determined (see Aviation System Performance Metrics (ASPM) red curve below). For 35 airports located in the United States, the graph lists the weather disruption encountered.
The study uses an indirect method to assess the economic impact that improved weather forecasts can generate. The findings show a potential direct operating cost savings of approximately $260M in avoidable queuing delays and about $70M in avoidable cancellations. **These costs are calculated only for airlines and do not include the potential savings for airports and passengers.** Extending this method to the top 75 airports in the United States brings the avoidable cost to around $400M annually.

Extrapolating further the same model to Europe and the major routes to Asia, this number could easily triple reaching more than **$1B in annual avoidable cost.** This cost can be reduced as weather forecasts improve, and more fully realised when they are accurate enough to eliminate the avoidable delays and cancellations caused by errant or inaccurate forecasts.

If we consider the above estimate of $1B annual avoidable cost due to potential weather forecast improvement and the estimated 10% **AMDar contribution to weather forecast accuracy** [Ref 1, WIGOS-Tech. Rep. 2014], together with a knowledge that the AMDAR program is still only partially implemented at around 50% and is an extremely low-cost program to implement and operate, we can surmise that the additional benefits and impact of a fully implemented global AMDAR program, contributing to a reduction to airline costs related to weather disruption, would be considerable. The resulting shared cost saving to airlines, would come in addition to the fuel saving for each individual airline (documented in section 12 in this report).

With the addition of in situ water vapor observations and the resulting improved forecast model performance, the benefit to the aviation community will continue to increase. As the above case studies demonstrate, water vapor sensor deployment on AMDAR aircraft are critical to further improve forecasts of fog development and dissipation, icing, and thunderstorms, all of which are crucial to ATI operations and safety. This improvement is expected to yield significant benefits to aviation efficiency through better planning and
preparedness. It is therefore believed that the 10% AMDAR contribution estimate used above is very conservative and will increase in the future as a result of program expansion and enhancement through the wider measurement of water vapor and turbulence.

15. Weather Parameters and Phenomena Impacts on Air Traffic Management

As shown in Table 2 the impacts on Air Traffic Management are predominantly direct and mostly threshold based. The grey color code indicates that forecast accuracy does not affect the cost of the function itself, but it obviously will render a better service to the ATI (mainly the airlines and the airports) if the forecasts are accurate. Ultimately, airlines and airports will shoulder the economic impact of ATM services quality that depend on weather forecast accuracy.

An example of this occurs when ATM adjusts flying corridors and cruise levels to enable flights to benefit from tail winds and avoid head winds at jet-stream altitudes.

In Europe, ATM will not clear an aircraft for take-off if the forecast indicates that the runway throughput at the destination airport is limited because of cross winds or fog. The estimation of the costs arising from such decisions and the extent to which such costs can be reduced is linked to the accuracy of the forecast and the resulting additional lead time available to make related operational decisions. Such savings incurred by the European airlines for the above cases would be calculable by running a WITI-FA analysis for Europe.

16. The Value of AMDAR Data for the SESAR and NextGen Initiatives

So far we have discussed the use of AMDAR data to improve weather forecasts for the ATI. The data are assimilated into NWP models at varying frequencies. This results in forecasts being generated at intervals ranging from 4 times daily to almost continuous updates. Such short term weather forecasts are critical to support the decisions made by ATM as illustrated in the previously cited examples. The operational solutions aimed for in the NextGen (United States) and the Single European Sky ATM Research (SESAR) initiatives both rely on very accurate weather forecasting. The concepts are defined to optimize traffic throughput and augment efficiencies through, for example, 4D trajectory calculations, which imply real time wind information that AMDAR can readily provide.
17. Benefit of Turbulence Measurement

Increasingly more aircraft are implementing automatic turbulence reporting (Eddy Dissipation Rate)\(^{20}\) as a component of AMDAR. Information about turbulence is important for NWP as areas of turbulence indicate weather boundaries and the data enable fine tuning of NWP models. Turbulence information is used to inform aircraft flying in the same zone about conditions that may be encountered in the near future. This can be especially important in severe turbulence situations which can cause injuries to passengers and crew and sometimes even fatalities - fortunately, this is a rare event with on average less than 1 fatality reported per year. However, significant structural damage to the aircraft can happen during turbulence events, which not only may incur large costs to repair but also impact on the operational costs of the airline as a result of the aircraft being non-operational for a longer period of time. For significant turbulence events, or when flying in turbulent prone areas, airlines are obliged to perform a standard maintenance check on the aircraft to ascertain the structural fatigue or the extent of any damage. It is therefore clearly to the economic advantage of an airline for its aircraft to endeavor to avoid any significant turbulence events whenever possible.

18. AMDAR Data Impact on the Monitoring of Aircraft Sensors

Accurately measuring in-flight wind, temperature and pressure are important elements to help ensure the safety of the aircraft, its crew and passengers and also to ensure the reliable and efficient operation of the aircraft during flight. The on-board sensors taking these observations are examined regularly for accuracy and are calibrated during routine maintenance checks.

However, sensors can malfunction and this often is not quickly noticed or detected. An additional benefit of AMDAR data availability is the capability of the partner meteorological service to routinely and accurately check sensor performance by comparing measured and reported values with those from NWP systems and also with nearby AMDAR-equipped aircraft. Alerting of error or drift in sensor performance by the NMHS could potentially lead to significant cost savings associated with flight operation performance degradation. In section 12 we show an example of the importance of measuring the correct temperature in order to optimize flight levels.

19. Conclusions

With the current 650,000 daily AMDAR observations provided by 39 participating airlines, the ATI benefits from significant cost savings through improved weather forecast accuracy. AMDAR data facilitate 3 major sources of these savings:

1. The flight planning phase benefits from increased forecast accuracy which enables optimization of the fuel load prior to take-off and triggers significant fuel burn savings during the flight.
2. In the air, flight crews can optimize their flying parameters using updated forecasts and actual weather observations made available through AMDAR validation and correction.

3. Major savings may come from disruption cost avoidance made possible because operational decisions are being made based on more accurate weather forecasts. These cost reductions will increase in the future because most of these disruptions are a consequence of snow, freezing rain, fog and thunderstorms which all will be better forecasted with the progressive inclusion of water vapor measurements.

This report establishes that, through the availability and use of AMDAR data:

1. A potential, tangible fuel saving of $10M per annum is realizable for a typical large airline participating in the AMDAR program and actively taking advantage of the improvements to wind forecast accuracy.
2. A significant benefit and direct cost savings for all airlines globally through a contribution to the reduction in disruptions associated with and arising from improved weather forecasting accuracy.

In addition to these saving, we must still mention the safety increase stemming from improved forecast especially for prediction of turbulence and other potentially dangerous weather phenomena. As safety is mainly affected by the simultaneous combination of several unexpected events, some of them being weather related, we could not quantify, in the scope of this study, the safety increase due to forecast accuracy gained with the use of AMDAR data.

20. Recommendations

1. The contribution of AMDAR data to the augmentation in average wind forecast accuracy is well documented. **A future analysis of the reduction in the frequency and magnitude of wind, pressure and temperature related forecast errors in major events, resulting from the use of AMDAR data, should be pursued.** It would certainly demonstrate a measurable and potentially significant impact on aircraft safety and on fuel contingencies.

2. Sections 14.1, 14.2 and 14.3 list typical examples where a detailed analysis of actual AMDAR data and the existing forecasts are compared to determine if the detection of disruptive weather phenomenon like fog, snow, icing and thunderstorms minimized or prevented delays. In these cases, dedicated operational decisions could be taken and led to cost avoidance. These local and specific analyses are particularly useful to airports which regularly encounter disruptive weather events. **The industry could survey airports to learn which of them encounter frequent weather disruptions and, of those, which have a weak spatial and/or temporal AMDAR coverage.** It is believed that greater availability of AMDAR data for such airports could readily lead to direct benefits for the ATI, the airport operations and the relevant national NMHS or other meteorological service providers.

3. WMO should consider requesting and encouraging organizations such as International Air Transport Association (IATA) and International Civil Aviation Organization (ICAO) to **extend the Weather Impact Traffic Index analysis and the Forecast Accuracy Index to Asia and Europe** to help measure the impact that AMDAR data and improvements to forecast accuracy have on the ATI.

4. **Consider extending the simulation and calculation of fuel saving arising from wind forecast accuracy improvement due to AMDAR (see section 12.1) to the worldwide commercial fleet.** This will provide a quantified estimate of the
global value of the program to the ATI and, through the resulting overall reduction in fuel burn, to the global environment and climate issues.

5. The impact of temperature on flight performance and the role of AMDAR data in increasing the forecast accuracy remains a topic for continued investigation. AMDAR data denial tests have shown a forecast temperature accuracy gain of less than 1°C. *Further analysis of the effective temperature forecast accuracy improvement arising from AMDAR and its resulting impact on flight performance and ATI cost savings is needed.*

21. Acknowledgement

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Many phone interviews were conducted along with discussions during industry conferences with experts, including in particular, Prof. Ralph Petersen (University of Wisconsin), Dr. Herbert Püempel (WMO & AustroControl), as well as with several authorities from the Airport Council International and International Air Transport Association (IATA) and with airline captains.
Annex 1  Wind, Temperature and Pressure Forecast Improvement Analysis due to AMDAR

We have excerpted from [Ref 3, Dr. R. Petersen] some relevant figures and analysis that show the impact of the wind, temperature and pressure forecast accuracy resulting from AMDAR data denials tests. With the inclusion of AMDAR data, the tests yielded a 15% to 20% wind accuracy average improvement at typical flight levels. With 5 times more daily observations done (650,000 compared to 130,000 done 10 years ago), the impact on of the wind, temperature and pressure forecast has probably even further increased. In Annex 2, we will explain what this means in terms of wind accuracy gained in absolute knots.

Figure 9: Wind forecast value of AMDAR observations as compared to other data sources

Figure 10: RMSV wind errors improvement

a-(Left) - Vertically averaged and normalized difference in RMSV wind errors in RUC analyses and 12-, 9-, 6- and 3-hour forecasts of wind (blue), temperature (red) and relative humidity (yellow) valid at 0000 and 1200 UTC with and without aircraft ascent/descent data. 

b-(Right) - Normalized difference in RMSV wind errors in 3-hour RUC forecasts valid at 0000 and 1200 UTC with and without the inclusion of any aircraft observations (Right Panel, after Benjamin 2004).
Figure 11: Impact of AMDAR Temperature (upper-left in each panel) and Wind (lower-right) observations on 12, 24, 36 and 48 hour forecasts at 500, 300, 200 and 100 hPa in the Northern Hemisphere (left panel) and North America (right). Based on data provided by ECMWF Kelly (2004).

Figure 12: Improvement in Day-1 through Day-4 ECMWF Northern Hemisphere 500 hPa forecast skill due to AMDAR, RAOB and all satellite data. After results of 1996, 2000 and 2003 Data Denial Experiments from Kelly, 2007
Annex 2  Examination of the Absolute Wind Forecast RMS Error Reduction Due to the Use of AMDAR Data in NWP

In this annex we are providing a set of examples showing the magnitude of the RMS vector wind forecast error and will apply the relative forecast improvement due to AMDAR data illustrated in Annex 1 in order to determine the RMS wind forecast improvement.

The tables below from [Ref 8, SRS Ltd., 2010] compare long range (13-24 hour forecasts) and short range (0-4 hour forecasts) wind and temperature forecasts with the actual winds and temperatures observed using AMDAR data as the reference. In both tables, the results show a wind velocity error (RMS) of 18 and 14 knots and a wind direction error (RMS) of 42 and 24 degrees respectively. The study does not state if the forecasts were made using AMDAR data.

The above tables are from [Ref 8, SRS Ltd., 2010]

Extracted from [Ref 10, E. Robert & D. De Smedt, EUROCONTROL 2013]

"Studies have been conducted in the PHARE program showing that during winter, where the jet streams tend to be stronger in the northern hemisphere (around FL300-340), the Root Mean Square (RMS) wind vector error of aviation forecast data could exceed 20 kts in a 24 hour forecast, 15 kts in a 12 hour forecast and 10 kts in a zero hour forecast. Over Europe as a whole, where the average wind strength is weaker, the errors were found smaller, being 16 knots in a 24 hour forecast, 12 kts in a 12 hour forecast and 8 kts in a zero hour forecast."
Figure 13: Seasonal Variation of North Wind Forecast Errors at Phoenix Sky Harbor International Airport (PHX) (from [Ref 11])

Figure 14: Seasonal Variation of East Wind Forecast Errors at PHX (from [Ref 11])

Figure 13 and Figure 14 are extracted from [Ref 11, Optimal Synthesis Inc. & NASA Ames Research Center] and show other statistics on wind forecast error. Note that both tables indicate relatively low flight levels.

Other studies demonstrate that AMDAR data reduce the wind RMS error by 15% to 20% at typical flight cruising levels. Using the above tables and concepts, we can derive an absolute wind forecast error improvement of:

- 3.6 kts (18kts*20%) compared to the long range forecast (table 1 above)
- 2.8 kts (14kts*20%) compared to the short range forecast (table 2 above)
• 4.0 kts (20kts*20% using a 20 hour forecast) [see above extract [Ref 10]]
• 3.0 kts (15kts*20% using the 12 hour forecast) [see above extract [Ref 10]]
• 2.0 kts (10kts*20% using a 0 hour forecast) [see above extract [Ref 10]]

As a consequence of the above absolute forecast wind error reduction value, in this report, we are taking the lowest value, i.e. an average of 2 knots wind error (RMS) reduction due to the use of AMDAR.

The impacts derived from the assumption are likely to be conservative because it is an average and does not take into account larger error reductions which may lead to more significant cost savings associated with individual events and scenarios. The value is expected to increase in the future with the expected improvement in coverage of AMDAR and AMDAR water vapor measurement.
Annex 3  Model of the Impact of the Wind Forecasting RMS Error Reduction on the Aircraft Fuel Burn

The wind speed and direction influences the ground course and speed of an aircraft and as such affects flight duration. Figure 15 shows the influence of the head/tail wind (horizontal axis) on the time of flight (vertical axis). For example, a tail wind of 40 kts at a typical cruising speed of 400 kts/h will reduce the flying time by 10%. Passengers experience this on northern hemisphere flights from west to east versus east to west. The usual difference is about 1 hour flight time between the outbound versus the inbound routes on a segment such as New York – Paris.

Flight planning systems – using the latest weather forecast - will choose the best course by minimizing the Route Integrated Equivalent Head Wind (RIEHW) for a multitude of potential routes. Of course other parameters like temperatures at various flight levels and others constraints like non-flying zones, overflying charges etc, also must be considered.

If, for the chosen route, the RIEHW was underestimated, the aircraft will use more fuel than foreseen. The industry practice is to add 3% to 5% as a fuel reserve to cope with weather forecast uncertainties.

A plausible finding from Annex 2 shows that AMDAR data enables a reduction of the wind root mean square error (RMSE) by 2 knots at cruising altitude. Obviously the absolute value of the RMSE reduction simply can’t be applied to a positive or negative 2 kts RIEHW since the wind error can be of any direction. For reasons of simplicity we shall divide it into 2 cases:

Case 1: The RMSE is applied at angles of -90 to +90 degrees from the aircraft path.

We shall take the integral from -90 to +90 degree of the 2 knots RMSE. So an equivalent additional 1.27 knots of RIEHW.

In other words, the forecast improvement leads to better calculation of the RIEHW and to adjust it on an average by 1.27

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21 In addition different fuel reserves are taken for different events like: deviation to alternate airport(s), missed approaches, 30’ holding time, etc

\[
\frac{1}{\pi} \int_{0}^{\pi} \sin x \, dx
\]
kts. Without this increased accuracy of 1.27 kts of RIEHW the airlines would need to augment the default fuel reserve to maintain their safety standards and the statistical risk of deviation to alternate airports due to fuel shortages.23

As a result, case 1 demonstrates that the quantity of fuel reserve can be reduced when weather forecast accuracy increases.

Case 2: The RMSE is applied at angles of +90 to +270 degrees from the aircraft path.

The integration now gives a (negative) -1.27 RIEHW kts or tail wind error. When tail winds are under-estimated the aircraft arrives faster than foreseen at the destination thereby burning less fuel. Knowing that an aircraft, carrying “unnecessary weight”, burns needless fuel we shall, as in case 1, analyze the impact of the fuel burn on this “dead fuel weight” when the tail wind is under-estimated by 1.27 knots.

We can now calculate the additional fuel burn as a consequence of carrying an unnecessary additional amount of fuel (or dead payload), required when there is a 1.27 kts RIEHW forecast inaccuracy.

**Method to Quantify Wind Error on the Fuel Burn**

Aircraft fuel consumption is directly related to the weight carried by the aircraft. In addition, the longer the route, the more fuel needed which itself leads to more fuel burn. This is a well-known downward spiral effect. Following this same logic, the larger the wind forecast error, the more fuel that may be needed to account for the uncertainty. The added fuel load (caused by the wind forecast error) itself triggers excess fuel burn that can be evaluated using the 5 following steps:

1. The fuel burn is calculated for a set of aircraft types and route length with no wind component
2. The fuel burn is calculated for the same routes but with the aircraft facing a 1.27 kts RIEHW
3. The fuel burn difference between steps 1 and 2 is calculated and represents a "dead fuel weight" that an aircraft would need to carry if it were not to benefit from a wind forecast improvement of 2 kts RMS.
4. The fuel consumption as for step 1 (no wind component) is recalculated but with the extra “dead fuel weight” calculated from step 3
5. The fuel burn difference is calculated between step 4 and 1. This represents the impact of the benefit from a wind forecast improvement of 2 kts RMS.

Figure 16 summarizes the outcome of the simulation for 4 groups of aircraft types showing the additional fuel burn (vertical axis) with the flight length (in hours). The graph is plotted for a 2 kts RMS wind forecasted error that translates into a 1.27 kts component in the flight direction.

The reader will note that the calculation was made using several RMS wind forecasted error values and the impact on the fuel burn is linear for the values that are pertinent to the purpose of this analysis. As a consequence one can use the same impact model with other

23 The latter case is rare but statistically it would happen more frequently if larger forecast errors occurred while at the same time not increasing fuel reserves to compensate.
RMS wind forecasted errors values. For instance, Figure 16 can be used to find the impact of a 4 kts RMS wind forecast error improvement (instead of 2kts) by doubling the additional fuel burn value on the vertical axis.

**Figure 16: Additional xtra Fuel Burn due to a Wind forecast Error**

Before interpreting Figure 16, we must investigate the wind forecast RMS error evolution along the route lengths, route types and forecast lengths with the four questions below:

**Question 1: Should we care about the effect of wind forecast RMS error on short routes?**

Figure 16 indicates there is little noticeable impact (in the range of a few Kgs of fuel) on short routes flown by single aisle aircraft. However, it should not be ignored as most airlines utilize a single fuel upload for several short segments. For instance, as turnaround time for *Low Cost Airlines* is a key economic factor, fuel will be upload every 2 to 4 one-hour duration segments.

⇒ Conclusion: The additional fuel burn (vertical axis on Figure 16) for an aircraft flying 4 segments of 1 hour each, must be considered as a single 4 hours segment.

**Question 2: Can we apply the same wind forecast RMS error on short vs. long routes?**

Statistically, the longer the route, the more unlikely the wind forecast RMS error will influence the aircraft in the same direction along the flown path.

We can presume that within a synoptic scale weather system, considered as a short route, the wind RMS error will tend to vary little from point to point as the atmosphere is more or less a physical continuum over these distances. When crossing several weather systems, considered
a longer route, there should be a greater variation of the wind error direction, which may tend to compensate for each other and therefore may have a smaller overall effect on the aircraft route.

Yet aircraft often are constrained within flying zones and sometimes may need to reach some point within a certain timeframe. They must remain within a defined limit of waypoints which are uploaded into the Flight Management System. This constraint is called Assigned Spacing Goal (ASG). An aircraft deviating from its planned route because of stronger than expected cross winds, must have its course corrected to match the ASG. If, on the next waypoint segment, the flight incurs an opposite cross wind then it would again have to compensate its course in the opposite direction.

¬ Conclusion: Because of ATC requirements, long routes can be treated as a suite of medium routes segments for most commercial flights.

Question 3: Has the Wind forecast RMS error the same effect on different routes type (e.g.: short rotation between cities vs. long routes)?

One could believe that when an aircraft executes a quick turnaround between two cities, the RIEHW error component might be cancelled out and therefore has little impact. This is a specific case of situation 2 with a more severe constraint in terms of Assigned Spacing Goal in that the aircraft has less freedom. There is only one specific instance where wind forecast RMS error is aligned to the aircraft course. The error is either a pure head- or tail-wind error and has no influence on the additional fuel burn as the tailwind error will become a headwind error on the return flight. This case is quite rare as it assumes no wind forecast error changes between flight segments.

¬ Conclusion: The Wind forecast RMS error does not influence differently the aircraft flying different route types.

Question 4: Which forecast window is used for different flight types and is the amount of forecast improvement due to AMDAR data equivalent among the different forecasting windows?

As we calculate the additional fuel burn caused by the unnecessary fuel load related to the wind forecast error, we must understand the wind forecast quality at the time of the flight plan calculation. Indeed, the projected fuel burn is calculated by the flight plan well before the aircraft encounters the actual weather.

Figure 17 below gives an indication of the improvement of the wind forecast along the forecasting window. It clearly shows that AMDAR data have a greater influence (measured in marginal improvement) on short term forecasts when compared to those of longer time scales. There is an underlying logic here - as weather observations have a larger impact on 3 hours NWP forecasts as compared to 48 hours predictions. On the other hand we know that the forecast error increases in magnitude with the forecasting window.

24 This area needs to be further investigated to arrive at a better understanding of the statistical impact of the Wind RMS Error reduction with the length of the route-- and this needs to be applied to several regions of the world.
Figure 17: Impact of AMDAR Wind observations on 12-, 24-, 36- and 48-h ECMWF forecasts at 100, 200, 300, 500 hPa and for the 100-500 hPa layer average over the Northern Hemisphere (left) and Northern Atlantic (right), calculated as % error reduction using aircraft data.

So with these two opposite trends, we will, for the purpose of this study, apply a constant 2 kts wind forecast RMS error reduction for the timeframe between 3 and 24 hours.

To continue answering question 4, we will use Figure 18 below describing the forecast look-ahead time that a flight plan will use to determine the quantity of fuel to load prior take off.

Figure 18: GFS and Flight Cycle Comparison

The flight plan usually is made using inputs from the Global Forecast System (GFS) run by the U.S. National Oceanic and Atmospheric Administration’s National Centers for Environmental Prediction (NOAA/NCEP). This model is run every 6 hours. Consequently the flight operations department uses forecasts that are 3+0 to 3] hours old to compute the flight plans which usually are completed 1 hour prior fuel load. Typically, this occurs 1 hour prior to the aircraft push back on the apron. In the best cases, aircraft fuel weight is calculated for the first part of the flight with wind forecast that are 3+0 to 3] hours old while at the end of a 16 hours flight the fuel weight has been calculated using a forecast 19+0 to 3] hours latency.

As we have seen above, even if aircraft are flying short segments, from a weather forecast and fuel load perspective, they are managed operationally as if they are flying medium segments. In the case of re-fuelling every third 1-hour segments of a flight, given a 1-hour turn around, the last segment is flown using forecasts that are 7+0 to 3] hours old.
Conclusion: For the purpose of this analysis, Figure 17 and Figure 18 support the hypothesis of applying a constant 2 kts wind RMS forecast improvement for the different flight lengths.

Important note: The reader may object that cost and environmental conscious airlines will upload the cockpit with the most recent wind forecast while flying and therefore are less subject to wind forecast errors. This is an almost common practice for all flights above 6 hours duration. But it only has a positive impact on the fuel burn by optimizing the last segments of the routes and does not influence the fuel burn because of the "dead fuel weight" due to the wind error forecast.

**Interpretation & Conclusion of Figure 16 p. 40.**

As examples:

- For a flight from London (UK) to Singapore [~12h30], given a RMS wind forecast error of 2 knots, a Boeing 777-300 will burn an additional 155 kg of fuel while a Boeing 747-400ER will burn an additional 210 kg of fuel.
- For a flight from Hamburg (Germany) to Cape Town (South Africa) [11h27], an A380 will burn an additional 167 kg fuel for each RMS error of 2 knots.
- For a single aisle aircraft type (A320 and B738-800), the added fuel burn is approximately around 2 kg [+/− 50%] for a one hours segment. However, as per the above remark it relates to the effective fuel operation, the additional fuel burn is about 8 kg for three 1 hour flight segments.

The impact of the wind RMS forecast error reduction gained from the use of AMDAR data becomes more impressive for medium to long or extra-long routes. It is important to note that the number of extra-long flights connecting directly city pairs is growing as urban areas increase in population along with congestion at airport hubs. Examples of very long commercial flights: Johannesburg - Atlanta 16:55 hours/ Dubai - Los Angeles 16:35 hours / Doha – Houston 16:20 hours.

Remark:

- We have excluded narrow body aircraft (jet or turbo-propellers) from our analysis. Although they represent around 10% of the commercial airline fleet, they contribute a much smaller share of the total number of hours flown.

**Modelling the Impact of the Wind RMS Error Reduction for an Airline**

The curve shape on Figure 16 depicts the exponential additional fuel burn per segment length for each aircraft type. Using statistical analysis based on published airline schedules, we can calculate the number of segments flown with their respective length and apply the additional fuel burn calculation model.

Figure 19 captures the output of the model for a major airline using the Middle-East as a hub between the Orient and Occident. Note that we have applied the model on a 350 days per year basis to account for the various maintenance schedules which take the aircraft out of service.
Figure 19: Fuel Savings Resulting from an AMDAR related Wind Error Reduction for a Major Airline

Results interpretations:

1. Assuming a reduction of the wind forecast RMS error by 2 knots (due to AMDAR data inclusion) this airline saves 8,400T of fuel per year which, at a rounded price of $500 per ton, yields an annual saving of $4.2M [+/-25%]

2. If the wind forecast error reduction was to improve to an average of 3 knots - (a value that scientists believe is reasonable) – due to worldwide AMDAR data coverage by most aircraft, then the saving would increase by 50%, to reach 6.3M $ [+/-25%] per year. (See Figure 5)

3. Assumptions made in this model:
   a. Double deck aircraft include B747-400ER and A380
   b. Large double aisle aircraft include with B777-300ER and A340
   c. Double aisle aircraft include A330
   d. Segments length and daily number of flight hours are shown in the tables
   e. Number of aircraft in service as of November 2014 were determined through published data on the internet.
   f. 350 average annual flight days were used in this study to account for the required B, C, D maintenance checks when the aircraft are taken out of service.

The above model can be run for various worldwide airlines and can be extended for the worldwide commercial airlines using the statistics on the average number of segments flown per day and the average segment duration.
Annex 4  Wind Root Mean Square Error Illustration

The concept of root mean square error is illustrated in the figure below where 2 different wind forecasts are plotted. The forecast using AMDAR data is shown by the black arrow, while the forecast made without AMDAR data is shaded blue. The red vector depicts the effective wind observed.

The vector $\text{rms}_{\text{v improvement}}$ illustrates the difference in the wind error measurements.

Illustration of the comparison of 2 wind forecast errors and what an “improvement” means

Assumptions: wind forecast done for a given position, altitude and time:

$\text{Wind}_{\text{fcst (denial)}}$: Wind forecast without AMDAR data input

$\text{Wind}_{\text{fcst}}$: Wind forecast with AMDAR data input

$\text{Wind}_{\text{observed}}$: Wind observed

$\text{rms}_{v}$: Wind forecast error

$\text{rms}_{v_{\text{denial}}}$: Wind forecast denial error

$\text{rms}_{v_{\text{improvement}}}$: (rms $v$ - rms $v_{\text{improvement}}$)

$\text{rms}_{v_{\text{improvement}}} = \frac{|\text{rms}_{v} - |\text{rms}_{v_{\text{denial}}}|}{|\text{rms}_{v_{\text{denial}}}|}$
Calculating an economic impact requires using a fuel cost value. The graph shows the high volatility of fuel prices. However, the upward trend is clear and probably will be further accelerated as exploitation of petroleum reserves become more expensive.
Annex 6  Questions and Answers

Question: An aircraft uplinks the latest wind forecast and saves 200 kg of fuel because the flight management system recalculates the route using the updated information. Should this be considered an AMDAR benefit?

Answer: This is not an AMDAR benefit, but a benefit of using the most recent forecast to which AMDAR contributes. A portion - (which is difficult to quantify) - of this 200 kg fuel saving is attributable to AMDAR data.

Question: This report lists fuel saving derived for optimizing the absolute fuel upload by a couple of kg while the fuel uplift on the apron can only be done in multiples of 100 kg. Is such a precise measurement necessary?

Answer: While the fuel uplift is rounded to hundreds of kg on the apron, an optimization of 1 kg can trigger either the rounding down or up. Statistically any precision gained in the fuel calculation translates into the fuel uplift.

Question: This report lists savings derived from optimizing the absolute fuel upload while not accounting for the additional 1,000 kg of fuel that a B747 will burn while taxiing for 15 minutes. Also, a heavy hand on the throttle for a few seconds will trigger hundreds of kg of additional fuel burn. Does it make sense?

Answer: These points are true; but they are separate from the savings gained from accurate weather forecasts. The ATI is continually searching for every possible cost savings. We illustrate in this report cumulative cost savings in addition to intangible benefits such as safety and passenger comfort.
Annex 7  References


[Ref 2] Do automated meteorological data reports from commercial aircraft improve forecasts? Dr. Ralph A. Petersen - Cooperative Institute for Meteorological Satellite Studies University of Wisconsin - Madison - 2004


[Ref 9] Summary of Impact Tests of Automated Wind / Temperature Reports from Commercial Aircraft - Ralph A. Petersen- Cooperative Institute for Meteorological Satellite Studies, University of Wisconsin, - Geoffrey Manikin and Dennis Keyser- Environment Modeling Center, National Center for Environmental Prediction, Camp Springs

[Ref 10] Comparison of operational wind forecasts with recorded flight data Emilien Robert & David De Smedt Navigation and CNS Research Unit EUROCONTROL


[Ref 12] Studies of the effectiveness of the water vapor sensing system, WVSS-II, in supporting airline operations and improved air traffic capacity by Mr. Randy Baker - Senior Meteorologist, United Parcel Service, Louisville, KY; Mr. Rick Curtis -Chief Meteorologist, Southwest Airlines, Dallas, TX; Mr. David Helms - Observation Focal Point, U.S. National Weather Service, Silver Spring, MD; Mr. Al Homans Sr. Program Manager, ARINC GLOBALink Services, Annapolis, MD; Mr. Bryce L. Ford Vice-President of Atmospheric Programs, SpectraSensors, Inc., Bethesda, MD

[Ref 13] Automated Meteorological Reports From Commercial Aircraft: Improving Weather Forecasts And Aviation Safety And Efficiency, Ralph A. Petersen, and Lee Cronce / Performed under contract 1) to the World Meteorological Organization, 2) University of Wisconsin-Madison, 3) Cooperative Institute for Meteorological Satellite Studies (CIMSS)