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Quality assessment of Automatic Dependent Surveillance Contract (ADS-C) wind and temperature observation from commercial aircraft

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Abstract. Aircraft observations of wind and temperature are very important for upper air meteorology. In this article, the quality of the meteorological information of an Automatic Dependent Surveillance-Contract (ADS-C) message is assessed. The ADS-C messages broadcast by the aircraft are received at air traffic control centres for surveillance and airline control centres for general aircraft and dispatch management. A comparison is performed against a global numerical prediction (NWP) model and wind and temperature observations derived from Enhanced Surveillance (EHS) air-traffic control radar which interrogates all aircraft in selective mode (Mode-S EHS). Almost 16 000 ADS-C reports with meteorological information were compiled from the Royal Dutch Airlines (KLM) database. The length of the data set is 76 consecutive days and started on 1 January 2011. The wind and temperature observations are of good quality when compared to the global NWP forecast fields from the European Centre for Medium-Range Weather Forecasts (ECMWF). Comparison of ADS-C wind and temperature observations against Mode-S EHS derived observations in the vicinity of Amsterdam Airport Schiphol shows that the wind observations are of similar quality and the temperature observations of ADS-C are of better quality than those from Mode-S EHS. However, the current ADS-C data set has a lower vertical resolution than Mode-S EHS. High vertical resolution can be achieved by requesting more ADS-C when aircraft are ascending or descending, but could result in increased data communication costs.

1 Introduction

Aircraft related observations are widely used for numerical weather prediction (NWP). Aircraft Meteorological Data Relay (AMDAR) and Mode-S Enhanced Surveillance (EHS) have been shown to be beneficial when used for initializing an NWP model (Benjamin et al., 2010; de Haan and Stoffelen, 2012). AMDAR observations are generated especially for the meteorological community and are downlinked when the aircraft is in the vicinity of a ground station. Wind information is derived from the information in the flight management system, and temperature is measured by on-board equipment (Painting, 2003). Designated aircraft provide AMDAR observations created using software (and in some instance by hardware) which provides additional quality and enhancement of the observations (Painting, 2003). The meteorological messages are sent to the meteorological community through ground stations (e.g. located at aerodromes). An advantage of AMDAR is that the coverage includes data sparse areas such as over the oceans. However, intercontinental flights are using almost the same routes, leaving some areas unsampled. Moreover, these long-haul flights will provide observations at high flight levels only (approximately at 10 km altitude). Mode-S EHS wind observations are gathered by using the selective mode (Mode-S) of an enhanced surveillance air traffic control (ATC) radar (de Haan, 2011). All aircraft in view of the radar are interrogated individually very frequently (at Amsterdam Airport Schiphol every 4 s) and reply to the request by downlinking information from which wind and temperature information can be inferred. Using the ATC radar at Schiphol airport, de Haan (2011) showed that the wind information from this source has a quality comparable to AMDAR wind observations. The downlinked information consists of Automatic Dependent Surveillance Broadcast (ADS-B) messages. The ADS-B system was initially developed to prevent aircraft collisions by constantly broadcasting of the aircraft position. As such, ADS-B is FAA's satellite-based successor to radar positioning. ADS-B makes use of Global Navigation Satellite System technology to determine and share precise aircraft location information, and streams additional flight information to cockpits of other properly equipped aircraft. Additionally, more information on flight path can be requested by other aircraft or ATC radars.

In this paper a different type of surveillance technique is used to extract meteorological information from commercial aircraft. ADS-C (Automatic Dependence Surveillance Contract) differs from ADS-B in that it can only be initiated by registered users. Moreover, ADS-C is a surveillance technique in which aircraft automatically provide on request, via a data link, data derived from on-board navigation and position-fixing systems, including aircraft identification, four-dimensional position and additional data as appropriate. Specific ADS-C messages may contain meteorological information obtained from the Flight Management System (FMS), when asked for.

ADS-C messages are different from AMDAR and Mode-S but contain the same type of information. In case of Mode-S, the information can be identical to an ADS-C message, because Mode-S is related to ADS-B. ADS-B, ADS-C and AMDAR wind and temperature observations are based on direct read outs from the FMS, while AMDAR uses its own algorithms (Painting, 2003). Mode-S, on the other hand requires an additional calibration and correction step (De Haan, 2011). Figure 1 shows schematically the information flow of AMDAR, ADS-C and Mode-S.

In this paper, a set of ADS-C messages from Royal Dutch Airlines (KLM) aircraft has been extracted for a period of 76 consecutive days starting 1 January 2011. This data is global and is delivered generally with a very short latency (in the order of seconds) to the data server at KLM headquarters. ADS-C messages are used for air traffic control in areas without radar coverage (ocean, desert etc.). To assess the quality of the meteorological components of the ADS messages, the observations are compared to a global NWP model from the European Centre for Medium Range Weather Forecast (ECMWF) and to Mode-S observations in the vicinity of Amsterdam Airport Schiphol. Unfortunately, no KLM aircraft already delivering AMDAR reports were queried for ADS-C messages and thus an extra cross check possibility is not available.

This article is set up as follows. First a description is given of the data used. Next, the comparison between model and observations is presented. And finally, the conclusions are presented.

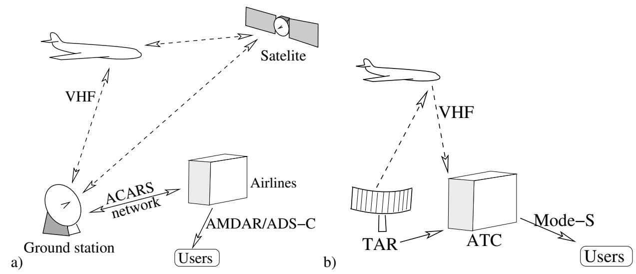

Fig. 1. Information flow for **(a)** ADS-C and AMDAR using ACARS network, and **(b)** Mode-S EHS observations only available in the vicinity of an Mode-S EHS tracking radar.

2 Data

Aircraft are equipped with sensors which measure the speed of the aircraft, its position and ambient temperature and pressure. Wind information can be derived from position and ground speed together with airspeed and heading. At present, a selection of these observations are transmitted to a ground station using the AMDAR (Aircraft Meteorological Data Relay) system for use in NWP and operational weather forecasting. An atmospheric profile can be generated when measurements are taken during take-off and landing. See Painting (2003); de Haan (2011) for more details.

2.1 Mode-S EHS

Recently, a new type of aircraft-related meteorological information has become available. The wind vector can be estimated by the difference between the motion of the aircraft relative to the ground and its motion relative to the air (defined by the airspeed and heading). Mode-S data used in this paper are collected using the tracking and ranging radar (TAR) at Amsterdam Schiphol (EHAM) airport. The radar performs a full scan every four seconds and covers an area of 270 km around the radar. The coverage is location dependent since Mode-S needs a direct line of sight which causes the lower bound for possible altitudes to rise with distance, due to the curvature of the earth. The recorded messages contain information generated by the flight computer including the transponder-id, flight level, Mach-number, roll, true airspeed and heading. The message is complemented with information on the position and ground track from the tracking radar. As said before, all aircraft are queried, resulting in about 1.5×10^6 raw Mode-S observations per day around Amsterdam Airport Schiphol.

Air temperature can be obtained from direct readings of the sensors on-board of the aircraft. However, Mode-S temperature is inferred from the reported Mach number, true air speed (V_t) and flight level, which is directly related to pressure (see de Haan, 2011). The vertical coordinate of aircraft observations is generally expressed in flight levels, which is a height related to a ICAO standard atmosphere (ICAO, 1993) at the observed pressure (expressed in 100 feet). For example FL100 is at pressure 696 hPa, FL200 at 465 hPa, FL300 at 300 hPa and FL400 at 187 hPa (approximately).

In de Haan (2011) it was shown that, when heading correction and calibration on Mode-S EHS observations are applied, good quality wind observations can be obtained. After applying the corrections and calibration, the wind observations from Mode-S are of nearly the same quality as the wind observations from AMDAR (typically RMS difference of 2 to 3.5 m s^{-1} with NWP reference winds, depending on height). The temperature observations are of worse quality as compared to AMDAR. All Mode-S observations used in this study are calibrated and corrected using the methods described in de Haan (2011).

2.2 ADS-C

The new type of data used in this study are Automatic Dependent Surveillance Contract(ADS-C)-messages. These messages are only generated by contract request. The contract request however may contain a query to report repeatedly at certain intervals. The basic ADS (Broadcast or Contract, ADS-B or ADS-C) data block is required from all ADS-equipped aircraft. This data block consists of aircraft identification, position, time and flight level. Additional ADS data blocks can be included as necessary. Table 1 shows the different data blocks of an ADS message.

In addition to the transmission of the ADS-C data block (a) and (b) for air traffic surveillance purposes, the Meteorological information data block may also be requested. The Meteorological information group (f) may be requested to satisfy conditions specified in ICAO (2010), Sect. 5.3.1, air traffic management applications, or airline monitoring systems, etc.

The ADS-C data contains a large number of parameters; here attention is paid to atmospheric parameters wind and temperature. This information is made available from the flight management computer. The temperature is measured directly but the wind speed and direction is inferred from the ground track and the speed (and direction) of the aircraft relative to air. In total 71 832 ADS-C messages were collected in the period from 1 January 2011 00:13 UTC to 17 March 2011 14:30 UTC. In total 15 995 ADS-C messages contained meteorological information and 5818 messages air vector information; 4934 messages contained both ADS-C types (d) and (f). Figure 2 shows the coverage of the data set used in this study. An example of a decoded ADS-C message containing meteorological information is shown in Table 2.

2.2.1 Direct wind observations from ADS-C

The ADS-C messages of the meteorology-group contain information on wind speed and direction and temperature (see Table 1, Report f). The vector difference between the ground track and the direction and speed relative to the air is the wind vector; the aircraft has to correct for the wind to fly along a desired ground track. In reverse, when the air vector $\boldsymbol{V}_{\mathrm{t}}$ and ground speed vector $\boldsymbol{V}_{\mathrm{g}}$ are known the wind vector $\boldsymbol{V}$ can be calculated:

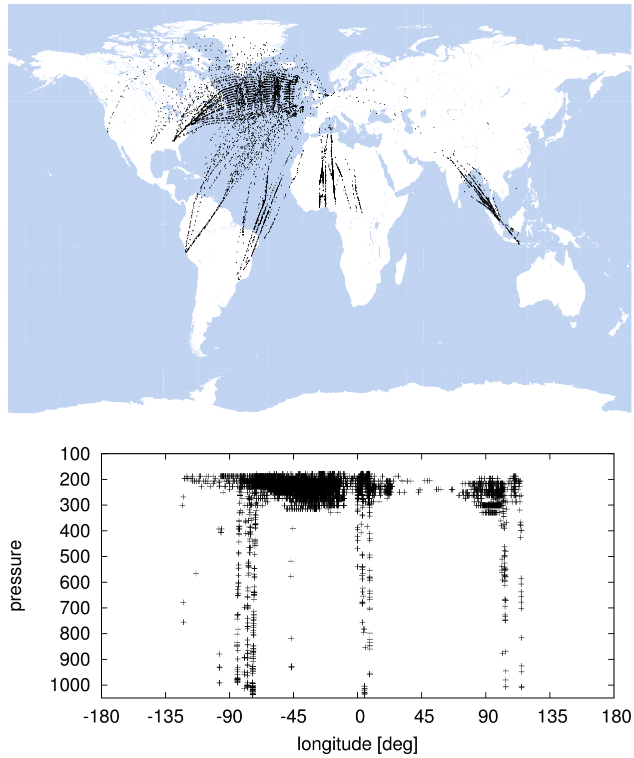

Fig. 2. Horizontal and vertical distribution of ADS-C messages.

$$\boldsymbol{V} = \boldsymbol{V}_{\mathrm{g}} - \boldsymbol{V}_{\mathrm{t}}. \quad (1)$$

The vector $\boldsymbol{V}$ is reported in the ADS-C meteorological information group. These wind observations will be called direct ADS-C wind observations, in the following.

2.2.2 Derived wind observations from ADS-C

There are also ADS-C message (of the type "Ground Vector" and "Air Vector", Table 1, Report c and d) which contain the ground track information, the heading and the Mach number but no direct atmospheric information. Wind information cannot be inferred directly because an estimate of the airspeed is missing. However, with additional temperature information, wind information can be obtained since the Mach number is the quotient of the airspeed and the speed of sound and the latter is dependent on the temperature through,

$$c_s = \sqrt{\frac{\gamma R T}{M}}, \quad (2)$$

where $\gamma = 1.4$, the adiabatic index, $R = 8.3145\,\mathrm{J\,mol^{-1}\,K^{-1}}$ molar gas constant, T temperature and $M = 0.0289645\,\mathrm{kg\,mol^{-1}}$ molar mass of dry air. $\boldsymbol{V}$ can be expressed as

Table 1. Contents of ADS-C, from ICAO (2007).

	ADS report	Contents
(a)	Aircraft identification	
(b)	Basic ADS-C	Latitude, Longitude, Altitude, Time, Figure of merit
(c)	Ground vector	Track, Ground speed, Rate of climb or descent
(d)	Air vector	Heading, Mach or Indicated Airspeed, Rate of climb or descent
(e)	Projected profile	Next way-point, Estimated altitude at next way-point, Estimated time at next way-point, (Next + 1) way-point Estimated altitude at (next + 1) way-point ...
(f)	Meteorological information	Wind speed, Wind direction, Temperature, Turbulence and Humidity (if available)
(g)	Short-term intent	Latitude at projected intent point, Longitude at projected intent point, Altitude at projected intent point, Time of projection
(h)	Extended projected profile	(in response to an interrogation from the ground system), Next way-point Estimated altitude at next way-point Estimated time at next way-point (Next + 1) way-point

Table 2. Example of an ADS-C message.

Message Type:	Periodic report
ADS-C Message:	072B7AC7467D8...
latitude	61.1430
longitude	−44.9054
altitude	35992.0
time stamp	20:53.999
Message Type:	Flight ID group
	KLMX
Message Type:	Meteorological group
wind speed	63.5
true wind direction	−89.296875
temperature	−55.25

$$\boldsymbol{V} = \boldsymbol{V}_{\mathrm{g}} - \mathrm{Mach} \cdot \sqrt{\frac{\gamma R T}{M}} \begin{pmatrix} \sin\phi_h \\ \cos\phi_h \end{pmatrix}, \quad (3)$$

where ϕ_h is the heading of the aircraft with respect to true north.

Errors due assumptions in T are

$$\Delta \boldsymbol{V}(\Delta T) = -\frac{\Delta T}{2T} \mathrm{Mach} \sqrt{\frac{\gamma R T}{M}} \begin{pmatrix} \sin\phi_h \\ \cos\phi_h \end{pmatrix}. \quad (4)$$

Suppose that the error in T is 1 K this will result in an error of less than 0.5 % in airspeed. Because of the linear relationship between wind and airspeed, this temperature related error is thus also small. The wind observations obtained using ground track vector, the air vector and additional temperature information from NWP are called derived ADS-C observations, in the following.

2.3 ECWMF NWP Data

The direct and derived ADS-C observations are compared to the operational global NWP model from ECMWF. Satellite, radiosonde and aircraft observations are the main input for upper air initialisation at analysis time. The resolution of ECMWF-model was reduced to 1 degree due to computational limitations, with 91 vertical levels. Because the operational model is started every 12 h, observations are compared to at least a 12 h forecast. ECMWF wind and temperature from the model are linearly interpolated bilinear in position and linear in time between two successive forecast. These forecasts are 3 h apart, with a maximum forecast length of 12 h.

3 Quality Evaluation of ADS-C observations by comparison with ECMWF and Mode-S

The quality of the ADS-C messages is compared to ECWMF model data and to Mode-S observations in the vicinity of the Amsterdam Schiphol airport. Because the time of observation differ for Mode-S and ADS-C, the positions of ADS-C and Mode-S will differ. A match between ADS-C and Mode-S is found when the distance between the observation locations is less than 20 km.

The ECMWF temperature is used to calculate the wind vector when the ADS-C report contains Mach and heading. The estimated ECMWF temperature error in the upper air is less than 1 K.

3.1 Temperature

Table 3 shows the statistics of the comparison of temperature of ECMWF and ADS-C and the statistics of the triple comparison of ADS-C, Mode-S and ECMWF. In total 15 995 direct ADS-C observations are used for the global comparison, while only 67 direct ADS-C observations were reported in

Table 3. Statistics of the comparison of temperature observations from ADS-C versus ECMWF for the whole set, and triple comparison for ADS-C observations, Mode-S and ECMWF in the vicinity of Amsterdam Schiphol airport.

	Temperature			
	Num	mean ECMWF	bias	stddev
ECWMF – ADS-C	15995	224.62	−0.44	0.93
ECMWF – ADS-C	67	243.99	−0.78	0.96
ECMWF – Mode-S	67	243.99	−0.71	1.78
ADS-C – Mode-S	67	243.99	0.06	1.49

the vicinity of Amsterdam Schiphol airport for triple comparison with Mode-S and ECMWF.

The global ADS-C temperature data set has a bias of around −0.5 K and a standard deviation of less than 1 K when compared to ECMWF. The mean ECMWF temperature is 224 K, indicating that the average observation height is around 200 hPa (see also Fig. 2). These statistics are similar to those found for AMDAR observations (Schwartz and Benjamin, 1995; Drüe et al., 2007, 2010; de Haan, 2011).

Nearly the same statistics are found when 67 ADS-C observations near Schiphol airport are compared to ECMWF. The Mode-S temperature observations are known to be more noisier due to the method of derivation of temperature from a Mach number (De Haan, 2011). Both ADS-C and Mode-S have a bias of around 0.7 K with ECMWF, while between each other almost no bias is present. This is most likely related to the fact that the observations, although derived differently, are based on the same measurements. Note that the mean ECMWF temperature is around 241 K, which is at approximately at 500 hPa. The ADS-C temperature observations are of good quality, comparable to AMDAR, and better then Mode-S temperatures.

3.2 Wind speed and direction

Wind observations from ADS-C can be obtained in two different ways. Either it is observed directly or it is derived from the track vector and air vector of the aircraft (with additional temperature information, see Sect. 2.2.2). The number of direct wind observations are 15 995 (the same number as for temperature observations), while the number of derived ADS-C wind observations is 5818. From these 5818, in total 4934 have also direct wind measurements. In total 67 direct ADS-C wind observations are in the vicinity of Schiphol airport from 13 ascending or descending aircraft; the number of derived ADS-C wind observations near Schiphol airport is 35 (7 profiles).

Wind speed biases from direct measurements are of the order of 0.5 m s^{-1} and standard deviation is around 2.8 m s^{-1} as presented in Table 4. Derived wind speed biases and standard deviations are of the same order, however, the data sets sample different parts of the globe and atmosphere as can be seen from the difference in mean ECMWF wind speed and wind direction for the data sets.

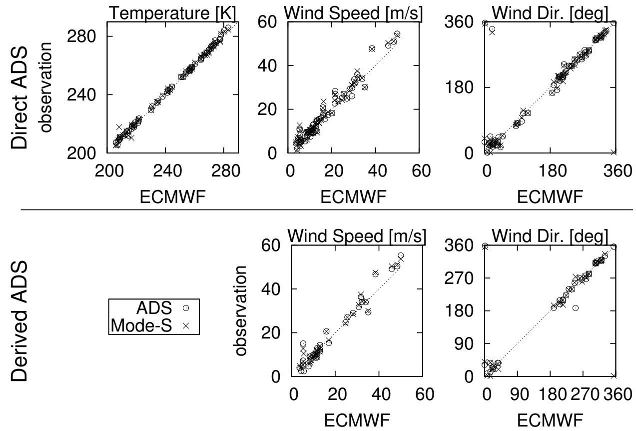

Fig. 3. Scatter plots showing ECMWF temperature and wind versus ADS-C (direct and derived) and Mode-S.

The wind direction statistics are calculated on a subset of the data sets by excluding observations for which the ECMWF wind speed was less than 4 m s^{-1}. For wind direction the direct measurement wind direction bias against ECMWF is small with a standard deviation of less than 10 degrees (Table 4). Note that the mean wind direction is south-west. The statistics for derived wind measurements also show a small mean difference with ECMWF. The standard deviation however, is 13 degrees which is larger than the standard deviation of the direct wind direction standard deviation. The mean ECMWF wind direction for the derived wind data set is north-west which differs by 30 degrees from the direct observation data set; the data sets sample different region and times.

The 67 direct ADS-C observations in the vicinity of Schiphol airport show nearly the same wind statistics as the global direct data set. Mode-S versus ECWMF has a similar bias and a slightly larger standard deviation for wind speed than ADS-C. Figure 3 (top row) shows the scatter plots of temperature and wind for direct ADS-C and Mode-S versus ECMWF. The statistics for the 35 data points show that the bias and standard deviation of the ADS-C and Mode-S wind speed observations compared to ECMWF are similar, with Mode-S having a slightly smaller standard deviation. The wind speed standard deviation of the difference

Table 4. Statistics of the comparison of wind observations from ADS-C versus ECMWF.

	Wind Speed				Wind Direction			
Comp	Num	mean	bias	stddev	Num	mean	bias	stddev
ECWMF-ADS-C(direct)	15995	25.45	−0.52	2.80	14072	−65.66	0.26	9.87
ECWMF-ADS-C(derived)	5818	19.61	−0.43	2.91	4618	−34.18	0.52	13.07
Direct ADS-C near Schiphol Airport (13 profiles)								
ECMWF-ADS-C(direct)	67	16.59	−0.69	2.52	67	−46.30	0.55	11.25
ECMWF-Mode-S	67	16.59	−0.78	2.66	67	−46.30	0.93	11.93
ADS-C(direct)-Mode-S	67	16.59	−0.08	1.67	67	−46.30	0.37	5.74
Derived ADS-C near Schiphol Airport (7 profiles)								
ECMWF-ADS-C(derived)	35	18.55	−0.61	3.08	32	−56.37	−1.97	8.09
ECMWF-Mode-S	35	18.55	−0.92	2.93	32	−56.37	−0.87	10.61
ADS-C(derived)-Mode-S	35	18.55	−0.31	1.58	32	−56.37	1.10	4.68

between ADS-C and Mode-S is around $1.6\,\mathrm{m\,s^{-1}}$, approximately half the standard deviation of observation versus model. The Mode-S and ADS-C observations are not exactly at the same position and therefore part of the error of the difference is related to difference in position. The statistics of the wind direction are similar. Mode-S versus ECMWF wind direction standard deviation is slightly larger that that of ADS-C versus ECMWF. The wind direction observations are close to each other indicated by the small standard deviation. The bottom row in Fig. 3 shows the scatter plots of wind speed and direction of the derived ADS-C and Mode-S observations versus ECMWF.

In total 4934 ADS-C observations reported both direct wind and temperature as well as ground track vector and air vector. With temperature information, the wind vector can be derived when ground track and heading are present. In Table 5 the statistics are shown for these 4934 observations. Clearly, the quality of both types are very close. The biases and standard deviations between the observations and ECWMF are almost equal. The mean wind speed and direction difference between the two ADS-C observations types are very small, with small standard deviations.

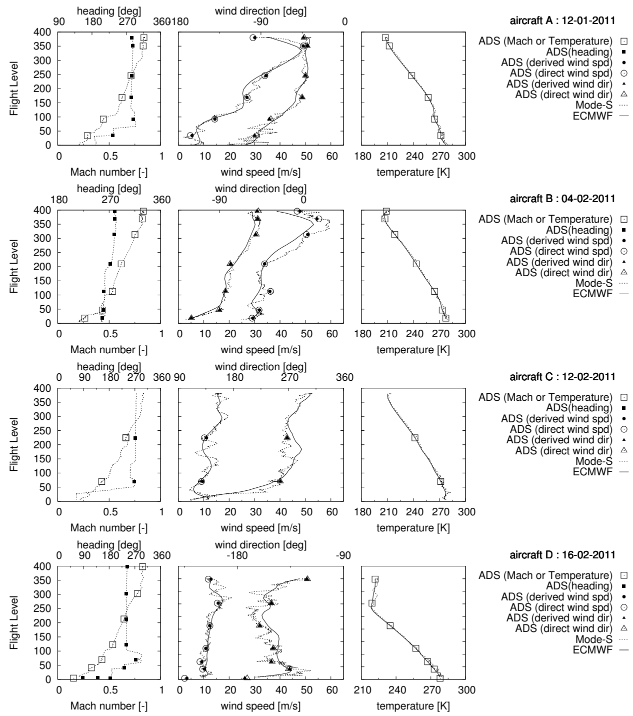

Fig. 4. Profiles of Mach number, heading, wind speed and wind direction for ADS-C reports (direct and derived) in the vicinity of Schiphol airport. Left panel of each sub graph shows the mach number and heading (solid and open squares, resp.); right panel shows wind speed and direction (solid and open triangles, resp.). Also shown are Mode-S heading, Mach number and wind speed and direction (dashed line) and ECMWF wind speed and direction (solid line).

3.3 Profiles of Wind and Temperature

In Fig. 4 the profiles of all ADS-C reports with both direct and derived wind observations are shown for 7 profiles of 5 different aircraft. Mach number and heading are shown for each profile in the left panel; wind speed and direction are depicted in the right panel. Also shown are ECMWF data (solid lines) and Mode-S data (dashed lines).

In some instances Mach number and heading compare well. This is not surprising since both observations are observed by the same instruments but can be a few seconds apart, since the observation frequency of Mode-S is 4 s. Consequently, the derived wind observations match the Mode-S wind observations. Also, the direct ADS-C reports of wind are close to the Mode-S and derived ADS-C wind observations. Note that the ECMWF profile is very smooth compared to Mode-S wind observations. The Mode-S profile matches ECMWF closely when the vertical wind variability is small (panels c and e). The other panels show more wind variability. For example panel (g) shows a very smooth Mach number and heading profile while the wind speed shows

Table 5. Statistics of the comparison of wind (direct and derived) observations from ADS-C versus ECMWF.

	Wind Speed				Wind Direction			
Comp	Num	mean	bias	stddev	Num	mean	bias	stddev
ECMWF-ADS-C(direct)	4934	19.13	0.47	2.91	3860	−25.97	0.22	13.32
ECMWF-ADS-C(derived)	4934	19.13	0.47	2.95	3860	−25.97	0.34	13.24
ADS-C(direct)-ADS-C(derived)	4934	19.13	0.02	0.60	3860	−25.97	−0.02	5.13
ECWMF-ADS-C(derived only)	884	22.36	0.20	2.59	758	−75.12	1.48	12.14

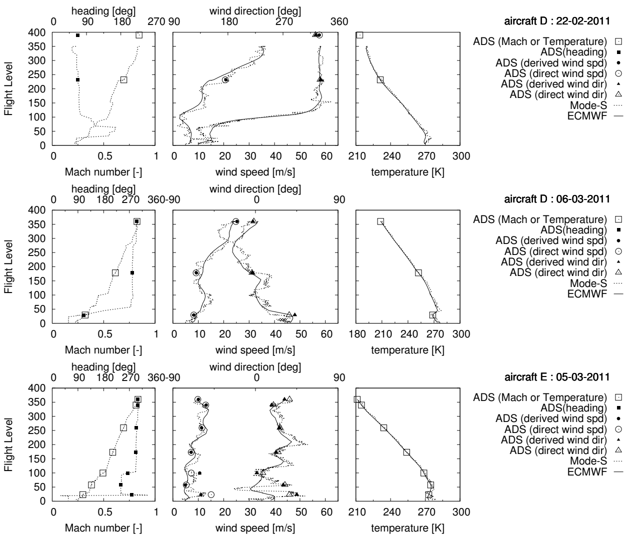

Fig. 4. Continued.

more small scale variability. Note the large difference in wind speed with ECMWF below FL50, observed by ADS-C and Mode-S.

Clearly, the ADS-C reports provide a quality wind similar to AMDAR and Mode-S EHS observations. However, the vertical sampling rate in the present data set is less than Mode-S. Note that the vertical sampling rate is highly correlated with the temporal sampling during ascent or descent of an aircraft.

4 Conclusions

In this article the quality of meteorological information inferred from ADS-C reports is assessed by comparison with ECMWF and Mode-S wind and temperature information. The data set contained 16 000 temperature and wind data points and nearly 6000 Mach number and heading data points. From the latter data set, using additional temperature information, from for example ECMWF, wind vectors can be derived.

The direct temperature and wind observations are of the same quality as AMDAR when compared to ECMWF. The ADS-C temperature observations are of better quality (lower standard deviation) than Mode-S. Wind observations from direct ADS-C reports and derived ADS-C reports have similar quality. Both types of ADS-C wind observations compare reasonably well to Mode-S wind observations, although the number of comparisons is small.

The general quality of ADS-C wind and temperature observations is comparable to AMDAR observations; the measurement uncertainty of AMDAR temperature is approximately 1 K (Schwartz and Benjamin, 1995; Drüe et al., 2007, 2010). Benjamin et al. (1999) found an observation error wind component 1.1 $\mathrm{m\,s^{-1}}$ and 0.5 K for temperature above the boundary layer. Within the boundary layer larger values were found. In Ballish and Kumar (2008) it was shown that temperature observation from AMDAR exhibit a considerable variation with aircraft model and are on average warmer than radiosondes. Drüe et al. (2010) found in a comparison of AMDAR with a wind profiler radar a wind vector difference of approximately 2.5 $\mathrm{m\,s^{-1}}$. Furthermore, Drüe et al. (2007) also showed that systematic deviations in AMDAR wind measurements can be regarded as an error vector, which is fixed to the aircraft reference system. They found systematic deviations in wind measurements from different aircraft types (more than 0.5 $\mathrm{m\,s^{-1}}$) parallel to the flight direction. A intensive ADS-C comparison study over a longer period is needed to investigate whether this aircraft dependecy is also present for ADS-C measurements.

Mode-S wind information is available with a temporal resolution of 4 s, while ADS-C reports are less frequent. Because of this difference in temporal resolution profile in formation from ADS-C is limited.

In conclusion, the accuracy of ADS-C meteorological information as observed in this article is of good quality and can be valuable source of wind and temperature information for operational weather forecasting and assimilation in NWP models.

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References

Ballish, B. A. and Kumar, K. V.: Systematic Differences in Aircraft and Radiosonde Temperatures, B. Am. Meteorol. Soc., 89, 1689–1707, 2008.

Benjamin, S. G., Schwartz, B. E., and Cole, R. E.: Accuracy of acars wind and temperature observations determined by collocation, Weather Forecast., 14, 1032–1038, doi:10.1175/1520-0434(1999)014¡1032:AOAWAT¿2.0.CO;2, 1999.

Benjamin, S. G., Jamison, B. D., Moninger, W. R., Sahm, S. R., Schwartz, B. E., and Schlatter, T. W.:Relative short-range forecast impact from aircraft, profiler, radiosonde, VAD, GPS-PW, METAR and mesonet observations via the RUC hourly assimilation cycle, Month. Weather Rev., 138, 1319–1343, 2010.

de Haan, S.: High-resolution wind and temperature observations from aircraft tracked by Mode-S air traffic control radar, J. Geophys. Res., 116, D10111, doi:10.1029/2010JD015264, 2011.

de Haan, S. and Stoffelen, A.: Assimilation of High-Resolution Mode-S Wind and Temperature Observations in a Regional NWP model, Weather Forecast., 27, 918–937, doi:10.1175/WAF-D-11-00088.1, 2012.

Drüe, C., Frey, W., Hoff, A., and Hauf, T.: Aircraft type-specific errors in AMDAR weather reports from commercial aircraft,Q. J. Roy. Meteorol. Soc., 134, 229–239, 2007.

Drüe, C., Hauf, T., and Hoff, A.: Comparison of Boundary-Layer Profiles and Layer Detection by AMDAR and WTR/RASS at Frankfurt Airport, Bound.-Lay. Meteorol., 135, 407–432, 2010.

ICAO: Manual of the ICAO Standard Atmosphere (extended to 80 kilometres (262 500 feet)), 3rd Edn., 1993.

ICAO: Procedures For A Navigation Services, Air Traffic Management, 15th Edn., Doc 4444-AMT/501, International Civil Aviation Organization, 2007.

ICAO: Annex 3 – Meteorological Service for International Air Navigation, 17th Edn., International Civil Aviation Organization, July 2010.

Painting, J. D.: WMO AMDAR reference manual, WMO-no. 958, available at: http://www.wmo.int (last access: 11 February 2009), WMO, Geneva, 2003.

Schwartz, B. E. and Benjamin, S. G.: A Comparison of Temperature and Wind Measurements from ACARS-Equipped Aircraft and Rawinsondes, Weather Forecast., 10, 528–544, doi:10.1175/1520-0434(1995)010¡0528:ACOTAW¿2.0.CO;2, 1995.