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Quality assessment of ADS-C wind and temperature observations

Deliverable of KDC project: TP Next Generation – The KNMI component

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Summary

In this report, the quality of the meteorological information of an Automatic Dependent Surveillance-Contract (ADS-C) message is assessed. Comparison against a global numerical prediction (NWP) model and Mode-S derived wind and temperature observations is performed.

The messages used in this study are ADS-Contract (ADS-C) reports. Almost 16 thousand ADS-C reports with meteorological information were compiled from the Royal Dutch Airlines (KLM) database. The length of the data set is 76 days. 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 derived observations in the vicinity of Amsterdam Airport Schiphol shows that the wind observations are of similar quality and the temperature observations of ADS are of better quality than those from Mode-S. However, the current ADS-C data set has a lower vertical resolution than Mode-S. High vertical resolution can be achieved by requesting more ADS-C when aircrafts are ascending or descending, but could result in increased data communication costs.

Contents

1 Introduction

This report is a deliverable of the KDC project: Trajectory Prediction (TP) Next Generation – The KNMI component. Aim of this deliverable is to investigate the availability and quality of meteorological information in aircraft reports of KLM.

The TP functionality of Air Traffic Control (ATC) calculates the four-dimensional flight path of an individual flight and is used to make a planning for inbound traffic. The accuracy of its calculations is strongly influenced by the quality of meteorological data.

More accurate calculations of the TP functionality enable optimization of flight paths and Continuous Descent Operations (CDOs) on high density traffic airports, both resulting in reduced noise and emissions. Accurate calculations can also ensure early detection of conflicts, which improves safety.

The objective of The Royal Netherlands Meteorological Institute (KNMI) is to provide accurate nowcasts and forecasts of wind and temperature data to increase the accuracy of the Trajectory Prediction in the ATC system and in aircraft Flight Management Systems (FMS).

In order to realise the accuracy required by users KNMI intends to expand the use of meteorological upper air observations in numerical weather prediction (NWP) by investigating new ways of collecting upper air weather observations utilising already existing aircraft data.

Aircraft related observations are widely used for numerical weather prediction. Aircraft Meteorological Data Relay (AMDAR) and Mode-S have shown to be beneficial when used for initializing a NWP model (De Haan and Stoffelen, 2011); Benjamin, 2010). AMDAR observations are generated especially for the meteorological community and are down linked when the aircraft is in the vicinity of a ground station. Mode-S observations use a combination of the Automatic Dependent Surveillance (ADS) messages together with the position tracked by an enhanced air traffic control radar (De Haan, 2011). These observations are available within the range of the tracking radar. All aircraft in view of the radar of ATC at Amsterdam Airport Schiphol are requested to respond to the radar every 4 seconds.

ADS is a surveillance technique in which aircraft automatically provide, 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 messages contain meteorological information obtained from the Flight Management System.

The method of data link determines the type of ADS report. Aircraft broadcast ADS messages through VHF for other aircraft and ground stations to receive; these reports are called ADS-B. The ADS reports used in this study are so-called ADS-C (ADS-Contract) because these messages are transmitted at standard positions or intervals or on request of the dispatch department of KLM; note that these messages are sometimes called ADS-A.

The Federal Aviation Administration (FAA) has decided that ADS-B is the satellite-based successor to radar surveillance. ADS-B makes use of GPS technology to determine and share precise aircraft location information, and streams additional flight information to the cockpits of properly equipped aircraft.

ADS (B or 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. AMDAR is generated using software which provides additional quality and enhancement of the observations (WMO, 2003), while Mode-S require an additional calibration and correction step (De Haan, 2011). A set of ADS-C messages from Royal Dutch Airlines (KLM) has been extracted for a period of 76 days. 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. These messages are used for air traffic control and the airline Dispatch organization and are different from position reports of KLM aircraft because they contain more information. To assess the quality of the meteorological components of the ADS-C messages, the observations are compared to a global NWP model from the European Centre for Medium-Range Weather Forecasts (ECMWF) and to Mode-S derived observations in the vicinity of Amsterdam Airport Schiphol.

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

2 Data

2.1 ADS-C messages

The data used in this study are Automatic Dependent Surveillance-Contract (ADS-C)-messages. These messages are transmitted at standard positions or intervals, but can also be send on request of KLM dispatch. The basic ADS data block is required from all ADS-equipped aircraft. The basic ADS 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.

Table 1: Contents of ADS position reports (according to ICAO, Doc4444)

	ADS report	**Contents**
a)	Basic ADS	Latitude, Longitude, Altitude, Time, Figure of merit
b)	Ground vector	Track, Ground speed, Rate of climb or descent
c)	Air vector	Heading,Mach or IAS, Rate of climb or descent
d)	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 ...
e)	Meteorological information	Wind speed, Wind direction, Temperature, Turbulence (if available), Humidity (if available)
f)	Short-term intent	Latitude at projected intent point, Longitude at projected intent point, Altitude at projected intent point, Time of projection
g)	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

In addition to any requirements concerning its transmission for ATS purposes, data block e) (Meteorological information) shall be transmitted in accordance with ICAO, Annex 3, section 5.4.1.

The ADS data contains a large number of parameters; here attention is paid to atmospheric parameters wind and temperature. In total 71832 ADS-C messages were collected in the period from 2011/01/01 00:13 UTC to 2011/03/17 14:30 UTC. In total 15995 ADS-C messages contained meteorological information and 5818 messages air vector information; 4934 messages contained both types. Figure 1 shows the coverage of the data set used in this study. An example of a decoded ADS message containing meteorological information is shown in Table 2.

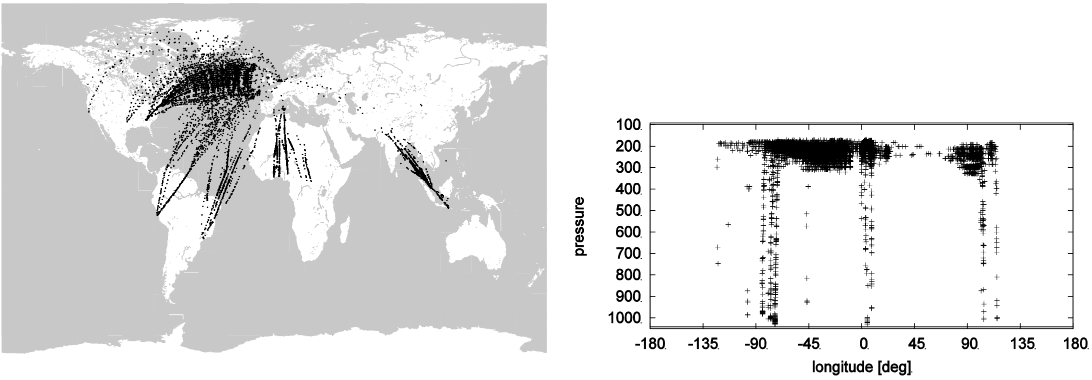


Figure 1: Horizontal and vertical distribution of ADS messages.

Table 2: Example of an ADS-C message.

ADS (Automatic Dependent Surveillance)		
Message Type	PERIODIC_REPORT	072B7AC7467D8F8C9939810089C..
	LATITUDE	61.143035888671875 (deg)
	LONGITUDE	-44.90541458129883 (deg)
	ALTITUDE	35992.0 (feet)
	TIME_STAMP	20:53.999 (MM:SS)
	T	1
	FOM	6
	R	1
Message Type	FLIGHT_ID_GROUP	KLMXXX
Message Type	METEOR_GROUP	
	WIND_SPEED	63.5 (knots)
	VALID_BIT_TRUE_WIND_DIRECTION	Valid
	TRUE_WIND_DIRECTION	-89.296875 (deg)
	TEMPERATURE	-55.25 (degree Celcius)

2.2 Direct Wind observations from ADS-C

The ADS-C messages of the meteor-group contain information on wind speed and direction and temperature. This information is extracted from the onboard avionics system. 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 (called air vector). The vector difference between the ground track and the air vector 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 V_{air} and ground speed vector V_g are known the wind vector V can be calculated:

$$V = V_g - V_{air}$$

The vector V is reported in the ADS meteor group. These wind observations will be called Direct ADS-C wind observations.

2.3 Derived Wind observations from ADS-C

There are also ADS-C message (of the type Earth-reference) which contain the ground track information, the heading and the Mach number. The Mach number is the quotient of the airspeed and the speed of sound. The latter is dependent on the temperature through,

$$c_s = \sqrt{\frac{\gamma RT}{M}} ,$$

where γ = 1.4, the adiabatic index, R =8.3145 J mol^{-1} K^{-1} molar gas constant, T temperature and M = 0.0289645 kg mol^{-1} molar mass of dry air. The wind vector can be deduced from the ground track and the air vector as follows:

$$V = V_g - Mach\sqrt{\frac{\gamma RT}{M}}\begin{pmatrix}\sin(\alpha)\\ \cos(\alpha)\end{pmatrix}.$$

Here α is the heading of the aircraft. Errors due assumptions in T are

$$\Delta V = -\frac{\Delta T}{2T}\sqrt{\frac{\gamma RT}{M}}\begin{pmatrix}\sin(\alpha)\\ \cos(\alpha)\end{pmatrix}$$

Suppose that the error in T is 1 K then the error in airspeed will be at most 0.5%. 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 and air vector are called Derived ADS-C wind observations.

2.4 Numerical Weather Prediction Data

The observations are compared to the operational global numerical weather prediction (NWP) model from the European Centre for Medium-Range Weather Forecasts (ECMWF). This model uses a large set of observations to initialise the model at analysis time. Satellite, radiosonde, and aircraft observations are the main input for upper air analysis. The resolution of the ECMWF-model was reduced to 1 degree due to computational limitations, with 91 vertical levels. Because the operational model is started every 12 hours, observations are compared to at most a 12-hour forecast. The ECMWF wind and temperature from the model are linearly interpolated in time between two successive forecasts. These forecasts are 3 hours apart, with a maximum forecast length of 12 hours.

3 Quality Evaluation by comparison with ECMWF and Mode-S

The quality of the ADS-C messages is compared to global ECMWF model data and to Mode-S derived observations in the vicinity of Amsterdam Airport Schiphol. The Mode-S data is created using the corrections described in De Haan (2011). Mode-S derived observations are obtained with a temporal resolution of 4 seconds. The positions of ADS-C and Mode-S will differ and a match between ADS-C and Mode-S is found when the distance between the observation locations is less than 5 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 1K and thus the error in wind speed and direction will be small.

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 15995 direct ADS-C observations are used for the global comparison, while only 67 direct ADS-C observations were reported in the vicinity of Amsterdam Airport Schiphol 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 Figure 1). These statistics are similar to AMDAR observations.

Nearly the same statistics are found when 67 ADS observations near Schiphol Airport are compared to ECMWF. The Mode-S derived temperature observations are known to be more noisier due to the method of derivation of temperature from Mach number (De Haan, 2011). Both ADS-C and Mode-S have a bias of around 0.7K 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 241K, which is at approximately at 500hPa.

The ADS-C temperature observations are of good quality, comparable to AMDAR, and better then Mode-S derived temperatures.

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 Airport Schiphol.

Temperature	Num	mean ECMWF (K)	Bias (K)	Standard deviation (K)
ECMWF - ADS-C	15995	224.62	-0.44	0.93
ECMWF - ADS-C(EHAM)	67	243.99	-0.78	0.96
ECMWF - Mode-S	67	243.99	-0.71	1.78
ADS-C(EHAM) - Mode-S	67	243.99	0.06	1.49

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). The number of direct wind observations are 15995 (the same as the temperatures), 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 and standard deviation is around 2.8 m/s as presented in Table 4. Derived wind speed biases and standard deviations are of the same order, however, the data sets sample clearly different parts of the globe and atmosphere because the mean ECMWF wind speed and wind direction differs.

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. For wind direction the bias is small with a standard deviation of less than 10 degrees. Note that the mean wind direction is southwest. The statistics for derived wind measurements show also 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 northwest which differs by 30 degrees from the direct observation data set; the data sets sample different region and times.

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

	Wind speed				**Wind direction**			
	Num	mean ECMWF (m/s)	Bias (m/s)	Std. dev. (m/s)	Num	mean ECMWF (deg)	Bias (deg)	Std. dev. (deg)
ECMWF - ADS-C(direct)	15995	25.45	-0.52	2.80	14072	-65.66	0.26	9.87
ECMWF - ADS-C(derived)	5818	19.61	-0.43	2.91	4618	-34.18	0.52	13.07
Direct ADS 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 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

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 ECMWF has a similar bias and a slightly larger standard deviation for wind speed than ADS-C. Figure 2 (top row) shows the scatter plots of temperature and wind for direct ADS-C and Mode-S versus ECMWF. Only 35 derived wind observations near Schiphol Airport were found in the data set. The statistics for these 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 between ADS-C and Mode-S is around 1.6 m/s, 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 than 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 Figure 2 shows the scatter plots of wind speed and direction of the derived ADS-C and Mode-S derived observations versus ECMWF.

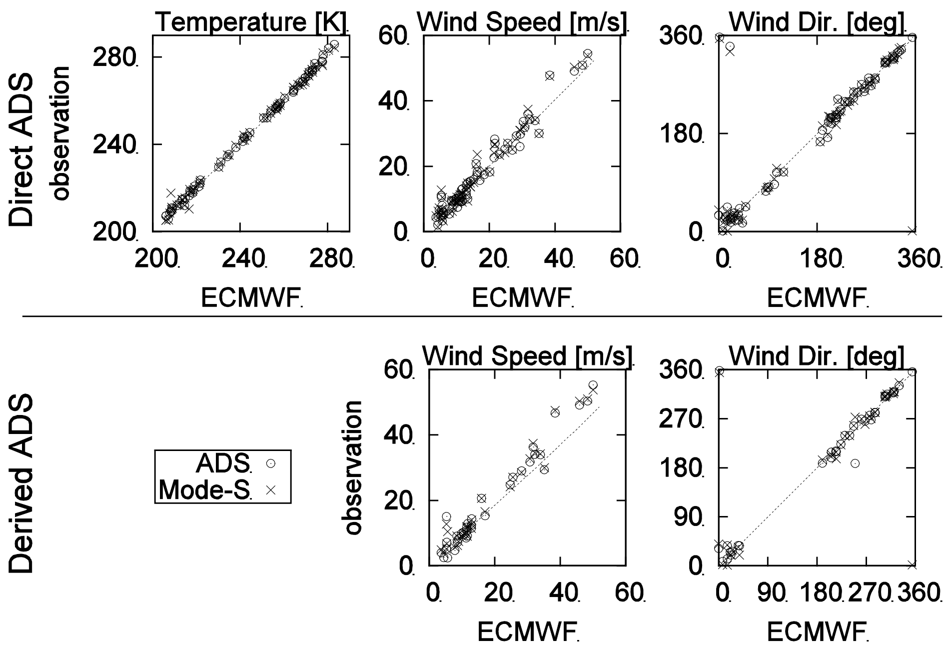


Figure 2: Scatter plots showing ECMWF temperature and wind versus ADS-C (direct and derived) and Mode-S.

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 air vector are present. Here the ECMWF temperature is used. In Table 5 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 ECMWF are almost equal. The mean wind speed and direction difference between the two ADS-C observations types are very small, with small standard deviations.

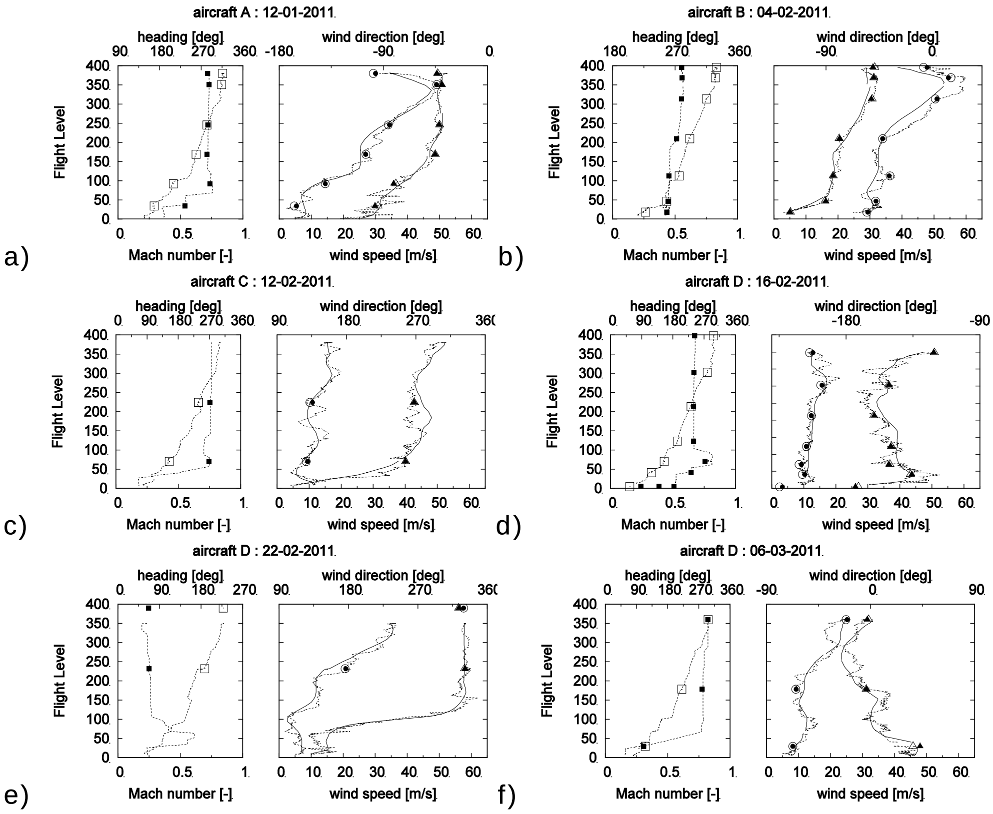
Table 5: Statistics of the comparison of wind (direct and derived) observations from ADS-C versus ECMWF.

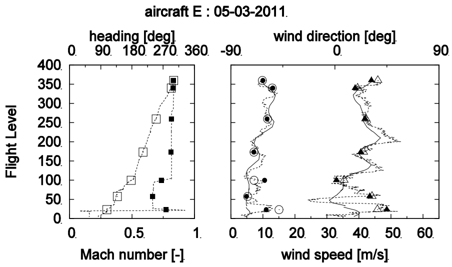
	Wind speed				**Wind direction**			
	Num	mean ECMWF (m/s)	Bias (m/s)	Std. dev. (m/s)	Num	mean ECMWF (deg)	Bias (deg)	Std. dev. (deg)
ECMWF-ADS-C(direct)	4934	19.13	0.47	2.91	3860	-25.97	0.22	13.32
ECMWF-ADS-C(derived)	4934	19.13	0.47	2.95	3860	-25.97	0.34	13.24
ADS-C(direct)-ADS-C(derived)	4934	19.13	0.02	0.60	3860	-25.97	-0.02	5.13
ECMWF-ADS-C(derived)	884	22.36	0.20	2.59	758	-75.12	1.48	12.14

3.3 Profiles of Wind and Temperature

In Figure 3 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 derived data (dashed lines).

In general, the Mach number and heading match very 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 seconds. Consequently, the derived wind observations match the Mode-S derived wind observations. Also, the direct ADS-C reports of wind are close to the derived Mode-S and derived ADS-C wind observations. Note that the ECMWF profile is very smooth compared to Mode-S derived wind observations. The Mode-S profile matches ECMWF very good when the vertical wind variability is small (panels c) and e)). The other panels show more wind variability, which is most likely realistic. For example panel g) shows a very smooth Mach number and heading profile while the wind speed shows more small scales. Note the large difference in wind speed below FL50, observed by ADS-C and Mode-S.





g)

Figure 3: 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). Clearly, the ADS-C reports give good quality wind 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 report the quality of meteorological information inferred from ADS-C reports is assessed by comparison with global ECMWF and regional Mode-S derived wind and temperature information. The data set contained more than 15 thousand temperature and wind data points and nearly 6 thousand 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 good quality compared to ECMWF. The ADS-C temperature observations are of better quality than Mode-S. Wind observations from direct ADS-C reports and derived ADS-C reports have the same quality. Both types of ADS-C wind observations compare reasonably well to Mode-S derived wind observations, although the number of comparisons is small.

Mode-S derived wind information is available with a temporal resolution of 4 seconds, while ADS-C reports are less frequent. Because of this difference in temporal resolution profile information from ADS-C in this data set is limited. Improving the vertical resolution of wind and temperature observations can be achieved by requesting more reports for ascending and descending aircraft, but could result in increased data communication costs.

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7 Document Information

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