High resolution temperature and wind observations from commercial aircraft

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ABSTRACT

The tracking and ranging (TAR) radar of Schiphol airport follows all aircraft in the airspace around the Netherlands for air-traffic control. This enhanced radar contacts each aircraft every four seconds on which the transponder in the aircraft responds. This message contains information on flight level, direction and speed. Together with the ground track of an aircraft, meteorological information on temperature and wind can be inferred from this information. Because all aircraft are required to respond to the TAR-radar, the data volume is extremely large, being around 1.5 million observations per day.

In this paper, the quality of these observations is assessed by comparison to AMDAR (Aircraft Meteorological Data Relay) and numerical weather prediction (NWP) model information. A method to improve the temperature and wind observations is applied to obtain good quality wind and temperature observations, albeit with a reduced time frequency of one observation of horizontal wind vector and temperature per aircraft per minute. These real-time observations are used as input for an hourly cycle of the HIRLAM NWP-model. The impact of these observation on the short-range weather forecasts will be discussed.

1. INTRODUCTION

Wind and temperature observations from radiosonde and AMDAR-aircraft are the main sources of in situ upper air information to data assimilation systems for Numerical Weather Prediction (NWP). Radiosonde are generally launched two or four times a day and report also on upper air humidity. Wind information is inferred from tracking the radiosonde.

AMDAR observations exploit the meteorological sensors on-board commercial aircraft. Designated aircraft have software installed on the board-computers which generate meteorological messages and sends these to the meteorological community through satellite links. The coverage includes data sparse areas such as the oceans, however intercontinental flights are using almost the same routes leaving areas unsampled. These observations have a slightly worse quality than radiosonde. [1] showed that temperature observation from AMDAR exhibit a considerable variation with aircraft model and are on average warmer then radiosonde. See [6] for more details.

In this paper a novel data source is investigated. Aircraft are obliged to broadcast information on heading and flight level for air-traffic control. This information is collected for all aircraft visible to the tracking radar of the airport. Meteorological parameters can be deduced from this information in a similar way as with AMDAR. The major difference with AMDAR is that information from all commercial aircraft are gathered, in contrast to AMDAR where only dedicated aircraft are equipped with AMDAR software. Furthermore, no extra costs for a data link is necessary; the messages are received operationally for air-traffic management. The observation frequency is every four second.

2. DATA

2.1. Aircraft Data

Aircraft are equipped with a large number of sensors for flight safety. Some of these sensors measure atmospheric parameters, or can be used to derive atmospheric parameters.

2.1.1. Mode-S

Mode-S (Mode-Selective) data is collected using the TAR-radar at Schiphol airport. The radar performs a full scan every four seconds and the area covered is 200 NM (or 270 km) around the radar. Note that the vertical coverage is limited by the curvature of the earth.

All aircraft are queried, resulting in about 1 500 000 observations per day of temperature and wind. Figure 1 shows the observations on 2008/03/13 between 11:00 UTC and 13:00 UTC.

2.1.2. AMDAR

As stated before, not all aircraft are equipped with AMDAR. Figure 2 shows the coverage of this data on 2008/03/13 from 11:00 UTC to 13:00 UTC.

2.2. Numerical Weather Prediction

At KNMI a High Resolution Limited Area Model (HIRLAM,[2]) is run operationally. This Numerical Weather Prediction (NWP) model is started every three hours and has a forecast length of 24 hours. For the period under consideration, the model had a resolution of

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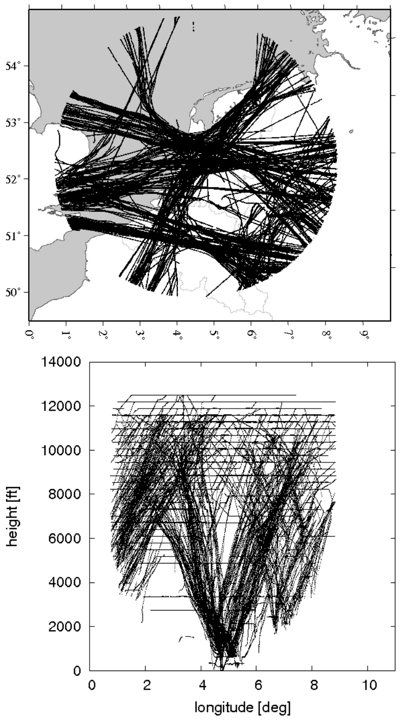

Figure 1. Horizontal and vertical coverage of Mode-S data on 2008/03/13 from 11:00 UTC to 13:00 UTC.

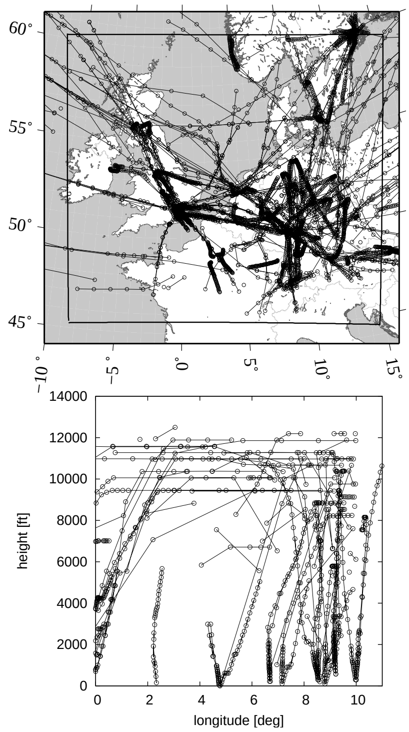

Figure 2. Horizontal and vertical coverage of Mode-S data on 2008/03/13 from 11:00 UTC to 13:00 UTC. Top panel also shows the boundaries of the NWP region.

11 kilometers. The domain is shown in Figure 2. Synoptic observations, such as wind, temperature and humidity from radiosonde and surface pressure observations, are used to analyze the initial state of the atmosphere. The previous three hour forecast is used as background information and, because the model is a limited area model, the forecast at the boundaries of the region is retrieved from larger HIRLAM forecast which has a six hour cycle. The latter run is embedded in global forecast fields from the European Centre for Medium Range Weather Forecasting.

3. ATMOSPHERIC OBSERVATIONS FROM COMMERCIAL AIRCRAFT

Systems like Mode-S and AMDAR use internal fight data to observe wind and temperature. The method of deducing wind information is equal for both systems. For temperature the method is different: temperature is observed for AMDAR while it is inferred from other aircraft parameters for Mode-S.

3.1. Observations of Temperature and Wind

Mode-S reports information for each aircraft tracked by the radar on: flight level (F) Mach-number (M), roll, true airspeed (V_t), heading (α_t), groundspeed (V_g) and track angle (α_g). Other information is available, but these are not relevant for the current study.
From the V_t and M the temperature can be deduced using the relation between the speed of sound and temperature and the ideal gas law,

$$M = \frac{V_t}{c}, \tag{1}$$

where $c = \sqrt{\gamma R_d T}$, where $\gamma = c_p/c_v = 1.397774$ is the ratio of specific heats. Thus, given M and V_t, T can be calculated by

$$T = 2.493 \cdot 10^{-3} \frac{V_t^2}{M^2} \text{ [K]}, \tag{2}$$

where V_t is in [m/s].
The wind vector $\mathbf{V}$ is obtained from the difference in heading vector, defined by length V_t and angle α_t, and the ground track, defined by length V_g and angle α_g, that is

$$\mathbf{V} = \mathbf{V}_g - \mathbf{V}_t \tag{3}$$

3.2. Quality control

Based on the mechanical properties of the aircraft and on possible errors in data transmission a number of checks has been proposed by [4, 5]. For example, during manoeuvres, the airflow around the pitot-tube can be irregular and thus observations with a large roll are omitted.

3.3. Preprocessing Temperature Observations

Mode-S data is raw data from the internal computers in the aircraft. Although internally possibly more samples are available, no averaging is applied and a Mode-S observation like with an AMDAR observation. Nevertheless, the observation frequency of four seconds can be used to improve the observations.

The reported significance of the Mode-S for ground and true air speed is 2 kt and for Mach it is 0.004. This significance determines the quality and the accuracy of the inferred meteorological parameters. This implies that using the reported values of M and V_t, the temperature will show rapid fluctuations of the order of 2-5 K.

A smoothing algorithm is applied to the raw data to deal with this problem. The reports of M and V_t are linearly fitted over a time window. The values of the linear fit of M and V_t in the center of the window is used to calculate T (according to Eq. 2). For level flight a window of 60 seconds (15 observations), and for ascending/descending aircraft a window of 12 seconds (3 observations) is used. Additionally the atmospheric observation are averaged with similar time window lengths as AMDAR: 10 seconds for ascending/descending flight phase and 60 seconds for level flight.

3.4. Preprocessing Wind Observations

Accurate values of true air speed (V_t) and heading α_t are essential for accurate wind observations. At low wind speeds, errors in V_t and/or α_t can lead to large errors in wind direction, however, systematic errors in α_t are also very important.

3.4.1. Magnetic Heading correction

The reported heading is given with respect to the magnetic north. A correction is applied to α_t using the International Geomagnetic Reference Field [3]. Currently, the magnetic correction around Schiphol is close to zero. The heading, when corrected with the magnetic correction, will be a true north angle.

3.4.2. Heading Correction

It appeared that the magnetic correction is insufficient and that an additional correction per aircraft is needed. The size of the correction can be detected by inspecting the heading of the aircraft when it (just) has landed on the runway. In this case the heading and runway angle should match (within measurement accuracy). For a 12 month period the heading corrections are determined for all landing aircraft. The method of detection uses the exact position of the aircraft on the runway, a ground speed of the aircraft between 55 and 120 kt and a constant flight level. At least three data points should meet these criteria in order to store the mean difference between the heading and the runway angle. For aircraft with more than 10 separate landings the mean heading offset and the total standard deviations of the offset is presented in Figure 3. Some aircraft exhibit a very large spread in heading offset (B735), while other are very stable (B744).

4. TRIPLE COMPARISON AMDAR, MODE-S AND NWP

The smoothing and heading corrections are used to calibrate the Mode-S observations. Over a period of 12 months (March 2008-February 2009) a triple collocation of Mode-S, AMDAR and HIRLAM is performed. At least

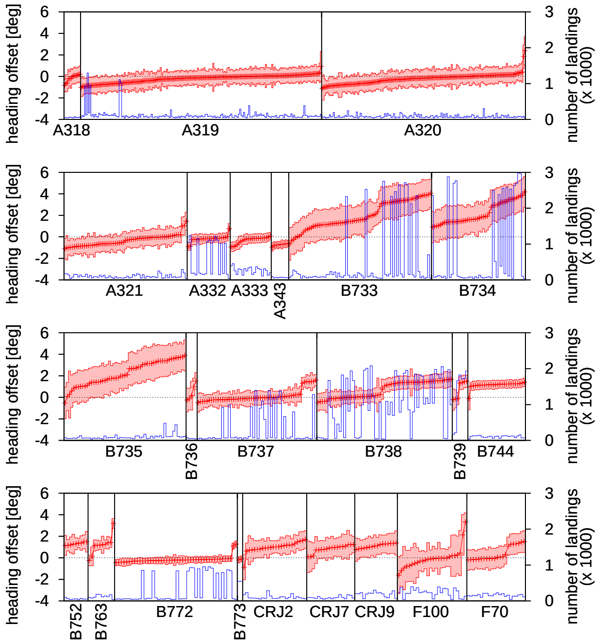

Figure 3. Mean and standard deviation of the heading offset for each transponder-id separately. The data is ordered with respect to aircraft type and mean heading offset. Also shown on the left scale is the number of landings for the specific aircraft.

a two hour NWP forecast is used in the the comparison to avoid that AMDAR information used in the collocation has been assimilated. Hourly NWP forecast fields are linearly interpolated to observation time. The vertical interpolation to the observation height is based on the linear interpolation in the logarithmic of the pressure.

Nearly half of the triple collocated observations stem from B733 and B735; these aircraft have a large uncertainty in the heading offset (see Fig. 3), which may influence the assessment of quality.

Figure 4 (top panel) shows the temperature bias and RMS of the triple collocation. The RMS between Mode-S and NWP is slightly larger than that of AMDAR and NWP; the bias is zero from Mode-S, while AMDAR has a positive bias. Figure 4 (bottom panels) show the wind speed and wind direction bias and RMS of the triple collocation. Again, for both parameters, the RMS between Mode-S and NWP is slightly larger than that of AMDAR and NWP. The bias of wind speed is smaller for Mode-S than for AMDAR when compared to NWP.

5. ASSIMILATION OF MODE-S OBSERVATIONS

The calibrated Mode-S temperature and wind observations are assimilated in HIRLAM for a period of one week (1-7 February, 2008). No other upper air data was assimilated. The NWP model has a resolution of 11km and an hourly update cycle. Boundaries are extracted from a three-hourly run. The hourly forecasts are compared to Mode-S observation which were ob-

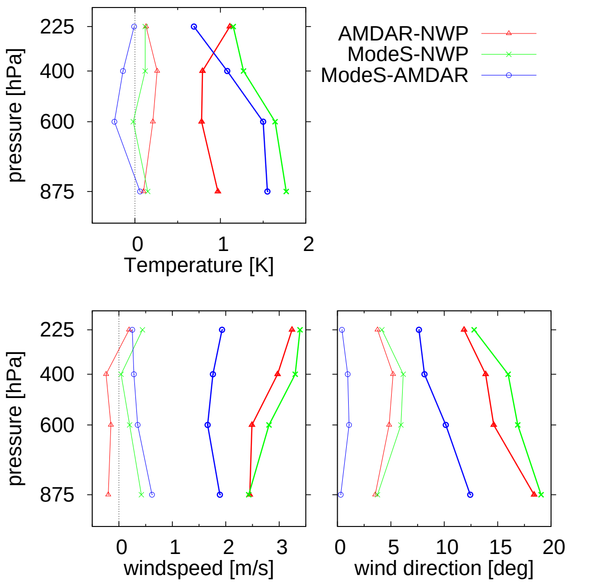

Figure 4. Comparison statistics of triple collocations of Mode-S, AMDAR and NWP for all observations within the range of the tracking radar over a 12 month period.

served within 10 minutes of the validation time. The three-hourly run was used as reference (H11-run).

In Figure 5 the statistics are shown for temperature, wind speed and wind direction with respect to forecast time for the levels 875hPa and 400hPa. When the temperature, wind speed of wind direction bias differ substantially, the Mode-S-run shows to have the smallest bias. The RMS of the Mode-S-run in the first hour of the forecast is smaller for all parameters and levels than the RMS of the H11-run. The reason for this the assimilation of Mode-S observations. The decrease of wind direction bias and the strong increase in RMS of the Mode-S-run with forecast time needs further investigation.

The experiment period of seven days is probably too short: statistics based on a longer run are necessary to obtain a good impression on the impact of Mode-S in NWP.

6. CONCLUSIONS AND OUTLOOK

The Mode-S observations are a valuable source of information for meteorology, when the observations are calibrated and smoothed. The quality of these observations is close to that of AMDAR.

An assimilation trial shows that bias in temperature and wind direction is improved over a forecast length of four hours when compared to a reference; the improvement in RMS is smaller and disappeared after one hour.

The impact of assimilation of Mode-S can be better assessed with a longer period (e.g. one month) and longer forecasts. Assimilation of high resolution observations (in space and time) requires special attention due to fro example over-fitting problems.

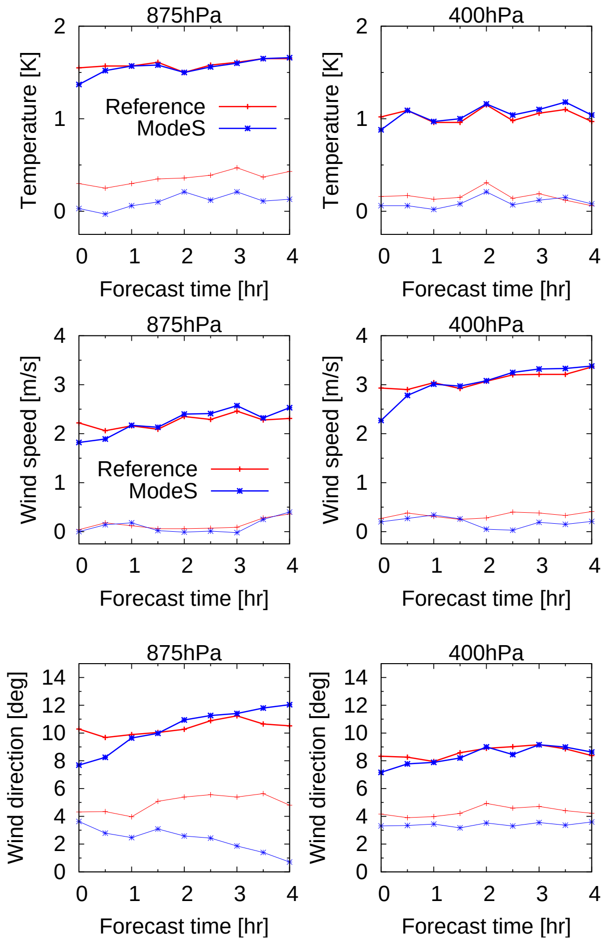

Figure 5. Validation of NWP forecasts with Mode-S observations.

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