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Evaluation and impact of aircraft humidity data in ECMWF's NWP system

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Abstract

Assimilation of temperature and wind data from aircraft is very well established, but about 10% of the commercial aircraft reports now include humidity data - mainly over North America so far but with some reports over Europe. This report primarily evaluates the quality and impact of aircraft humidity data on global NWP. Two different systems are available: 1) laser diode measurements, available in some AMDAR (Aircraft Meteorological DAta Relay) reports, mainly from long-haul aircraft), 2) TAMDAR (Tropospheric Airborne Meteorological Data Reporting) capacitive humidity measurements, mainly from short-haul aircraft with more ascent/descent profiles but less data in the upper troposphere.

Separate winter and summer experiments were performed at ECMWF assimilating quality controlled AMDAR humidity data and/or TAMDAR temperature/wind/humidity data in addition to the data used operationally. Observation minus background statistics were compared between AMDAR, TAMDAR and radiosonde reports over North America. The results suggest that after quality control the accuracy of aircraft humidity is similar to that of the radiosondes - slightly better in the case of AMDARs. The extra data had rather minor impact on synoptic scale forecasts but some benefit at short range when compared to the US precipitation fields based on NEXRAD radar and surface observations. ECMWF has assimilated AMDAR humidity operationally since March 2016.

Introduction

Wind and temperature reports from commercial aircraft have been available for decades, but the numbers started to increase dramatically in the 1990s - Moninger et al. (2003) provide an overview. Pilot voice reports (usually called **AIREP**s after the code format used) are now vastly outnumbered by automated **AMDAR** (aircraft meteorological data relay) reports, although over the North Atlantic AIREPs still provide a significant part of the coverage. AMDAR reports from US airlines are sometimes referred to as Aircraft Communication Addressing and Reporting System (**ACARS**) data. AIREP reports are almost exclusively at aircraft cruise levels, AMDAR/ACARS reports are from all phases of flight: ascent, cruise and descent, but with somewhat fewer descent reports.

AMDAR/ACARS reports are primarily from long-haul aircraft, see Petersen (2016). Tropospheric Airborne Meteorological Data Reporting (**TAMDAR**) reports are primarily from short-haul aircraft (and started in 2004). The TAMDAR reports for this study were provided for research evaluation by Panasonic avionics (who took over AirDat in 2013) and a license would be required for real-time use. In November 2018 FLYHT Aerospace Solutions Ltd. acquired Panasonic Weather Solutions Assets, including the TAMDAR data. Most work described in this report was performed in 2014/2015 for EUMETNET, a network of 31 of European National Meteorological Services. This is an edited update of a EUMETNET contract report.

The World Meteorological Organisation (WMO) provides various online resources about aircraft-based observations (https://public.wmo.int/en/our-mandate/what-we-do/observations/Aircraft-based-observations) with a section on the AMDAR programme. WMO (2018, CIMO Guide, Part II, Chapter 3) describes both AMDAR and TAMDAR measurements, see also WMO (2017). In mid-2019 about 830,000 distinct aircraft reports (AMDAR plus AIREP, but not TAMDAR) were being received and processed daily at ECMWF.

Figure 1 shows the typical coverage of aircraft humidity over North America in mid-2014. At low-levels (top plots) there are clusters of reports around the airports visited, at mid/upper-levels the tracks spread out, but many of the TAMDAR flights do not reach the upper troposphere. There were a few European AMDAR aircraft reporting humidity (not shown, these humidity data were not assimilated in the experiments below). There were a few TAMDAR aircraft reporting over Europe and one over Australia (not shown), these were assimilated in the TAMDAR experiments. The vast majority of the extra data were over/near North America.

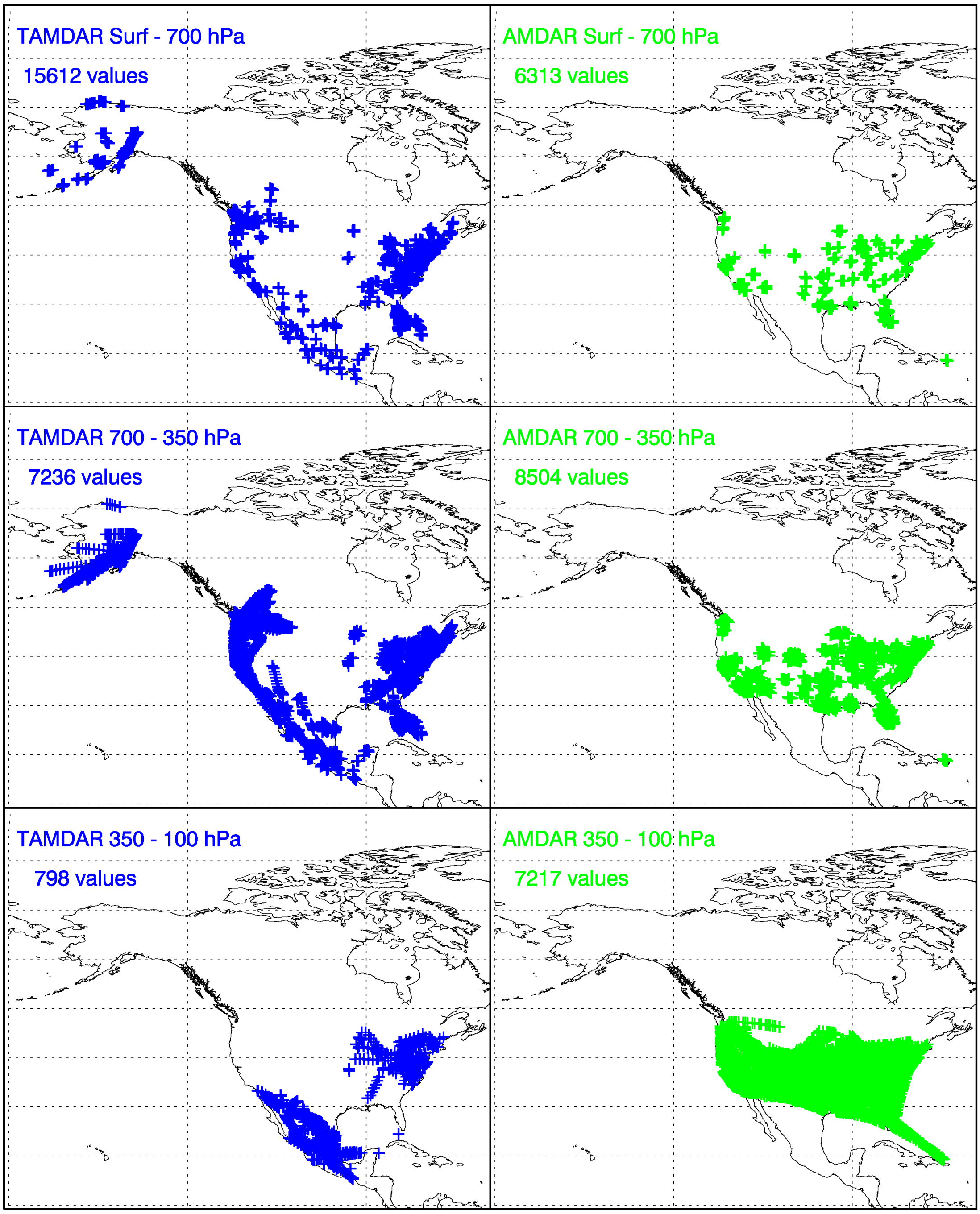

Figure 1 TAMDAR (left) and AMDAR (right) humidity coverage for 1 July 2014 for low-, mid- and high-levels – number of data points listed top left. These are the assimilated observations, after thinning and quality control. Most TAMDAR aircraft do report humidity, but only around 10% of AMDAR aircraft (with a much broader spatial coverage) do.

Figure 2 shows the vertical distribution in more detail and also the difference between number reported and number assimilated (mainly due to thinning, see section 2.1). During June 2014 there were 2722 ACARS aircraft reporting, 1427 other AMDAR aircraft and 227 TAMDAR aircraft. Of the ACARS aircraft 440 apparently reported humidity, however 330 always reported zero humidity and 110 reported (mostly) non-zero humidity. Those reporting humidity made up 4% of ACARS aircraft but 14% of ACARS reports - or almost 11% of all AMDAR reports. Presumably the sensors were fitted on aircraft that send large numbers of reports. Both ACARS and TAMDAR provided about 1.6 million valid humidity reports during June 2014. For comparison there were about 14% fewer ACARS reports at flight level in April 2011 and more than 30% fewer TAMDAR reports.

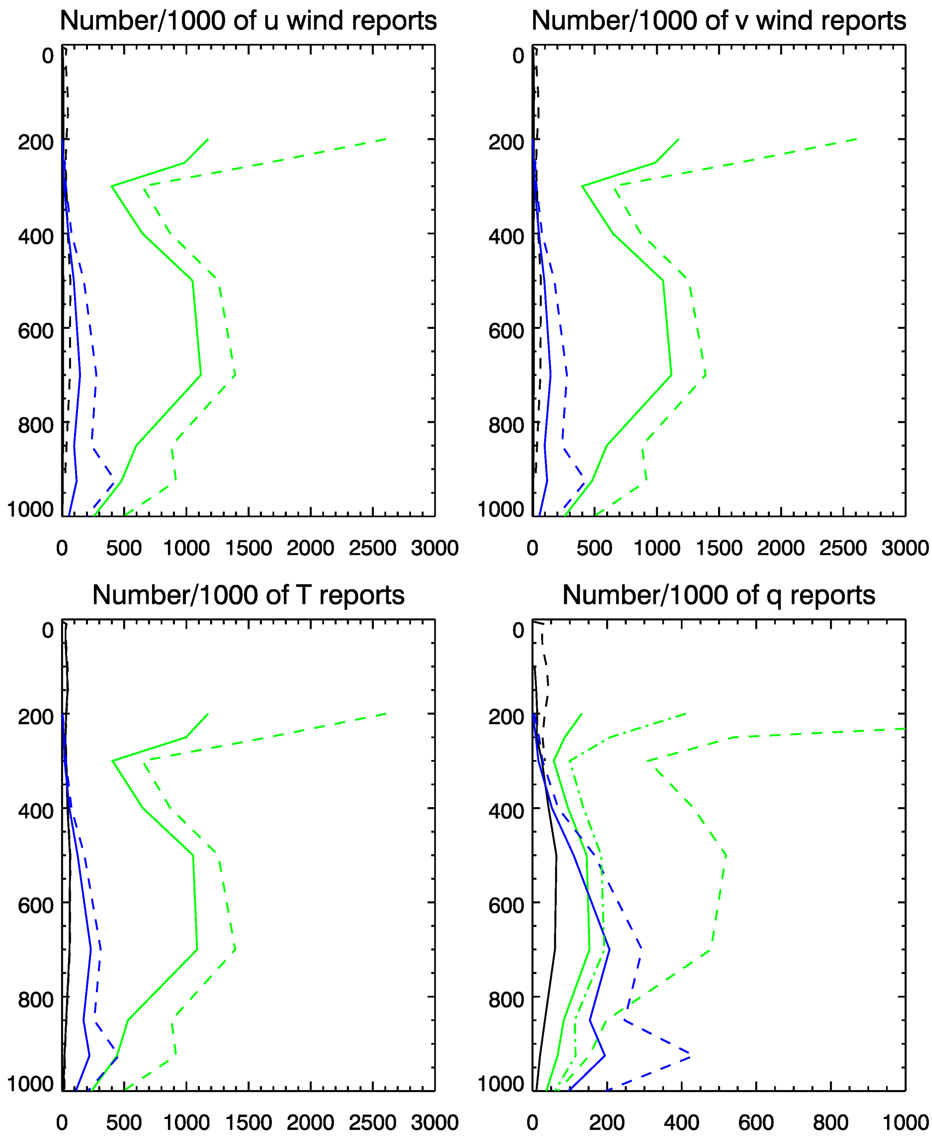

Figure 2 Number of reports over North America (here taken as 10-90°N, 50-180°W) as a function of pressure for June 2014 for u and v (identical), temperature and humidity (different x-axis). Green: ACARS, blue: TAMDAR, black: radiosonde; solid line – number assimilated, dashed line – number reported, dot-dashed line – number of non-zero values (humidity only)

The computation of wind and ambient temperature from aircraft measurements is non-trivial and is similar for commercial or research aircraft (WMO, 2018; Wendisch and Brenguier, 2013). Note that the measured temperature is higher than the ambient air temperature due to Mach heating – kinetic energy from the velocity difference between the aircraft and the air is converted into heat energy (the temperature difference can be 20K or more). The derived air temperatures tend to be slightly warm (Ballish and Kumar, 2008), the biases can depend on aircraft type and whether the aircraft is ascending or descending (Drüe et al, 2008). Isaksen et al (2012) implemented aircraft temperature bias corrections at ECMWF in 2011. Zhu et al (2015) tested similar corrections at NCEP and provide more details, including possible causes of the biases. Some aircraft with older instrumentation can have heading errors that affect the derived winds; Jacobs et al (2014) document a wind correction procedure that is applied to some TAMDAR-equipped aircraft once sufficient statistics have been accumulated.

1.1 Aircraft humidity measurement and reporting

Mamrosh (2015) provides a short history of the development of humidity sensors for commercial aircraft and Petersen et al (2016) look at the impact and benefits of the data. Some ACARS aircraft are equipped with Water Vapor Sensing System II (WVSS-II). The WVSS-II uses a diode laser to measure water vapour mixing ratio. Vance et al (2015) trialed the WVSS-II on the FAAM research aircraft. In cloud free conditions they found good agreement between chilled mirror hygrometers and a WVSS-II using a Rosemount inlet – with the WVSS-II reacting quicker at low temperatures. Using a standard flush inlet ('air sampler', used on commercial aircraft) good agreement was seen in relatively moist conditions but there was an increasing wet bias at lower humidities. Vance et al used data direct from the WVSS-II at full precision, but there are concerns that the precision used for reporting mixing ratio (0.01 g/kg) is rather coarse, especially at temperatures below about -50°C (Pauley and Baker, pers. comm. 2014). This is partly due to the different orders of magnitude of humidity mixing ratio in the atmosphere. A plus point of measuring/reporting mixing ratio is that it is an absolute measurement – unlike relative humidity (below).

Most TAMDAR units include measurement of humidity using thin film capacitive sensors (two sensors were used – now increased to three - and a consensus RH is reported, Anderson, 2006). One issue is that such sensors react more slowly in cold conditions (Anderson 1995). Despite the use of very sensitive sensors (Jacobs, pers. comm. 2014) and the effect of Mach heating there is still a question about the performance in very cold temperatures. Fast response is particularly important on an aircraft because of its high speed, on the other hand TAMDAR reports sample the (very cold) upper troposphere much less than AMDAR reports. Capacitive humidity sensors are also commonly used on radiosondes and at surface stations. At surface stations they are found to drift to higher values over time – probably related to episodes of saturation, or sometimes chemical contamination – necessitating regular (annual) replacement/recalibration (Ingleby et al, 2013). The original TAMDAR design had wetting issues, but all sensors in the field now have a hydrophobic membrane that prevents wetting (during flight the sensor RH is reduced due to Mach heating, but there will be saturated conditions on the ground). The added benefit is protection from de-icing fluid contamination – extending the sensor lifetime to four years or more. The wind and humidity calibration constants can be updated remotely. (Information from Jacobs, pers. comm. 2015). The ambient RH has to be calculated from the measured RH and at temperatures below about -40°C there are, in effect, several different definitions of RH with respect to water depending on the saturation vapour pressure equation used – see Appendix A. As for AMDAR (above) the measurements will have some dependence on the air intake used.

2 Data and assimilation system used

2.1 Aircraft data usage

During aircraft turns (high roll angle) derived winds, and to some extent temperatures, have larger uncertainty. During sensor de-icing and for a period afterwards temperature and humidity measurements should not be used. Traditionally in situ data values regarded as suspect have not been reported on the GTS, either the whole report has been suppressed or that value has been set to missing. However, TAMDAR reports (and to a lesser extent AMDAR reports) include suspect values but with a flag to indicate their status. Values flagged as 'highly suspect' or 'bad' were not assimilated in the ECMWF system, neither were TAMDAR humitities with 'percentage uncertainty' over 15. All the zero humidity reports from ACARS systems were rejected. There was a problem converting TAMDAR flight levels to pressure, due to incorrect BUFR reporting, such that the TAMDAR trials had to be rerun, see Appendix B for details. Operationally there is regular monitoring of all types of assimilated data and stations/variables with particularly poor quality are excluded from the assimilation. Similar exclusions of a small proportion of the extra data were performed by looking at the O-B (observation minus background) statistics from the first week of the trial periods, but this was necessarily somewhat cruder than for the operational system. Before assimilation thinning is performed within aircraft flights: each report is assigned to an 'aircraft level' and a 30 minute time slot, if there are two or more reports with the same aircraft level and time slot and within 60 km of each other then only one report is used (as in Cardinali et al., 2003). The effect of thinning is greatest on flight level ACARS reports where over 50% are thinned whereas for ascent/descent it is less than 20% except around 925 hPa (see Figure 2). This study used 50 'aircraft levels' and in 2003 they approximately matched the model levels up to 100 hPa. Given the increase in model vertical resolution since then (from 60 levels to 91 levels in 2006 and to 137 levels in 2013) the number of 'aircraft levels' was increased to 80 in 2017, reducing the vertical thinning. The horizontal thinning was reduced to 30 km in 2017. Arguably a report with an active humidity datum should be preferred to one without (this is not done at present and would add to the code complexity) but, within reports from the same aircraft, this would have a fairly small effect. There is no duplicate check between reports with different aircraft identifiers, as they are considered independent. There is a check for unreasonable implied aircraft speeds (over 1200 km/h for non-supersonic aircraft) between reports from the same aircraft.

AMDAR/ACARS and TAMDAR temperature bias corrections were calculated/updated using variational bias correction (as in Isaksen et al, 2012, but without dependence on ascent/descent rate). The corrections were independent of height and phase of flight but did depend on aircraft identifier (they were not applied to AIREP reports because the flight identifier available is not specific to a particular aircraft; none of the codes provide aircraft type).

2.2 Humidity analysis

The experiments used the ECMWF Integrated Forecasting System (IFS) cycle 40r3 and cycle 41r1 (Rabier et al, 2000; see ECMWF, 2015, for documentation of IFS cycle 41r1). IFS cycle 41r1 was operational from May 2015 until March 2016. ECMWF uses a nonlinear transform in its humidity analysis (Hólm et al, 2002; Andersson et al, 2005) – a similar method is now used in the Met Office system (Ingleby et al, 2013). The humidity observing systems at the time were described by Andersson et al (2007), but since 15 November 2011 6-hour accumulated precipitation fields from the US radar system have also been assimilated (Lopez, 2011). To be precise, the data used are the NCEP Stage IV precipitation composites, which are based on the NEXRAD network of ground-based radars but also on a few thousands of calibrating rain gauges over the USA (Lin and Mitchell, 2005). In wintertime, the number of NEXRAD observations assimilated in 4D-Var is much reduced, since snowfall situations are rejected. Lopez (2014) compared ECMWF short-range precipitation forecasts with NEXRAD fields for 11.5 years. Radiosonde and aircraft humidity observations are presented to 4D-Var as specific humidity (q) values (surface humidity observations are presented as RH).

2.3 Experiments performed

Period	Start	End	IFS Cycle	Outer loop Res.	NEXRAD	Notes
1	Mar 2011	May 2011	40r3	T511	N/A	TAMDAR altitude problem (see Appendix B for details). Static background errors (see text).
2	Dec 2013	Feb 2014	40r3	T511	Yes	
3	Apr 2014	Jun 2014[1]	41r1	T639	Yes	Extra trials with modified q σ_o

Table 1. Experiment periods and forecast resolution used ([1] these experiments continued to 15 July 2015, but there was an interruption in the ECMWF archive of TAMDAR data after 6 July 2015). All experiments used 137 vertical levels, 12-hour 4D-Var and analysis horizontal resolution of T95/T159/T255 at successive outer loops. Period 1 included ACARS data imported from the Met Office (Appendix B).

Table 1 shows the periods and resolutions used and Table 2 the different experiments performed. For the 2011 period NEXRAD data were not available in a suitable format for assimilation, for the later periods NEXRAD data were available and they were assimilated following operational practice at the time. In recent years there has been increasing use of the Ensemble of Data Assimilations (EDA, Isaksen et al 2010) in providing realistic flow-dependent background error covariances to the deterministic 4D-Var (Bonavita et al, 2012, 2014). The flow-dependent background errors were implemented operationally in May 2011 and were not available for the March-May 2011 experiments.

Operational EDA fields were used with the 2013-2014 experiments. The later periods have more extra aircraft data available and also NEXRAD available for comparison, so they are of more relevance when considering the potential benefit of using more aircraft humidity data operationally. When the problem with TAMDAR altitude was discovered the TAMDAR experiments (TA and AHTA) for the two later periods were rerun, but not for the 2011 period due to prioritizing of computer resources. Following the main set of experiments two extra sets were run for the third period: TA* and AHTA* with TAMDAR humidity observation errors using the same formulation as radiosondes and AMDAR and AH^ and AHTA^ using reduced humidity observations errors for radiosondes and all aircraft humidities (see section 3.2). AH^ was a prospective candidate for operational implementation at ECMWF – note that it includes changes to the use of radiosonde humidity as well as the addition of AMDAR humidity (as noted above the operational use of TAMDAR data would need agreement with FLYHT).

Experiment	CTRL	AH	TA	AHTA
AMDAR humidity	No	Yes	No	Yes
TAMDAR	No	No	Yes	Yes

Table 2. Main experiments performed.

2.4 Previous studies

Petersen (2016) summarises previous studies on the usefulness of AMDAR temperatures and winds – the impact is mainly on days one and two of the forecast. Zhang et al (2015) present a recent evaluation of TAMDAR impact. Other studies include Cardinali et al (2003), Kelly et al (2004), Andersson et al (2005), Wang and Huang (2008), Benjamin et al (2010), Moniger et al (2010), and Gao et al (2012). Morgan (2014, unpublished report) found a slight positive impact from the assimilation of AMDAR humidities and the Met Office started to use the data operationally in 2016. At American Meteorological Society conferences there have been many presentations about aircraft data, including humidity, over North America – mostly looking at case studies. Most previous studies have looked at either AMDAR or TAMDAR data without providing comparisons between them (as we do in the next section).

3 Results

3.1 Observation minus background statistics

Figures 3 and 4 show O-B statistics for experiments 2 and 3 respectively. Assuming that observation and background errors are uncorrelated (which should be approximately true for these variables) these statistics provide a measure of the observation quality, albeit with background errors still included. The statistics are limited to the North American region, but there are differences of sampling within this region which may affect the results to some extent. A brief attempt was made to compare GPS (geometric) heights from TAMDAR reports with background values but the results were relatively poor, it isn't clear whether this is due to poor reported data or a processing error at ECMWF

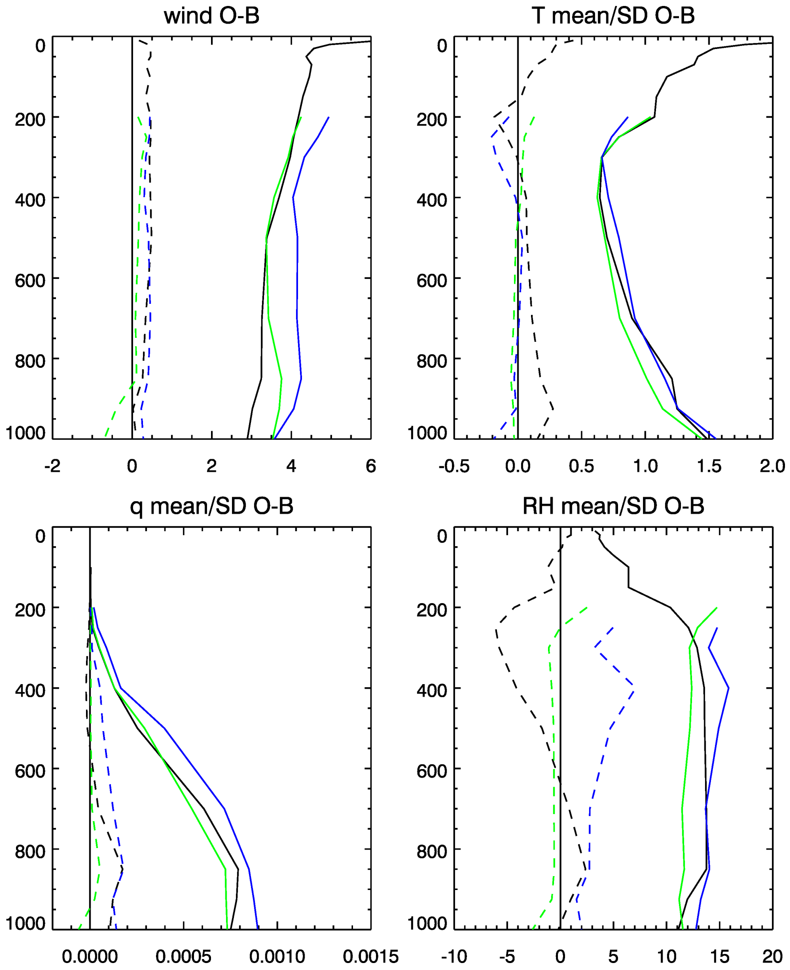

Figure 3 Observation minus background (O-B) statistics for North American region, Dec 2013 – Feb 2014, black – radiosonde standard levels, green – AMDAR, blue – TAMDAR. For wind speed bias (dashed) and vector rms (solid) are plotted (m/s), for other variable the bias (dashed) and standard deviation (solid) are plotted. For wind, temperature and specific humidity (kg/kg) only assimilated values are included in the statistics (AHTA experiment used), for relative humidity (%) values that have passed basic quality checks are included. Temperature bias corrections (and humidity bias corrections for radiosondes) have been applied before the O-B is calculated. Levels with fewer than 200 data points are not plotted.

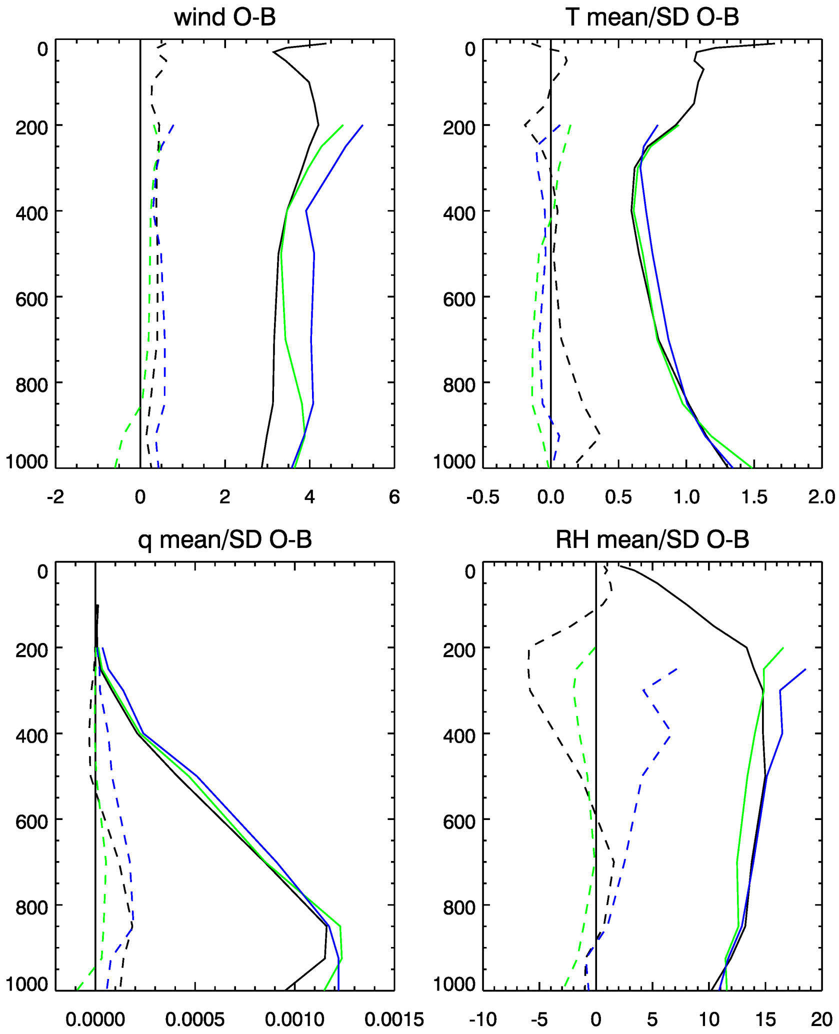

Figure 4 As Figure 3 but for April – June 2014.

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Reported wind speeds are generally slightly stronger than the background, but for ACARS (AMDAR) this is less true and near the surface the ACARS speeds are weaker than the background by about 0.5 m/s. For vector root mean square (rms) differences radiosondes are generally best (smallest O-B) and TAMDAR worst, with AMDAR similar to TAMDAR at low levels but similar to radiosondes in the mid-/upper-troposphere. Temperature O-B SDs are quite similar between the different observation types, although in the winter experiment AMDAR SDs are the smallest up to about 500 hPa. Radiosonde temperatures show a lower tropospheric O-B bias peaking at 925 hPa. The aircraft temperatures match the mean background temperature quite closely – partly due to the adaptive bias correction (in winter TAMDAR has somewhat larger biases at lowest and highest levels and in summer the AMDAR O-B bias has different signs at flight levels and mid-troposphere). The q SDs are larger in summer than Winter (reflecting the temperature dependence – they will also be affected more by low latitude reports than Arctic ones). The q SDs have a maximum near 850 hPa especially in summer (not seen in the TAMDAR statistics), this is probably linked to high variability near the boundary layer top, especially with a moist boundary layer and subsidence above (discussed by Ingleby et al, 2013). The q biases are mainly positive in the lower troposphere, suggesting that the background is slightly too dry. In the upper troposphere the TAMDAR reports are moister than the background and other observations. (In the upper troposphere note that background humidities have been calculated using a different saturation vapour pressure (SVP) equation, see Appendix A; this is responsible for some of the radiosonde minus background RH bias at these levels.) The AMDAR humidity statistics look similar to or slightly better than the radiosonde statistics (especially when looking at RH, the low-level summer q statistics are somewhat worse). Overall the three data types compared have fairly similar quality, with TAMDAR being marginally worse, particularly for winds.

3.2 Observation error estimates

Figure 5 shows the specified observation error (or uncertainty) estimates, σ_o, used in the assimilation system – these are generally larger than the background error estimates, σ_b. The humidity background error estimates in Figure 5 should not be taken at face value because the non-linear humidity transform (Hólm et al, 2002) is used, but appear to suggest that the background humidity errors are underestimated. For radiosondes RH σ_o (in %) was specified as

$$RH_{err} = \min(18, \max(6, -0.15T + 54))$$

where T is the temperature in Kelvin (ECMWF, 2015, section I.2.6.2; in 2017 they were reduced and made a function of radiosonde type), this is then converted to q σ_o. It was assumed that this would also be approximately correct for aircraft humidity. However, in retrospect these RH σ_o estimates (about 10/13/16 %RH at 20/0/-20°C respectively) are too large (greater than the O-B SD statistics) and should be updated. For TAMDAR a value of σ_o=15 %RH was specified during the development phase, and by an oversight this was not replaced by the formula above. The Vaisala RS92 datasheet (http://www.vaisala.com/Vaisala%20Documents/Brochures%20and%20Datasheets/RS92SGP-Datasheet-B210358EN-F-LOW.pdf) suggests a measurement uncertainty of 5 %RH, some other radiosonde types are rather worse particularly in the upper troposphere (due to slow reaction of the sensor in cold conditions and also sometimes 'wetting' as the sensor passes through cloud). Note that the measurement error is combined with representativeness error (accounting for point measurements versus grid box average differences) to give the 'observation error' as used in the data assimilation system (and it is the ratio of σ_o / σ_b that determines the observation weight). The O-B statistics in figures 3 and 4 suggest somewhat smaller values of σ_o near the surface than an approximately constant value (not the continued increase with height as in Figure 5). Humidity data are not assimilated in the stratosphere so σ_o there doesn't matter in practice. Gao et al (2012, table 2 and figure 11) suggested TAMDAR RH measurement errors of between 5.5% at 1000 hPa and 8% at 300 hPa and above. These values seem approximately consistent with the ECMWF O-B statistics (see next subsection) and a σ_o profile of 6%RH at 1000 hPa, 8%RH at 850 hPa and 10%RH at 700 hPa and above was trialed for both radiosonde and aircraft data. Note that reduced σ_o also tightens the background check - the number of radiosonde humidity values assimilated is reduced by 2-3% (mainly at upper levels in the tropics).

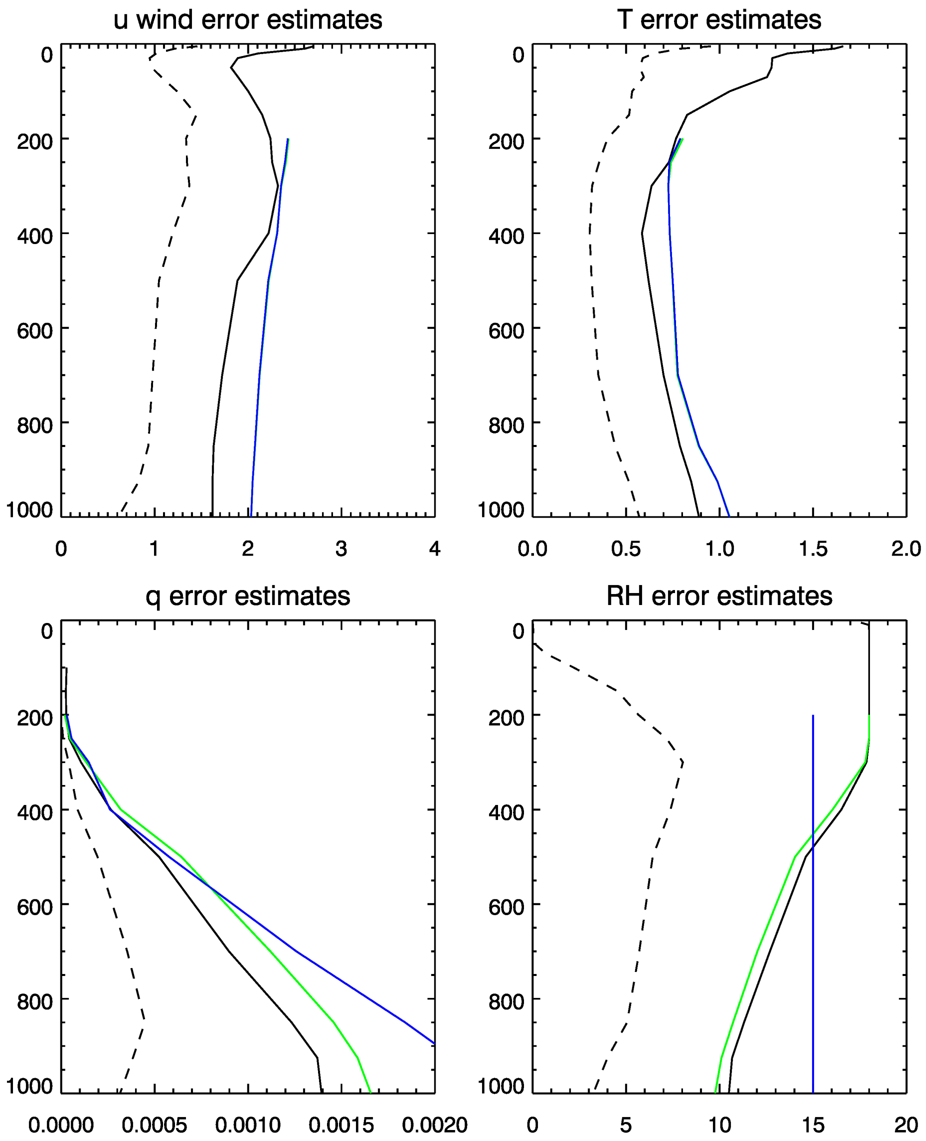


Figure 5 Average specified observation error (or uncertainty), σ_o, estimates for June 2014 – solid lines (colours and units as in Figure 3; radiosonde temperature and humidity, σ_o, estimates have since been reduced for most radiosonde types). The temperature and wind estimates are time independent, see text regarding humidity estimates. Multiply the u-wind σ_o by $\sqrt{2}$ for comparison with vector rms. For wind and temperature AMDAR and TAMDAR have the same error profile specified. The dashed lines show an estimate of background error at the radiosonde locations (it is similar at aircraft locations – not shown) calculated using the EDA spread. For wind and temperature this is the HBHT used in the 4D-Var, for humidity the background error estimate is complicated by the non-linear humidity transform.

3.3 Synoptic verification

For synoptic scale verification the 500 hPa geopotential height scores against the operational analyses were investigated for the three trial periods. Overall the impact is small and visible more at longer range (not shown). In trials 1 and 3 the signal is similar at different levels and also for rms (not shown), but in trial 1 AHTA is slightly worse than the control whereas in trial 3 it is marginally better. Looking at score differences with estimated error bars (example in Figure 6) the impact in trial 1 was detrimental at day 1 (in trial 1 AH was very similar to the control but TA was slightly worse). Recall that the TAMDAR experiments in trial 1 used the wrong TAMDAR altitude so the results of the TA and AHTA trial 1 experiments should perhaps be discounted. In trial 2 there is little signal at 500 hPa (not shown) but some at 1000 hPa, with AHTA marginally better than the control (lower panel of Figure 6). Results with reduced humidity σ_o (not shown) are slightly improved but the differences are generally small compared to the uncertainties in the scores (one exception is that RMS Z100 scores against operational analyses are improved at short range, perhaps reflecting small changes in biases).

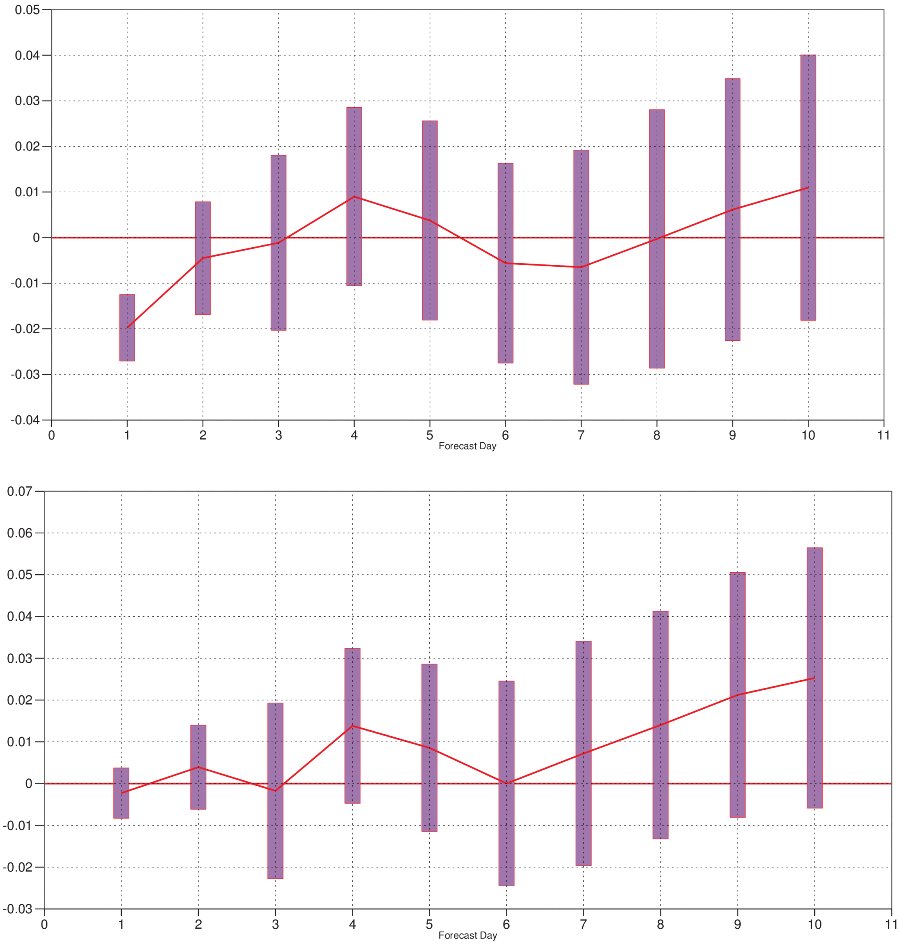


Figure 6 AHTA minus control anomaly correlation scores with an estimate of the uncertainty for the northern extratropics. Top: 500 hPa trial 1, bottom 1000 hPa trial 2. Positive (negative) values indicate that AHTA is better (worse) than the control.

3.4 Humidity fields

For temperature, humidity and wind maps of various mean and rms fields were examined, most of these did not show any statistically significant impact. However, Figure 7 shows that some mean RH changes were introduced by the TAMDAR reports in some North American locations (similar mean differences were found in trial 2, not shown, there are also small mean temperature differences in the same locations). These mean differences are consistent in the vertical but fade over the first two days of the forecast. These localized North American differences, for specific airports, are slightly suspicious (and not seen in the AH experiment) but further investigation would be needed to provide a more definitive assessment. The tropical region differences are just due to small model field differences causing changes in the exact location of tropical convection.

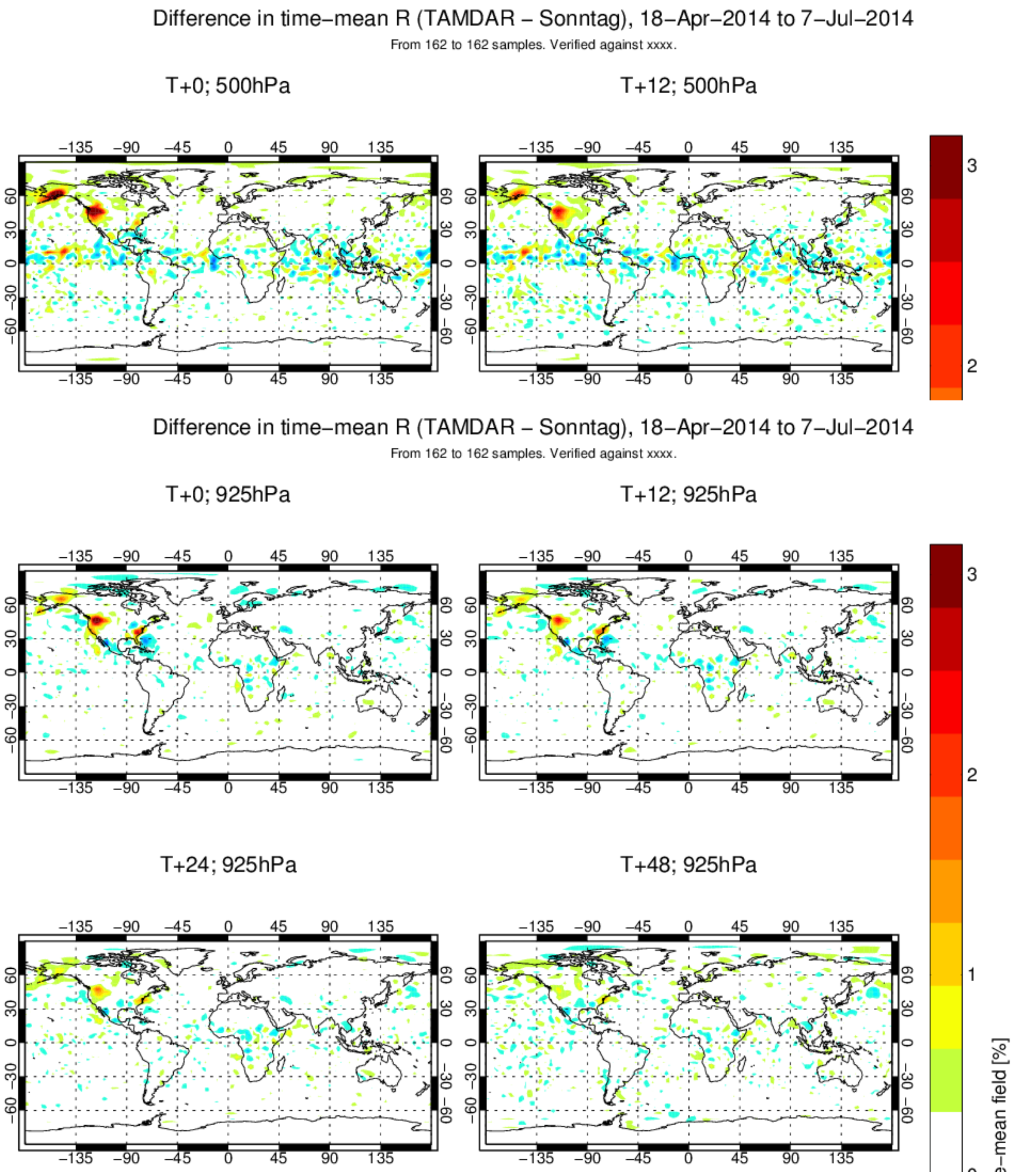


Figure 7 Time mean humidity differences, TAMDAR – Control experiments, trial 3.

3.5 Precipitation verification

The precipitation variable used in assimilation is ln(RR+1) where RR is the rain rate in mm/h averaged over six hours (Lopez, 2011). Figure 8 shows mean differences for this variable between the observations (gridded composites of NEXRAD and SYNOP) and background for the different experiments for trial 3 – including TA* and AHTA*: experiments in which TAMDAR humidity σ_o uses the same formulation as for radiosondes/AMDAR. (Similar plots are available for trial 2, but the number of observations is much lower due to the exclusion of snow conditions.) Both the AH (top right) and TA (bottom left) experiments give some improvements (more grey squares, indicating little bias) relative to the control (top left). TA* represents an improvement over TA, but the difference between AHTA and AHTA* is less clear cut. Tables 3 and 4 summarise the fit of the different experiments to the precipitation composites, for both trials AH gives the best mean O-B fit and good SD O-B but the best SD O-B are for TA*/AHTA* (SD O-A is slightly larger with some of the extra data, because the analysis is then a compromise between more sources of data). Mostly the extra aircraft data (but not AH in trial 2) result in a slight increase in the numbers of precipitation pixels passing the quality control (reflected in the number of points) – also a sign of slightly improved precipitation background.

	Background	Background	Analysis	Analysis	Number of
Experiment	Mean O-B	SD O-B	Mean O-A	SD O-A	points
Control	-0.030	0.346	-0.000	0.237	169759
AH	-0.020	0.346	-0.000	0.236	172953
TA	-0.029	0.346	-0.000	0.238	170098
AHTA	-0.023	0.345	-0.000	0.237	172484
TA*	-0.025	**0.344**	-0.000	0.238	170952
AHTA*	-0.020	**0.344**	-0.003	0.237	172336
AH^	-0.017	**0.344**	-0.001	0.237	171994
AHTA^	**-0.016**	**0.344**	-0.002	0.239	173216

Table 3. Summary of fit to NCEP precipitation estimates for April – June 2014 (trial 3). * indicates experiments in which TAMDAR humidity σ_o uses the same formulation as radiosondes/AMDAR and ^ indicates lower humidity σ_o values (6-10%RH) for both aircraft and radiosonde data.

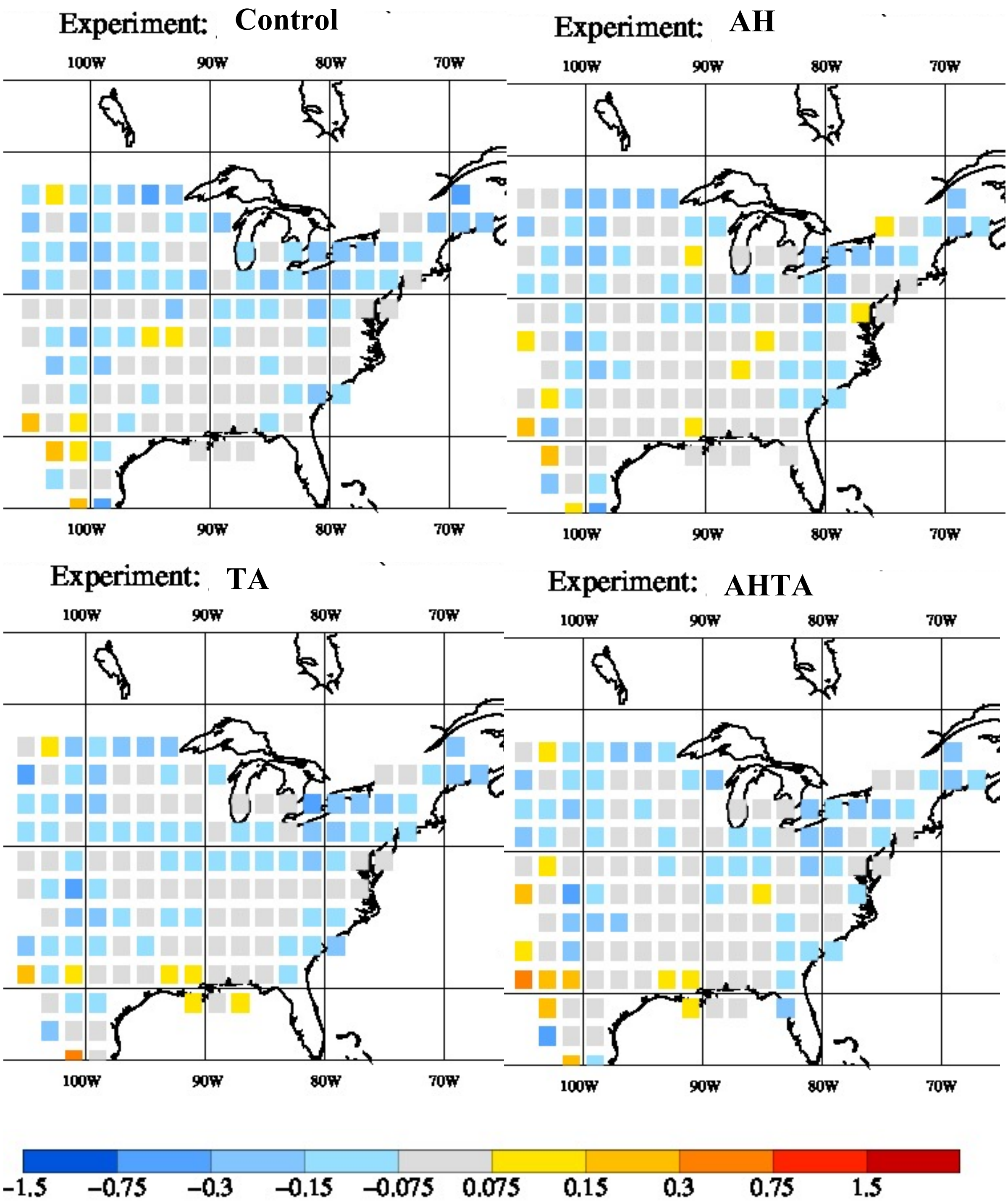


***Figure 8** Mean fit to NEXRAD/SYNOP precipitation fields: O-B Ln(RR+1) normalised departures for 1 April – 30 June 2014. Top left Ctrl, top right AH, bottom left TA, bottom right AHTA.*

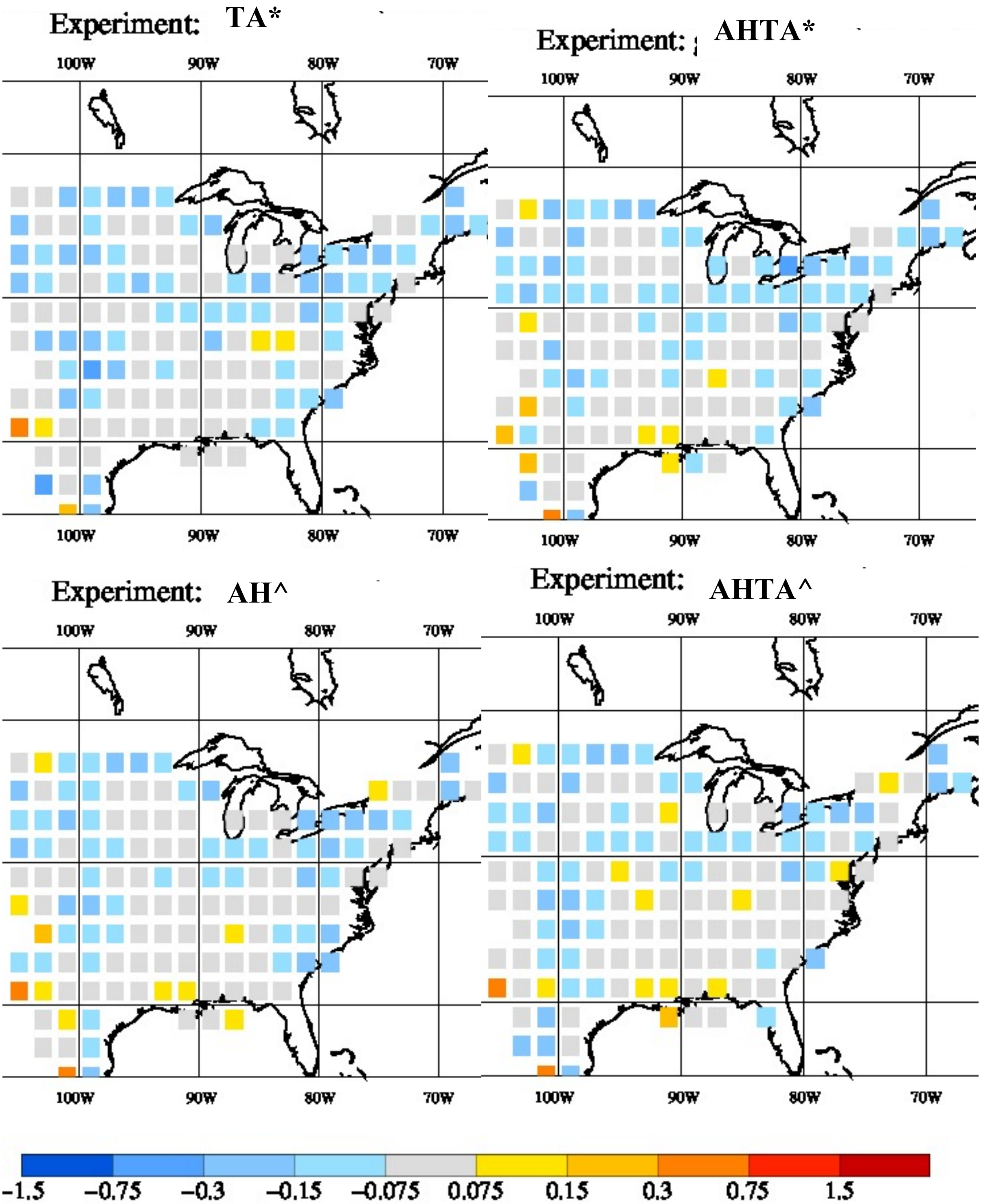


Figure 8 continued. Top: left TA*, right AHTA*, experiments with TAMDAR humidity σ_o using the same formulation as for radiosondes/AMDAR. Bottom: left AH^, right AHTA^ using smaller humidity σ_o for all aircraft and radiosonde reports.

	Background	Background	Analysis	Analysis	Number of
Experiment	Mean O-B	SD O-B	Mean O-A	SD O-A	points
Control	-0.010	0.271	-0.005	0.197	55423
AH	**-0.003**	0.267	-0.005	0.199	55256
TA	-0.008	0.269	-0.009	0.199	55530
AHTA	-0.006	**0.266**	-0.009	0.199	55586

Table 4. Summary of fit to NCEP precipitation estimates for December 2013 – February 2014 (trial 2).

Figures 9 and 10 show Equitable Threat Scores (ETS) for trial 3, with forecasts from 00 and 12 UTC analyses shown separately. For 6-12 hour forecasts (Figure 9) the extra aircraft data gives larger (better) ETS scores than the control, for the forecasts from 12 UTC AH and TA perform similarly and AHTA is best, for the forecasts from 00 UTC the situation is more mixed. For 18-24 hour forecasts (Figure 10) from 00 UTC the AHTA forecasts are slightly improved over the control but AH and TA are not, from 12 UTC the experiments all have similar ETS for lower thresholds but the control is slightly better for higher thresholds. Somewhat different precipitation biases are seen at different times of day (not shown).

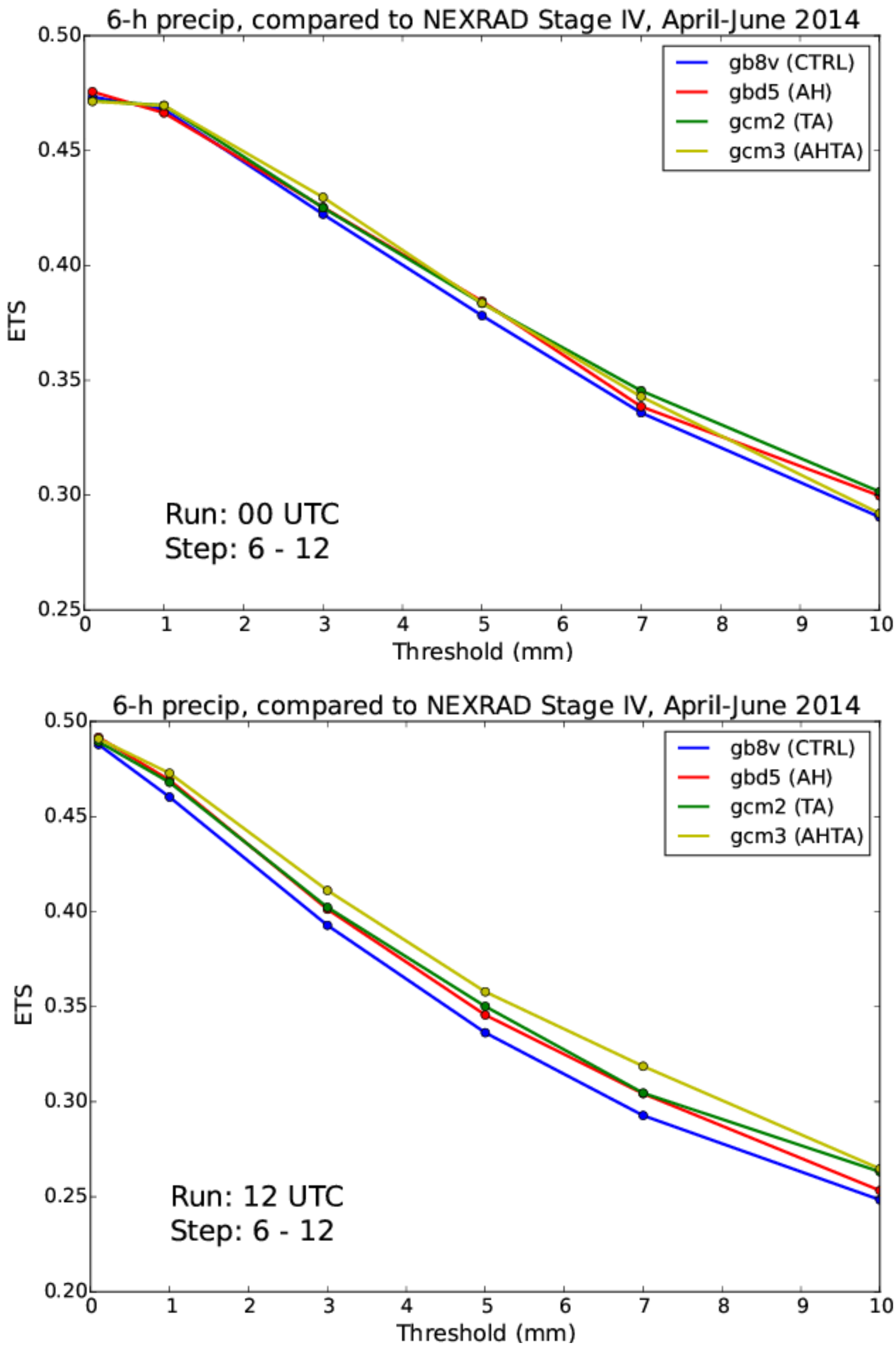
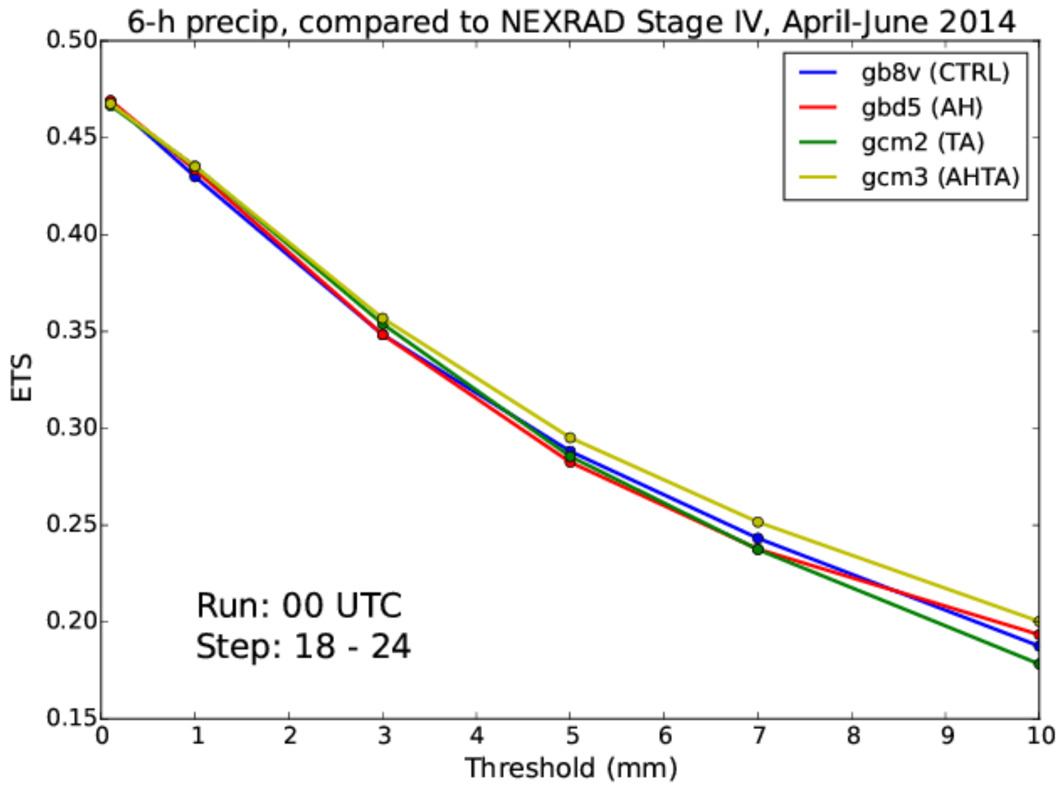


Figure 9 Equitable threat score vs NEXRAD/SYNOP composite. Forecast hours 6-12 (overlaps the assimilation window by 3 hours). Forecasts from 00 UTC (top) and 12 UTC (bottom).



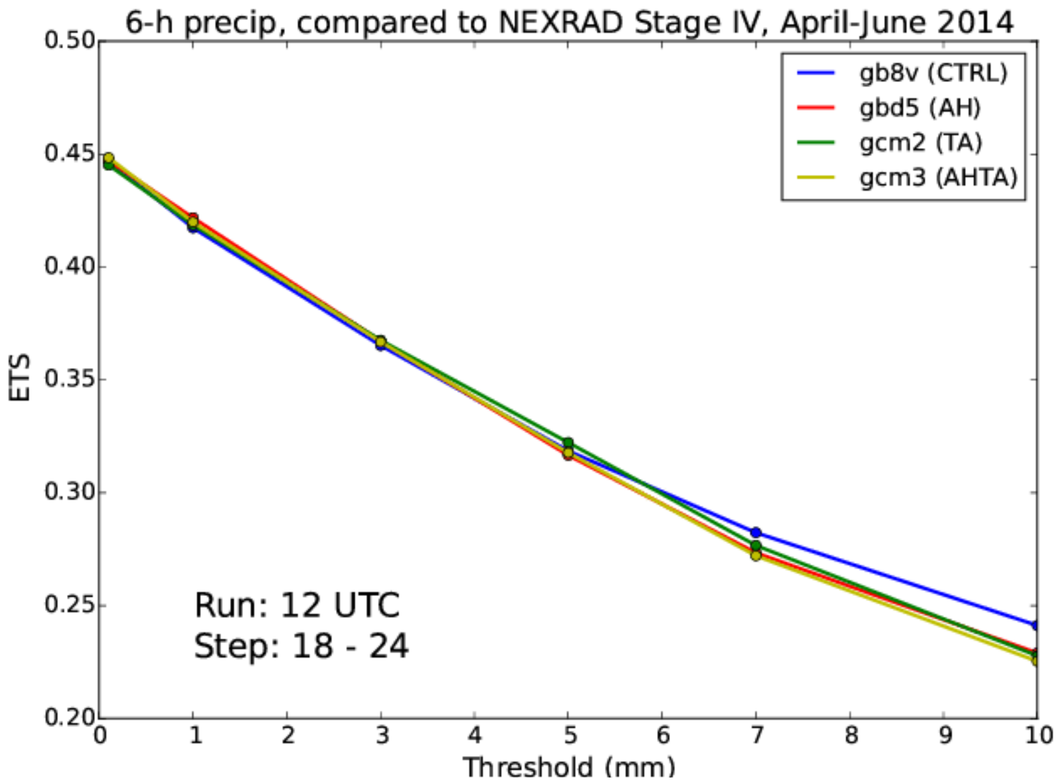


Figure 10 As figure 9 but for 18 -24 hour forecast.

3.6 Comparison with SYNOP variables

Several results are shown for comparison of trial 3 forecasts over North America with SYNOP observations. From days 3-6 the precipitation verification is generally slightly improved over North America (possibly due to improved soil moisture), Figure 11. The forecast precipitation is higher than that measured and increases slightly with forecast range. For screen temperature AHTA forecasts show slightly improved rms over the control at days 5 and 6 (real signal or not?), Figure 12. At 12 and 24 hour range there is slightly improved rms fit to SYNOP dew point temperature from the extra aircraft data (but TAMDAR slightly increases the bias), Figure 13. As this is at short range the link to the extra observations is clearer. See Appendix C for results on analysis and forecast sensitivity to the aircraft data.

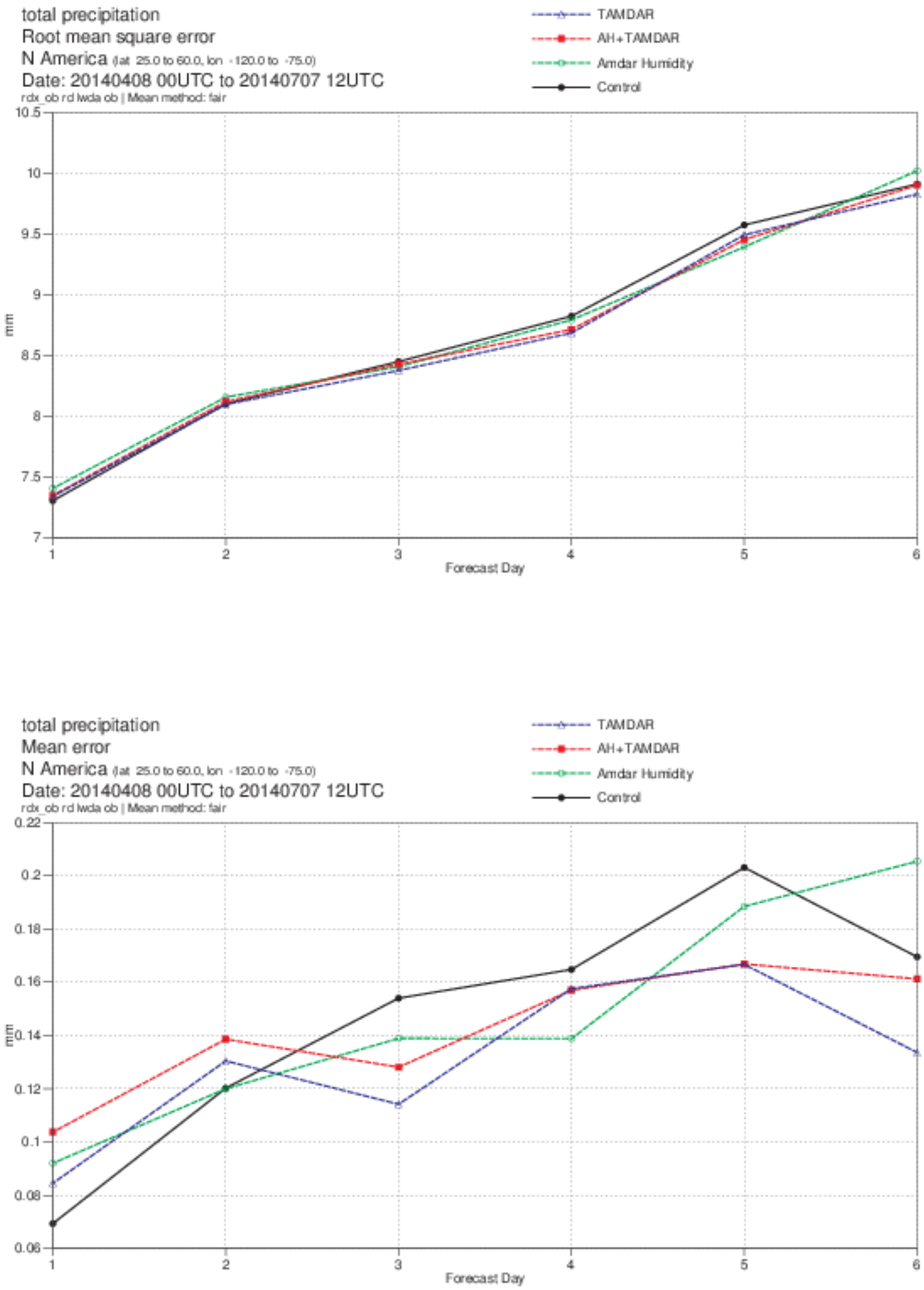
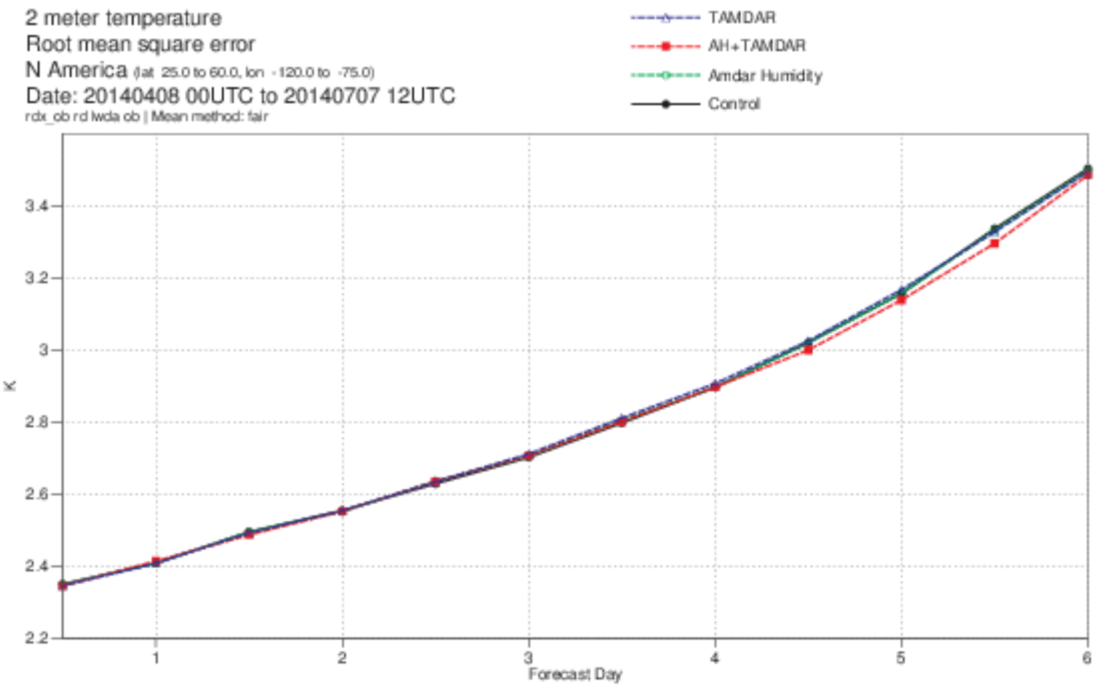


Figure 11 Rms and mean verification against North American SYNOP precipitation data, trial 3.



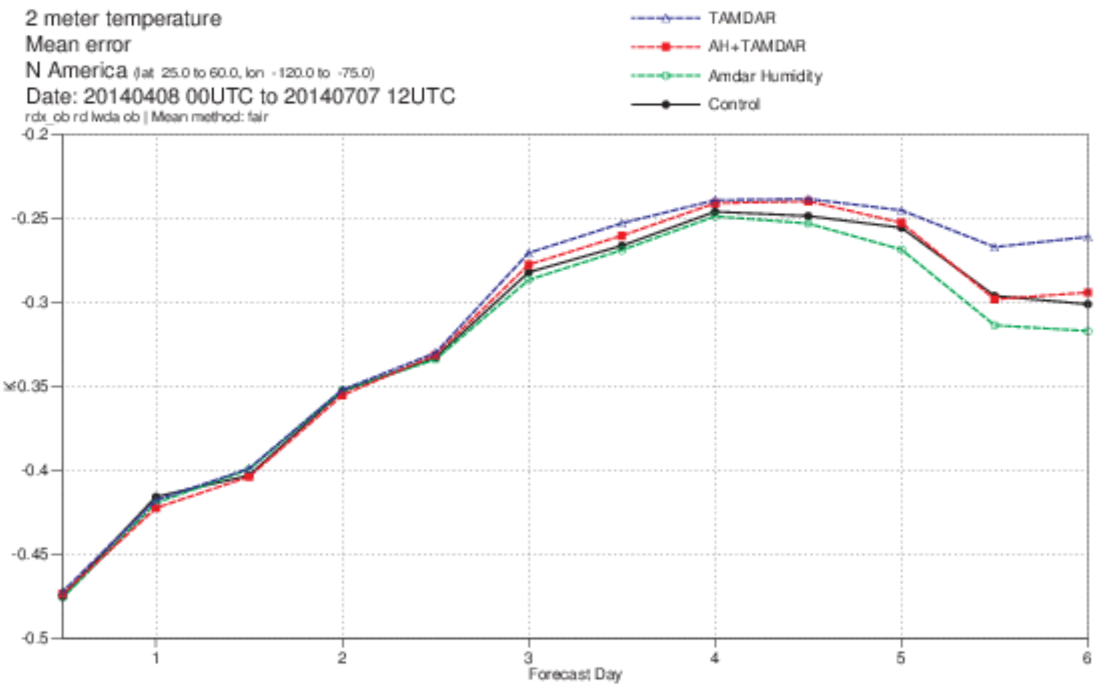
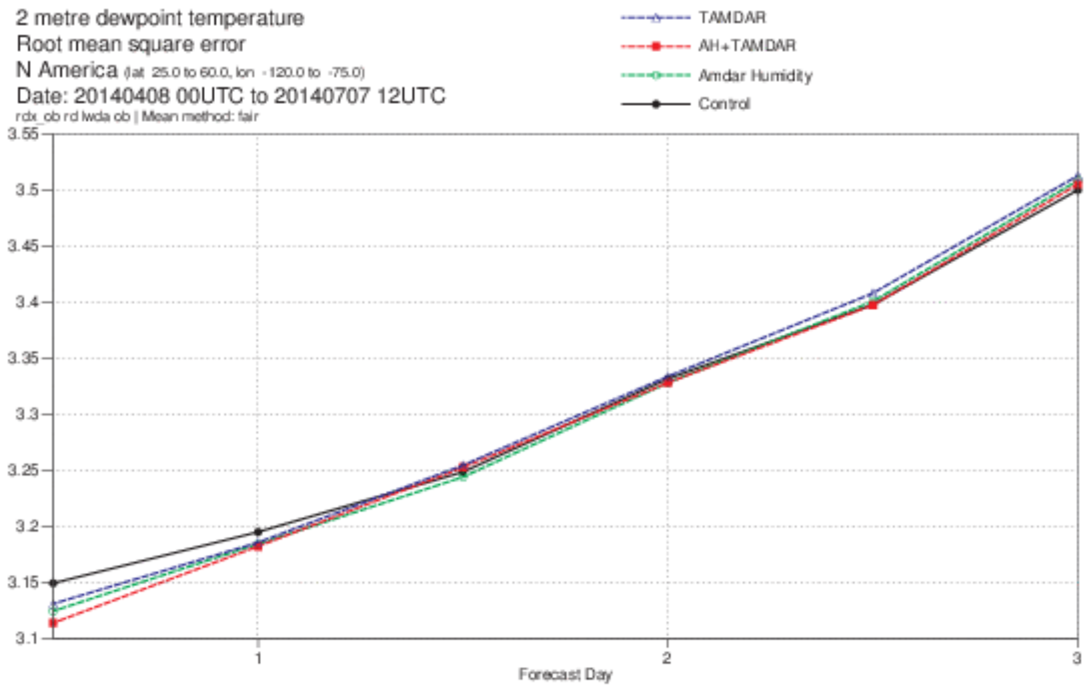


Figure 12 As Figure 11 but for screen temperature.



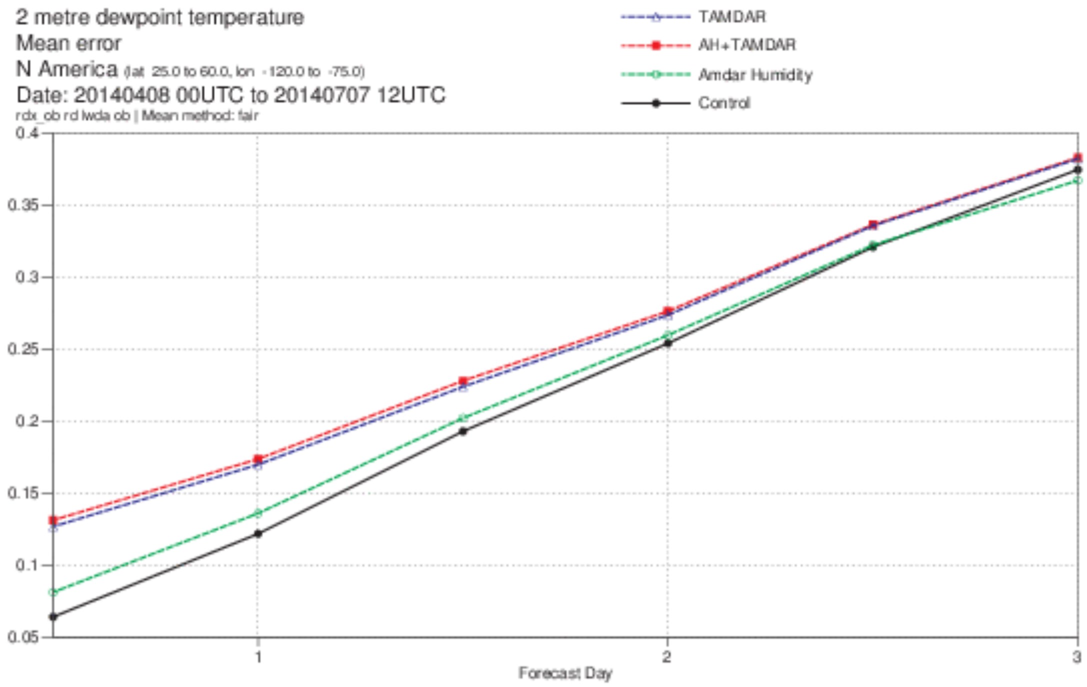


Figure 13 As figure 11 but for dew point temperature and first three days only (all experiments similar for days 4-6).

4 Developments in assimilation of aircraft data at ECMWF since performing these experiments

The assimilation experiments in this study were performed some time ago using IFS cycle 40R3 and cycle 41R1 from 2014-15. Here we provide a brief description of aircraft related developments since then, especially at ECMWF. In November/December 2014 European AMDAR reports migrated (airline by airline) to the "WIGOS" BUFR format (template 311010). In March 2017 the US AMDAR reports changed to use the "WIGOS" AMDAR format (and stopped being known as ACARS in the ECMWF IFS). Smaller numbers of reports are still being received in old versions of the AMDAR format and the even older AIREP format (AIREP data is still relatively dense over the North Atlantic, but in some cases there may also be AMDAR reports from the same flight).

On 8 March 2016 (with the operational introduction of IFS cycle 41r2), ECMWF started the operational assimilation of humidity data from commercial aircraft reporting via the AMDAR programme. Most of the humidity data comes from the US AMDAR programme but there are also nine aircraft from its European equivalent, E-AMDAR. Comparison with the ECMWF forecast fields was useful for finding and resolving some teething problems when the E-AMDAR aircraft upgraded to a newer version of the WVSS-II. After the end of the study described in section 2 and 3 TAMDAR data was still received for some months but could not be used operationally due to restriction on the operational use of the data. The roll out of TAMDAR to European airlines proved to be slower than originally expected and EUMETNET did not fund operational acquisition. Hoover et al (2016) describe experiments with aircraft humidity data at NCEP.

Overall aircraft data volumes are increasing, Ingleby et al (2016) mention an E-AMDAR increase in February 2016, although the biggest increases have come from the US AMDAR program. In November 2016, supported by NOAA, LATAM data from South America became available. Some of the increase in reporting comes from data being converted from air traffic control reports (called ADS-C data). Very high resolution aircraft data have been derived from air traffic control messages received directly by a ground station (de Haan and Stoffelen, 2012). These "MODE-S" observations have been investigated/used at several European NMSs. MODE-S winds are good quality but the temperature data has poor precision. As they become more standardised and widely exchanged we expect that ECMWF will start to receive and test MODE-S data, but they would need considerable thinning for use in a global NWP system.

Aircraft temperature values are typically biased high by between 0.2 and 0.5˚C, depending on the aircraft (eg Isaksen et al, 2012; Zhu et al, 2015). In November 2011, ECMWF implemented a variational bias correction scheme similar to the one applied to satellite soundings (Isaksen et al, 2012). It dynamically estimates the bias for each AMDAR reporting aircraft. On 5 June 2018 (with IFS cycle 45r1) the aircraft data bias correction method was updated in two ways a) two additional predictors for ascending and descending biases, computed as function of dz/dt, calculated from successive reports from an aircraft, were introduced, b) all AIREP temperatures were given the same bias correction (previously these were uncorrected because we cannot identify individual aircraft). AIREP observations are concentrated in the North Atlantic flight routes between Europe and the USA, where they account for up to 50% of cruise level aircraft reports. With IFS cycle 45r1 there were also a significant reduction in horizontal and vertical thinning of aircraft data (Ingleby et al, 2018). The new bias correction scheme has also been applied in ERA5.

Since November 2017, most aircraft that provide AIREPs have, via ADS-C, provided AMDARs as well (but not exactly at the same positions or using the same identifier, making duplicate checking difficult). With the availability of most data in AMDAR format it was decided to stop assimilating the AIREP temperatures from 10 January 2018.

In late 2017 ECMWF noted a quasi-intermittent error in some aircraft wind directions. It turned out to be a known problem affecting a subset of reports from Boeing 787 aircraft. Unfortunately, aircraft type is not available in the AMDAR code. It may become available via OSCAR/Surface. In 2018 there was a blacklist change, based on a selective list of most of the active Boeing 787 aircraft. which reduced the problem at the cost of rejecting many good aircraft winds. Work is ongoing to resolve this issue. The problem and the ECMWF response will be reported more fully elsewhere.

5 Discussion and conclusions

Comparison with short range forecasts suggests that the quality of AMDAR and TAMDAR reports is similar to that of radiosondes – with TAMDAR being slightly worse for wind and possibly upper level humidity. For humidity the fit to background suggests that over North America the AMDAR quality is better than radiosonde quality at some levels. The observation influence on analyses of all the in situ humidity observations is rather low – primarily because synoptic scale weather is generally determined from the temperature and wind fiends and partly because the observation error was overestimated for radiosondes and the same profile was used for AMDAR. By an oversight TAMDAR was given even larger humidity errors at low levels, but this was corrected in reruns for one trial period, though without change in the impact. It is also possible that the effective background humidity error is underestimated. So, the impact on large scale verification scores is rather small.

Comparison with radar precipitation estimates over North America shows some improvements from the extra aircraft data at short range. The modest impact is partly because North America is already a data dense area and the ECMWF forecasts are already very good in general (it is always easier to improve indifferent forecasts). However, note that occasional poor 6-day forecasts over Europe can be traced back to analysis problems over North America in strongly convective situations (Rodwell et al, 2013). An examination of verification timeseries for downstream regions did not lead to any clear conclusions for this study.

Based on background error covariances, which tend to be shorter scale for humidity than for temperature, the ideal sampling density for humidity should be at least as high as for temperature.

The study identified a number of observation format and quality issues. We excluded all zero humidity reports from ACARS because about 300 aircraft reported zero instead of missing data (since fixed). There was a problem with altitudes in the TAMDAR BUFR format (Appendix B) such that some of the experiments had to be rerun.

ECMWF started to monitor E-AMDAR humidity data (from nine Lufthansa aircraft) operationally in the first half of 2015 and provided useful feedback about teething problems when the E-AMDAR systems were upgraded to the latest version of WVSS-II. AMDAR humidity data (from both American and European aircraft) was assimilated operationally from March 2016. In January 2018 ECMWF stopped assimilating AIREP temperatures (due to bias issues and because most of the data became available in AMDAR format). Finally, an improved variational bias correction of AMDAR temperatures and reduced thinning of aircraft data was implemented with IFS cycle 45R1 in June 2018. One aspect under consideration is to further evaluate and possibly implement a reduction in the assigned humidity observation error for aircraft data.

6 Acknowledgements

This study was supported by EUMETNET. Panasonic provided the TAMDAR data for evaluation and Neil Jacobs and Peter Childs provided various details of TAMDAR processing. Philippe Lopez and Thomas Haiden from ECMWF provided the comparisons with NEXRAD data. Adam Maycock supplied ACARSmr data from the Met Office for the 2011 trial. At ECMWF Peter Lean helped to ingest the ACARSmr data, and Ioannis Mallas, Enrico Fucile and Drasko Vasiljevic helped to set up the other new data streams.

7 Appendix A: Humidity calibration and computation

From WMO (2018, chapter 12): "The saturation with respect to water cannot be measured much below -50 °C, so manufacturers should use one of the following expressions for calculating saturation vapour pressure relative to water at the lowest temperatures, Wexler (1976, 1977), Hyland and Wexler (1983) or Sonntag (1994) and not the Goff Gratch equation recommended in earlier WMO publications." The recommended equations for saturation vapour pressure (SVP) all give very similar results (see http://cires1.colorado.edu/~voemel/vp.html) and we understand that most major radiosonde manufacturers use one or other of them in calibration/computation procedures. Until November 2016 the ECMWF operational system used the Buck (1981) SVP equation below 0°C for converting radiosonde dew point temperature to specific humidity. As discussed by Ingleby (2017) we changed to operational use of the Sonntag (1994) equation at cycle 43r1 and this was used in the control experiments described above. Atmospheric humidity (above screen level) is presented to the assimilation as specific humidity.

Information about the calibration of TAMDAR sensors was provided by Chris Flynn of Panasonic (2014):

"We use capacitive humidity sensors in TAMDAR. These come from the factory with an accuracy of +/-2.5%RH over the operating range. We also request for the manufacturer to perform a factory calibration of each sensor. This is a 2 point calibration and improves the accuracy a bit; approximately +/-2%RH. However, we do our own proprietary calibration after that that uses 20 points, and this improves the accuracy further. This is done in a Thunder Scientific 2500-LT humidity chamber. We just vary temperature and humidity and capture the sensor output voltage at 20 different points.

The unique 20 point calibration data that is used to generate coefficients is proprietary 2D (temp and humidity) 2nd order curve fit for humidity. I can't publish this.

The Chamber is a Thunder Scientific, Model 2500-LT. We use it for humidity values from 9% to 95% and temperature values from -12C to +40C.

For approximately 0% humidity we use a desiccant filled container (the desiccant absorbs all the moisture in the container). We put the container in a temperature chamber and calibrate over a range of -40C to +40C.

We use 20 points over the ranges described above to calibrate our humidity sensors."

It isn't clear which SVP equation is used (implicitly or explicitly) in the calibration – however it is below -40C that they deviate most. Perhaps the calibration should focus more on the low RH range because of Mach heating.

The measured RH has to be converted to the ambient or static RH (using an SVP equation), see WMO (2018, section 3.8.2.2) or Fleming (1996, Appendix). "The range of RH that will be experienced by the RH sensor is also reduced due to the Mach heating. At high speeds, the RH internal to the probe will generally be less than 10% due to the Mach heating of the air." WMO (2018). The reported RH is relative to water (even below 0°C) following WMO practice.

The SVP equation used for TAMDAR processing is

$$e_s(T) = 0.61078.10^{\left(\frac{C_1 T}{T+C_2}\right)}$$

Where T is in Celsius, e in kPa, $C_1 = 7.5\ and\ C_2 = 237.3$ (D Mulally, 2008, forwarded by N Jacobs, 2014; this is the Magnus Tetens formulae as given by Murray, 1967).

In retrospect this equation should ideally have been used (instead of Sonntag, 1994) to convert reported TAMDAR RH to specific humidity in the ECMWF trials (and to convert model q to RH at TAMDAR locations for RH diagnostics), however it only makes much difference at low temperatures (give example). Note also that the reported RH and the model RH are not strictly comparable because they use different equations for SVP over water. If there is a move to use TAMDAR data operationally then this issue should be reconsidered and discussed with Panasonic. One option would be for the TAMDAR processing to use the Sonntag (1994) equation for consistency with WMO (2018).

8 Appendix B: Processing details

Operationally ECMWF had 'ACARS' input files which do not include humidity even if that was present in the data as received from the GTS – 'ACARSmr' files were set up that do include the humidity mixing ratio were used instead. (For 2011 the ACARSmr data had to be obtained from the Met Office and various problems with missing data indicators had to be overcome. The Met Office data did not include quality indicators, but for ACARS this is a minor issue; there was also a problem generating 'observation feedback' files, this does not affect the analysis quality but does mean that some diagnostics are not available.) To avoid slight differences in observation coverage due to fractionally different cut-off times the Control runs used 'ACARSmr' but without the humidity being assimilated. The small numbers of E-AMDAR humidities were not included in the trials, they have been monitored operationally since June 2015.

After the TAMDAR trials had been run it was noticed that a) there were large 500 hPa analysis height differences over Mexico which persisted and spread during the forecast and b) there was a very marked height dependent temperature bias in the TAMDAR O-B differences over Mexico. Investigating further and discussing the issues with Panasonic we realised that the wrong altitude had been converted to pressure using the standard atmosphere equations – this was corrected and the TAMDAR trials rerun for two of the trial periods. The TAMDAR BUFR reports contain both i) pressure altitude or flight level and ii) GPS altitude. Following the WMO definition of BUFR indicator 0 07 010 as flight level both ECMWF and DWD converted that to pressure (see WMO Codes https://www.wmo.int/pages/prog/www/WMOCodes.html). In the TAMDAR code (unofficial BUFR template) 0 07 010 is misused as GPS altitude. Over the Contiguous US the two altitudes match relatively closely, at least on average. In the trials it was easy to convert the other altitude to pressure, but in our opinion the coding issue should be corrected before any operational use of TAMDAR data. There is also some misuse of BUFR to store the RH percentage uncertainty – a two-bit quality flag as for the other variables would be simpler/clearer.

9 Appendix C. Analysis sensitivity to observations

It was decided to look at analysis sensitivity to observations, a discussion on how this compares to the more frequently used forecast sensitivity can be found at the end of the section. Analysis influence diagnostics measure the change in the analysis (projected into observation space) for a small change in the observation y_i: $\partial\hat{y}_i/\partial y_i$ (Cardinali et al, 2004). Computing them involves some extra computations in the 4D-Var analysis. Values are computed for each assimilated datum and then averaged as required. Figure C1 shows values from the summer trial and for aircraft wind and temperature can be compared to Figure 4.4 of Cardinali (2013). The basic features are similar: wind observation influence increases with height whereas it is more constant in the vertical for temperature, however the magnitudes are smaller than in Cardinali (2013; at flight levels values reached 0.4) – probably because North America is a data dense area. For AMDAR and TAMDAR the values are rather similar, for radiosondes they are somewhat larger (with the suggestion of reduced influence at aircraft flight levels). There are several possible reasons for the larger influence of radiosonde data, slightly smaller σ_o, locally less dense observations (aircraft tend to cluster in certain areas), and the fact that radiosondes report near the start of the assimilation window. Figure C2 shows that reports near the start of each analysis window (2100-0900 UTC and 0900-2100 UTC) have larger analysis influence than those near the end of the window (also seen for wind and for TAMDAR, not shown; most radiosonde reports have nominal times of either 0000 or 1200 UTC). The likely explanation for this is that observations near the start of the analysis window can be fitted using decaying modes. Observations near the end of the window project more onto growing modes – and therefore are more important for constraining forecast error growth.

Zero analysis sensitivity to an observation would suggest zero forecast sensitivity, but apart from this there is no direct link between analysis and forecast sensitivity. The rather small analysis influence of near surface wind reports (top panels of figure C1) is probably related to the boundary condition – wind goes to zero at the surface. Ten-metre winds from land stations have little impact on forecasts whereas screen temperature and humidity together have a noticeable positive impact (Ingleby, 2015, and references). Humidity analysis influence becomes very small near the surface. (The typical range of RH values at a particular surface location can be quite small, especially at night when the distribution bunches up near saturation (Ingleby, 2015), however this would not affect the observation influence diagnostic.)

The other obvious feature of Figure C1 is the rather low influence of humidity observations – due partly to the overestimate of σ_o and the possible underestimate of σ_b. For humidity the influence of AMDAR and radiosondes is similar (perhaps suggesting that it is not limited by observation density), the TAMDAR influence deviates consistently with the relative specification of σ_o. Figure C3 shows results for q observation influence using a) the same σ_o function for TAMDAR as for radiosondes and AMDAR – the TAMDAR influence is much closer to the other types as expected, and b) a σ_o of 6%RH at 1000 hPa, 8%RH at 850 hPa and 10%RH at 700 hPa and above. The smaller (more realistic) σ_o estimates give greater weight/influence to the observations, but still less than for temperature. In section 3.6 some precipitation results are shown for modified TAMDAR σ_o (option a).

One related option to provide an estimate of forecast impact is Forecast Sensitivity to Observations Influence (FSOI), see Baker and Daley (2000) and Langland and Baker (2004) (in computational terms analysis sensitivity adds slightly to the cost of 4D-Var whereas FSOI adds significantly to the cost and has to be run separately, one day later, when the verifying analysis is available). For a more recent period figure C4 shows the FSOI as a function of observation time within the analysis window. This uses a dry energy norm at T+24 and verification against analyses (see Cardinali, 2018, for a comparison with verification against observations). (Lorenc and Marriott (2013) use specific humidity in a moist energy norm – this choice gives a larger sensitivity to humidity observations in summer than in winter; which may or may not be desirable.) Negative values indicate an improvement to the forecast, so aircraft winds provide more benefit than aircraft temperatures. Aircraft humidity only gives a small net benefit, but the use of a dry norm for verification will tend to underestimate the impact of humidity data.

The other clear signal in figure C4 is that data near the end of the assimilation window provides more benefit than data near the start - this is also seen for surface and satellite data. However it seems to be in direct contradiction to the analysis sensitivity results in figure C2. McNally (2019), using satellite data denial experiments, supports the FSOI implication that data late in the assimilation window is (much) more valuable. FSOI uses a global metric to look at the impact whereas analysis sensitivity uses a point value - at the observation location and time. For an observation at the start of the window it is "easy" to fit the datum using a relatively localized perturbation, an observation at the end of the window is more difficult to fit and advection and diffusion will mean that the perturbation involved will be much less localized at the end of the window. FSOI statistics need to be interpreted with care (there are various assumptions/linearisations and both analyses and observations have limitations for verification) but overall they are useful. It appears that analysis sensitivity statistics are less useful and that they can be misleading when comparing observations at different points during the 4D-Var assimilation window.

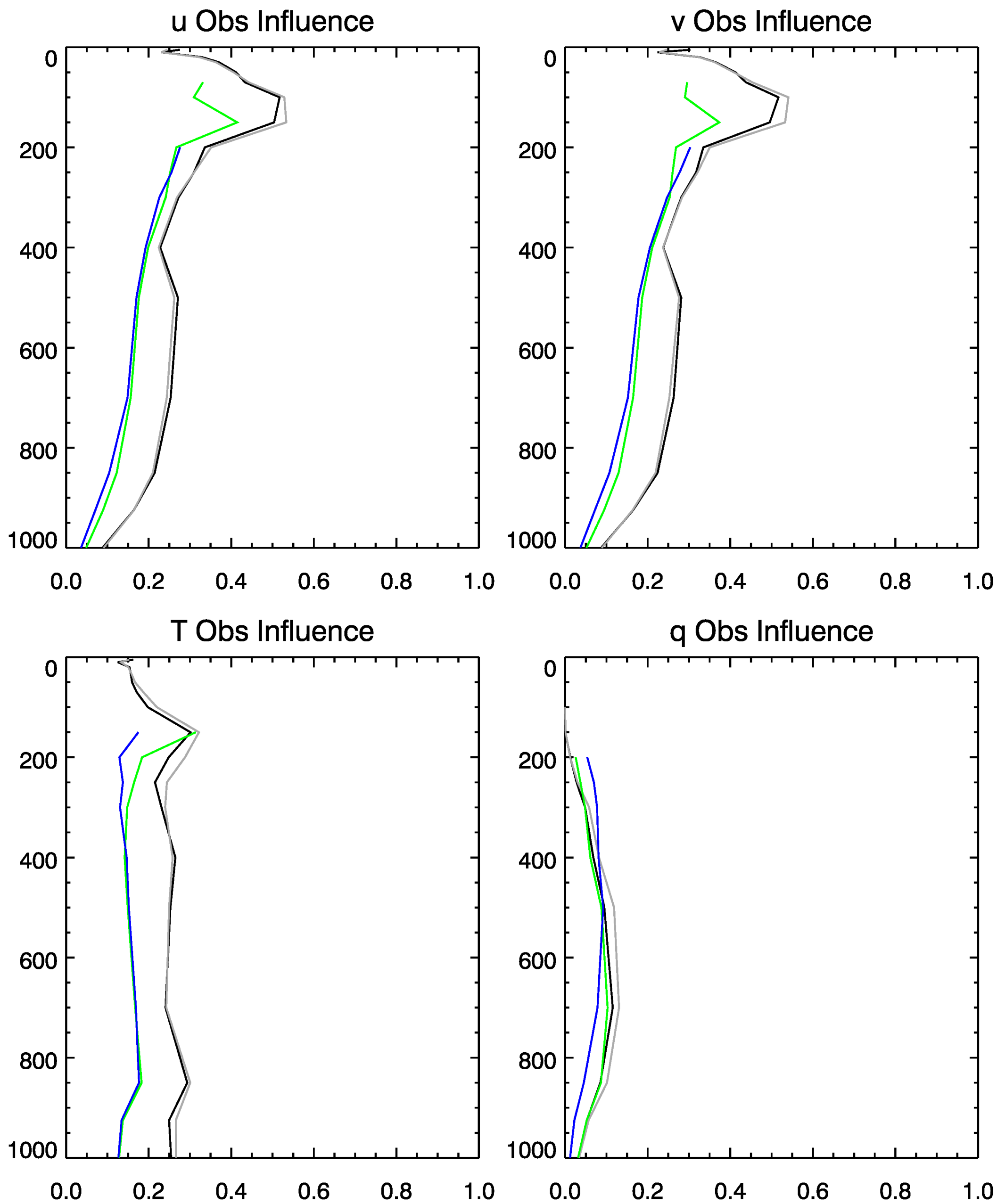


Figure C1 Analysis influence of observations for North American region April – June 2014 AHTA trial. Colours are green - AMDAR, blue - TAMDAR, black/grey - radiosonde standard/significant levels. Zero would mean that the analysis has ignored a datum, one that the analysis has 'drawn to' the datum exactly. The winter experiment (not shown) had similar profiles, but even lower influence for humidity observations.

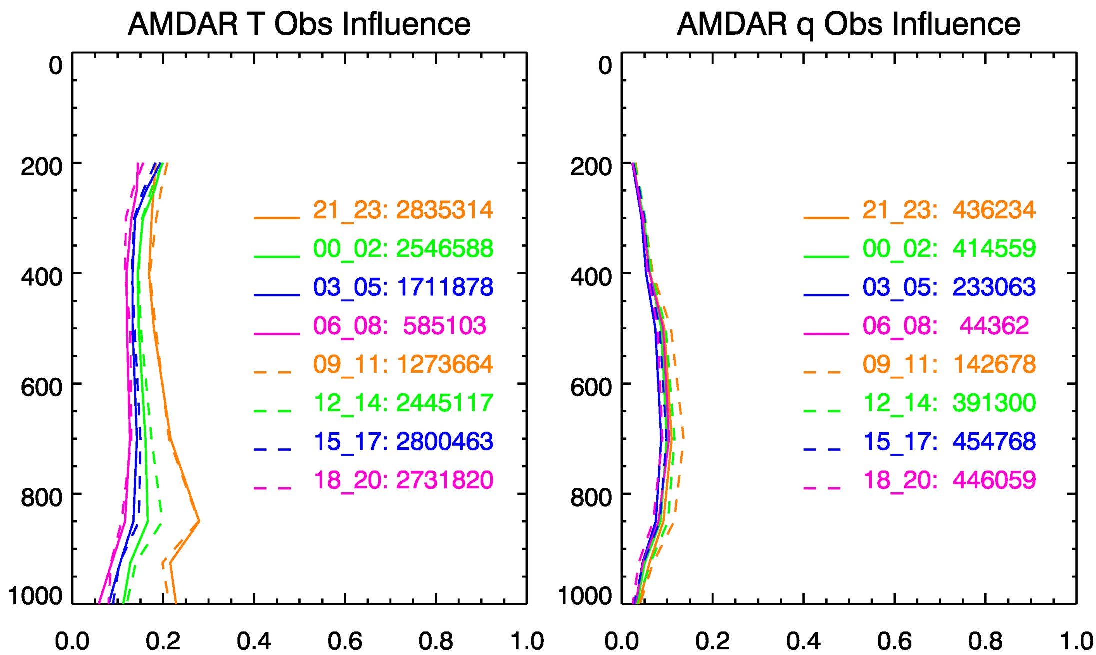


Figure C2 As figure C1 but for AMDAR (ACARS) only showing influence by 3 hour sub-windows. The key shows the sub-windows (e.g. 21_23 is 2100-2359 UTC) and the numbers of reports in each sub-window.

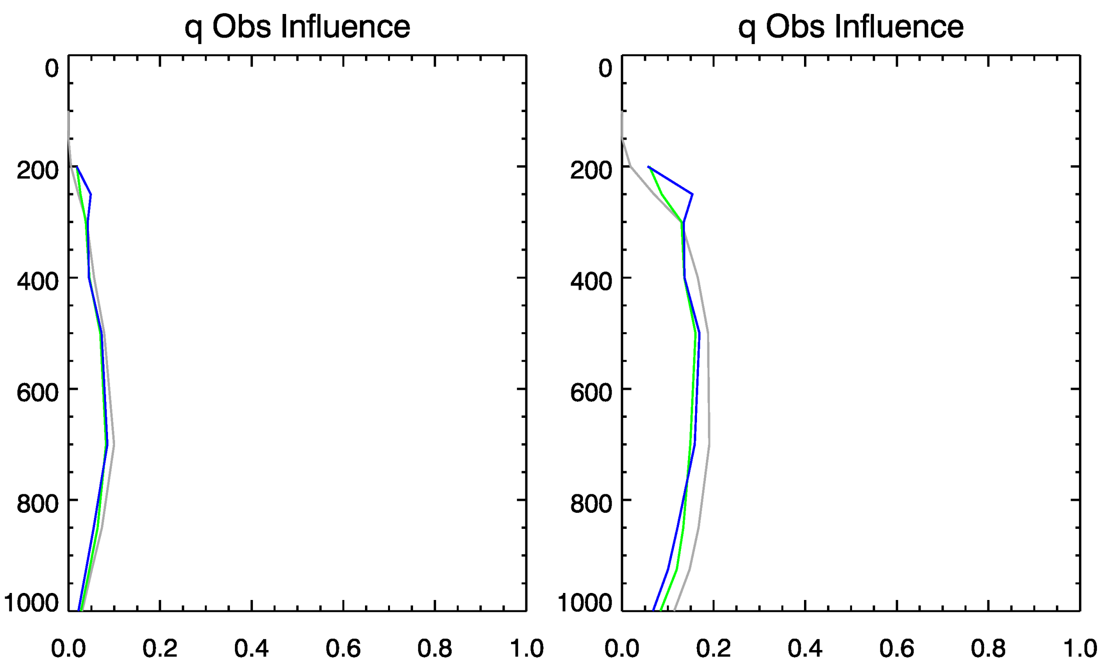


Figure C3 As Figure C1 but for q only and a shorter period. Left: TAMDAR humidity σ_o as for radiosondes, right: revised σ_o for all three types (see text for details). These results have been computed for 1-3 April 2014, this would be much too short a period to look at impact but observation weight/influence will vary much less.

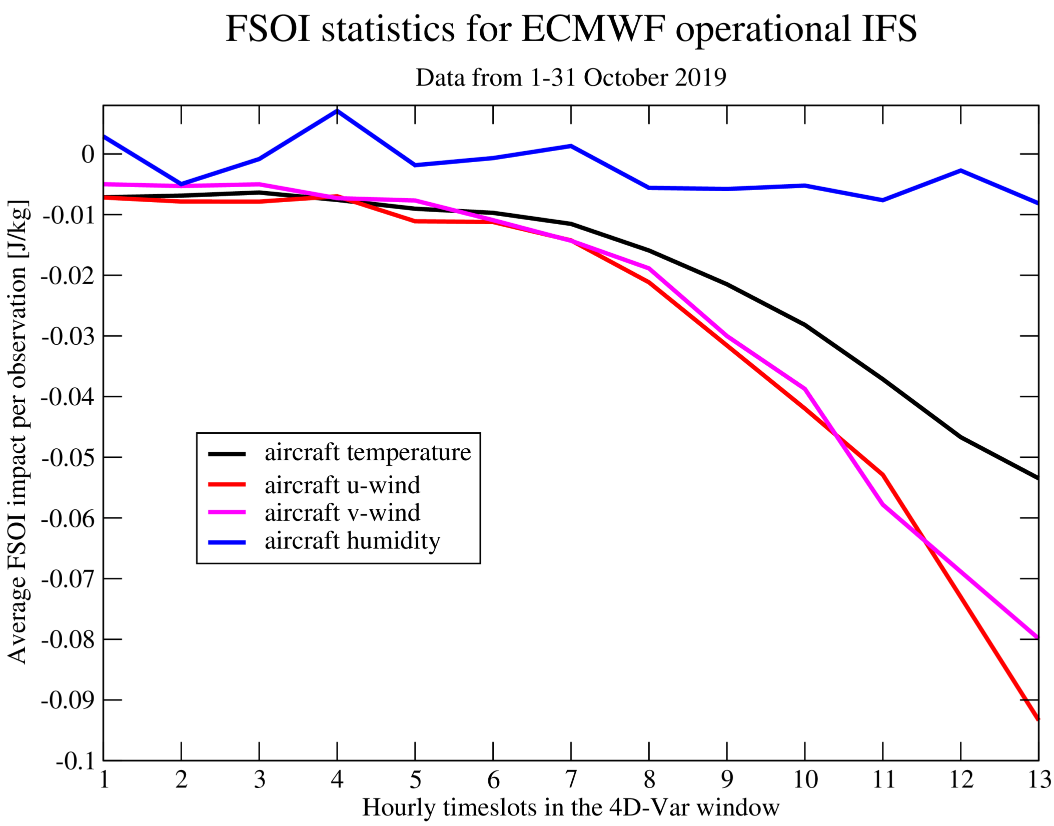


Figure C4. FSOI per datum as a function of time within the assimilation window (operational system, October 2019) for different variables - see legend. negative values imply forecast benefit, see text for more details.

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