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INVESTIGATION OF SYSTEMATIC DIFFERENCES IN AIRCRAFT AND RADIOSONDE TEMPERATURES WITH IMPLICATIONS FOR NWP AND CLIMATE STUDIES

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Automated aircraft temperatures exhibit considerable variance with aircraft models and are on average warmer than radiosonde temperatures; therefore, field studies and bias corrections for NWP models are recommended.

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ABSTRACT

Automated aircraft data are very important as input to numerical weather prediction (NWP) models due to their accuracy, large quantity, extensive and different data coverage compared to radiosonde data. On average, aircraft mean temperature observation increments (MTOI defined here as the observations minus the corresponding 6-h forecast (background)) are more positive (warmer) than radiosondes, especially around jet level. Temperatures from different model types of aircraft exhibit a large variance in MTOI that vary with both pressure and the phase of flight (POF), confirmed by collocation studies. This paper compares temperatures of aircraft and radiosondes by collocation and MTOI differences along with discussing the pros and cons of each method, with neither providing an absolute truth.

Arguments are presented for estimating bias corrections of aircraft temperatures before input into NWP models based on the difference of their MTOI and that of radiosondes, which tends to cancel systematic errors in the background while using the radiosondes as truth. These corrections are just estimates as radiosonde temperatures have uncertainty and the NCEP background has systematic errors, especially a MTOI of almost 2^{o} C at the tropopause attributable in part to vertical interpolation errors, which can be reduced by increasing model vertical resolution. The estimated temperature bias corrections are predominantly negative, of the order of 0.5 to 1.0^{o} C, with relatively small monthly changes, and often have vertically deep amplitudes.

This study raises important issues pertaining to the NWP, aviation and climate communities. Further metadata from the aviation community, field experiments comparing temperature measurements and input from other NWP centers are recommended for refining bias corrections.

1. Introduction

Wind and temperature data from radiosondes and aircraft are main sources of in-situ information to data assimilation systems for Numerical Weather Prediction (NWP). Currently, there are about 150,000 automated aircraft reports per day, used at the National Centers for Environmental Prediction (NCEP), with approximately three times as many temperature observations than from radiosondes. NCEP operational analyses use automated aircraft reports known as Aircraft Meteorological Data Relay (AMDAR) data, which includes automated aircraft data from US aircraft referred to as Aircraft Communication Addressing and Reporting System (ACARS). Automated aircraft reports from outside the US are referred here as NUS-AMDAR for clarity. For more information on automated aircraft data, see Moninger et al. (2003) and Painting (2003). A newer type of US automated aircraft data known as Tropospheric Airborne Meteorological Data Reporting (TAMDAR) (Moninger et al. 2006) are not yet used in operational models at NCEP and therefore are not analyzed. However, discussions of some past tests with these data and suggestions for possible field tests are given.

Zapotocny et al. (2000) showed that with the data assimilation system of the NCEP Eta model, winds and temperatures from ACARS data had significant impact on analyses and short-range forecasts, but generally less than that of radiosondes for 12-hour forecasts, but no verifications scores were presented. Graham et al. (2000) studied impact on 60-hour forecasts with the United Kingdom Meteorological Office model, with various data types withheld for 15 hours prior to the analysis. These impact tests showed that both radiosondes and aircraft data were important, with winds generally more useful than temperatures, but the aircraft temperatures were important in some oceanic cases. Cardinali et al. (2003) analyzed the impact of variable thinning of aircraft data on an improved 4DVAR version of the European Centre for Medium-Range Weather Forecasts (ECMWF) model. Their data denial tests with no aircraft data below 350 hPa over North America and Europe indicated that there were differences in forecast mean temperature due to the aircraft data being warmer on average than the radiosonde data, which is consistent with the finding that ACARS units are more often warmer than the model background (Moninger et al. 2003).

All types of data used for atmospheric analysis have bias as do the analyses and forecasts from NWP models, which is a serious concern (Dee 2005). In this paper, the word "bias" denotes a true mean difference of the observations from reality as opposed to a mean model error. Although such biases cannot be precisely determined, observational data believed to have significant bias can be bias corrected. It is understood that such corrections are just estimates. For many years, satellite radiances have been useful for atmospheric analysis, but required bias corrections of the data by statistical comparison to the background as in Harris and Kelly (2001). Operational bias corrections are performed to surface pressure observations at the ECMWF using average differences in surface pressure observations with the background based on the assumption that background surface pressure has little bias (http://www.ecmwf.int/publications/newsletters/pdf/108.pdf). Here it was found necessary to employ an anti-buddy check so that only observations that had disagreement with their neighbors were corrected; otherwise, a problem occurred where a spurious correction formed over North America.

Since the model's background field has bias (Derber and Wu 1998; Auligne et al. 2007), bias corrections are statistically anchored to a data type such as radiosondes that have presumably small bias. These latter types of bias corrections are adaptive since if the bias of the data being corrected changes with time, so do the corrections. Such corrections involve sophisticated statistics, but are just estimates of the corrections as they involve assumptions on how to compare the data to be corrected to the data assumed to be without bias. The standard data such as radiosondes are not perfect and have uncertainty and small biases for various reasons.

Field tests can be performed to compare different types of data such as in Bedka et al. (2006), where TAMDAR temperatures were compared with those of an Accurate Temperature Measuring (ATM) radiosonde, with multicolored radiosonde temperature sensors (Schmidlin et al. 1986). Further field experiments conducted with the ATM radiosondes in Schmidlin and Northam (2005) helped quantify uncertainty in radiosonde temperatures. TAMDAR temperatures were studied in a wind tunnel, compared to temperatures measured on a NOAA aircraft and to dropsonde data (Daniels et al. 2004a). TAMDAR temperatures were further compared with those coming from a Rosemont temperature sensor that is similar to temperature measurements on large commercial aircraft (Daniels et al. 2004b). Such field experiments can provide valuable results, but it is not likely that all types of aircraft temperatures can be calibrated for all pressures, temperature conditions, aircraft airspeeds or Phase of Flight (POF). In addition, aircraft temperature biases of a certain aircraft type may change with time due to gradual clogging of the pitot tubes or changes in new aircraft. However, field tests can provide anchoring standards for bias corrections derived from data assimilation systems.

Given that radiosonde and aircraft temperatures are critical sources of data for weather prediction and earlier studies have shown differences in their biases, further detailed investigation of the bias differences is essential. Schwartz and Benjamin (1995) showed that there were differences in collocated ACARS and radiosonde temperatures in an area around Denver, Colorado in February and March 1992. They also showed some dependence of temperature differences on the aircraft's POF, such as ascent, descent or level, as did Mamrosh et al. (2002). The ACARS collocation statistics were refined further in Benjamin et al. (1999), where collocation limits were reduced to 10 km in the horizontal, 10 minutes in time and 30.4m in the vertical. Ballish and Kumar (2006), using longer periods of time and a global data base including radiosondes, ACARS, NUS-AMDAR and AIREP (non automated aircraft report) data found persistent differences in the sign of their mean temperature observation increments (MTOI) between radiosonde and aircraft temperatures with radiosonde

MTOI averaging roughly .5^{o} C colder around 250 hPa, as indicated in Fig. 1a,b. A list of acronyms is provided in Table 1. Observation increments are defined here as the observations minus the corresponding 6-h forecast (background) from the NCEP Global Forecast System (GFS) interpolated to the observation locations. Here the monthly averaged MTOI (for non-gross data, explained in Section 2) are shown for a 3-yr period from July 2002 through June 2005 for 00Z (Fig. 1a) and 12Z (Fig. 1b) for the NCEP Global Data Assimilation System (GDAS) analyses. These findings of temperature differences raise the issue and the paradigmatic conundrum of what constitutes the absolute truth, what is the impact of these temperature differences on model analyses and forecasts, and how to correct any biases. This paper is the first refereed study to show substantial evidence that the aircraft MTOI vary with aircraft types, pressure levels and the POF as well as to suggest bias corrections of aircraft temperatures.

2. NCEP GDAS

The NCEP GDAS used in the study, prior to May 2007, is described in Parrish and Derber (1992). As of May 2007, NCEP implemented a new Grid-point Statistical Interpolation (GSI) analysis system (Derber et al. 2007). Both systems use a data gross check, where data that deviate from the background by more than 10 times the observational error estimate are considered gross and are not used in operational analyses nor used in computing MTOI, as large gross errors could adversely affect computed biases. Table 2 shows the temperature observation error estimates for radiosondes and AMDAR data that are used by the NCEP GDAS analysis, with constant values between 800 and 350 hPa (not shown). For observations at elevations (in pressure) not in the table, the errors are considered linear in the logarithm of pressure. AMDAR temperature error estimates are similar to those from radiosondes. NCEP operational practice is that when an aircraft has a monthly MTOI of 2.0^{o} C or more in magnitude in any of the three pressure bands for statistics using all POF, the unit is added to the reject-list for temperatures. Once the MTOI decreases in magnitude below 1.0^{o} C, the unit is removed from the reject-list. For units where the MTOI varies considerably with pressure, subjective judgment is used to decide for what pressures the unit is on to the reject-list. Observational units on the reject-list are not used in operational analyses, but the data can still be monitored. Observations are subjected to additional quality control (QC) procedures (Collins 1998; Woollen 1991).

Radiosonde temperatures may be adjusted by the NCEP radiation correction (RADCOR) procedure (Collins 1999), which adjusts different radiosondes to make their MTOI for matching solar angles similar to those of a Vaisala RS80 DigiCora radiosonde rather than adjusting towards the average background.

The GDAS uses the observation increments that pass QC along with the background to create the analysis. To interpolate the background from the model to observation locations, the background is first interpolated horizontally to observation locations on model levels and then vertical interpolation is done using a linear in the logarithm of pressure assumption.

3. Aircraft Temperature Bias Analysis

3.1 Versus NCEP Background

Aircraft temperatures vary due to many factors such as the aircraft model, airline practices, POF, atmospheric pressure, software and temperature sensors. Large commercial aircraft fuselages have pitot tubes, which are about 12 millimeters in diameter and include a temperature sensor inside. Painting (2003) explains how total and static air pressure measurements are used to derive temperatures and winds along with estimates of their uncertainty.   Adjustment is needed to the temperature due to large dynamic heating of the order of 25^{o} C at flight level. Approximations are made with no turbulence assumed, an ideal gas constant for dry air is used and heat exchange with the aircraft is estimated. Different aircraft types can also have different temperature sensors and software that may average the data before they are reported. Aircraft measurements involve rapid motion through the air in an environment where the air speed and temperature change with pressure, time and horizontal position. Therefore, there can be error or uncertainty in the temperature due to time delay for the sensors to adjust to the true air temperature as well as to time averaging of the data. With aircraft, the temperature sensing equipment may not be repaired or replaced for a long time. A spurious increase in temperature may occur when the pitot tubes sometimes become corroded or clogged with debris.

Aeronautical Radio Inc. (ARINC) processes the ACARS data downlinks from the aircraft into the Meteorological Data Collection and Reporting System (MDCRS the ACARS data in the Binary Universal Form for the Representation of meteorological data (BUFR) format). The resulting data has the tail numbers encrypted at the request of the airlines to protect the autonomy of the data. Since NCEP is the World Meteorological Organization (WMO) lead center for aircraft data, we had access to the tail number encryption software. By means of real tail numbers in conjunction with the Federal Aviation Administration (FAA) web site (http://registry.faa.gov/aircraftinquiry/), the aircraft model types for all legitimate ACARS reports are determined. Based on information for European AMDAR models obtained from the WMO AMDAR panel[1], the relevant aircraft model types were determined for most European AMDAR units.

Detailed statistics of AMDAR temperature data as a function of aircraft model numbers were computed which revealed a characteristic dependence of the MTOI on individual aircraft model types. Figures 2a,b show monthly averaged ACARS MTOI for 300 hPa and above for all observation cycles combined (00Z, 06Z, 12Z and 18Z) for non-gross data over 12 months as a function of aircraft model types for two select groups of aircraft types. Group 1 in Fig. 2a was selected for its large data counts, while group 2 in Fig. 2b was chosen to show large variations in MTOI. If an aircraft's MTOI differed by more than three standard deviations from the

[1] Lists of EU AMDAR data are available from Stewart Taylor, stewart.taylor@metoffice.com

mean of those of a particular type, then that aircraft's data were not used in the final computation. The bar graphs shown in Fig. 2a,b include data from all POF and would change insignificantly if data from the few aircraft in ascent or descent were omitted from the calculations in this pressure range. Different aircraft model types tend to have different MTOI that change slowly with time, with most being positive. The steadiness in time of the MTOI along with their sizable variation, suggests that bias correction of the temperatures based on aircraft type could be worthwhile. The FAA registration information from its web site reveals that almost all reporting ACARS units of a particular model type are operated by a single airline and have similar registration dates. Thus, it is likely that a particular model type has similar equipment and software that affect the reported temperatures. On the other hand, it is possible that different types of aircraft may have identical temperature measuring and processing systems, and could be treated as one group, if the airlines could provide this information. Aircraft bias correction based on aircraft type is similar to performing radiation correction of radiosonde temperatures based on instrument types rather than individual sites. Bias correction based on each aircraft tail number would encounter problems when data counts become too low. Exceptions to model types being a good predictor of bias corrections and other difficulties will be discussed below.

3.2 Aircraft to Aircraft Collocation Studies

In order to assess observational temperature differences independent of the background, collocation studies comparing different aircraft temperature observations together are performed. Collocation involves generating statistics for different observational data that are close together in time, pressure and horizontal location so that the data can be compared. As temperature tends to change with altitude, the collocation statistics were done using aircraft data that are within one hPa in pressure, pass the temperature gross check, and in addition, the two compared observations had to be within 150 kilometers and one hour in time, and neither unit is on the reject-list. Experiments with changing the limits for collocations result in changes in counts and minor changes in mean temperature collocation differences (MTCD). For collocations near the ground, one would need tighter limits due to increased atmospheric variability as well as needing to account for the POF. Figure 3a shows MTCD comparing aircraft model type 757-222 with other types for January 2007, with the types with the largest number of collocations to the left ranging from 716,796 to 16,416. Here, the MTCD are averages of the temperatures from aircraft type 757-222 minus temperatures from the other aircraft types in the figure that meet the collocation constraints. Since the 757-222 units have negative MTOI, most of the MTCD are negative. The MTCD are similar to MTOI differences “MTOID”, even though the collocations involve a small subset of the total data, while the MTOI are global involving all observations. Figure 3b has similarly computed MTCD, but now the MTCD are averages of the collocations between the aircraft type shown on the horizontal axis and all other aircraft types that were within the collocation limits, weighted by collocation counts ranging from 1,625,824 to 79,370. Type 767-332 has the largest differences in MTOID and MTCD shown Fig. 3a,b and will be examined in the next section.

3.3 Vertical and POF Dependence of MTOI

Figure 4a shows MTOI for select ACARS types for January 2005 interpolated to the nearest mandatory pressure level. Figure 4b is the same for select NUS-AMDAR types for a longer period, December 2005 through February 2006, used to achieve larger counts. These statistics include all POF. The above figures show that there is considerable variation in the magnitudes, sign and vertical behavior of the MTOI, with most types showing a predominantly positive (warm) MTOI.

Many types of US ACARS units do not report the POF and some only report near jet level, while most of the European AMDAR units report data during all POF through a variety of pressure ranges. Therefore, Fig. 5 shows European AMDAR MTOI interpolated to the nearest mandatory pressure levels for different POF: missing (MISS), ascent (ASNT), descent (DSNT) and level (LEVL). MTOI near the ground may be large due to possible systematic errors in the background being larger at low levels, and the descent data tend to be colder than ascent. This temperature difference between ascent and descent is typical for almost all aircraft types that report the POF. One type, Airbus type A318-100 has an atypical pattern with ascent MTOI colder than descent (not shown). Recently, Drüe, et al. (2008) found that different Lufthansa aircraft types showed average temperature differences by collocations for descending aircraft at the Frankfurt airport as large as 1^{o} C even though the aircraft all had the same software for processing the temperature measurements and had comparable environmental conditions. Computing MTOI for all aircraft types, for different POF to the nearest mandatory pressure levels would lead to problems with very low counts for some types.

See Tables 3 and 4 respectively for more detailed information on MTOI and counts of observations for different ACARS and NUS-AMDAR types for January 2007 for four different pressure bands. These statistics are for all times of day and all POF. The ACARS statistics were for observations passing the QC in NCEP GDAS runs, while for the NUS-AMDAR data, the statistics were for non-gross data, as some types have no data passing the QC due to all of their data being on the reject-list. There is considerable variation in counts and MTOI with different aircraft types and pressure bands.

For ACARS types 767-322 and 767-332, there is an atypical pattern where data with a missing POF have large MTOI differences compared to data with a level POF, which is not expected at cruise level, (Fig. 6a,b). The 767-322 units reporting with a missing POF are roughly 1^{o} C colder than those reporting a level POF, see Fig 6a. With type 767-332, the sign of the MTOI differences is the opposite, (Fig 6b). For each of these two types, there appears to be two subtypes with different MTOI and reporting practices. So far, we have no explanation for these abnormal differences. Likely, it is a software difference since one subtype is reporting a missing POF when the aircraft is not likely to be changing altitude. These subtypes represent a small fraction of the total data, but for bias correction, they could be treated as different types.

4. Radiosonde Temperature MTOI Analysis

Radiosondes use different types of temperature sensors as part of a sensor package hanging from a balloon that rises through the atmosphere. The reported temperature may differ from its true value due to a number of factors such as the characteristics of the temperature sensor; solar and infrared heating or cooling depending on the current state of the atmosphere and the surface below; variable air conduction rates; impact from the balloon and its tether; and all the parts of the radiosonde and the computer processing of the temperatures before distribution. Changes in any of the above factors can influence the reported temperature (Gaffen 1994). Radiosonde temperatures have been shown to be slow to respond to rapid temperature changes in the vertical and have error if the sensor is too warm or cold at the balloon launch compared to the current surface conditions (Mahesh et al. 1997; Hudson et al. 2004).

4.1 Radiation Correction

Attempt to correct radiosonde temperatures for radiative effects, called the radiation correction, is a difficult and challenging problem as outlined in Luers and Eskridge (1995); therefore, there is some uncertainty in corrected results. The uncertainty in radiosonde temperatures continues to be an active area of research due to the importance of estimating global warming (Thorne et al. 2005).

Investigation of the negative (cold) MTOI of radiosondes around 250 hPa reveals that the NCEP RADCOR procedure makes it more negative. Figure 7a shows global MTOI for 250 +/- 25 hPa for 00Z with and without the NCEP RADCOR for a period from July 2004 to June 2006. The figure shows the largest MTOI during the northern hemisphere winter, which is due to the MTOI being larger in winter conditions and most radiosondes are in the northern hemisphere. Similar results for 12Z are shown in Fig. 7b.

One problem found was that the NCEP RADCOR was still correcting the Chinese radiosondes after they were corrected at the site starting some time in January 2001 (Yatian et al. 2002). When this double correction for the Chinese radiosondes was removed in September 2005, the net effect of the NCEP RADCOR on the global MTOI was reduced, see Fig 7a,b, as expected considering the Chinese correction was relatively large (not shown). The mean cooling due to the NCEP RADCOR and the analysis are smaller after this correction. Another problem with RADCOR was an error involving the radiosonde ascent rate in the RADCOR applied at the site for US RS80 radiosondes (Redder et al. 2003). Uncertainties in the radiation correction are found to be small compared to the MTOI at the tropopause as explained later. The NCEP RADCOR is not the primary focus of the paper, but it needs to be revised in the future in light of the new NCEP GSI analysis system and if aircraft bias corrections are applied.

4.2 Tropopause Bias

The vertical minimum of the MTOI of the radiosondes has been occurring for a long time outside the tropics and has a vertical peak around 250 hPa as shown by the NCEP non-operational verification website by S. Saha (http://wwwt.emc.ncep.noaa.gov/gmb/ssaha/maps/obs/month/monthly_cross.html). For available cases, select the desired month and then select the vertical map option. These plots indicate mostly positive MTOI values around 250 hPa especially in the winter, as the definition of MTOI is just the opposite of ours. Forecasts from the ECMWF show similar characteristics at the same website.

Further investigation into the negative (cold) MTOI around 250 hPa showed that for temperature observations labeled as tropopause data, there was a negative MTOI of almost two degrees C over the continental US

(CONUS) for January 2006 (not shown). MTOI at the tropopause are smaller than the MTOI using the NCEP reanalysis (Randel et al. 2000), where the forecast model has less vertical resolution. The tropopause is often a narrow and relative minimum in temperature in the vertical profile of a radiosonde's temperature; therefore, it could be difficult for both forecast models to predict and to perform accurate vertical interpolation from model vertical coordinates to the observations.

4.3 Vertical Interpolation Experiments

Since the MTOI at the tropopause were larger than expected considering the accuracy of the observed data and because the tropopause is vertically narrow, an experiment was conducted to examine the role of vertical interpolation in producing the bias. Radiosonde temperature data over the CONUS that passed NCEP analysis QC were taken as the truth and used to initialize model sigma levels assumed to be at the same locations as the radiosondes and with the same surface pressure. With the temperature on model levels derived from the assumed true temperatures, one can then perform interpolation from the model levels back to the radiosonde levels to check on interpolation errors. Since radiosonde data are approximately linear in the logarithm of pressure between reported levels, we use this relation for all vertical interpolation experiments. According to the above assumptions, one would expect these "true" model temperatures vertically interpolated back to the radiosonde levels, to agree well with the observed data.

To understand this pedagogical experiment better, a skewt-logP diagram is shown in Fig. 8a, for the site 72340 for 12Z on 4 January 2007, with observed temperatures shown as red asterisks and temperatures at the centers of model levels derived from the interpolation of the observations to the model shown as blue triangles. The temperatures represented by blue triangles match the radiosonde profile, red curve, throughout except for relatively large error at the tropopause given by the asterisk just above 200 hPa. Smaller error is evident just below 150 hPa. The vertical locations of the blue triangles show typical model vertical resolution. This case was selected as it has a simple sharp tropopause where the error in interpolation can be easily seen. The error in the vertical interpolation of the model compared to the observations is the distance between the blue and red curves.

Figure 8b summarizes average temperature statistics to the nearest mandatory pressure levels for this temperature interpolation experiment over the CONUS for 00Z and 12Z combined for January 2006. The curve labeled as “I64” of Fig. 8b shows that there are sizeable average errors with the interpolations of the observations to the model and then back to the observations, where the 64 refers to the model’s 64 vertical levels. The center of model levels are shown on the right side of Fig. 8b based on a surface pressure of 1000 hPa. The MTOI for these same radiosonde temperatures are labeled “MTOI”, and there is a large MTOI at 200 hPa. These MTOI include significant level radiosonde data with statistics taken to the nearest mandatory pressure levels. The curve labeled as “NTRP” is the same as “MTOI” but excludes any observations reported as a tropopause level from the MTOI calculations and shows that removing tropopause data reduces the MTOI. Here, the tropopause data had to be between 300 to 175 hPa or else they were treated as non-tropopause observations. The interpolation errors shown by curve I64 are a significant fraction of the MTOI around 250 hPa, which involves the operational forecast from an analysis six hours earlier and then vertical and horizontal interpolation from the model to the observations. Interpolation experiment I72 was the same as I64, except the model’s vertical resolution was doubled between sigma levels centered at .3297 and .1382, resulting in 8 more levels and twice as much vertical resolution around jet level. The biases shown by curve I72 are roughly half those shown in curve I64 around jet level. These tests indicate that there can be significant vertical interpolation error especially for the tropopause. The model would also need more vertical resolution to capture sharp tropopauses, and further work with the vertical interpolation problem appears worthwhile. The negative MTOI near the tropopause for the Vaisala RS80 DigiCora radiosonde type contributes to the overall cooling of the NCEP RADCOR near 250 hPa as it is based on the MTOI of this radiosonde type.

4.4 Aircraft to Radiosonde Collocation Studies

Since the background has bias and there are large MTOI at the tropopause, it is useful to generate collocation statistics between ACARS types and radiosonde temperatures that do not rely on the accuracy of the background. Over the CONUS area, comparisons were made with temperatures from ACARS and radiosonde data. Here, radiosonde temperatures that passed the QC were interpolated in the vertical again using the assumption that the temperatures are linear in the logarithm of pressure. The vertical interpolation is necessary since the nearby radiosonde data may have pressure differences as large as the mandatory pressure differences. To count as a collocation, the aircraft and radiosonde temperatures had to be within 200 km with a time separation of 1.5 hours or less. No collocations with any vertical separation of over 25 hPa were used. Figure 9a shows the results of the collocations using all CONUS radiosondes for 00Z in January 2007 for the 11 aircraft types with the largest collocation counts sorted to the left side of the plot. The average of the aircraft minus radiosonde temperatures meeting the above limits are labeled as “MTCD”, while the same differences in their MTOI were labeled as “MTOID”. For different aircraft types, MTOID and MTCD are similar despite tropopause problems and some small differences due to the collocations being a small subset of the total data used in the MTOI calculations. Figure 9b shows the same for 12Z, but the aircraft types displayed are the same as in Fig. 9a. The MTCD tend to be more positive for 00Z, which could be due to diurnal differences in aircraft routes, reporting pressures and times or may indicate a problem with RADCOR for the radiosondes.

5. Evidence of Systematic Temperature Problems

If the average of the observation increments were zero, and the background and analysis had no systematic errors, then there would be no systematic changes in the analysis minus background temperature field. However, Fig. 10a,b show, respectively, nonzero monthly average temperature differences of the analysis minus background for 00Z and 06Z for July 2007 at 250 hPa. Fig. 11a,b similarly show changes for 12Z and 18Z. The analysis introduces areas of warming over the CONUS, except at 18Z. Systematic temperature changes and their relation to data biases are not always obvious in part because the analysis uses a variational technique assimilating different types of conventional temperature and wind data as well as satellite radiances. Analysis temperature changes at one point are influenced by data from all over the globe. Further work would be needed to show whether systematic temperature changes by the analysis are due to bias in the observations or the background.

In order to investigate the systematic temperature differences over the CONUS around 250 hPa, Fig. 12a,b show, respectively, the average counts of radiosonde and ACARS temperature observations for 12Z +/- 3 hours for July 2007 at 250 +/- 25 hPa on a 5x5^o grid. This pressure level was chosen as the biggest contrast in MTOI is near this level. Figures 13a,b show the same for MTOI in tenths of a degree C. The ACARS data show mostly positive (warm) MTOI and radiosondes negative (cold). For this period over the CONUS, the NCEP RADCOR is near zero, so it plays little role in the MTOI differences. The CONUS area especially around 250 hPa is an area of temperature uncertainty due to the contrasting MTOI, where the differences are larger in magnitude than the analysis minus background changes shown in Figures 10 and 11.

6. Bias Correction Strategy and Consistency Checks

By using radiosonde temperatures as the truth and differences in radiosonde and aircraft temperatures as a basis for deriving aircraft bias corrections, some practical considerations have to be made to carry this out. One potentially good method would be to use collocations between radiosonde and aircraft temperatures to derive bias corrections. Unfortunately, some types of aircraft would have too few such collocations to allow for reliable corrections of temperatures involving all aircraft types and pressures. One problem with collocations is that not all the aircraft of one type may be sampled uniformly as some aircraft could be flying in areas with few radiosondes. When collocation counts are low, the derived corrections are less reliable.

A more practical approach is to use differences in MTOI between aircraft and radiosondes. In Section 3, these were shown to be similar to collocation differences. Still, there are problems to overcome using MTOI differences. Since radiosonde MTOI have a large average of almost 2^{o} C at the tropopause, and the radiosondes always report tropopause observations if the temperature profile meets reporting standards for tropopause data, while aircraft may not report at the tropopause, radiosonde data may over emphasize the tropopause bias problem compared to aircraft observations. This overemphasis is likely to be reduced by deriving the corrections through relatively thick pressure layers. Thick layers are also likely to reduce problems where the background may have diurnal errors near the ground, which may be aggravated further by only having the background available every 6 hours, rather than a higher resolution time interpolation. Problems with low data counts for bias correction are further reduced by using thick layers. If the model background has systematic biases that vary with space, pressure or time, then using MTOI differences will have some error, as the data distributions are not uniform. Similarly, if the true bias in the observations vary with space, pressure or time, then using collocations with radiosondes may have sampling problems as most radiosondes have limited distribution and are primarily at 00Z and 12Z.

To reduce the number of figures shown, proposed bias corrections of aircraft temperatures will be shown without differentiating between different POF, although the actual corrections will differentiate for different POF for types reporting the POF and large counts at low levels. Since many types of aircraft do not report the POF or do not report frequently at low levels, these types will have bias corrections that are not a function of the POF. It is possible that for NWP centers with better time interpolation and less diurnal bias, increased vertical resolution for the corrections would be beneficial. As a first attempt at bias correction, four pressure groups were decided to be used, namely the surface to 700 hPa, 700 to 500 hPa, 500 to 300 hPa, and 300 to 150 hPa.

To make differences in MTOI between radiosondes and aircraft similar to collocation differences, observation increments from similar areas of the globe were used. For ACARS data, MTOI for the aircraft types and radiosondes were calculated on an area approximating the CONUS. For AMDAR units that were mostly in the northern hemisphere, MTOI were derived for 20^o northward outside the CONUS. For aircraft types with most of their observations in the tropics, a third region from 20^o S to 20^o N was used. For aircraft types with most of their observations south of 20^o S, the southern hemisphere was used as a fourth region.

Since there can be errors in reported data that affect derived MTOI, only radiosonde temperatures that passed the QC were used. For most aircraft types, the same rule was applied except for types where all temperature data were on the reject-list. For types on the reject-list such as Japanese, Chinese and South African AMDAR data that have either very warm biases or excessive position errors, non-gross temperatures were used rather than those that passed the QC for deriving bias corrections.

Using the above rules for deriving bias corrections, Fig 14a shows these corrections for 15 ACARS types for January 2007. The corrections are mostly negative, have amplitudes of the order of several tenths of a degree at all pressures, which makes significant impact of the corrections on forecasts likely. The aircraft types further to the left have the largest counts. The 15 types in the graphic represent about 96% of the total ACARS data. Data types with lower counts (not shown) have similar patterns of differences, but some would have no differences displayed below 300 hPa due to very low data counts. For January 2007, the average NCEP RADCOR correction over the CONUS near 250 hPa is roughly -0.1^{o} C, so it is a small part of the total correction. Figure 14b shows the differences between the bias corrections for January 2007 and the previous month. Notice, the monthly changes in the differences are small. This indicates that corrections could be derived using monthly MTOI, but additional work may show a more optimal period or method for the corrections.

Figure 15a is the same as Fig. 14a, but for July 2007. Figure 15b is the same as 14b except the difference is for January 2007 minus July 2007. For aircraft types, 737-3H4, 737-832 and 767-332, the differences in bias corrections between January and July are of the order of .5^{o} C in the surface to 700 hPa layer. These differences are large and need further investigation. Since there can be regional differences in the background bias, new corrections were derived using only observation increments that were nearby collocations, but large differences were still found. It was found that collocations with small distance separation limits of only 10 km can have problems in coastal areas where aircraft could be sampling the cold marine air while the nearby radiosonde measures warm inland air. Similar calculations avoiding near coastal areas still showed large six-month differences in corrections. Using small collocations limits reduces counts and may favor ascent over descent or vice versa, as aircraft landings and takeoffs are not randomly associated with radiosonde data.

Possible explanation of the large six-month differences with the bias corrections is that the true aircraft temperature corrections may depend on a factor such as true airspeed or temperature lapse rates. If airspeed is an important factor in bias corrections, comparing aircraft temperatures with radiosondes without this factor may give reasonable average corrections, but will not fully explain all the variance in the data or changes in bias corrections with time as mean airspeed may change with time. No attempt was made to derive MTOI based on true air speed because the aircraft data we receive do not have this. Similarly, temperature lapse rates coupled with rates of ascent and descent may be another important predictor for bias corrections. Another possible problem is the lack of more accurate time interpolation of the background especially near the ground.

Similar to Fig. 14a,b, Fig. 16a,b show the same except for NUS-AMDAR data. Here, the 14 data types with the largest counts represent roughly 83% of the total. For European aircraft, the model types are shown in the figures, while the other symbols are JP, Japanese; AU, Australian; B- Chinese; AF South African and NZ for New Zealand. Notice, that some of the NUS-AMDAR bias corrections are bigger than the observational error estimate of 1^{o} C for NUS-AMDAR data above 800 hPa. Again, the monthly changes in the differences are small. The bias corrections for the ACARS and NUS-AMDAR temperatures are much bigger than typical for the radiosonde radiation corrections in the troposphere.

Any potential operational correction of temperature data at NCEP may be different from the above plans, as testing may reveal unexpected problems and revisions may be made as more is learned concerning the corrections. Further testing will be done with the new GSI analysis. Interactions from other NWP centers about the possible methods, impact and implications of bias corrections would be desirable. Detailed numerical investigations to study the full impact of bias correction on the current NCEP operational forecasts in the short, medium and extended range are currently underway. Since the US airlines have agreed to allow other government meteorologists to have access to lists of what type of aircraft each unit is, interested parties may contact the lead author for the latest information on aircraft types. So far, we have no information on NUS-AMDAR aircraft model types except for European units.

7. Conclusions and Plans for Future Work

Aircraft temperatures have been shown to vary considerably depending on aircraft model types, pressure and the POF based on MTOI and collocation studies. The aircraft show predominantly positive (warm) MTOI while the radiosondes show average negative (cold) MTOI especially around 250 hPa, which results partially from both errors in forecast of the tropopause and interpolation from model levels to the tropopause.

Arguments were presented towards deriving bias corrections by using MTOI differences between aircraft types and radiosondes using four pressure levels. These bias corrections are relatively large, of the order of .5 to 1^{o}C, with amplitudes that are often large at all pressures and consistent from one month to the next, but show some longer term changes at lower levels that are suspect, indicating more work is needed in this area. Since there is some uncertainty in radiosonde temperatures due to different temperature sensors and possible errors in the radiation correction, it may be best to only correct aircraft temperatures that meet a minimum threshold.

A precise field test is recommended to help decide the truth in comparing aircraft and radiosonde temperatures. This study also raises several intriguing questions. What are the impacts of bias corrected temperatures as proposed here, and can other NWP centers derive more optimal corrections? Are model temperatures warmer than they should be due to increases in the quantity and area coverage of aircraft reports with their relatively warm temperatures? Would additional model vertical resolution result in both better assimilation of radiosonde tropopause temperatures and forecast skill? Would better use of aircraft temperatures be made in NWP and climate studies if the aviation community could provide more metadata concerning aircraft temperature measurements? In order to address some of the above questions, we need concerted efforts in data analysis, data impact studies with NWP and climate models to assess fully the implications at short, medium and climate time scales. With that perspective, we have initiated impact studies with the NCEP GDAS and GFS with and without bias correction of aircraft temperatures, and the completed results will be reported in a separate paper.

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FIGURES

Fig. 1. Three year monthly mean temperature observation increment history for non-gross data between 300 and 200 hPa levels for Radiosondes, ACARS, NUS-AMDAR and AIREP at a) 00Z and b) 12Z

Fig. 2. Monthly mean temperature observation increment sequence for two groups of ACARS types 300 hPa and above at all times of day for non-gross data with outliers removed for a) Group1 and b) Group 2

Fig. 3. Aircraft to aircraft statistics 300 hPa and above by aircraft types during January 2007 a)mean temperature collocation differences and observation increment differences for Type 757-222 and b) mean temperature collocation differences between aircraft types on the x-axis with all other types

Fig. 4. Average vertical dependence of mean temperature observation increments for select aircraft types versus pressure for non-gross data for a) ACARS types and b) NUS-AMDAR types

Fig. 5. POF and pressure dependence of European AMDAR mean temperature observation increments for non-gross data for winter 2006

Fig. 6. Vertical dependence of mean temperature observation increments versus missing and level POF for January 2006 for ACARS types a) 767-322 and b) 767-332

Fig. 7. Monthly averaged global temperature differences versus the background at 250 +/- hPa, raw observation minus background (RAWMB), NCEP RADCOR corrected observation minus background (RADMB) and analysis minus background (ANLMB) from July 2004 to July 2006 for a) 00Z and b) 12Z.

Fig. 8. Radiosonde temperatures profiles for vertical interpolation experiments. a) Skewt logP temperature profile for site 72340, 12Z 4 January 2007, with observations given in red and interpolations to model in blue. b) Monthly averaged temperature differences for January 2006 to the nearest mandatory pressure level for vertical interpolation experiment over the CONUS. See text for explanation of symbols

Fig. 9. ACARS mean temperature collocations and observation increment differences with CONUS radiosondes 250 +/- 25 hPa during January 2007 a) 00Z and b) 12Z

Fig. 10. Monthly average values of analysis (AN) minus background (BG) temperature at 250 hPa during July 2007 for a) 00Z and b) 06Z

Fig. 11. Same as Fig. 10 but for a) 12Z and b) 18Z

Fig. 12. Radiosonde and ACARS daily average data counts on a $5x5^o$ grid for 250 +/-25 hPa during July 2007 for 12 +/- 3Z a) radiosondes b) ACARS

Fig. 13. Radiosonde and ACARS mean temperature observation increments in tenths of degrees C on a $5x5^o$ grid for 250 +/-25 hPa during July 2007 for 12 +/- 3Z a) radiosondes b) ACARS

Fig. 14. Proposed ACARS temperature bias corrections for aircraft types for different pressures with highest total data counts for a) January 2007 and b) difference to same for December 2006

Fig. 15. Proposed ACARS temperature bias corrections for aircraft types for different pressures with highest total data counts for a) July 2007 and b) difference to same for January 2007

Fig. 16. Same as in Fig. 14 but for NUS-AMDAR data

Table 1. Acronym definitions

Acronym	Definition
ACARS	Aircraft Communication Addressing and Reporting System
AIREP	Air Report
AMDAR	Aircraft Meteorological Data Relay
ARINC	Aeronautical Radio Inc.
ASNT	Ascent
ATM	Accurate Temperature Measuring
BUFR	Binary Universal Form for the Representation of meteorological data
CONUS	Continental US
DSNT	Descent
ECMWF	European Centre for Medium-Range Weather Forecasts
FAA	Federal Aviation Administration
GDAS	Global Data Assimilation System
GFS	Global Forecast System
GSI	Grid-point Statistical Interpolation
LEVL	Level
MDCRS	Meteorological Data Collection and Reporting System
MISS	Missing
MTCD	Mean Temperature Collocation Differences
MTOI	Mean Temperature Observation Increments
MTOID	Mean Temperature Observation Increment Differences
NCEP	National Centers for Environmental Prediction
NCO	NCEP Central Operations
NOAA	National Oceanic and Atmospheric Administration
NUS	Non-US
NWP	Numerical Weather Prediction
NWS	National Weather Service
POF	Phase of Flight
QC	Quality Control
RADCOR	Radiation Correction
TAMDAR	Tropospheric Airborne Meteorological Data Reporting
WMO	World Meteorological Organization
4DVAR	Four-Dimensional Variational Data Assimilation

Table 2. Temperature observation error estimates in degrees C for radiosondes (Sonde) and AMDAR data

Pressure in hPa	Sonde	AMDAR
1000.0	1.20	1.47
950.0	1.10	1.35
900.0	.900	1.24
850.0	.800	1.12
800.0	.800	1.00
…		
350.0	.800	1.00
300.0	.900	1.00
250.0	1.20	1.00
200.0	1.20	1.00
150.0	1.00	1.00

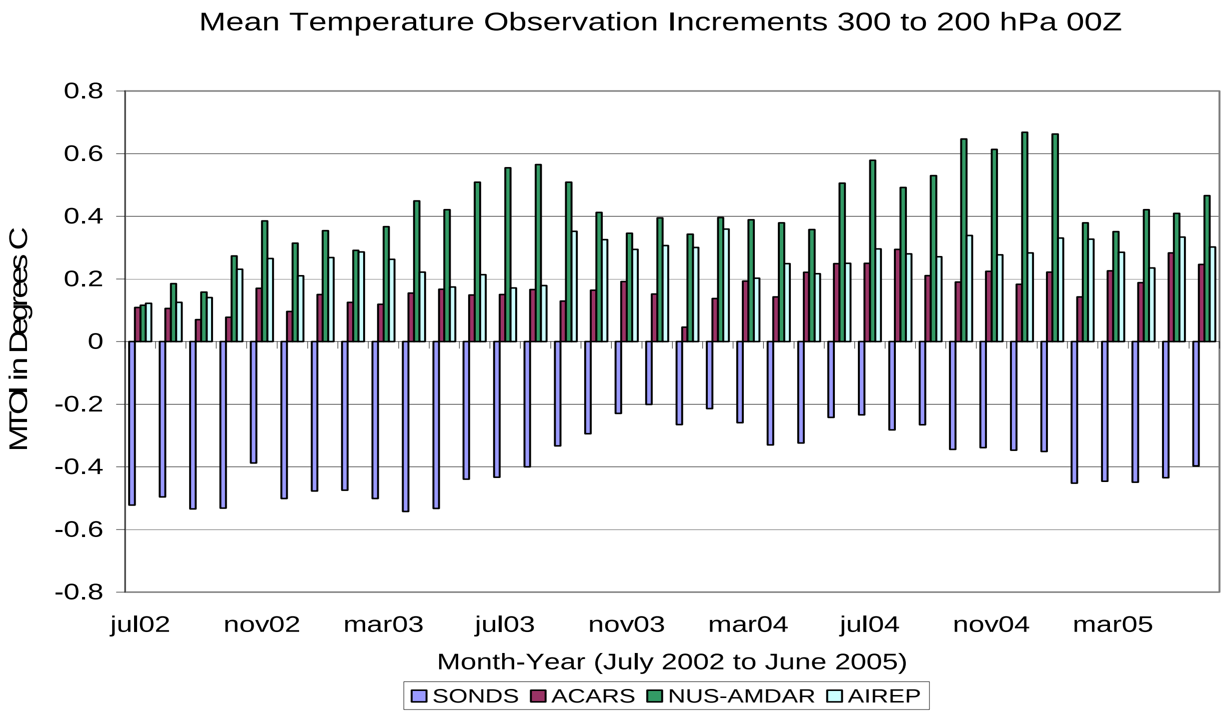
Table 3. ACARS statistics January 2007 all times of day for non-gross data

	SFC-700 hPa		700- 500 hPa		500-300 hPa		300-150 hPa	
Type	NUM	MTOI °C	NUM	MTOI °C	NUM	MTOI °C	NUM	MTOI °C
737-322	4407	0.22	6222	-0.1	7997	-0.1	8763	-0.2
737-3H4	102517	0.28	49104	0.55	35446	0.71	24087	0.48
737-522	47066	0.32	27358	0.25	15665	0.26	21387	-0.01
737-724	0	0	0	0	100	0.43	567	0.19
737-823	111	0.36	118	0.23	1642	-0.02	9966	0.26
737-824	0	0	0	0	327	0.09	1856	0.05
737-832	7612	0.07	8826	0.21	13864	0.05	68500	0.37
737-924	0	0	0	0	0	0	253	0.29
747-422	589	0.17	600	-0.36	666	-0.76	1571	-0.66
757-222	72329	0.27	90427	-0.19	112123	-0.25	306598	0
757-223	133777	0.19	91944	-0.12	64925	-0.19	3730	0.1
757-224	0	0	0	0	0	0	4477	0.14
757-232	3558	0	1754	-0.43	11521	-0.44	167844	-0.13
757-24APF	118746	0.39	65160	-0.03	50367	0.12	57476	0.3
757-251	11561	0.16	12011	-0.07	14103	-0.03	49698	0.27
767-224	0	0	0	0	0	0	718	0.32
767-322	619	0.24	568	-0.63	1257	-0.99	3015	-0.83
767-323	0	0	0	0	119	0.64	699	0.54
767-332	2261	0.43	544	0.07	3079	-0.33	32012	-0.51
767-34AF	51458	0.43	26050	-0.03	29685	0.04	57083	0.03
767-424ER	0	0	0	0	141	0.02	138	0.02
777-222	423	0.99	361	0.43	475	0.25	2524	0.29
777-223	0	0	0	0	191	0.37	2875	0.54
777-224	0	0	0	0	0	0	109	0.1
A300F4-60	67897	0.24	33529	0.07	4424	0.12	12639	0.05
A310-203	33207	0.37	18539	0.12	1647	0.18	6867	0.06
A310-222	11349	0.32	6821	0.14	499	0.15	2029	-0.03
A310-324	15685	0.34	8476	0.14	722	0.09	2801	-0.02
A319-131	1465	0.04	1239	-0.13	1498	-0.09	2935	-0.32
A320-232	1739	0.04	1554	-0.13	2251	-0.17	5054	-0.13
MD-10-10F	867	-0.07	0	0	1924	-0.15	447	-0.31
MD-11	147	0.36	281	0.14	342	-0.07	119	0.3
MD-11F	30354	0.44	17424	0.3	14155	0.41	36914	0.38
MD-88	11115	0.77	12451	0.73	23433	0.53	40498	0.37
TOTAL	730926	0.3	481280	0.05	414212	0.02	931151	0.06

Table 4. NUS-AMDAR statistics January 2007 all times of day for non-gross data

	SFC-700 hPa		700- 500 hPa		500-300 hPa		300-150 hPa	
Type	NUM	MTOI ^{o} C	NUM	MTOI ^{o} C	NUM	MTOI ^{o} C	NUM	MTOI ^{o} C
737-	60291	-0.1	25737	-0.17	19189	-0.24	24444	0.02
737-300	65223	0.22	20757	-0.04	46828	-0.05	26441	-0.06
747-	7104	0.39	2494	-0.12	1639	0.05	51158	0.34
747-400	3895	0.65	1013	0.23	2053	0.26	15256	0.4
757-	16389	-0.08	5758	-0.26	1215	-0.29	3741	-0.43
767-	6170	0.11	2090	-0.3	679	-0.29	9603	-0.05
A300-600	4344	0.3	1352	0.25	2390	0.15	5958	0.05
A318-100	5570	0.13	4469	-0.08	5195	-0.18	803	-0.04
A319-100	35533	0.61	17978	0.27	22771	0.25	21495	0.7
A320-100	4849	0.07	3747	-0.13	5323	-0.28	584	-0.54
A320-200	56785	-0.1	32796	-0.2	50819	-0.35	29179	-0.39
A321-100	16890	0.58	6083	0.43	12375	0.45	13834	0.44
A330-300	6140	0.41	2653	0.37	3336	0.23	12408	0.36
A340-	5830	0.17	2607	-0.15	987	-0.07	22374	0.05
A340-300	5850	1.13	2635	0.44	3689	0.39	21354	0.44
A340-600	1344	0.82	519	0.71	410	0.47	3254	0.56
MD-11-	2935	0.44	446	0.53	179	0.55	2706	0.51
MD-11F	6931	0.5	2343	0.37	4898	0.26	17835	0.03
AU	34747	0.56	11805	0.29	15991	0.26	49155	0.33
AF	33943	-0.13	6766	-0.42	3030	0.78	38490	1.16
B-	30705	0.67	15895	0.13	25531	0.36	17302	0.97
HK	13645	0.69	4527	0.32	1059	0.04	6834	0.12
JP	137758	1.11	85604	0.28	46875	0.22	70663	0.97
MK	1617	0.77	497	0.54	192	0.13	2174	1.06
NZ	19449	0.03	4909	-0.12	5255	-0.25	6902	-0.08
SA	2644	0.62	734	-0.17	299	-0.07	3829	0.64
SV	8099	1.02	3683	0.88	3148	0.75	223	0.78
MISC	34294	0.2	13715	0.05	13513	0.33	27407	0.32
TOTAL	628974	0.44	283612	0.1	298868	0.07	505406	0.41

a)



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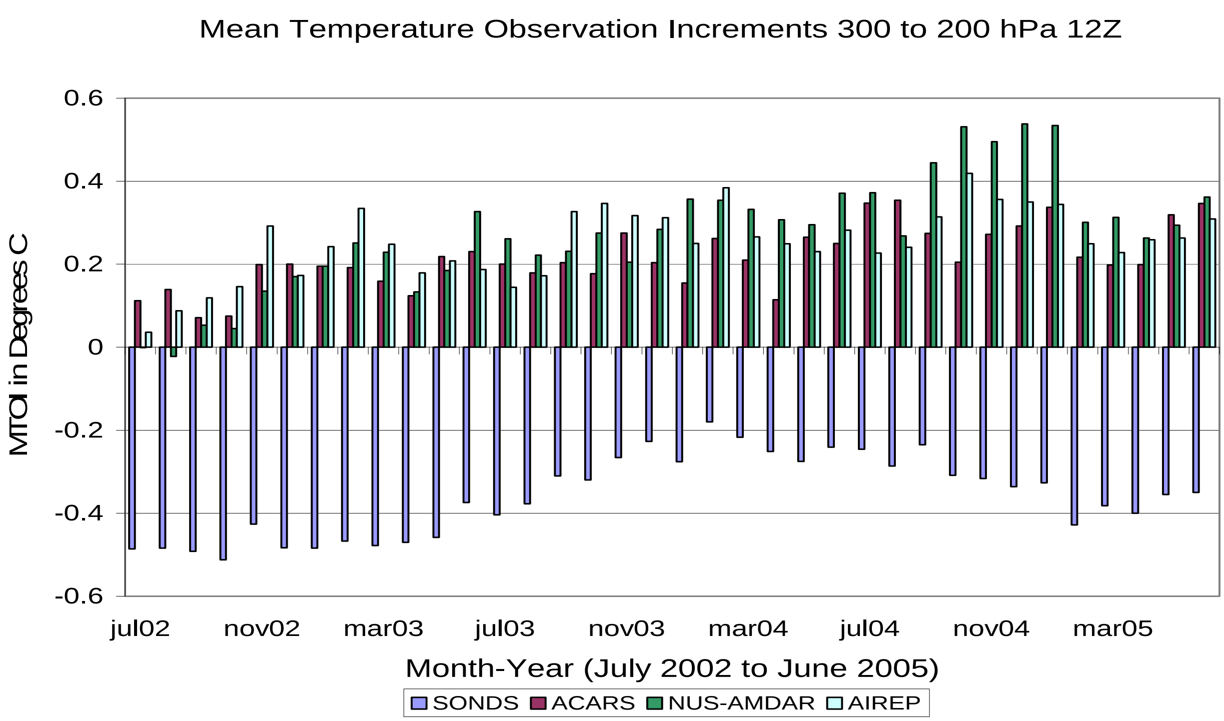

Fig. 1 Three year monthly mean temperature observation increment history for non-gross data between 300 and 200 hPa levels for Radiosondes, ACARS, NUS-AMDAR and AIREP at a) 00Z and b) 12Z

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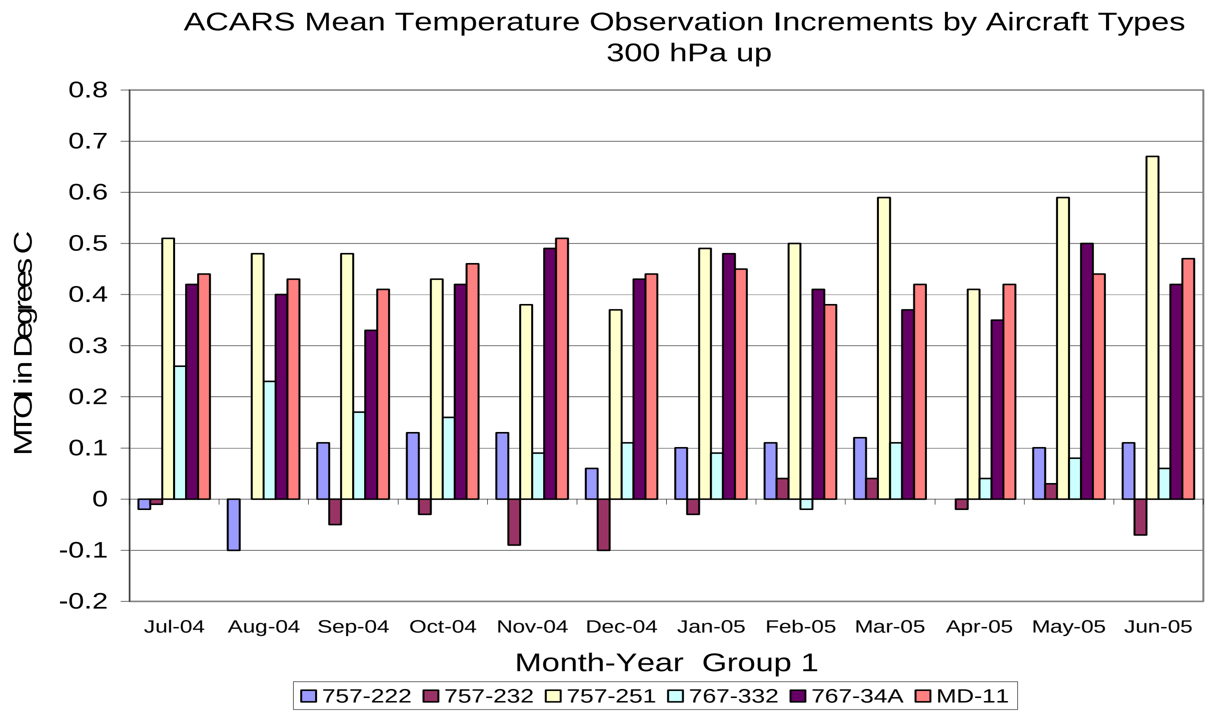
a)



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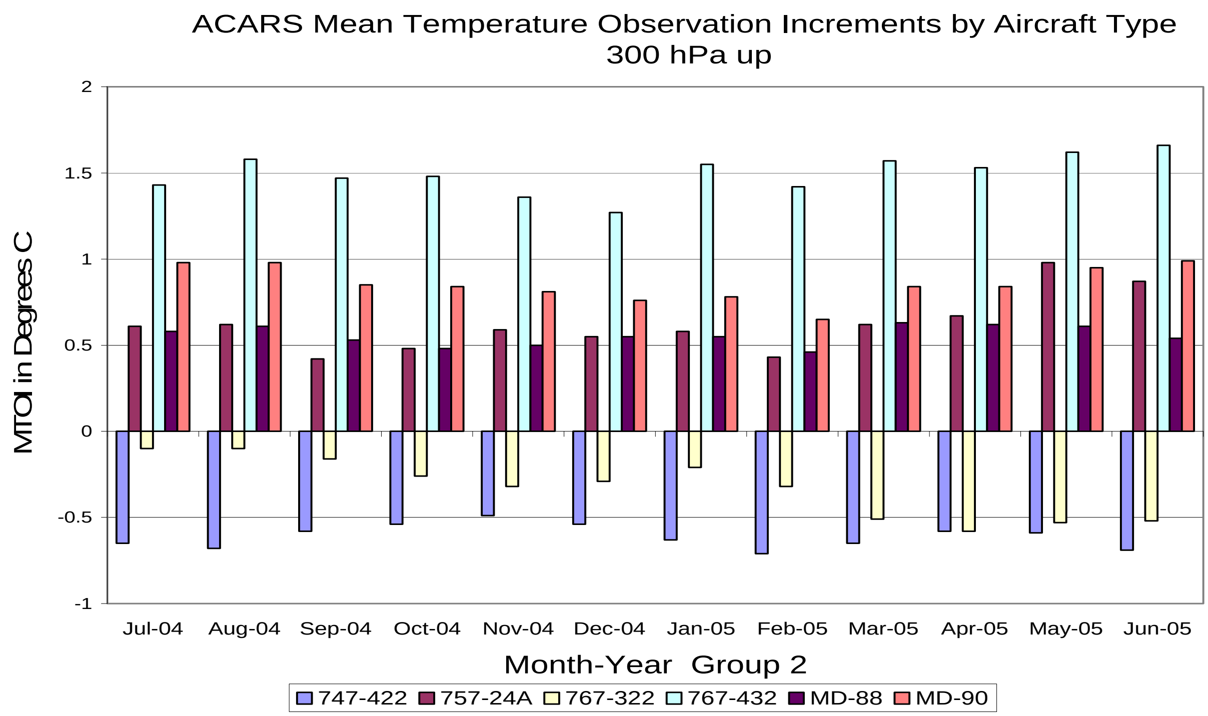
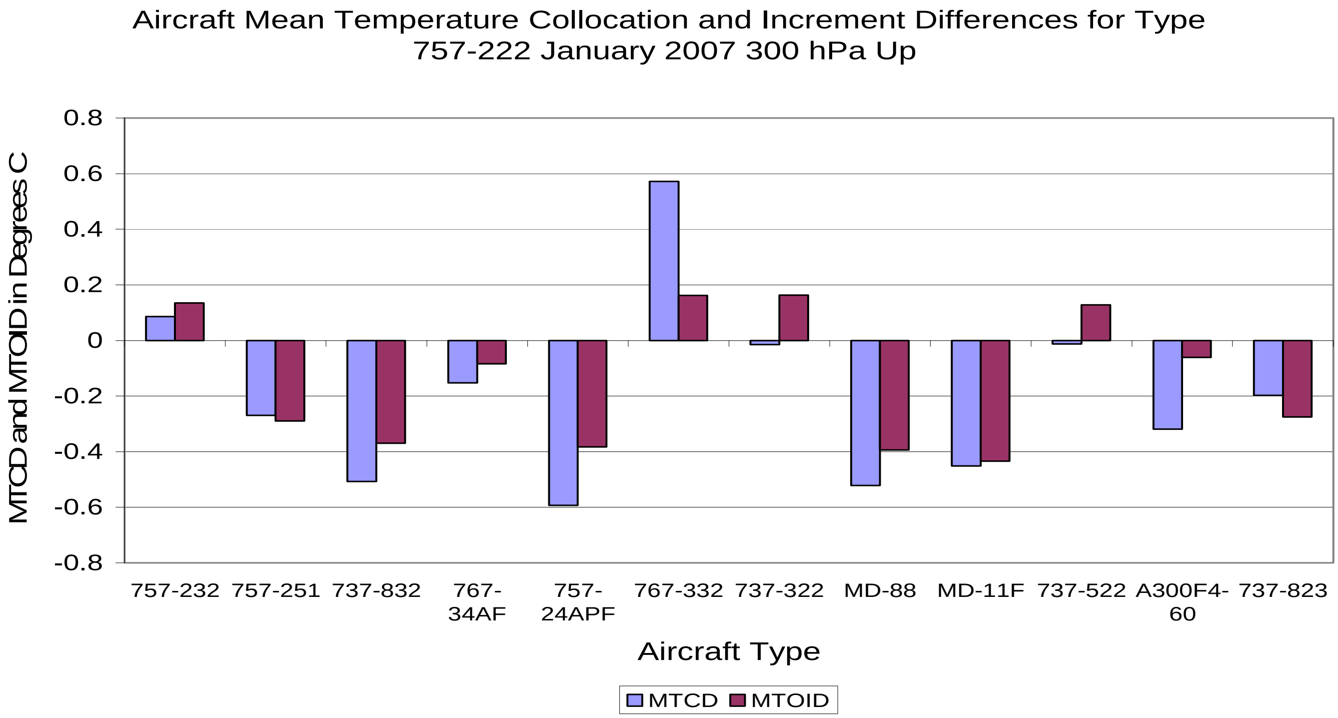


Fig. 2 Monthly mean temperature observation increment sequence for two groups of ACARS types 300 hPa and above at all times of day for non-gross data with outliers removed for a) Group1 and b) Group 2

a)



b)

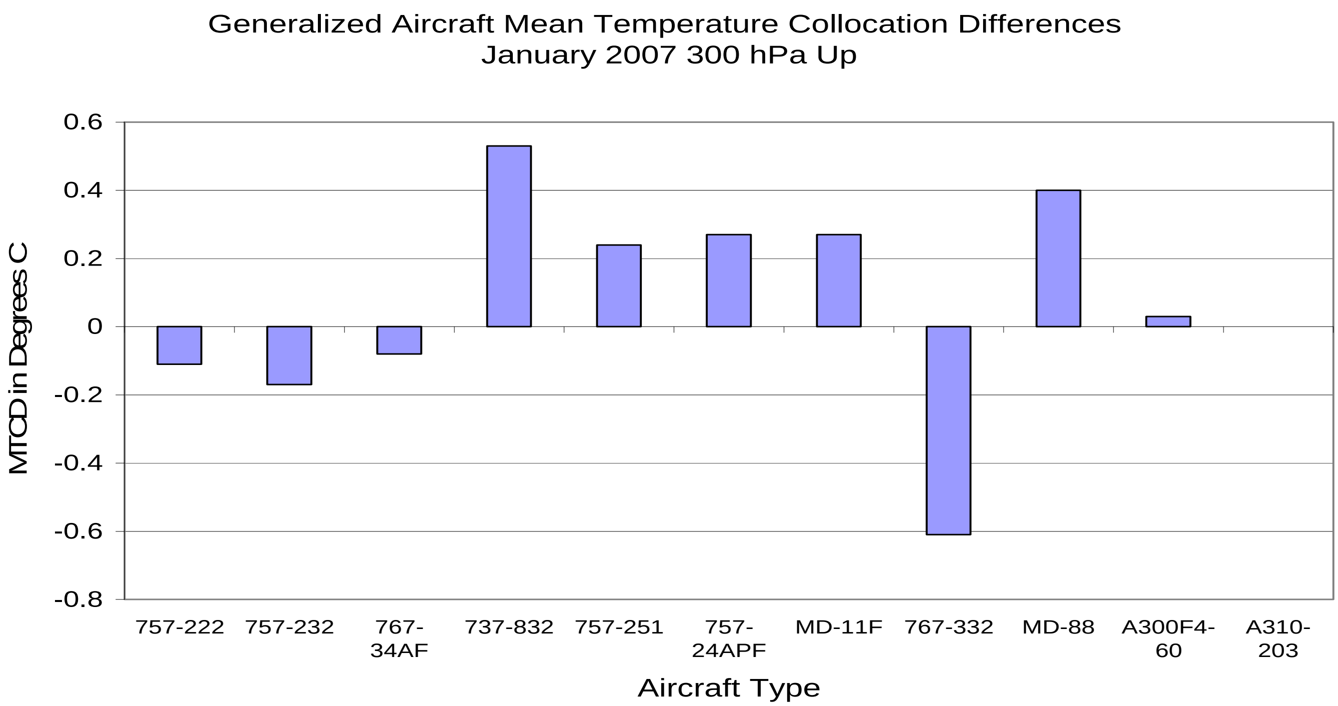


Fig. 3 Aircraft to aircraft statistics 300 hPa and above by aircraft types during January 2007 a)mean temperature collocation differences and observation increment differences for Type 757-222 and b) mean temperature collocation differences between aircraft types on the x-axis with all other types

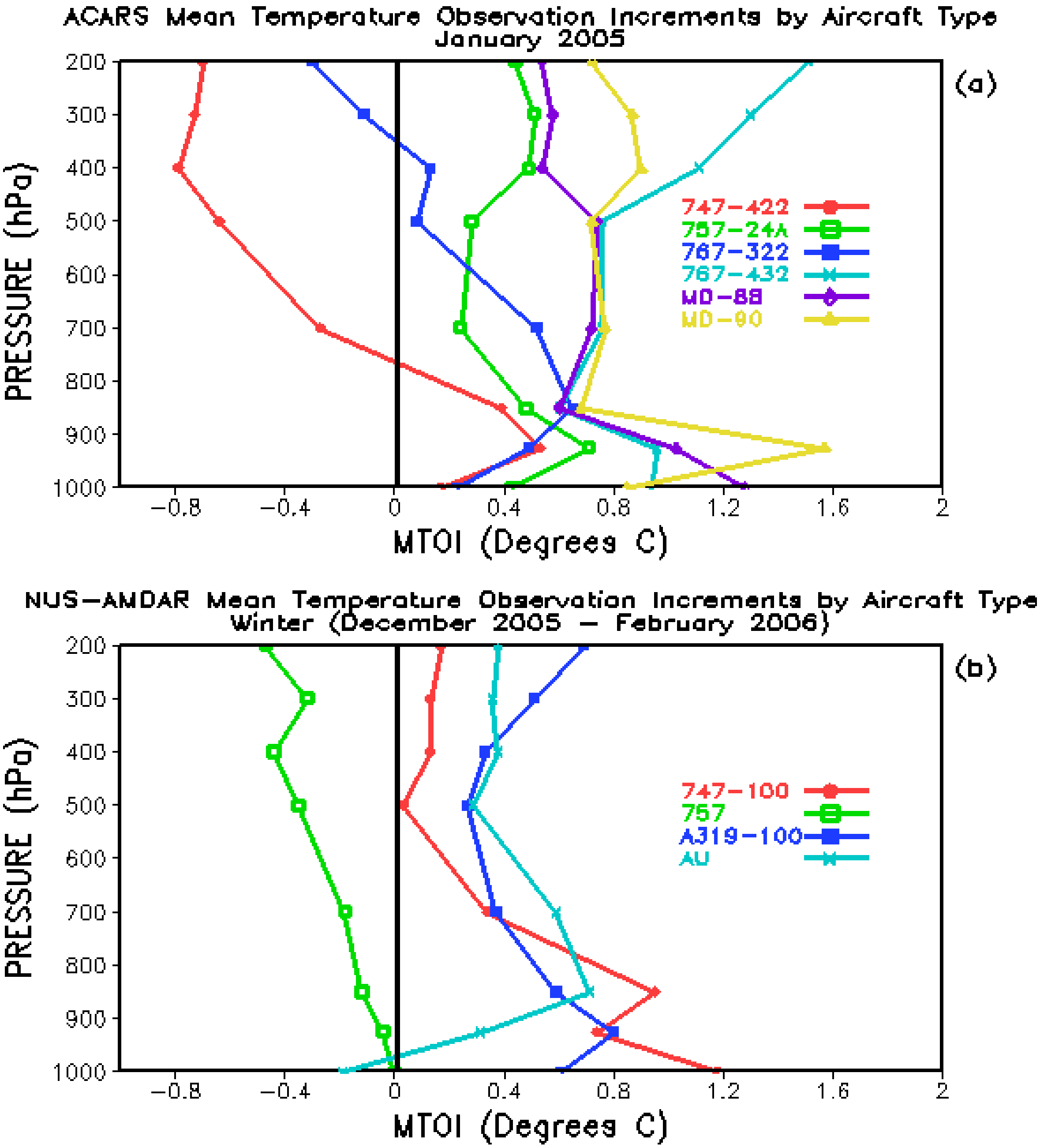


Fig. 4 Average vertical dependence of mean temperature observation increments for select aircraft types versus pressure for non-gross data for a) ACARS types and b) NUS-AMDAR types

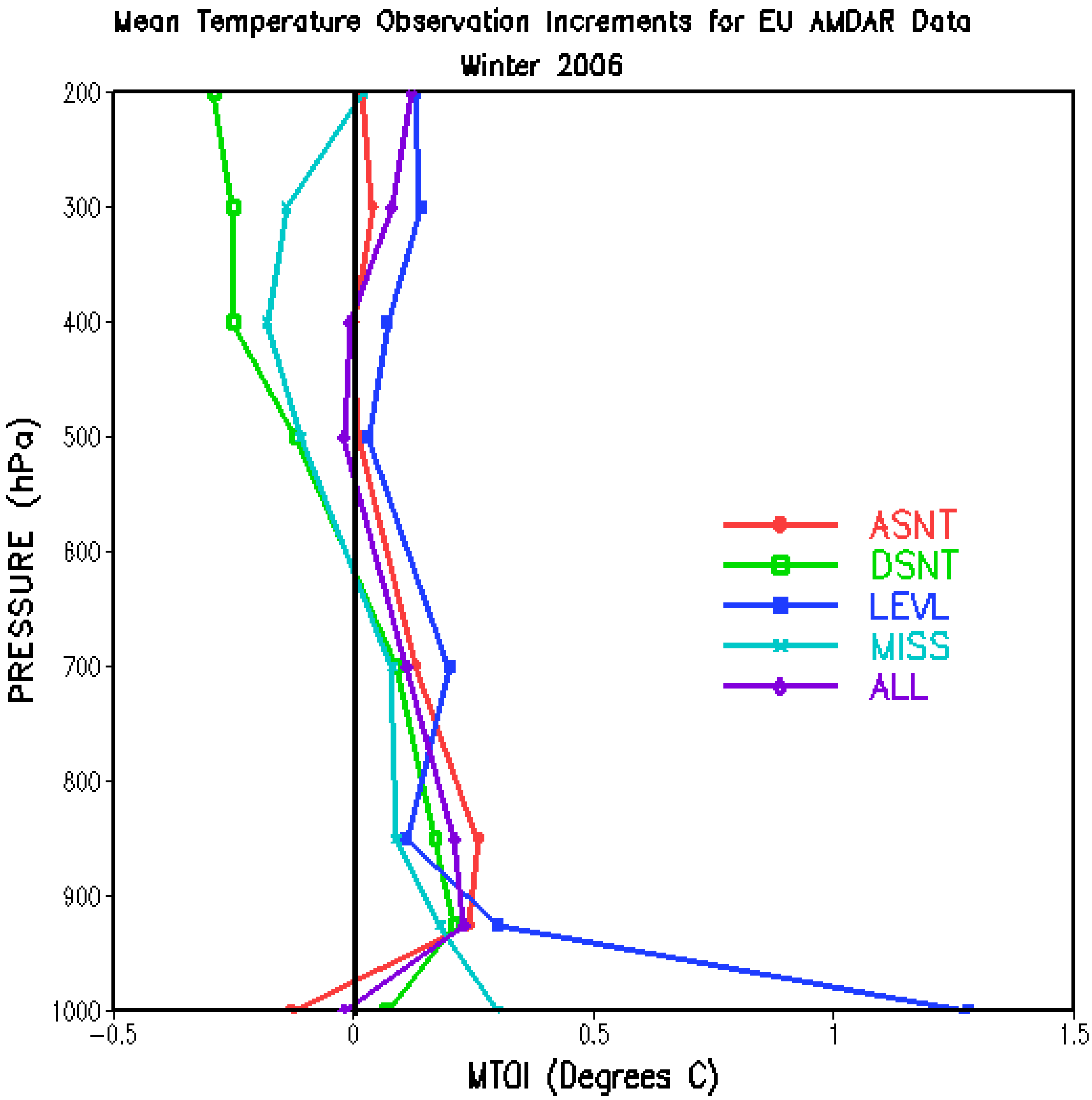


Fig. 5 POF and pressure dependence of European AMDAR mean temperature observation increments for non-gross data for winter 2006

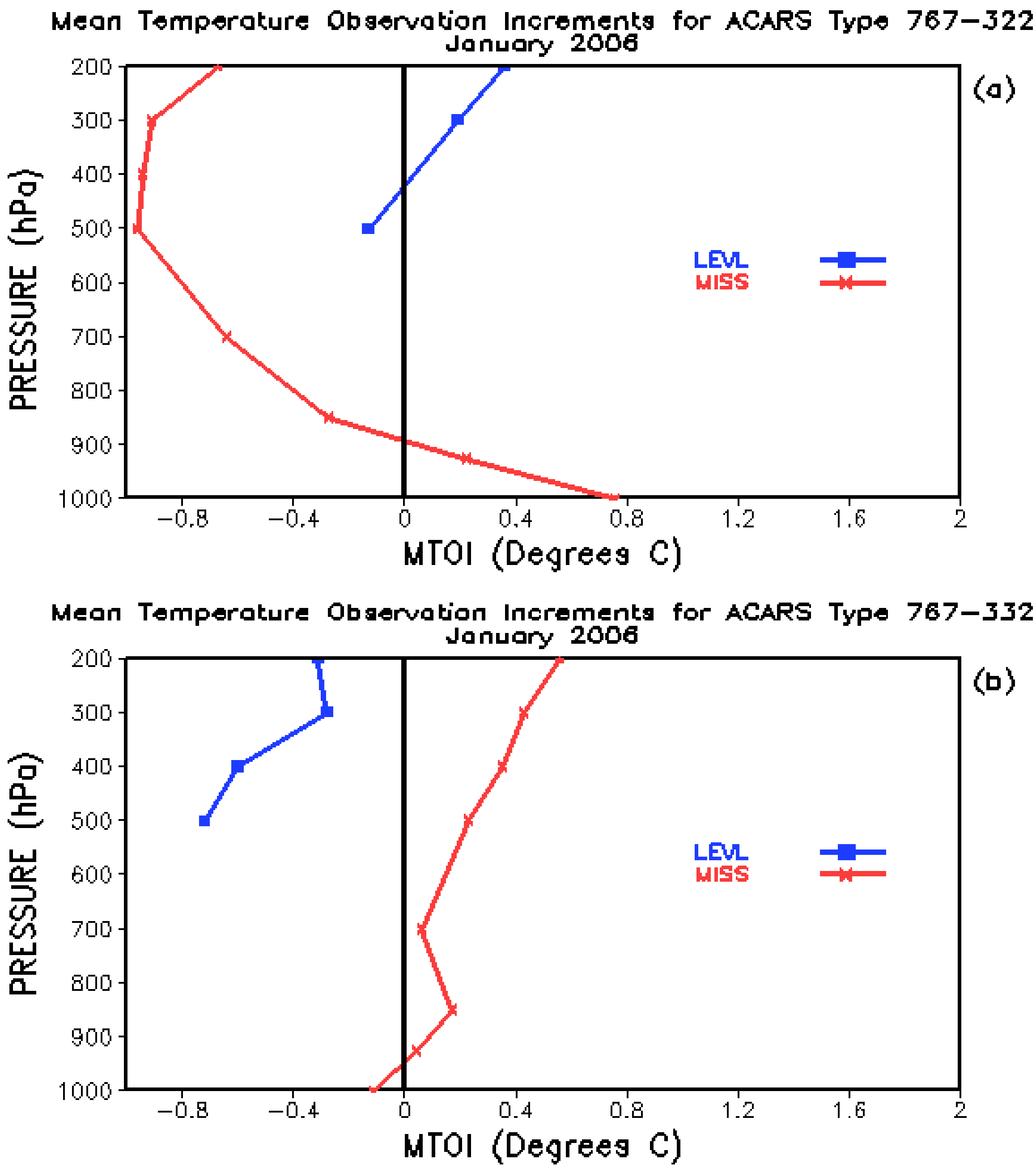
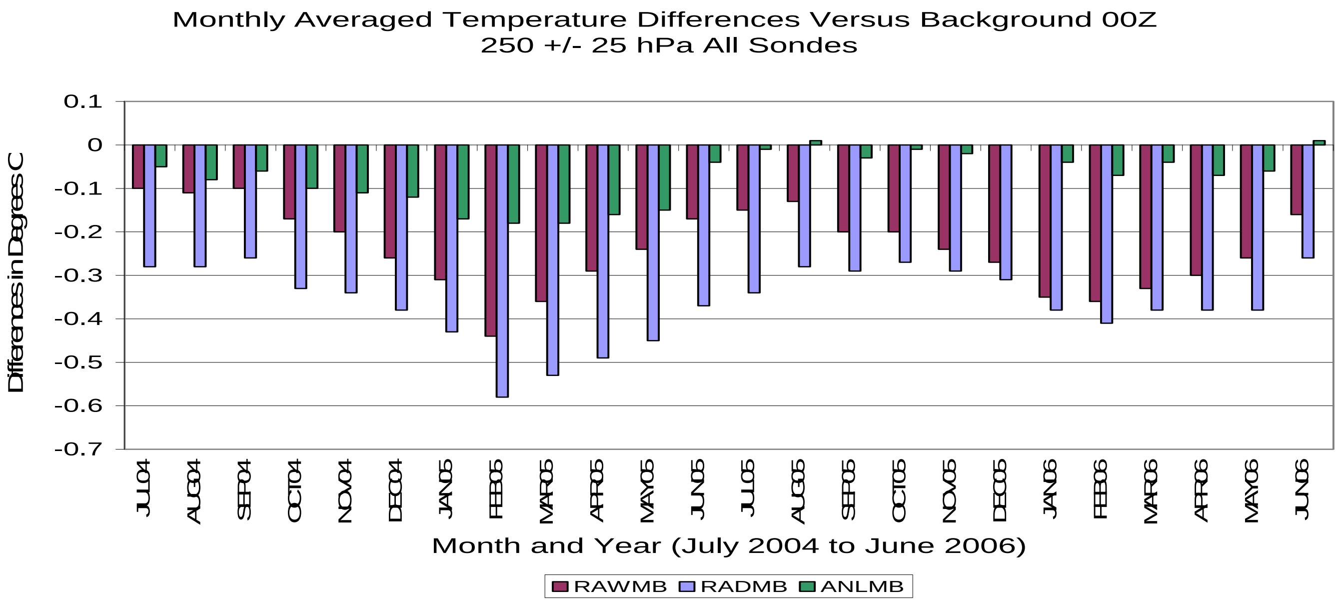


Fig. 6 Vertical dependence of mean temperature observation increments versus missing and level POF for January 2006 for ACARS types a) 767-322 and b) 767-332

a)



b)

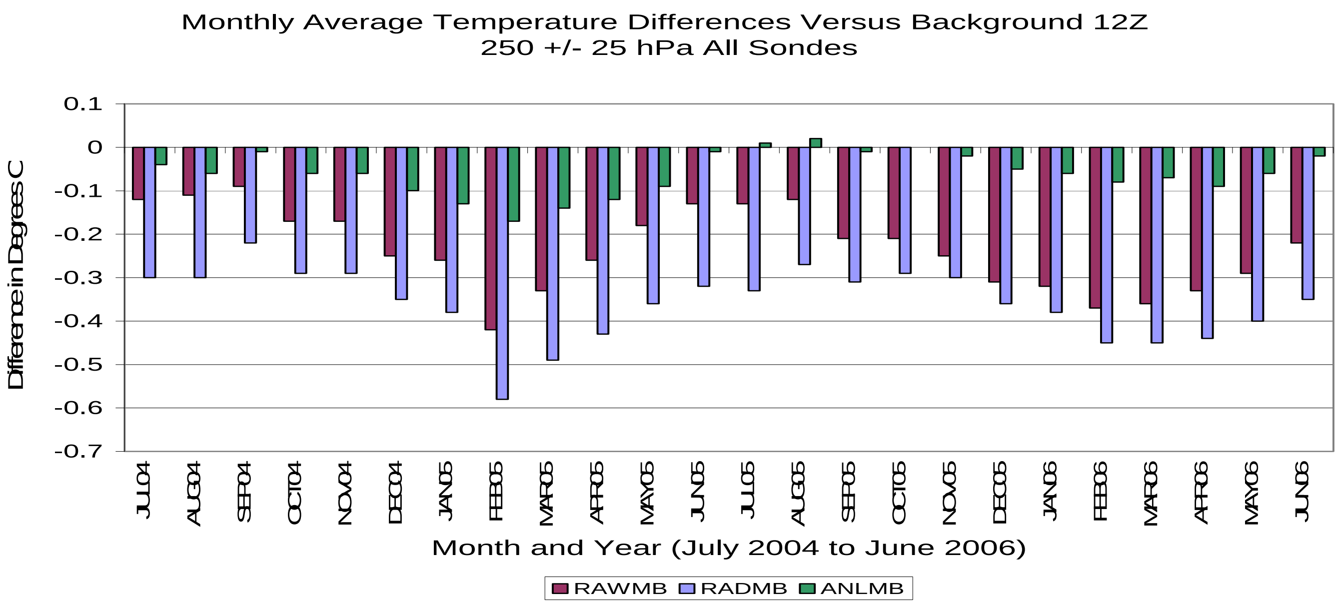
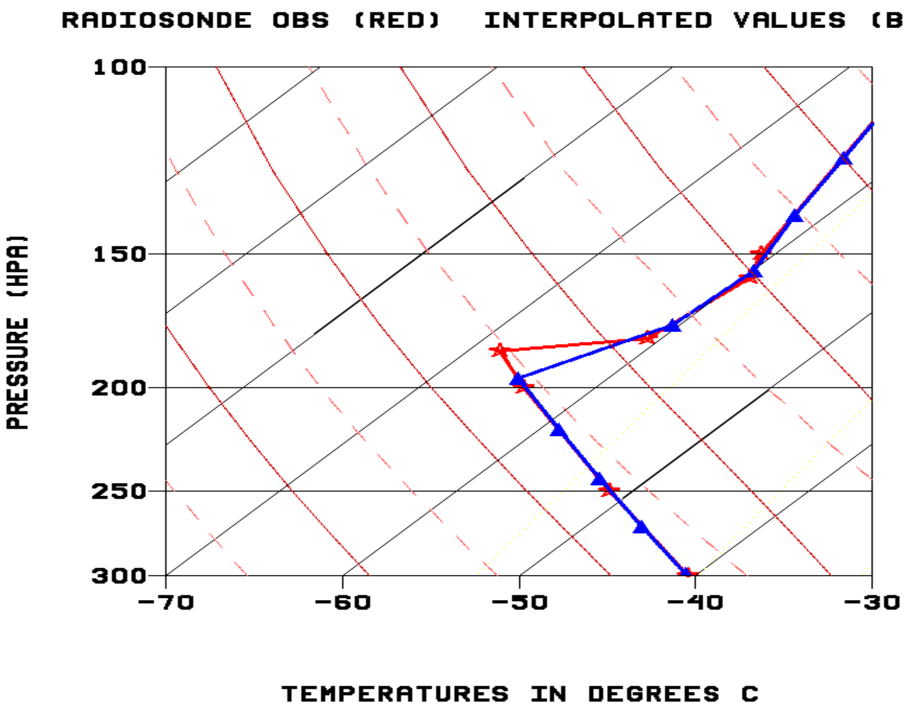


Fig. 7 Monthly averaged global temperature differences versus the background at 250 +/- hPa, raw observation minus background (RAWMB), NCEP RADCOR corrected observation minus background (RADMB) and analysis minus background (ANLMB) from July 2004 to June 2006 for a) 00Z and b) 12Z

a)



b)

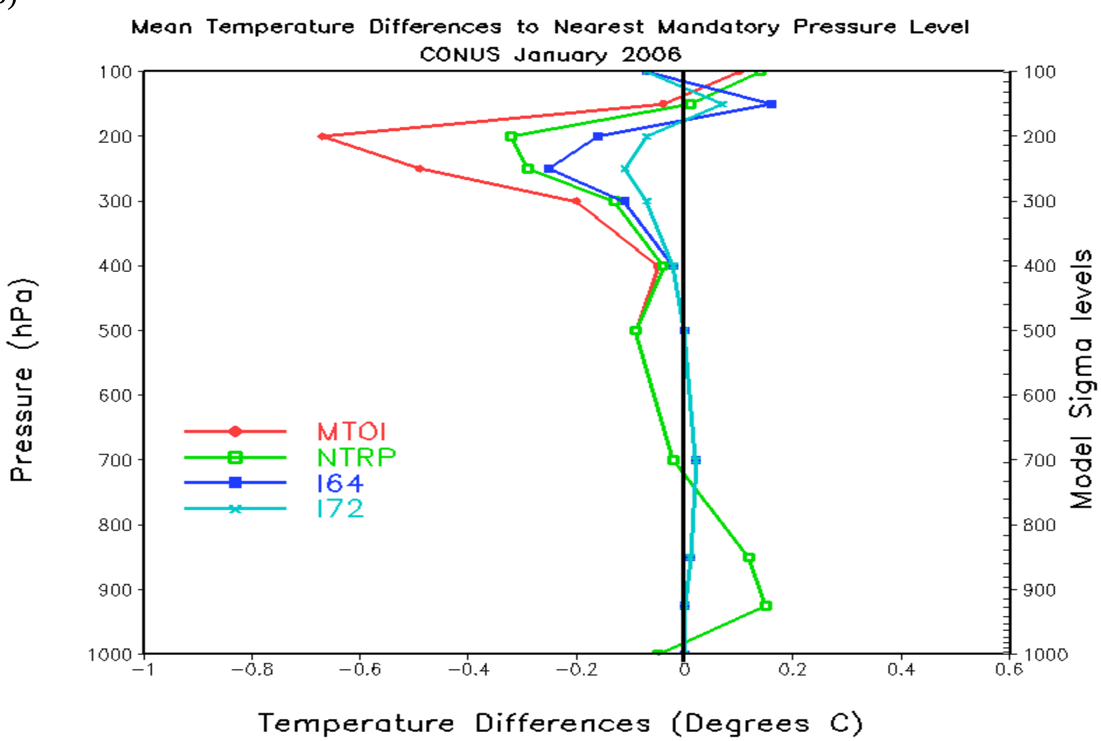
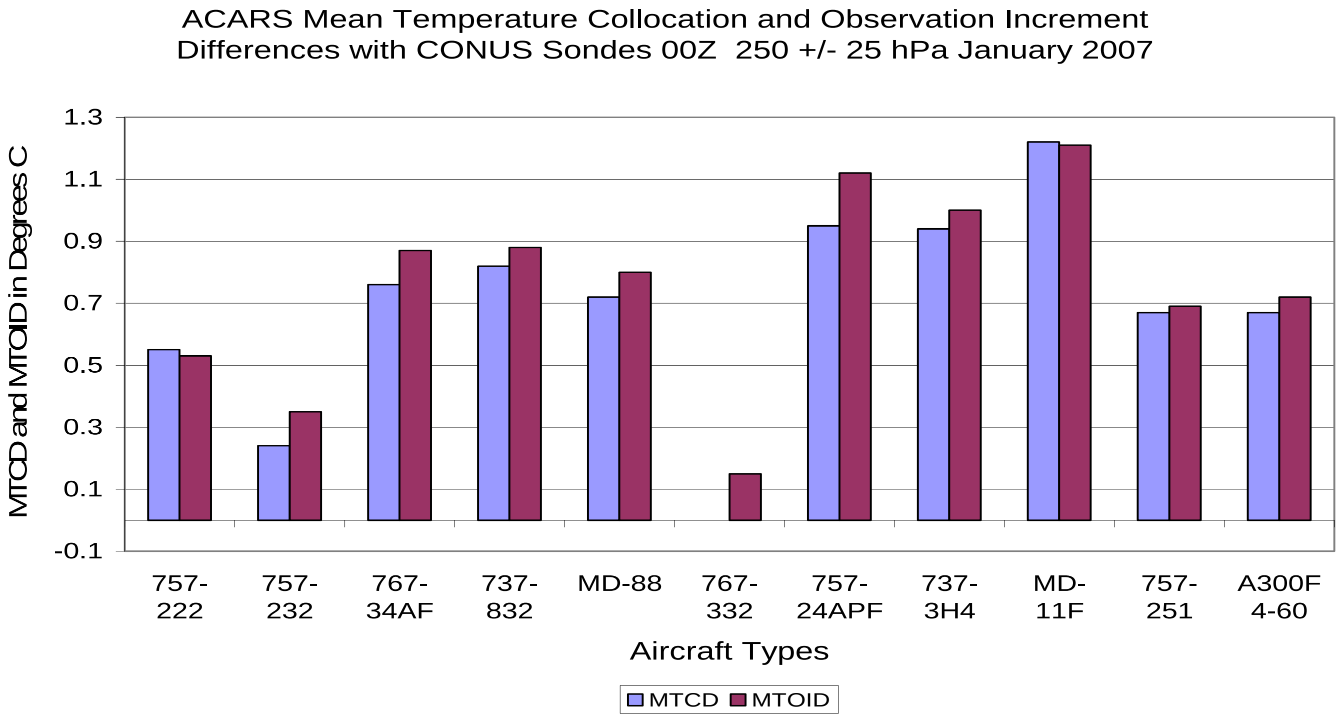


Fig. 8 Radiosonde temperatures profiles for vertical interpolation experiments. a) Skewt logP temperature profile for site 72340, 12Z 4 January 2007, with observations given in red and interpolations to model in blue. b) Monthly averaged temperature differences for January 2006 to the nearest mandatory pressure level for vertical interpolation experiment over the CONUS. See text for explanation of symbols

a)



b)

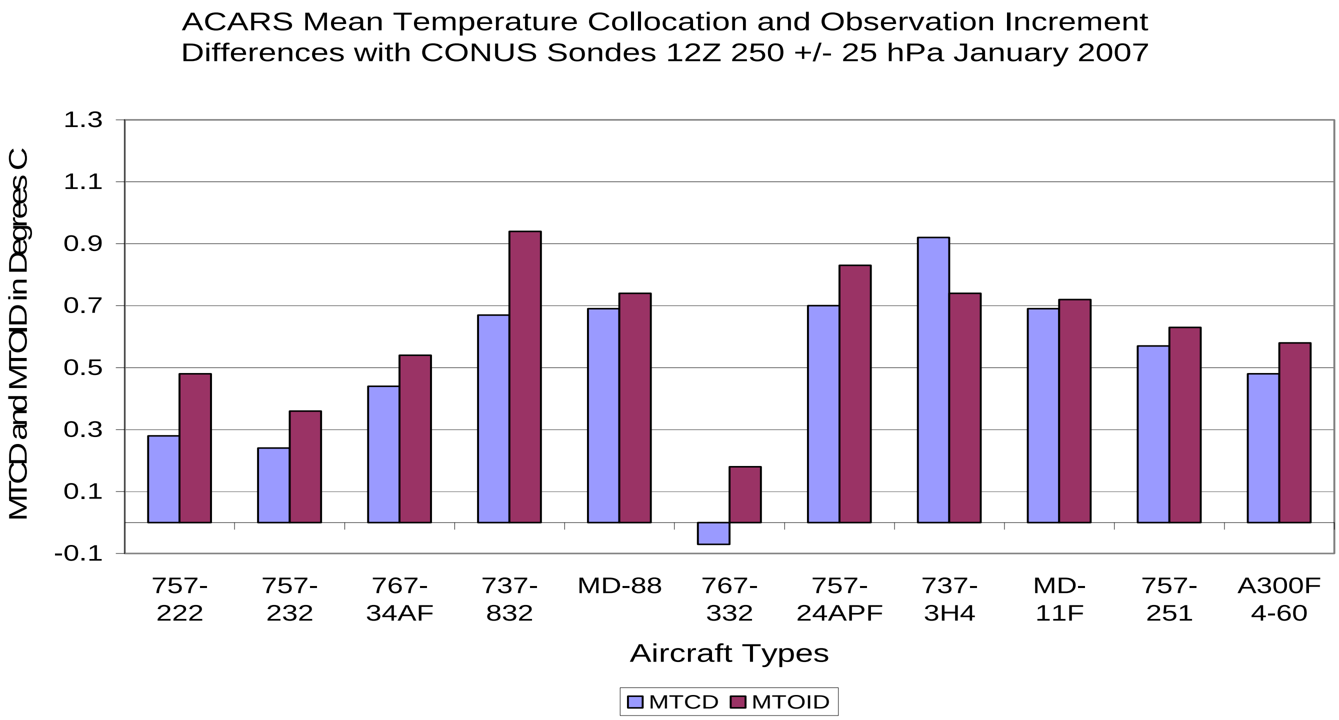


Fig. 9 ACARS mean temperature collocations and observation increment differences with CONUS radiosondes 250 +/- 25 hPa during January 2007 a) 00Z and b) 12Z

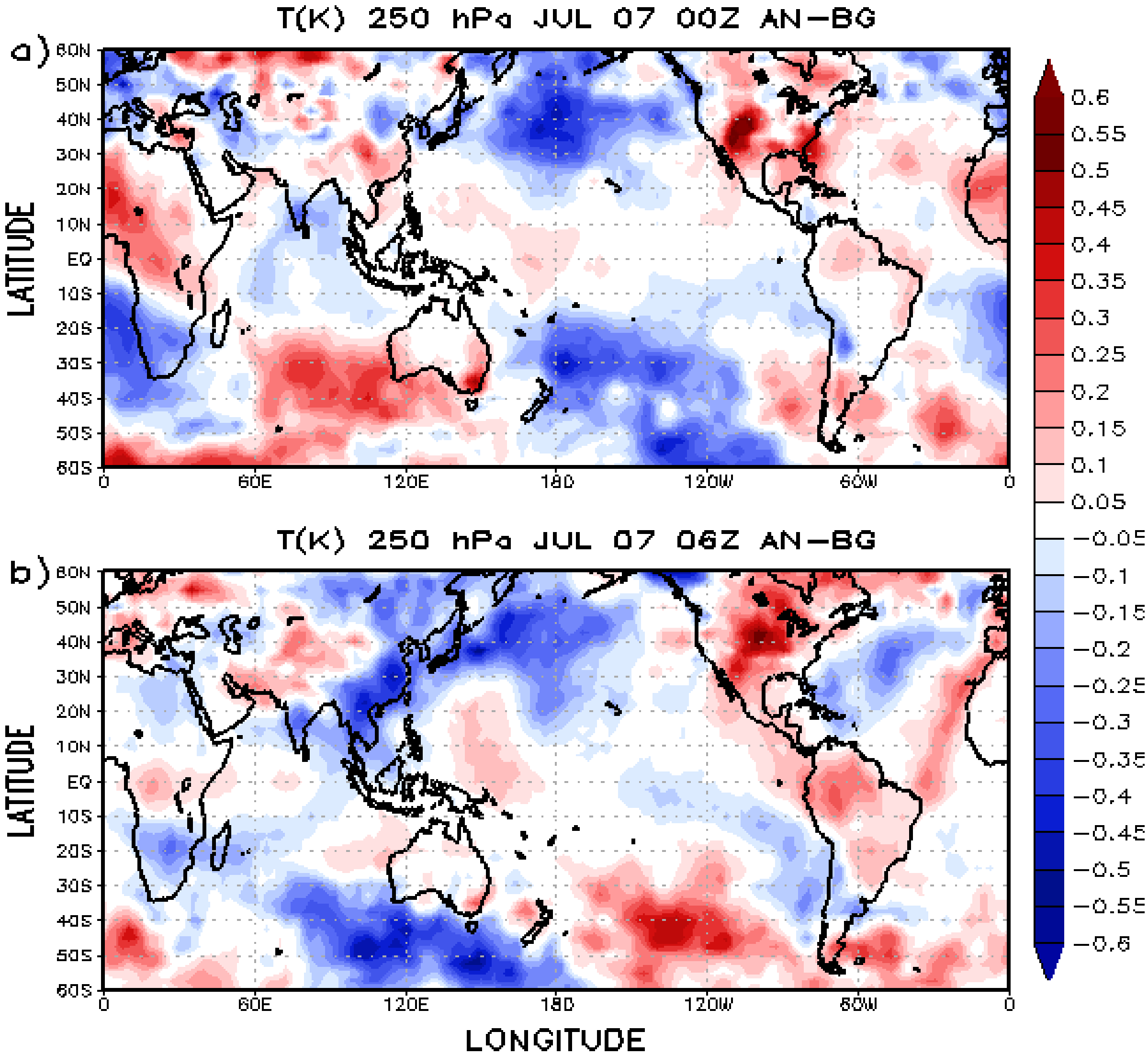


Fig. 10 Monthly average values of analysis (AN) minus background (BG) temperature at 250 hPa during July 2007 for a) 00Z and b) 06Z

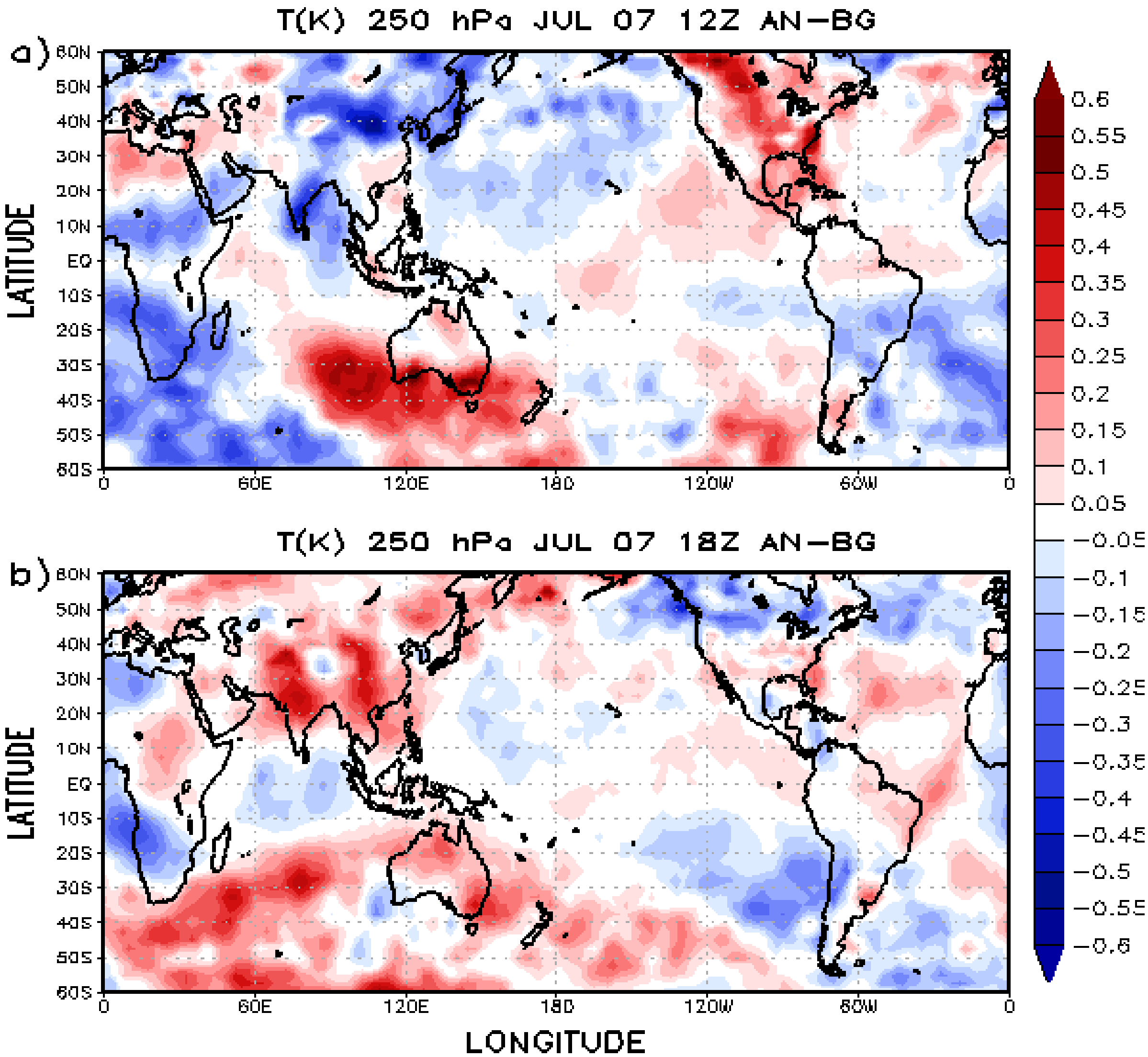
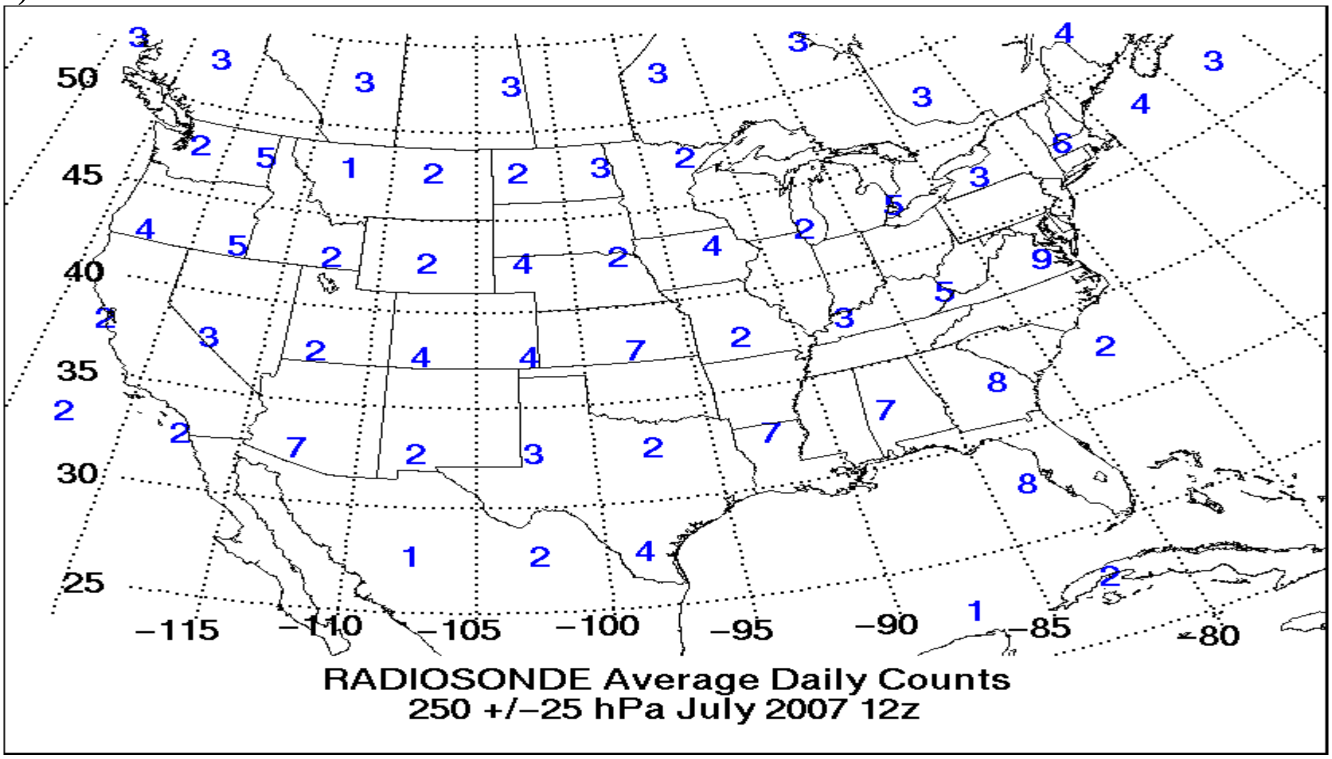


Fig. 11 Same as Fig. 10 but for a) 12Z and b) 18Z

a)



b)

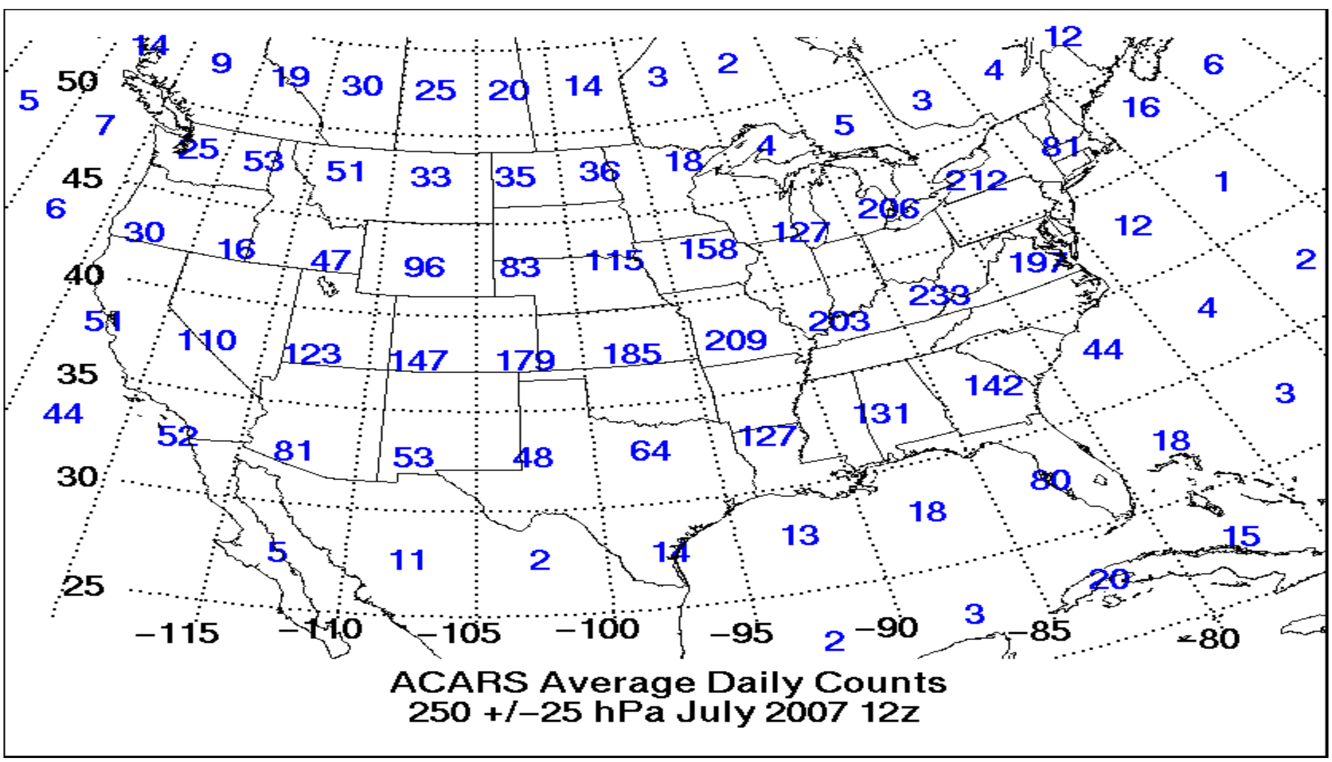
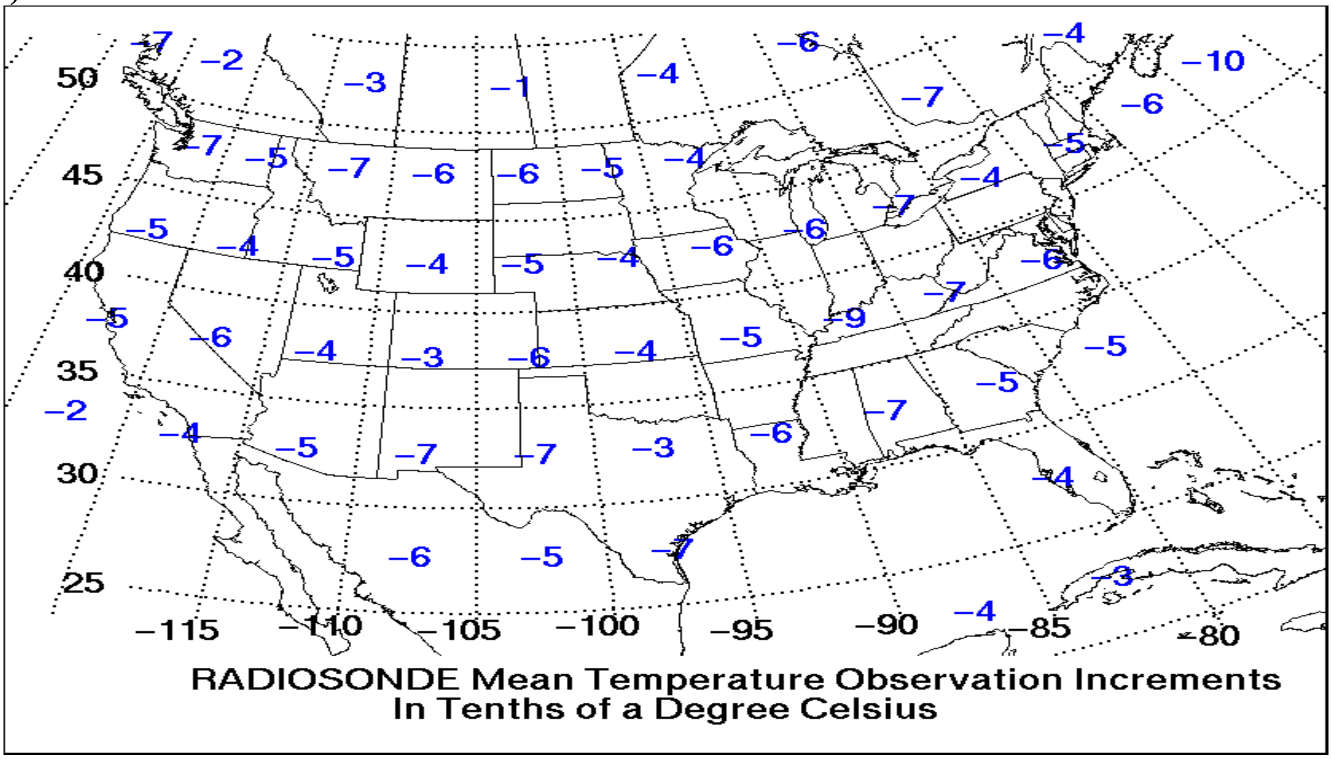


Fig. 12 Radiosonde and ACARS daily average data counts on a 5x5^{o} grid for 250 +/-25 hPa during July 2007 for 12 +/- 3Z a) radiosondes b) ACARS

a)



b)

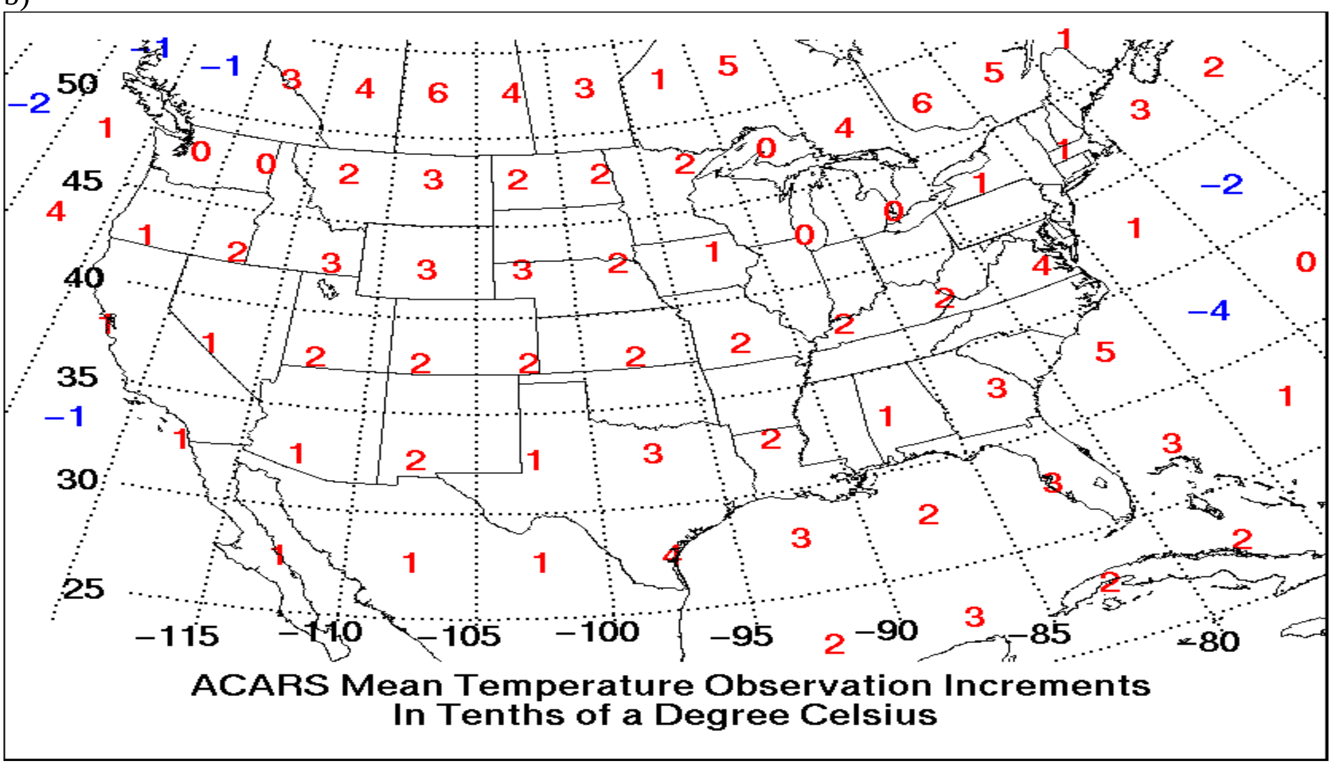
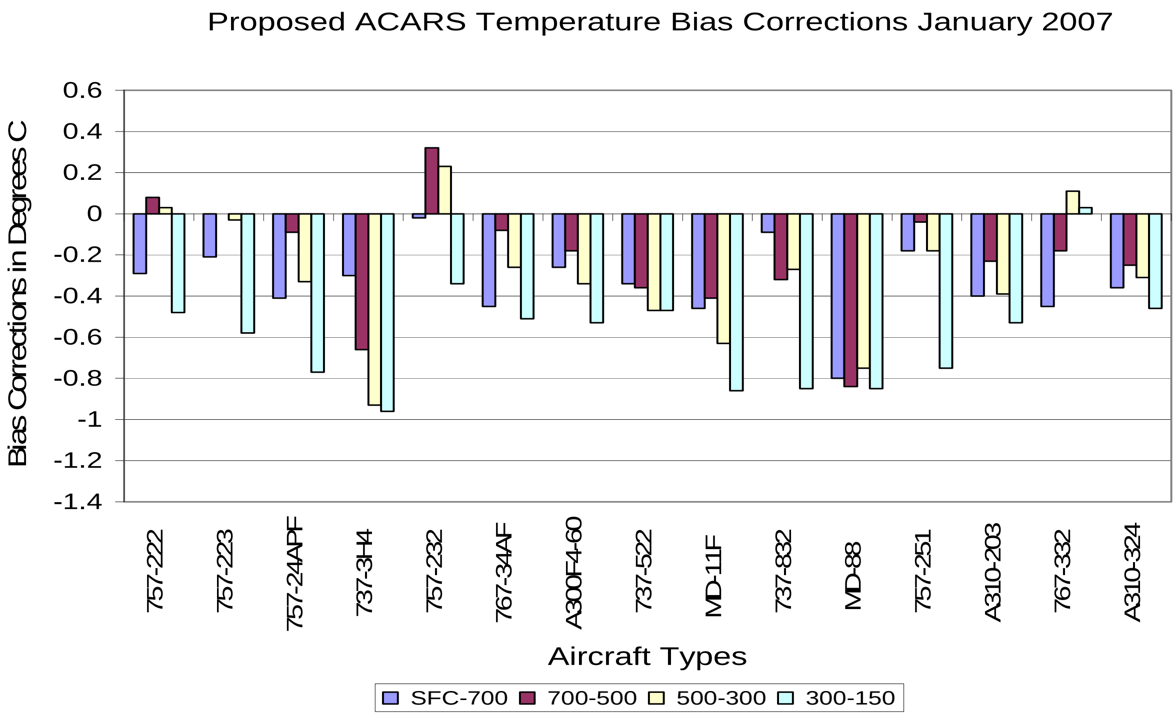


Fig. 13 Radiosonde and ACARS mean temperature observation increments in tenths of degrees C on a 5x5^{o} grid for 250 +/-25 hPa during July 2007 for 12 +/- 3Z a) radiosondes b) ACARS

a)



b)

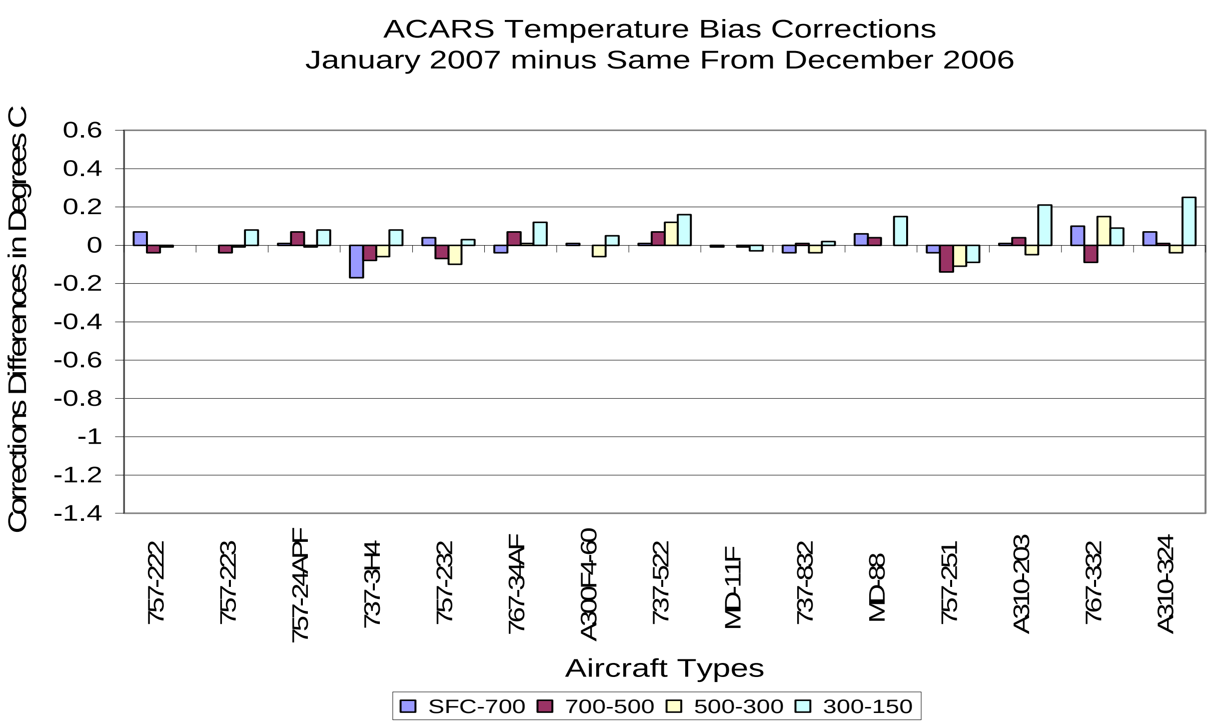
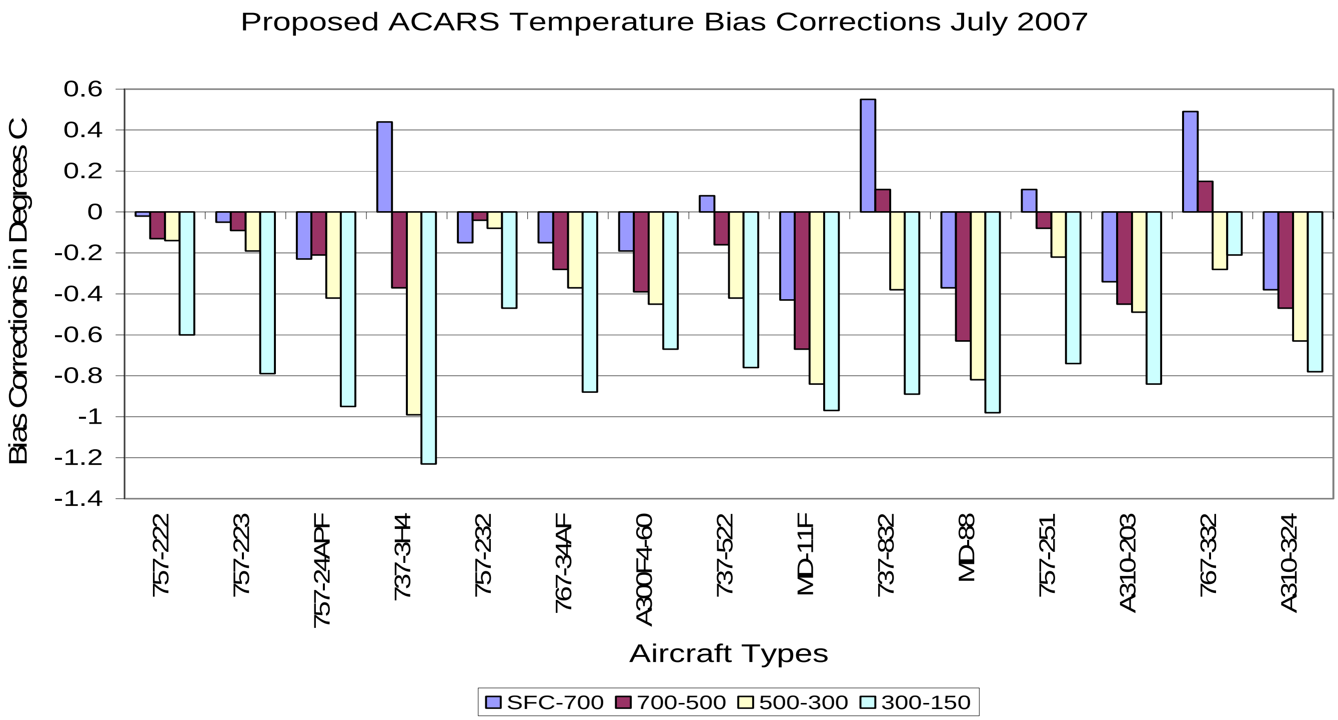


Fig. 14 Proposed ACARS temperature bias corrections for aircraft types for different pressures with highest total data counts for a) January 2007 and b) difference to same for December 2006

a)



b)

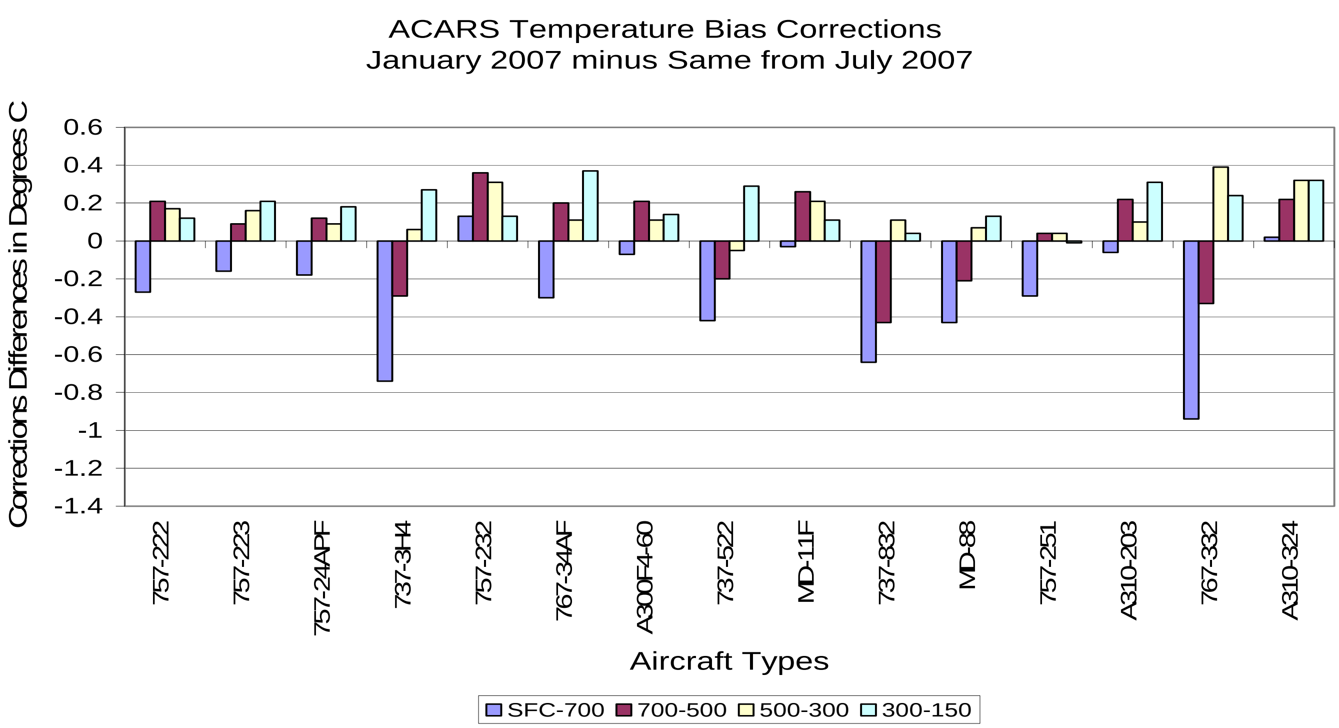
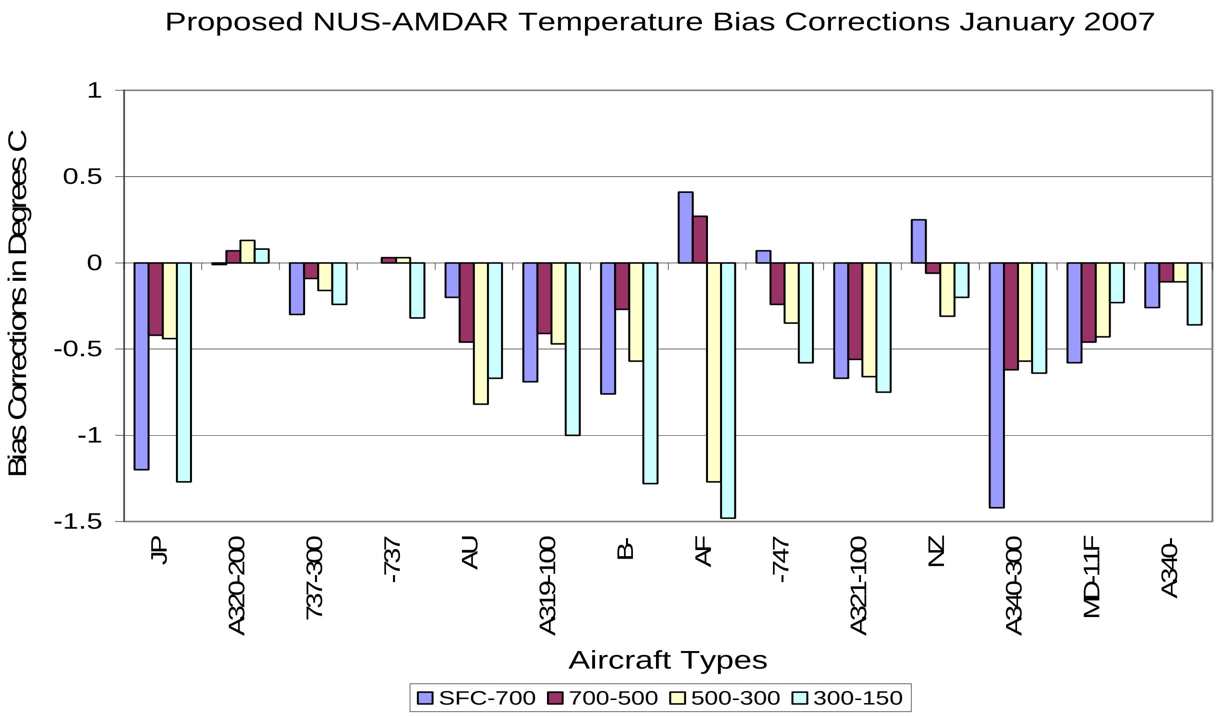


Fig. 15 Proposed ACARS temperature bias corrections for aircraft types for different pressures with highest total data counts for a) July 2007 and b) difference to same for January 2007

a)



b)

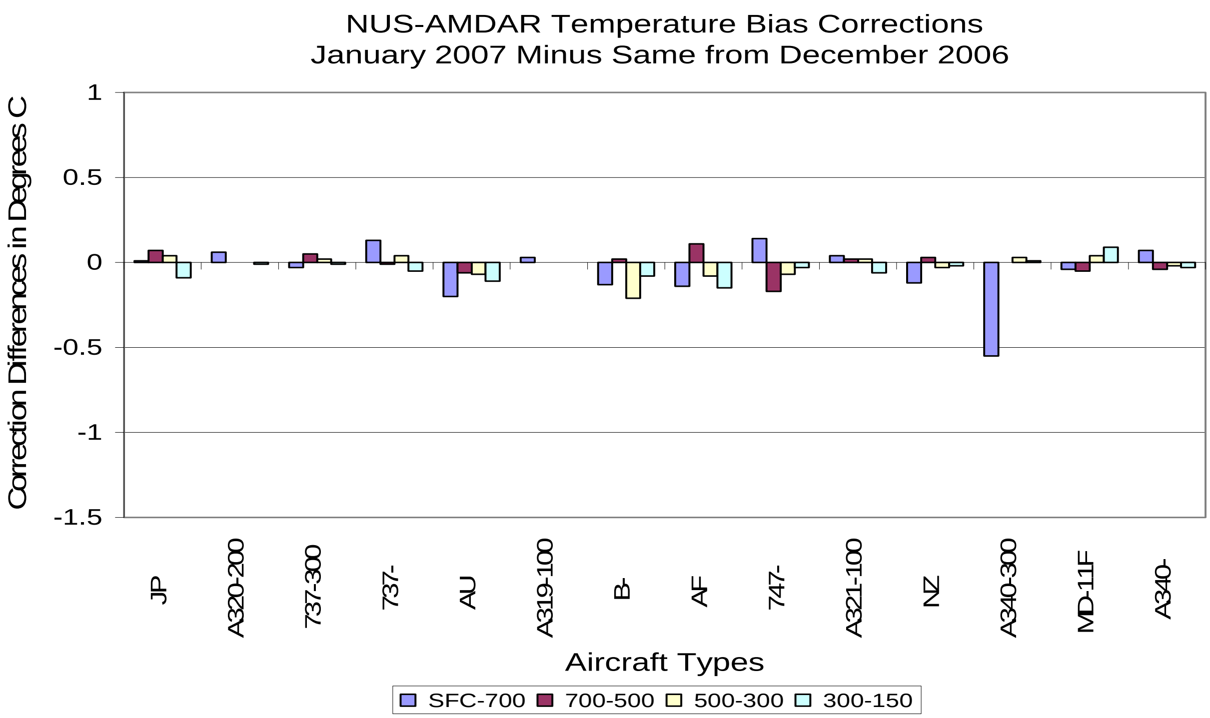


Fig. 16 Same as in Fig. 14 but for NUS-AMDAR data