SYSTEMATIC DIFFERENCES IN AIRCRAFT AND RADIOSONDE TEMPERATURES

Implications for NWP and Climate Studies

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

Wind and temperature data from radiosondes and aircraft are main sources of in situ information to data assimilation systems for NWP (see Table 1 for acronym definitions). Currently, there are about 150,000 automated aircraft reports per day, used at the NCEP, with approximately 3 times as many temperature observations than there are from radiosondes. NCEP operational analyses use automated aircraft report data known as AMDAR, which include automated aircraft data from U.S. aircraft referred to as ACARS. Automated aircraft reports from outside the United States 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 U.S. automated aircraft data, known as 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 a significant impact on analyses and short-range forecasts, but generally less than that of radiosondes for 12-h forecasts; however, no verification scores were presented. Graham et al. (2000) studied the impact on 60-h forecasts of mean sea level pressure with the Met Office model, with various data types withheld for 15 h 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

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Table 1. Acronym definitions.

Acronym	Definition
ACARS	Aircraft Communication Addressing and Reporting System
AIREP	Air report
AMDAR	Aircraft Meteorological Data Relay
ANLMB	Analysis minus background
ARINC	Aeronautical Radio, Inc.
ASNT	Ascent
ATM	Accurate temperature measuring
BUFR	Binary universal form for the representation of meteorological data
CONUS	Continental United States
DSNT	Descent
ECMWF	European Centre for Medium-Range Weather Forecasts
EU	European Union
FAA	Federal Aviation Administration
GDAS	Global Data Assimilation System
GFS	Global Forecast System
GSI	Gridpoint 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–United States
NWP	Numerical weather prediction
NWS	National Weather Service
POF	Phase of flight
QC	Quality control
RADCOR	Radiation correction
RADMB	RADCOR-corrected observation minus background
RAWMB	Raw observation minus background
TAMDAR	Tropospheric Airborne Meteorological Data Reporting
WMO	World Meteorological Organization
4DVAR	Four-dimensional variational data assimilation

impact of variable-thinning of aircraft data on an improved 4DVAR version of the 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 resulting from 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 correction of the data by statistical comparison to the background, as in Harris and Kelly (2001). Operational bias corrections are performed on 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 (see information online at www.ecmwf.int/publications/newsletters/pdf/108.pdf). Here it was found that it was 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.

Because the model's background field has bias (Derber and Wu 1998; Auligne et al. 2007), bias corrections are statistically anchored to a specific data type, such as radiosondes, which presumably have a small bias. These latter types of bias corrections are adaptive because if the bias of the data being corrected changes with time, then so too do the corrections. Such corrections involve sophisticated statistics, but they are just estimates of the corrections because they involve assumptions on how to compare the data to be corrected with the data assumed to be without bias. The standard data, such as that from 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 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. 2004b). 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. 2004a). 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 POF. In addition, aircraft temperature biases of a certain aircraft type may change with time because of 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.

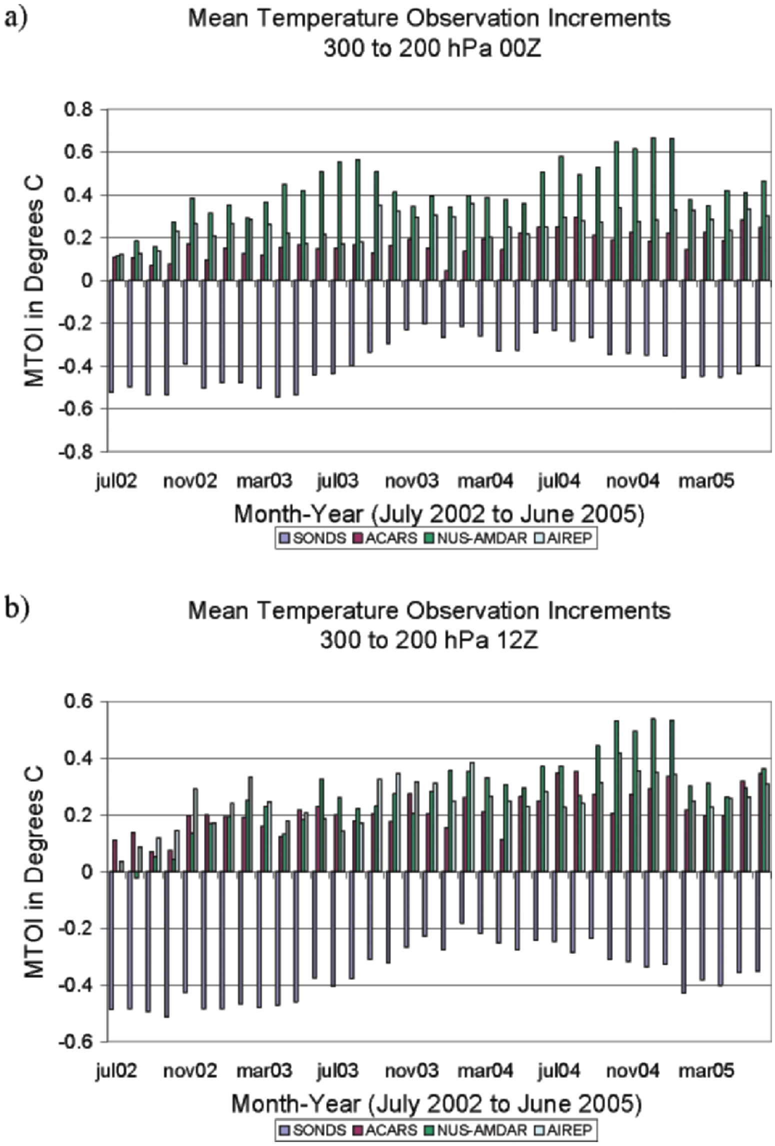

Fig. 1. Three-year monthly mean temperature observation increment history for nongross data between 300- to 200-hPa levels for radiosondes, ACARS, NUS-AMDAR, and AIREP at (a) 0000 and (b) 1200 UTC.

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 min in time, and 30.4 m in the vertical. Ballish and Kumar (2006), using longer periods of time and a global database including radiosondes, ACARS, NUS-AMDAR, and AIREP (nonautomated aircraft report) data, found persistent differences in the sign of their MTOI between radiosonde and aircraft temperatures, with radiosonde MTOI averaging to be roughly 0.5°C colder around 250 hPa, as indicated in Figs. 1a,b. Observation increments are defined here as the observations minus the corresponding 6-h forecast (background) from the NCEP GFS interpolated to the observation locations. Here the monthly averaged MTOI (for nongross data, explained in the "NCEP GDAS" section) are shown for a 3-yr period from July 2002 through June 2005 for 0000 (Fig. 1a) and 1200 UTC (Fig. 1b) for the NCEP GDAS analyses. These findings of temperature differences raise the following issues and the paradigmatic conundrums: what constitutes the absolute truth, what is the impact of these temperature differences on model analyses and forecasts, and how should the biases be corrected? This paper is the first refereed study both to show substantial evidence that the aircraft MTOI vary with aircraft types, pressure levels, and the POF, and to suggest bias corrections of aircraft temperatures.

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 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 neither used in operational analyses nor in computing MTOI, because 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°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°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 subject to additional QC procedures (Collins 1998; Woollen 1991).

Radiosonde temperatures may be adjusted by the NCEP 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 toward the average background.

The GDAS uses the observational 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 an assumption that model fields are linear in the logarithm of pressure between model levels.

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

Pressure (hPa)	Sonde	AMDAR
1000.0	1.20	1.47
950.0	1.10	1.35
900.0	0.900	1.24
850.0	0.800	1.12
800.0	0.800	1.00
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350.0	0.800	1.00
300.0	0.900	1.00
250.0	1.20	1.00
200.0	1.20	1.00
150.0	1.00	1.00

AIRCRAFT TEMPERATURE BIAS ANALYSIS.

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 mm 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 to the temperature is needed because of large dynamic heating of the order of 25°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 airspeed and temperature change with pressure, time, and horizontal position. Therefore, there can be either error or uncertainty in the temperature because of the time delay during which the sensors adjust to the true air temperature as well as to time averaging of the data. With aircraft, the temperature-sensing equipment may be neither repaired nor replaced for a long time. A spurious increase in temperature may occur when the pitot tubes sometimes become corroded or clogged with debris.

ARINC processes the ACARS data downlinks from the aircraft into MDCRS (the ACARS data in the BUFR format). The resulting data have the tail numbers encrypted at the request of the airlines to protect the autonomy of the data. Because NCEP is the WMO lead center for aircraft data, we had access to the tail number encryption software. By means of obtaining real tail numbers in conjunction with the FAA Web site (online at 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 (list of EU AMDAR data available from Stewart Taylor at stewart.taylor@metoffice.com), 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 (0000, 0600, 1200, and 1800 UTC) for nongross 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 mean of those of a particular type, then that aircraft's data were not used in the final computation. The bar graphs shown in Figs. 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 good predictors of bias corrections and other difficulties will be discussed below.

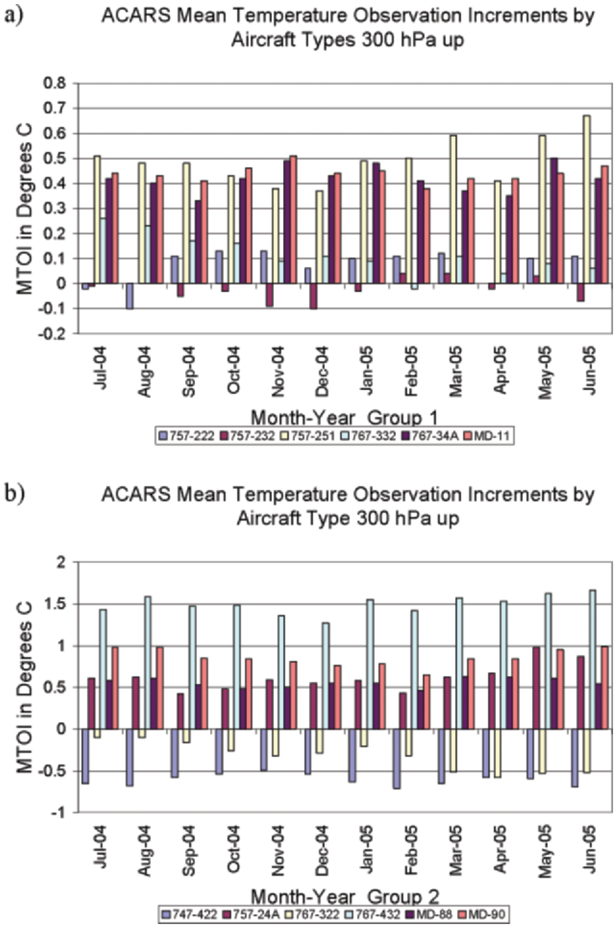

Fig. 2. Monthly mean temperature observation increment sequence for two groups of ACARS types at 300 hPa and above at all times of day for nongross data with outliers removed for group (a) 1 and (b) 2.

Aircraft-to-aircraft collocation studies. 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. Because temperature tends to change with altitude, the collocation statistics were done using aircraft data that are within 1 hPa in pressure and pass the temperature gross check; in addition, the two compared observations had to be within 150 km and 1 h 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 MTCD. For collocations near the ground, one would need tighter limits because of increased atmospheric variability as well as the need 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. Because the 757-222 units have negative MTOI, most of the MTCD are negative. The MTCD are similar to MTOID, even though the collocations involve a small subset of the total data, while the MTOI are global and involve 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.

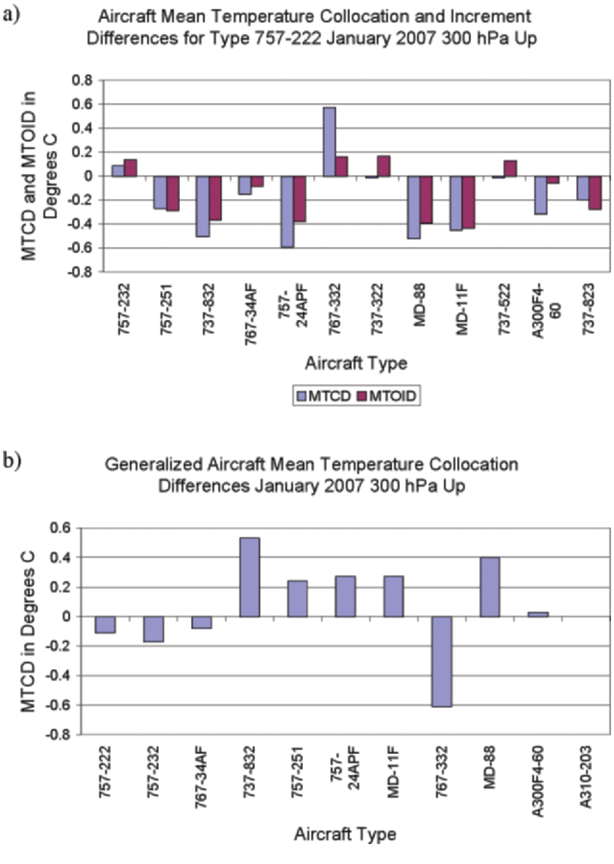

Fig. 3. Aircraft-to-aircraft statistics at 300 hPa and above by aircraft types during Jan 2007 (a) mean temperature collocation differences and observation increment differences for type 757-222 and (b) mean temperature collocation differences between aircraft types on the *x* axis with all other types.

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, from 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,

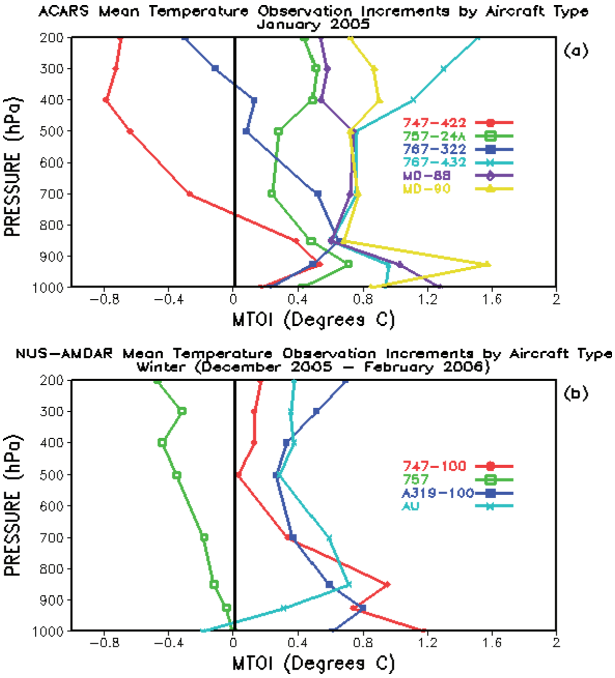

Fig. 4. Average vertical dependence of mean temperature observation increments for select aircraft types versus pressure for nongross data for (a) ACARS types and (b) NUS-AMDAR types.

and vertical behavior of the MTOI, with most types showing a predominantly positive (warm) MTOI.

Many types of U.S. 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 the following different POF: MISS, ASNT, DSNT, and LEVL. MTOI near the ground may be large because of 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 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°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 the 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 nongross data, because some types have no data passing the QC because all of their data are 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 (Figs. 6a,b). The 767-322 units reporting with a missing POF are roughly 1°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 because 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.

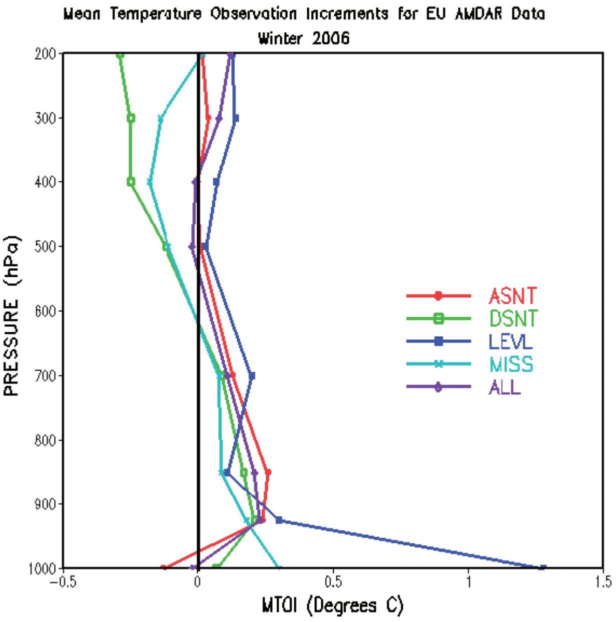

Fig. 5. POF and pressure dependence of European AMDAR mean temperature observation increments for nongross data for winter 2006.

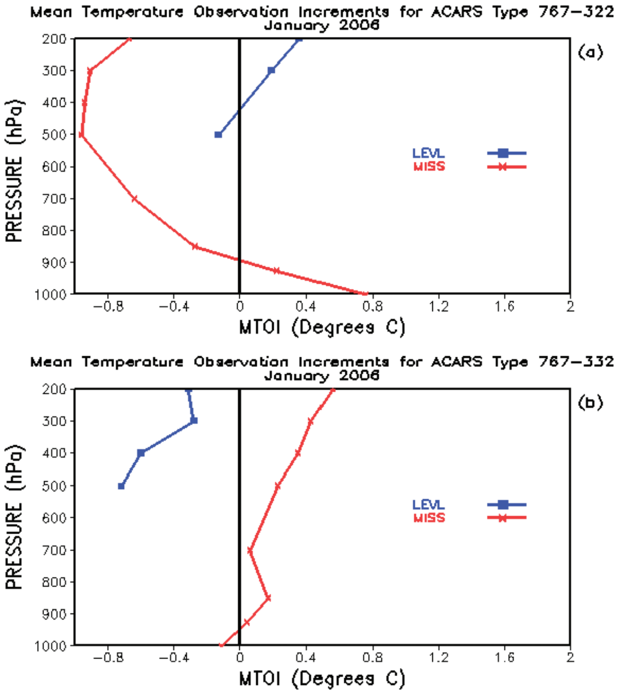

Fig. 6. Vertical dependence of mean temperature observation increments versus missing and level POF for Jan 2006 for ACARS types (a) 767-322 and (b) 767-332.

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 because of 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

Table 3. ACARS statistics Jan 2007 all times of day for nongross data.

Type	Surface–700 hPa		700–500 hPa		500–300 hPa		300–150 hPa	
	No.	MTOI (°C)	No.	MTOI (°C)	No.	MTOI (°C)	No.	MTOI (°C)
737-322	4,407	0.22	6,222	−0.1	7,997	−0.1	8,763	−0.2
737-3H4	102,517	0.28	49,104	0.55	35,446	0.71	24,087	0.48
737-522	47,066	0.32	27,358	0.25	15,665	0.26	21,387	−0.01
737-724	0	0	0	0	100	0.43	567	0.19
737-823	111	0.36	118	0.23	1,642	−0.02	9,966	0.26
737-824	0	0	0	0	327	0.09	1,856	0.05
737-832	7,612	0.07	8,826	0.21	13,864	0.05	68,500	0.37
737-924	0	0	0	0	0	0	253	0.29
747-422	589	0.17	600	−0.36	666	−0.76	1,571	−0.66
757-222	72,329	0.27	90,427	−0.19	112,123	−0.25	306,598	0
757-223	133,777	0.19	91,944	−0.12	64,925	−0.19	3,730	0.1
757-224	0	0	0	0	0	0	4,477	0.14
757-232	3,558	0	1,754	−0.43	11,521	−0.44	167,844	−0.13
757-24APF	118,746	0.39	65,160	−0.03	50,367	0.12	57,476	0.3
757-251	11,561	0.16	12,011	−0.07	14,103	−0.03	49,698	0.27
767-224	0	0	0	0	0	0	718	0.32
767-322	619	0.24	568	−0.63	1,257	−0.99	3,015	−0.83
767-323	0	0	0	0	119	0.64	699	0.54
767-332	2,261	0.43	544	0.07	3,079	−0.33	32,012	−0.51
767-34AF	51,458	0.43	26,050	−0.03	29,685	0.04	57,083	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	2,524	0.29
777-223	0	0	0	0	191	0.37	2,875	0.54
777-224	0	0	0	0	0	0	109	0.1
A300F4-60	67,897	0.24	33,529	0.07	4,424	0.12	12,639	0.05
A310-203	33,207	0.37	18,539	0.12	1,647	0.18	6,867	0.06
A310-222	11,349	0.32	6,821	0.14	499	0.15	2,029	−0.03
A310-324	15,685	0.34	8,476	0.14	722	0.09	2,801	−0.02
A319-131	1,465	0.04	1,239	−0.13	1,498	−0.09	2,935	−0.32
A320-232	1,739	0.04	1,554	−0.13	2,251	−0.17	5,054	−0.13
MD-10-10F	867	−0.07	0	0	1,924	−0.15	447	−0.31
MD-11	147	0.36	281	0.14	342	−0.07	119	0.3
MD-11F	30,354	0.44	17,424	0.3	14,155	0.41	36,914	0.38
MD-88	11,115	0.77	12,451	0.73	23,433	0.53	40,498	0.37
Total	730,926	0.3	481,280	0.05	414,212	0.02	931,151	0.06

balloon and its tether, and all the parts of the radiosonde and the computer processing 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

TABLE 4. NUS-AMDAR statistics for Jan 2007 at all times of day for nongross data.

	Surface–700 hPa		700–500 hPa		500–300 hPa		300–150 hPa	
Type	**No.**	**MTOI (°C)**	**No.**	**MTOI (°C)**	**No.**	**MTOI (°C)**	**No.**	**MTOI (°C)**
737	60,291	−0.1	25,737	−0.17	19,189	−0.24	24,444	0.02
737-300	65,223	0.22	20,757	−0.04	46,828	−0.05	26,441	−0.06
747	7,104	0.39	2,494	−0.12	1,639	0.05	51,158	0.34
747-400	3,895	0.65	1,013	0.23	2,053	0.26	15,256	0.4
757	16,389	−0.08	5,758	−0.26	1,215	−0.29	3,741	−0.43
767	6,170	0.11	2,090	−0.3	679	−0.29	9,603	−0.05
A300-600	4,344	0.3	1,352	0.25	2,390	0.15	5,958	0.05
A318-100	5,570	0.13	4,469	−0.08	5,195	−0.18	803	−0.04
A319-100	35,533	0.61	17,978	0.27	22,771	0.25	21,495	0.7
A320-100	4,849	0.07	3,747	−0.13	5,323	−0.28	584	−0.54
A320-200	56,785	−0.1	32,796	−0.2	50,819	−0.35	29,179	−0.39
A321-100	16,890	0.58	6,083	0.43	12,375	0.45	13,834	0.44
A330-300	6,140	0.41	2,653	0.37	3,336	0.23	12,408	0.36
A340	5,830	0.17	2,607	−0.15	987	−0.07	22,374	0.05
A340-300	5,850	1.13	2,635	0.44	3,689	0.39	21,354	0.44
A340-600	1,344	0.82	519	0.71	410	0.47	3,254	0.56
MD-11	2,935	0.44	446	0.53	179	0.55	2,706	0.51
MD-11F	6,931	0.5	2,343	0.37	4,898	0.26	17,835	0.03
AU	34,747	0.56	11,805	0.29	15,991	0.26	49,155	0.33
AF	33,943	−0.13	6,766	−0.42	3,030	0.78	38,490	1.16
B	30,705	0.67	15,895	0.13	25,531	0.36	17,302	0.97
HK	13,645	0.69	4,527	0.32	1,059	0.04	6,834	0.12
JP	137,758	1.11	85,604	0.28	46,875	0.22	70,663	0.97
MK	1,617	0.77	497	0.54	192	0.13	2,174	1.06
NZ	19,449	0.03	4,909	−0.12	5,255	−0.25	6,902	−0.08
SA	2,644	0.62	734	−0.17	299	−0.07	3,829	0.64
SV	8,099	1.02	3,683	0.88	3,148	0.75	223	0.78
Misc	34,294	0.2	13,715	0.05	13,513	0.33	27,407	0.32
Total	628,974	0.44	283,612	0.1	298,868	0.07	505,406	0.41

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).

Radiation correction. Attempts to correct radiosonde temperatures for radiative effects, called the radiation correction, pose 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 because of 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 procesure makes it more negative. Figure 7a shows global MTOI for 250 ± 25 hPa for 0000 UTC both 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; most radiosondes are in the Northern Hemisphere. Similar results for 1200 UTC 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 Figs. 7a,b) as expected, considering the Chinese correction was relatively large (not shown). The mean cooling resulting from the NCEP RADCOR and the analysis are smaller after this correction. Another problem with RADCOR was an error involving the radiosonde ascent rate in RADCOR applied at the site for U.S. RS80 radiosondes (Redder et al. 2004). 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.

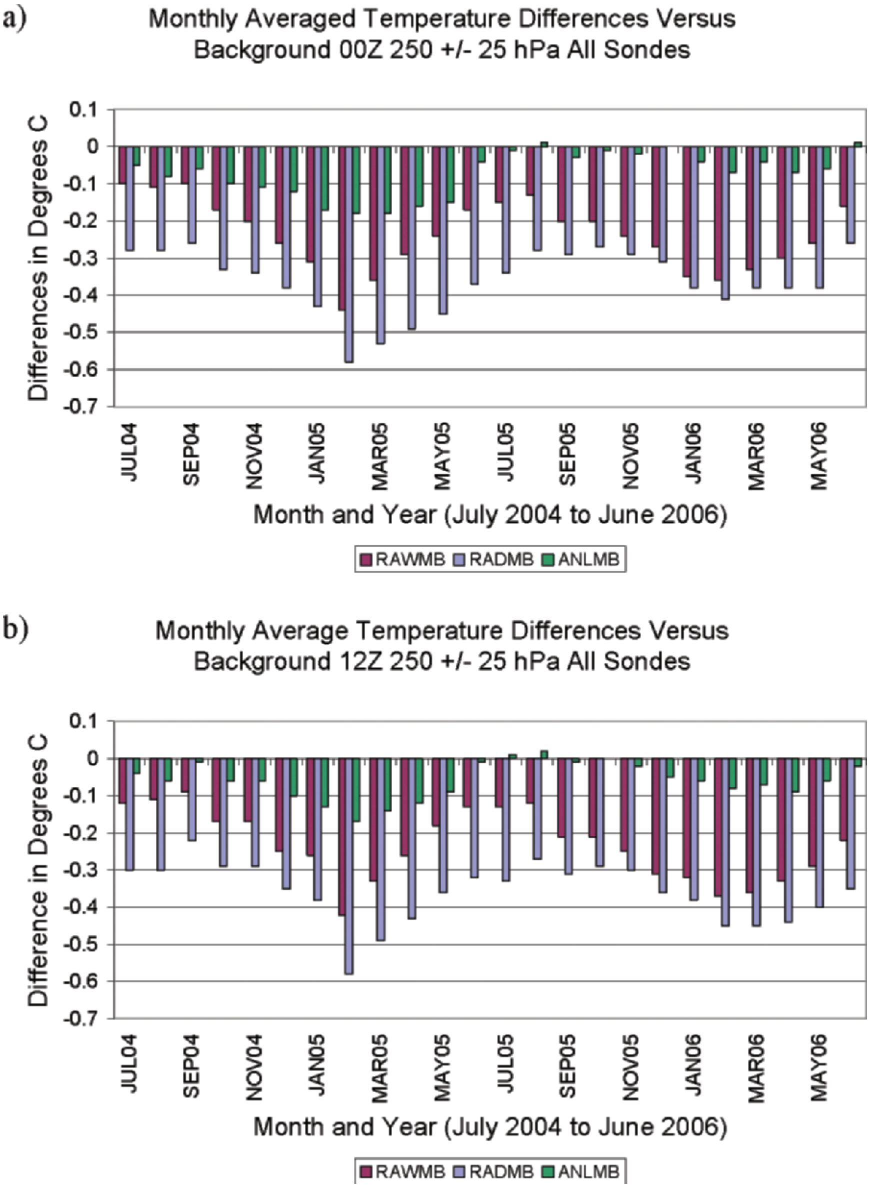

Fig. 7. Monthly averaged global temperature differences versus the background at 250 ± 25 hPa, RAWMB, RADMB, and ANLMB from Jul 2004 to Jul 2006 for (a) 0000 and (b) 1200 UTC.

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 nonoperational verification Web site by S. Saha (online at wwwt.emc.ncep.noaa.gov/gmb/ssaha/maps/obs/month/monthly_cross.html). For the 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, because the definition of MTOI is just the opposite of ours. Forecasts from the ECMWF show similar characteristics at the same Web site.

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 2°C over the 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.

VERTICAL INTERPOLATION EXPERIMENTS. Because 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 that were 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. Because 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.

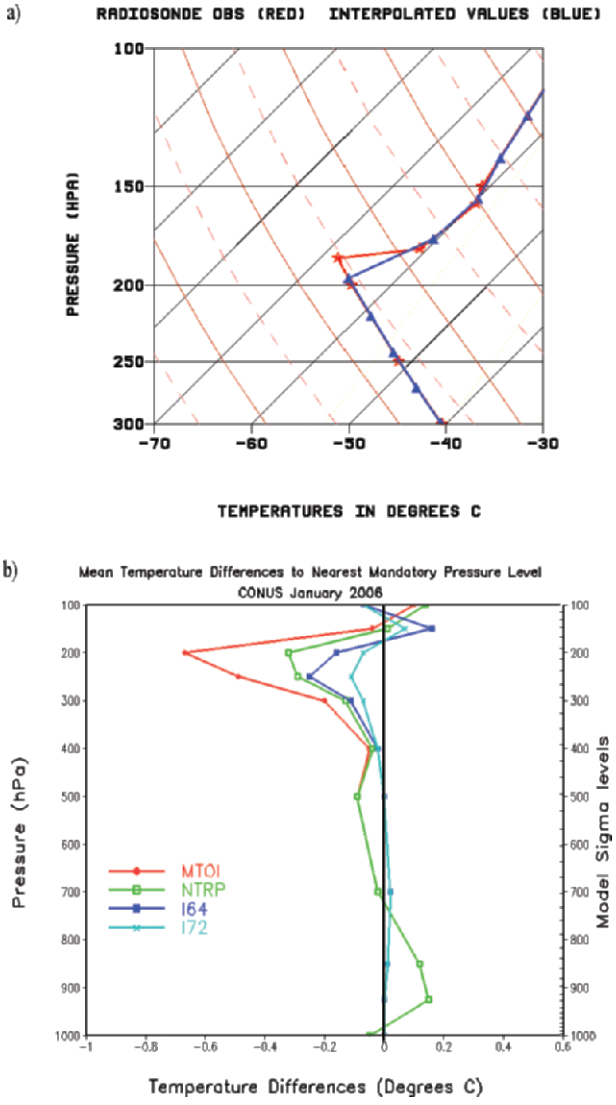

Fig. 8. Radiosonde temperatures profiles for vertical interpolation experiments. (a) Skew *T*–log*P* temperature profile for site 72340, 1200 UTC 4 Jan 2007, with observations given in red and interpolations to model in blue. (b) Monthly averaged temperature differences for Jan 2006 to the nearest mandatory pressure level for vertical interpolation experiment over the CONUS. See text for explanation of symbols.

To understand this pedagogical experiment better, a skew t–log$p$ diagram is shown in Fig. 8a, for site 72340 for 1200 UTC 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

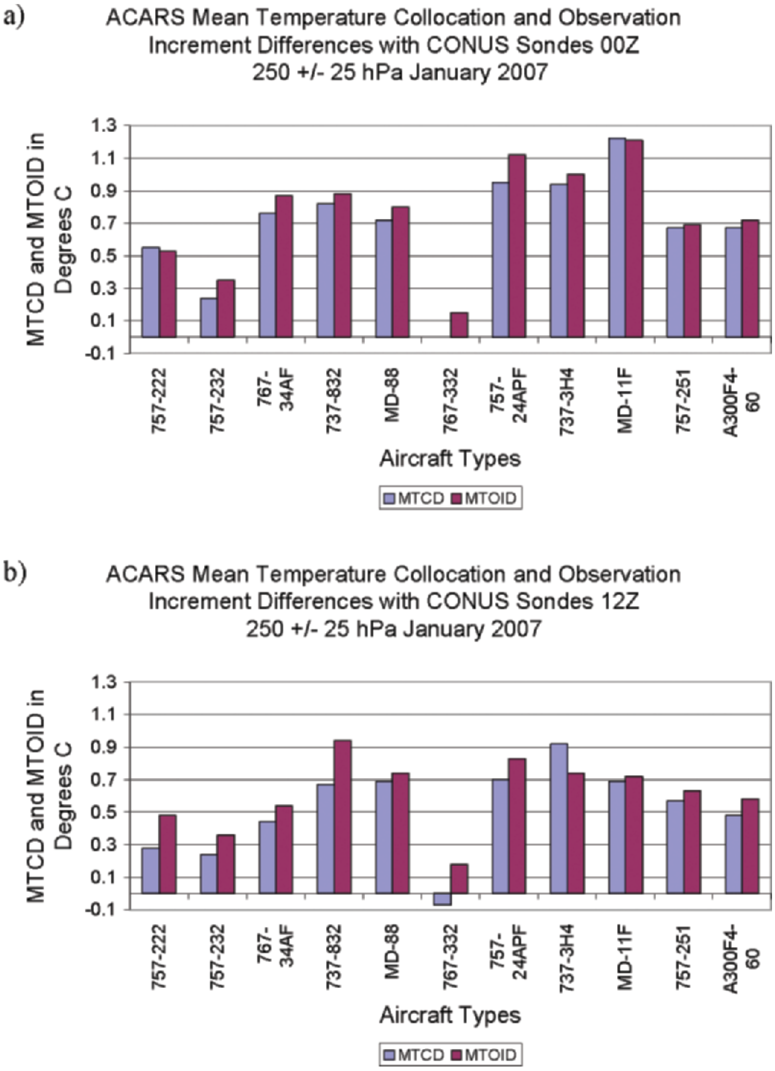

Fig. 9. ACARS mean temperature collocations and observation increment differences with CONUS radiosondes at 250 ± 25 hPa during Jan 2007: (a) 0000 and (b) 1200 UTC.

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 0000 and 1200 UTC 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 and 175 hPa or else they were treated as nontropopause 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 6 h 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 0.3297 and 0.1382, resulting in eight 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 the sharp tropopause, 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 because it is based on the MTOI of this radiosonde type.

Aircraft to radiosonde collocation studies. Because 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

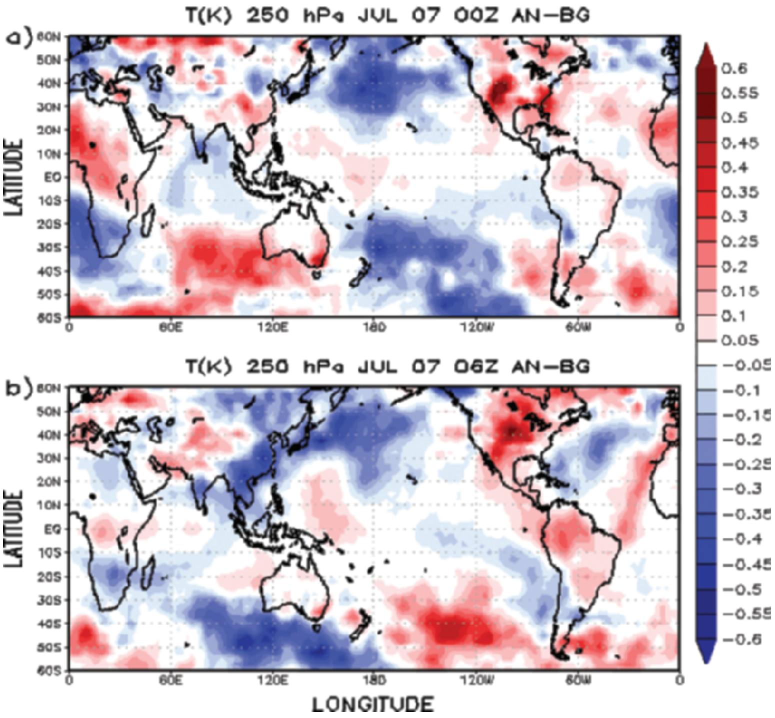

Fig. 10. Monthly average values of analysis (AN) minus background (BG) temperature at 250 hPa during Jul 2007: (a) 0000 and (b) 0600 UTC.

interpolation is necessary because 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 0000 UTC 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 resulting from the collocations being a small subset of the total data used in the MTOI calculations. Figure 9b shows the same for 1200 UTC, but the aircraft types displayed are the same as in Fig. 9a. The MTCD tend to be more positive for 0000 UTC, which either could be due to diurnal differences in aircraft routes, reporting pressures, and times, or may indicate a problem with RADCOR for the radiosondes.

EVIDENCE OF SYSTEMATIC TEMPERATURE PROBLEMS.

If the average of the observation increments was 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, Figs. 10a,b show, respectively, nonzero monthly average temperature differences of the analysis minus background for 0000 and 0600 UTC for July 2007 at 250 hPa. Figures 11a,b similarly show changes for 1200 and 1800 UTC. The analysis introduces areas of warming over the CONUS, except at 1800 UTC. Systematic temperature changes and their relation to data biases are not always obvi-

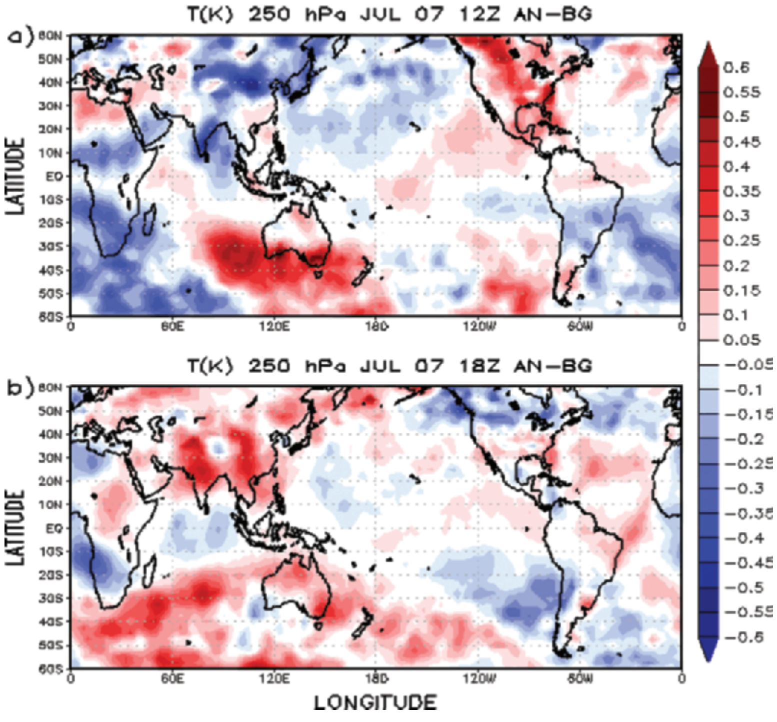

Fig. 11. Same as Fig. 10, but for (a) 1200 and (b) 1800 UTC.

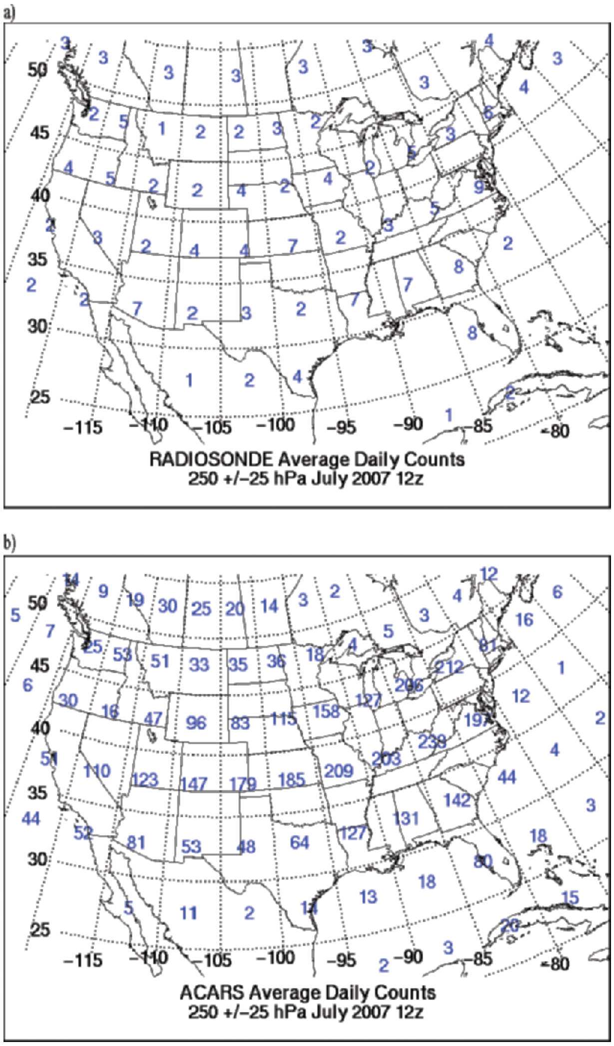

Fig. 12. Radiosonde and ACARS daily average data counts on a 5° × 5° grid for 250 ± 25 hPa during Jul 2007 for 1200 ± 0300 UTC (a) radiosondes and (b) ACARS.

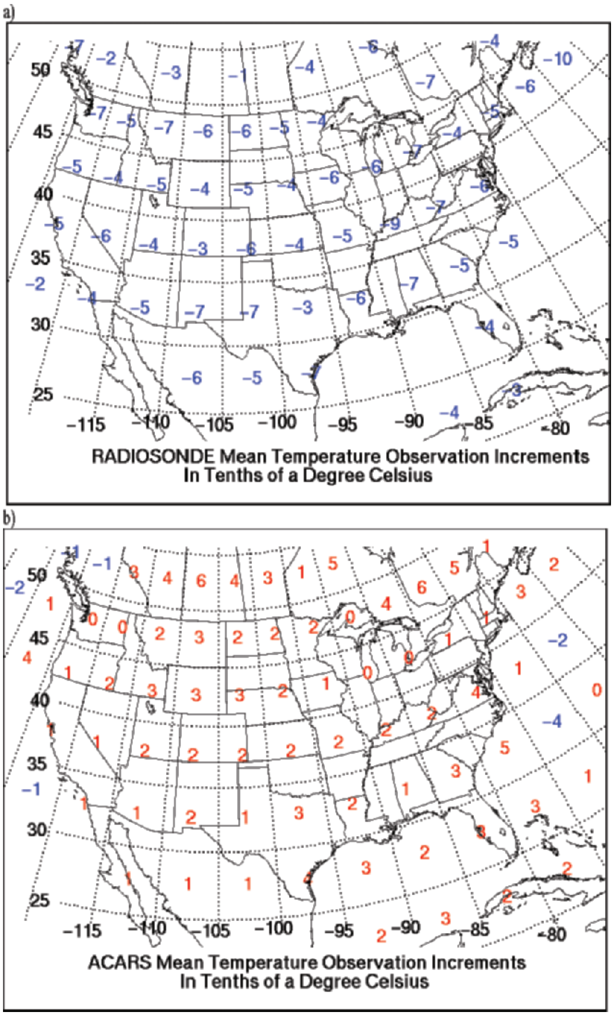

Fig. 13. Radiosonde and ACARS mean temperature observation increments in tenths of degrees Celsius on a 5° × 5° grid for 250 ± 25 hPa during Jul 2007 for 1200 ± 0300 UTC (a) radiosondes and (b) ACARS.

ous, 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, Figs. 12a,b show, respectively, the average counts of radiosonde and ACARS temperature observations for 1200 UTC ±3 h for July 2007 at 250 ± 25 hPa on a 5° × 5° 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 Celsius. The ACARS data show mostly positive (warm) MTOI and those of the radiosondes are 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 resulting from the contrasting MTOI, where the differences are larger in magnitude than the analysis minus background changes shown in Figs. 10 and 11.

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 of the aircraft of one type may be sampled uniformly because 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 the "Aircraft temperature bias analysis" section, these were shown to be similar to collocation differences. Still, there are problems to be overcome using MTOI differences. Because radiosonde MTOI have a large average of almost 2°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 overemphasize 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 h, 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, because 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 0000 and 1200 UTC.

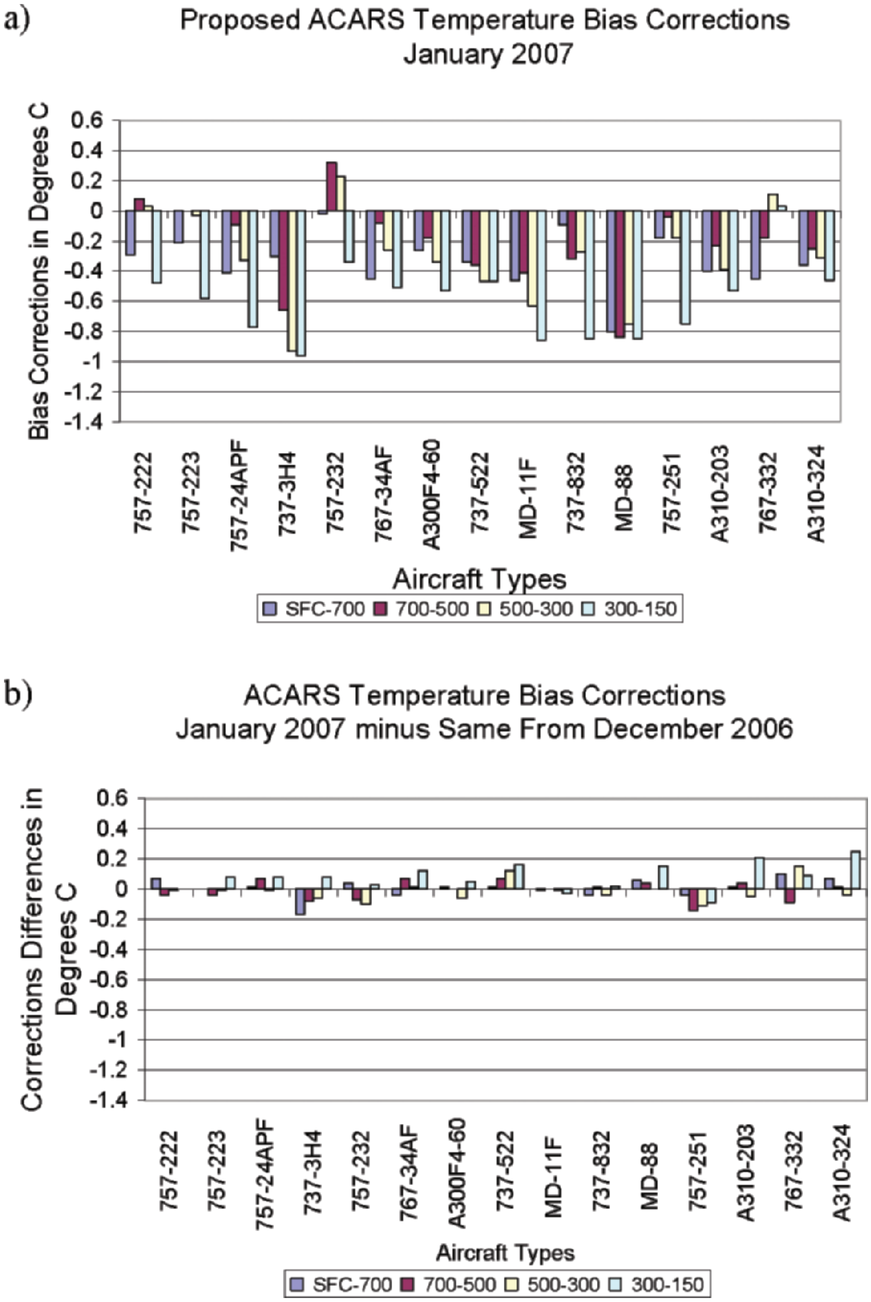

Fig. 14. Proposed ACARS temperature bias corrections for aircraft types for different pressures with highest total data counts for (a) Jan 2007 and (b) Jan 2007 – Dec 2006.

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. Because 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–700 hPa, 700–500 hPa, 500–300 hPa, and 300–150 hPa.

To make differences in MTOI between radiosondes and aircraft similar to collocation differences, observational 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° northward outside the CONUS. For aircraft types with most of their observations in the tropics, a third region from 20°S to 20°N was used. For aircraft types with most of their observations south of 20°S, the Southern Hemisphere was used as a fourth region.

Because there can be errors in reporting 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, nongross 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 and 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 farther to the left have the largest counts. The 15

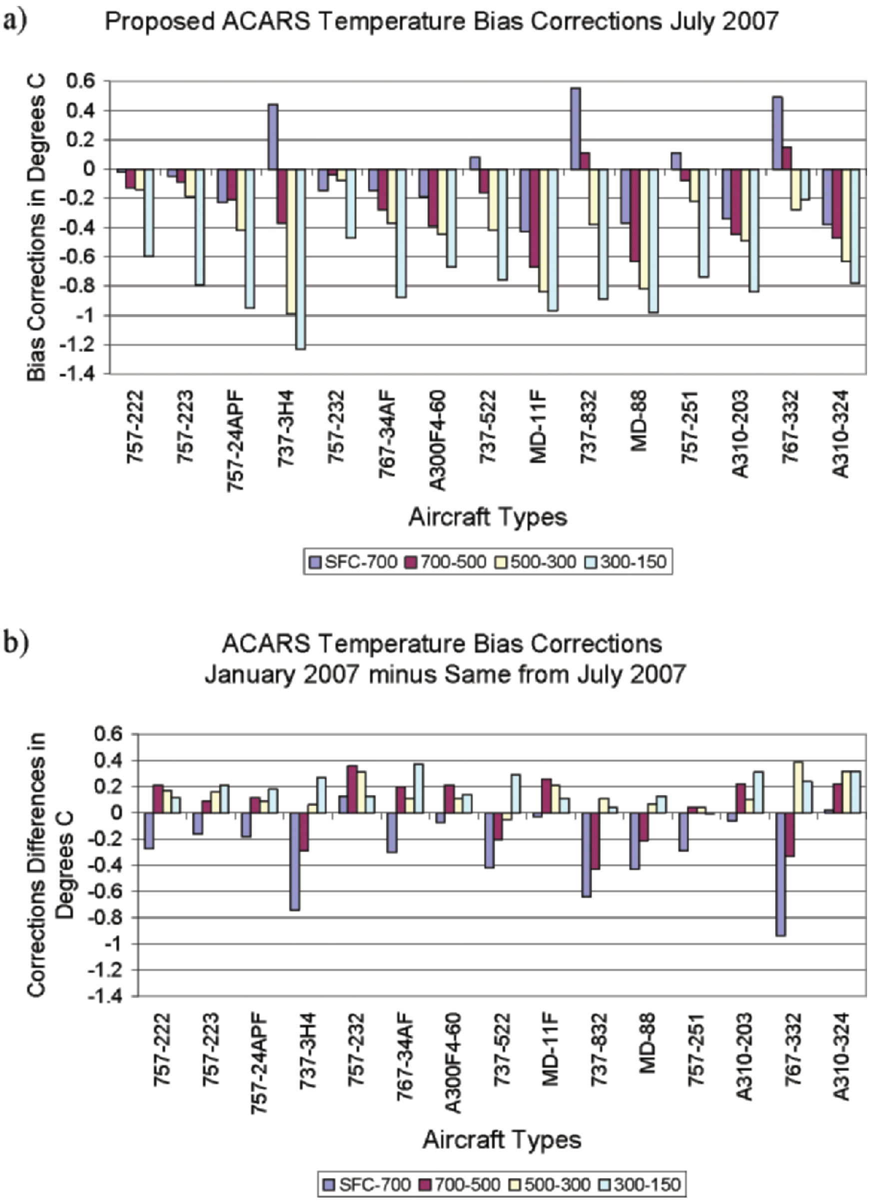

Fig. 15. Proposed ACARS temperature bias corrections for aircraft types for different pressures with highest total data counts for (a) Jul 2007 and (b) Jan–Jul 2007.

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°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.

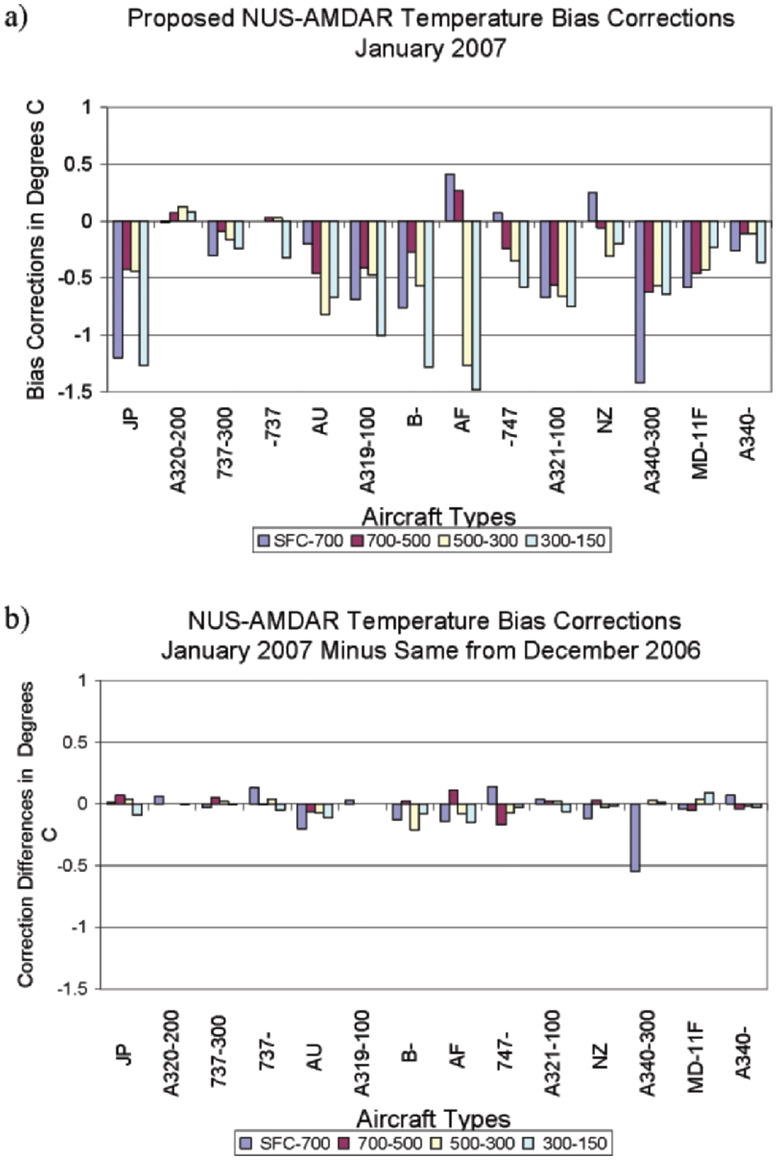

Fig. 16. Same as in Fig. 14, but for NUS-AMDAR data.

Figure 15a is the same as Fig. 14a, but for July 2007. Figure 15b is the same as Fig. 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 0.5°C in the surface–700 hPa layer. These differences are large and need further investigation. Because 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 6-month differences in corrections. Using small collocations limits reduces counts and may favor ascent over descent or vice versa, because aircraft landings and takeoffs are not randomly associated with radiosonde data.

A possible explanation of the large 6-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 of the variance in the data or changes in bias corrections with time because mean airspeed may change with time. No attempt was made to derive MTOI based on true airspeed 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 Figs. 14a,b, Figs. 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 (the other symbols are JP: Japanese, AU: Australian, B: Chinese, AF: South African, and NZ: New Zealand). Notice, that some of the NUS-AMDAR bias corrections are bigger than the observational error estimate of 1°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, because 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, impacts, 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. Because the U.S. 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.

CONCLUSIONS AND PLANS FOR FUTURE WORK.

Aircraft temperatures have been shown to vary considerably depending on aircraft model types, pressure, and 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 toward 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 0.5°–1°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. Because there is some uncertainty in radiosonde temperatures because of 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 climatic time scales. With that perspective, we have initiated impact studies with the NCEP GDAS and GFS, both with and without bias correction of aircraft temperatures, and the completed results will be reported in a separate paper.

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