A Comparison of Temperature and Wind Measurements from ACARS-Equipped Aircraft and Rawinsondes

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ABSTRACT

A comparison was made of temperature and wind observations reported by rawinsonde and Aircraft Communications, Addressing, and Reporting System (ACARS)-equipped commercial aircraft separated by less than 150 km in distance and 90 min in time near Denver, Colorado, in February and March 1992. Only data made on aircraft ascents and descents reported automatically were used. A total of 4440 matched data pairs were obtained for this period. The sample was analyzed in total but also as a function of time and distance separation, height, time of day, and ascent versus descent. A standard deviation temperature difference of 0.97°C and rms vector wind difference of 5.76 m s^{-1} were found for the entire sample but were reduced, respectively, to 0.59°C and 4.00 m s^{-1} when only data pairs separated by less than 25 km and 15 min were used. The study provides an upper limit to the combination of rawinsonde and ACARS observation and reporting errors and mesoscale variability, but it is not possible to distinguish the exact contributions from each of these sources. However, overall, these statistics indicate that the rawinsonde data used were more accurate than that reported in a previous study and that the accuracy of the ACARS data was somewhat higher still.

1. Introduction

Real-time meteorological observations have been made from commercial aircraft since the early days of commercial aviation. Until the past few years, these reports were made under either of two classifications: aircraft reports (AIREPs) or pilot reports (PIREPs). Both types of reports were made by a radio relay of voice information. AIREPs and PIREPs have provided and continue to provide useful information about winds and temperatures, icing, turbulence, and cloud information, often where no other data are available. However, these reports are subject to an error rate of about 30% for wind and temperature reports (Sparkman et al. 1981; Brewster et al. 1989), primarily due to two reasons: 1) communication errors from poor voice transmission and inaccurate data entry, and 2) relatively inaccurate wind estimates for aircraft without modern navigation systems. The communication problems were unquestionably exacerbated by the manually intensive workload placed upon aircraft crew members and flight service station personnel transcribing reports. These problems are described in more detail in a task force report on aviation weather forecasting (NCAR 1986).

The accuracy of aircraft-derived wind data improved as a new generation of navigation systems such as the Inertial Navigation System (INS) became more commonplace in commercial fleets. Also, modern avionics and digital communication systems have led to a capability for fully automated aircraft reports of meteorological conditions. This capability has been implemented aboard some of the major commercial carriers in the United States through a communications system called ACARS (Aircraft Communications, Addressing, and Reporting System) (Benjamin et al. 1991).

ACARS was developed originally by Aeronautical Radio, Inc. (ARINC) for air-ground communications of nonmeteorological information such as engine performance data, but the addition of weather observations has been a valuable addition for the meteorological community. ACARS messages are sent most commonly via a direct air-ground VHF link, but some aircraft are now equipped for reporting by a satellite link. VHF messages are much less expensive but can be made only within line-of-sight of ground-receiving stations that cover most but not all of North America. Systems similar to ACARS are operated in other parts of the world.

Operational numerical prediction centers have begun to ingest automated aircraft reports from ACARS and similar systems into regional and global data assimilation systems over the past few years. Both the National Meteorological Center (NMC) in the United States and the U. K. Meteorological Office have reported improved forecasts from using ACARS and ACARS-like data (DiMego et al. 1992; Bell 1994). A high-frequency regional data assimilation system called

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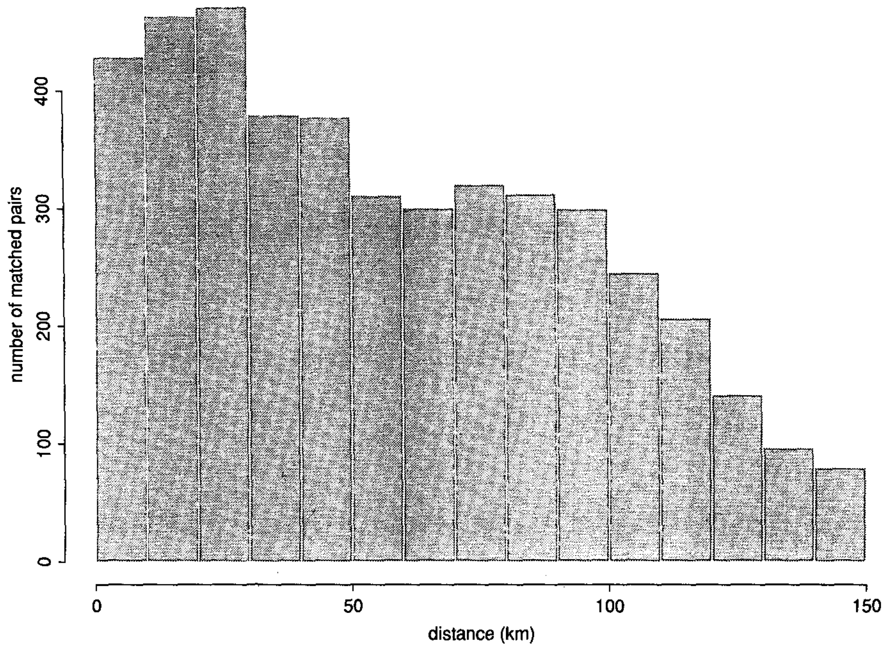


FIG. 1. Histogram of matched radiosonde-ACARS data pairs separation distance for ascents and descents combined.

the Rapid Update Cycle (RUC) has recently been implemented at NMC, providing new three-dimensional analyses and short-range forecasts every 3 h over the lower 48 United States and adjacent areas. The RUC (Benjamin et al. 1994a,b) is highly dependent on ACARS reports for the accuracy of these asynoptic analyses and forecasts. ACARS data impact studies have been performed using the developmental version of the RUC, the Mesoscale Analysis and Prediction System (MAPS) at the National Oceanic and Atmospheric Administration's (NOAA) Forecast Systems Laboratory. An earlier study (Benjamin et al. 1991) indicated that ACARS reports could result in substantial improvements in upper-level wind forecasts. At the time of this previous study, only about 7000 reports day^{-1} were made over the United States, compared to a volume of over 14 000 as of late 1994. More recently, Smith and Benjamin (1994) reported that ACARS reports gave a substantial incremental improvement to short-range forecasts of upper-level winds and temperatures when added to wind profiler data over the central United States.

These studies suggest a high degree of accuracy for ACARS and other automated aircraft reports. In this study, we have taken another approach to investigating the accuracy of ACARS reports: by comparing them to data from rawinsondes. Since the rawinsonde data themselves are contaminated by some degree of error and since the data pairs are not exactly collocated, our purpose is to establish an upper bound on combined error of ACARS and rawinsonde data and to search for systematic errors in either dataset.

A previous study specifically comparing ACARS wind data to rawinsonde, cloud drift, and satellite-derived thermal winds was performed by Lord et al. (1984). Their study was limited by a small number of data pairs (only 25) but indicated, at least, that ACARS wind data were more accurate than both types of satellite wind estimates. Brewster et al. (1989), in applying automated quality control algorithms to different kinds of aircraft data, found an error rate of only 1% for ACARS data compared to much higher errors for aircraft reports with manual intervention.

We have compared, in our study, wind and temperature reports reported via ACARS during ascents and descents near a rawinsonde station (Denver, Colorado) with the rawinsonde data. The matched dataset, its processing, and the overall experiment design are described in more detail in the following section (section 2). In section 3, the sources of differences between the ACARS and rawinsonde observations are discussed, followed by the results themselves in section 4. We end in section 5 by presenting our conclusions.

2. Data preprocessing and experimental design

The data were collected during the 1992 field experiment known as STORM-FEST (Stormscale Operational and Research Meteorology-Fronts Experiments Systems Test) (Cunning and Williams 1993). This experiment lasted over the period from 1 February to 15 March of that year.

Data pairs were created for each ACARS ascent/descent report that occurred within 150 km and 1.5 h of a rawinsonde report from Denver.

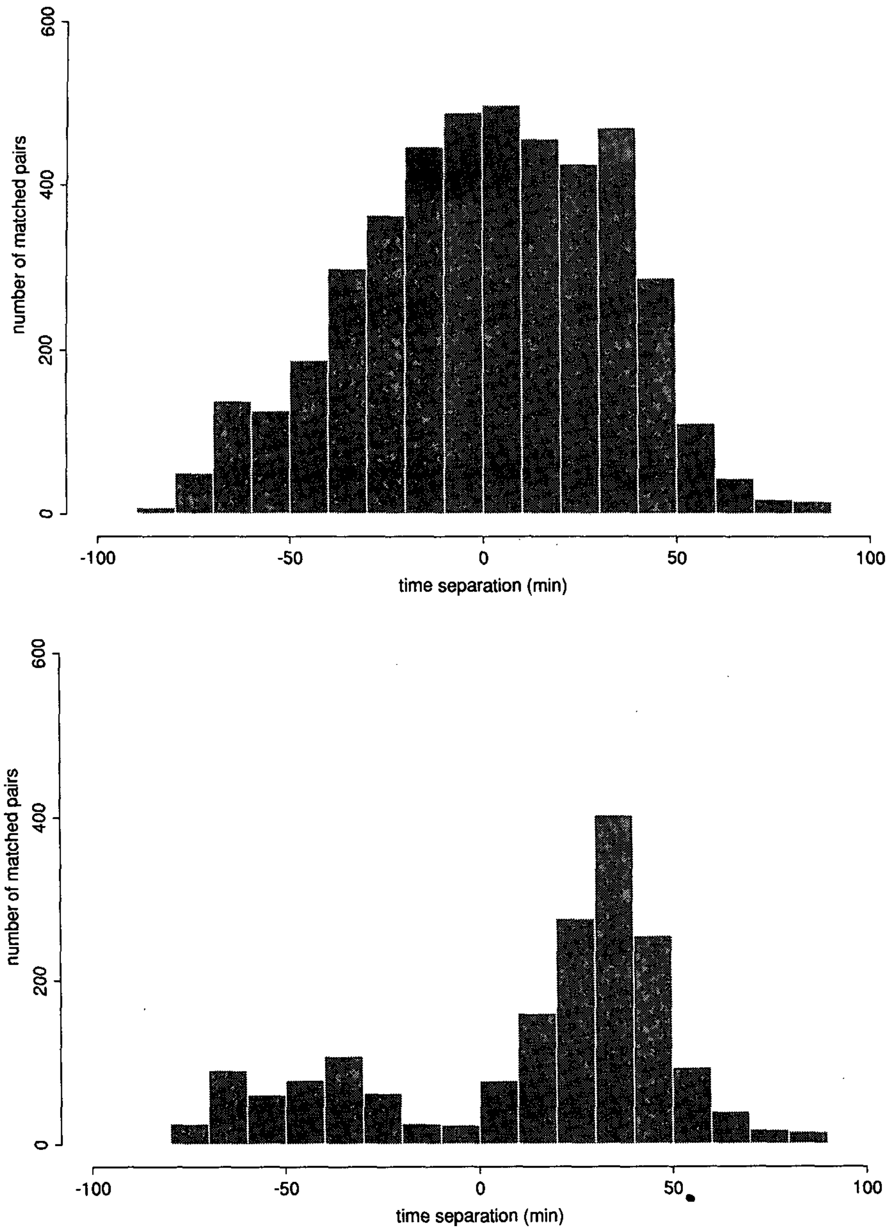


FIG. 2. (a) Same as Fig. 1 except for time separation; (b) for ascents only; (c) for descents only.

a. Rawinsonde data

High-resolution rawinsonde data for the STORM-FEST period were obtained containing routine and specially launched 3-h National Weather Service (NWS) soundings over much of the central and western United States. [Other soundings taken by the National Center for Atmospheric Research (NCAR) and the Canadian Atmospheric Environment Service (AES) are included in the dataset but were not needed for this study.] The STORM dataset was constructed by interpolating the originally observed NWS 6-s microcomputer Automated Radiotheodolite System (micro-ART) data to 10-hPa levels.

These data contain information that is not routinely transmitted over the Global Telecommunications System (GTS) nor available in the National Climate Data Center's (NCDC) rawinsonde data archive. This includes the many additional data levels resulting from the interpolation of 6-s data to the 10-hPa levels, the elapsed time into the rawinsonde flight, and balloon ascent rate. Using the elapsed time and ascent rate, exact time and position (latitude

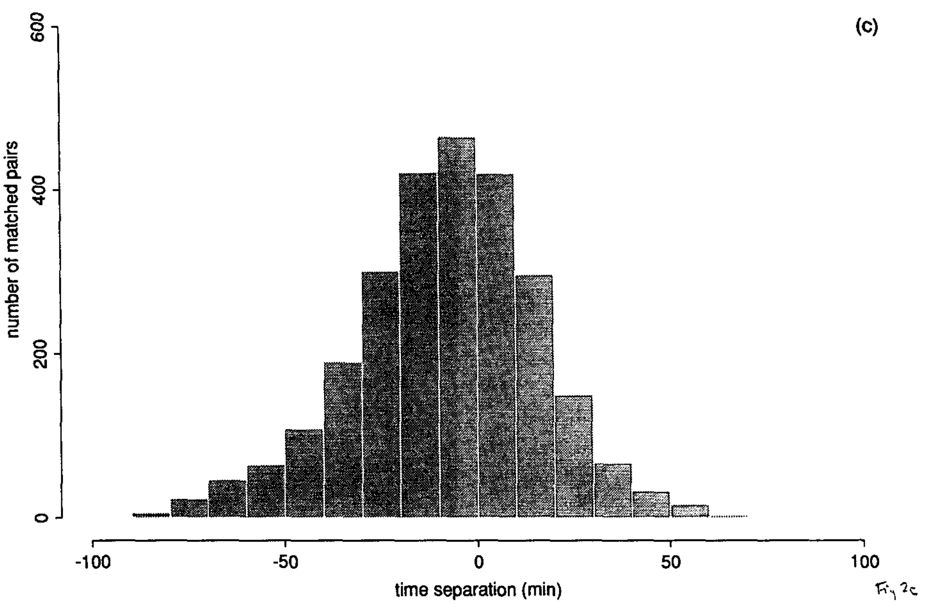


FIG. 2. (*Continued*)

and longitude) were determined at each 10-hPa level. Time and space differencing between rawinsonde and ACARS reports was determined using this exact position data at each level. The rawinsonde data were interpolated linearly with respect to the logarithm of pressure ($\log P$) to the pressure levels at which the ACARS data were reported in this study. The error due to vertical interpolation is assumed to be negligible since the interpolation is performed only over very short vertical distances.

Rawinsonde wind reports are time averaged over at least several seconds, since they are determined by balloon tracking over finite time intervals.

b. *ACARS ascent/descent data*

During the STORM-FEST period, only United Airlines provided ACARS reports with increased frequency on ascent and descent of flights. The only airport for which a large amount of ascent/descent ACARS data were available that was also near to a STORM-FEST NWS rawinsonde site was Stapleton International Airport at Denver (1611 m).

The ascent/descent data from United Airlines were reported at 2000-ft (609.6 m) intervals from 6000 ft (1828.8 m) to 30 000 ft (9144.1 m). The levels correspond to pressure altitudes above mean sea level (MSL) in the *U.S. Standard Atmosphere,* 1976. For these and other ACARS automated reports, the levels are not influenced by the local altimeter setting, and the actual pressure can be calculated from them. Although these ascent/descent reports give fairly good vertical resolution, commercial aircraft "soundings" from ascents and descents are now becoming available (Fleming and Hills 1993) with much higher vertical resolution [~300 ft (100 m) at low levels]. The ascent/descent data used in this study, then, is quite coarse compared to the newer high-resolution ascent/descent data. The reports are not time averaged but represent instantaneous values.

The actual data available from the ACARS reports used in this study provided the following variables:

- latitude/longitude [tenths of a minute (~150 m), actual reporting accuracy for many of the aircraft in this study was about 4 min (~6 km)];
- time (nearest minute);
- temperature (nearest tenth but actual reporting accuracy is nearest 0.25°C);
- flight level [nearest hundred feet (~30 m), corresponding to pressure altitude as described in last paragraph];
- wind direction (to nearest degree); and
- wind speed (to nearest knot).

TABLE 1. Number of matched rawinsonde-ACARS observations for radiosonde observation times.

Time (UTC)	Number (% of total)
0000	2476 (55.8%)
0300	476 (11.7%)
0600	78 (1.7%)
0900	0
1200	0
1500	575 (13.0%)
1800	756 (17.0%)
2100	79 (1.8%)

A small number of ACARS wind reports with zero wind speeds were found in the overall dataset and removed from the sample. No systematic errors such as those discussed by Moninger and Miller (1994) were found from this dataset.

c. Analysis of data pairs

A total of 4440 matched raob/ACARS data pairs were found meeting the time and distance separation constraints. The convention in the rest of this paper is that *separation is defined as rawinsonde value minus ACARS value.* The distribution of these pairs by distance separation is depicted in Fig. 1. Approximately 50% of the data pairs were separated by less than 50 km. The distribution by time separation (Fig. 2a) shows that nearly 60% of the data pairs are separated by less than 30 min with a skew toward positive time separation. Separation by ascent and descent (Figs. 2b,c) reveals that ascent data pairs have a distinct peak of ACARS reports 30–40 min before rawinsonde report time, whereas descent data pairs are normally distributed with respect to time separation, centered with ACARS reports occurring just a few minutes after rawinsonde reports, on the average.

The time of the matched pairs (Table 1) indicates that the majority of the data occurred near to 0000 UTC, with a secondary peak at 1500–1800 UTC. This time distribution is a result of the intersection of United Airlines flight schedule in and out of Denver, and the schedule for rawinsonde releases during the special STORM-FEST observing period.

The positions of rawinsonde reports over the entire period (Fig. 3) indicates that, horizontally, the balloon remained relatively close to Denver up to about 30 000 ft; compared to the aircraft, the balloons had a much more vertical trajectory. The positions of ACARS reports are separated into ascent and descent (Figs. 4a,b). They indicate the air traffic patterns into Denver out of the northeast and southeast and departing Denver in the cardinal directions. Most of the air traffic for United in and out of Denver during this period was connecting with points east. The approximately 4-min latitude/longitude reporting resolution mentioned in section 2b is responsible for the clumping of reports into rows and columns in Figs. 4a and 4b.

3. Sources of data differences in intercomparison

The differences between ACARS and rawinsonde observations in this study are due to the following sources: rawinsonde measurement and reporting error, aircraft measurement and reporting error, and mesoscale variability. For aircraft data, wind observations are calculated by adding the motion vector of the aircraft with respect to the earth determined from the onboard INS, to the motion vector of the air with respect to the aircraft, determined from the total airspeed measurement and heading measurement (Lenschow 1986). In general, commercial aircraft wind measurements using INS are of high accuracy ($\sim$0.5 m s^{-1} rms vector error for calibrated equipment, Nicholls 1982) but are subject to somewhat larger errors when

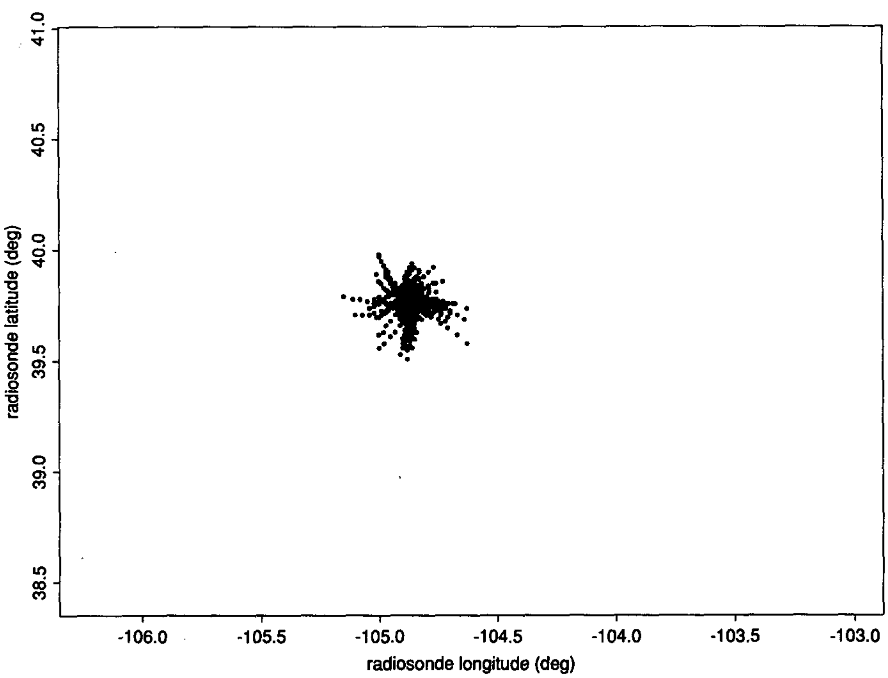
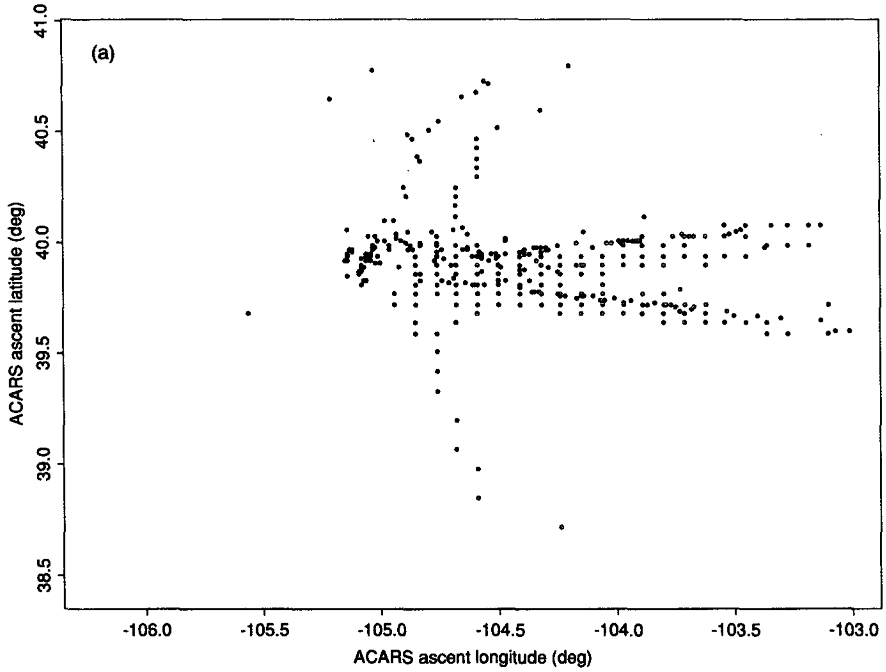


FIG. 3. Latitude/longitude (position) of radiosonde ascents from Denver for the 1 February to 15 March 1992 period.



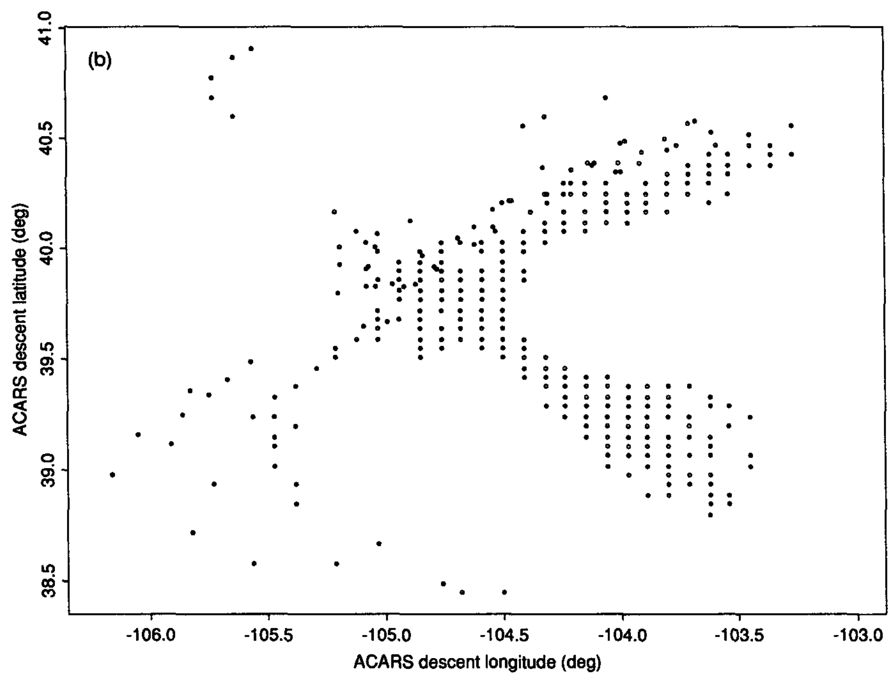


FIG. 4. (a) Same as Fig. 3 except for ACARS ascents; (b) for ACARS descents.

maneuvers are being made. Bisiaux et al. (1983) show an example of very large errors in wind speed and direction when the aircraft roll angle exceeds 5°. In Bisiaux's example, the 5° threshold was exceeded in about 30% of the reports on an aircraft ascent. As shown in section 2, no indication of aircraft maneuver was available in the ACARS reports used in this dataset. Such an indicator will be included with future high-resolution ascent/descent data (Fleming and Hills 1993). A preliminary dataset (321 reports) with this indicator provided by Baker (personal communication, 1995) for ascents over United States airports showed that the roll angle exceeded 5° in about 20% of the high-resolution reports; out of that 20%, about half were noticeably inconsistent (deviations of greater than 8° in direction or 6 kt in speed) with adjacent reports from the same ascent/descent profile. The exact nature of maneuver-related error and possible correction by accessing additional data (e.g., yaw) not now used in wind calculation is under investigation (Fleming 1995, personal communication).

The reporting accuracy for ACARS temperatures (0.25°C) by itself contributes a standard deviation error of about 0.1°C. The temperature instrument precision is estimated at 0.7°–1.0°C (Baker 1995, personal communication). For wind reports, the speed reporting precision (1 kt) contributed a standard deviation error of 0.15 m s^{-1}. The contribution of the direction precision standard deviation (0.3°) to the overall rms vector error is proportional to wind speed; at 50 m s^{-1}, it is about 0.25 m s^{-1}. Overall, the reporting precision error is relatively minor for temperatures and very minor for winds proportionate to other errors.

Radiosonde measurement error statistics are described in a report by Hoehne (1980) and more recently by Ahnert (1991). In Table 2, which summarizes these results, values are shown for the various ways these functional precision tests were performed. Two rawinsondes of similar design were flown on the same balloon train. Values were compared at equal elapsed time into the flight (time) and at equal pressure and equal heights in the atmosphere. Since the pressure and temperature measurements themselves contain error, functional precision values vary from smallest to largest in the order of comparison by time, pressure, and height. Note that the table is incomplete and that the resolution of the precisions varies. These values are the overall averages for the troposphere; in the original references, values are shown as a function of pressure but are not included here. It is unfortunate that there has apparently been no functional precision testing for wind since the 1980 study and that wind statistics are available only at constant height levels. For our purposes, we use the temperature precision at equal pressure since we are interpolating the rawinsonde data to the pressure of the ACARS observations. The temperature error estimates ranged from 0.54° to 0.68°C, and the wind speed error estimate from Hoehne was 3.1 m s^{-1}.

Fortunately for commercial air safety and the rawinsonde data collection program, there are almost always time and/or distance separations between rawinsondes and aircraft making ACARS reports. Thus, mesoscale atmospheric variability is a contributor to the differences between rawinsonde and ACARS reports in this study. In fact, it is very difficult to completely distinguish between mesoscale variability and measurement error. Lenhard (1973) reported a maximum rms vector difference of 3.6 m s^{-1} at an elevation of 12 km between paired rawinsonde flights separated by 16.25 km at launch. Lenschow et al. (1991) reported differences of high-frequency research aircraft measurements in a convective boundary layer of 2.8 and 1.8 m s^{-1} for two different cases with aircraft separation of only 30 m. Hoehne's measurements are closest to pure observation error; the others are a sum of observation error and local variability.

A last source of error discussed in section 2a is the negligible error produced by vertical interpolation of rawinsonde data.

4. Results

The results will be discussed for the entire matched data pair sample first, followed by sections on the dependence of the results on different individual factors such as distance and time separation, height, time of day, and ascent versus descent. A special section (4e) is devoted to differences between raob and ACARS data at small time and distance separations, where the contribution of mesoscale variability is minimized.

For temperature, an overall scatterplot of ACARS versus rawinsonde data (Fig. 5) shows quite close agreement. The correlation coefficient between the two datasets is 0.99, and 68% (94%) of the differences are within 1°C (2°C). The overall rms (root mean square) difference is 0.97°C. A few outliers of up to 8°–10°C are

TABLE 2. Summary of the functional precision tests for rawinsonde data reported by Hoehne (1980) and Ahnert (1991). See text for explanation and Ahnert (1991) for description of rawinsonde types (viz., SDD).

Study/sonde type quantity	Hoehne (1980) (viz., A)			Ahnert (1991) (viz., A)		Ahnert (1991) (viz., B)		Ahnert (1991) (viz., SDD)	
	Height	Time	Pressure	Time	Pressure	Time	Pressure	Time	Pressure
Pressure (hPa)	0.7	1.9	—	1.3	—	2.0	—	2.1	—
Temperature (deg C)	0.84	0.67	0.61	0.34	0.54	0.31	0.54	0.33	0.68
Height (m)	—	92.9	23.7	103	16.4	159	15.3	231	16.3
Humidity (%)				2.1	2.55	1.6	2.3	2.2	2.2
Dewpoint depression	3.84	3.67	3.26	3.45	2.82	2.4	2.66	2.8	3.4
Wind direction (deg)	14-2 (* see below)								
Wind speed (m s^{-1})	3.10								
Wind vector (m s^{-1})	3.10								

* 14° at 10 knots; 2° at 120 knots as reported by Hoehne (1980).

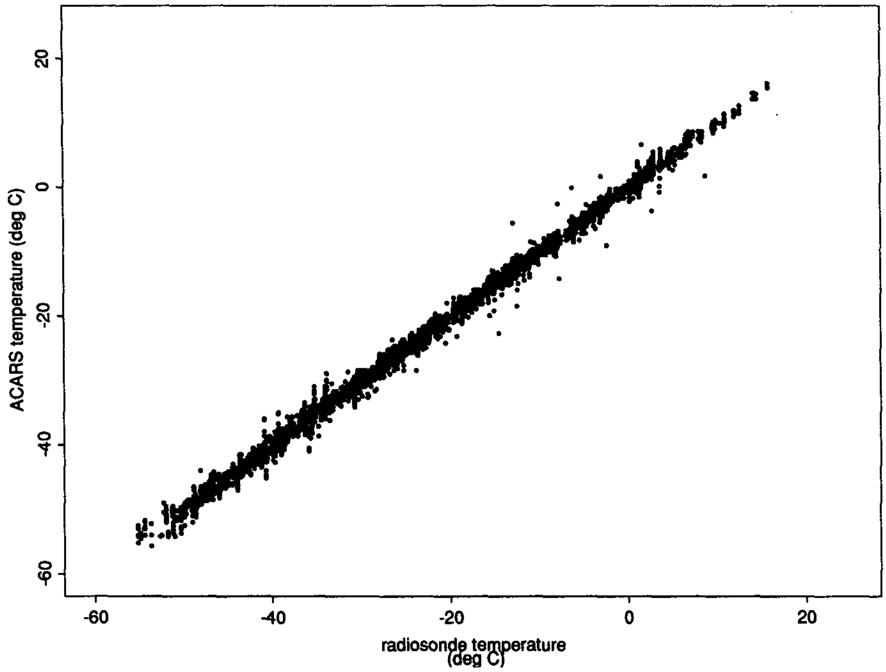


FIG. 5. Scatterplot of ACARS temperatures vs rawinsonde temperatures.

shown in the range of −15° to +5°C. The overall temperature bias indicates that rawinsonde temperatures are an average of 0.22°C warmer than ACARS temperatures. This bias is also apparent in the outliers; among the differences greater than 2°C, the rawinsonde temperature is warmer twice as often as the ACARS report.

For wind speed (Fig. 6), there is a much larger degree of variation, with an overall correlation coefficient of 0.83 and standard deviation speed difference of 4.1 m s^{-1}. There is a small bias (0.22 m s^{-1}) toward higher wind speed with raobs than with ACARS reports. Wind direction (no scatterplot) correlation was 0.65 with an

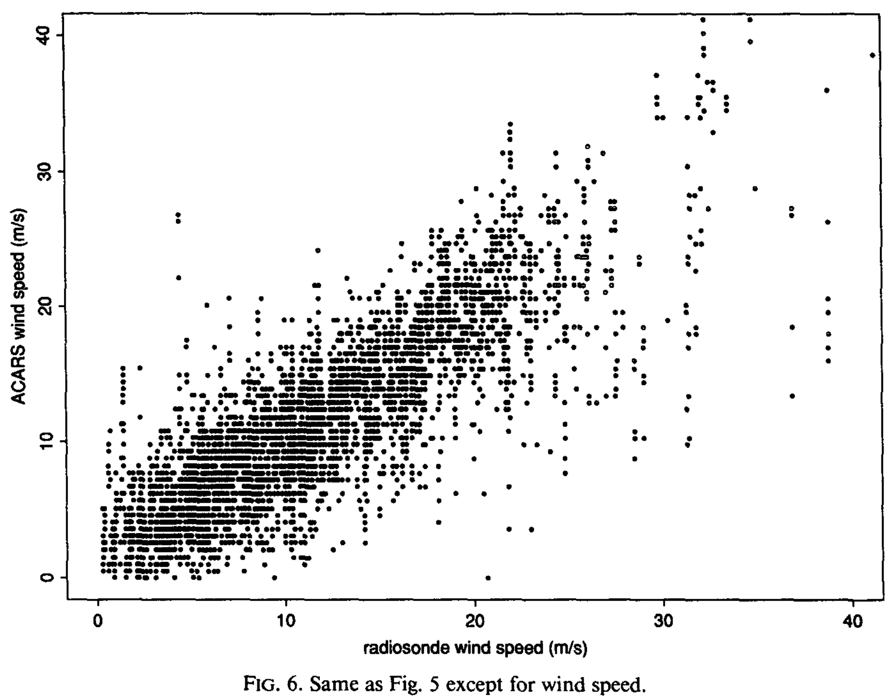


FIG. 6. Same as Fig. 5 except for wind speed.

rms direction difference of 35.1°. The overall rms vector wind difference for the entire sample is 5.76 m s^{-1}. A scatterplot of ACARS/rawinsonde direction difference versus raob wind speed (Fig. 7a) indicates that direction difference is highly correlated with lighter wind speeds. This suggests that the large direction differences at low wind speed is related to mesoscale variability, especially from turbulence in the boundary layer. Larger vector differences are also found at lower wind speeds (Fig. 7b), whereas at wind speeds above 30 m s^{-1}, vector differences are limited to less than about 12 m s^{-1}.

a. Dependence on distance separation

Temperature difference is plotted against distance separation in Fig. 8, revealing two patterns superim-

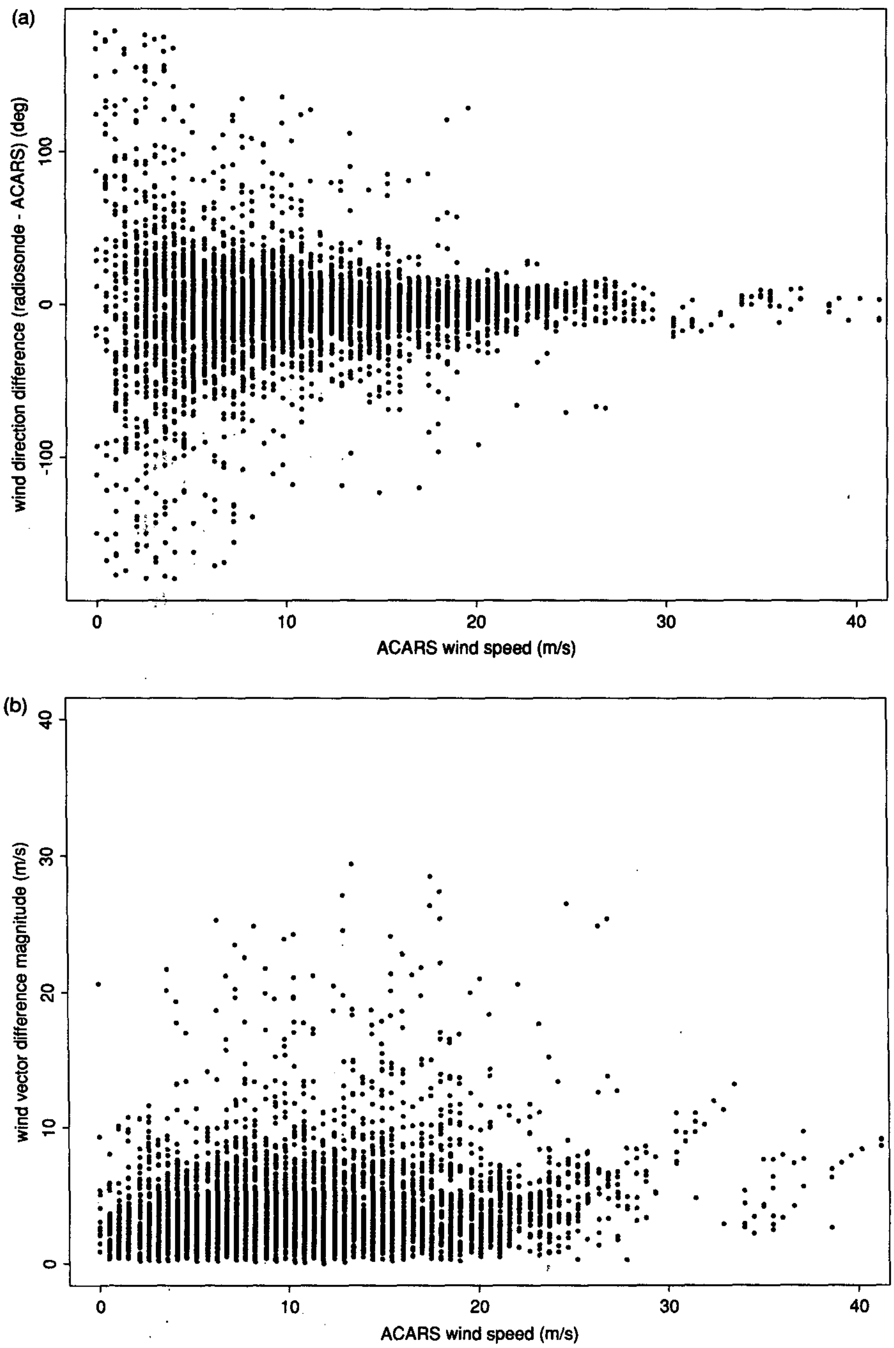


FIG. 7. Scatterplots vs ACARS wind speed of (a) wind direction difference (radiosonde-ACARS) and (b) wind vector difference magnitude.

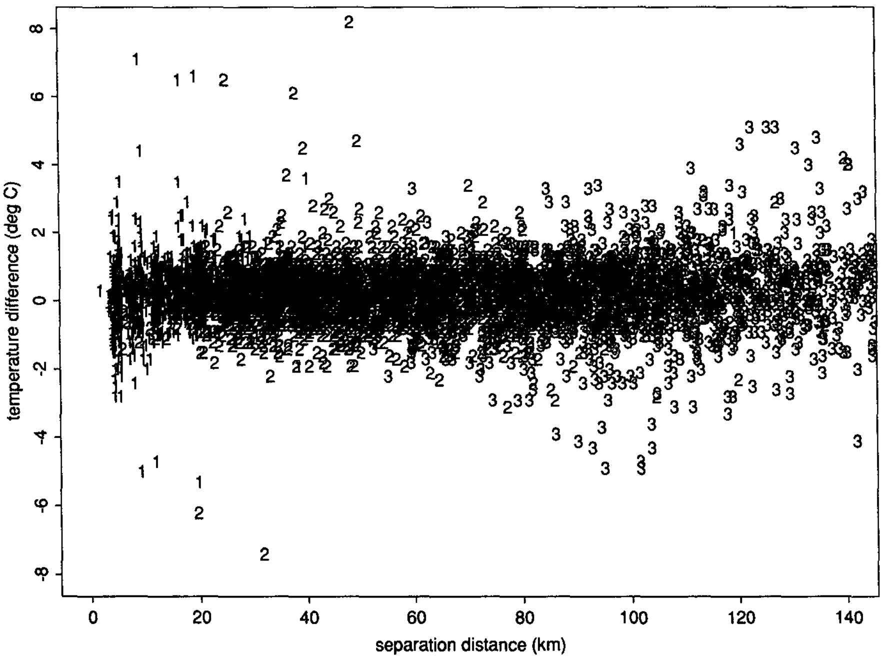


FIG. 8. Same as Fig. 7 except for temperature difference (radiosonde-ACARS) vs separation distance. Numbers indicate pressure altitude range: 1 (up to 11 999 ft; 3657 m), 2 (12 000–20 999 ft; 3657–6400 m), and 3 (21 000–30 000 ft; 3657–9144 m).

posed on top of each other. First, the largest outliers all occur at distances of less than 50 km (almost all from within 2000 m of the ground). Ignoring the large outliers, a steady progression toward larger differences at larger distance separation is apparent. Table 3, a breakdown of ACARS/rawinsonde differences by distance separation, shows that the temperature difference standard deviation is at a minimum for the distance range of 20–30 km. The mean temperature difference increases substantially at distances of greater than 120 km, where the mean altitude has increased to about 8000 m. The high correlation between distance and height in this dataset makes it difficult to distinguish between the effects of those two factors.

TABLE 3. Effect of distance separation on the mean, standard deviation (Std dev), and root mean square (rms) of the difference (rawinsonde − ACARS) for matched rawinsonde and ACARS temperature and wind observations. (All ascents and descent data combined for all observational times).

Distance (km)	Mean time (min)	Mean altitude MSL (m)	Sample size	Temperature (°C)		Wind direction (°)	Wind speed (m s^{-1})		Vector rms
				Mean	Std dev	Std dev	Mean	Std dev	
0–10	−12.8	2204	427	0.06	1.00	54.16	0.39	2.83	3.98
10–20	−12.2	2819	460	0.29	0.90	45.16	−0.07	2.78	4.13
20–30	−0.1	3612	470	0.27	0.75	34.26	−0.47	3.03	3.93
30–40	−1.0	4330	381	0.25	0.93	23.99	−0.38	2.35	4.40
40–50	−0.3	4958	376	0.19	0.91	24.92	0.00	3.03	4.30
50–60	1.7	5427	314	0.18	0.80	25.36	−0.01	2.67	4.41
60–70	4.3	6012	301	0.14	0.84	26.70	−0.06	3.25	6.31
70–80	5.3	6447	323	0.23	0.92	29.67	0.49	4.00	5.58
80–90	9.7	6925	310	0.11	0.96	33.10	0.40	4.42	6.21
90–100	10.6	7428	301	0.11	1.08	29.38	0.15	4.94	6.68
100–110	10.1	7698	250	0.22	1.14	29.62	0.91	5.64	7.93
110–120	9.2	8003	208	0.28	1.17	29.40	0.23	5.75	7.63
120–130	10.5	7982	140	0.46	1.30	43.78	0.08	5.23	8.74
130–140	10.8	8227	99	0.45	1.31	35.63	1.15	6.09	9.98
140–150	8.5	8170	80	0.60	1.32	41.14	0.61	6.40	10.84
all	1.3	5316	4440	0.22	0.97	35.12	0.15	4.08	5.76

Mesoscale variability is evident in scatterplots of wind speed difference versus distance separation (Fig. 9a) and wind vector difference versus distance separation (Fig. 9b). Wind speed differences increase sharply at distance separation greater than 60 km (Table 3, Fig. 9a), as does a bias in wind speed toward slower ACARS speeds. Wind direction (Table 3) actually shows *larger* differences at less than 30-km distance separation, presumably due to boundary layer turbulence and the high correlation of small distance separation to low height. Wind direction differences show some increase again when the platforms are separated by greater than 120 km, apparently a result of atmospheric variability in the free atmosphere above the boundary layer. The rms vector wind differences (Table 3), consistent with

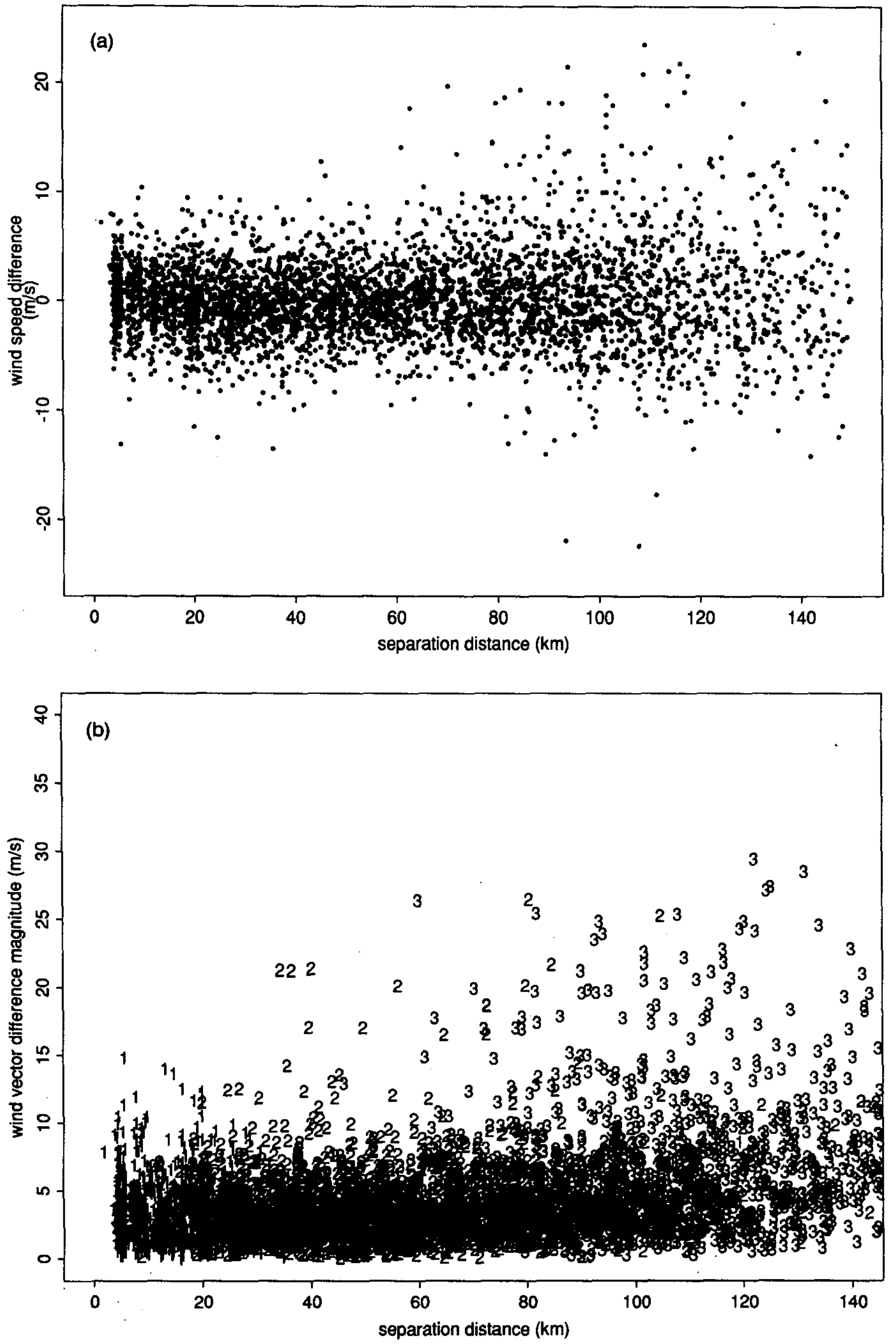


FIG. 9. Scatterplot vs separation distance (km) of (a) wind speed difference and (b) wind vector difference magnitude. Pressure altitude range for Fig. 9b is as described in Fig. 8.

TABLE 4. Same as Table 3 except for time separation difference (m indicates time differences < 0, i.e., ACARS time later than rawinsonde time).

Time differences (min)	Mean distance (km)	Mean altitude MSL (m)	Sample size	Temperature (°C) Mean	Temperature (°C) Std dev	Wind direction (°) Std dev	Wind speed ($m s^{-1}$) Mean	Wind speed ($m s^{-1}$) Std dev	Vector rms
<m60	27.7	3721	183	−0.10	1.03	42.90	−0.39	2.84	4.38
m60–m50	51.7	5217	125	0.05	0.86	35.21	1.36	3.54	5.18
m50–m40	44.1	4361	175	0.26	1.22	36.49	0.71	3.24	4.59
m40–m30	44.8	4378	293	0.41	1.19	30.44	0.60	3.68	5.42
m30–m20	45.8	4388	356	0.39	0.97	37.35	−0.08	3.54	5.29
m20–m10	47.0	4412	442	0.42	0.66	33.08	−0.29	3.01	4.18
m10–0	63.4	5126	491	0.50	0.71	31.66	−0.13	2.98	4.49
0–10	73.7	5827	495	0.41	0.90	29.36	0.11	4.02	5.56
10–20	78.7	6280	464	0.26	1.07	38.62	−0.06	4.49	6.78
20–30	61.6	5506	423	0.13	0.97	36.94	−0.36	4.62	6.67
30–40	55.7	5278	470	0.03	0.97	36.09	0.39	4.64	6.44
40–50	63.9	6340	314	−0.18	0.89	37.63	0.40	5.76	7.16
50–60	70.4	7061	125	−0.30	1.12	38.77	0.96	5.00	7.19
>60	67.3	6810	84	−0.42	0.97	26.57	0.72	4.21	6.18
all	58.6	5316	4440	0.22	0.97	35.12	0.15	4.08	5.76

wind speed, also show a sharp increase beyond 60-km distance separation. The larger vector differences beyond 60 km are almost entirely from observation pairs above 21 000 ft (6400.8 m, Fig. 9b).

b. Dependence on time separation

The influence of time separation on temperature differences must be interpreted in light of the predominance of data pairs (Table 1) near to 0000 UTC, a time of evening boundary layer cooling. This is apparent in larger warm bias (Table 4) (rawinsonde warmer than ACARS) at negative time difference (rawinsonde taken before ACARS observations), also shown in Fig. 10 where larger differences at negative time difference are mostly from observation pairs below 12 000 ft (3657.6 m). A smaller bias toward the rawinsonde being cooler than the ACARS report is shown when the ACARS report

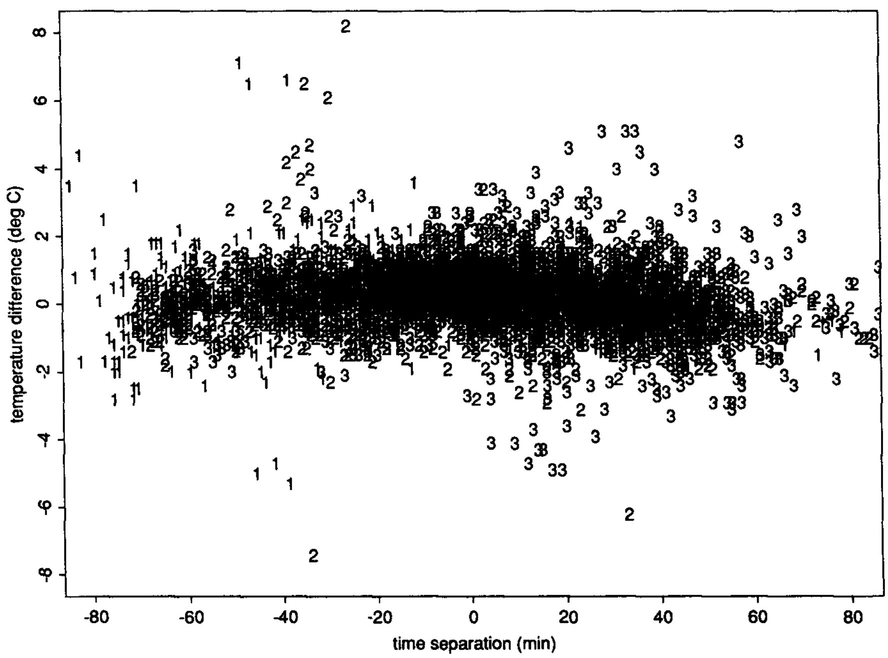


FIG. 10. Same as Fig. 8 except for time separation.

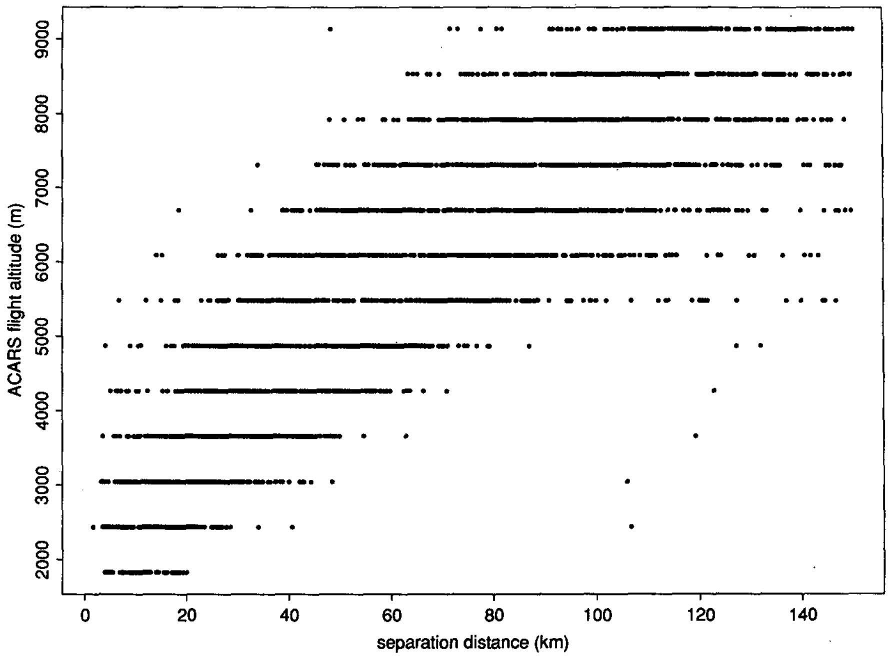


FIG. 11. Scatterplot of ACARS flight altitude vs separation distance.

was taken first. However, the overall warm bias toward rawinsonde observations is still clearly present overall. The temperature difference standard deviation is smallest at close to zero time separation (Fig. 10, Table 4), an indication of "meso-timescale" variability for temperatures.

Wind speed difference and rms vector difference increase when the ACARS observation is taken earlier than the rawinsonde observation, but this is probably related to the increased distance separation (Table 4) for those time separations. Direction difference reaches a minimum near-zero time separation.

c. Dependence on height

The dependence of data differences upon height is very similar to that upon distance separation due to the high correlation of height upon distance separation (Fig. 11). This correlation is from the fact that commercial aircraft soundings are somewhat less vertical than rawinsonde ascents (Figs. 3, 4). For completeness, the distribution of data differences by height are presented in this section (Table 5). Temperature difference standard deviation is smallest between 2000 and 5000 m MSL, corresponding to relatively small distance

TABLE 5. Same as Table 3 except for ACARS flight altitude.

Flight alt (m MSL)	Mean distance (km)	Mean time (min)	Sample size	Temperature (°C) Mean	Temperature (°C) Std dev	Wind direction (°) Std dev	Wind speed (m s^{-1}) Mean	Wind speed (m s^{-1}) Std dev	Vector rms
1828.8	7.7	−17.4	336	0.13	1.08	63.15	0.32	2.52	3.80
2438.4	14.6	−13.3	354	0.32	0.78	41.89	0.27	2.82	4.14
3048.0	21.9	−10.5	361	0.34	0.83	39.10	−0.69	2.90	4.00
3657.6	29.6	−7.2	363	0.31	0.93	24.62	−0.73	3.51	4.30
4267.2	39.7	−4.2	364	0.31	0.79	25.41	−0.05	2.97	4.17
4876.8	47.0	−0.9	373	0.22	0.90	29.01	−0.10	2.79	4.31
5486.4	59.2	2.6	373	0.22	0.88	31.69	0.31	3.13	5.10
6096.0	69.7	5.9	375	0.14	0.93	33.76	0.38	3.49	5.25
6705.6	79.5	8.4	378	0.15	0.99	26.09	0.46	4.79	6.26
7315.2	89.5	12.8	359	0.08	1.07	24.04	−0.11	4.89	6.65
7924.8	98.3	15.9	334	0.15	1.02	30.02	0.20	5.86	8.36
8534.4	108.8	17.6	294	0.24	1.20	31.80	0.82	5.90	8.66
9144.0	119.7	18.0	176	0.23	1.42	40.22	1.10	6.43	9.06
all	58.6	1.3	4440	0.22	0.97	35.12	0.15	4.08	5.76

TABLE 6. Overall statistics for radiosonde-ACARS matched data for the overall sample, and by ascent and descent. Data segregated for all times combined (overall) and for 0000 UTC only.

	All times combined			0000 UTC only		
	Overall	Ascents	Descents	Overall	Ascents	Descents
Sample size	4440	1819	2621	2476	1060	1416
Mean time diff	1.3	14.3	−7.7	14.6	33.4	0.5
Mean dist diff	58.6	50.4	64.2	57.3	48.7	63.7
Mean temp diff	0.22	−0.10	0.44	0.19	−0.13	0.43
Std dev temp diff	0.97	0.88	0.98	1.04	0.90	1.08
Std dev dir diff	35.12	37.63	33.28	35.81	38.16	33.96
Mean speed diff	0.15	0.25	0.03	0.33	0.39	0.28
Std dev speed diff	4.08	4.42	3.82	4.32	4.53	4.16
Wind vector rms	5.76	5.98	5.61	6.18	6.26	6.11

separation (≤60 km). Wind speed standard deviation ranges from 2.5 to 3.5 m s^{-1} below 6000 m MSL. The rms vector error is less than 4.3 m s^{-1} below 5000 m MSL.

d. Dependence on time of day

Since over half of the data pairs occurred near 0000 UTC, the statistics for those pairs were separated from the entire data sample. This comparison (Table 6, overall columns) indicates that there was virtually no distinction by time of day for temperature or wind direction. There was a slightly higher speed and rms vector error for the 0000 UTC dataset compared to the combined sample.

e. Limited distance/time separation

This section describes ACARS/rawinsonde data differences when the time separation is limited to 15 min and the distance separation is limited to 25 km (Table 7). Although some mesoscale variability is still present, perhaps similar to that in the Lenhard (1973) study referred to in section 3, it is limited by the constraints used. Unfortunately, the mean elevation of the data pairs was also considerably reduced by these constraints (in particular, the distance constraint), but the results shown below are still of interest.

TABLE 7. Statistics for ACARS-rawinsonde matched data for distance separation of less than 25 km and time separation less than 15 min for all data combined (overall) and segregated by ascent and descent.

	Overall	Ascents	Descents
Sample size	193	57	136
Mean time diff	−2.2	6.7	−6.0
Mean dist diff	13.5	13.9	14.8
Mean alt (m)	2532	2587	2602
Mean temp diff	0.22	0.07	0.42
Std dev temp diff	0.59	0.59	0.58
Std dev dir diff	40.95	47.83	37.89
Mean speed diff	0.12	0.11	0.13
Std dev speed diff	2.84	3.36	2.61
Wind vector rms	4.00	4.70	3.66

The temperature difference standard deviation in this dataset is only 0.59°C, compared to 0.97°C for the entire sample. The temperature bias in the limited sample is identical to that for the entire sample, 0.22°C. The wind speed difference standard deviation is 2.84 m s^{-1}, considerably reduced from 4.42 m s^{-1} for the entire sample. A similar reduction is apparent with the rms wind vector difference, going from 5.76 m s^{-1} for the entire sample versus 4.00 m s^{-1} for the limited distance/time separation sample. The reduction in wind difference is also apparent visually in comparing a scatterplot of ACARS versus rawinsonde wind speed for the limited sample (Fig. 12) versus that for the entire sample (Fig. 6). It is also evident in comparing these two figures that the limited distance/time sample is limited to lower elevations and, therefore, lower wind speeds. A few outliers remain in the speed data pairs even with limited distance/time separation. Some of these events were examined subjectively, and it was found that some but not all were due to mesoscale variations. At least some of the others are likely due to large errors in ACARS wind reports produced during aircraft maneuvers (section 3). It should also be noted that limited time/distance sample is relatively small (193), less than 5% of the overall sample.

f. Ascent versus descent

Data differences are broken down into ascent versus difference for both the full sample (Table 6) and for the limited time/distance separation sample (Table 7). In general, there was not much distinction when the data pairs were stratified between ascent and descent ACARS reports. Temperature differences were slightly smaller for ascents, but rms vector wind differences were slightly smaller for descents for the entire sample. For the limited time/distance separation dataset, temperature differences were almost identical but rms vector wind differences were significantly smaller for descents than for ascents (3.66 vs 4.70 m s^{-1}). This runs

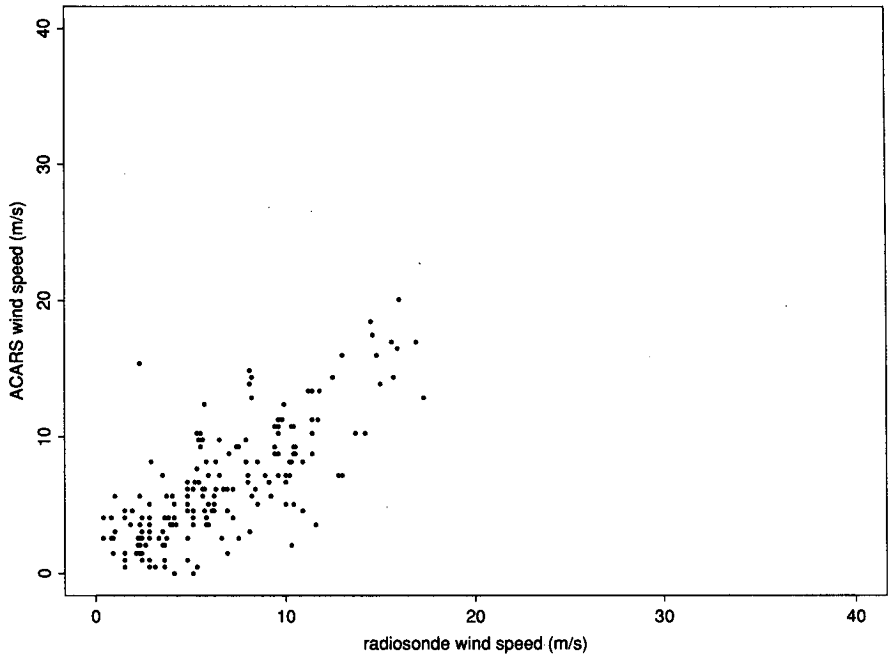


FIG. 12. Scatterplot of ACARS wind speed vs rawinsonde wind speed limited to matched data pairs separated by less than 25 km in distance and less than 15 min in time.

counter to expected higher accuracy for data on ascent, since fewer maneuvers are made then, in general, than on descent. It is possible that the unexpected result is because descents in this dataset were made closer to rawinsonde observation times, on the average, than ascents (Figs. 2b,c). Also, as noted in the last section, the sample size for the limited time/distance separation is relatively small.

The temperature bias noted earlier turned out to be significantly dependent on ascent versus descent (Tables 6 and 7). For the overall sample (Table 6), the ACARS cool bias was much stronger on descent (0.44°C) but reversed to a very slight warm bias (−0.10°C) on ascent. There are different possibilities for this behavior, including airspeed differences (Baker, personal communication), different angles of attack of the aircraft on ascent versus descent, and the effect of humidity/condensation on descent (Lenschow, personal communication).

5. Conclusions

A comparison has been made of temperature and wind data reported by rawinsonde and commercial aircraft using ACARS on ascent and descent in the same space/time vicinity. A total of 4440 matched pairs of reports were obtained near Denver for the period 1 February–15 March 1992. Maximum separations of 1.5 h for time and 150 km for distance were allowed. Rawinsonde data were interpolated to the level of the aircraft reports.

The sensitivity of temperature and wind differences to distance and time separation, height, time of day, and ascent versus descent was examined. The greatest dependence was found to be on distance separation, an indication of mesoscale atmospheric variability. A lesser dependence was found for time separation. This comparison must be calibrated by the typical time and distance separations of this study; the maximum separations of each were 90 min and 150 km, respectively. It was not possible to distinguish the influence of height versus distance separation, since those variables were highly correlated as a result of the relatively vertical ascent path for rawinsonde balloons versus a more slantwise path for aircraft ascents/descents. There was little sensitivity to time of day, but wind differences were somewhat smaller for aircraft descents than for ascents, indicating that ACARS wind observations may have been more accurate for descents in this sample.

A temperature bias was found indicating that rawinsonde temperatures are an average of 0.22°C warmer than those reported through ACARS. This bias appears to be related to the aircraft measurement since it was found to be about 0.4°C too cool, on the average, during descent, but almost absent on ascent.

To limit the influence of mesoscale variability, statistical differences were also calculated for a sample of data pairs with limited distance separation (25 km) and time separation (15 min). For this sample, a temperature difference standard deviation of 0.59°C was obtained, along with an rms vector wind difference of 4.00 m s^{-1}.

These differences represent a sum of instrument and reporting error from both rawinsondes and ACARS-equipped aircraft, along with a limited mesoscale variability difference. There are also minimal differences introduced by limits in reporting precision.

The differences from the limited distance/time separation sample establish an upper bound on the combined observation error for ACARS and rawinsonde data, and it is remarkably low, indicating considerable accuracy for both platforms. In fact, the combined rawinsonde/ACARS/mesoscale difference found in this study with this limited sample was smaller than that found in previous studies of rawinsonde error alone (Hoehne 1980; Ahnert 1991, summarized in Table 2) for wind speed and about equal to that for temperature. In this study, the combined wind speed standard deviation difference was 2.84 m s^{-1} for the limited sample compared to 3.1 m s^{-1} in Hoehne's study. For temperature, the combined temperature standard deviation difference was 0.59°C compared to 0.54°–0.68°C in previous studies for rawinsonde error alone.

The total difference variance (square of the rms error), which is the quantity calculated in this study, is equal to the sum of the variances from observational and reporting error from each type of observation and the variance from mesoscale variability (section 3). For both temperature and wind speed, since the previously reported errors for rawinsonde errors is close to or exceeds the total difference reported in this study, we infer that the errors from ACARS reports are quite small in comparison. For temperature observations, combining our results with those from the previous studies suggests that the ACARS temperature observation standard deviation errors are very small (estimated at less than 0.3°C) and somewhat less than the rawinsonde temperature errors. The fact that the combined standard deviation wind speed difference from our results was lower than that from Hoehne for rawinsonde errors only may be due to the fact that the limited distance sample was biased toward data pairs from the lower troposphere where wind speeds are smaller. Nevertheless, the ACARS wind observation errors appear to contribute far less to the overall difference than the rawinsonde errors. It is likely that the ACARS wind observations had a speed accuracy of $\leq$1.0 m s^{-1}, approaching the "best possible" values given by Nicholls (1982, section 3). Overall, this study indicates that, since our overall differences were approximately equal to those from previous estimates from rawinsonde errors alone, the accuracy of ACARS temperature and wind observations is somewhat higher than from rawinsondes.

Some outliers in data pairs of both temperature and wind were observed. Some of these were examined on a case-by-case basis, and it was found that some but certainly not all were explainable by possible mesoscale variations. It is likely that some of the wind outliers were a result of erroneous ACARS observations caused by aircraft maneuvers. In addition, the statistics were examined by aircraft tail number to look for systematic problems. These sample sizes were also quite small, but suggested that some aircraft were more likely to have errors than others. Recent work on quality monitoring of ACARS data has been described by Moninger and Miller (1994) and Brewster et al. (1989). The future addition of a maneuver flag in ACARS reports and improved quality monitoring will lead to improvements in the quality of ACARS datasets.

For wind measurements alone, a three-way intercomparison between ACARS, rawinsonde, and wind profiler data is possible. Such a study is under way and will be reported in a future paper.

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