NOTES AND CORRESPONDENCE

Temperature, Humidity, and Pressure Response of Radiosondes at Low Temperatures

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ABSTRACT

The response of radiosondes to an instantaneous change of environment was studied by taking the instruments from a warm building into the cold environment at South Pole Station. After being initialized inside, the radiosondes were carried outside and placed on the snow surface, where they were left until they reported stable values of temperature, pressure, and relative humidity. Three models of radiosondes were tested: Vaisala RS80, Atmospheric Instrumentation Research (AIR) 4A, and AIR 5A.

The reported temperature equilibrated to the outside conditions within 30 s. However, it frequently took 30 min before the relative humidity outside was accurately reported. Additionally, the reported pressure rose by several hectopascals over a 5-min period when the sonde was taken outside. In the RS80s this bias was as large as 10 hPa, and disappeared in about 30 min. In the AIR sondes, the maximum pressure bias was never much over 2 hPa, but seemed not to diminish with time.

The RS80s were also tested to see if, once equilibrated to the outside conditions, they could respond to smaller changes that would be encountered in flight. The results in this case indicate that, with some corrections for time lag, the RS80 can provide accurate data at low temperatures if allowed to equilibrate initially.

The results of these tests together indicate that the quality of upper-air data in cold regions could be improved if radiosondes are stored and prepared at ambient temperature or are given at least 30 min to equilibrate outside after being prepared inside.

1. Introduction

Although new methods are under development for gathering upper-air meteorological data, the atmospheric science community still relies heavily on radiosondes. Data from radiosondes are subject to many errors, including radiational heating and cooling of the sensor arm, which affects both the temperature and humidity measurements (Luers and Eskridge 1995; Wang et al. 2002); calibration errors (Miloshevich et al. 2001); and chemical contamination of sensors (Wang et al. 2002), to name just a few. These errors are sometimes worse when the instruments are used in cold environments, as discussed by Miloshevich et al. (2001).

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In addition to these steady-state errors, a time-dependent error can be introduced when the radiosondes are prepared in a warm building and are not given adequate time to fully equilibrate to the outside surface conditions prior to launch. Mahesh et al. (1997) showed that, because the response time of the thermistor on radiosondes is several seconds, the preparation of radiosondes in a heated building at South Pole Station leads to a significant error in the near-surface temperature data when the balloons are released immediately after being taken outside. Radiosonde hygrometers can become sluggish at low temperatures (Antikainen and Paukkunen 1994), so it is reasonable to expect that the problem Mahesh et al. described would be even worse for near-surface humidity data. Additionally, Hirasawa and Kizu (1999) showed that radiosondes prepared inside a warm building report erroneous pressure data when they are taken outside into cold conditions.

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Atmospheric humidity over the Antarctic Plateau is of interest not only for meteorological studies, but also to determine the feasibility of sites for infrared astronomy; the latter was the motivation for the analysis of South Pole radiosonde humidities by Chamberlin (2001). However, the response of radiosonde sensors to sudden, large changes in environmental conditions, as encountered when taken from a heated building to cold ambient conditions, has not been well characterized. To further investigate the utility of radiosonde data from South Pole Station for analyzing the climatology of relative humidity, we conducted tests to characterize this type of response in radiosondes that have been used at South Pole. These trials were carried out during the 2000/01 year-long field campaign of the South Pole Atmospheric Radiation and Cloud Lidar Experiment (SPARCLE; Walden et al. 2001).

To characterize this type of response, the radiosondes were initialized inside a heated building, then taken outside and allowed to equilibrate to ambient conditions. All three radiosonde models used routinely at South Pole between 1991 and 2001 were tested in this way. These were the Atmospheric Instrumentation Research, Incorporated (AIR), models 4A and 5A and the Vaisala model RS80. In addition, the RS80 radiosondes were tested to see if, once equilibrated to ambient conditions, they could quickly respond to the smaller changes in temperature, pressure, and humidity that are encountered on a balloon flight through the atmosphere.

The instruments and tests are described in section 2. Section 3 contains the results of the tests. A discussion of the results and some recommendations for radiosonde users are in section 4, followed by conclusions in section 5. Although the tests were conducted only at South Pole, the results suggest that changes in radiosonde launch procedures in many cold climates could improve the quality of operational upper-air data in those regions.

2. Instruments and methods

The radiosondes included in this study were chosen based both on their use at South Pole, by the South Pole Meteorological Office (currently operated by Raytheon Polar Services Company, Denver, Colorado) and by the SPARCLE project, and on their availability at South Pole in 2001. In all, five combinations of radiosondes and ground stations were included.

From 1991 through 1996 the South Pole Meteorological Office (SPMO) used the AIR model 4A for their routine balloon flights. One of these older sondes, manufactured in 1994, was still unopened at South Pole in January 2001. This sonde was used for three series of tests during the year. Between tests, the sonde was stored in a sealed bag along with desiccant. In 1997 SPMO began routinely using the AIR model 5A, which they continued using until August 2001. Three series of tests were also conducted using three separate 5A sondes.

Since August 2001, the SPMO has been using RS80 radiosondes for their routine balloon launches. During the year, four series of tests were carried out using their RS80 system. In all four cases the data were received by a Marwin ground station. Since 1993 Vaisala has been producing RS80 sondes with two different humidity sensors: the A-Humicap and the H-Humicap. While based on the same capacitive technology, the two sensors differ in their chemical composition and data processing algorithms (Miloshevich et al. 2001). Three of the four SPMO RS80 sondes we tested had the newer H-Humicap; the fourth had an A-Humicap. In the 2001/02 summer, the SPMO began using the Vaisala RS90 radiosonde for some routine flights. However, as these did not arrive at the station until after we had left, we have no data for these newer instruments.

Finally, the SPARCLE project also used RS80 radiosondes, with the H-Humicap. The SPARCLE radiosondes transmitted through a TMAX-C board, and their data were transferred from the receiver to a personal computer, via a modem. The TMAX board converts frequency-encoded meteorological data from the Vaisala RS80 radiosonde to a digital format with a measurement frame rate of approximately 8 s. It was originally designed, and is still routinely used at South Pole Station, by the National Oceanic and Atmospheric Administration's (NOAA) Climate Monitoring and Diagnostics Laboratory (CMDL), to interface ozone sensors to an RS80 for data transfer. Once reaching the computer, the data were processed using TMCalc software (developed by T. Thompson; information online at http://63.228.74.201/tmax/index.html). In addition to some tests that were carried out specifically to characterize these radiosondes, considerable data from SPARCLE's routine use of the RS80 radiosondes with TMAX boards are also available to help characterize them; therefore, this is the system for which we have the most data.

Although the RS80 sondes from the SPMO were powered by the water-activated batteries included in the packaging from Vaisala, and those used by SPARCLE were powered by lithium batteries, there was no noticeable difference between the data produced by the two systems.

The RS80 radiosondes measure temperature with a small, temperature-sensitive capacitor, consisting of two electrodes separated by a ceramic dielectric. The humidity is measured with their Humicap technology, which separates two electrodes with a thin polymer film. Two different films are used, depending on whether it is the A-Humicap or the H-Humicap, but both cause the capacitance to vary depending on the amount of water absorbed by the polymer film and on the film temperature. The proprietary Vaisala routines correct for the temperature dependence of the Humicap. Pressure is measured using a capacitive aneroid barometer, in which two electrodes are separated by a distance that varies depending of the volume of an expandable, partially evacuated cell. These sensors are briefly described in the Vaisala's brochure on the RS80 (Vaisala 1997), and

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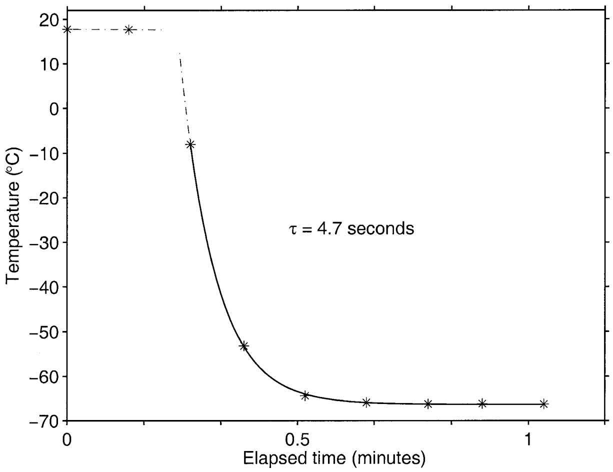

FIG. 1. RS80 temperature response upon being moved outside from a +18°C building when the outdoor air temperature was −66°C on 20 Sep 2001. The asterisks are the reported data, at 8-s intervals, the solid curve is an exponential decay fit to the data, and the dash–dot line approximates what would likely have been recorded with higher-resolution data with a gap left near the transition.

on the Web site of the British Atmospheric Data Centre (http://badc.nerc.ac.uk/data/radiosonde/radhelp.html).

Both types of AIR sondes used small thermistor beads to measure the temperature, and capacitive aneroid barometers to measure pressure. The newer, 5A sonde measured humidity with a thin polymer-film capacitance hygrometer, while the older, 4A sonde measured humidity with a carbon hygristor (R. Shellhorn, Vaisala Inc., 2003, personal communication).

AIR radiosondes have not been widely used operationally (Connell and Miller 1995), so their characterization is of interest mainly because of their past use at South Pole. On the other hand, the RS80 is routinely used not only at South Pole, but also at over 400 upper-air stations around the world, as of December 2002 (WMO 2002).

The purpose of our investigation was to determine the response time and other characteristics of the sensors' response to environmental changes, not to determine their absolute accuracy. Therefore, no corrections were applied to the data produced by the receiving systems. Also, as is routine at South Pole, no ground check procedures were performed beyond seeing that initial reports inside were accurate.

In order to characterize the radiosonde response to sudden, large changes in temperature and humidity, a radiosonde was initialized inside either a heated building, with the indoor temperature between 0° and +25°C, or an unheated building, with a temperature of −43° to −55°C. Shortly after being initialized it was taken outside, and placed on the snow surface or about 5 cm above it, where it remained until it reported stable values of temperature, humidity, and pressure. Sometimes the radiosonde was then returned to the heated building,

TABLE 1. Summary statistics of exponential decay time constants (s) for temperature response of RS80, AIR 4A, and AIR 5A sondes.

Type of sonde	RS80	4A	5A
No. of tests	33	5	6
Min	2.6	4.8	5.6
Median	5.2	6.3	6.7
Max	10.9	10.2	7.6

and allowed to equilibrate, and the procedure was repeated.

In all these tests the instrument was not ventilated, except by any ambient wind. At the times of the tests, outside temperatures ranged from −24° to −71°C, and were between 17 and 94 K colder than the temperature inside the building.

In addition to the tests involving large changes, the RS80 radiosondes were also tested to see if, once equilibrated to cold outside conditions, they could respond to small changes in a timely manner. To do this, a pulley was placed at the top of a 22-m tower at South Pole. The radiosonde was attached to one end of a line that ran from the surface, through the pulley, and back to the surface. The instrument was then raised from the surface to about 20 m above the surface, where it was held for 2 min, then lowered to the surface.

This procedure was carried out a total of 8 times, on two winter days. In all the experiments on the tower, the radiosonde used was an RS80 with an H-Humicap, transmitting through a TMAX-C board. On both days there was a strong surface-based temperature and humidity inversion, so that at the top of the tower the temperature was 3–5 K higher and the relative humidity was 3%–5% higher than at the surface (all differences in relative humidity are given as absolute differences, e.g., 65% is 5% greater than 60%). The approximate rate of ascent and descent of the radiosonde ranged from 0.4 to 1.0 m s^{-1}, significantly slower than the 3–6 m s^{-1} typical of a free-launched balloon in the lower atmosphere.

3. Results

a. RS80 response to large changes in temperature and humidity

Figure 1 shows a representative response of temperature reported by an RS80, after being taken outside from a warm building. In this case, the reported temperature decayed exponentially toward the outside temperature, with a time constant of 4.7 s. In all of the 33 cases in which data were recorded as an RS80 was moved from inside to outside, the temperature responded in a fashion similar to Fig. 1. The exponential decay time constants for these tests, summarized in Table 1, have a median value of 5.2 s. The variability of the time constants and the lack of correlation with thermal shock are shown in Fig. 2a. Since most of the tests began at

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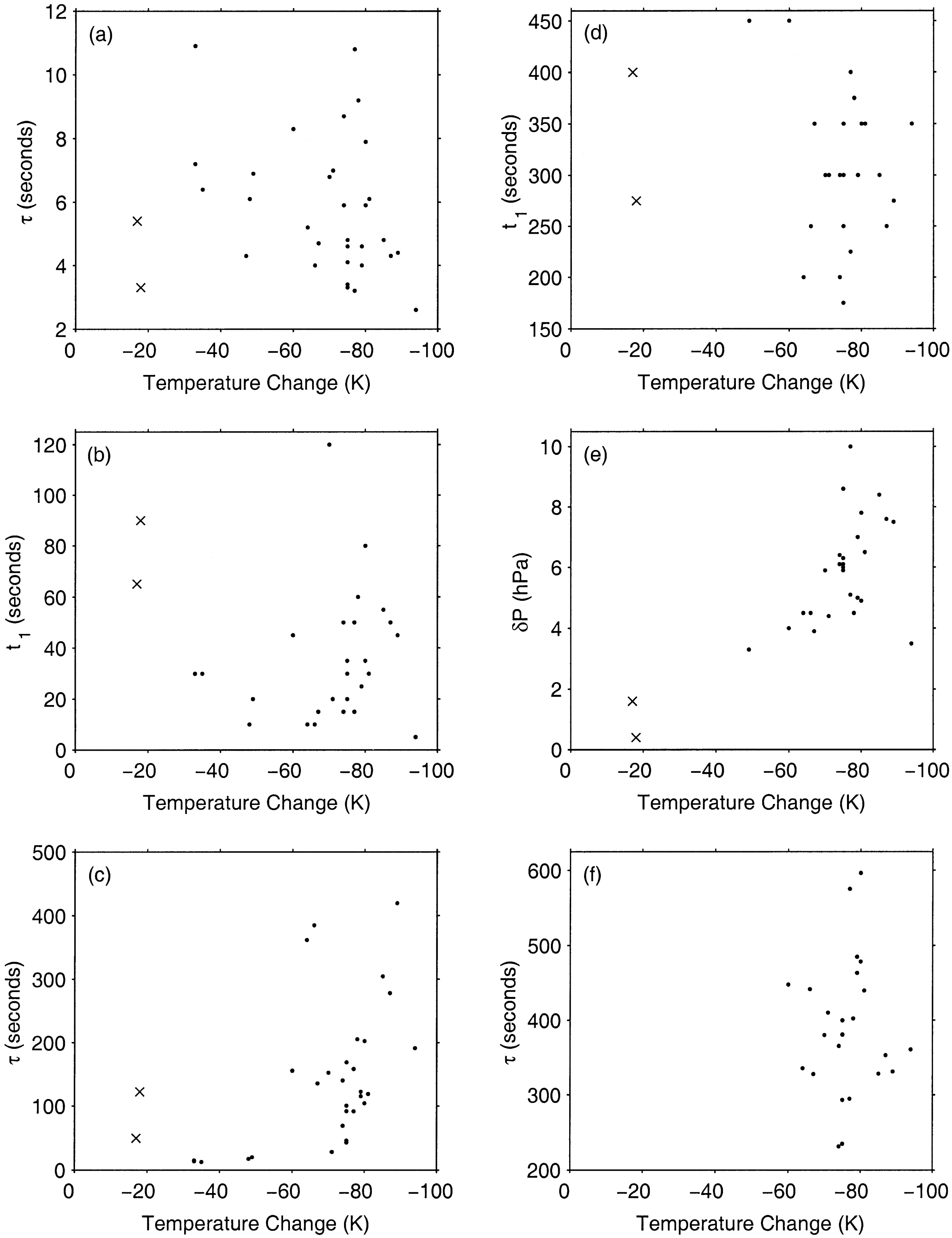

FIG. 2. Scatterplots of (a) *e*-folding time for the RS80 temperature response, (b) time t_1 before the exponential decay in RS80 relative humidity response, (c) *e*-folding time for the RS80 relative humidity response after time t_1, (d) time to reach maximum error in RS80 pressure response, (e) maximum error in RS80 pressure response, and (f) *e*-folding time for the RS80 pressure response, all vs the change in temperature as the sonde was moved from inside to outside. The crosses indicate data collected as a sonde was moved outside from an unheated building; all other data are plotted as dots.

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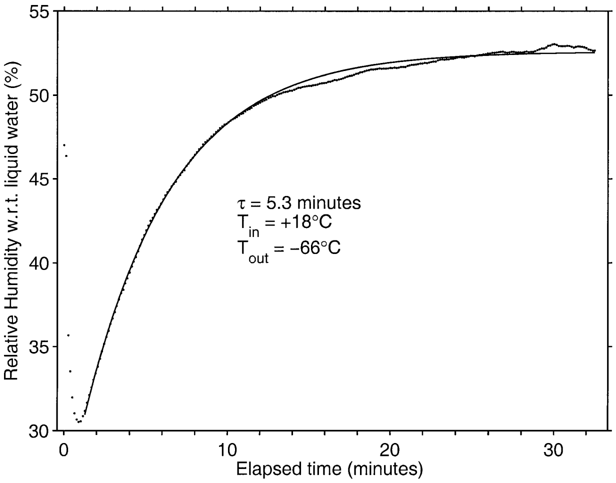

FIG. 3. RS80 humidity response for the same case as in Fig. 1. The relative humidity indoors was about 47% and outdoors was about 53% (101% w.r.t. ice). The dots are the reported data, at 8-s intervals, and the solid curve is an exponential decay fit to the data.

temperatures between +10° and +20°C, scatterplots versus outside temperature were very similar to those shown in Fig. 2, and are not shown here.

The relative humidity response of the RS80 was not as well behaved as the temperature response. Figure 3 shows the reported relative humidity from the same experiment as in Fig. 1. The time constant of the exponential decay varied considerably throughout the year, but the shape of the curve in Fig. 3 is representative of those from all the tests, regardless of temperature or type of RS80. When taken outside, the reported humidity initially drops, then exponentially decays toward the value of the outdoor relative humidity. The initial decrease in reported humidity could be caused by a thermal lag in the hygrometer, which would lead to the hygrometer being warmer than the ambient temperature, leading to an improper temperature correction being applied in the calculation of relative humidity.

In Fig. 3, the exponential decay does not begin until about 70 s after the radiosonde is taken outside; the decay to equilibrium has an *e*-folding time constant of 320 s. Table 2 summarizes the responses that were observed in different conditions. In tests done in the summer, the time interval from when the radiosonde was taken outside to when the exponential decay began ranged from 10 to 30 s, and the *e*-folding time constant ranged from 13 to 20 s. In winter, the time before the exponential decay began ranged from 5 to 120 s, and the *e*-folding time ranged from 30 to 420 s; neither time showed any apparent correlation with the outside air temperature or with the magnitude of the thermal shock.

During the winter there were also two cases in which the radiosonde was taken outside from a building at −43°C when the outside temperature was −60°C. Although this was the only time a sonde with an A-Humicap was used, the response to this situation was similar to other winter cases, with times before exponential decay began of 65 and 90 s, and *e*-folding times of 50 and 120 s.

TABLE 2. Times associated with the RS80 relative humidity response curves in different situations. The time interval t_1 is the amount of time that passed from when the instrument was moved outside to when the exponential decay began, with an *e*-folding time of τ. Medians are given only for winter cases because of the small number of tests in summer and unheated winter cases. All sondes had the H-Humicap except for the one used in the unheated winter cases, which had an A-Humicap.

	Summer	Winter	Unheated winter
No. of tests	5	25	2
Inside temp (°C)	+8 to +24	+2 to +24	−43
Outside temp (°C)	−24 to −25	−45 to −71	−60 to −61
Min t_1 (s)	10	5	65
Median t_1 (s)	—	30	—
Max t_1 (s)	30	120	90
Min τ (s)	13	30	50
Median τ (s)	—	140	—
Max τ (s)	20	420	120

Figure 2b shows the variability in the times before the exponential decay began, and Fig. 2c shows the variability in the *e*-folding times for the relative humidity response. It is also clear from these two figures that there is no correlation between temperature change and either of these values for the many cases with temperature changes between 60 and 100 K.

A final interesting note on the relative humidity regards the accuracy of the equilibrated measurement. In Fig. 3 we can see that, after equilibration, the reported relative humidity was 52.6%. At the ambient temperature of −66.4°C, this corresponds to a relative humidity with respect to ice (RH_i) of 100.9%, which is close to the values reported by a nearby frost-point hygrometer at the same time: 102%–105%. Typically, the RS80s used by SPARCLE equilibrated to within ±5% of the RH_i that was reported by a nearby frost-point hygrometer, even when supersaturated. Relative humidities with respect to ice were reported as high as 123%, and were frequently between 100% and 110%. All conversions between RH_i and relative humidity with respect to water (RH_w) were done using the equations for saturation vapor pressure over water by Wexler (1976) and for saturation vapor pressure over ice by Hyland and Wexler (1983), to be consistent with Vaisala's calibration (Miloshevich et al. 2001).

Not all of the RS80 radiosondes were able to perform this well. SPARCLE's radiosondes were packaged with a new sealed protective cover over the sensor arm, which Vaisala began using on all RS80s in June 2000. This cover eliminated a dry bias that was caused by contamination of the hygrometer resulting from the packaging, described by Wang et al. (2002). The RS80s used by SPMO did not have this new sealed cover. Their RS80s with the H-Humicap generally showed a dry bias, and never reported supersaturated conditions. In the one test

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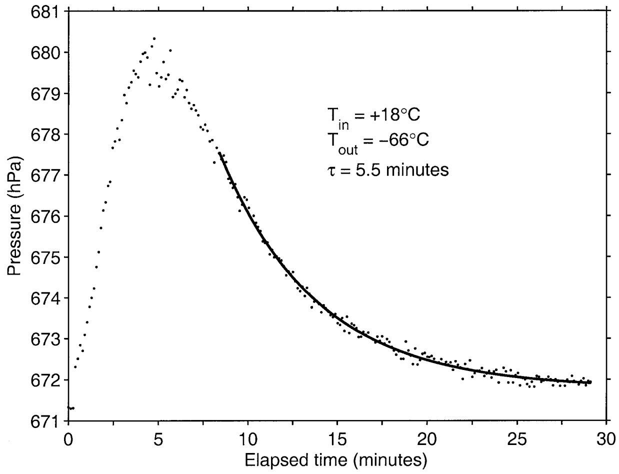

FIG. 4. Pressure reported by an RS80 after being taken outside for the same case as in Figs. 1 and 3. The dots show the reported data, and the solid curve is an exponential decay fit to the latter part of the data.

that was done using an SPMO RS80 with the A-Humicap, at a temperature of −61°C, and RH_w (from the frost-point hygrometer) of about 60%, the sonde showed a dry bias of about 30%, or roughly a factor of 2, consistent with Miloshevich et al. (2001).

b. Response of the RS80 pressure sensor

As reported by Hirasawa and Kizu (1999), the RS80s showed a response in the reported pressure when taken outside from a warm building. Figure 4 shows that, upon being moved outside from a building at +18°C when the outside temperature was −66°C, the reported pressure initially increased, until reaching a value about 8–9 hPa higher than the actual pressure. After about 300 s the pressure began to recover, and then exponentially decayed toward the actual pressure, with a time constant of 330 s. While the pressure bias always decreased to near zero after 30–40 min, it frequently recovered to a value slightly higher than was reported before being taken outside, as seen in Fig. 4. Going back into the warm room, the response was the mirror image of Fig. 4: a *decrease* of 8 hPa and a slow recovery.

This kind of response is seen in the pressure data at all temperatures at which the tests were conducted. The characteristics of the response in different conditions are summarized in Table 3. In the cases in which the radiosondes were moved between a heated building and outside during the winter, the time for the reported pressure to rise to its maximum ranged from 175 to 450 s, with a median and mean of 300 s. The maximum error in the reported pressure in these cases ranged from 3.5 to 10 hPa, with a median and mean of 6 hPa, and the *e*-folding time in the latter part of the response ranged from 230 to 600 s, with a median and mean of 380 and 385 s.

In the two tests done using an unheated building in winter, 275 and 400 s elapsed before reaching maximum errors of 0.4 and 1.6 hPa. The data after the maximum error were more linear than exponential, but about 1500 s passed before they fully recovered, similar to the time required in the other tests.

TABLE 3. Times associated with the RS80 pressure response curves in different situations. The time interval t_1 is the time elapsed before the reported pressure reached its maximum value; δP is the difference between the maximum reported pressure and the actual pressure; τ is the exponential decay time constant of the response after the maximum was reached. Medians are given only for winter cases because of the small number of tests in summer and unheated winter cases.

	Summer	Winter	Unheated winter
No. of tests	1	25	2
Inside temp (°C)	+24	+2 to +24	−43
Outside temp (°C)	−25	−45 to −71	−60 to −61
Min t_1 (s)	450	175	275
Median t_1 (s)	—	300	—
Max t_1 (s)	450	450	400
Min δP (hPa)	3.3	3.5	0.4
Median δP (hPa)	—	6.0	—
Max δP (hPa)	3.3	10.0	1.6
Min τ (s)	N/A*	230	N/A**
Median τ (s)	—	380	—
Max τ (s)	N/A*	600	N/A**

* Too little data to characterize recovery.
** Data were not exponential. Correct pressure was reported about 1500 s after sonde was moved outside.

Unfortunately, we did not notice this strange behavior of the pressure sensor until winter (and were unaware of the work of Hirasawa and Kizu), and we departed South Pole in late spring, so we do not have completed experiments at higher temperatures. There was one case in the previous summer in which a radiosonde was taken outside to −25°C and left stationary long enough to reach the peak in the pressure response curve. After 450 s the reported pressure was 3.3 hPa higher than it was initially; it was taken inside too soon to get enough data to characterize the recovery. In two other summer cases, at −24° and −25°C, the pressure error reached 2.1 and 2.2 hPa, but had not started to recover before being moved.

Figures 2d–f show the variability in the three characteristics of the pressure response: time to reach peak error, magnitude of peak error, and *e*-folding decay time. We can see that, from the data available, it appears the times t_1 and τ that characterize the pressure response are not functions of thermal shock over the range that these data cover. The maximum error in reported pressure, on the other hand, seems to increase with increasing thermal shock. Figure 5 shows the maximum error versus temperature change for all cases, including those where the sonde was moved from outside to inside. Here we can see a linear relationship between the maximum pressure error and the magnitude of the thermal shock, such that $\delta P = -0.070(\delta T) + 0.575$, where δP is the maximum pressure error in hectopascals and δT is the

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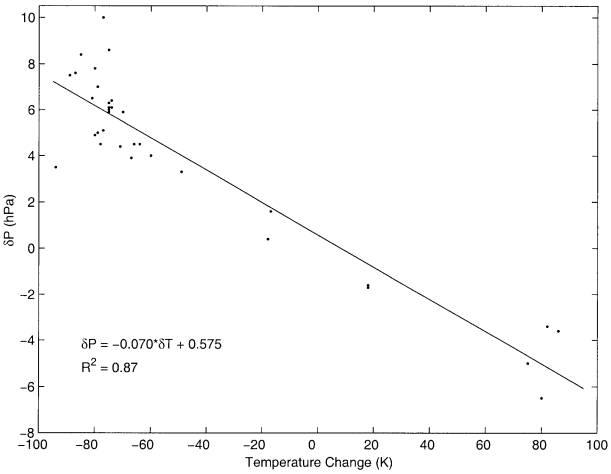

FIG. 5. The maximum error in pressure reported by an RS80 (δP) vs the difference between starting and ending temperature, for all cases, including those that went from outside to inside (positive temperature changes). The results of a linear regression on the data are also shown.

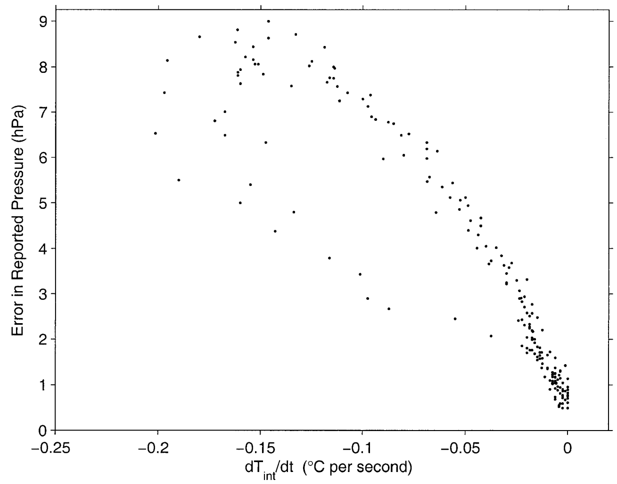

FIG. 6. The error in pressure reported by an RS80 vs the rate of change of the internal temperature with time (dT_{int}/dt) for the same case as is shown in Fig. 4.

change in temperature in kelvins. This equation accounts for 87% of the variance in these data.

Hirasawa and Kizu (1999) conducted similar tests with RS80 radiosondes at Dome Fuji Station on the East Antarctic Plateau, whose climate is similar to that at South Pole. They presented results from eight tests, with temperature differences ranging from 46 to 75 K. The character of the pressure response reported for their tests was similar to what was seen at South Pole, with the exception that the maximum pressure errors reported by the Dome Fuji tests were generally only 50%–75% of what was observed at South Pole. The Dome Fuji tests were carried out much like those at South Pole, except that, when outside, the sondes were in a snow cave, rather than on the snow surface. The ambient pressure in the Dome Fuji tests was between 610 and 630 hPa, while at South Pole it was between 660 and 700 hPa.

To explain the pressure error we must discuss the design of the instrument. The aneroid cell in the RS80 provides pressure information by measuring the volume of an expandable, partially evacuated chamber. Since this volume will be affected by both the external pressure and the temperature of the aneroid cell, an adjustment must be made to account for the temperature of the cell. Significant errors in reported pressure are possible from this type of sensor when temperature gradients develop across the aneroid cell and associated electronics (WMO 1996). It seems likely that this pressure error is a result of such temperature gradients that develop in response to the sudden change in ambient temperature. Figure 6 shows how this error in pressure seems to be closely related to the rate of change of this internal temperature with time. This explanation provides hope that the pressure response may be less of a problem operationally, when the sonde is well ventilated.

Hirasawa and Kizu (1999) cited a personal communication with Vaisala indicating that strain on the metal leads in the aneroid cell (used to measure its volume through capacitance), caused by contraction of the metal in the cold, can lead to pressure errors at low temperatures. Perhaps this explains the roughly 0.5-hPa bias often seen in the data after the sonde equilibrated.

This error in reported pressure will lead to an apparent temperature error in a sounding since the temperature measured at a particular pressure level will appear to have come from a lower height (higher pressure). To estimate the magnitude of the error that could be caused in a temperature sounding by this pressure response, a polynomial was fit to data similar to those shown in Fig. 4, from a day with an outside temperature of −61°C, and from which the original pressure had been subtracted. This polynomial was then used to correct the pressure data from a routine sounding taken at 0000 UTC 16 October 2001, when the surface temperature was −61°C. No other data corrections were applied.

In performing this calculation, it was assumed that the error in the reported pressure during the flight was the same function of time that it was during a ground test at the same surface temperature. At least two factors are likely to reduce this error during a flight: the increased ventilation, and the fact that the sonde does not remain at a constant temperature during flight. Thus, these results probably represent a maximum possible error.

The magnitude of the resulting error is clearly highly dependent on the shape of the temperature profile and, in particular, on the rate of change of temperature with height. The sounding used here represents a typical winter sounding at South Pole.

The reported profile is shown in Fig. 7a, and the error estimation in Fig. 7b. The surface pressure at the time of this sounding was 671 hPa. The surface data in the

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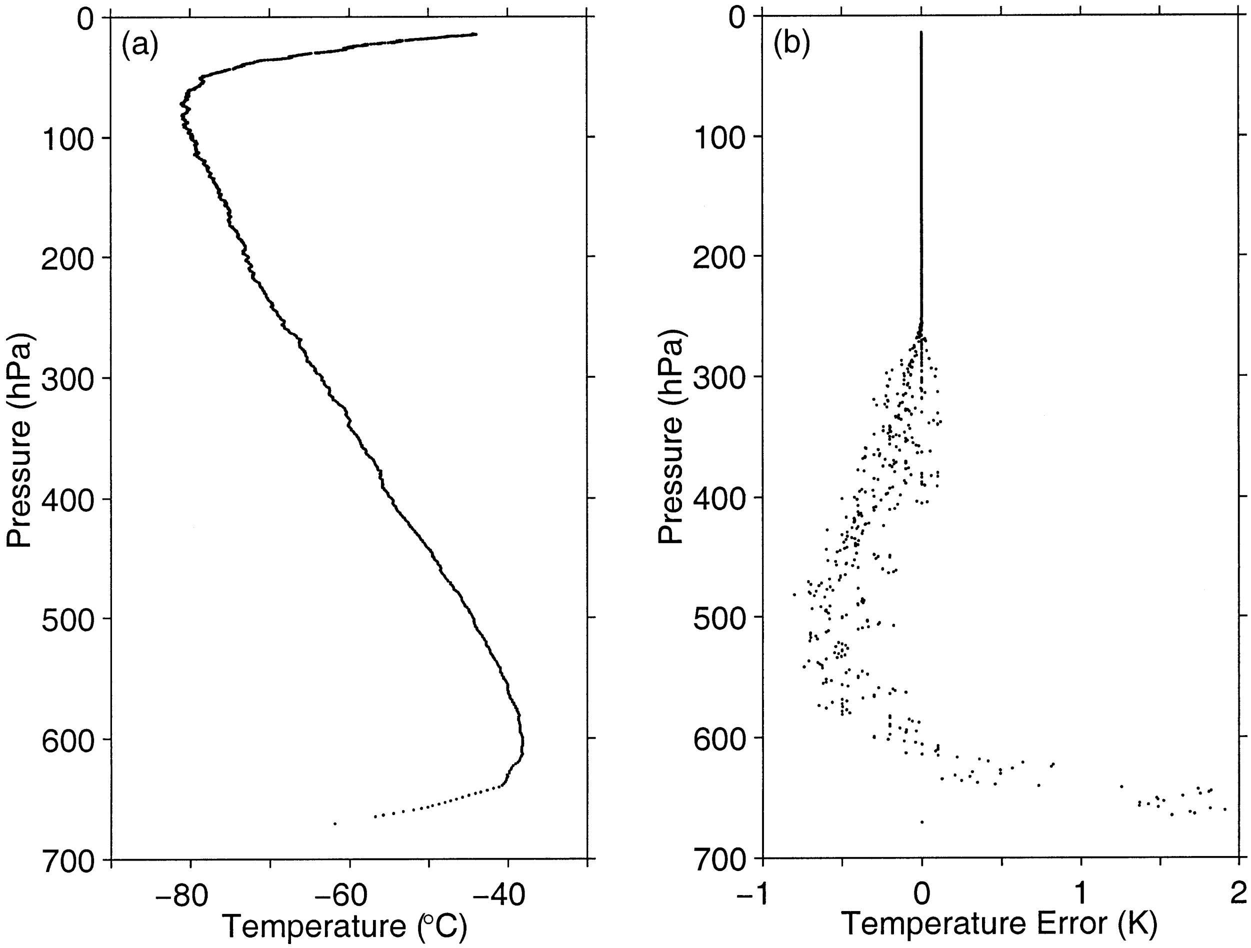

FIG. 7. (a) The temperature profile from the sounding at 0000 UTC 16 Oct 2001, made using an RS80, and (b) the estimated error in the temperature profile that results from the pressure error.

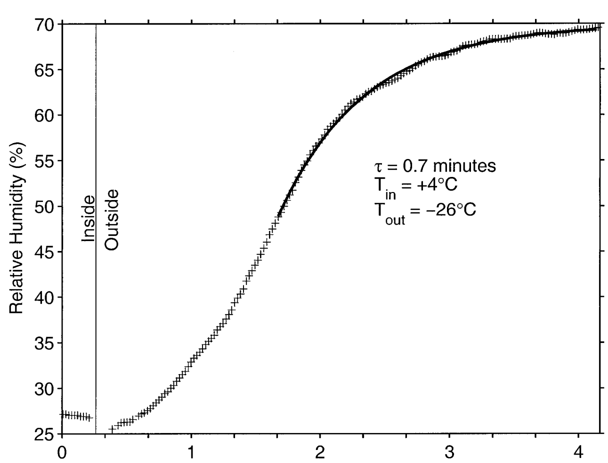

FIG. 8. Relative humidity reported by an AIR 4A sonde after being taken outside from a +4°C building on 18 Jan 2001, when the outdoor air temperature was −26°C. The plus signs are the recorded data and the solid curve is an exponential decay fit to the latter data.

profile were entered from surface observations, and were excluded from the correction. Although the maximum pressure error (not shown) did not occur until the sonde had passed 550 hPa, we can see that the maximum apparent temperature error, nearly 2 K, occurs near the surface, where the magnitude of the lapse rate is very large. The pressure bias does not fully disappear until the sonde reaches about 250 hPa.

c. AIR response to large changes

The response of the temperature data reported by the AIR 4A and 5A sondes, after being taken outside, was similar to that of the RS80s shown in Fig. 1. The exponential decay time constants for the temperature response of the AIR sondes are summarized in Table 1.

At temperatures above −40°C the 4A sonde reported reasonable values of relative humidity within about 2 min of being taken outside. Figure 8 shows the response of the reported relative humidity for a case when the sonde was moved outside when the ambient temperature was −26°C. The reported RH_w quickly begins to in-

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TABLE 4. Characteristics of the AIR 4A relative humidity response to large changes in ambient conditions.

Date	Outside T (°C)	t_1 (s)	τ (s)	RH_w (%)	Actual RH_w (%)
18 Jan 2001	−27	40	60	76	73
18 Jan 2001	−26	75	40	70	73
18 Jan 2001	−27	30	30	76	73
8 Feb 2001	−39	125	70	69	59
8 Feb 2001	−39	100	30	65	59
7 Aug 2001	−68	250	4000	35	55

t_1 = time before exponential decay began.
τ = e-folding time constant.
RH_w = final reported relative humidity w.r.t. water.
Actual RH_w = RH_w reported by a nearby, stationary instrument.

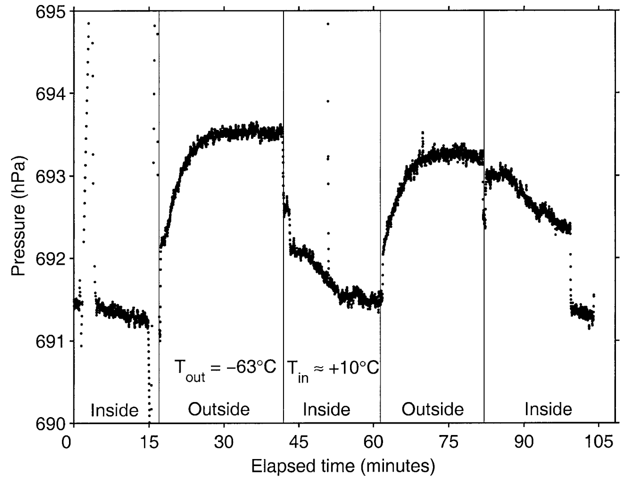

FIG. 9. The pressure reported by an AIR 5A sonde on 6 Jun 2001 as it was repeatedly moved between a heated building and outside; the outside temperature was −63°C. Dots show the recorded data, and solid vertical lines indicate when the sonde was moved inside or outside.

crease, at first with the rate of change increasing with time. After about 75 s, it follows an exponential decay toward the value of the outdoor relative humidity, with a time constant of 40 s. The shape of this response curve is similar to all of those for tests at temperatures above −40°C. Table 4 gives the response times for the various tests that used the 4A sonde, as well as the value to which the relative humidity equilibrated.

The final row in Table 4 shows data from the one test that used the AIR 4A sonde in the winter. In this case, the equilibration not only took well over an hour, but also, unlike the other 4A cases, reached a value much drier than that reported by other instruments at the same time.

Although the older (4A) sonde seems capable of reporting reasonable relative humidity data to temperatures at least as low as about −40°C, the newer AIR 5A sonde was grossly inaccurate at all temperatures encountered at South Pole, as Chamberlin (2001) also concluded. When taken outside, these sondes typically showed a strong dry bias and very slow response, or quickly stabilized at a relative humidity of 1%. This behavior was seen in the ground tests as well as in SPMO's routine flights with the 5A sondes.

As with the RS80s, the pressure reported by the AIR sondes was affected by large temperature changes. Figure 9 shows the reported pressure as an AIR 5A sonde was taken repeatedly inside and outside, between temperatures of about +10° and −63°C. In this case the pressure increased by about 2 hPa when taken outside, and decreased by the same amount when taken inside. Unlike the RS80s, there is no indication in this case that the data recover to the correct value after being taken outside. The AIR sondes also frequently reported spurious data when used at the surface, as is seen in Fig. 9 near 5, 15, and 50 min. It is clear that the response when the sonde was moved inside was not the mirror image of when it was moved outside, but instead showed some peculiar timing, especially after the final transition shown in Fig. 9. It is not known what caused this timing while inside, but at least some of it may have been a result of changing conditions in the building, due to the heater being on (the indoor temperature varied between −5° and +25°C while the sondes were inside).

The data shown in Fig. 9 are the most extreme example of this response that we saw in the AIR sondes, but similar responses, of smaller magnitudes, were seen in most cases that tested the AIR 4A or 5A sondes in this way. The results of these tests are shown in Table 5. After a transition from 0° to −68°C a 4A sonde showed an increase in reported pressure of 1.7 hPa. In the unheated winter cases, the 4A sonde showed pressure increases of 0.7 hPa, while the 5A sonde showed small decreases in reported pressure. At temperatures between −25° and −40°C the 4A sonde showed a pressure increase of 0.1–0.5 hPa when taken outside from a heated building. There are no similar summertime data for the 5A sonde.

TABLE 5. The change in reported pressure (δP) from AIR sondes when taken from inside to outside.

Date	Inside T (°C)	Outside T (°C)	δP (hPa)
AIR-5A sondes			
6 Jun 2001	+6	−63	2.2
6 Jun 2001	+3	−63	1.8
16 Oct 2001	−42	−61	−0.1
16 Oct 2001	−43	−61	−0.3
AIR-4A sondes			
18 Jan 2001	+2	−27	0.3
18 Jan 2001	+4	−26	0.1
18 Jan 2001	+4	−27	0.1
8 Feb 2001	+5	−39	0.5
8 Feb 2001	+1	−39	0.4
7 Aug 2001	0	−68	1.7
7 Aug 2001	−55	−68	0.7
7 Aug 2001	−55	−68	0.7

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d. RS80 response to small changes after equilibration

Figure 10 shows a sample of the data collected while an RS80 descended from near the top of the 22-m tower. In the case shown, the data begin after equilibration to the conditions at the top of the tower, and they extend through the equilibration to surface conditions. The vertical lines in the figure show when the descent, which took 34 s, began and ended.

The pressure generally responded to within the level of the noise by the time the ascent or descent was completed. This is apparent in Fig. 10a, where the reported pressure 1 s before the end of the descent was approximately equal to the pressure reported while at the surface. Furthermore, it is encouraging that, in all cases, the pressure differences between the top and bottom of the tower agreed well with what is expected from the hypsometric equation. For the case in Fig. 10, using a layer-averaged temperature of $-61°C$ and a surface pressure of 691.5 hPa, we would expect the pressure at 20 m to be about 2.2 hPa lower than at the surface, similar to what was observed.

Figure 10b shows that the sonde responds to the temperature change with a lag. There is one data point, reported 7 s after the descent was completed, that is still indicating a temperature somewhat warmer than the later data, suggesting that it took the sonde 8–15 s, after reaching the surface, to equilibrate to the temperature change. This delay was seen in all of these tests, but, given that the time between successive data points is nearly as long as the response time, it is not possible to characterize the response precisely.

The relative humidity response is shown in Fig. 10c. Full equilibration of the relative humidity was typically reached about 15–20 s after the descent ended. As with the temperature data, precise characterization of this response was not possible.

4. Discussion

The data presented in section 3 require some caveats, and will hopefully inspire more work on this subject. A better, more robust characterization of the radiosondes would be possible if more radiosondes were used to collect a larger set of data, and if these experiments were repeated under more controlled conditions, while ventilating the instruments as they would be during flights. Given that the data shown here often were collected with little ventilation, the results may be closer to the maximum errors that occur when radiosondes are prepared in a heated building than to the average errors.

Clearly the data in section 3d would be more applicable if ascent and descent rates were closer to those experienced in a typical radiosonde flight. While the faster ascent rate of a balloon causes more ventilation of the instrument, it also carries it through the changed ambient conditions more quickly. These opposing factors make it difficult to know whether the lag experi-

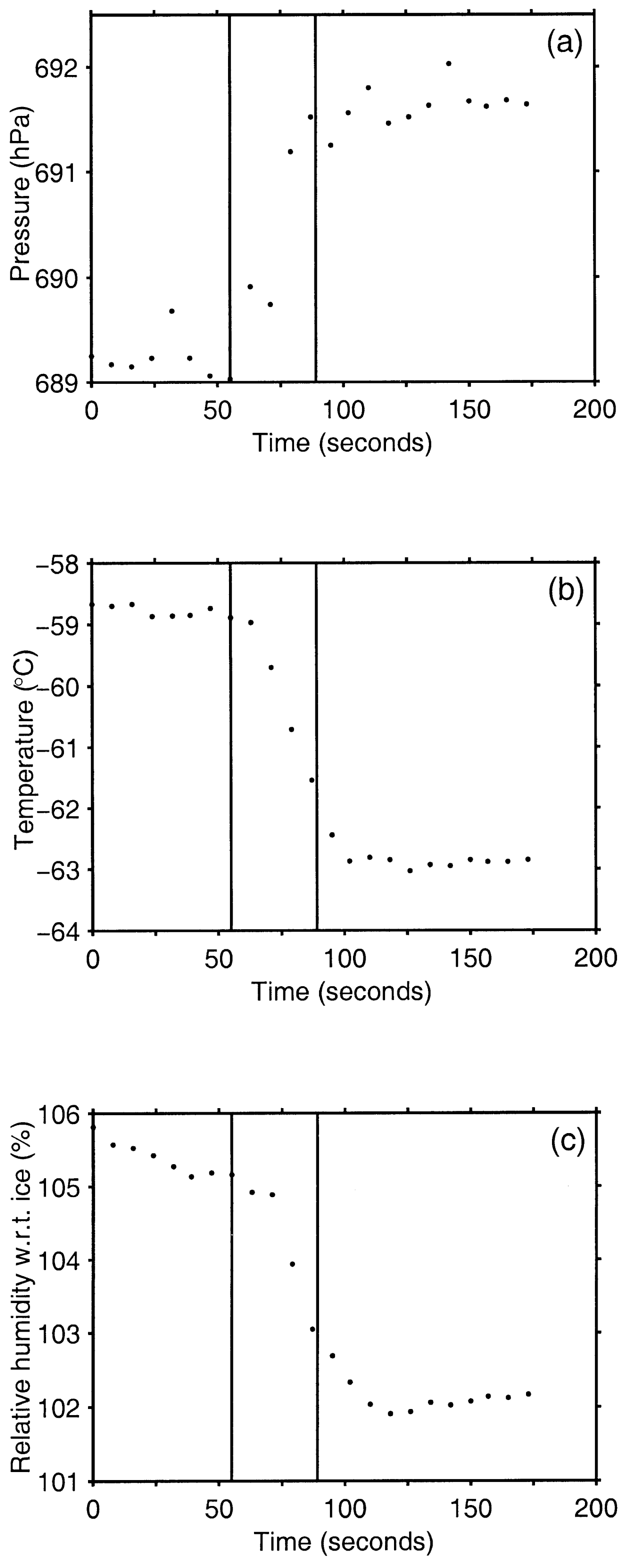

FIG. 10. The reported (a) pressure, (b) temperature, and (c) relative humidity w.r.t. ice as an RS80 was lowered from approximately 20 m above the surface to the surface on 19 Jul 2001. The dots indicate the data, at 8-s intervals, and the vertical solid lines show the times when the descent began and ended.

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enced in operational use of the RS80s is likely to be better or worse than that observed in these experiments.

Despite the less-than-ideal conditions just noted, these data provide not only some valuable information applicable to radiosonde preparation procedures around the world, but also another reason to be cautious when using archived radiosonde data in climate studies (Elliott and Gaffen 1991).

Although the data were collected at South Pole, their application should not be limited to the Antarctic Plateau. The conditions at South Pole during the summer are similar to those found at many continental, midlatitude, Northern Hemisphere stations in winter. Furthermore, Arctic, sub-Arctic, and coastal Antarctic stations experience these conditions during long portions of the year, and at times have conditions similar to those in some of the winter cases presented here.

Ideally radiosondes would be stored and prepared in ambient conditions to eliminate any bad data resulting from preparation in a climate controlled building. It is evident from the tests using an unheated building that even relatively small differences between inside and outside conditions should be avoided, indicating that any shelter that is used would need to be unheated and well ventilated.

Working in extreme cold can obviously be difficult. Not only is it hard on the observer to prepare the balloon and sonde in very cold temperatures, but also the cold can make preparation of water batteries and connection and manipulation of rubber-insulated battery leads impossible. Therefore there are likely times and places where the storage and preparation of radiosondes will have to be done inside a heated building. If this is the case, these data suggest that the instrument should be placed outside for at least 30 min prior to launch to allow for equilibration. While not shown here, data collected when sondes were moved from outside into a building showed similar responses in pressure, but of opposite sign. They also indicated that the humidity sensor collects a large amount of frost very quickly, causing erroneous relative humidity reports. Thus, the sonde should not be brought back inside after equilibration, even for a very short period to attach it to the balloon.

The data presented in section 3d indicate that the RS80s are capable of responding reasonably quickly to changes encountered in the atmosphere once they have equilibrated to the initial shock of being taken outside. This indicates that by providing a time lag correction to the data, as in Mahesh et al. (1997), and by following the recommended preparation procedures, these radiosondes are capable of providing more accurate data than with current procedures, even in a cold boundary layer with a steep inversion. Such procedural changes could contribute to a large improvement in upper-air data from cold regions.

It seems apparent that while procedural changes may lead to improved data quality, it is still necessary to continue pursuing improved technologies that are inexpensive enough to be incorporated into future radiosondes. Decreasing the effect of thermal shock on the instruments and shortening their response times are improvements important for making radiosondes fully suitable for operational and research use.

5. Conclusions

Vaisala RS80, AIR 4A, and AIR 5A radiosondes were tested at South Pole to characterize their response to being taken outside in cold conditions after being prepared in a warm building. The results show that, while the reported temperature can equilibrate in under 30 s, the reported relative humidity and pressure take much longer to equilibrate after the temperature change.

Radiosonde hygrometers are notoriously slow to respond at low temperatures, so it was not surprising to find that a half hour was frequently required for the instruments to report accurate humidity measurements after being taken outside. It is perhaps less well known, however, that it also takes this long for the radiosondes to report an accurate pressure.

While these results were discouraging, results from the tower experiment indicate that the RS80 is capable of accurately reporting changes of pressure, temperature, and humidity in the atmosphere, once equilibrated to ambient conditions. These responses were not always as rapid as the changes were encountered, but they did occur fast enough that the data could likely be corrected with a time lag correction.

It appears that either storing and preparing radiosondes in ambient conditions, or allowing them at least 30 min to equilibrate after being taken outside from a warm building, could make a substantial improvement in the quality of upper-air data collected at cold stations.

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