TEST RESULTS USING SUGGESTED TEMPERATURE CORRECTIONS FOR THE US RADIOSONDE AND APPLICATION TO THE INTERCOMPARISON MEASUREMENTS

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1. INTRODUCTION

The results of the recent World Meteorological Organization (WMO) sponsored radiosonde intercomparison (Nash and Schmidlin, 1987) concluded that incompatibility between operational radiosondes continues to exist and that temperature measurement corrections are necessary. The lack of temperature corrections for the US radiosonde is known to affect height calculations resulting in large day-night differences (McInturff et al., 1978). This observed bias suggests that reported temperatures are probably too warm during the day and too cold at night, relative to ambient temperatures. At 100 hPa the height bias can reach magnitudes of nearly 50 meters.

Radiosonde temperature measurements contain errors composed of thermal lag, short- and long-wave radiation, ground and flight equipment anomalies, calibration and other instrumental errors, and observer mistakes. Only the bias errors resulting from short- and long-wave radiation are of interest in this report. Ballard and Rubio (1968) reported that the daytime measurement error due to radiation is largest, reaching 1.8°C at 10 hPa. Talbot (1972), in a theoretical study suggested that nighttime temperature errors reach negative values of -1.6°C at 10 hPa. In a much earlier paper, Badgley (1957) suggested that the radiational error of the US outrigger radiosonde at 11 hPa was negative both day and night (i.e., -0.9°C during day and -2.0°C during night).

Investigation to resolve the magnitude of this measurement error was initiated at NASA's Wallops Flight Facility. A discussion of the instrumental design and preliminary estimates of nighttime and daytime radiation errors resulting from this investigation were reported by Schmidlin, et al (1986). Because of the small data sample additional instruments were launched from Wallops Island between December 1986 and July 1987, and from San Juan, Puerto Rico during July 1987. These observations provided information for solar elevation angles between -7 and 86 degrees.

2. EXPERIMENTAL SENSOR DESIGN

To determine the long- and short-wave radiation errors of the thermistor, the emissivity ϵ and solar absorptivity γ for each of the thermistor coatings must be known (Daniels, 1968; Staffanson, 1974). Various coatings were tested in the University of Dayton Research Institute's laboratory to determine not only ϵ and γ but also to determine whether coatings selected met the requirement for largest separation of the emissivities and absorptivities. The standard white coating, aluminum and black coatings were selected. Thus, thermistors having different spectral characteristics would respond differently to the same radiant energy environment. Once acceptable values of ϵ and γ were determined they can be used in a known form of the heat-transfer equation,

$$-H(\Delta T) - \sigma\epsilon A T^4 + \epsilon R + \gamma S = 0, \qquad [1]$$

to solve for the thermistor error ΔT. The convective heat transfer coefficient H is calculated from Nusselt and Reynolds numbers, R and S are the long-wave and incident radiant short-wave powers, respectively, A is the thermistor's surface area, and σ is the Stefan-Boltzmann constant. Since R and S must also be known Equation 1 is solved simultaneously for as many thermistors as desired. Nighttime observations require a minimum of two thermistors (since $S = 0$ at night) and daytime observations a minimum of three thermistors.

To provide more precise and efficient retrieval of the measurements a new 8-channel radiosonde was used. Computerized data reduction procedures were adapted to this 8-channel system that helped to reduce subjectivity resulting from manual reduction methods. All channels are commutated by the 8-channel switch giving four temperatures, one relative humidity, two pressures, and one low reference. Each sensor transmits for a period of two seconds. The four temperature sensors were matched calibrated (i.e, calibrations were matched within 0.05°C). The primary data were recorded in digital form at a sample rate of 10 points per second.

3. TEMPERATURE CORRECTIONS

Quality checks of the observations were made to separate reliable and unreliable measurements. For example, the aluminum-coated thermistors indicated the coldest temperatures in some cases suggesting either, calibration errors; values of ϵ and γ were measured inaccurately; the coatings were not consistent from thermistor-to-thermistor; or the background radiative environment seen by the thermistors was such that the aluminum sensor actually measured colder values. If this last is correct, then a serious question arises whether a mean temperature correction will be adequate for all observations.

Attempts to structure ΔT vs solar angles into clusters bounded every 10 degrees showed only a small change in ΔT between clusters. After suitable smoothing the correction curves were fit into clusters with bounds of -7 to 15, 15 to 30, 30 to 60, and 60 to 90 degrees. The corrections are illustrated in Figure 1.

The corrections are noted to become smaller with decreasing pressure at levels above 30 hPa. This characteristic probably is caused by the very large long-wave emissivity that must dominate the other radiative error inputs at these altitudes.

Study of the ΔT in relation to solar angles showed that ΔT increases immediately (i.e., "jumps up") as soon as the sensor "sees" the sun, and decreases in the same manner at sunset. After the initial increase observed at sunrise, there is a gradual rise to a peak correction near midday, followed by a gradual fall when at sunset the radiative error rapidly decreases (i.e., "jumps-down") to the nighttime value. This relationship is shown qualitatively in the schematic given in Figure 2. Teweles and Finger (1960) in their original study of the day-night differences also suggested this effect.

5. GEOPOTENTIAL BIAS DISCUSSION

In order to avoid using the radiosonde's pressure-cell measurements corrected temperatures including corrections for sensor thermal lag were merged with corresponding one-minute radar heights and pressures were calculated, interpolating when necessary to obtain the standard constant-pressure levels. Radar height data were obtained as part of the WMO intercomparison held in 1985. Curve 2 in Figure 3 depicts the mean height difference for the 1700 UT observations between radar and radiosonde calculations using uncorrected temperatures. Agreement is excellent, and the small differences are believed caused by contribution of the pressure-cell error to the height error. Figure 5 shows similar information for the 2300 UT observations. Results obtained for the 1400 UT and 2000 UT observations are not shown.

Use of corrected temperatures and radar heights made available two sets of pressure-height data, one from radar heights using uncorrected temperatures and one from radar heights using corrected temperatures. Comparison of these two sets of pressure-heights provides the magnitude of the geopotential error resulting from the temperature error (i.e., uncorrected minus corrected). Curve 3 shown in Figure 3 illustrates the magnitude of this height error.

Figure 3 also gives the magnitude of the geopotential error arising from radiosonde calculations using uncorrected and corrected temperatures. These differences (curve 1) are larger than that for the radar pressure-height data (curve 3). A comparison was also made of the pressure-heights obtained from corrected temperatures with radar heights and from corrected temperatures using radiosonde pressures. If the temperature error is fully explained, this difference should also be small, however, a bias was discovered as shown in curve 4. This bias was first believed to be a result of insufficient temperature correction, however, simple logic dictates that smaller temperature corrections would be needed to remove this bias.

Geopotentials were derived from Finnish pressure measurements that were married to uncorrected and corrected US radiosonde temperatures. Curve 1 of Figure 4 represents the mean difference of geopotentials derived using uncorrected and corrected temperatures. Examination of the magnitude of the mean height difference vs pressure shows that they are approximately of the same magnitude as the differences obtained for the radar pressure-heights shown in curve 3 of Figure 3. Comparison of geopotentials calculated from corrected US radiosonde data with Finnish pressure results, curve 3 of Figure 4, shows that a height bias of about 9 meters exists. Since the same temperatures were used, this indicates a pressure sensor bias of about 0.05 percent. Height differences between radar pressure-heights and Finland pressure-heights using corrected temperatures is also shown in curve 2 of Figure 4.

A comparison of day-night height differences obtained using uncorrected US radiosonde temperatures is shown in Figure 5. The most obvious characteristic of this curve is that the daytime geopotentials are always higher than those at night. The magnitude of the day-night differences at 100 hPa is about 32 meters. The day-night difference at 10 hPa is about 125 meters.

After applying corrected temperatures to the radar data the daytime atmosphere was found to be higher than that of the nighttime between the surface and about 70 hPa, reaching a maximum difference of about 40 meters. At levels above 70 hPa, the daytime geopotentials became lower than nighttime, reaching a negative difference of about -42 meters. Further, geopotentials derived with US radiosonde corrected temperatures show the same day-night difference profile as seen with the radar data. Measurements made by the other WMO intercomparison participants were examined in a similar manner; the day-night differences from Australian and Indian data were close to those given by the US radiosonde before temperature corrections were applied. However, the day-night difference depicted by the Finnish instrument at levels below 30 hPa shows the same vertical gradients (except for a small bias) as that of the US radiosonde differences. At levels above about 30 hPa, the Finnish radiosonde day-night differences continue to increase while that from the US corrected radiosonde decreases.

Deviations from the mean height were used to examine geopotential behavior over time. Figure 6 shows that the daytime data are generally higher than the nighttime data. A clear division exists between the positive and negative values; i.e., positive values to the left and negative values to the right of a vertical line located near 1400 LST. After applying temperature corrections, shown in Figure 7, a much more dynamic pattern emerges showing little difference at levels below 200 hPa. This suggests that temperature corrections below that level may be too small to have a noticeable effect. The most significant change is seen at levels above 200 hPa.

6. SUMMARY AND CONCLUSIONS

The experimental observations showed evidence that occasionally the coldest measurements were provided by the aluminum thermistors. Investigation is necessary into whether this was due to sensor calibrations, instrumental problems, or was real. McMillin (private communication) argues that the environmental radiative background can greatly influence the magnitude, even the sign, of the correction. It is possible that winter-time conditions usually experienced in the US Great Plains region may influence the radiosonde temperature sensor measurements differently then when measurements are made over the oceanic region near Wallops. Future observations are being planned to take place at mid-continent locations during winter.

Various comparisons were made using the uncorrected and corrected US temperature measurements with radar heights, with US radiosonde measured pressures, and with pressure measurements of the Finnish radiosonde. Geopotential heights were improved when corrected temperatures were used. Radar vs radiosonde derived geopotentials suggest that differences remaining between these two techniques are due to pressure measurement errors. Furthermore, comparison of geopotentials derived with Finnish radiosonde pressures and US radiosonde pressures (both with US corrected temperatures) showed a mean difference of about 9 meters. (Although not discussed, the standard deviations of the US heights were larger.)

After application of temperature corrections the mean geopotential derived from radar heights and US radiosonde temperatures were lower during the day during the period of the intercomparison (Feb-Mar, 1985), than were the nighttime geopotentials, at levels above 70 hPa. The day-night differences were reduced to about 6 meters at 100 hPa and -14 meters at 10 hPa. When measurements obtained with the Finnish radiosonde and its sensors were compared they agreed with radar and corrected US radiosonde geopotentials up to about 30 hPa. However, the differences continued to increase above 30 hPa. Further effort is needed to determine the reason for the divergence observed.

The sample size should be increased over the next few months and should improve the confidence in the derived corrections. The larger data base should permit a more definitive separation of the corrections vs solar angles. It also will be necessary to reconfirm the laboratory measurements of the emissivities and absorptivities. Since the sensitivity of the heat-transfer equation to these parameters is critical it is important that any error, even small ones, be removed (Luers, personal communication).

Although this paper shows that mean corrections work well, it is important to realize that individual corrections may need to be derived for each observation. It is believed that the radiative environment background determines the sensor correction and therefore, the correction would differ given different environments. The test data set had available radar measurements that permitted comparison of mean heights as described in this report. It is planned to compare heights of individual observations with the radar heights on a minute-by-minute basis. Thus, corrections derived for each observation using techniques similar to the three thermistor method should produce geopotentials that agree with the radar heights. For future improvement of operational radiosonde network data the best approach might be to equip operational radiosondes with the three-thermistor technology and correct all observations on a real-time basis.

It also is suggested that a multi-thermistor "radiation diversity" technique such as used here would make a reasonably good reference radiosonde. The meteorological community has long-sought such as instrument and, although only temperature measurement technology has been discussed, other sensors could be adapted to this approach.

7. REFERENCES

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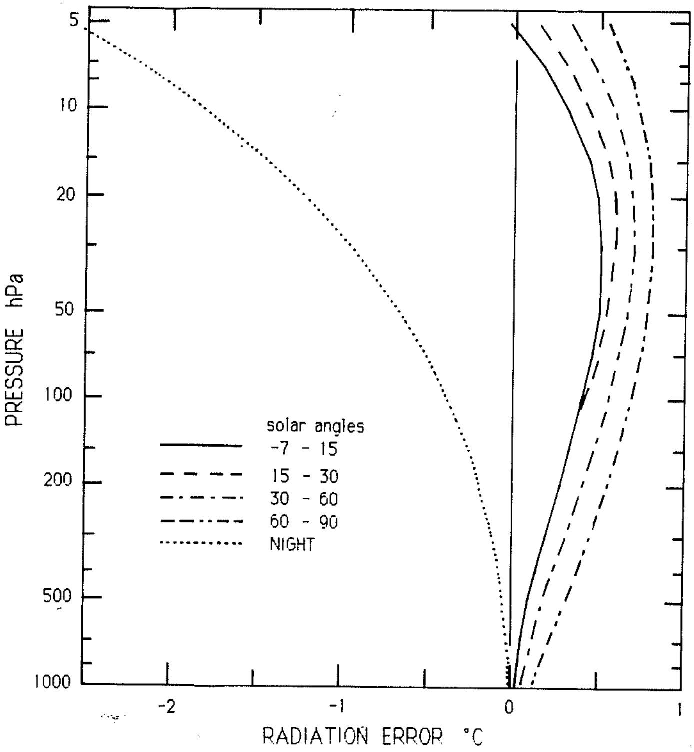

Fig. 1 Radiation errors (temperature corrections) vs solar elevation angles as a function of pressure.

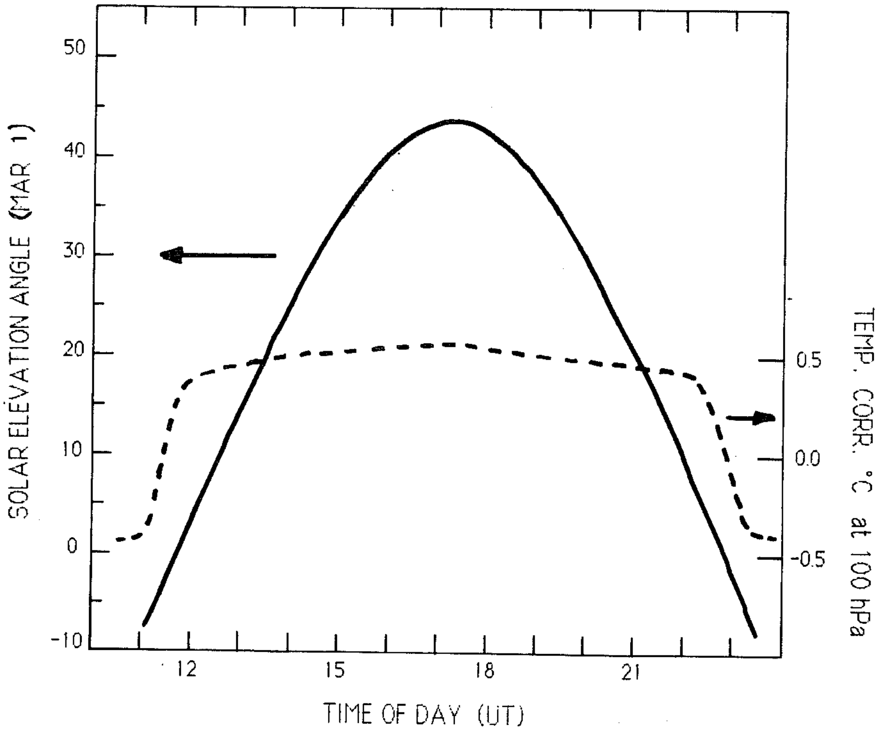

Fig. 2 Schematic of rate of change of temperature error with relation to solar elevation angle vs time of day.

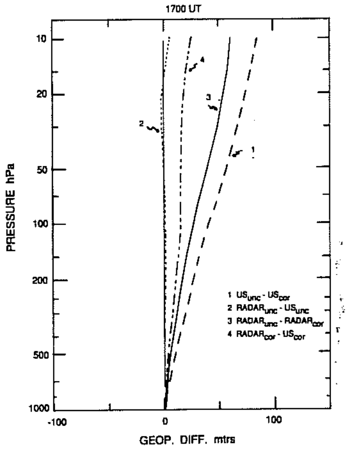

Fig 3 Improvement noted in geopotential as a result of applying temperature corrections.

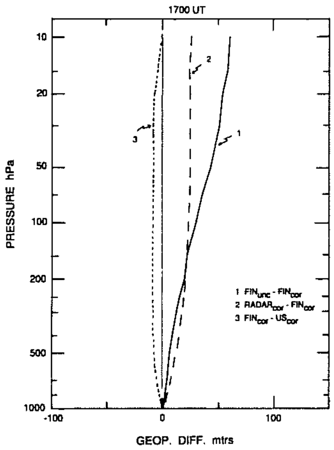

Fig. 4 Similar to Fig. 3 except US corrected temperatures were used with pressures from Finnish radiosonde.

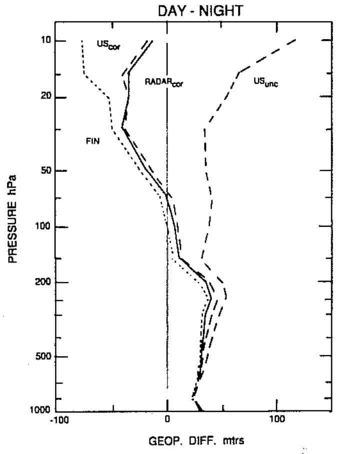

Fig. 5 Day-night differences in geopotential from uncorrected and corrected temperatures using US radiosonde and radar data, and Finnish radiosonde measurements.

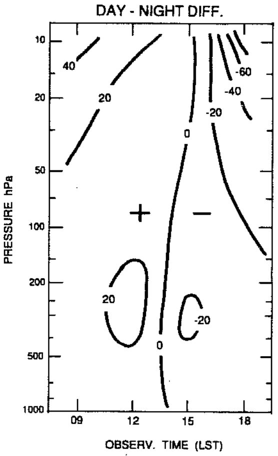

Fig. 6 Time-section of day-night differences for WMO intercomparison data using uncorrected US radiosonde temperatures.

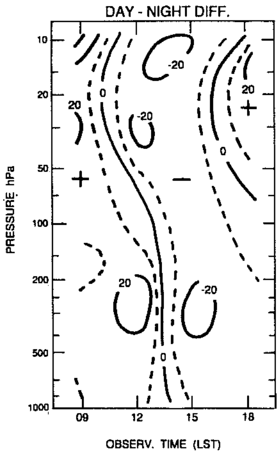

Fig. 7 Similar to Figure 6, except corrected US radiosonde temperatures.

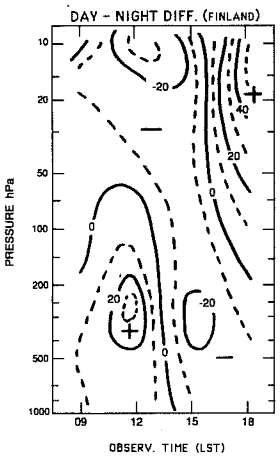

Fig. 8 Similar to Figure 6, except for Finnish radiosonde data from WMO intercomparison.