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**Scientific and Technical
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PRELIMINARY ESTIMATES OF RADIOSONDE THERMISTOR ERRORS

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INTRODUCTION

The United States standard radiosonde instrument (manufactured by VIZ Manufacturing Company) provides routine or synoptic measurements of pressure, temperature, relative humidity, and wind. These measurements are generally available between the earth's surface and 10 hPa (about 30 km). At the present time, temperature data are reported as actually measured, i.e., transmitted without corrections or adjustments of any kind. Johnson and McInturff [1] suggested in an earlier study that daytime reported temperatures can exceed nighttime temperatures by 2°C at high altitudes. According to McInturff *et al*. [2] these reported temperatures result in day-night differences larger than can be expected from tidal considerations alone. These studies resulted in the introduction of adjustments at various analysis centers that have helped reduce the differences reported by various countries. This suggests that radiosonde temperatures be corrected earlier than this, e.g., during the measurement phase.

Radiosonde measured temperatures contain random and bias errors composed of lag, short- and long-wave radiation, ground equipment anomalies, calibration errors and other instrumental errors, as discussed in Lenhard [3,4], Ballard and Rubio [5],

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Schmidlin et al. [6], Nestler [7], and others. Random errors are not discussed in this paper. Ballard and Rubio [5] noted that the daytime increase in reported temperature resulting from incident solar radiation could be as large as 1.8°C at 10 hPa when measured with the AN/AMT-4 radiosonde. Talbot [8] concluded that negligible radiation effects occur during the day on the white-coated rod thermistor, while at night a negative error of about 1.6°C occurs at 30 kilometers. The white-coated rod thermistor discussed by Talbot has been in use in Australia and the United States for over two decades. The thermistors referred to by Ballard and Rubio, and by Talbot are slightly different in diameter, nonetheless their measuring characteristics are very similar [9]. These authors report day-night measurement differences that agree in magnitude, but we are not aware of any efforts being made quantitatively to determine the contribution of radiation errors to these differences.

The greatest contribution to the bias error of the temperature measurement is believed to come from short- and long-wave radiation. Daniels [10] suggested that radiation errors may be determined and removed by using multiple sensors with coatings having different spectral response. During this same period Staffanson [11] proposed to NASA Wallops Flight Center a similar method for obtaining radiation corrections for bead thermistors used with meteorological rocketsondes. Staffanson proposed a radiation diversity technique, i.e., three thermistor coatings having different spectral characteristics that would respond differently to the same radiant energy. In this way the ambient temperature can be determined in an absolute manner by solving simultaneous equations, and thus obtain the radiation error. The University of Dayton Research Institute was requested to undertake a study of the radiation error of the rod thermistor using a similar procedure.

Coatings were applied to the rod thermistors after suitable laboratory tests were made to determine their emissivity and absorptivity values. The objective was to obtain coatings with sufficient difference in their spectral response to permit efficient and accurate solution of the simultaneous equations. White, black, and aluminum coatings were determined to provide the required spread in emissivity and absorptivity values. Initially, radiosondes were modified to allow two thermistors to be utilized on one radiosonde, and two radiosondes (four thermistors) were released on a single balloon. Later tests were made with four thermistors on a single instrument. The white-coated thermistors used in this study were standard, operational thermistors flown on the current U.S. (NWS) radiosonde. The preliminary results presented here were obtained from twenty-four balloon flights using a similar thermistor configuration.

There are plans to obtain more definitive results of the radiation error over the range of solar angles expected operationally. These results should be available in about one year.

PROCEDURE

Given known values of emissivity ε and solar absorptivity γ for each of the coated thermistors a standard form of the heat exchange equation may be solved to determine the thermistor error ΔT. Thus,

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

where H is the convective heat-transfer coefficient and R and S are the long-wave and incident radiant short-wave powers, respectively. The term A represents the thermistor surface area and σ the Stefan-Boltzmann constant.

To determine ε and γ, three 2.5-cm diameter disks were each treated with the white, black, and aluminum coatings selected in The University of Dayton Research Institute's laboratory and then subjected to spectral response measurements. Emissivity was determined between 2 and 20 μm using an infrared reflectometer. Solar absorptivity was determined between 0.25 and 2.5 μm by integrating the product of the measured spectral absorptivity and spectral irradiance for zero air mass. The assumption of zero air mass ensures more reliable and accurate results above 20 km where solar attenuation is smallest. Table 1 gives the values obtained for ε and γ for each coating.

TABLE 1.

ε and γ for various thermistor coatings

Coating	ε	γ
White (Standard VIZ)	0.86	0.12
Aluminum	0.22	0.31
Black	0.86	0.94

For thermistors flown at night the short-wave radiation term S in equation 1 is equal to 0. Thus, if two thermistors are selected such that one has low emissivity and the other high emissivity, their heat transfer equations may be solved simultaneously to determine the long-wave radiation error. The objective of using widely separated emissivity values is to improve the accuracy in which the error is determined. The thermistors meeting these conditions were the standard white-coated rod (T_w) and the aluminum-coated rod (T_a). Using the corresponding emissivity values for the white and aluminized thermistors from Table 1, ε_a and ε_w, respectively, the simultaneous equation,

$$\left.\begin{aligned} -H(\Delta T_w) - \sigma\varepsilon_w A T_w^4 + \varepsilon_w R &= 0 \\ -H(\Delta T_a) - \sigma\varepsilon_a A T_a^4 + \varepsilon_a R &= 0 \end{aligned}\right\} \qquad (2)$$

is solved to obtain ΔT_w by elimination of R. Thus,

$$\Delta T_w = T_w - \frac{\varepsilon_a T_w - \varepsilon_w T_a}{\varepsilon_a - \varepsilon_w} - \frac{\sigma A}{H} \cdot \frac{\varepsilon_a \varepsilon_w}{\varepsilon_a - \varepsilon_w} \cdot T_w^4 - T_a^4$$

is the correction (ΔT_w) to be applied to the standard thermistor as a function of pressure (height) for nighttime measurements. This value of ΔT_w may then be substituted into the first of equation 2 to derive R. As can be seen from equation 2 imprecise determination of ε_a or ε_w would result in large errors of ΔT_w.

Measurements during the daytime may be made by using the same thermistors if one has a high solar absorptivity and the other a low solar absorptivity (e.g., the white- and black-coated thermistors of Table 1). Since incident solar radiation is present, the heat transfer equations will each contain the four terms shown in equation 1. However, R, previously determined during nighttime tests, may be assumed to remain constant over the short term and used in these daytime tests. Thus,

$$\left.\begin{aligned} -H(\Delta T_w) - \sigma\varepsilon_w A T_w^4 + \varepsilon_w R + \gamma_w S &= 0 \\ -H(\Delta T_b) - \sigma\varepsilon_b A T_b^4 + \varepsilon_b R + \gamma_b S &= 0 \end{aligned}\right\} \qquad (3)$$

may be solved. Eliminating S results in

$$\Delta T_w = T_w - \frac{\gamma_b T_w - \gamma_w T_b}{\gamma_b - \gamma_w} + \frac{R}{H} \cdot \frac{\gamma_b \varepsilon_w - \gamma_w \varepsilon_b}{\gamma_b - \gamma_w} - \frac{\gamma A}{H} \cdot \frac{\gamma_b \varepsilon_w T_w^4 - \gamma_w \varepsilon_b T_b^4}{\gamma_b - \gamma_w} .$$

Again, ΔT_w for daytime measurements may be substituted in the first of equation 3, to estimate a value for the incident solar radiation S. Correct usage of equations 2 and 3 should result in internally consistent solutions for R, S, and ΔT_w.

It is more efficient to add a third equation using a third thermistor with emissivity and absorptivity values different from the two thermistors used to solve equation 3. In actual fact, the method will work even if only one of these factors is different. Thus, using the white, aluminum, and black thermistors allows the three equations to be solved for the environmental, or ambient temperature T_e. Thus,

$$T_e = \frac{\begin{vmatrix} (H-\sigma\varepsilon_w A T_w^3)T_w & \varepsilon_w & \gamma_w \\ (H-\sigma\varepsilon_a A T_a^3)T_a & \varepsilon_a & \gamma_a \\ (H-\sigma\varepsilon_b A T_b^3)T_b & \varepsilon_b & \gamma_b \end{vmatrix}}{\begin{vmatrix} H & \varepsilon_w & \gamma_w \\ H & \varepsilon_a & \gamma_a \\ H & \varepsilon_b & \gamma_b \end{vmatrix}} \qquad (4)$$

from which the correction for the standard white rod thermistor can be obtained, i.e., $\Delta T_w = T_w - T_e$. It should be noted that the single, three-thermistor daytime flight provides the same information as the day-night pair of two-thermistor flights.

In the above equations the value for the heat transfer coefficient H is missing and a further assumption must be made. Because the thermistors are mounted in a horizontal position during flight and are in cross-flow ventilation as the radiosonde rises, a relatively good approximation for H can be assumed that uses the Nusselt number and the calculated Reynolds number (which varies between 400 and 6 from the surface to 10 mbar). Full details will follow in a later report.

EXPERIMENTAL DATA

Sixteen radiosonde balloons were launched from Goddard Space Flight Center's Wallops Flight Facility, Virginia, during February, March, and September 1983; each balloon carried two radiosonde instruments and each instrument two thermistors. It was necessary to make two modifications to the radiosonde. The first was an adaptation to that part of the electronics circuit used to measure relative humidity to enable it to measure a second temperature and, the second was to rewire the pressure switch to alternate measurements between these two thermistors to the level of balloon burst. This latter was accomplished by tying the low reference and relative humidity switch segments together so that the second temperature would be transmitted whenever the baroswitch was on either a relative humidity or a low reference segment. Low reference leads were then tied to the high reference segments. Pre-release calibration was performed on each thermistor. Thus, four thermistors were flown with each balloon allowing a redundant measurement of at least one of the coatings (aluminum) during each flight. This permitted equation 4 to be solved twice increasing the confidence in the results.

Table 2 gives the combination of thermistor coatings that was flown with each radiosonde and balloon. The order of the thermistors shown for radiosondes numbers 1 and 2 was also the order of commutation. The emissivities ε of the black and white (standard) thermistors' coatings were found to be radiationally equivalent (Table 1), and, in the absence of incident solar radiation, the temperatures to be recorded from these thermistors were expected to be identical. In fact, the nighttime flights showed that temperatures obtained with these thermistors were virtually the same, verifying the long-wave radiational equivalence of these coatings. The aluminum coating with its smaller emissivity was expected to record a warmer temperature at night relative to the white- and black-coated thermistors, and, again the flight tests gave the expected results. Thus, the white/black coating combination provided no other information other than to verify their emissivity equivalence, while the combination of white/aluminum was used to calculate R and subsequently the error due to radiation of the white-coated thermistor during darkness.

The three-thermistor-coating arrangement (four thermistors) used during the daytime tests permitted equation 4 to uniquely determine S the solar flux, R the long-wave flux, as well as ΔT. The two-thermistor equation was solved for some daylight flights using the white/aluminum thermistor pairs and the nighttime-

TABLE 2

Thermistor Coatings Used on the Flight Tests and the Matchup Combinations.

Flight No.	Date	Time (GMT)	Radiosonde Instrument	
			1	2
1	1983 Feb. 16	2342	white/black	black/white
2	Feb. 17	0151	white/aluminum	aluminum/white
3	Feb. 17	1441	white/black	black/white
4	Feb. 17	1755	black/white	white/aluminum
5	Feb. 24	2300	white/white	black/black
6	Feb. 28	1428	white/black	aluminum/white
7	Mar. 8	2307	white/aluminum	aluminum/white
8	Mar. 8	1834	white/black	black/white
9	Sept. 6	1723	aluminum/white	white/black
10	Sept. 7	1321	aluminum/white	white/black
11	Sept. 8	1329	white/black	black/white
12	Sept. 8	1727	white/black	aluminum/white
13	Sept. 9	1317	white/black	aluminum/white
14	Sept. 9	1714	white/black	aluminum/white
15	Sept. 13	2317	white/aluminum	aluminum/white
16	Sept. 14	0153	white/aluminum	aluminum/white
17	1985 Aug. 5	1416	See Note	
18	Aug. 6	1405	" "	
19	1986 Jan. 8	1528	" "	
20	Jan. 22	1441	" "	
21	Jan. 22	2108	" "	
22	Jan. 23	1429	" "	
23	Jan. 23	1730	" "	
24	Jan. 23	2101	" "	

Note: A single radiosonde with a white, a black, and two aluminum thermistors and electronic commutation was flown.

derived value for R. These results, using equation 3, were compared against the results of equation 4 and were found to agree. The daytime radiation errors however were obtained using equation 4.

Figure 1 is an example of daytime profiles obtained on September 6, 1983, at 1723 GMT (Flight No. 9) characterizing the measurements obtained from white-, aluminum-, and black-coated thermistors. Data from profiles such as these were obtained at one-minute intervals for use in equation 4. The resulting temperature error profile exhibited variability in the vertical. It is not clear what is causing this noise but it could be a result of using the simple experimental design. This variability might be expected at lower altitudes from short-wave scattering, reflection from clouds and from surface features but, more likely, is an artifact resulting from manually reading the measurements from two radiosondes and two sets of ground systems. The influence of these variations in determining the temperature error can be seen in Figure 2. In spite of the presence of the noise, the

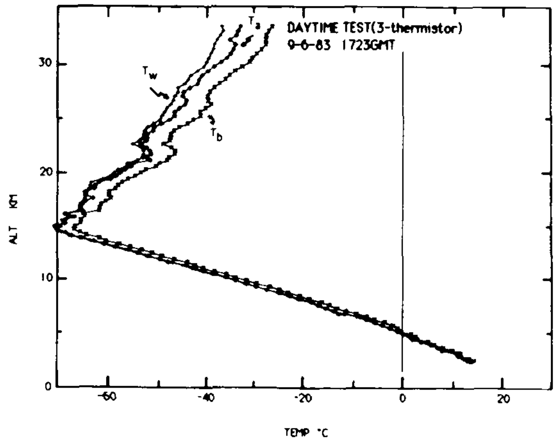

Fig. 1. Temperature profiles measured using white (standard) T_w, black T_b, and aluminum T_a thermistors flown on the same balloon during daytime on September 6, 1983.

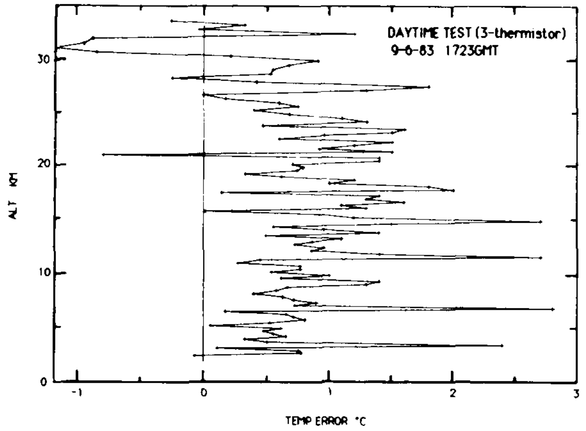

Fig. 2. Temperature error associated with the white-coated (standard) thermistor resulting from long- and short-wave radiation. The large variations may be from the reading of measurements of two radiosondes on two ground stations.

mean shape of the error profile is obvious. Above 25 km during the day the white thermistor apparently cools due to the long-wave radiation away from the thermistor. This cooling is more dominant than the heat input due to incident solar radiation. This characteristic of the US rod thermistor was recently demonstrated in the temperature comparisons obtained during the World Meteorological Organization's International Radiosonde Intercomparison [12].

Nighttime radiational errors based on the 2-equation mode (eq. 2) using the white (standard) and aluminized thermistors are similar in shape to the daytime results and also contain similar variation. The major difference found is that nighttime values are lower than daytime values by an approximately constant amount; of course, solar radiation is absent. The vertical variability observed in daytime shown in Figure 2 is also present in the nighttime measurements suggesting that the noise possibly results from the instrumental and data reduction arrangement and not necessarily the atmosphere, since solar radiation is absent.

Eight additional balloons were flown during September 1985, and January and February 1986. The two flown in September 1985 contained an electronic switch in place of the typical baroswitch; heights and pressures were obtained by radar. These two instruments each contained four thermistors and replaced the earlier configuration requiring two radiosondes containing two thermistors each. A further adaptation was incorporated in the January and February 1986 flights which employed an eight-channel electronic commutator and the pressure baroswitch as well. These recently flown radiosondes each contained a white, a black, and two aluminum thermistors on a single frame. The two aluminum thermistors permitted redundant calculation of T_e using equation 4. In future tests, this same configuration will be employed. The additional tests are necessary to confirm these preliminary results and the extent that radiation errors are dependent on solar angles, season, latitude, and possibly even the vertical temperature structure. Once fully tested, this radiosonde may also qualify as a reference standard for temperature measurements, if so desired.

Results of the 24 balloon flights were averaged to obtain an estimate of daytime and nighttime errors and are shown in Figure 3. These errors also should be considered as the corrections needing to be applied to individual temperature measurements made at the time of observation or at analysis centers. The test data showed differences in the radiation error at different times and in different months.

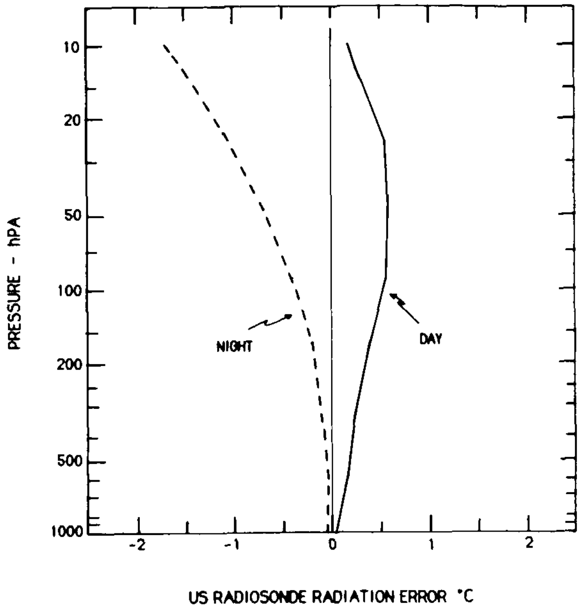

Fig. 3. Preliminary estimate of radiation error of the white-coated (standard) thermistor used with the US radiosonde. The shape of the daytime radiation error at levels above 100 hPa is considered to arise because of the dominant influence of the sensor's emissivity.

The daytime curve is interesting because it indicates that the radiation error of the white thermistor is approximately -0.6°C between 20-100 hPa (i.e., the thermistor indicates a reading higher than ambient and therefore requires a negative adjustment). The daytime error becomes smaller at lower pressures and indications are that it becomes negative at higher altitudes. On the other hand, the nighttime radiation error is negative from the surface to the 10 hPa level where the error is shown to be -1.8°C. The difference between the day and night errors is, on average, about 1°C near the 100 hPa level; this difference is comparable to that suggested by McInturff et al. [2]. Because of the smaller sample size near 10 hPa (due to early balloon burst) nighttime errors while acceptable, must be confirmed. In conducting the daytime tests, solar angles were confined between approximately 20-50°, data between solar angles of approximately -5° to 75° and higher, are needed.

Results of the radiosonde observations obtained in the WMO International Radiosonde Intercomparison [12, 13] are expected to provide adjustment of profiles between the various instruments. These same data can also provide some insight into the radiation errors being discussed. The observation sample size was 25 pairs each during day and night.

Average temperature differences between the Vaisala and Viz instruments are shown in Figure 4a. The Vaisala temperature sensor has a 0.7°C correction added at 10 hPa during darkness [14] intended to compensate for long-wave cooling of the sensor. Figure 4a suggests that, given the Vaisala correction is proper, the US sensor is reading approximately 3°C colder. If the corrections added to the Vaisala temperature measurements are removed to provide a basically 'raw' temperature, the US instrument still indicates colder values. During the daytime, the mean difference between Vaisala and Viz temperatures are opposite to the nighttime difference, i.e., the Viz rod-thermistor indicates a warmer measurement than Vaisala. For the time of these daytime observations, the solar angle was approximately 40°. The Vaisala correction [14] during the day is -1.5° to -2.5°C between 50 hPa and 10 hPa, a function of solar angle. The US instrument indicates increasingly warmer temperatures to about the 20-30 hPa level at which point the difference decreases, until at the 10 hPa level the Vaisala and Viz sensors differ by about 0.2°C. If the corrections added to the Vaisala temperatures were removed, the US instrument would read colder than Vaisala. If the Vaisala corrections as applied to the intercomparison data set are adequate, then the corrections to the US temperatures suggested by this radiation error study, if applied to the radiosonde temperatures gathered during the International Intercomparison, would reduce the differences between the Viz and Vaisala measurements.

This reduction in differences, or better agreement between Viz and Vaisala data, is shown in Figure 4b. The temperatures obtained with the US radiosondes were corrected according to the values shown in Figure 3 and new mean differences were calculated between the Viz and Vaisala measurements. Clearly, a dramatic change is evident. The major changes resulting from the temperature corrections are the good agreement in day and night values from the surface to about 70 hPa, and the decidedly much smaller differences to 10 hPa.

The change in temperature differences shown between Figures 4a and 4b is quite large between the surface and about 20 hPa. This change is in a direction that also reduces the difference in calculated geopotential between the two radiosondes. At pressures between 10-20 hPa, the nighttime (2300 UT) temperature difference is still relatively large. This could be a result of the small nighttime sample size or the Vaisala temperature measurements may be overcorrected. Additional studies are in progress that indicate day-night temperature differences and day-night geopotential differences are considerably smaller. These additional studies also explore the consequence of ignoring sensor thermal lag corrections.

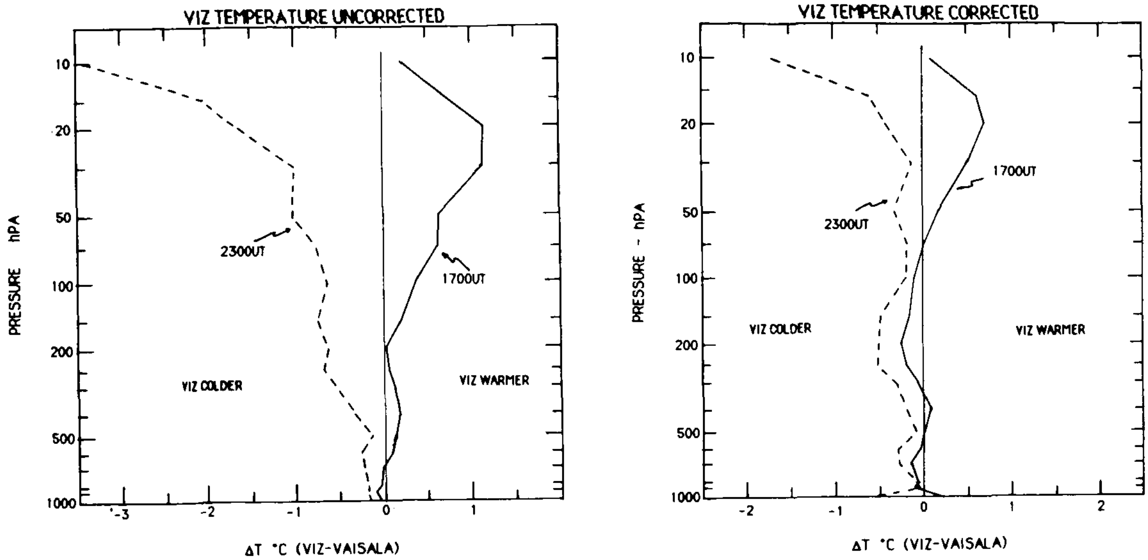

Fig. 4. Data set obtained from WMO International Radiosonde Intercomparison, Phase II. a) Day and night mean temperature differences between US (VIZ) and Finnish (VAISALA) radiosondes for uncorrected VIZ temperature measurements. b) Same as for a) after VIZ temperature measurement corrections were applied.

SUMMARY AND FUTURE PLANS

Measurements using radiosondes equipped with up to four thermistors having coatings that respond differently to emissivities and absorptivities were made in an attempt to derive an estimate of the radiation influence on the US radiosonde's temperature measurement. Preliminary results, based on 24 balloon flights, indicate that the daytime radiation error of the standard rod thermistor is positive up to altitudes near 20 hPa and then decreases in magnitude as the instrument rises higher into the atmosphere. The nighttime long-wave error appears to follow the same pattern (curve) as the daytime correction but is negative in magnitude over the range of altitudes studied. An approximately similar magnitude and direction for these corrections to the US instrument were confirmed from the many radiosonde comparisons made in the recent WMO International Radiosonde Intercomparison [12,13]. These results reinforce the need to improve the US radiosonde temperature measurement by taking into consideration the long- and short-wave radiation influences. Corrections to the present rod-thermistors seem to be the most efficient solution for operational, routine use of the radiosonde. Such an approach was taken with the US radiosonde data set obtained from WMO International Radiosonde Intercomparison held at Wallops during February and March 1985. The result of applying the temperature corrections required to compensate for the radiation error reduces the difference between day and night temperatures considerably and into better agreement with McInturff et al. [2].

The technique developed to investigate radiation errors also may be used to directly derive an absolute temperature. This approach would be more satisfactory than applying corrections since the affect of solar angles is explicitly accounted for. The complexity of the software required and the additional cost for the instrument however, would overshadow its use for typical operational purposes.

Because of the limited sample of measurements presently available, and the unwieldy complexity of using two instruments and two ground systems, improved methods were considered and tested. The baroswitch used in the radiosonde to control the switching of the various parameters was replaced with a rapid sequence electronic switch that permits using four (or more) thermistors on the same instrument. The rapid switching and a single instrument coupled to digital recording techniques will permit a larger number of data sets to be gathered more efficiently and subsequently enhance the analysis required to confirm these preliminary estimates of the radiation errors. Plans to launch a large number of instruments at as many solar angles as possible are being formulated. The results should permit a family of corrections to be derived that would be applicable for different solar angles (i.e., latitude and time of day). Because long-wave radiation upwelling and reflections from the earth are different at various locations it may also be necessary to perform sensitivity tests to determine the magnitude and the influence of radiation during different seasons, cloud conditions, and for different terrain.

New results as they are obtained will be made available as soon as possible.

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16. Abstract

It has been long realized that radiosonde temperature measurements are subject to errors, not the least of which is the effect of long- and short-wave radiation. Methods of adjusting the daytime temperatures to a nighttime equivalent temperature were developed a number of years ago, and are used by some analysis centers. Other than providing consistent observations for analysis this procedure does not provide a true correction. The literature discusses the problem of radiosonde temperature errors but it is not apparent what effort, if any, has been taken to quantify these errors. In order to quantify this radiation error, radiosondes containing multiple thermistors with different coatings were flown at Goddard Space Flight Center/Wallops Flight Facility. The coatings employed had different spectral characteristics and, therefore, different absorption and emissivity properties. Discrimination of the recorded temperatures enabled day and night correction values to be determined for the US standard white-coated rod thermistor. The correction magnitudes are given and a comparison of US measured temperatures before and after correction are compared with temperatures measured with the Vaisala radiosonde. The US and Vaisala radiosonde data are from the recently completed WMO International Radiosonde Intercomparison held at Wallops. The corrections are in the proper direction, day and night, and reduce day-night temperature differences to less than 0.5°C between surface and 30 hPa. The present uncorrected temperatures used with the Viz radiosonde have day-night differences that exceed 1°C at levels below 90 hPa. Additional measurements are planned to confirm these preliminary results and determine the solar elevation angle effect on the corrections. The technique used to obtain the corrections may also be used to recover a true 'absolute' value and might be considered a valuable contribution to the meteorological community for use as a reference instrument.

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