

A Method for the Use of Satellite Retrievals as a Transfer Standard to Determine Systematic Radiosonde Errors

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ABSTRACT

This paper presents the results of a feasibility study to evaluate a method for the use of satellite measurements as a transfer standard to determine temperature biases between radiosonde types. The method was evaluated on a sample of satellite observations that were paired with nighttime radiosonde observations. Only nighttime cases were used in this study in order to avoid the additional complication of heating of the radiosonde by solar radiation; however, the method should be equally valid in daylight. Radiances were calculated from radiosonde temperature profiles and compared to radiances for the same location as measured from the satellite. With the use of radiosonde-satellite pairs for two different radiosonde types, the satellite radiances were used to remove radiance differences due to atmospheric temperature differences from the radiosonde radiances. This step allowed radiosondes at different locations to be compared. Biases between the U.S. civilian instrument and the Väisälä instrument were derived and compared with published values; the results of the new method were found to be consistent with results obtained from direct comparisons of radiosonde instruments when measurements were made under similar atmospheric conditions. However, the direct measurements were made in a limited range of atmospheric conditions, whereas the satellite measurements were made under a wide range of atmospheric conditions. Results based on the indirect satellite comparisons showed substantial variation in the biases obtained under different atmospheric conditions. This variation is consistent with differences in temperature errors that are the result of differences in the radiation balance between the instrument and its surroundings. The results demonstrated the ability of the method to provide estimates of radiosonde biases. They also show that radiosondes are subject to substantial errors owing to longwave radiation and other sources. These errors are not only large (0–2 K), but also highly variable.

1. Introduction

This study started as an attempt to use satellite measurements to remove biases between different radiosonde types. The biases need to be taken into account when satellite measurements are compared to radiosondes. If they are not, then the biases between radiosonde types contribute to the root-mean-squared (rms) differences between satellites and radiosondes. When these differences are used to create retrieval coefficients for satellite data, the biases cause errors in the coefficients. The radiosonde biases also cause problems when the rms differences between radiosonde and satellite temperature profiles are used to evaluate the accuracies

of satellite retrievals. Errors due to infrared cooling at night were examined first because they were thought to be less variable than the errors due to solar radiation. It soon became obvious that the infrared cooling error is very dependent on the particular profile.

Temperature profiles derived from radiosondes are subject to errors from several sources. These include errors due to the thermal lag of the temperature sensor as well as errors due to differences in energy between the incoming and outgoing radiation. In the past, attempts have been made to determine these errors from special launches, from closely located radiosondes, and from day-night differences. Since satellites measure temperatures over the globe with a single instrument, they offer the possibility of routinely monitoring biases between various radiosonde types on a global scale, as well as the possibility of comparing individual stations with others of the same type. However, satellite retrievals are also subject to errors. In order to use satellite

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data to determine radiosonde biases, these satellite errors must be removed.

Because some of the largest errors in satellite retrievals are caused by the lack of vertical resolution, it is convenient to derive radiosonde biases in terms of differences in radiance temperatures for the satellite channels, rather than radiosonde temperatures. This is done by integrating the radiative transfer equation using the temperatures provided by the radiosondes, then converting from radiances to brightness temperatures in K, $BT(\nu)$, using the inverse of the Planck relationship

$$BT(\nu) = 1.438833 * \nu / \ln[1 + 1.191066 \times 10^{-5} \nu^3 / R(\nu)] \quad (1)$$

where the quantity $R(\nu)$ denotes the measured radiance in units of $\text{mW}/(\text{m}^2 \text{ sr cm}^{-1})$ at wavenumber ν . The bias between radiosondes, when expressed in terms of radiance temperatures, takes the form

$$\Delta BT(\nu, A, B) = [BTc(\nu, A) - BTc(\nu, B)] - [BTm(\nu, A) - BTm(\nu, B)] \quad (2)$$

where $\Delta BT(\nu, A, B)$ is the difference in radiosonde bias between radiosonde types "A" and "B" averaged over the weighting function of the channel centered at wavenumber ν , $BTc(\nu, A)$ is the radiance temperature calculated at wavenumber ν from measurements from radiosonde type A, $BTc(\nu, B)$ is the same quantity from radiosonde type B, $BTm(\nu, A)$ is the clear radiance temperature measured by the satellite for radiosonde type A, and $BTm(\nu, B)$ is the same quantity for type B. In theory, the quantities on the right-hand side of Eq. (2) can refer to individual measurements, but individual measurements are subject to random noise that can be reduced by averaging. In practice, they refer to averages over a sample. Although radiances in the infrared are affected by clouds, the brightness temperatures, $BTm(\nu, A)$ and $BTm(\nu, B)$, used in Eq. (2) were derived from clear column radiances. These clear radiances were extracted from a mixture of cloudy and clear measurements using the method (McMillin and Dean 1982) routinely used in the operational processing of satellite data. More details about Eq. (2) are given in section 2.

The use of satellite measurements as a transfer standard is unique because it allows comparisons of radiosondes to be made in different atmospheric conditions. This is in contrast to conventional evaluations of radiosondes where the instruments being compared are subject to similar atmospheric conditions. Because of the similarity in measurement conditions, errors that are dependent on the atmospheric situation do not show up in most comparisons. For this reason, radiosondes are often perceived to have errors that are independent of location and atmospheric situation. It will be shown that longwave radiation errors are subject to substantial variations due to differences in the ra-

diation environment when the atmospheric conditions at the sites of two radiosondes differ.

2. Approach

The radiance, $R(\nu)$, measured by a satellite is given by

$$R(\nu) = B(T(sf), \nu)\tau(sf, \nu) + \int_{\tau(sf, \nu)}^1 B(T(l), \nu)d\tau(\nu) \quad (3)$$

where $B(T(sf), \nu)$ is the radiance emitted by a blackbody at the temperature of the surface, $T(sf)$, at wavenumber ν ; $\tau(sf, \nu)$ is transmittance for the atmosphere between the satellite and the surface; $B(T(l), \nu)$ is the radiance emitted by a blackbody at the temperature of the layer l denoted by $T(l)$ at wavenumber ν ; and $d\tau(\nu)$ is the transmittance for the layer. When the atmosphere is divided into layers, a calculated radiance, $Rc(\nu)$, can be determined from

$$Rc(\nu) = B(T(sf), \nu)\tau(sf, \nu) + \sum_l B(T(l), \nu)\Delta T(l, \nu). \quad (4)$$

Equation (1) can be used to convert either $R(\nu)$ or $Rc(\nu)$ to radiance temperature.

Radiosondes give values of $T(l)$ for only some of the contributions to the radiation sensed by the satellite. Some of the satellite channels receive significant portions of their signal from the ground, while others receive significant portions of the signal from layers above the heights reached by radiosondes. To complete the calculation, estimates of these additional temperatures must be made. Since the radiosondes are collocated with soundings, values of $B(T(sf), \nu)$ and of $T(l)$ are available from the satellite retrieval. The value of $B(T(sf), \nu)$ is used for the surface. The method used for the upper atmosphere is more complicated. At the point where the radiosonde stops, the radiosonde and the satellite may measure different temperatures. Above the radiosonde, several assumptions about the difference between the radiosonde and the satellite retrieval are possible. We adjusted the satellite retrieval to agree with the radiosonde at the top level reported by the radiosonde, and allowed the adjustment to decrease with height to a value of zero at 0.2 hPa. This assumption has the effect of forcing the difference between the radiosonde and the satellite to zero for channels which respond to levels above the top of the radiosonde report. It also has the effect of forcing the difference between two radiosondes to zero in the upper atmosphere.

For two radiosondes, the difference in calculated brightness temperature,

$$\Delta BTc(\nu, A, B) = [BTc(\nu, A) - BTc(\nu, B)], \quad (5)$$

can be determined. When comparisons are made between pairs of radiosondes measuring the same atmospheric conditions, the radiosonde bias is given by

$\Delta BTc(\nu, A, B)$. However, the radiosondes can come from different locations with different atmospheric conditions. When they do, the differences between radiosonde profiles reflect true differences in atmospheric temperature as well as radiosonde biases. The difference in atmospheric temperature can be removed by using the radiance temperature measured by the satellite, $\Delta BTm(\nu, A, B)$, as given by

$$\Delta BTm(\nu, A, B) = [BTm(\nu, A) - BTm(\nu, B)]. \quad (6)$$

Since $\Delta BTm(\nu, A, B)$ is made with a single instrument, it contains no instrumental bias but does contain the difference in atmospheric temperature. Subtracting Eq. (6) from Eq. (5) cancels the differences in temperature profiles and results in Eq. (2). The differences in radiance temperature given by (2) represent the average biases between the two radiosondes when the biases are averaged over the layers represented by the various channels. When (2) is used to compare radiosondes that are geographically separated, radiosonde errors that are dependent on atmospheric conditions are included in the bias, and the resulting bias patterns can be quite different from those that are obtained when the radiosondes are taken in pairs in the same atmospheric conditions. Limiting the radiosonde pairs to those cases for which the value of $\Delta BTm(\nu, A, B)$ is below some acceptable value produces a more conventional bias pattern.

Although Eq. (2) gives the radiosonde bias in terms of radiance temperatures, a large segment of the meteorological community thinks in terms of in situ air temperatures. Differences in radiance temperature can be converted to differences in air temperature. We can use the regression approach for making satellite retrievals to convert from radiance temperature biases to air temperature biases. The regression solution takes the form

$$\Delta T(l) = \sum_{\nu} \beta(\nu, l) \Delta BTm(\nu) \quad (7)$$

where $\Delta T(l)$ is the temperature difference from the mean value of the regression sample at layer l , and $\beta(\nu, l)$ is the regression coefficient for the channel at wave-number ν for level l . The $\Delta BTm(\nu)$ is the difference between the vector of measured radiance temperatures for a profile and the mean vector of radiance temperatures averaged over all radiosonde locations in the regression sample, and ν takes on the values associated with the centers of specific sounding channels. The measured values in Eq. (7) can be replaced by calculated values, provided a constant is added. This constant is required because the values of $\beta(\nu, l)$ are derived from measured, not calculated values. The constant is the average difference between the right-hand side of Eq. (7) as determined using the measured brightness temperatures and as determined using the calculated brightness temperatures when the average is taken over the dependent dataset. When Eq. (7) is used to calculate

values of $\Delta T(l)$ for two radiosonde types, the constant is added to both. When the results for the two radiosonde types are subtracted, the constants cancel because we use a universal set of coefficients, and the constant as well as the mean values are independent of the radiosonde types. Because the constants cancel, it is possible to combine Eqs. (6) and (7) to get

$$\Delta Tm(l, A, B) = \sum_{\nu} \beta(\nu, l) \Delta BTm(\nu, A, B) \quad (8)$$

where $\Delta Tm(l, A, B)$ is the temperature difference between radiosonde types A and B as derived from measured radiances. An equation similar to Eq. (8) can also be written for the calculated radiances by replacing $\Delta Tm(l, A, B)$ with $\Delta Tc(l, A, B)$ and $\Delta BTm(\nu, A, B)$ with $\Delta BTc(\nu, A, B)$. When Eq. (8) for the measured radiances is subtracted from (8) for the calculated radiances, the difference between $\Delta BTc(\nu, A, B)$ and $\Delta BTm(\nu, A, B)$ is given by $\Delta BT(\nu, A, B)$ as given by Eq. (2) and the difference can be written as

$$\Delta T(l, A, B) = \sum_{\nu} \beta(\nu, l) \Delta BT(\nu, A, B) \quad (9)$$

where $\Delta T(l, A, B)$ is the difference in temperature bias at level l between radiosonde types A and B.

The most obvious way to use satellite measurements is to use actual retrievals rather than Eq. (9). In the operational retrievals, the means are computed for fixed latitude zones and the mean for an individual retrieval is interpolated from the two nearest zonal means using the procedure described by Phillips et al. (1979). This approach allows the retrievals from different radiosonde types to have different means. Because the satellite retrievals retain much of the fine scale structure present in the first guess, radiosonde biases calculated by using actual retrievals as a transfer standard contain artificial structure. This artificial fine structure is the result of differences between the fine structures of the two means used for the satellite retrievals associated with the two samples.

For the foregoing reasons, we have used a single set of regression coefficients and a single mean for both radiosonde types. For a given latitude zone and time period, satellite radiances and corresponding radiosonde temperatures for all available instruments were used to generate a single set of regression coefficients. All radiosondes types were used to minimize correlations that could result from the use of a single radiosonde type. Values of $\Delta BT(\nu, A, B)$ used in Eq. (9) were obtained by averaging all the radiosonde-satellite matches for one radiosonde type in the sample and subtracting the average for a second radiosonde type.

Even though individual radiosondes may experience large changes in temperature when passing through clouds and inversions, radiosonde biases for large samples are relatively smooth functions of height. Because of the smooth nature of the bias, an alternative approach is to assume that the radiance temperature bias

for each channel represents the mean bias for the levels measured by that channel. This approach avoids doubts about the method that results from concerns about the accuracy of satellite retrievals because it involves only the integration of the radiative transfer equation. As a check on the retrieval, radiance temperature biases were generated for channels 5, 6, 15 and 23 which form an average representing the middle of the troposphere. Biases were generated for two cases: the first between the Väisälä and the VIZ radiosonde; the second between the VIZ radiosondes in the early half of the time period and the VIZ radiosondes in the second half of the time period. Both the time periods and the results are shown in Table 1. All the comparisons between the VIZ radiosondes are less than 0.25 K, which is consistent with expected changes in atmospheric conditions between the first and last halves of the period. Comparisons between the two radiosondes show biases of about 1.0 K. Retrievals should show similar biases for the middle troposphere.

As an additional check, retrievals were generated for two samples of VIZ instruments. The samples were collected between 30° and 60°N during the period starting 3 December, 1986 and ending 30 December 1986. Fifty cases were collected in the first half of the period and 71 cases in the second half. Although there is a slight time difference between the periods, the mean profiles shown in Fig. 1 are very similar and the expected bias is near zero. If the retrieval process introduced significant error into the process, the bias between the two samples would differ significantly from zero. However, the results shown in Fig. 2 show a bias that is very near zero except near the ground where biases due the diurnal temperature cycle are expected, between 100 and 200 hPa where a slight positive bias is observed, and in the upper atmosphere where Fig. 1 indicates that a bias would be expected.

3. Bias study

To use and evaluate the method, radiosondes have been collected from November 1985 to February 1986. These collocations are restricted to time differences of

TABLE 1. Middle tropospheric bias between radiosondes for the time periods and latitudes listed VIZ(p2) - VIZ(p1) denotes the difference for the VIZ instrument between the first and last half of the time period. Differences between the Väisälä and the VIZ are significantly greater than differences between two samples of the VIZ instrument.

Time period (mo/d/yr)	Latitude zone	Radiosondes	Bias
01/28/87-02/24/87	60°-90°N	Väisälä - VIZ	0.92 K
12/03/86-12/30/86	60°-90°N	Väisälä - VIZ	1.16 K
01/14/87-02/10/87	30°-60°N	Väisälä - VIZ	0.99 K
01/14/87-02/10/87	30°-60°N	VIZ(p2) - VIZ(p1)	0.11 K
11/29/86-12/16/86	30°-60°N	VIZ(p2) - VIZ(p1)	0.21 K
12/03/86-12/30/86	30°-60°N	VIZ(p2) - VIZ(p1)	0.18 K

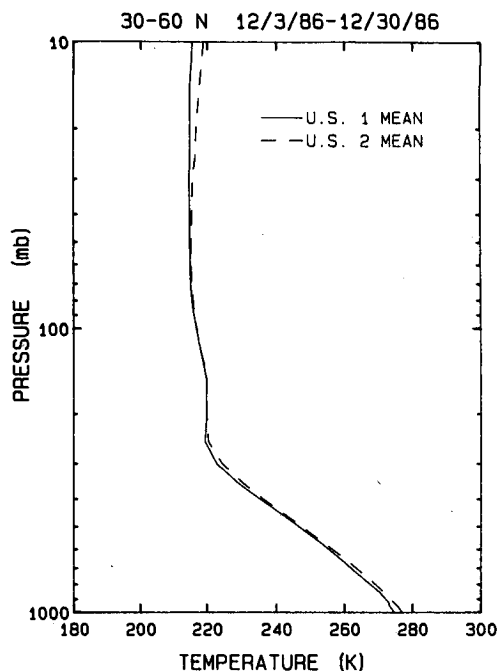


FIG. 1. Mean profiles for two midlatitude winter samples of the VIZ radiosonde.

six hours or less and a space difference inversely related to the radiosonde density and never exceeds 3° of latitude. Radiosonde types were associated with stations using identifications on a computer file maintained by

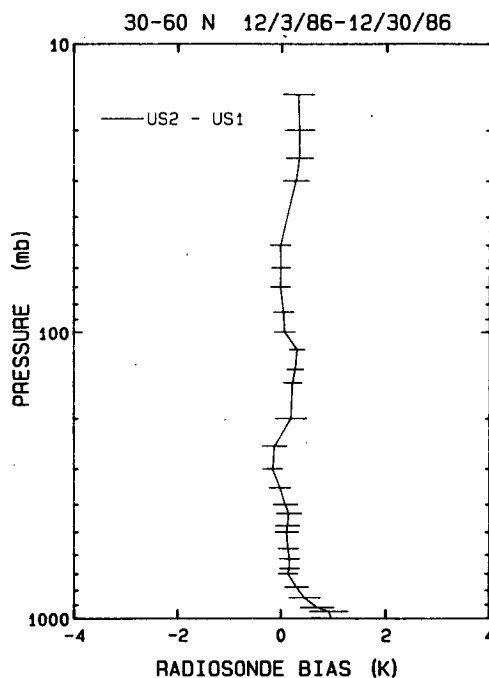


FIG. 2. Relative bias between two midlatitude winter samples of the VIZ radiosonde.

NOAA's National Meteorological Center. In the Northern Hemisphere, the U.S. radiosonde was arbitrarily picked as a standard and other types were compared against it. Owing to the highly variable nature of the solar radiation effects, this initial feasibility study was limited to nighttime soundings. It was also limited to radiosonde matches available from the TIROS Operational Vertical Sounder (TOVS) processing.

For a given latitude zone and time period, all radiosonde and satellite collocations were collected and used to generate regression coefficients. For each radiosonde type, the mean bias was calculated along with the uncertainty of the bias, which is calculated from the relation

$$\epsilon B = \{[\sigma(A)]^2/(ns(A) - 1) + [\sigma(B)]^2/(ns(B) - 1)\}^{-2} \quad (10)$$

where ϵB is the uncertainty of the bias; $\sigma(A)$ and $\sigma(B)$ are the standard deviations of $\Delta T(l, A)$ and $\Delta T(l, B)$ about their mean values. The $ns(A)$ and $ns(B)$ are the sample sizes for radiosonde types A and B; and values $\Delta T(l, A)$ are given by

$$\Delta T(l, A) = \sum \beta(v, l) * [BTc(v, A) - (BTm(v, A))]. \quad (11)$$

A similar equation holds for B. Because of the limited sample sizes in this feasibility study, only the Väisälä manufactured in Finland had a large enough sample for comparison with the VIZ instrument. However, the TOVS processing system can be changed to increase sample sizes of other radiosonde types in the future.

4. Radiosonde errors

Radiosonde measurements are not error free. Error sources for the nighttime observations in this study include thermal lag effects, longwave radiation effects, pressure errors, and analysis procedures. The error due to time lag can be significant for the U.S. civilian instrument. Williams and Acheson (1976) estimate the time constant of this instrument to be near 5 sec at 1000 hPa and to range from 10.6 sec (Sanders et al. 1975) to 14.5 sec (Badgley 1957) at 100 hPa. According to the British Meteorological Office (1961), the ascension rate of a typical radiosonde is 7 m s^{-1} near 100 hPa. The result of these values is that the temperature sensed by the radiosonde represents a level 75 to 100 m below the radiosonde when the radiosonde is at 100 hPa. At a given level, the effect has a strong atmospheric dependence, being largest in the lower atmosphere for profiles with steep lapse rates and smallest for atmospheres with isothermal layers. Near 100 hPa the error can reach 0.7 to 0.9 K depending on the lapse rate and time constant. In normal lapse conditions, the time lag causes radiosonde measurements to be too warm in the troposphere and too cool in the stratosphere.

Radiation errors are caused by the difference between energy absorbed by the instrument from incoming radiation, and energy emitted from the instrument as outgoing radiation. In a typical situation at night, the outgoing longwave radiation exceeds the incoming radiation, so the temperature sensor is cooled below the ambient air temperature until the rate of energy loss by radiation is balanced by a gain in energy due to conduction and convection. The outgoing radiation is relatively simple to evaluate, being proportional to the fourth power of the temperature of the temperature sensor. The incoming radiation is more complex, being affected by radiation reflected and emitted by other components of the instrument, the balloon, nearby clouds, the sky, and the earth. Schmidlin et al. (1986) report errors due to longwave radiation for a series of special radiosonde launches at their Wallops Island facility. They report a cooling of 0.5 K at 100 hPa and 1.75 K at 10 hPa. Ney et al. (1961) report a heating of 0.25 K at 100 hPa and a cooling of 2.0 K at 10 hPa for an August profile. Gergen (1957) demonstrates the seasonal nature of the longwave radiation error. In a related paper, Schmidlin et al. (1986) report an infrared emissivity of 0.86 for the white coating used for the VIZ radiosonde. With an infrared emissivity of 0.86, the VIZ instrument is quite sensitive to the infrared radiation balance.

It is convenient to divide the incoming radiation into two components: the upward component from the earth below, and the downward component which is largely affected by the amount of moisture above the instrument, since moisture has strong absorbing bands across the infrared region. In a moist tropical atmosphere, the downward component is greater than it is in a polar atmosphere with less infrared emission by less water vapor.

The upward component is determined by the temperature of the surface, the lower atmosphere, and of any lower clouds. In a clear tropical atmosphere, the upward component from the warmer surface and lower atmosphere is also greater than the upward component from a cold polar atmosphere. At the upper levels, the upward component of the incoming radiation is larger in a tropical atmosphere than in a polar one and the net cooling of the radiosonde due to radiation is less than in a typical polar case. These effects are illustrated by Gergen (1957) and by Figs. 3 through 6. Figures 3 and 5 show the cooling rates in degrees K per day for the two atmospheres from McClatchey et al. (1971) that are shown in Figs. 4 and 6. The cooling rates near the surface are highly dependent on the surface to air temperature difference, which was zero for the cases shown.

In the construction of these curves, the cooling rate for a layer was plotted at the average pressure for the layer. These curves have the same general shape as the profiles of radiation difference between the sensor and its surroundings, but there are differences in the speed

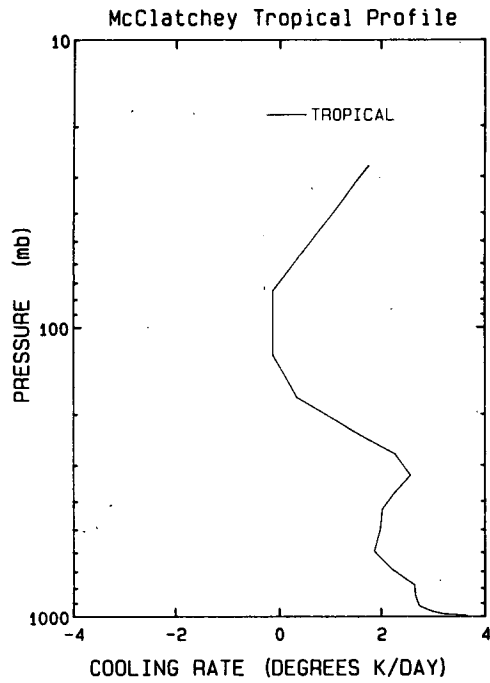


FIG. 3. Cooling rate in degrees K per day for a tropical profile.

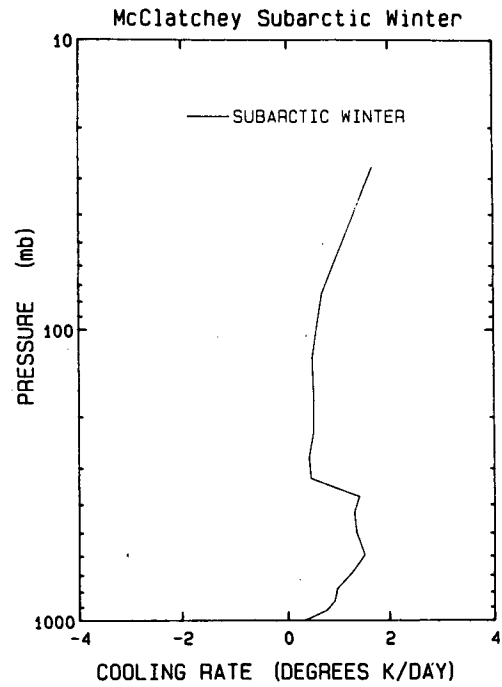


FIG. 5. Cooling rate in degrees K per day for an arctic winter profile.

of the response and the relative weighting of the different regions of the infrared spectrum because the sensor is far more opaque to radiation. The major difference is that a thermistor absorbs more radiation in the atmospheric windows where the atmosphere is

nearly transparent. As a result, the radiation from the ground has a larger effect on a thermistor than it does on air at the same level. In spite of this difference, the

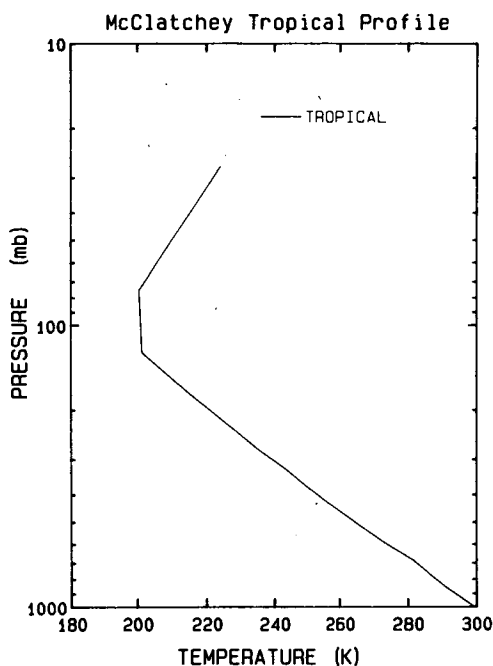


FIG. 4. Temperature as a function of pressure for a tropical profile.

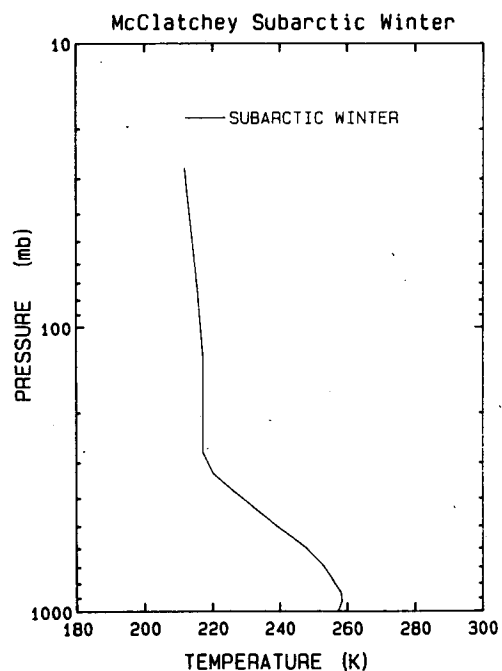


FIG. 6. Temperature as a function of pressure for an arctic winter profile.

curves of cooling rate help illustrate the effects of the temperature profile on the longwave radiation balance. For the tropical atmosphere shown in Fig. 3, the cooling rate actually becomes negative near the tropopause as was also demonstrated by Gergen (1957) for midlatitude summer profiles. A radiosonde at the same levels in the profile shown in Fig. 4 would be subject to even more heating because it would absorb more of the longwave radiation emitted by the warm ground. For the subarctic winter cases shown in Fig. 5, the area of minimum cooling occurs at a lower pressure corresponding to the lower tropopause. It also differs from the tropical case in that cooling occurs at all levels. Certainly a thermistor exposed to these different radiation environments would experience differences in cooling tendencies similar to those experienced by the air at the same level. The largest cooling occurs when the instrument is warmest relative to the brightness temperature of the incoming radiation. Perhaps the most extreme cooling occurs when an instrument is in a warm stratospheric layer over a cold surface and lower atmosphere. This condition is commonly found in high latitudes in the spring. Another situation where strong cooling occurs is above 100 hPa in a tropical atmosphere over clouds at 100 hPa. In this situation, the upward radiation corresponds to the temperature of the cold tropical tropopause rather than the warm ground.

Radiosondes are also subject to errors, such as errors in the pressure sensor, which can depend on instrument type and for which the satellite provides no information. Some of these are discussed in Schmidlin and Finger (1987). Although some errors are random and can be expected to cancel in a large sample, others can affect the bias. Examples are the use of different models of the same radiosonde, the use of different analysis and correction methods, and differences in the heights reached at different stations.

Some general statements can be made about the expected nature of radiosonde errors in different atmospheric conditions. Near the ground, the temperature depression required to balance a given radiation loss is small due to the large air density. In the tropics, longwave radiation effects are not only relatively small due to the large amounts of water vapor, but radiation errors oppose errors due to thermal lag. Thus, as a general rule, radiosonde biases caused by longwave radiation should be minimal near the ground and in tropical atmospheres, and they should be larger at higher elevations and in polar atmospheres. Errors are minimized when the radiosonde is below clouds and enhanced when the radiosonde is above clouds. Since errors due to both longwave radiation, time lag, and possibly some of the other errors are strongly dependent on the profile shape, it should be expected that biases between radiosonde profiles taken in different types of atmospheres will contain an error component due to the difference in profile shape in addition to the bias

between two radiosondes subject to the same atmospheric conditions. It should also be obvious that these additional effects are not present in comparisons of two collocated radiosondes.

5. Results

Bias patterns of temperature as a function of pressure for the VIZ instrument, used on U.S. civilian radiosondes and in other countries, and the Väisälä instrument, manufactured in Finland, are shown in Figs. 7, 9, 11, 13 and 15 along with error bars indicating the values of ϵB from Eq. (10) while Figs. 8, 10, 12, 14 and 16 show the associated mean profiles. While we have elected to use the VIZ instrument as the reference in our figures, it should be noted that this instrument uses a white coating that reflects visible radiation but has an infrared emissivity of 0.86, while the Väisälä instrument uses a metallic coating with a much smaller infrared emissivity. Schmidlin et al. (1986) report an infrared emissivity of .22 for the aluminum paint used for the Väisälä instrument. As a result of the difference in infrared emissivity, the Väisälä instrument has smaller radiation errors, and the difference between the two instruments shows as a positive value. Figure 7 shows the bias between the U.S. civilian (VIZ) and the Finnish (Väisälä) instruments for the period 27 November 1985–24 December 1985. Figure 9, for the next time period of 8 January–4 February 1986, shows a very different pattern. Explanations for the shift may be seen in Figs. (8 and 10) which show the mean profiles for the two periods. In the first period, (Fig. 8), the mean profiles for the two instruments are similar, as is always the case for comparison studies when the radiosondes are launched from a single site. When the temperature profiles for two radiosondes differ, biases derived for the radiosondes contain the additional error factor that is reflected in the bias pattern in Fig. 9. In contrast to Fig. 8, Fig. 10 shows the mean temperatures in the areas covered by the U.S. instruments are 10 to 20 K warmer in the stratosphere than the areas covered by the Finnish instruments. This means that when the U.S. instruments are in the stratosphere, they are radiating more energy to their surroundings. At the same time, the troposphere is colder for the U.S. instruments, so the energy coming from below to balance the loss is less. Either effect by itself leads to greater radiative cooling for the U.S. instrument. Where the difference in temperature profiles is large, the normal bias between the Finnish and U.S. instruments is amplified by the addition of the atmospheric component of the radiative cooling on the U.S. instrument.

To substantiate the reasoning given in the last paragraph, the radiosonde data for the second period were screened. In the first sample, the Finnish radiosondes that agreed most closely with U.S. mean profile were selected. These results are shown in Figs. 11 and 12. The bias in Fig. 11 agrees well with both the bias shown

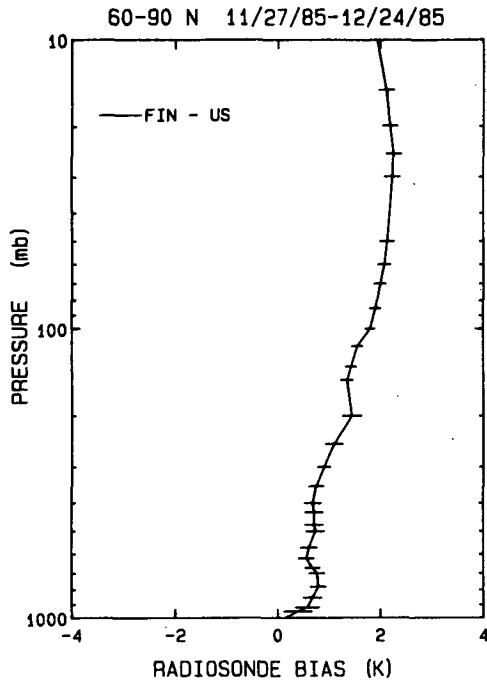


FIG. 7. Relative bias between the U.S. civilian and Finnish Väisälä instruments for high latitude early winter as determined with the use of satellite measurements.

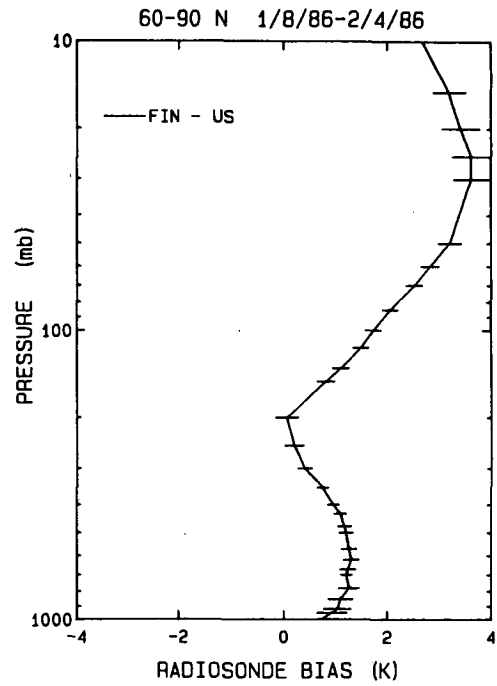


FIG. 9. Relative bias between the U.S. civilian and Finnish Väisälä instruments for high latitude late winter profiles as determined with the use of satellite measurements.

in Fig. 7 as well as the independent results shown in Fig. 17. Figure 12 shows that the biases are similar when the mean profiles are similar to each other even

though the mean profiles in Fig. 12 differ from those shown in Fig. 8. In the second sample, the Finnish radiosondes that differed most from the U.S. sondes

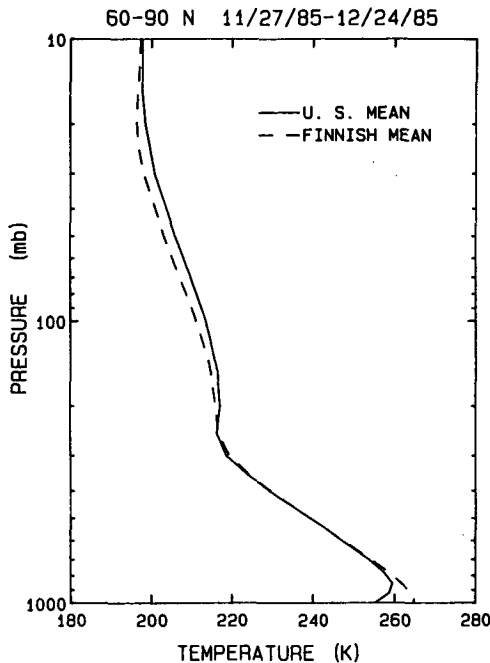


FIG. 8. Mean profiles for the U.S. civilian and Finnish Väisälä instruments for high latitude early winter.

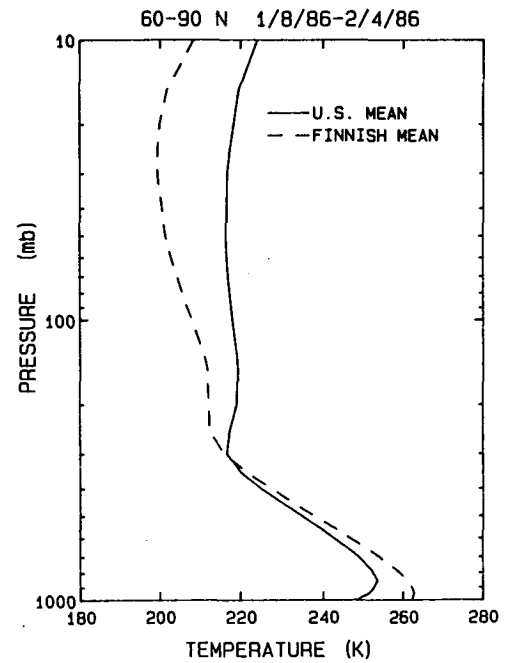


FIG. 10. Mean profiles for the U.S. civilian and Finnish Väisälä instruments for high latitude late winter.

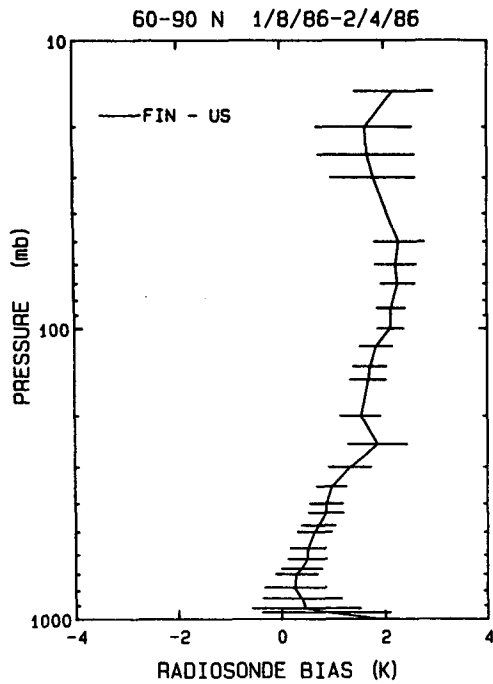


FIG. 11. Relative bias between the U.S. civilian and Finnish Väisälä instruments for matched high latitude late winter profiles as determined with the use of satellite measurements.

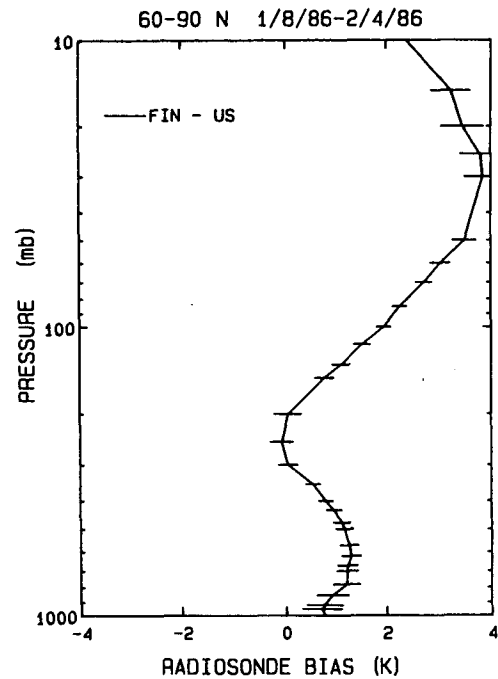


FIG. 13. Relative bias between the U.S. civilian and Finnish Väisälä instruments for mismatched high latitude late winter profiles as determined with the use of satellite measurements.

were selected and these results are shown in Figs. 13 and 14. These show patterns similar to those shown in Figs. 9 and 10 in that the bias is enhanced in a region

where the mean profiles differ. The bias profile shown in Fig. 13 agrees with the pattern expected as a result of Figs. 3 and 5. Near the surface where other effects

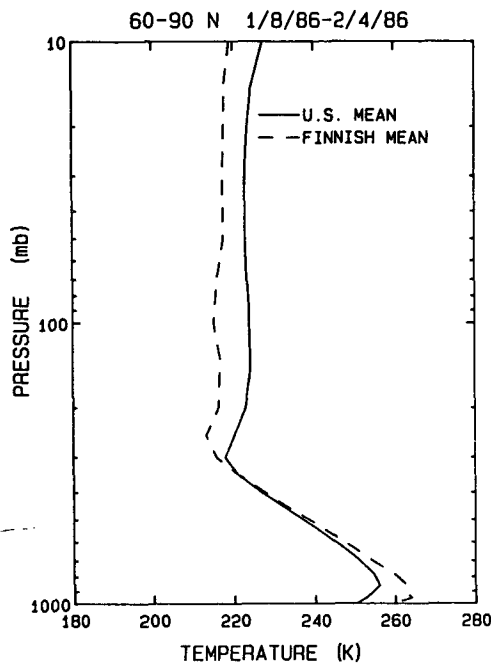


FIG. 12. Mean profiles for the U.S. civilian and Finnish Väisälä instruments for matched high latitude late winter.

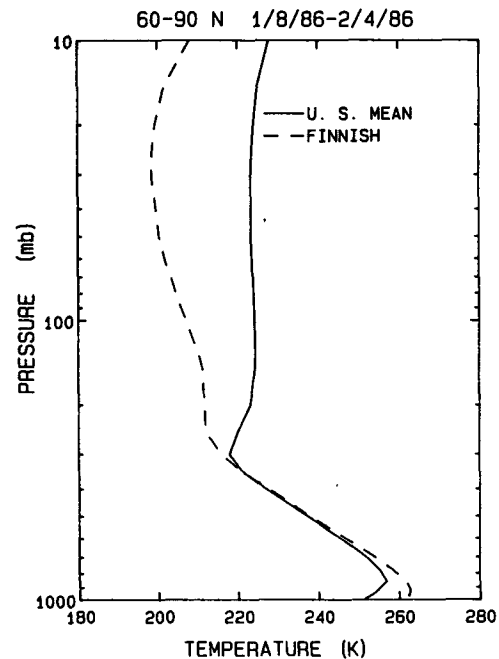


FIG. 14. Mean profiles for the U.S. civilian and Finnish Väisälä instruments for mismatched high latitude late winter.

are important, the error tends to be small; it increases in the middle of the troposphere, decreases near the tropopause where the radiation emitted by the thermistor is a minimum, increases in the stratosphere, and decreases at the upper levels owing to the constraints placed on the solution. The results shown in Figs. 7 and 9 are also consistent with the bias estimates shown in Table 1. From 850 to 300 hPa, both figures show errors that agree with the value of 1.0 K shown in the table.

Figures 15 and 16 show the bias pattern and mean profiles for the latitude zone between 30°S and 30°N. As expected, the biases are small in this region because radiation effects and sensor lag for a radiosonde in a tropical profile nearly balance. Figure 15 also illustrates some limitations of the method. At the top of the atmosphere, the sample is small compared to 100 hPa because a large proportion of the radiosondes stop before the 10 hPa level is reached. As mentioned earlier, the missing levels are filled in with the satellite retrieval. This has the effect of forcing the difference between radiosondes to zero at some height, an effect that is evident in the other bias patterns in addition to that in Fig. 15. Because of this effect, the bias patterns are questionable at the upper levels, as indicated in Fig. 15 by the larger error bars above 30 hPa, and the tendency for the difference to approach zero above 30 hPa. Near the surface, some radiosondes are at high elevations and the diurnal temperature cycle becomes a factor. One or both of these effects are evident in the

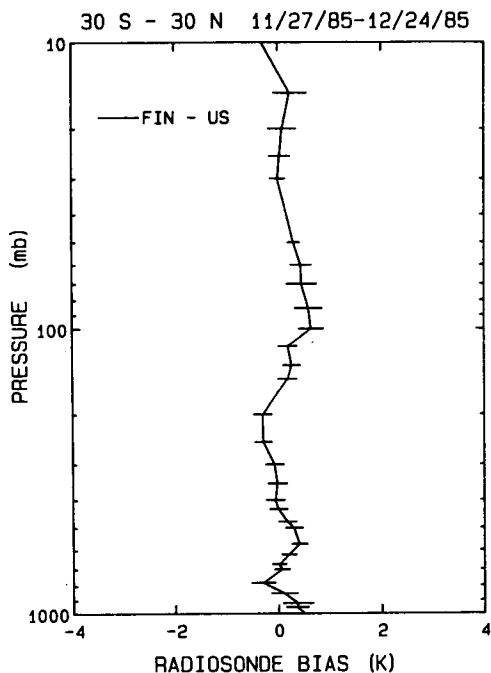


FIG. 15. Relative bias between the U.S. civilian and Finnish Väisälä instruments for tropical profiles as determined with the use of satellite measurements.

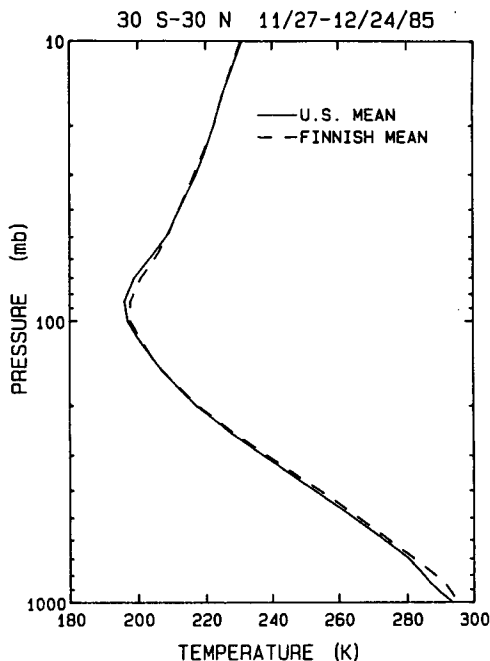


FIG. 16. Mean profiles for the U.S. civilian and Finnish Väisälä instruments for the tropics.

difference in mean profiles shown in Fig. 16 and in the bias shown in Fig. 15.

Results from an independent comparison by Schmidlin and Finger (1987) are shown in Fig. 17. Their results are consistent with the more direct estimates of radiosonde error given by Schmidlin et al. (1986). Their results support the patterns shown in Figs. 7 and 11. However the biases shown in Figs. 7 and 11 are somewhat larger than those shown in Fig. 17, which is consistent with the trend shown by Figs. 7 and 15. The pattern shown in Fig. 17 (0.7 K at 100 hPa) lies between the values shown for the tropical case with minimal cooling of the radiosonde sensor (0.5 K at 100 hPa) shown in Fig. 15 and the polar case with maximum cooling of the sensor (1.9 K at 100 hPa) shown in Fig. 7. In Fig. 17, the measurements for phase I took place at Beaufort Park, UK, during June–July 1984, and the measurements for phase II took place at Wallops, Virginia, during February–March 1985. Although the difference between phase I and phase II is small, it is consistent with the pattern in that the observations for the atmospheres expected to be closer to the conditions of Fig. 7 (phase II) showed the larger bias pattern. Studies similar to those of phase I or phase II under the atmospheric conditions of either Fig. 7 or Fig. 11 would be more appropriate for verifying the patterns shown by the satellite results.

4. Discussion of results

Although it has been commonly assumed that radiosonde errors due to radiation are significant in day-

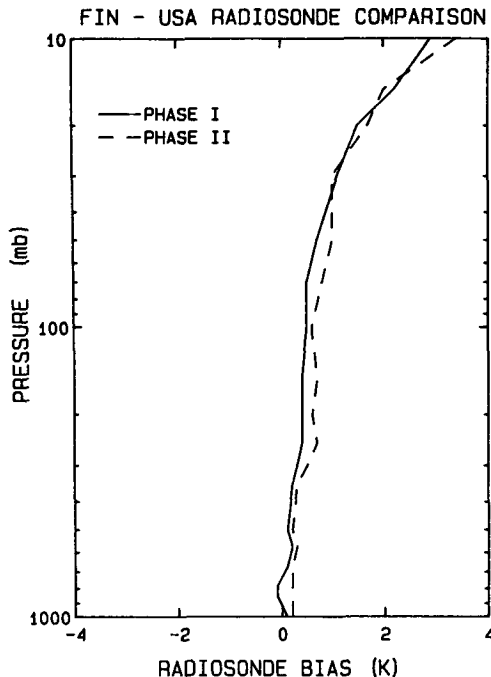


FIG. 17. Relative bias between the U.S. civilian and Finnish Väisälä instruments as determined by direct comparisons of radiosondes on the same balloon (from Schmidlin et al. 1986).

light (McInturff et al. 1979) little attention has been given to the possibility of variable radiation corrections at night. Radiosondes with low emissivities in the infrared (<0.1) are relatively insensitive to infrared radiation. However, radiosondes with white coatings have relatively large (>0.8) emissivities in the infrared. Results independent of our study show that the longwave radiation error at 100 hPa for the VIZ instrument ranges from a slight warming for a clear tropical atmosphere to 0.5 K for a typical midlatitude case. These independent results predict that the difference between an instrument with a large infrared emissivity and one with a low infrared emissivity should be small in the tropics and larger at higher latitudes. Our results show that the typical tropospheric difference between two radiosonde types differs very little in the tropics to near 1 K in high latitude winter soundings. Both radiosondes are subject to errors caused by several effects including the cooling effect of long wave radiation. If one assumes the error is proportional to the infrared emissivity, the error in the VIZ radiosonde would be slightly larger than the difference between the two instruments. If the error due to longwave radiation changes from a polar to a tropical case, it must also change between a clear and a cloudy case. When the radiosonde is below the cloud, the upward radiation is balanced by downward radiation from clouds rather than cold space; when the radiosonde is above the clouds, the upward radiation from the warm surface is replaced by upward radiation from the cold clouds. Based on our results, we estimate

that differences between clear and cloudy areas due to this one component could easily reach 0.5 K. This value is also consistent with a recent study by Schmidlin et al. (1986) that shows the U.S. radiosonde is about 0.5 K too cold at night and about 0.5 K too warm in daylight.

Satellite measurements show rms differences of 1.5 to 2.0 K (McMillin et al. 1983) when compared to radiosondes. In a region where the difference between satellite and radiosonde measurements is 1.5 K, a day to night difference of 1.0 K in radiosonde measurements, when added to a typical precision, means that the radiosonde errors account for a significant portion of the rms difference in satellite-radiosonde comparisons.

Schlatter (1981) presented a comparison of satellite and radiosonde measurements in an attempt to assess the error in satellite soundings. He showed mean differences between retrieved and analyzed mean virtual temperatures that changed by about 1.0 K between clear and cloudy cases. In that study no allowance was made for differences in radiosonde errors between clear and cloudy cases. Although there are valid reasons to suspect that satellite retrievals differ in clear and cloudy areas, our results indicate that radiosonde errors are also large enough to have been a significant factor in the differences in radiosonde versus satellite bias that was reported. In addition, locally coherent radiosonde errors of 0.5 K and greater can cause inconsistencies when satellite and radiosonde reports are both used as input to a forecast model.

If radiosonde errors were independent of the temperature profile, samples at two different locations could simply be collected and averaged. Since they are not, it is necessary to match profiles at the two locations to produce "conventional" bias patterns between radiosonde types. This can be done by selecting only those profiles for which the atmospheric conditions match. While this selection procedure would limit the sample size, reasonable samples can still be obtained.

However, it is doubtful that the conventional bias patterns are desired. If the bias between two radiosonde types contains differences caused by differences in the atmospheric conditions in which they are used, the validity of a comparison in which the atmospheric difference is eliminated becomes questionable. The validity of applying the measured biases to atmospheric conditions different from those in which the measurement was made also becomes questionable. The results of this feasibility study show that the procedure can provide a useful tool for evaluating radiosonde differences. One use of this technique is to compare day and night differences for a given radiosonde type to determine parameters to be used for deriving radiation corrections. Most other approaches (for example, McInturff et al. 1979) have difficulty distinguishing between errors due to solar radiation, errors due to longwave radiation, and true diurnal temperature

changes. The fact that radiation errors are a function of atmospheric conditions has a positive result. It offers the possibility of solving for the absolute radiation effect of radiosondes as well as the bias between two or more types. All that is required is a model that can express the error for a given radiosonde as a function of a small number of parameters.

6. Summary

The feasibility of using satellite measurements as a transfer standard to determine systematic errors in radiosondes has been evaluated. Between 850 and 30 hPa, the method provides estimates of biases between radiosonde types that are consistent with values determined from direct comparisons of radiosondes. The comparisons presented here differ from previous comparisons in that radiosondes in different atmospheric conditions can be compared. As a result of this ability, the method has provided new insight about the nature of radiosonde error due to longwave radiation, particularly about its variability with season and latitude. The bias patterns produced by the method are largest when the temperature difference between the radiosonde and its surroundings, and thus between the outgoing and incoming longwave radiation, are large. Although variations in the biases between radiosonde types due to solar heating are widely recognized, this study indicates that longwave radiation effects are also variable, and can cause errors in the range of 1 to 2 K for some radiosondes. Radiosonde errors of this magnitude have important implications about the interpretation of satellite retrieval minus radiosonde temperature differences. They certainly have implications for attempts to match calculated and observed radiances. Since these errors are undoubtedly affected by clouds, they contribute to the local coherency in satellite minus radiosonde temperature difference that is commonly attributed entirely to errors in satellite temperature retrievals. The results of this study, as well as other recent evaluations of radiosonde accuracy, indicate that much of the current difficulty in matching satellite and radiosonde observations is due to radiosonde rather than satellite errors.

Although the method described here can be used to make average corrections for average conditions, the results demonstrate effects that can have significant variations on a local scale, especially in the presence of clouds. Some of this variability can be taken into account by one of several methods, including the one used to correct some Väisälä data. Because of the atmospheric dependence of the cooling, we are developing procedures to calculate directly the radiation striking a radiosonde to estimate the error. These pro-

cedures should allow corrections to be made for the large scale atmospheric variations. However, it would be extremely difficult to correct for all the local conditions, such as changes in cloud cover, without some direct measurement of their effects. One way the VIZ instrument could be improved is to change to coating with a low emissivity in both the infrared and visible regions. The best way to eliminate these errors would be to use a radiosonde that is not affected by radiation errors. One approach would be to use a thermistor with a very low infrared emissivity as recommended by Ney et al. (1961). A second approach would be to fly a radiosonde with several temperature sensors with different coatings to measure the radiation error. This is the approach used by Schmidlin et al. (1986).

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