Temperature Corrections for the VIZ and Vaisala Radiosondes

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(Manuscript received 18 February 1994, in final form 20 August 1994)

ABSTRACT

The National Weather Service VIZ radiosonde and the Vaisala RS-80 radiosondes are used worldwide to obtain upper-air measurements of atmospheric temperature and moisture. The temperature measured by each sensor is not equal to the atmospheric temperature due to solar and infrared irradiation of the sensor, heat conduction to the sensor from its attachment points, and radiation emitted by the sensor. Presently, only the RS-80 radiosonde applies corrections to the sensor temperature to compensate for these heating sources, and this correction is only considered to be a function of solar angle and pressure.

Temperature correction models VIZCOR (VIZ sonde) and VAICOR (Vaisala RS-80 sonde) have been developed that derive the atmospheric temperature from the sensor temperature, taking into account all significant environmental processes that influence the heat transfer to the sensor. These models have been validated by comparing their corrected profiles with atmospheric temperature profiles derived from the NASA multithermistor radiosonde. All three radiosondes were flown on the same balloon during the potential reference radiosonde intercomparison. Excellent agreement has been found between all profiles up to an altitude of 30 km. Since the significant error sources in the VIZCOR, VAICOR, and multithermistor techniques are largely independent, agreement between all profiles implies that the corrected sensor profiles are providing an unbiased estimate of the true atmospheric temperature.

1. Background

Current numerical climate models predict strong surface warming in the polar regions and marked cooling in the stratosphere when the model atmospheric CO_2 concentration is doubled. Verification or refutation of these model results requires the existence of reliable long-term data records. The National Climatic Data Center and the All-Union Research Institute of Hydro Meteorological Information of Russia have initiated a joint project, Comprehensive Aerological Reference Data Set (CARDS). The goal of the CARDS project is to produce an upper-air dataset based on radiosonde and pibal observations, suitable for evaluating climate models and detecting global change. The CARDS project is producing a long-term (1960–90) daily dataset of concomitant upper-air and surface synoptic observations, using the entire global collection of upper-air and collocated surface observations.

CARDS consists of three databases. First, there is a "raw" database consisting of all the upper-air reports in the form the data are received (no corrections applied); second, there is a quality-controlled database. The third database is the one in which detected biases in the data have been flagged or removed from the quality-controlled database.

Systematic errors or biases occur in upper-air data as a result of radiational heating of the sensor, a change in the data reduction method, or a change in the radiosonde instrument that affects the sensor measurements. The magnitude of the error in the upper-air temperatures has been estimated to be 1°–3°C with current radiosondes. Errors of this magnitude are larger than any century-scale predicted climatic change for most areas. Therefore, these errors must be identified and removed from the climatic dataset.

Several methods are being used to detect systematic radiosonde errors: analysis of station histories, mathematical–physical models of radiosonde sensors, and statistical techniques. Unfortunately, station histories are, at best, incomplete and in many cases nonexistent.

A keystone of the CARDS research program is the development of methods to identify systematic errors (biases) in the upper-air data using statistical techniques and to develop temperature correction models for the most widely used radiosondes of the 1960–90 period.

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The systematic error due to radiational, convective, and conductive effects on the radiosonde instruments and housing are particularly amenable to correction by mathematical–physical models. The detailed design of a temperature adjustment model is the subject of this paper. Applying the model to correct the temperature requires a knowledge of where and when the radiosondes were used and the environmental conditions, such as cloud cover and solar angle, at the time measurements were taken.

International radiosonde comparison experiments are another means of estimating biases in radiosonde measurements. Unfortunately, comprehensive standardization of all radiosonde biases would require comparisons of the full suite of radiosonde types ever used. This would not be feasible even if all instrument types were still available. Since radiosonde biases are time and location dependent, tests would have to be carried out in many portions of the world and at several times of day. Nonetheless, the studies conducted by Nash and Schmidlin (1987) and Ivanov et al. (1991) are very useful. These studies show the likely magnitudes of the errors and how the biases vary with the time response of the instruments and with the physical properties of the sonde. These studies also provide data from which temperature and humidity correction models for the various radiosondes can be validated. Intercomparison data obtained from the recent potential reference radiosonde (PREFRS) tests in Crawley, England, in 1992 have been used to evaluate the temperature correction models for the VIZ and Vaisala radiosondes described in this paper.

2. Introduction

The measurement of atmospheric temperature by every radiosonde instrument is contaminated by heating from sources other than the air itself. Solar and infrared radiation, heat conduction to the sensor through its attachment points, and infrared radiation emitted by the sensor are heat sources and sinks that make the temperature of the sensor different from that of the air that it is trying to measure. Thus, a correction is required for each instrument in order to deduce the atmospheric temperature from the temperature of the radiosonde sensor. For most radiosondes this correction is small (<0.5°C) at altitudes below 15 km but can become quite significant (several degrees) at altitudes between 20 and 30 km. Some radiosondes use a correction table to compensate for sensor heating, while other radiosondes do not. For many of the early radiosondes, the temperature correction was on the order of 3°–10°C, while for today's leading radiosondes this correction has been reduced to less than 3°C. The correction, however, varies from day to day, depending upon solar angle, cloud cover, ground temperature, humidity, and other parameters. None of the correction tables used with today's radiosondes take into account all the important parameters that influence the temperature correction. Thus, to produce a compatible stratospheric temperature database from radiosonde instruments requires the development of a correction technique for each radiosonde that takes into account those parameters that significantly affect the temperature of the radiosonde sensor.

A model has been developed that calculates the temperature correction for the VIZ instrument used by the National Weather Service (NWS). This model, VIZCOR, calculates the temperature correction as a function of environmental parameters (Luers 1989). It has been tested and validated by comparing its predicted temperature correction with the correction directly measured by the National Aeronautics and Space Administration (NASA) multithermistor radiosonde (Schmidlin and Luers 1988; Luers and Schmidlin 1992). The VIZCOR model requires the use of the LOWTRAN7 atmospheric transmission code (Kneizys et al. 1988) to establish the radiation environment experienced by the sensor along its ascent profile. Recently, a model similar to VIZCOR has been developed for the Vaisala RS-80 radiosonde. The Vaisala correction model (VAICOR) was developed to estimate the temperature correction for the RS-80 sonde. A recent PREFRS radiosonde intercomparison experiment has provided data from which comparisons can be made between corrected profiles from the VIZ, RS-80, and multithermistor radiosondes.

The PREFRS intercomparison radiosonde tests were conducted in Crawley, England, during February and March 1992. Carried aboard each balloon flight were up to five different types of radiosondes that transmitted temperature and other profile data to ground receiving stations. The radiosonde instruments included the Vaisala RS-80 sonde, a multithermistor AIR sonde, a multithermistor VIZ sonde, and a Swiss and United Kingdom radiosonde. The multithermistor radiosondes contained three rod thermistors having different surface coatings. These radiosondes were being tested and evaluated as a potential reference radiosonde. One of the three thermistors on each multithermistor radiosonde was the standard white-coated VIZ thermistor used operationally for NWS VIZ radiosonde flights. A picture of the RS-80, VIZ, and AIR radiosondes is shown in Fig. 1.

The RS-80, the AIR, and the VIZ multithermistor radiosondes provided temperature sensor data from which five atmospheric temperature profiles were derived. From each (AIR and VIZ) multithermistor sonde, two atmospheric temperature profiles were produced: one derived from the temperature differences between the three coated thermistors, and a second by correcting the white-coated VIZ thermistor using the VIZCOR model. The fifth profile was derived by correcting the temperature of the RS-80 bead sensor using

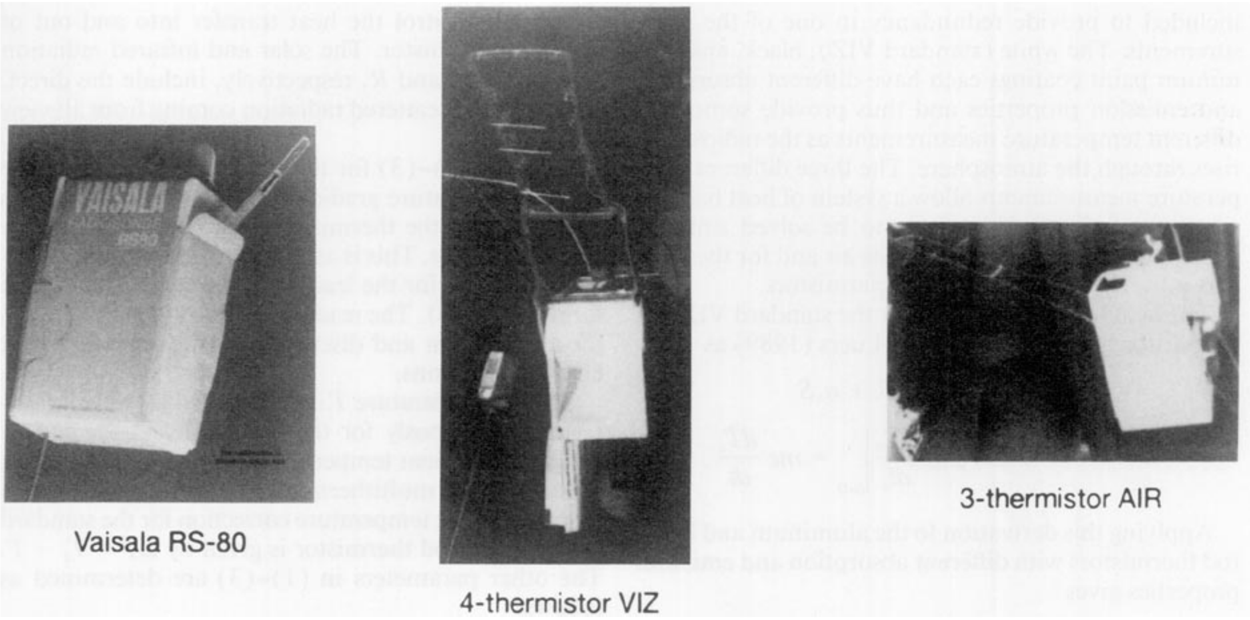

FIG. 1. Vaisala RS-80, four-thermistor VIZ and three-thermistor AIR sondes.

the VAICOR model. Since considerable independence exists between the techniques used in deriving the various profiles, agreement between all profiles would give a high level of confidence that the composite profile is an accurate estimate of the true atmospheric temperature. The following sections describe how each radiosonde temperature correction profile is generated and the significant sources of error in the corrected profiles.

3. The multithermistor radiosonde

The multithermistor radiosonde has been developed at NASA Wallops Flight Facility as a reference instrument to measure the absolute temperature of the atmosphere (Schmidlin et al. 1986; Schmidlin 1992). The instrument uses three rod thermistors, each prepared with a different surface coating, to deduce the temperature of the atmosphere. A fourth thermistor is

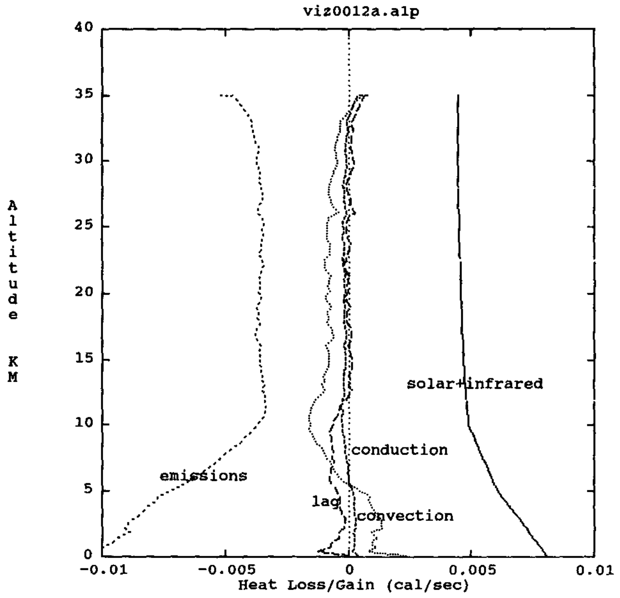

FIG. 2. Heat flux to VIZ thermistor.

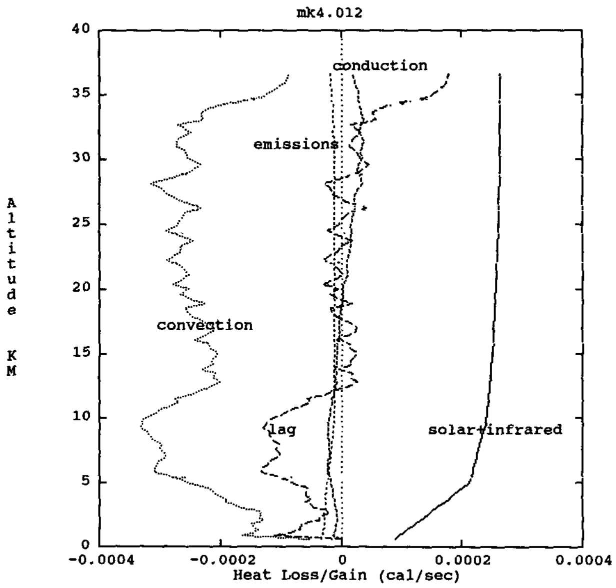

FIG. 3. Heat flux to Vaisala temperature sensor.

included to provide redundancy in one of the measurements. The white (standard VIZ), black, and aluminum paint coatings each have different absorption and emission properties and thus provide somewhat different temperature measurements as the radiosonde rises through the atmosphere. The three different temperature measurements allow a system of heat balance equations for each thermistor to be solved simultaneously for the temperature of the air and for the solar and infrared irradiation of the thermistors.

The heat balance equation for the standard VIZ rod thermistor has been derived by Luers (1989) as

$$-H(T_s - T)A - \sigma\epsilon_s A T_s^4 + \epsilon_s R + \alpha_s S + 2\pi r_w^2 k_w \left.\frac{dT_w}{dl_s}\right|_{l=0} = mc\frac{dT_s}{dt}. \quad (1)$$

Applying this derivation to the aluminum and black rod thermistors with different absorption and emission properties gives

$$-H(T_a - T)A - \sigma\epsilon_a A T_a^4 + \epsilon_a R + \alpha_a S + 2\pi r_w^2 k_w \left.\frac{dT_w}{dl_a}\right|_{l=0} = mc\frac{dT_a}{dt} \quad (2)$$

$$-H(T_b - T)A - \sigma\epsilon_b A T_b^4 + \epsilon_b R + \alpha_b S + 2\pi r_w^2 k_w \left.\frac{dT_w}{dl_b}\right|_{l=0} = mc\frac{dT_b}{dt}, \quad (3)$$

where

H = convective heat transfer coefficient,
T_s, T_a, T_b = temperature of the standard, aluminum, and black thermistors, respectively,
α_s, α_a, α_b = solar absorptivity of the standard, aluminum, and black thermistors, respectively,
ϵ_s, ϵ_a, ϵ_b = emissivity of the standard, aluminum, and black thermistors, respectively,
T_w = temperature of the wire,
T = air temperature,
A = surface area of the thermistor,
R = infrared radiation irradiating the thermistor,
S = solar radiation irradiating the thermistor,
σ = Stefan–Boltzman constant,
r_w = radius of the thermistor lead wires,
k_w = thermal conductivity of the lead wires,
l = length of the lead wires,
m = mass of the thermistor,
c = specific heat capacity of the thermistor, and
t = time.

This system of equations assumes that the mass, dimensions, and orientation of all thermistors are identical. Equations (1)–(3) contain all the significant terms that control the heat transfer into and out of each rod thermistor. The solar and infrared radiation parameters, S and R, respectively, include the direct, reflected, and scattered radiation coming from all view directions.

To solve (1)–(3) for the atmospheric temperature T, the temperature gradient of the wire dT_w/dl at its interface with the thermistor must be determined for each thermistor. This is achieved by solving a heat balance equation for the lead wire that is very similar in form to (1)–(3). The reader is referred to Luers (1989) for a derivation and discussion of the lead wire heat balance equations.

The air temperature T is determined by solving (1)–(3) simultaneously for the unknowns T, R, and S. Thus, the ambient temperature is a direct output from processing the multithermistor radiosonde data. As a by-product, the temperature correction for the standard (white VIZ) rod thermistor is given by $\Delta T = T_s - T$. The other parameters in (1)–(3) are determined as follows.

The heat transfer coefficient H is calculated from the empirical Nusselt number equation for a cylinder in laminar cross-flow given by Fan and Keswani (1972) as a function of Reynolds number.

The Reynolds number Re is calculated using the balloon rise rate and the atmospheric density measured at each point in the flight. The thermistor radius is provided by the manufacturer. The specific heat capacity of the thermistor c and thermal conductivity of the lead wires k_w were taken from Ballard and Rubio (1968). The solar absorptivity α and infrared emissivity

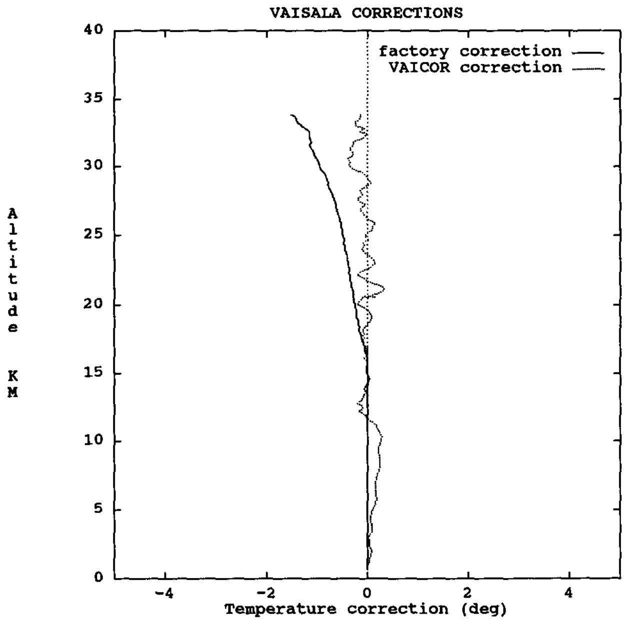

FIG. 4. Vaisala RS-80 correction; night flight 006.

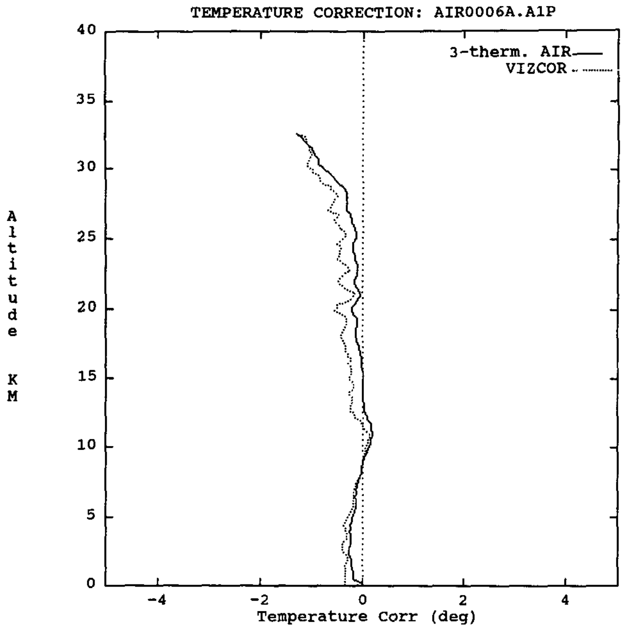

FIG. 5. VIZCOR model-predicted vs three-thermistor-measured profiles; AIR sonde; night flight 006.

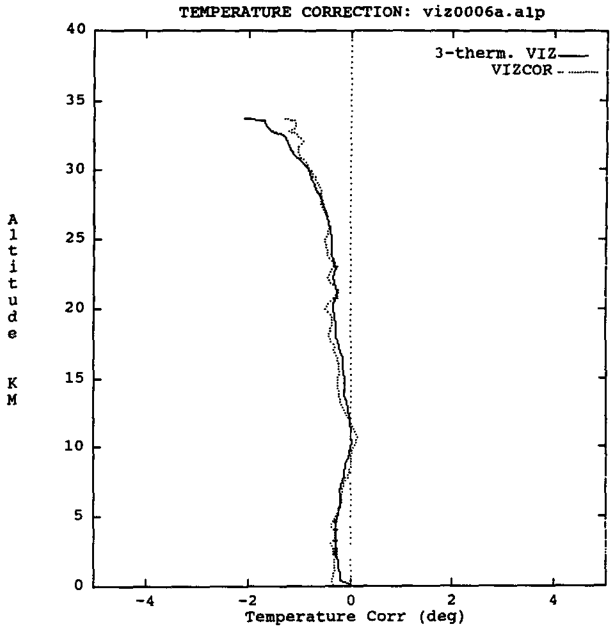

FIG. 6. VIZCOR model vs three-thermistor-measured profiles; VIZ sonde; night flight 006.

ϵ of each thermistor were determined by laboratory measurements.

A theoretical error analysis was performed (Luers 1992) to establish the accuracy of the atmospheric temperature that is measured by the three-thermistor radiosonde. This error analysis consisted of a sensitivity study to determine the influence of each parameter in (1)–(3) on ΔT. Then using nominal values for the certitude (accuracy) of each parameter, the accuracy of ΔT was deduced. The most significant error sources were found to arise from the inaccuracy in the absorptivity measurement of the aluminum thermistor and the random error in the measurement of the temperature of each thermistor. If the random temperature measurement error can be maintained to less than 0.2° and the absorbtivity known to within 0.03, then the resulting temperature correction should be accurate to ±0.3°C. Additional errors of significance will arise with this system if the diameters of the three thermistors are not identical to within a few percent.

4. VIZ radiosonde

The VIZ radiosonde, using a white-coated rod thermistor, has been the primary radiosonde instrument used by the NWS for measuring atmospheric temperature since the early 1960s. The white-coated thermistor is 4 mm long with diameter 1.2 mm. It is well known that at high altitudes, above 20 km, the thermistor temperature is warmer than that of the atmosphere during the daytime and colder at nighttime (Ballard and Rubio 1968; Luers 1990). Presently, no corrections are made to the VIZ radiosonde data to compensate for this temperature error.

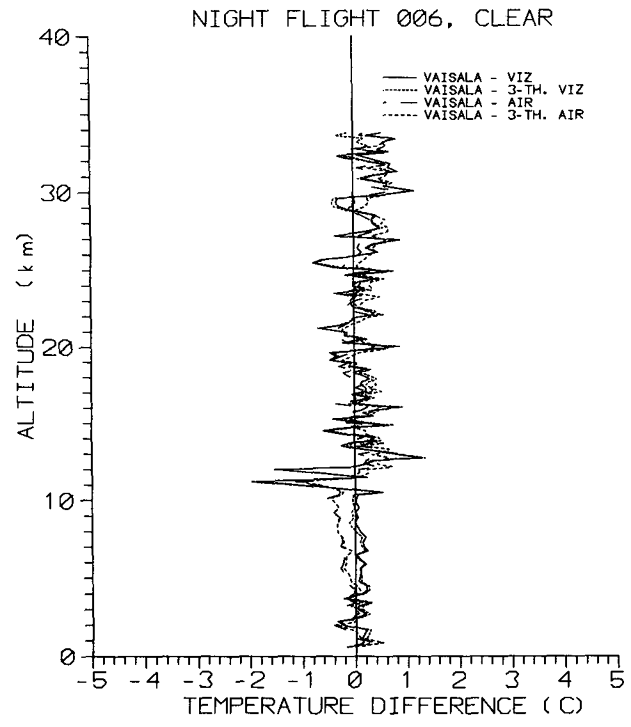

FIG. 7. Difference between corrected profiles; night flight 006, clear.

The temperature correction for the VIZ rod thermistor can be estimated by using the radiosonde measurements of altitude, thermistor temperature, balloon rise rate, and pressure, along with independent estimates of the amount of solar and infrared irradiation of the thermistor as a function of the environment. The irradiation estimates are derived using the LOWTRAN7 atmospheric transmission model with the appropriate input values that describe the surface and atmospheric conditions. When predicting the radiosonde temperature correction using the VIZCOR model, the heat transfer equation for the rod thermistor, Eq. (4), is solved directly for the air temperature from which the temperature correction $\Delta T = T_s - T$ is derived. The heat transfer equation for the rod thermistor, previously given by (1), can be rewritten as

$$mc\frac{dT_s}{dt} = q_{\mathrm{abs}} - \sigma\epsilon_s A T_s^4 - \mathrm{AH}(T_s - T) + 2\pi r_w^2 k_w \left.\frac{dT_w}{dl}\right|_{l=0}, \quad (4)$$

where the term q_{abs} is the combined solar and infrared radiation terms of (1). This term is calculated from the radiation properties of the thermistor and the LOWTRAN7 output data. The remaining heat transfer terms are evaluated in the same manner used to evaluate this equation with the multithermistor radiosonde.

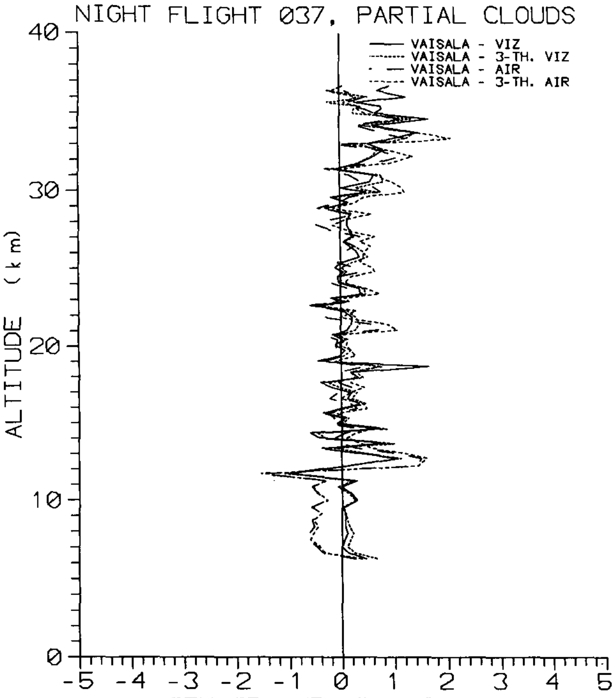

FIG. 9. Difference between corrected profiles; night flight 037, partially cloudy.

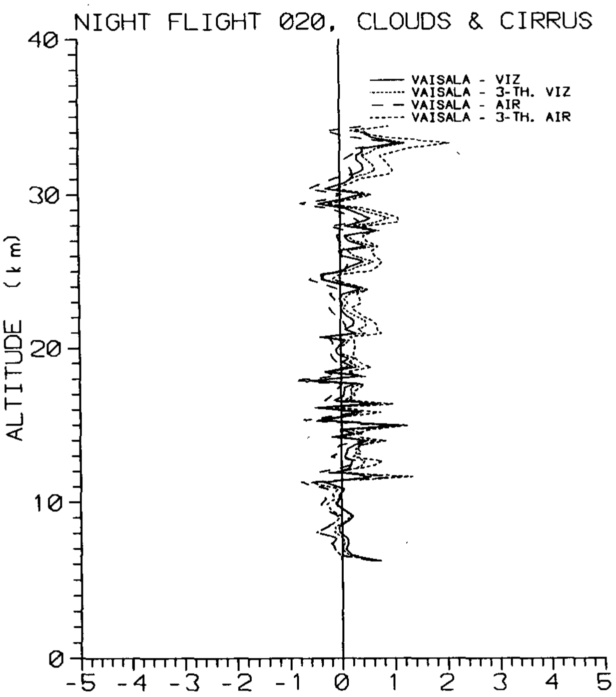

FIG. 8. Difference between corrected profiles; night flight 020, clouds and cirrus.

The total absorbed radiation term q_{abs}, including both the solar (αS) and infrared (ϵR) contributions, is given by

$$q_{\mathrm{abs}} = \int_\lambda\int_\theta\int_\phi I(\lambda, \theta, \phi)\alpha(\lambda)\,\mathrm{Ap}(r, l, \theta)\,d\lambda d\theta d\phi$$

$$0.25 \leq \lambda \leq 28\ \mu\mathrm{m}, \quad (5)$$

where $I(\lambda, \theta, \phi)$ is the intensity of radiation of wavelength λ irradiating the thermistor from the direction whose azimuth angle is ϕ and elevation angle is θ, $\alpha(\lambda)$ is the wavelength-dependent absorption coefficient of the thermistor, and $\mathrm{Ap}(r, l, \theta)$ is the average presented area of the cylindrical rod thermistor during one revolution as viewed from the direction θ.

The integration is performed over the solar and infrared wavelength spectrum $0.25\ \mu\mathrm{m} < \lambda < 28\ \mu\mathrm{m}$. The average presented area Ap for the thermistor is that of a cylinder as a function of view angle. From the vertical direction, the presented area always equals the cross-sectional area of the cylinder, while a horizontal view of a rotating cylinder reduces the average presented area to 65% of the cross-sectional area (Talbot 1972). The intensity of radiation $I(\lambda, \theta, \phi)$ is derived by running the LOWTRAN7 atmospheric transmission code under the specified environmental conditions associated with the radiosonde flight.

Each of the terms in (4) has been calculated for a representative daytime flight 012 and is plotted in Fig. 2. The two largest terms, the total absorbed solar and infrared radiation and the emitted radiation, are of opposite signs and of similar magnitude. The thermistor absorbs 15% of the solar radiation ($\alpha = 0.15$) and 86% of the infrared radiation ($\epsilon = 0.86$) that irradiates its surface. The infrared radiation is the predominate term of the total absorbed radiation as deduced from the fact that the total absorbed radiation decreases with altitude. The solar component of the total radiation increases with altitude because of the absorption and scattering in the dense lower atmosphere. The thermistor emits radiation proportional to the fourth power of its temperature. Because of its high emissivity and warm temperature at low altitudes, it emits more energy than it absorbs below 5 km, resulting in a slight cooling of the thermistor. Above 5 km more total radiation is absorbed than emitted, resulting in the thermistor temperature being warmer than the ambient air. This warmer thermistor is partly cooled by convection, which attempts to bring the thermistor temperature toward that of the air. Figure 2 shows the convection term to be negative above 5 km, indicating heat loss from the thermistor above this altitude. The conduction term is small and the flow of heat from the lead wires to the thermistor generally tends to make the thermistor temperature approach that of the air. This happens because the lead wires for the thermistor have a very low solar absorptivity and low emissivity, which results in a wire temperature that is closer to the air temperature than that of the thermistor. The lag term corrects for the response time of the thermistor in adapting to a changing atmospheric temperature. The lag term is negative from the surface to the tropopause, indicating that the sensor temperature is warmer than the air temperature. The lag term becomes positive when the atmospheric temperature begins to warm in the upper stratosphere.

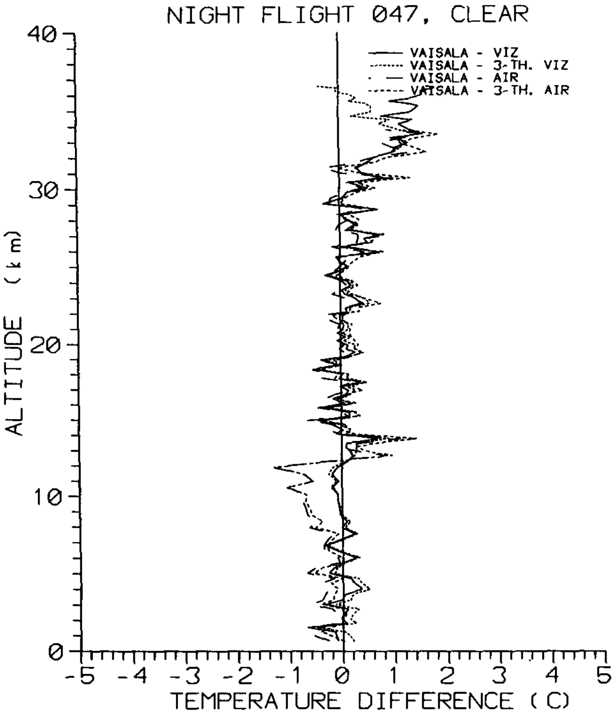

FIG. 10. Difference between corrected profiles; night flight 047, clear.

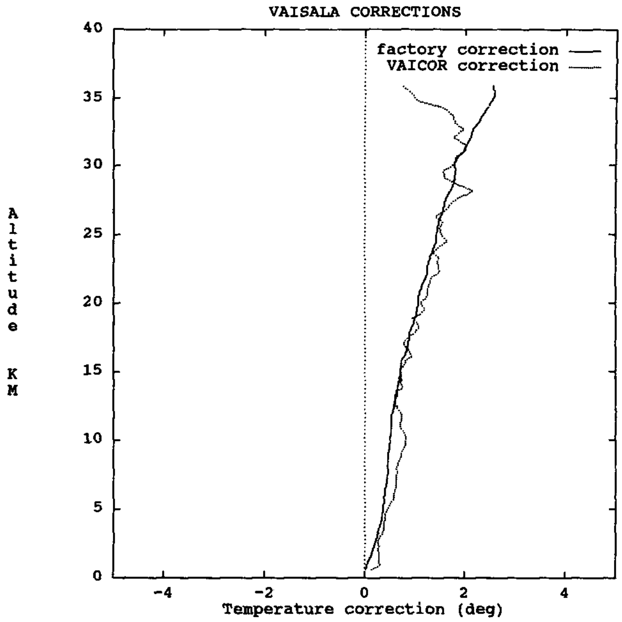

FIG. 11. Vaisala RS-80 correction; day flight 012, clear.

The error in the temperature correction arises from errors in all parameters of (4). In general, the contribution that a source makes to the error in the temperature correction varies with altitude and with the magnitude of the temperature corrections itself. The influence of each error source on the error in the temperature correction has been assessed by a sensitivity analysis using both day and night flight conditions (Luers 1992). The results from this study indicate that the temperature correction is most sensitive to inaccuracies in the convective heat transfer coefficient and the thermistor and lead wire dimensions. The latter controls the heat conduction through the lead wires. The error in the temperature correction is also sensitive to inaccuracies in the specification of cloud cover (including cirrus), solar angle, and surface temperature that are inputs to the LOWTRAN7 model that specify the radiation environment.

In contrast to the multithermistor radiosonde, the significant error sources for the VIZCOR predicted correction profile are different from those that influence the multithermistor profile. For the multithermistor radiosonde, the solar absorptivity of the aluminum thermistor and the thermistor temperature measurements themselves are the significant sources of error. These are not significant error sources in the temperature correction profile predicted by the VIZCOR model. In contrast, the VIZCOR sensitive parameters, the heat transfer coefficient, the thermistor and lead wire dimensions, and the environmental parameters have no discernible influence on the temperature profile derived by the multithermistor radiosonde. Thus, the parameters that cause errors in the corrected atmospheric temperature profiles are very different using the two different methodologies. Consequently, if agreement is good between the corrected temperature profiles derived from the two methods, there is high confidence that the profiles are measuring and modeling the true atmospheric temperature.

5. Vaisala RS-80 radiosonde

Vaisala radiosondes have been used at many worldwide locations for upper-air measurements since about 1940. Early Vaisala radiosondes (Vaisala 1967) used a bimetal strip to sense the temperature of the atmosphere. The bimetal strip was used on the RS-11, RS-12, RS-13, and RS-15 radiosondes that were commonly used until the introduction of the RS-18 sonde in 1976. The RS-18 and RS-21 sondes used a bimetal ring as a replacement for the bimetal strip as a means of reducing the temperature correction resulting from radiation (Antikainen 1973). These radiosondes were used until 1981 when the capacitive bead temperature sensor and the RS-80 sonde were introduced (Vaisala 1992). This radiosonde is in worldwide use today. A model has been developed to estimate the temperature correction for the Vaisala RS-80 radiosonde.

The heat balance equation for the capacitive bead temperature sensor can be written in the same form as (4) and (5) for the VIZ rod thermistor. However, several parameter values in the heat balance equation, as well as a change in the form of some of the heat transfer terms, are required. The parameters that differ are the sensor dimensions, surface area, mass, specific heat, presented area, absorptivity, emissivity, lead wire dimensions, and the convective heat transfer coefficient.

The geometric shape of the Vaisala bead sensor is approximated as a cylinder with cones attached to both ends. Measurements of the dimension of the thermistor have been made using a precision instrument that magnifies the image. Using the measured thermistor and lead wire dimensions, theory and software have been developed to calculate the average presented area of the thermistor and lead wires viewed from any direction (Luers 1993). This information is used in (5) to calculate the amount of solar and infrared radiation absorbed from each direction.

The solar and infrared absorption and emission properties of the bead coating, as provided by Vaisala, are $\epsilon = 0.02$ for the emissivity and $\alpha = 0.11$ for the solar absorbtivity. The mass of the coated bead was determined by weighing, and the specific heat estimated based upon the material composition of the bead.

The convective heat transfer coefficient is required for a conical-ended cylindrical sensor that is tilted about 35° from the vertical so that the vertical airflow interacts with an irregularly shaped object. Since no analytic heat transfer coefficient is known for the airflow over this object, an approximate heat transfer expression was developed. It was assumed that the heat transfer coefficient can be approximated as that of a sphere with appropriate diameter. The nominal sphere diameter was considered as the average of the maximum and minimum dimensions of the sensor as viewed in the direction of the airflow motion. The derived expression is

$$H = \mathrm{Nu}\,\frac{k}{d_{\mathrm{avg}}}$$

$$\mathrm{Nu} = 2 + (0.4\,\mathrm{Re}^{1/2} + 0.06\,\mathrm{Re}^{2/3})\,\mathrm{Pr}^{0.4}, \quad (6)$$

where Re is the Reynolds number ($3.5 < \mathrm{Re} < 76\,000$), Pr is the Prandtl number ($0.71 < \mathrm{Pr} < 380$), $d_{\mathrm{avg}} = (d + d')/2$, d is the maximum dimension of sensor viewed vertically, and d' is the minimum dimension of sensor viewed vertically.

Of the parameters used in (4) for the VAICOR model, those that are not accurately known are the

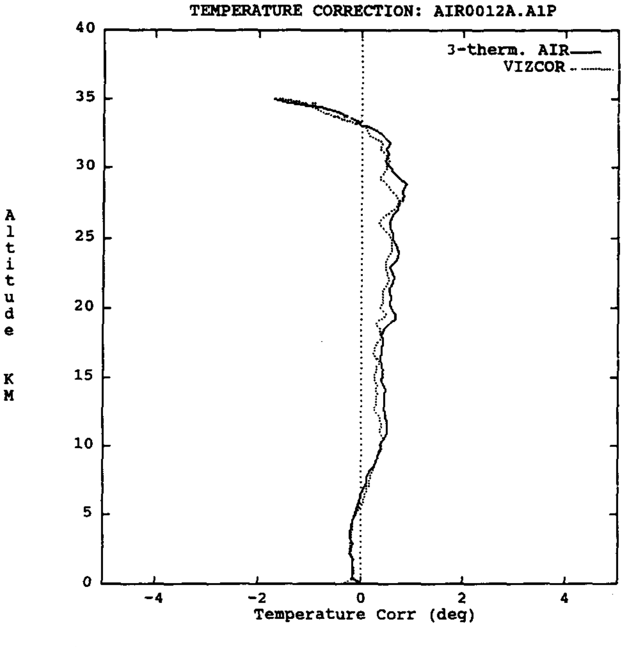

FIG. 12. VIZCOR model-predicted vs three-thermistor-measured profiles: AIR sonde; day flight 012, clear.

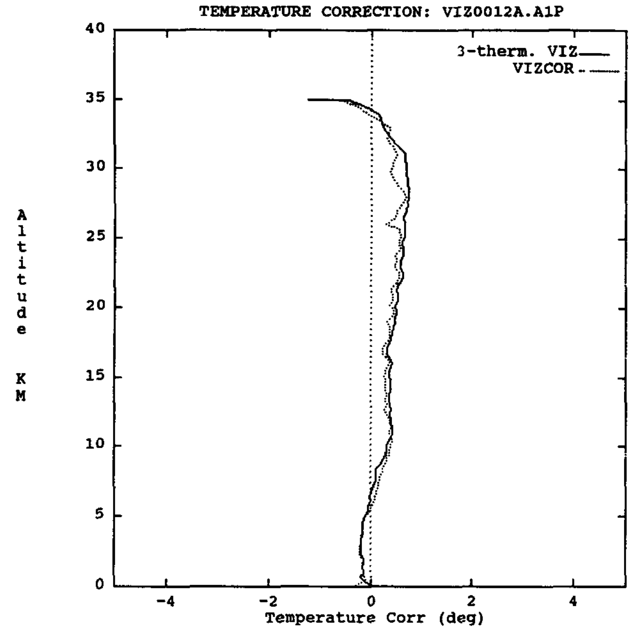

FIG. 13. VIZCOR model-predicted vs three-thermistor-measured profiles; VIZ sonde; day flight 012, clear.

convective heat transfer coefficient H and the solar absorptivity of the aluminized bead. The solar absorptivity value is uncertain because laboratory measurements of absorptivity are traditionally made on a coated flat plate specimen irradiated at an incidence angle of 15°–20° from the vertical. The absorptivity of an aluminum coating on a curved surface, such as a cylinder or sphere, is a function of the angle of incidence, with more absorption occurring at low grazing angles. For this reason, the absorptivity of the aluminized bead sensor is expected to be somewhat larger than the $\alpha = 0.11$ measured value.

The VAICOR model was tuned to establish the proper values of α and H. A "calibration set" of intercomparison day and night flights was established, and the VAICOR model was run with modified values of α and H until agreement was established between corrected RS-80, VIZ, and multithermistor profiles. A tuned value of $\alpha = 0.15$ and the H value of (6) resulted.

A sensitivity analysis performed on the VAICOR model indicated that the only significant source of temperature correction to be applied to night flights comes from the lag term in the heat balance equation. An accurate prediction of the lag correction term requires knowledge of the mass and specific heat of the capacitive bead. Because the aluminized coating has a very low emissivity, it is highly reflective of infrared radiation and, thus, the absorption and emission terms are not influenced by nighttime infrared radiation. Consequently, cloud cover, surface temperature, and albedo are not sources of temperature error in nighttime RS-80 flights.

The daytime temperature correction is sensitive to solar angle, cloud cover, and changes in the convective heat transfer coefficient that result from changes in the balloon rise rate. These parameters are known or can be modeled to approximately the same degree of accuracy as for the VIZ sonde. The estimated accuracy of the VAICOR correction profiles for the RS-80 sonde is similar to that of the VIZ, approximately ±0.3°C.

The magnitude of the individual terms of the heat transfer equation used in the VAICOR model are shown in Fig. 3 for day flight 012. The terms of largest magnitude, which are of opposite signs, are the solar and infrared radiation absorbed by the bead sensor and the convective cooling of the bead. The absorbed radiation comes primarily from the solar component of radiation ($\alpha = 0.15$) since the Vaisala bead absorbs only 4% ($\epsilon = 0.04$) of the infrared radiation. This is apparent from observing that the total absorbed radiation increases with altitude, indicating a dominate solar component. Because of the capacitive bead's low emissivity, it dissipates very little heat by emissions as observed in Fig. 3. Convection is seen to be the major component of heat removal from the bead. It modifies the bead temperature to approach that of air. The conduction term that represents the heat transfer from the lead wires to the bead is small. The lead wires have the same coating as the bead sensor and, consequently, the wire temperature deviates very little from the temperature of the bead. The lag term makes a significant contribution to the temperature correction. The lag term is negative when the atmospheric temperature decreases with altitude and positive when it increases.

In comparing the heat transfer terms for the VIZ sensor (Fig. 2) with that for the Vaisala (Fig. 3), several important differences are observed. The VIZ thermistor absorbs significant amounts of both solar and infrared radiation with the infrared term larger. Its temperature is sensitive to environmental parameters that modify either the solar or infrared irradiation of the thermistor. These include surface temperature, humidity, aerosols, cloud cover, and cirrus clouds. Because the infrared emission from the thermistor is large and is controlled by its temperature, which in turn is controlled by that of the air, the background profile of ambient air temperature strongly affects the temperature correction.

The Vaisala-based sensor absorbs and emits a minimal amount of infrared radiation. Because of its insensitivity to infrared radiation, the temperature correction for the Vaisala sonde does not depend, to any significant degree, on the surface temperature, the nighttime cloud cover, or the background temperature profile. Its sensitivity to solar parameters is similar to that of the VIZ sensor. Both radiosondes require correction for the lag of the temperature sensor.

6. Comparison of corrected temperature profiles

Preliminary data from the PREFRS intercomparison were provided by Mr. Schmidlin (NASA) and Dr. Nash

(United Kingdom) for use in deriving temperature correction profiles for the RS-80, VIZ, and AIR multithermistor radiosondes. This preliminary data contained timing errors and minor data discrepancies that are being removed in the finalized dataset. The VIZCOR and VAICOR models have been applied to the measured temperatures to arrive at corrected atmospheric temperature profiles. If the corrected profiles from all radiosondes agree, then the atmospheric temperature is accurately known, since the correction techniques are largely independent and the significant error sources differ between the three-thermistor and the VIZCOR and VAICOR model correction techniques. Furthermore, when one or more profiles is in disagreement, the profile in error can often be determined. This multicomparison of corrected radiosonde profiles provides an excellent method of assessing the absolute accuracy of radiosonde profiles. It also provides a standardized reference technology for assessing the accuracy of other radiosonde instruments.

Four day flights and four night flights from the PREFRS dataset were used in the evaluation. Each flight contained a VIZ three-thermistor radiosonde, an AIR three-thermistor radiosonde, and a Vaisala RS-80 radiosonde. These three radiosondes generated five corrected temperature profiles. The flight conditions included clear, partially cloudy, and overcast conditions, cirrus clouds, and solar zenith angles between 55° and 87°.

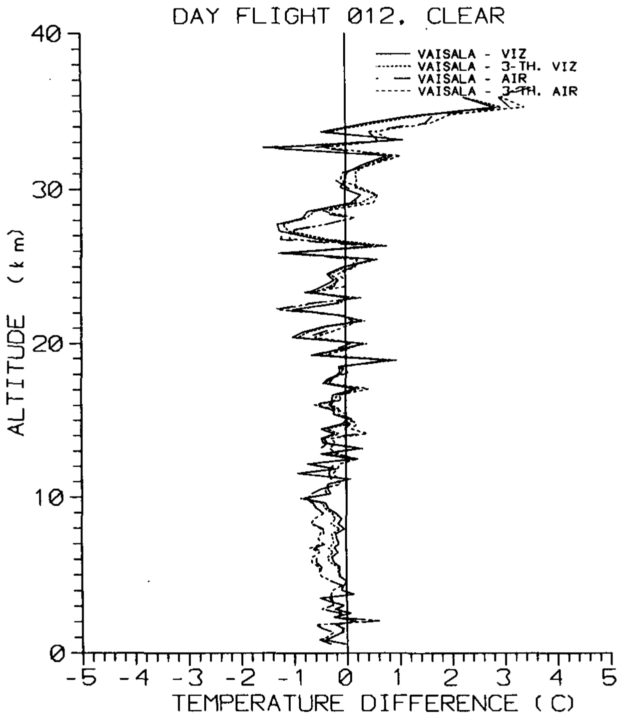

FIG. 14. Difference between corrected profiles; day flight 012, clear.

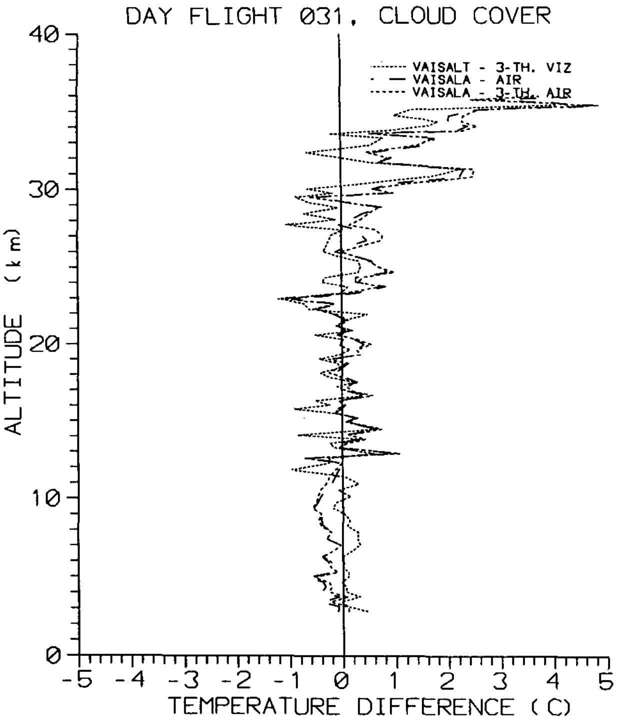

FIG. 15. Difference between corrected profiles; day flight 031, overcast.

Before running the VAICOR model on the RS-80 sonde, the Vaisala sonde data had to be uncorrected by removing the factory radiation correction that is applied in the Vaisala data reduction software. In removing this correction, it was necessary to calculate the ventilation factor k, which empirically corrects for the change in the convective heat transfer coefficient of the thermistor as the rise rate of the balloon varies. After the RS-80 data was uncorrected, the VAICOR correction was added, and the corrected RS-80 data was then compared with the other profiles. Plots were made of each of the five correction profiles and of the difference between the corrected Vaisala versus corrected VIZ, and corrected Vaisala versus corrected AIR profiles. For the sake of completeness, plots were also made showing the RS-80 factory correction versus the RS-80 VAICOR correction.

a. Night flights

The four night flights provided valid data from all radiosonde sensors so that comparisons could be made. Figures 4–7 show selected plots from the analysis of night flight 006. Figure 4 shows the VAICOR correction for the Vaisala RS-80 sonde. Also shown is the factory correction that is applied in the Vaisala software. The factory correction is known to overestimate the nighttime temperature error at higher altitudes. The VAI-

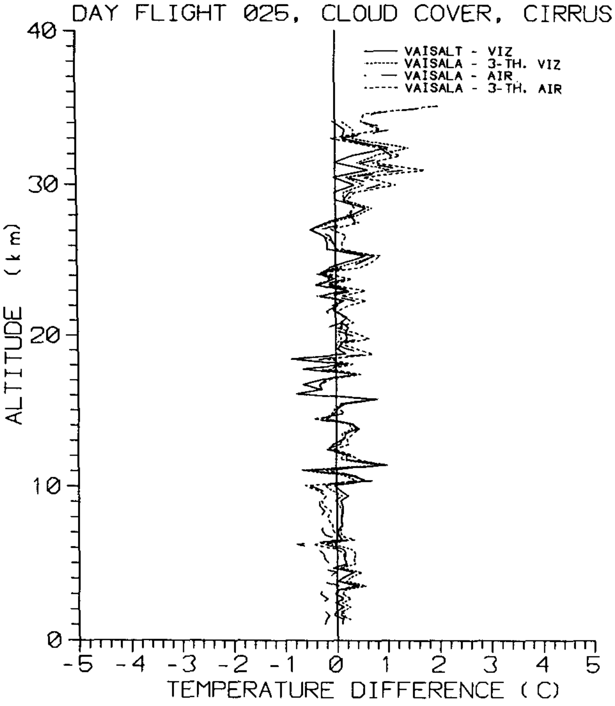

FIG. 16. Difference between corrected profiles; day flight 025, cloud cover and cirrus.

COR correction is variable and less than 0.5° at all altitudes. The source of this correction is the thermal lag of the thermistor. When the temperature gradient is negative, from the surface to about 10 km, the lag error is positive; that is, the thermistor temperature is warmer than that of the ambient atmosphere. Above 30 km a positive temperature gradient exists. There is no factory lag correction that is included in the Vaisala RS-80 software. Other than the temperature lag, there are no other heat sources that introduce significant error into the nighttime RS-80 temperature measurement.

Figures 5 and 6 show the VIZCOR model and three-thermistor-measured temperature correction profiles for the AIR and VIZ radiosondes. The VIZCOR profile includes significant contributions from absorbed and emitted infrared radiation as well as thermal lag. From Figs. 5 and 6, it is seen that agreement between three of the four profiles is excellent, while the measured three-thermistor AIR sonde profile is biased on the warm side by about 0.3°. A likely source of this bias is a bias in the calibration, or temperature sensing, of one of the three coated rod thermistors.

Figure 7 compares the corrected Vaisala RS-80 with the AIR and VIZ three-thermistor-measured and VIZCOR-predicted profiles. The Vaisala RS-80 profile is used as reference, with all other profiles subtracted from the corrected RS-80 profile. The high frequency variability seen in the profiles is primarily the result of the random error in the temperature measurements of the Vaisala sonde, since the other four sondes largely follow the same small-scale trends. Where the difference between the corrected profiles is near zero it can be concluded that all corrected profiles are accurate. The fact that the three-thermistor corrected profiles agree with the VIZCOR and VAICOR profiles gives corroborating evidence that all profiles are accurate in an absolute sense. From Fig. 7 it is seen that the corrected difference profiles oscillate about zero from the surface to about 25 km. Above this altitude the corrected RS-80 profile is slightly warmer than the other corrected profiles. The fact that the AIR corrected difference profile shows a negative bias of about 0.40 between 5 and 10 km, not seen in the VIZ corrected difference profiles, is because the temperature measurements themselves from these two sondes disagree in this region. This negative trend in the AIR profile has been found to be due to a timing bias in the data reduction procedure that introduced a spurious lag error in the temperature measurements. This timing bias is being removed in the finalized PREFRS dataset.

Each of the remaining three night flights were analyzed in the same manner as above. The corrected difference profiles are shown for each flight and each radiosonde in Figs. 8–10. The environmental conditions for these flights included cloud cover and cirrus clouds.

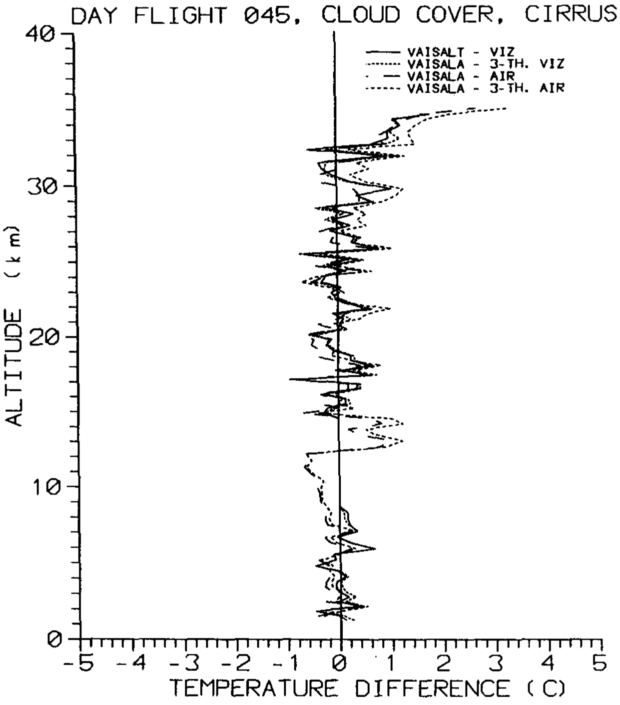

FIG. 17. Difference between corrected profiles; day flight 045, cloud cover and cirrus.

Although cloud cover does not influence the nighttime temperature of the Vaisala RS-80 sonde, it does influence the temperature of the rod thermistor used on both the VIZ and AIR sondes. Where cloud cover exists the model only calculates the temperature correction above the cloud-top altitude. All three night flights show excellent agreement in the temperature profiles from the three sondes up to 30 km. Above 30 km the corrected RS-80 temperature becomes warmer than the AIR and VIZ temperatures by about 1° at 35 km. The cause of this disagreement is not yet known.

b. *Day flights*

The corrected profiles from four day flights were compared in the same manner as for the night flights. The environmental conditions for these flights included clear sky, partial cloud cover, overcast, and a dense layer of cirrus clouds. Solar zenith angles from 87° to 55° occurred throughout these flights. The solar angle and daytime cloud cover influence the thermistor temperature for all three radiosondes. Thus, agreement between corrected profiles under this range of conditions would imply that the cloud cover and solar angle corrections are accurate for each instrument.

Figures 11–14 show the individual correction profiles, and the corrected difference profiles for the clear-sky day flight 012. Except for the lag term influence, the VAICOR and factory corrections show excellent agreement (Fig. 11). The three-thermistor and VIZCOR model correction profiles (Figs. 12 and 13) show agreement in the mean to within about 0.2°C at all altitudes. The difference between corrected temperature profiles (Fig. 14) also show excellent agreement up to 30 km. Above 30 km the RS-80 sonde again tends to be warmer than the VIZ and AIR sondes. Also, the consistent bias between 5 and 10 km seen in the AIR profiles is the result of the timing error in the AIR sonde.

For the day flight 031 there existed overcast conditions at 2.5 km. The corrected difference profiles (Fig. 15) shows good agreement to 30 km, with the same trend seen above this altitude. The three-thermistor VIZ sonde did not provide accurate data for this flight.

Day flights 025 and 045 include the influence of a layer of cirrus clouds. The corrected difference profiles from these flights (Figs. 16 and 17) show the same type of agreement as the other flights.

7. Conclusions

Three largely independent methods have been used to derive the temperature of the atmosphere from the temperature measured by the thermistor(s) on three different radiosondes. These three radiosondes provided five atmospheric temperature profiles that were compared by differencing each of the four corrected profiles from the corrected Vaisala RS-80 profile. The corrected temperature profiles were found to be in excellent agreement up to 30 km from all three instruments in both daytime and nighttime flight conditions. The flight environments included total and partial cloud cover, cirrus clouds, and daytime solar zenith angles from 55° to 87°. Above 30 km, the corrected Vaisala RS-80 temperature tends to be warmer than the other sondes. The cause of this disagreement is not yet known.

Agreement in corrected temperatures between the three independent methodologies gives strong evidence that the difference in corrected profiles represents the absolute accuracy of the measurements. The corrected profiles appear to be unbiased (up to 30 km) with a random component of error on the Vaisala system of about 0.5°C and less than 0.2°C for the VIZ and AIR sondes.

The VIZCOR and VAICOR models are shown to provide an accurate method of correcting the temperature measurements of the NWS VIZ sonde and the Vaisala RS-80 sonde provided the environmental flight conditions are known. The environmental flight condition of significance to the Vaisala sonde are solar angle and cloud cover, including cirrus clouds. For the VIZ sonde, the surface temperature is an additional significant environmental parameter. Thus, it is possible to operationally correct not only radiosonde measurements but also historical profiles provided cloud cover, solar angle, and surface temperature can be deduced about the observation. By correcting historical profiles, a database of compatible and unbiased temperature profiles can be developed from worldwide locations that have used the VIZ and RS-80 radiosondes.

Acknowledgments. The authors wish to thank Dr. John Nash and Mr. Francis Schmidlin for furnishing the PREFRS intercomparison data from the VIZ, Vaisala, and multithermistor radiosondes. Appreciation is also extended to the VIZ and Vaisala companies for furnishing technical information that made this study possible. James Luers is supported by NOAA Contract 50EANE-2-00077. Robert E. Eskridge is employed by the National Climatic Data Center. The CARDS project is supported by the Department of Energy under Contract DE-AI05-90ER61011, the NOAA Climate and Global Change Program, and the National Climatic Data Center.

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