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Assessment of radiosonde temperature measurements in the upper troposphere and lower stratosphere using COSMIC radio occultation data

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[1] Temperature profiles derived from Global Positioning System (GPS) Radio Occultation (RO) data from the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) mission are compared with those from four types of radiosonde systems from 12 to 25 km to assess the performance of these radiosonde systems in the upper troposphere and lower stratosphere. Results show that temperature measurements from the Vaisala-RS92 and Shanghai radiosonde systems agree well with those of COSMIC with a close-to-zero mean difference. Large temperature biases are shown for the MRZ and VIZ-B2 radiosonde systems relative to COSMIC, which are probably caused by diurnal radiative effects. In addition, we show that the temperature measurements from a new Chinese radiosonde system are improved compared to those of an older system through a comparison with COSMIC measurements. **Citation:** He, W., S.-P. Ho, H. Chen, X. Zhou, D. Hunt, and Y.-H. Kuo (2009), Assessment of radiosonde temperature measurements in the upper troposphere and lower stratosphere using COSMIC radio occultation data, *Geophys. Res. Lett.*, *36*, L17807, doi:10.1029/2009GL038712.

1. Introduction

[2] Radiosondes are the only operational instruments that have provided continuous atmospheric pressure, temperature, and humidity measurements in the troposphere and lower stratosphere (∼25 km) for more than three decades. Although their horizontal distribution is inhomogeneous, and their density is relatively low (particularly over the oceans and polar regions), radiosonde measurements are widely used for air temperature trend analysis [e.g., *Durre et al.*, 2005; *Thompson and Solomon*, 2005; *Thorne et al.*, 2005]. However, because the quality of radiosonde measurements varies with height and instrument type [*Luers and Eskridge*, 1998] (hereinafter referred to as Luers98), air temperature trends constructed from radiosonde measurements are subject to significant uncertainty. Many studies have attempted to quantify the temperature errors of different radiosonde types in upper air [*Seidel et al.*, 2004; *Randel and Wu*, 2006]. Due to the lack of benchmark temperature references, the identified temperature errors for different radiosonde types are still subject to uncertainty as well. It remains a challenge to use radiosonde measurements for climate studies [*Thorne et al.*, 2005; *Seidel et al.*, 2009].

[3] The measurements obtained from the Global Positioning System (GPS) radio occultation (RO) limb-sounding technique are free of mission-dependent and geographical-dependent biases [*Kuo et al.*, 2004; *Ho et al.*, 2009a, 2009b]. RO observations are of high vertical resolution (ranging from ∼60 m near the surface to ∼1.5 km at 40 km), and have all-weather coverage, and long-term stability [*Ho et al.*, 2009a]. *Ho et al.* [2007] demonstrated that high-resolution dry temperature soundings from the Challenging Minisatellite Payload satellite (CHAMP) are of high accuracy and are useful for assessing the quality of observations from other sensors, such as the Microwave Sounding Unit (MSU) and Advanced Microwave Sounding Unit (AMSU) microwave brightness temperature in the upper troposphere and lower stratosphere. By comparing CHAMP RO refractivity profiles with those calculated from radiosonde soundings, *Kuo et al.* [2005] showed that RO refractivity profiles are of high enough accuracy to differentiate the quality of different radiosonde sensor types.

[4] The successful launch of the six-satellite FORMOSAT-3/Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) in April 2006 [*Anthes et al.*, 2008] began a new era of GPS atmospheric remote sensing. Currently, COSMIC is providing approximately 1,500 to 2,500 GPS RO soundings every 24 hours, uniformly distributed around the globe. The precision of COSMIC-derived temperature profiles is estimated to be better than 0.05 K from 8 km to 30 km [*Ho et al.*, 2009a]. With about an order of magnitude more soundings than CHAMP, COSMIC provides a unique opportunity for validating the radiosonde temperature measurements in the upper troposphere and lower stratosphere.

[5] In this paper, we compare the temperature profiles derived from COSMIC RO refractivity from June 2006 to February 2007 with collocated radiosonde temperature profiles from 12 to 25 km in altitude, to assess the performance of different types of radiosonde systems. The data and matching method are introduced in Section 2. Results and discussions are presented in Section 3 and a summary of this study in Section 4.

2. Data and Matching Method

[6] The COSMIC data used in this study are from the COSMIC Data Analysis and Archive Center (CDAAC) (http://cosmic-io.cosmic.ucar.edu/cdaac/index.html). In a

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Table 1. Mean and Standard Deviation of Temperature Differences from 12 km to 25 km Between COSMIC and Four Types of Radiosonde

Radiosonde Type	Number of matches	Percentage[a] (%)	$\overline{\Delta T_{CR}}$(K)	$SD_{\overline{\Delta T_{CR}}}$ (K)
MRZ	4728	17.8	−0.26	1.98
Shanghai	1751	6.6	−0.03	1.85
VIZ-B2	1474	5.6	0.23	1.97
Vaisala-RS92	3786	14.3	−0.03	1.76

[a] The percentage of the observation numbers of the radiosonde type to the global radiosonde observations available in the same time period.

neutral atmosphere, the refractivity (N) is related to pressure (P in mbar), temperature (T in K) and water vapor pressure (P_W in mbar) according to the following equation [*Smith and Weintraub*, 1953]:

$$N = 77.6\frac{P}{T} + 3.73 \times 10^5 \frac{P_W}{T^2} \tag{1}$$

The so-called "dry temperature" is obtained by neglecting the water vapor term in equation (1); the dry temperature is always less than or equal to the actual temperature. Above the upper troposphere where moisture is negligible, the dry temperature and the actual temperatures are nearly equal [*Ware et al.*, 1996]. The procedures used in CDAAC to invert refractivity to dry temperature were summarized by *Kuo et al.* [2004]. COSMIC dry temperature profiles are used for comparison with radiosonde temperature profiles from 12 km to 25 km where water vapor is negligible in equation (1).

[7] Radiosonde data used in this study are also obtained from CDAAC (via NCAR mass store, DS353.4). DS353.4 contains global radiosonde observations from 1973 to February 2007 processed by the National Centers for Environmental Prediction (NCEP). This dataset was originally acquired from NCEP but maintained by NCAR. Although NCEP performed quality control during initialization, based on comparisons with other data, DS353.4 contains the original data values transmitted by stations [*Schroeder*, 2009]. No radiative or other corrections from NCEP are included in this dataset although some corrections may be made in each station. Owing to lack of complete metadata, hereafter we assume most of radiosodne measurement uncertainties are primarily due to inaccurate instrumental error for the sake of discussion. Radiosonde temperature measurements within 2 hours and 300 km of COSMIC RO soundings are compared to those from COSMIC. Operational radiosonde data are available once or twice a day at most of the stations at mandatory, significant, and some additional levels. RO data have higher vertical resolution than operational radiosonde data that are reported only at mandatory and significant pressure levels. To avoid the vertical resolution mismatch by interpolating the lower-resolution radiosonde data to the levels of the higher-resolution RO data, in this study we interpolate the COSMIC temperature profiles to the vertical levels of radiosonde profiles.

[8] Temperature measurements from Shanghai (from China), MRZ (from Russia), VIZ-B2 (from USA), and Vaisala-RS92 (from several different countries) radiosondes, which are manufactured by China, Russia, USA, and Finland, respectively, are compared with the dry temperatures derived from COSMIC. Each radiosonde type covers more than 5% of the global radiosonde observations (Table 1) for the period of study. MRZ radiosondes are all from higher latitudes (45°N to 60°N); Shanghai and VIZ-B2 radiosondes are from mid-latitudes (20°N to 45°N); and Vaisala-RS92 radiosondes are from 60°S to 60°N. For each COSMIC and radiosonde match, we compute the difference between COSMIC and radiosonde temperatures at vertical level i ($\Delta T_{CR}(i)$ = COSMIC(i)-radiosonde(i)). Only the COSMIC-radiosonde temperature difference at radiosonde mandatory levels from 12 km to 25 km are included in the calculation; below 12 km water vapor effects become important and the dry temperatures become significantly lower than the actual temperature. Then we sum up all available matches and levels to obtain the mean COSMIC-radiosonde temperature difference ($\overline{\Delta T_{CR}}$) and the standard deviation of the temperature difference ($SD_{\overline{\Delta T_{CR}}}$) for each radiosonde type.

3. Results and Discussions

3.1. COSMIC and Radiosonde Temperature Differences among Radiosonde Types

[9] Figure 1 depicts temperature differences between COSMIC and radiosonde for MRZ, Shanghai, VIZ-B2, and Vaisala-RS92, respectively. The sample number at each level is also plotted in Figure 1. The dramatic drop in sample size with height for MRZ data may be due to balloons bursting at lower elevation in cold environments than in warm ones. The mean and standard deviation of the temperature differences from 12 km to 25 km for each radiosonde type are summarized in Table 1. Despite the fact that COSMIC observations represent a weighted average over a cylindrical volume about 200 km long and a vertical scale of about 1 km [*Anthes et al.*, 2000] and radiosondes take point measurements, the temperature profiles of each radiosonde type in general agree well with those of COSMIC, with smaller than 0.5 K mean differences and less than 2.0 K standard deviations (Figure 1). A negative temperature difference (∼−0.26 K) between COSMIC and MRZ radiosonde occurs from 14 to 25 km, while a positive difference relative to COSMIC profiles is shown above 18 km for VIZ-B2 radiosonde (∼0.23 K). The standard error of the mean (SEM) is also computed, but is too small to be plotted in Figure 1. With about 4500 and 1500 COSMIC-radiosonde matches for MRZ and VIZ-B2 in Figure 1, the SEM at each level is less than 0.05 K. This indicates that although dramatic drop in sample size with height, the COSMIC-MRZ/VIZ-B2 differences are still statistically significant. Relaxing the collocation criteria for valid RO and radiosonde comparison pairs from 2 h and 300 km to 4 h and 500 km merely increases the standard deviation from 2.0 K to 2.2 K. The temperature profiles of Shanghai and Vaisala-RS92 radiosondes are strongly consistent with those of COSMIC, with a mean difference close to −0.03 K (Table 1 and Figure 1).

3.2. Radiative Effect on Radiosonde Temperature Anomalies

[10] The quality of radiosonde temperature measurements varies by day and night for different radiosonde sensor types (Luers98). To further identify the possible causes of the

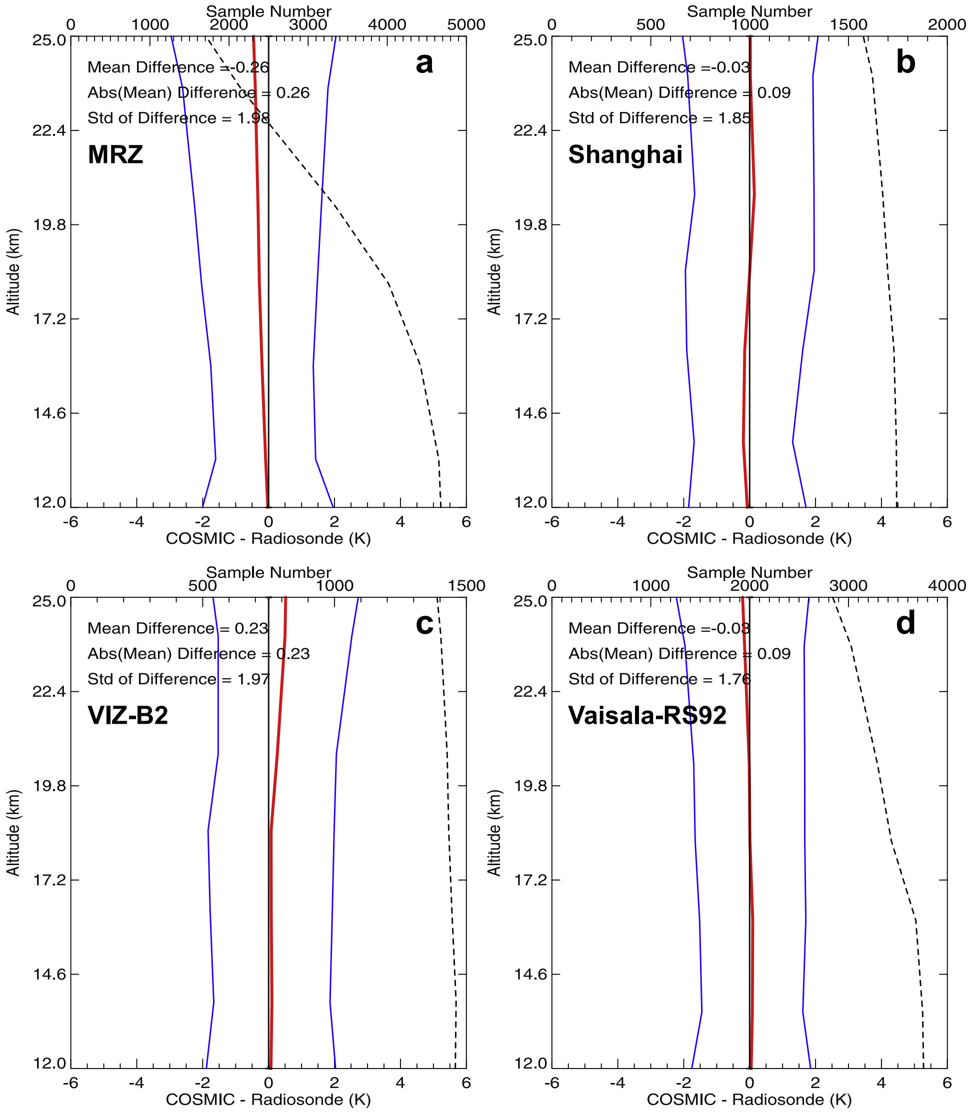

Figure 1. Comparisons of temperature between COSMIC and radiosonde for (a) MRZ, (b) Shanghai, (c) VIZ-B2, and (d) Vaisala-RS92. (The red line is the mean difference; the blue line is the standard deviation; the dotted line is the sample number. The top X axis shows the sample number. The same symbols are also used for the following plots.)

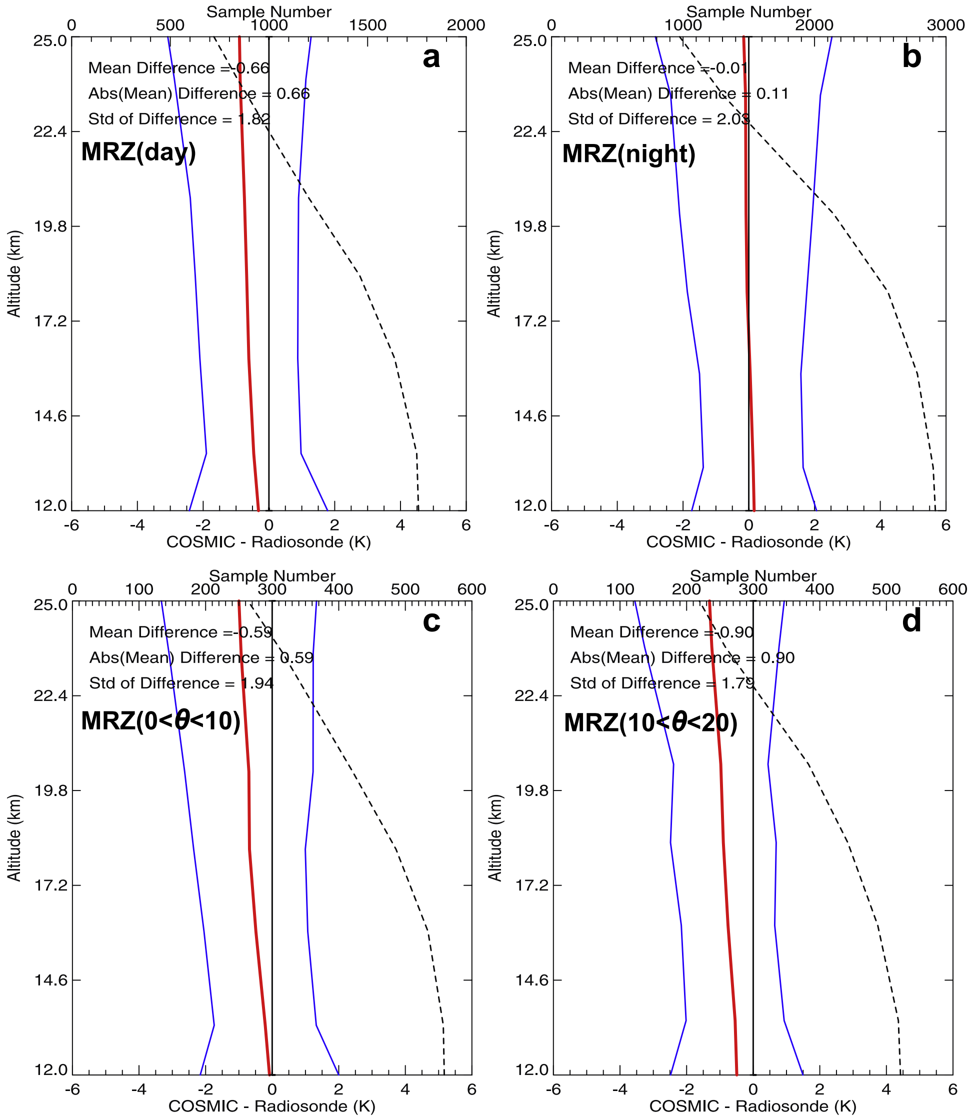

Figure 2. Temperature difference between COSMIC and MRZ radiosonde in (a) day, (b) night, (c) for solar elevation angle 0°–10°, and (d) for solar elevation angle 10°–20°.

statistically significant COSMIC and radiosonde differences for MRZ and VIZ-B2, we separate the COSMIC-radiosonde comparison for daytime and nighttime for MRZ and VIZ-B2 (Figures 2 and 3, respectively).

[11] Figure 2 shows a warm bias for MRZ relative to COSMIC above 12 km, and the bias increases to about 1.0 K at 25 km during the day, while there is a less than 0.1 K COSMIC-MRZ temperature difference at night. This roughly 1.0 K day/night temperature difference around 25 km for MRZ relative to COSMIC is probably caused by radiative effects. Luesr98 has demonstrated that because the Russian MARS radiosondes (the same manufacturer of MRZ) have a higher solar absorptivity (α = 0.2) and a very low sensor emissivity (ε = 0.04), the Russian MARS radiosondes also contain significant warm temperature biases with larger solar elevation during the day due to radiative heating, but with a close-to-zero temperature bias at night.

[12] To further investigate the possible cause of the temperature differences between COSMIC and MRZ during the day, we compare COSMIC and MRZ for different solar elevations angle (θ) in Figure 2. Here we divide COSMIC-MRZ matches into two groups, one with θ of 0°–10° and another with θ of 10°–20° since the solar elevation angle mostly ranges from 0° to 20° during the winter in the daytime over Russia. A large solar elevation angle indicates stronger direct solar heating. Comparisons show that MRZ has a larger mean temperature difference (~0.9 K) relative to COSMIC for θ of 10°–20° than for θ of 0°–10° (~0.59 K). Results demonstrated here are consistent with the temperature errors associated with radiative heating for Russian radiosondes (e.g., RKZ and MARS of Luers98).

[13] Figure 3 depicts the COSMIC-VIZ-B2 temperature comparisons for day and night. Relative to COSMIC, VIZ-B2 contains a warm bias (~0.37 K) during the day (Figure 3a). On the contrary, VIZ-B2 shows a cold bias relative to COSMIC of ~0.4–1.2 K at night (Figure 3b). Because VIZ radiosondes have higher sensor emissivity (ε = 0.85) and a solar absorptivity (α) of 0.15, the VIZ

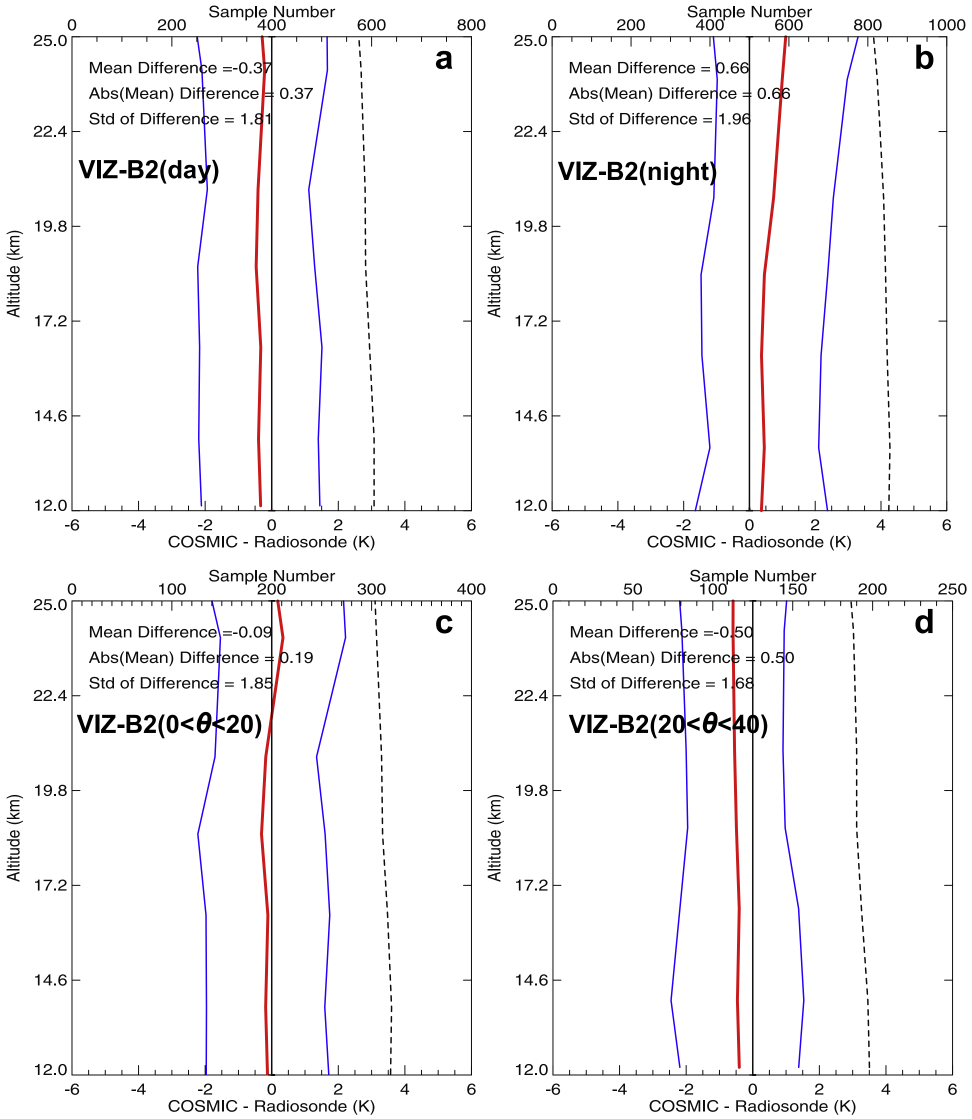

Figure 3. Temperature difference between COSMIC and VIZ-B2 radiosonde in (a) day, (b) night, (c) for solar elevation angle 0°–20°, and (d) for solar elevation angle 20°–40°.

sensors may be subject to radiative heating during the day (see below) and radiative cooling during the night, which results in the opposite temperature biases relative to COSMIC. Luers98 has also identified a cold bias in VIZ-B2 radiosondes at night.

[14] With a strong solar absorptivity (α = 0.15), the performance of the VIZ-B2 temperature sensor is also affected by solar radiation. Figure 3 depicts the COSMIC-VIZ-B2 temperature comparisons for θ of 0°–20° and 20°–40°. For θ of 0°–20°, a slight warm bias relative to COSMIC is shown below 20 km (Figure 3c) due to weaker solar heating. Stronger solar heating for θ of 20°–40° results in an increase of the mean COSMIC-VIZ-B2 temperature difference to about 0.5 K. Although this approach doesn't exclude thermal lag effect on radiosonde biases, which are unlikely dependent on the solar elevation angle, results here still demonstrate that high precision and geographically independent COSMIC dry temperature profiles are very useful for differentiating radiosonde temperature radiative errors resulting from instrument characteristics.

3.3. Temperature Anomalies Between "Old" and "New" Radiosonde Sensors in China

[15] Although the COSMIC-radiosonde temperature differences in general agree well with the temperature errors identified by Luers98 for VIZ-B2 and Russian radiosondes, the COSMIC-Shanghai comparison in Figure 1 disagrees with the results given by Luers98. Luers98 identified cold and warm biases in the lower stratosphere during the night and the day, respectively, whereas we find a much smaller (close to −0.03 K) mean COSMIC-Shanghai temperature difference, as shown in Figure 1. Note that this may be because Luers98 used an old version of the Chinese radiosonde, GZZ, which was introduced in 1960s, while an improved GZZ (named Shang/M) is compared with COSMIC in this study.

[16] Since 2006 a new type of radiosonde named Shang/E has been widely used in China. Compared to Shang/M, a bimetallic strip with a mechanical sounding system, Shang/E is a rod thermistor with an electronic system.

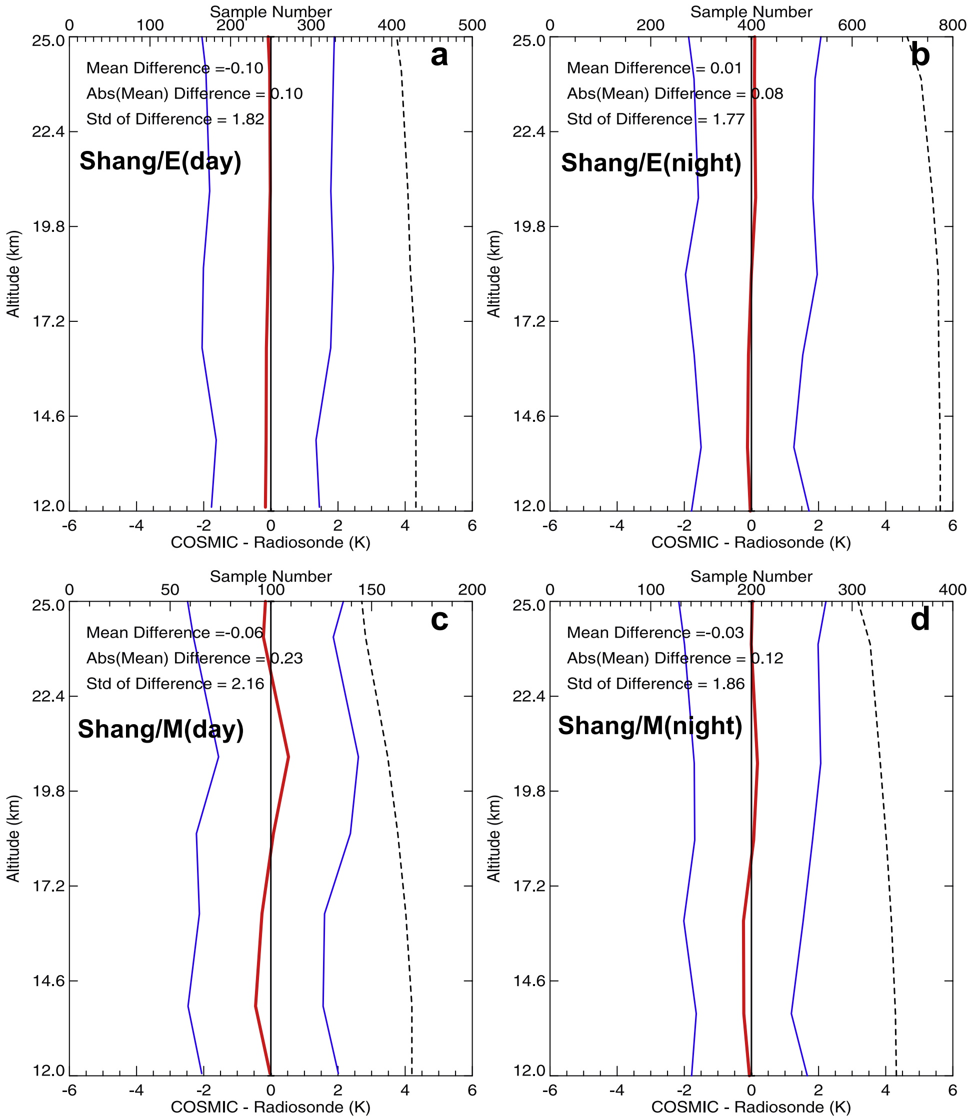

Figure 4. Temperature difference between COSMIC and Shang/E radiosonde in (a) day, (b) night, and temperature difference between COSMIC and Shang/M in (c) day, and (d) night.

Currently, 80 Shang/E radiosonde stations and 40 Shang/M stations are used for upper air soundings in China. To demonstrate that COSMIC temperature data are also useful for differentiating the quality between "old" and "new" radiosonde types used in the same geographical region, we compare COSMIC temperature profiles with those of Shang/M and Shang/E during the day and at night. The results, shown in Figure 4, indicate that the Shang/E temperatures are very close to those of COSMIC, with a close-to-zero mean difference in both day and night. In contrast, the Shang/M radiosonde shows an opposite temperature bias (~0.1 K) relative to COSMIC above and below 18 km in the night (Figure 4d). During the day, it has a warm bias of 0.5 K near 14 km and a cold bias of the same magnitude near 20 km (Figure 4c). The mean absolute COSMIC-radiosonde difference for Shang/M in daytime is about 0.3 K. This may be caused by radiation-heating-induced error and the high lag coefficient of the Shang/M radiosonde. With rapid development of meteorological operations in China, the higher accuracy Shang/E radiosonde system will gradually replace the Shang/M radiosonde system.

4. Summary

[17] Results from this study show that temperature measurements from Vaisala-RS92 and Shanghai radiosondes agree well with COSMIC with a close-to-zero difference. MRZ shows a warm bias above 15 km relative to COSMIC. This warm bias seems to be caused primarily by solar radiation heating. The warm bias increases with solar elevation angles during the daytime. For VIZ-B2, a cold bias relative to COSMIC occurs at night, which may result from radiative cooling. In addition, we show that the temperature measurements from a new Chinese radiosonde system are improved compared to an older system through comparison with COSMIC measurements. The COSMIC data agree better with the improved electronic system (i.e.,

Shang/E) rather than the old mechanical sounding system (i.e., Shang/M), although the mean differences for both comparisons are similar.

[18] Overall these results suggest that COSMIC temperature observations are extremely useful as benchmark observations for differentiating radiosonde temperature errors resulting from instrument characteristics.

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