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Comparison of GPS radio occultation soundings with radiosondes

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[1] The radio occultation (RO) sounding technique that uses signals transmitted by the Global Positioning System (GPS) has evolved as an important global observing technology. In this paper, we compare RO refractivity profiles from the CHAMP (CHAllenging Minisatellite Payload) satellite mission with those calculated from radiosonde soundings over five geographical areas, each of which uses a different type of radiosonde. CHAMP RO soundings that occur within 2 hours and 300 km of radiosonde soundings are used during the period from June 2001 through March 2004. The comparison was made between the altitudes of 5–25 km, where RO soundings are most accurate. These results indicate that the RO soundings are of sufficiently high accuracy to differentiate performance of various types of radiosonde. The differences in performance among various types of radiosonde present a challenge for climate analysis. In this regard, RO is a considerably more robust measurement technique for climate monitoring. **Citation:** Kuo, Y.-H., W. S. Schreiner, J. Wang, D. L. Rossiter, and Y. Zhang (2005), Comparison of GPS radio occultation soundings with radiosondes, *Geophys. Res. Lett.*, *32*, L05817, doi:10.1029/2004GL021443.

1. Introduction

[2] Active atmospheric limb sounding technique making use of radio signals transmitted by the Global Positioning System (GPS) was first demonstrated in the proof-of-concept GPS/MET experiment [*Ware et al.*, 1996]. A review of GPS radio occultation (RO) sounding technique is given by *Kursinski et al.* [1997] and *Lee et al.* [2000]. Comparison of RO soundings from GPS/MET with correlative data indicated that the RO soundings possess the equivalent temperature accuracy of ~1 K in the range from the lower troposphere to 40 km [*Ware et al.*, 1996; *Kursinski et al.*, 1996; *Rocken et al.*, 1997]. Evaluation of RO soundings from two follow-on missions, CHAMP (CHAllenging Minisatellite Payload) [*Wickert et al.*, 2004] and SAC-C (Satellite de Aplicaciones Cientificas-C), by *Hajj et al.* [2004] and *Kuo et al.* [2004], has substantiated the results of GPS/MET.

[3] The radiosonde represents the only operational instrument that measures atmospheric pressure, temperature, humidity, and wind profiles directly with high vertical resolution and near-global coverage, and has been operating for more than five decades. The radiosonde data have been the backbone for operational forecasting and a key data source for climate analysis. Radiosonde observations have also been used as a benchmark to calibrate satellite remote sensing observations and validate satellite-retrieved soundings. The underlying assumption is that the radiosonde observations are, in general, of higher accuracy than the satellite soundings. While this assumption may be valid for passive infrared and microwave sounders, which are based on nadir-viewing geometry and have relatively low vertical resolution, it is not necessarily true for RO soundings, which are active soundings based on limb-viewing geometry and have high vertical resolution. Perhaps, the biggest challenge for using radiosondes as benchmarks is their lack of absolute accuracy. Radiosondes are known to suffer from radiation errors in temperature measurements and have various errors/biases in humidity data, especially in the upper troposphere [e.g., *Luers and Eskridge*, 1998; *Wang et al.*, 2003]. In addition, global radiosonde data have spatial and temporal inhomogeniety errors because of irregular distribution of radiosonde stations and constant changes of instruments in space and time. The comparisons of global upper troposphere humidity with satellite data reveal variations of differences with regions associated with different types of radiosondes [*Soden and Lanzante*, 1996]. In addition, radiosonde soundings consist of a series of point measurements (that drift as they ascend through the atmosphere) while satellite soundings, including RO soundings, represent averages over finite volumes of the atmosphere, and hence there are significant representativeness issues when the two types of soundings are compared [*Kuo et al.*, 2004].

[4] Given the fact that the quality of RO soundings is independent of geographical location, one may ask the question: *Are RO soundings of sufficiently high accuracy to differentiate the performance of different types of radiosonde?* In this paper, we calculate the mean absolute difference in refractivity between CHAMP RO data and radiosonde soundings over five geographical areas that each uses only a single type radiosonde, from June 2001 through March 2004. We also calculate the corresponding difference between CHAMP RO data and the European Centre for Medium Range Forecasts (ECMWF) global analysis over the same geographical area over the same period. Through such comparison, we try to assess the relative accuracy between the RO soundings and the radiosondes, and the performance of different types of radiosonde.

2. Method of Comparison

[5] Globally, there are roughly 850 radiosonde stations using about fourteen different types of radiosonde systems

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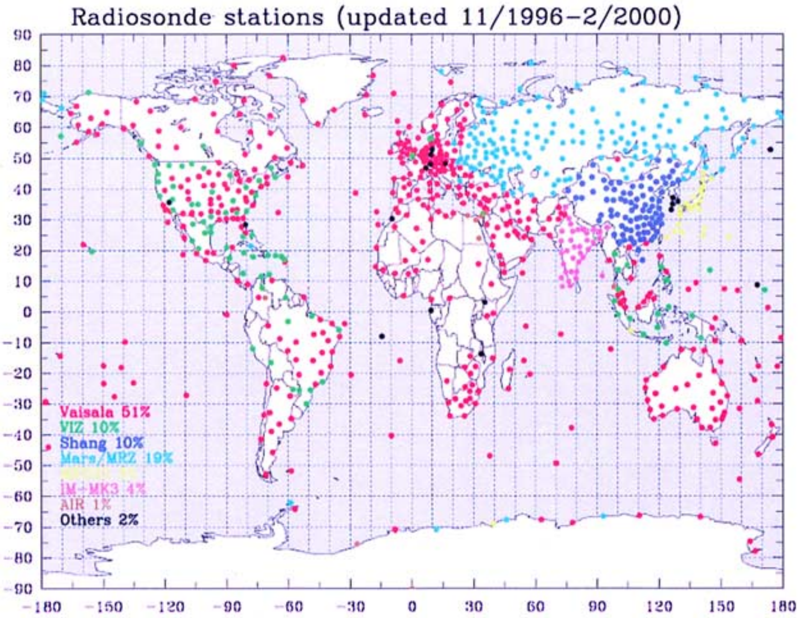

Figure 1. Geographic distribution of global radiosonde stations (total 852) colored by radiosonde types. The percentage given in legend is the percentage of stations used by each type of radiosonde.

(Figure 1). All radiosonde systems have known observational errors, and are dependent upon the type of sensors. Moreover, equipment and procedural changes are introduced from time to time. Such changes can introduce spurious climate change signals. Several countries use a mixture of different types of radiosonde. However, five countries use a single type of radiosonde. Australia, China, India, Japan, and Russia use Vaisala, Shanghai, IM-MK3, MEISEI, and Mars radiosondes, respectively. By comparing RO soundings with radiosonde soundings from these countries, we may be able to assess the performance of these different types of radiosondes because the errors of GPS RO soundings are independent of geographic areas. The radiosonde data used in this study were obtained from the DS353.4 radiosonde archive at the National Center for Atmospheric Research (NCAR). Operational radiosonde data are available twice daily at mandatory, significant, and some additional levels with a mean vertical resolution of ~53 hPa [*Wang et al.*, 2000].

[6] The German CHAMP mission was launched in July 2000, and its RO soundings are available since June 2001. In this study we compare radiosonde soundings from the five countries discussed above with CHAMP RO soundings that were located within 300 km and 2 hours of the radiosonde releases for the period from June 2001 through March 2004. There were a total of 1966 matches (averaged over the altitude of 5 to 25 km). This ranges from 87 matches for India (IM-MK3) to 1003 matches for Russia (Mars).

[7] Recently, *Kuo et al.* [2004] evaluated the accuracy of CHAMP and SAC-C RO soundings globally for the month of December 2001, by comparing the RO data against global analyses from ECMWF and NCEP. They found that RO soundings have the highest accuracy from about 5 km to 25 km. Therefore, we restrict the comparison between radiosondes and RO soundings between 5 and 25 km. Also, the comparison is performed in terms of refractivity, N, because 1) it is the fundamental RO retrieval parameter and 2) retrievals of pressure, temperature, and moisture contain additional errors related to the errors of *a priori* model information. The CHAMP refractivity profiles at 200 m vertical resolution are readily available from the COSMIC Data Analysis and Archival Center (CDAAC; http://www.cosmic.ucar.edu:8080/cdaac/index.html). For the radiosonde, refractivity is calculated from the temperature, pressure, and moisture using the following equation:

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

where N is refractivity, T is temperature in Kelvins, P and P_w are total air pressure and partial pressure of water vapor in hPa, respectively. The RO and radiosonde data are both interpolated by cubic splines to a standard altitude grid with 500-m intervals. Fractional refractivity differences are then calculated on this grid between 5 and 25 km, for each available match:

$$\Delta N_{CR}(l,n) = \frac{N_{CHAMP}(l,n) - N_{RS}(l,n)}{N_{CHAMP}(l,n)} \tag{2}$$

where, N_{CHAMP} and N_{RS} are CHAMP and radiosonde refractivity, respectively, and l and n are indices for vertical level and the RO and radiosonde match, respectively. For each radiosonde type, we sum over all available levels (not all balloons reach 25 km) and matches, to obtain the mean fractional refractivity differences:

$$\overline{\Delta N_{CR}} = \frac{1}{N \times L} \sum\nolimits_{l=1}^{L} \sum\nolimits_{n=1}^{N} \Delta N_{CR}(l,n) \tag{3}$$

where the subscript "CR" stands for CHAMP and radiosonde comparison.

Table 1. Mean Absolute Fractional Differences and Standard Deviation (S.D.) of Refractivity Between CHAMP RO Soundings and the Soundings From Five Different Types of Radiosonde Systems[a]

Region	Sonde Type	# of Matches	$\overline{\Delta N_{CR}}$/S.D. (%)	$\overline{\Delta N_{CE}}$/S.D. (%)
India	IM-MK3	87	0.82/3.2	0.15/1.0
Russia	Mars	1003	0.30/1.3	0.09/0.9
Japan	MEISEI	107	0.26/1.7	0.14/1.1
China	Shanghai	402	0.19/1.4	0.15/1.0
Australia	Vaisala	366	0.18/1.3	0.13/0.9

[a] The number of matches is computed as the average number of CHAMP – radiosonde (“CR”) matches from 5 to 25 km. The corresponding differences between CHAMP RO soundings and the ECMWF analysis are designated as “CE”.

[8] For comparison, we also calculate the mean fractional difference between the CHAMP RO soundings and refractivity profiles derived from the ECMWF global analysis. The global analysis was interpolated to the time and location of the RO soundings, and then the difference was computed. The results are designated as $\overline{\Delta N_{CE}}$, where the subscript “CE” stands for CHAMP and ECMWF comparison.

[9] We note from equation (1) that at these altitudes where the water vapor pressure is small, a percentage difference in refractivity N corresponds to the same percentage difference in absolute temperature. Thus for a temperature of 250K, a 1% difference in N corresponds to a 2.5 K difference in temperature. We will use this value of temperature to interpret the % differences in N in terms of temperature in the results.

3. Results

[10] Table 1 summarizes the mean absolute fractional differences between CHAMP RO soundings and the five different types of radiosondes (e.g., we take the absolute value of equation (2) before calculating the mean). The results indicate that Vaisala and Shanghai radiosondes used by Australia and China, respectively, agree most closely with the RO refractivity profiles. The mean absolute fractional differences are only 0.18% and 0.19% for Australia and China, respectively (corresponding to a temperature difference of about 0.5K). IM-MK3 radiosonde used by India, on the other hand, has the largest deviation from RO data (0.82%, or equivalent of ~2.05K). Japanese (MEISEI) and Russian (Mars) radiosonde systems are comparable, having $\overline{\Delta N_{CR}}$ of 0.26% (~0.6K) and 0.30% (~0.7K), respectively. Of course the RO soundings also contain errors, and these errors and the representativeness differences discussed above also contribute to $\overline{\Delta N_{CR}}$.

[11] CHAMP RO refractivity profiles are also compared with the ECMWF global analysis. We find that the mean absolute fractional differences in N between CHAMP and ECMWF do not vary significantly from one region to another. It varies from 0.09% (~0.2K) over Russia to 0.15% (~0.4K) over India and China. In contrast, the CHAMP and radiosonde differences vary by a factor of four (from 0.18% to 0.82%). This suggests that the quality

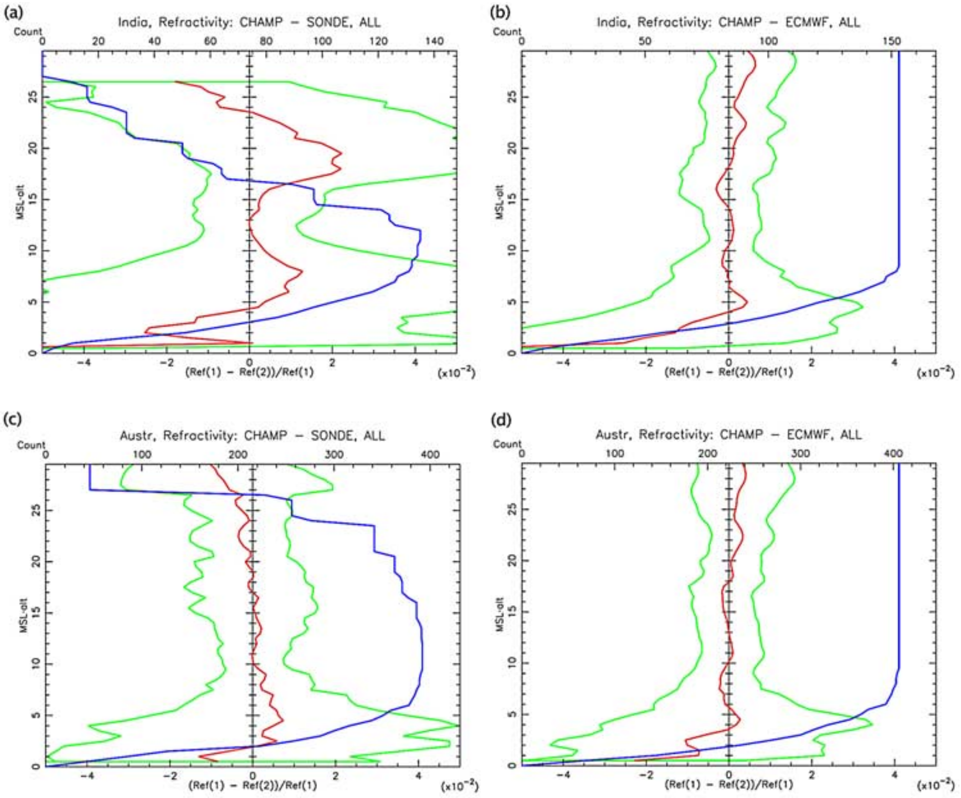

Figure 2. Comparisons of (a) RO and radiosonde and (b) RO and ECMWF over the India region. The red curves are mean differences, the green curves are standard deviations, and the blue curves are the data counts (label at the top of figure). Corresponding comparisons over Australia region are shown in (c) and (d).

of RO soundings does not vary significantly between different geographical regions.

[12] In order to gain further insight on these results, we show in Figure 2 the profile comparisons of (a) RO soundings with radiosonde and (b) RO soundings with ECMWF global analysis over India. Large deviations exist below 5 km, which reach $\sim$4% near the surface. This is attributed to the well-known negative refractivity bias associated RO soundings in the tropical lower troposphere [*Rocken et al.*, 1997; *Sokolovskiy*, 2003; *Ao et al.*, 2003], as a similar bias can be found in the RO and ECMWF comparison. Above 5 km, however, two large differences are found, one at 8 km, and the other at about 20 km, with maximum fractional differences of 1% ($\sim$2.5K) and 2% ($\sim$5K), respectively. Moreover, the standard deviations (S.D.) of these differences are very large, varying from 1 to 5% (with a mean S.D. of 3.2%). The number of matches (indicated by blue curves) drops significantly above 15 km, which is due to the early termination of the radiosonde soundings. For the RO – ECMWF comparison, the mean fractional differences are generally less than 0.5% throughout the layer of 5–25 km. Moreover, the standard deviation of the differences is generally less than 1% in the middle to upper atmosphere.

[13] Figures 2c and 2d show the corresponding plots over Australia. The differences between RO soundings, Vaisala radiosonde, and ECMWF global analysis are all of comparable magnitude. The negative refractivity bias of RO soundings below 3 km is also evident, but the magnitude is less. This is attributed to the fact that India is located mostly over tropical latitudes with ample moisture in the lower troposphere. Australia, on the other hand, is located at higher latitudes and has less moisture in the lower troposphere. In the layer between 5 and 25 km, the RO – ECMWF comparison is comparable to that over India. This again indicates that the quality of RO soundings do not vary significantly between different geographical areas. The large variations of RO – radiosonde deviations between different geographical areas can be attributed to the different performance of different types of radiosonde.

4. Summary

[14] In this paper, we compared CHAMP RO soundings, radiosonde soundings, and ECMWF profiles over five geographical areas, each using a single type of radiosonde, during the period of June 2001 through March 2004. We did not find significant variation of the quality of the RO soundings over different geographical areas. This is evidenced by the relatively small variations in the RO and ECMWF differences between geographical areas. Compared against the CHAMP RO refractivity profiles, Vaisala and Shanghai radiosondes follow most closely with the RO soundings, while IM-MK3 radiosonde shows the largest differences. These results indicate that the RO soundings are of sufficiently high accuracy to differentiate the variation in performance among various types of radiosonde. The corresponding differences in refractivity between RO soundings and the ECMWF analysis are smaller than the RO-radiosonde differences over any geographical area. The significant variations in performance among different radiosondes present a challenge for climate analysis. In this regard, RO is a considerably more robust measurement technique for climate monitoring. Also, as reflected by the close agreement between RO and ECMWF refractivities, the RO observations are more representative of global model values, which are volume averages rather than point measurements. A similar conclusion was reached by *Kuo et al.* [2004].

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