7.11 USE OF GPS RADIO OCCULTATION DATA FOR CLIMATE MONITORING

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1. INTRODUCTION

The Global Positioning System (GPS) satellite constellation was developed for precise navigation and positioning. The GPS today consists of 28 operational satellites that transmit L-band radio signals at two frequencies (L1 at 1.57542 GHz and L2 at 1.2276 GHz) to a wide variety of users in navigation, time transfer, and relative positioning and for an ever-increasing number of scientists in geodesy, atmospheric sciences, oceanography, and hydrology.

Atmospheric soundings are obtained using GPS through the radio occultation (RO) technique, in which satellites in low-Earth orbit (LEO), as they rise and set relative to the GPS satellites, measure the phase of the GPS dual-frequency signals. From this phase the Doppler frequency is computed. The Doppler shifted frequency measurements are used to compute the bending angles of the radio waves, which are a function of atmospheric refractivity. The refractivity is a function of electron density in the ionosphere and temperature, pressure, and water vapor in the stratosphere and troposphere.

A review of GPS RO sounding technique can be found in Kursinski et al. (1997) and a special issue of *Terrestrial, Atmospheric and Oceanic Sciences* -- TAO (2000). Comparison of RO soundings from GPS/MET (GPS Meteorology) experiment 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.

The GPS RO sounding technique, making use of highly coherent radio signals from the GPS has many unique characteristics, including: (i) high accuracy, (ii) high vertical resolution, (iii) all weather sounding capability, (iv) independent of radiosonde or other calibration, (v) no instrument drift and (vi) no satellite-to-satellite bias (Rocken et al. 1997; Kursinski et al. 1997; Kuo et al. 2004). These characteristics make GPS RO data ideally suited for climate monitoring and global weather prediction. Anthes et al. (2000) provided many examples on the possible applications of GPS RO data to meteorology and climate. In this paper we provide an overview of an upcoming GPS RO mission, known as COSMIC, and review a few GPS RO studies that are relevant to climate research.

2. BRIEF DESCRIPTION OF THE COSMIC MISSION

COSMIC (Constellation Observing System for Meteorology, Ionosphere and Climate) is a joint mission between Taiwan and U.S., with a goal to demonstrate the use of GPS RO data in operational weather prediction, climate analysis, and space weather forecast. COSMIC will launch six LEO satellites in late 2005. Each satellite will carry three atmospheric science payloads: (1) a GPS radio occultation receiver for ionospheric and neutral atmospheric profiling and precision orbit determination; (2) a Tiny Ionospheric Photometer (TIP) for monitoring the electron density via nadir radiance measurements along the sub-satellite track; and (3) a Tri-Band Beacon (TBB) transmitter for ionospheric tomography and scintillation studies. With the ability of performing both rising and setting occultation, COSMIC is expected to produce approximately 2,500 GPS RO soundings uniformly distributed around the globe per day. The COSMIC data will be available in near-real-time (within 2 hr of observations) to support the use of GPS RO data in operational numerical weather prediction. The climate-research quality COSMIC data will be available in about two weeks after real time. These data will make use of the most accurate satellite orbits information. The Brazilian EQUARS mission will be launched in early 2006, and will provide an additional 500 GPS

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RO soundings per day. Typical distribution of the combined COSMIC and EQUARS GPR RO over a 24-h period is shown in Fig. 1. Further information on the COSMIC Program can be found at: http://www.cosmic.ucar.edu/

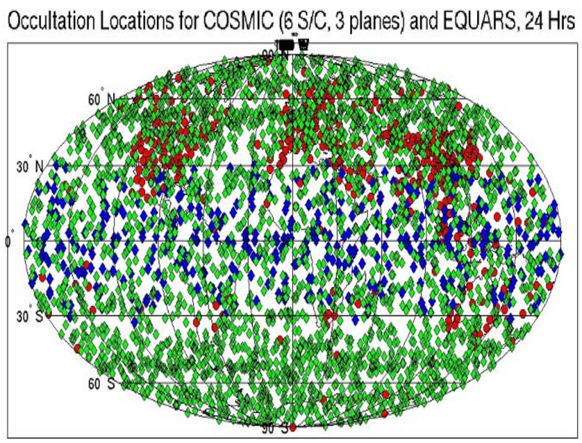

Figure 1. Typical GPS RO sounding locations from COSMIC (in green) and radiosonde sites in red. The figure also shows, in blue, the expected sounding locations from the Brazilian EQUARS mission. EQUARS is expected to overlap at least with part of the COSMIC mission and would nicely complement COSMIC in the tropics.

3. EVALUATION OF THE ACCURACY OF RADIOSONDE SYSTEMS

Balloon soundings from the global radiosonde network, which has been in existence for over 50 years, has been the backbone for operational forecasting and a key data source for climate analysis. Because of their reliability and known accuracy, radiosonde observations have been used as a benchmark to calibrate satellite remote sensing observations and sounding retrievals. 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 have relatively low vertical resolution, it is not necessarily true for GPS RO soundings, which are derived from an active sounding technique and have high vertical resolution.

Figure 3 shows the operational radiosonde network. Globally, there are roughly 850 radiosonde stations using about fourteen different types of radiosonde systems. All radiosonde systems have observational errors that are fairly well known, and are dependent upon the type of

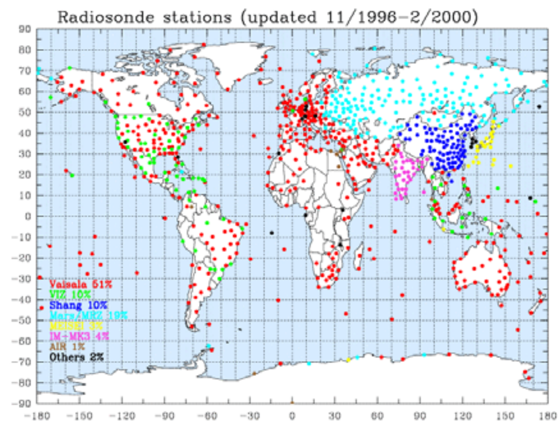

Figure 2. Geographic distribution of global radiosonde stations (total 852) colored by radiosonde types. The percentage given in legend is the percentage of stations used by each type of radiosonde.

sensors. Moreover, equipment and procedural changes are introduced from time to time. Such changes can introduce spurious climate change signals.

Given the fact that the quality of GPS RO soundings is independent of geographical areas, one may ask the question: *Are GPS RO soundings of sufficiently high accuracy to differentiate the performance of different types of radiosonde systems?* To answer this question, Kuo et al. (2005) calculated the mean absolute difference in refractivity between CHAMP RO data and radiosonde soundings (N_{CR}) from June 2001 to March 2004, from 5 km to 25 km in elevation, over five countries that only make use of one uniform type of radiosonde system. Kuo et al. (2005) also calculated the difference between refractivities from CHAMP and the European Centre for Medium Range Forecasts (ECMWF) global analysis (N_{CE}) over the same geographical area over the same period.

The results (Table 1) show that the Vaisala system and the Shanghai radiosonde system used by Australia and China have the best agreement with the CHAMP RO data. The mean absolute differences, compared with CHAMP RO data, are only 0.18% and 0.19% for Vaisala and Shanghai systems, respectively. The IM-MK3 system used by India has the largest disagreement (0.82%) with the CHAMP GPS RO data. The corresponding differences between the ECMWF analysis and RO soundings are smaller than the differences between RO and any of the radiosondes. It is interesting to note that the variation in mean absolute differences between

CHAMP and ECMWF does not vary significantly from one region to another (from 0.0.09% to 0.15%), while the CHAMP and radiosonde differences vary by a factor of 4.5 (from 0.18% to 0.82%).

Table 1. Mean fractional differences and standard deviation of refractivity between CHAMP RO soundings and the soundings from five different types of radiosonde systems. The number of matches is computed as the average number of "CR" matches from 5 to 25 km.

Region	Sonde type	# of match	N_{CR} (%)/ S.D.	N_{CE}(%)/ S.D.
India	IM-MK3	87	0.82/3.2	015/1.0
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

In order to gain further insight on these results, we show in Fig. 3a the profile comparisons of RO soundings with radiosonde over India. Large deviations exist below 5 km, which reach ~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), as a similar bias can be found in the RO and ECMWF comparison (not shown). Above 5km, however, two large differences are found, one at 8 km, and the other at about 20 km, with maximum fractional differences of 2% (~5K) and 3% (~7.5K), 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. Figure 3b shows the corresponding plots over Australia. The differences (both in terms of the mean and S.D.) between GPS RO and radiosondes are much smaller over Australia. 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 over Australia is comparable to that over India (see Table 1). 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.

These results suggest that the GPS RO soundings are of high enough accuracy to differentiate the difference in performance among the various radiosonde types. The differences in performance among different radiosondes present a challenge for climate analysis. In this regard,

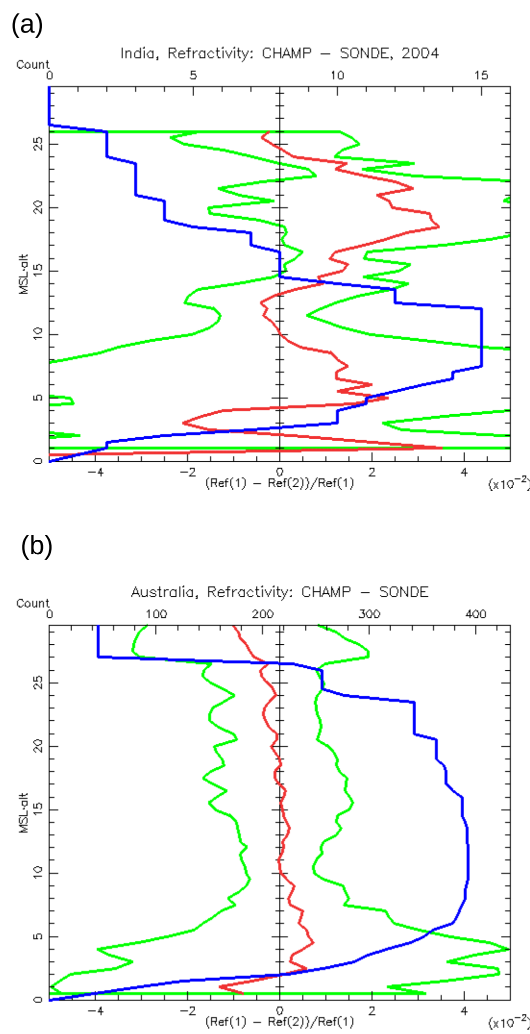

Figure 3. Comparisons of GPS RO and radiosonde over the (a) India and (b) Australia regions. The red curves are mean differences, the green curves are standard deviations, and the blue curves are the data counts (label at the top of figure).

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.

4. EVALUATION OF GLOBAL ANALYSES

Weather prediction models and data assimilation systems have evolved and improved steadily over the past fifty years. This is also true for the global observing system. As a result, the quality of operational global analyses has improved over the years. These improvements are obviously advantageous for operational numerical weather prediction. However, the significant differences over time in the quality of operational global analysis makes them problematic for analysis of climate change or variability. One problem is that the variations in the models and data assimilation systems can introduce fictitious climate change signals. In order to produce a consistent dataset suitable for climate analysis, global reanalyses using a stable and state-of-the-art data assimilation system were produced by a few operational centers. The NCEP/NCAR reanalysis project uses a global analysis/forecast system to perform data assimilation using historical observations, spanning the time period from 1948 to the present (Kalnay et al. 1996). The ECMWF has produced a global reanalysis for the period 1957-2002, including the stratosphere up to 1 hPa, based on the use of variational data assimilation techniques. This is known as the ERA 40 reanalysis. Description of the ERA40 can be found at the ECMWF web site (http://www.ecmwf.int). Using a constant data assimilation system, such global reanalyses provide useful information on climate variations. However, before they can be used reliably for climate analysis, it is important to evaluate the accuracy of these reanalyses.

Recently, Randel et al. (2004) compared the deseasonalized interannual variations in tropical tropopause temperatures from various global reanalyses against radiosonde (sparse) observations and GPS RO data (Fig. 4). They showed that GPS data agree well with the radiosonde data and the ERA40 reanalysis. However, the NCEP/NCAR reanalysis is an outlier after year 2000. Since the analysis system is constant, this must be related to variations in the input data or how such data are assimilated. For example, the transition from TOVS to ATOVS in July 2001 for the assimilation of the NOAA satellite data may possibly account for such variation. In any event, this comparison shows that the GPS RO data can be a valuable arbitrator for different data sets for global climate analysis.

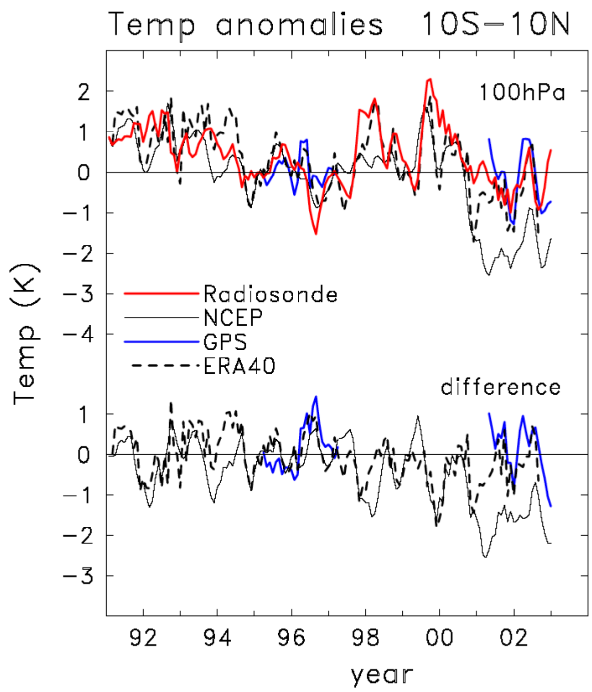

Figure 4. (top) time series of deseasonalized 100 hPa temperature anomalies over 10^o N-S, showing results from four different data sets. Each time series is normalized to be zero for April 1995 – February 1997. (bottom) Difference of the respective time series with averaged radiosonde data. (From Randel et al. 2004).

With the launch of COSMIC and EQUARS, we will obtain almost an order of magnitude more GPS RO soundings than the combined CHAMP and SAC-C missions. Results from the climate studies based on the limited GPS/MET, CHAMP and SAC-C GPS RO soundings provide strong support that the COSMIC and EQUARS data will make a significant contribution to climate research. In this regard, it is important that we maintain a robust GPS RO constellation for long-term climate monitoring.

Acknowledgement

This work was supported by the National Science Foundation (NSF) Atmospheric Sciences Division (ATM) and NSF office of Polar Programs (OPP) grant NSF #OPP-0230361, under the Cooperative Agreement ATM-9732665, the Office of Naval Research, code 322MM, the National Aeronautics and Space Administration, through grant NAG 5-9518 to Ohio State University and UCAR.

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