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CHAMP observations of global gravity wave fields in the troposphere and stratosphere

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[1] This paper presents the analysis of 56 months of CHAMP (Challenging Minisatellite Payload) RO (radio occultation) temperature profiles to study the global gravity wave fields in the troposphere and lower stratosphere. The relatively new GPS (Global Positioning System) RO technique is suitable for global monitoring and provides high vertical resolution, long-term stability, and opportunity of all-weather viewing. The CHAMP data set analyzed in this paper is the largest RO data set used for the investigation of global structure of gravity waves. The analysis also makes use of the global radiosonde data provided by the British Atmospheric Data Centre (BADC). First, the global winter temperature pattern and temperature fluctuations in the troposphere and lower stratosphere are discussed. The global structure of gravity wave variances in the upper troposphere and lower stratosphere for the summer and winter seasons indicate the dominance in the tropical region. The analysis reveals that the maximum potential energy (E_p) is observed around the equator with considerable longitudinal variation. Comparison of the wave energy derived from the CHAMP and radiosonde data sets for the low-latitude region (20°S–20°N) shows good similarity. The observed vertical wave number power spectra were compared with a model spectrum. The low-latitude power spectra show considerable similarities with the model spectrum. However, the disparity increases in the midlatitude or high-latitude sectors; particularly, in the high latitudes the observed spectral power is much underestimated for longer wavelengths. The results demonstrate the usefulness of GPS RO data in determining the global gravity wave fields.

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1. Introduction

[2] Many theoretical and observational studies emphasized the role of gravity waves in determining the large- and small-scale dynamics of the middle atmosphere. On the observational front, various techniques including radar [e.g., *Tsuda et al.*, 1989; *Fritts et al.*, 1990], rocketsonde [*Hamilton*, 1991; *Eckermann et al.*, 1994], radiosonde [*Allen and Vincent*, 1995; *Vincent et al.*, 1997; *Wang and Geller*, 2003], aircraft [*Nastrom et al.*, 1987; *Jasperson et al.*, 1990; *Nastrom and Fritts*, 1992], and lidar [*Mitchell et al.*, 1996; *Whiteway et al.*, 1997; *Sivakumar et al.*, 2006] were widely used to determine the morphology of gravity waves. *Wang and Geller* [2003] used a large database of radiosonde-derived wind and temperature with high vertical resolution from more than 90 stations in American territories including those in the tropical Pacific to develop climatology of gravity wave energy in the troposphere and lower stratosphere. These radiosonde observations cover diverse terrain ranging from tropical islands, to midcontinent plains, to mountains, and to the Arctic. They found that in the Northern Hemisphere the lower stratospheric gravity wave energies decrease poleward and are stronger in winter than in summer. In the troposphere also a similar seasonal variation is noted and they found maximum wave activity in the midlatitudes (35–40 degrees). The above referenced studies have, however, been limited to single locations and brief time periods. This raises the problem of insufficient data for establishing wave climatology on a global scale, despite the good results based on high temporal/spatial resolution profiles from many of the ground-based and space-borne instruments [*Steiner and Kirchengast*, 2000].

[3] New satellite-borne remote sensing measurements provide a detailed description of gravity wave morphology in the troposphere and lower stratosphere, especially over oceans and other radiosonde-sparse regions. Among satellite sensors, passive microwave sounders have been successfully utilized to observe gravity wave activity in the stratosphere with the Microwave Limb Sounder (MLS) on board the Upper Atmosphere Research Satellite (UARS) [*Wu and*

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Waters, 1996; *McLandress et al.*, 2000; *Jiang et al.*, 2004; *Wu and Zhang*, 2004]. The UARS-MLS results on gravity waves were further described with a numerical model by *Alexander* [1998]. GPS-based Radio Occultation (GPS-RO) technique is a relatively new remote sounding technique and it exploits the radio signals received on board a Low Earth Orbiting (LEO) satellite for atmospheric limb sounding. GPS-RO technique can furnish atmospheric profiles (with global coverage) with high vertical resolution (<1 km) and accuracy (<1–2 K in temperatures within the upper troposphere and lower stratosphere) practically unaffected by clouds, precipitation, or aerosols, and the occultations are almost uniformly distributed over the globe. These properties make the RO technique suitable for long-term monitoring of atmospheric change [*Steiner et al.*, 2001]. *Tsuda et al.* [2000] derived a global morphology of gravity wave activity in the stratosphere using GPS-RO data from the GPS/MET Microlab 1 satellite during the period April 1995 to February 1997 with special emphasis on winter months. In another investigation of CHAMP database, *Venkat Ratnam et al.* [2004] studied gravity wave activity in the stratosphere using the data from May 2001 to January 2003. They found large potential energies at tropical and midlatitude regions during winter, larger over continents than over oceans in both hemispheres. In a recent paper *Kishore et al.* [2006] described the climatological characteristics of tropopause parameters derived from CHAMP/SAC-C measurements. Further using the CHAMP data, *de la Torre et al.* [2006] performed a study of global long-term potential energy and mean potential energy per unit mass associated to wave activity in the lower stratosphere.

[4] In the present study we use CHAMP and global radiosonde observations taken during the period of 2001–2005. Long-term data of this kind are particularly useful to confirm the significance of annual and interannual variations in wave activity. Emphasis is given to determine the normalized temperature fluctuations ($T'/\bar{T}$) and gravity wave potential energy (E_p) in two altitude segments in the upper troposphere (10–20 km) and stratosphere (20–30 km); note that at every latitude the 10–20 km region will include part of the lowermost stratosphere, and at high latitudes this region may be almost entirely in the stratosphere. The investigation includes an overview of global gravity wave activity, discussion of the monthly and seasonal variations, and geographical distribution of the gravity wave energy. The tropical (20°S–20°N) behavior of the E_p values is compared with the global radiosonde-derived energy values. We have determined vertical wave number spectra of the normalized temperature fluctuations at 20–30 km during the winter and summer seasons. In the next section a brief description of the data analysis procedure is given and in the subsequent section results and discussion are presented. Finally, section 4 is devoted to summarize some of the conclusions of the present study.

2. Data Analysis

[5] The German CHAMP (Challenging Minisatellite Payload) satellite was launched on 15 July 2000 with an initial altitude of about 454 km. It uses a circular and near-polar orbit with an inclination of 87.2°. The RO experiment was started on 11 February 2001 and has provided data continuously since mid-2001. Details of the system and technical features are given by *Reigber et al.* [2000, 2003] and other detailed description including the retrieval algorithms used for deriving vertical atmospheric profiles is presented in a number of papers [*Hajj et al.*, 2004; *Wickert et al.*, 2004]. CHAMP carries a new generation GPS receiver for RO sounding of the Earth's neutral atmosphere and ionosphere. It records phase and amplitude variations with high temporal resolutions during an occultation event. The new Blackjack GPS receiver has a high signal-to-noise ratio and provides globally distributed atmospheric profiles. It was designed by JPL (Jet Propulsion Laboratory), and they have achieved significant progress in measuring water vapor and temperature profiles in the troposphere and stratosphere. The RO data analysis system at JPL involves mainly the data collection, orbit determination, calibration process, retrieval process, and quality control process. The retrieval uses Abel inversion under the assumption of spherical symmetry of the atmosphere about the ray tangent point. The atmospheric refractivity $N = 10^6(n-1)$ with refractive index n, is the basic meteorological observable derived with the GPS RO technique. The temperature profile is retrieved by means of the equation of refractivity, the hydrostatic equilibrium, and the equation of state [*Hajj et al.*, 2002]. Refractivity contributions due to water vapor pressure are negligible except in the lowest 5 km of tropical atmosphere where NCEP analysis is used to provide water vapor profile. The NCEP temperature at 30 km is used as an initial guess in the JPL retrieval. It is noted that about 150 (on average) high resolution temperature profiles per day were collected since May 2001 and this mission has generated the first long-term RO data set. The vertical resolution of the profiles ranges from 0.1 to 1 km. CHAMP temperature profiles were compared with radiosonde, lidar, ECMWF, NCEP, etc., data sets [e.g., *Wickert et al.*, 2001; *Schmidt et al.*, 2005; *Kishore et al.*, 2006] and authenticated the measurements.

[6] The present study considers a data sample for 56 months that begins from May 2001 to December 2005. The total number of occultation is 187,907 for the 56 months of observations. Radiosonde data used here in the analysis were made available by the British Atmospheric Data Centre (BADC), United Kingdom Meteorological Office (UKMO) for the years from 2001 to 2005. The data set consists of vertical profiles of temperature, dew-point temperature, wind speed, and wind direction from the surface to approximately 20–30 km. Data are reported up to four times daily. Here we used the temperature profiles only. We have found that the height resolution of the measurement varies from ~300 m at the lower troposphere to ~500 m at upper troposphere and lower stratosphere. Some concerns regarding this unequal height resolution are mentioned in the section that follows.

[7] The temperature fluctuation is an important parameter for estimating the potential energy of the gravity wave. It is assumed that the atmospheric temperature profile consists of the background temperature and a fluctuating component. For making the climatological background temperature profile, the use of GPS profiles obtained from various locations is not realistic and it has been shown that such an averaging procedure would make erroneous temperature

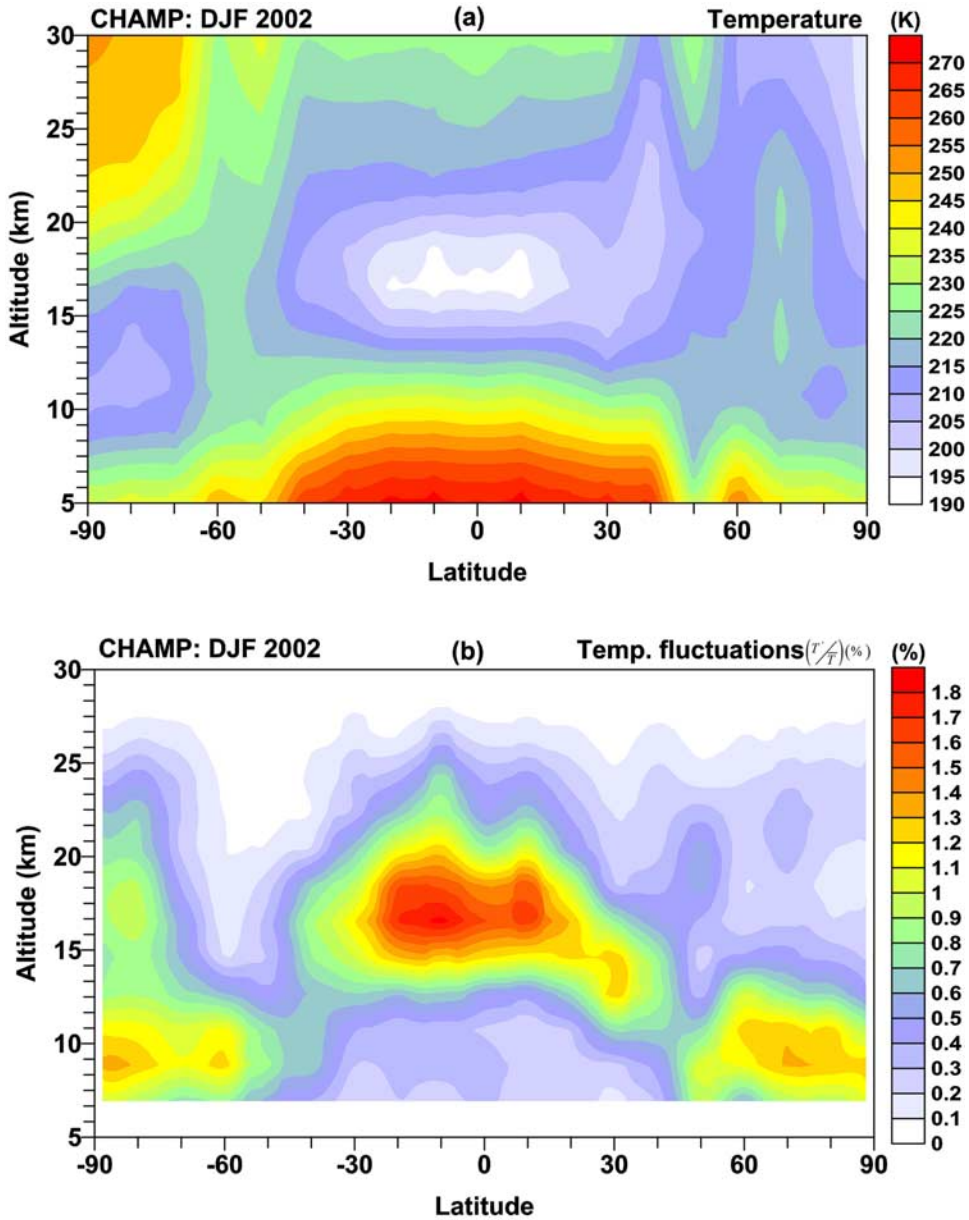

Figure 1. CHAMP estimate of latitude-height structure of the (a) mean temperature and (b) normalized temperature fluctuations for the Northern Hemisphere winter season of the year 2002. The color bar on Figure 1b indicates the amplitudes of the temperature fluctuations (in percentage).

fluctuation values. To overcome this deficiency, we extracted the fluctuating component from a single GPS profile by applying high-pass filter with a cutoff at 10 km. Similar procedures were implemented in previous GPS/MET studies [*Tsuda et al.*, 2000] and rocketsonde data analysis [*Eckermann et al.*, 1994].

3. Results and Discussion

[8] First, in order to note the global temperature fields in the lower atmosphere (5–30 km), Figures 1a and 1b show the latitude-height contours of the mean temperature and normalized-temperature fluctuations for the Northern Hemisphere (NH) winter season (December 2001 and January and February 2002). The zonal mean values are estimated by considering all the available temperature values at each height level and within each 5 degree latitude band. As expected, temperature (Figure 1a) in the troposphere steadily decreases and the minimum is observed at around 17 km in the tropical latitudes. The observed tropical tropopause temperature is 190 K. In the high latitudes, the winter hemispheric stratospheric temperature is considerably lower than the summer hemispheric temperatures. The normalized-temperature fluctuations ($\hat{T}' = T'/\bar{T}$) plotted in Figure 1b indicate the amplitudes of the fluctuations (in percentage). It is clear that the temperature fluctuations are much larger in the tropics than in the midlatitudes of the winter hemisphere, where the gravity waves are generated by orographic effects and meteorological disturbances [e.g., *Fritts and Nastrom*, 1992; *Nastrom and Fritts*, 1992; *Tsuda et al.*, 2000]. From

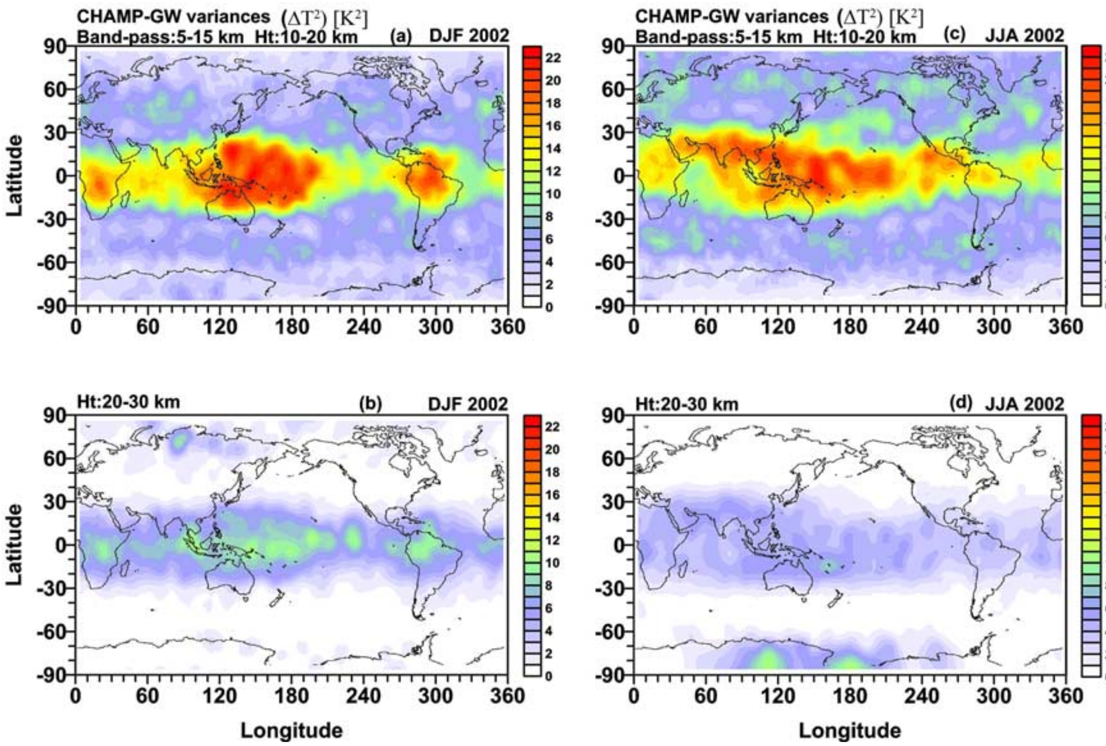

Figure 2. Global structure of the gravity wave variances observed during the (left) winter and (right) summer seasons of the year 2002. The results for the height ranges 10–20 km and 20–30 km are shown.

Figure 1, we can identify that the relative temperature fluctuations are dominant at tropics (30°S–30°N) at 14–20 km altitude range and at 7–12 km region in the high latitude Northern (60°N–90°N) and Southern (60°S–90°S) Hemispheres.

[9] The global structure of the gravity wave variances of CHAMP measurements for the winter (December 2001 and January and February 2002) and summer (June, July, and August 2002) seasons are shown in Figure 2. Here the spatial structure is estimated by averaging the values in 5 degree latitude by 5 degree longitude grid. The variances are estimated for the 10–20 km and 20–30 km altitude levels. Before estimating the variances, we have filtered the data with a band-pass filter. From Figures 2a–2d it can be seen that the gravity wave variances are large over the tropical latitudes (25°N–25°S) and small at high-latitude regions throughout the NH winter and summer seasons. It should be remembered that we have observed large temperature fluctuations in the tropical tropopause region and this is partly due to the high-pass filtering of the sharp bend in the background temperature profile near the tropopause. As a result the temperature variance at the corresponding altitudes should not be treated as solely due to gravity wave activity. However, *Allen and Vincent* [1995] demonstrated that contribution due to such high-pass filtering of the temperature profiles in the presence of the sharp gradients at the tropopause is not great. Both in winter and summer seasons the maximum variances are observed at 10–20 km altitude band. During winter (for the 10–20 km level) the wave activity is dominated over Southeast Asia, Australia, and Pacific Ocean. Enhanced wave activity can be further seen over African and South American tropics. It has been well documented that the maximum wave activity observed over the Indonesian, Malaysian, and nearby regions are caused by cumulus convection. It is also possible that Kelvin waves or other equatorially trapped waves have made contributions to the variances observed in these regions. Generally, the summer pattern is similar; however, the wave activity is less intense than the winter season. During summer, the Indian and the nearby eastern regions experience comparatively larger wave activity in the troposphere. Also a wider region of the equatorial Pacific Ocean experiences strong wave activity. The variances observed in the stratosphere are considerably smaller; especially the midlatitude sector in both hemispheres is marked with very low values. Comparing the seasonal variations, the stratospheric variances observed in winter are larger than the summertime variances. *Allen and Vincent* [1995] studied the seasonal variations of gravity wave energy per unit mass by using high resolution radiosonde temperature profiles collected from 18 stations in Australia/Antarctica. They reported that the wave activity is maximized in the upper troposphere and lower stratosphere (UTLS) during the winter season and proposed winter storm fronts as a seasonally varying source responsible for the seasonal cycle in wave activity in the midlatitude radiosonde observations.

[10] The energy density E_0 is an important parameter for the measure of gravity wave activity. It is defined by

$$E_0 = \frac{1}{2}\left[\underbrace{\overline{u'^2} + \overline{v'^2} + \overline{w'^2}} + \underbrace{\left(\frac{g^2\overline{\hat{T}'^2}}{N^2}\right)}\right] = E_k + E_p \qquad (1)$$

where u', v', and w' are the zonal, meridional, and vertical components of the first-order wind velocity perturbations,

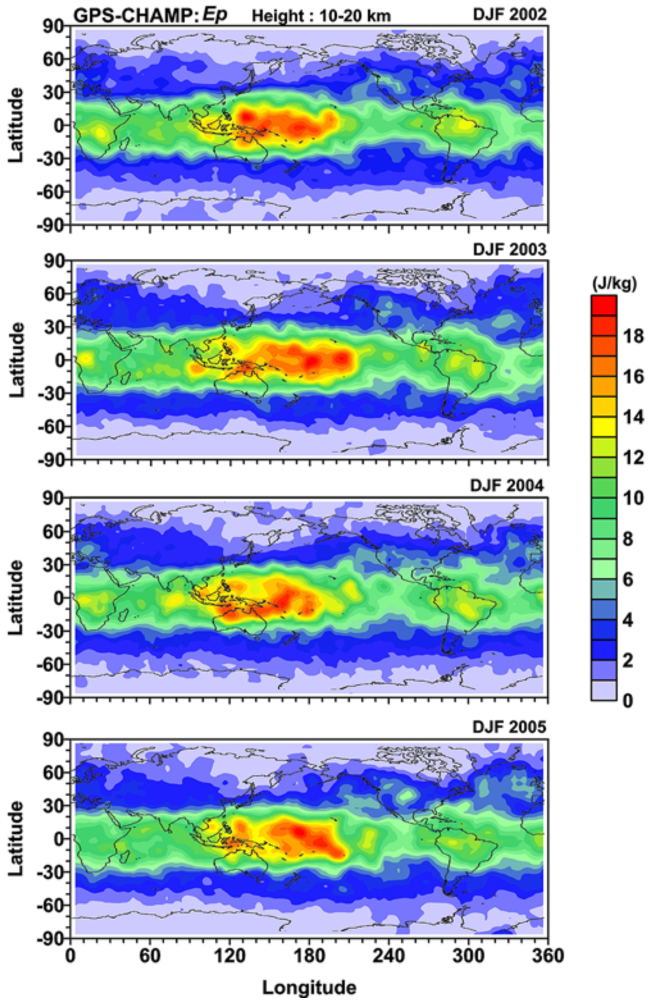

Figure 3. CHAMP-derived global structure of the potential energy for the winter season of 2002, 2003, 2004, and 2005. The sampled height range is 10–20 km.

respectively; g is the gravitational acceleration; N is the Brunt-Vaisala frequency; and $\hat{T}' = T'/\bar{T}$ is the normalized temperature fluctuations. According to the linear theory of gravity wave, the ratio of kinetic to potential energy, E_k/E_p, is a constant [*VanZandt*, 1985; *Tsuda et al.*, 2000]. Therefore, it is possible to estimate E_0 from temperature observations. In equation (1), the calculation of E_p mainly depends on the estimation of temperature fluctuations. For this, as mentioned in the previous section, we followed the method given by *Tsuda et al.* [2000] wherein they extracted gravity wave perturbations from GPS/MET temperature profiles by applying a high-pass filter with a cutoff at 10 km.

[11] The global structure of the potential energy derived by the CHAMP RO data averaged over the height region between 10 and 20 km for the NH winter (December, January, and February) for the years 2002 to 2005 and NH summer (June, July, and August) for the years 2001 to 2005 are shown in Figures 3 and 4, respectively. For generating these contours, we utilized 7960, 11,861, 11,299, and 8300 occultations during the winter season of 2002, 2003, 2004, and 2005, respectively, and 6787, 12,642, 10,906, 9544, and 9005 occultations during the summer season of 2001, 2002, 2003, 2004, and 2005, respectively. From the Figures 3 and 4, we can see enhanced values of E_p over the tropical latitudes (20°S–20°N) during winter and summer seasons. First describing the winter season (Figure 3) in particular, it is interesting to note that the maximum enhancement of E_p values is over Indonesia, northern Australia, and the Pacific Ocean. The E_p observed over the African and South American tropical regions are less intense. The maximum intensity observed during winter is nearly 19 J/kg. *Allen and Vincent* [1995] reported maximum energy densities of the order 12–14 J/kg at the Australian tropical troposphere and 9–11 J/kg in the lower stratosphere. Maximum E_p values observed over South America are 12–14 J/kg and 7–10 J/kg over Africa. The potential energy presented in Figure 4 for the summer season exhibits large values in the longitude sector 45°E–190°E. During summer also there is enhancement at tropical latitudes. During summer the Indian and the nearby east Asian regions exhibit comparatively larger intensities than the winter season.

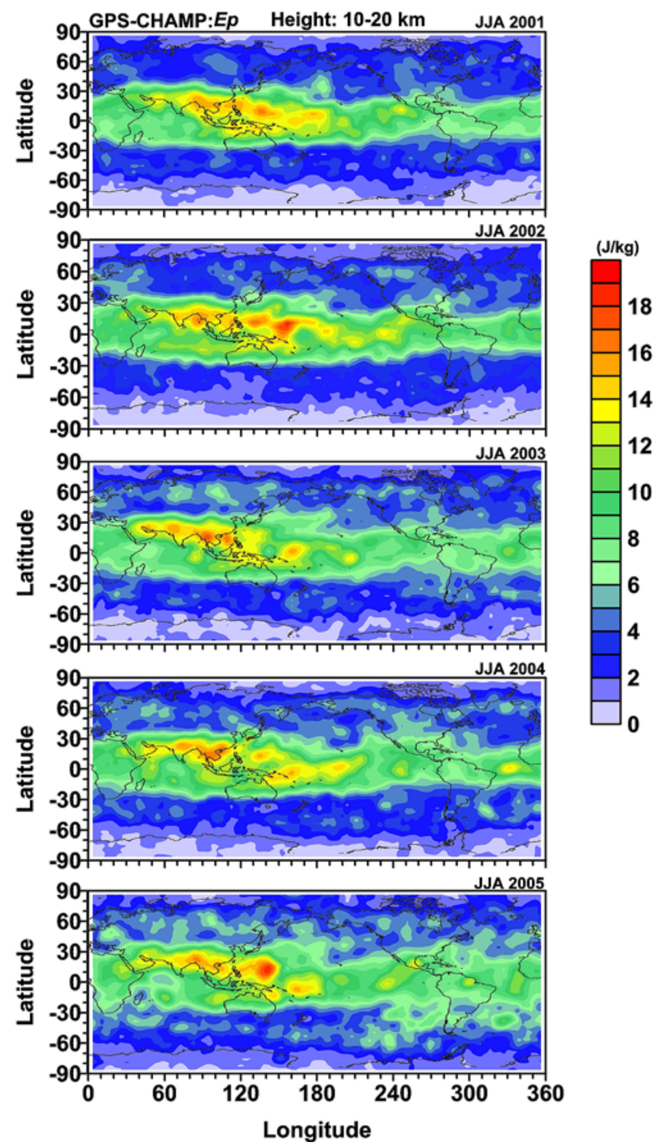

Figure 4. As in Figure 3 but for the summer season of 2001, 2002, 2003, 2004, and 2005.

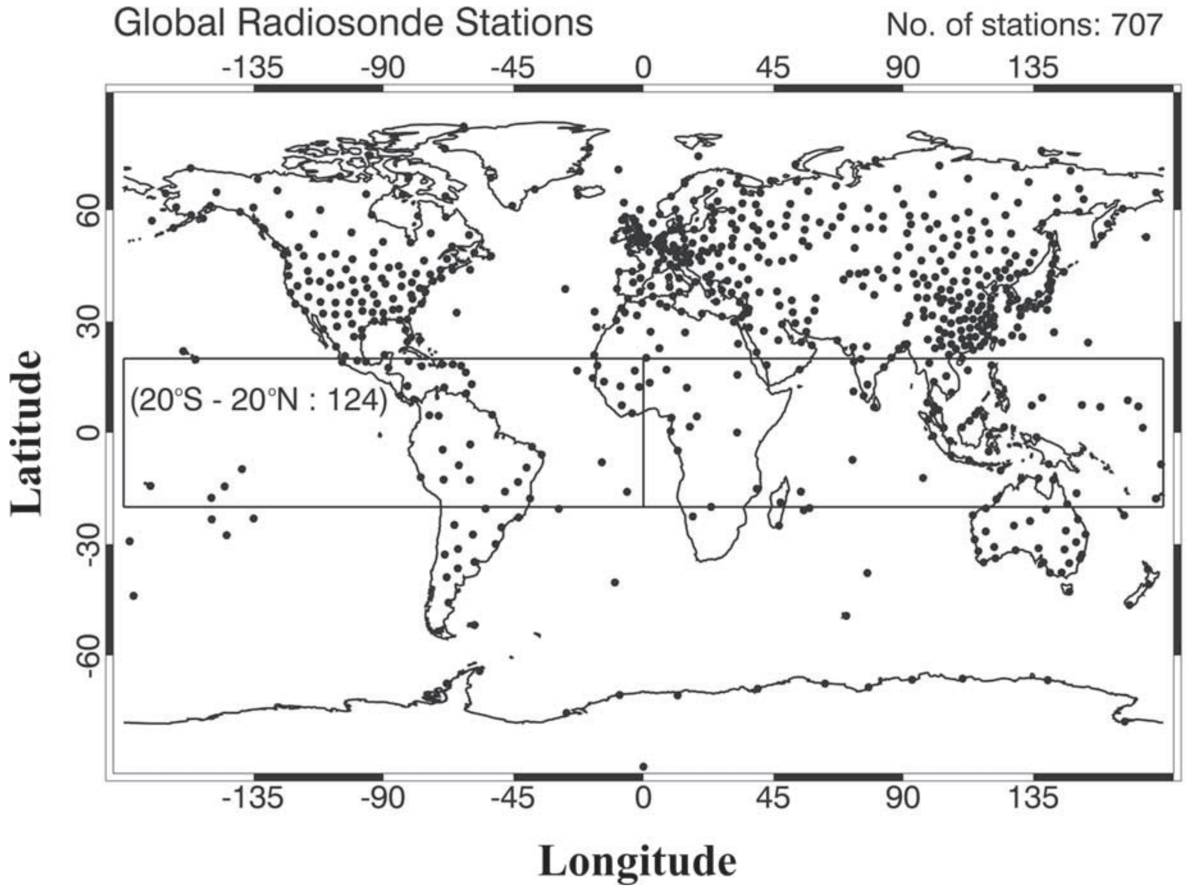

Figure 5. Locations of global radiosonde stations. The British Atmospheric Data Centre (BADC) archives include about 707 radiosonde stations, which are noted by dark dots. The latitude sector 20°S–20°N is marked with a rectangle.

Large wave activities over the tropical region suggest that convection is one of the main sources of gravity waves. Using the outgoing longwave radiation (OLR) data, *Venkat Ratnam et al.* [2004] examined the coherence of E_p with tropical convection and they concluded that convection is a primary source for the increased wave activity in tropics. It is also noteworthy that the large E_p values in the tropics are partly due to equatorial waves. Comparing the summer and winter seasons, it is clear that the wave activity is larger during the wintertime. The polar region exhibits relatively smaller E_p values and the behavior is nearly symmetric between the northern and southern high latitudes. *Tsuda et al.* [2000] used GPS/MET atmospheric temperature profiles in the upper troposphere and stratosphere between April 1995 and February 1997 and they found large intensities concentrated around the tropics between 25°N and 25°S, with particular enhancement over Indonesia, the Indian Ocean, Africa, and South America. For subtropics, they reported generally larger E_p values in winter and smaller values in summer, exhibiting an annual variation. The present seasonal behavior at low latitudes agrees qualitatively with the previous studies [*Hirota*, 1984; *Eckermann et al.*, 1994; *Allen and Vincent*, 1995; *Tsuda et al.*, 2000]. *Allen and Vincent* [1995] cautioned that the temperature fluctuations in the troposphere may be caused not only by gravity waves but also by other processes such as convection and inversions which are difficult to distinguish from wave activity and difficult to remove from the background temperature profile. *Wang and Geller* [2003] further pointed out that factors such as geographic difference; differences in wave periods, wavelengths, and height ranges covered; and wave types involved can all influence the direct intercomparisons among the different studies. Moreover, the potential energy values depend drastically on the filter applied and the filtering process. *Alexander* [1998] demonstrated that the observed variability in the background state can produce large variations in observable gravity wave activity without any variations in their sources.

[12] Figure 5 shows the geographic distribution of global radiosonde stations. There are about 707 stations in total, using about 14 different types of radiosonde systems. The radiosonde systems have known observational errors and are dependent upon the type of sensors. Equipment and procedural changes are introduced time to time and such changes can introduce spurious climate change signals. As can be seen in Figure 5, the midlatitude continental region in the NH has a large number of sites. As previously mentioned, the height intervals of the temperature and horizontal wind measurements are irregular, for convenience, the raw data were processed to have an identical height resolution (200 m) by applying a linear interpolation. It should be mentioned that such a common interpolation technique may cover up possible differences among the

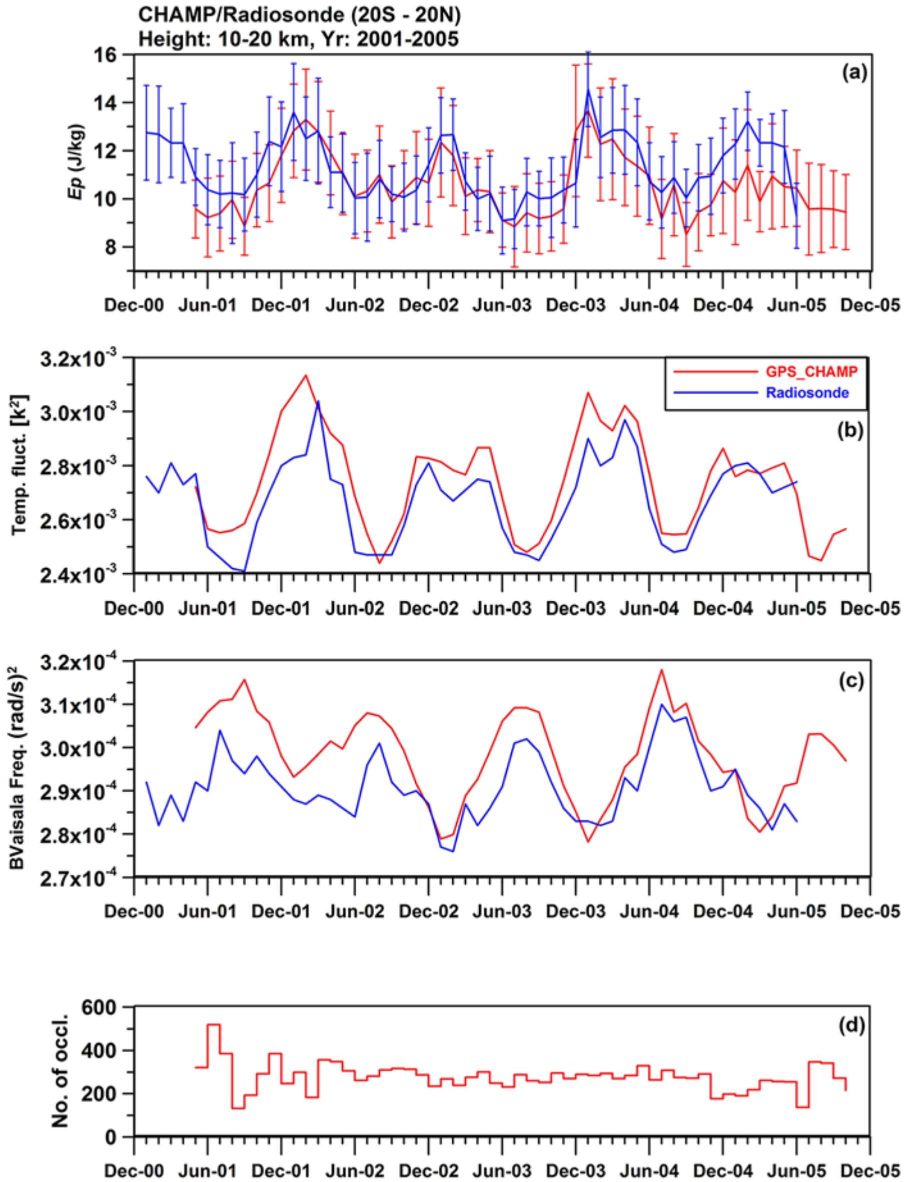

Figure 6. Monthly mean values of (a) potential energy, (b) temperature fluctuations, (c) Brunt-Vaisala frequency derived by the CHAMP (red curve) and radiosonde (blue curve) measurements for the 10–20 km and 20°S–20°N latitude range. (d) Number of GPS radio occultation. The period of observation is 2001–2005.

underlying data; the data at some stations may be at low resolution that it cannot realistically represent the variance in the shorter nominal wavelength. Before estimating the gravity wave parameters, each radiosonde profile was inspected visually. Profiles that had suspiciously large gradients in the wind or temperature profiles were not considered. Also, profiles with too many data gaps were discarded. We found that about 84% of measurements reached 20 km and only 36% reached 30 km for the period we considered in the present study. From each sounding conducted between the latitude sector 20°S–20°N (shown by a rectangle containing 124 stations), the potential energy, temperature fluctuations, and static stability parameters were estimated. Monthly averages of these parameters were further computed for 2001–2005 and these values were compared with the GPS-CHAMP data, and the results are shown in Figure 6.

[13] Figure 6 presents the monthly mean values of potential energy (Figure 6a), normalized temperature fluctuations (Figure 6b), Brunt-Vaisala frequency (Figure 6c), and number of occultation (Figure 6d), as derived from the GPS-CHAMP and radiosonde measurements at 10–20 km altitude region in the 20°S–20°N latitude sector for the period 2001–2005. In such comparison studies it should be explicitly mentioned that one basic expected difference derived from the nature of these two techniques. GPS RO profiles are obtained in the Earth frame of reference, while balloon data are obtained in a frame of reference driven by the mean wind. This important difference can affect vertical wavelengths or other parameters derived from both techniques. Describing the features of the plot, the E_p and

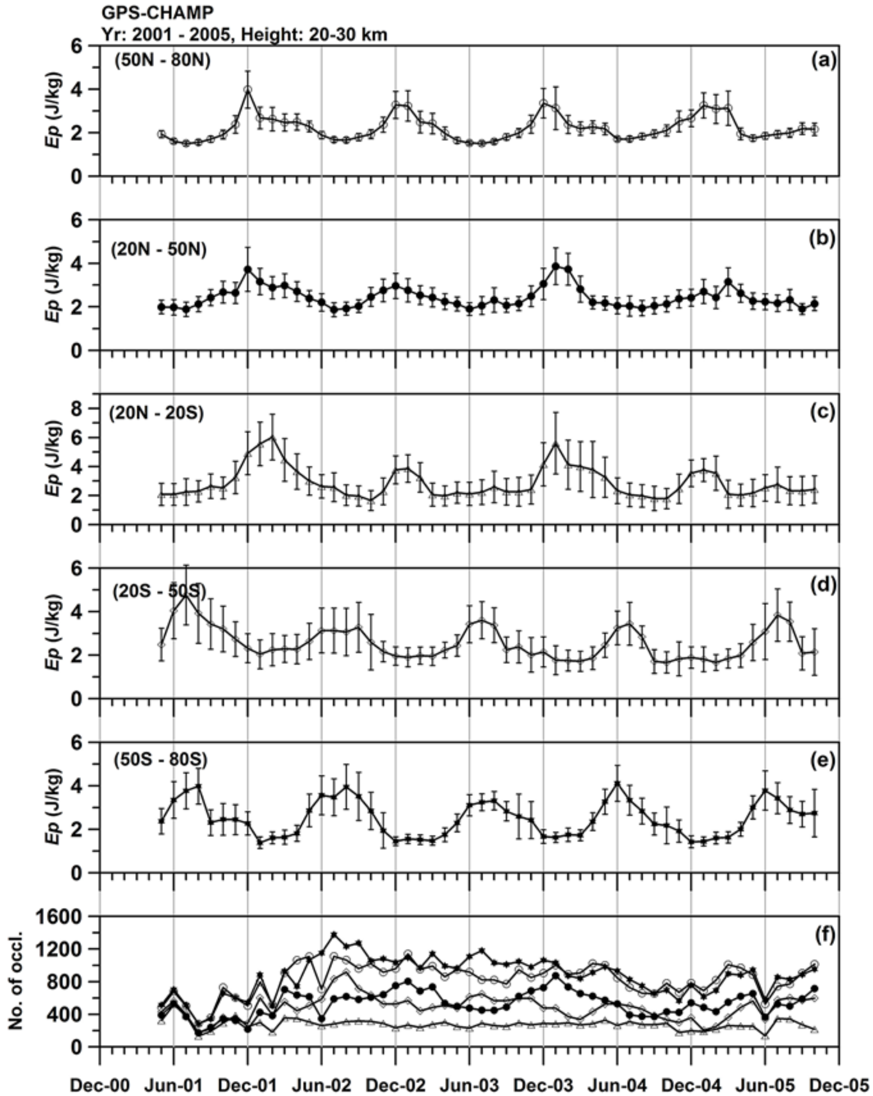

Figure 7. (a–e) CHAMP estimates of average potential energies for different latitudinal bands and for the height range 20–30 km. (f) The number of occultations.

normalized temperature fluctuations derived by both measurements show an annual cycle which is coherent throughout the tropics, with maximum values during winter (December–February) and minimum during summer (June–August). The standard deviations shown by vertical bars indicate large spread in E_p values. Annual oscillation is well documented in the Brunt-Vaisala frequency data set also. Comparing both measurements, we can see that the normalized temperature fluctuations and Brunt-Vaisala frequency derived by the GPS-CHAMP measurements are generally little larger than the corresponding radiosonde measurements. Typical maximum value of monthly mean potential energies of GPS-CHAMP (radiosonde) in winter is 13.8 J/kg (14.2 J/kg) and minimum (in summer season) is about 8.5 J/kg (9 J/kg), respectively. It is worthwhile to note that the potential energy derived by the GPS and radiosonde measurements show resemblance, with slightly smaller E_p values for the RO measurements. This small difference could be due to the issues related to height resolution or averaging over a wide horizontal area. Interannual variation is evident in both data sets. *Wang and Geller* [2003] estimated monthly mean gravity wave energy densities in the lower stratosphere using radiosonde data, for the latitude range 5°–15°N during 1998–2001. They found gravity wave energy maximum of 18 J/kg (January 1999) and minimum of 8 J/kg (August 1999). Gravity wave energy densities observed in our analysis are slightly lower than that observed by *Wang and Geller* [2003].

[14] GPS-CHAMP derived gravity wave energy for various latitudinal bands at 20–30 km during the period from May 2001 to December 2005 are shown in Figures 7a–7e. The selected latitudinal ranges in Figures 7a–7e are 50°N–80°N, 20°N–50°N, 20°N–20°S, 20°S–50°S, and 50°S–80°S, respectively, and Figure 7f indicates the number of occultation available at each latitudinal band at every month. Examining Figure 7, we can see that the wave activity is larger during the winter season in the NH and SH. Annual variation is very clearly evident in both hemispheres. The maximum potential energy of about 6 J/kg is observed in winter at low latitudes (20°N–20°S). The corresponding E_p at the middle or high latitudes is only 4 J/kg. The minimum

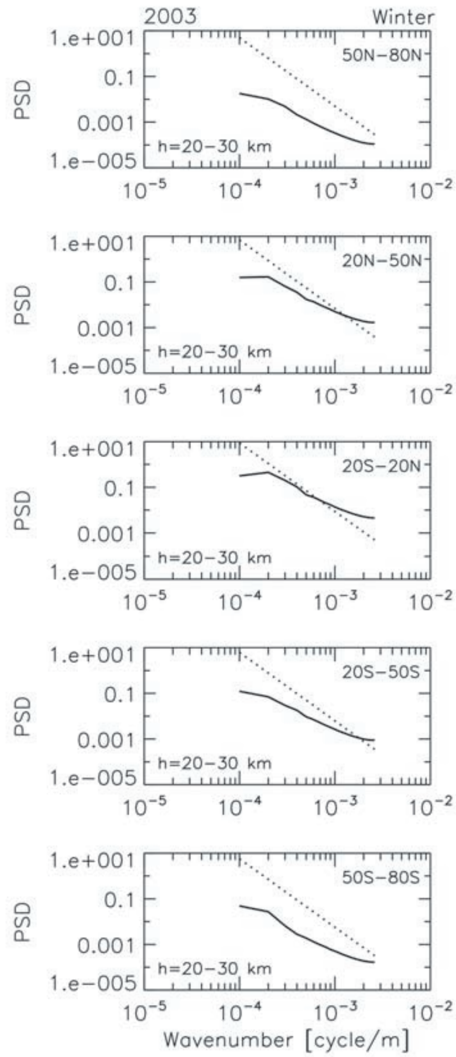

Figure 8. Vertical wave number power spectra of normalized temperature fluctuations within the 20–30 km region during the winter season of 2003. Results for five latitude bands are separately shown in different panels. The theoretical saturation limits of *Smith et al.* [1987] are also plotted for comparison purposes (dotted line).

values are in the range of 1–2 J/kg in all the latitude bands and are observed in the summer season. The observed seasonal behavior at low latitudes agrees qualitatively and quantitatively with the previous studies. *Hertzog and Vial* [2001] used super pressure balloon soundings of wind and temperature at Latacunga (Ecuador) during August and September 1998 and found potential energy of ~7 J/kg. *Tsuda et al.* [2000] using GPS/MET temperature profiles filtered between 2 and 10 km reported typical values of potential energy at 20–30 km ranging from 5 to 6 J/kg around the equator (25°N–25°S). *Vincent and Alexander* [2000] used high-resolution radiosonde observations made over a 6-year period at Cocos Islands in the Indian Ocean and they estimated potential energy of 5.6 J/kg at 22 km. *Preusse et al.* [2000] showed that the latitudinal distribution of potential energy at 25–40 km was consistent between the CRISTA and GPS/MET results, showing large E_p values (about 5–6 J/kg) at low latitudes (30°S–30°N).

[15] Vertical wave number spectra of normalized temperature fluctuations observed at five latitude bands for the winter (2003) and summer (2002) seasons within the altitude range of 20–30 km are presented in Figures 8 and 9, respectively. Again, we have selected the same latitude bands 50°N–80°N, 20°N–50°N, 20°N–20°S, 20°S–50°S, and 50°S–80°S. For comparison purposes we also show a model spectrum in each panel of Figures 8 and 9. Model spectrum estimation was defined by *Smith et al.* [1987]. The plots reveal that the power spectral density is larger at low-latitude region (20°N–20°S) than at middle and high latitudes. Also in the low latitudes, the observed spectral density and the theoretical limit show considerable similarity in both summer and winter seasons. We estimated the power law index of each spectrum in Figures 8 and 9 in a wave number range from 5.40×10^{-4} to 1.95×10^{-3} (cycles/m) (1.8–0.51 km in wavelength). The dominant vertical wavelength at 20°N–20°S can be inferred as

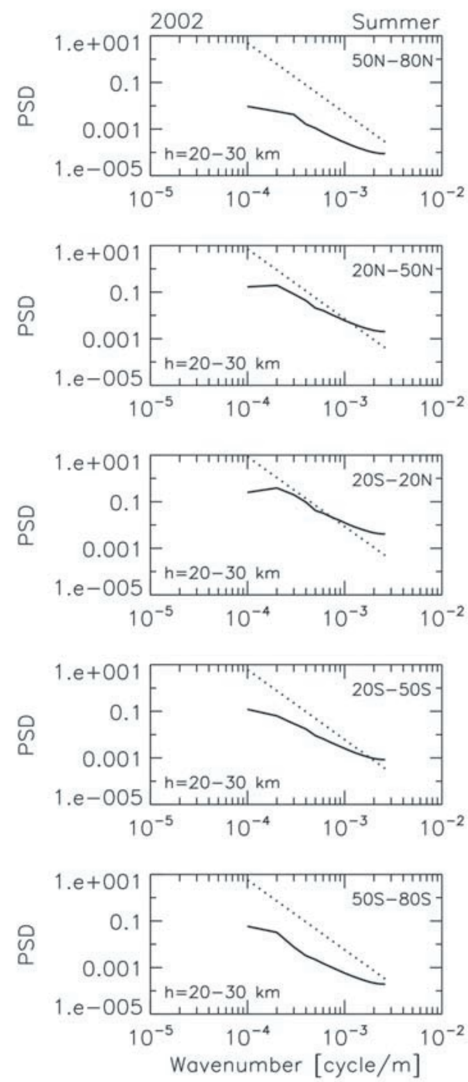

Figure 9. As in Figure 8 but for the summer season of 2002.

about 3.1 km. At extratropical latitudes (20°N–50°N and 20°S–50°S), the winter and summer spectral densities are near consistent with the model. However, the discrepancy between the observation and model becomes larger at higher latitudes. Such higher discrepancies for the high latitudes were also reported by *Steiner and Kirchengast* [2000].

4. Conclusions

[16] Nearly 5 years (May 2001–December 2005) of CHAMP RO data have been analyzed to study the global gravity wave field in the troposphere and lower stratosphere. We have also used the radiosonde data collected by the BADC, UKMO. The analysis has focused on the gravity wave variances, potential energy distributions, comparison of CHAMP and radiosonde measurements for the tropics, and the power spectral density characteristics for the winter and summer seasons, etc. The results clearly indicate the dominance of gravity wave activity in the tropical region. The wave activity is more intense in the troposphere than in the stratosphere. In the tropospheric height (10–20 km) considered in the present study, we observed that the potential energy E_p has maximum values in the tropical region. The energy is getting reduced to middle and high latitudes. The seasonal variation is also very clear with larger wave activity during winter conditions than the summer season, and this is a common feature of gravity wave observations. Factors such as enhanced forcing in the strong winter winds or reduced filtering of stationary waves during winter could make such seasonal trends. Interannual variations in gravity wave potential energy are observed in the CHAMP data. Comparison of the radiosonde and CHAMP measurements of the gravity wave parameters for the tropics shows good agreement. The present analysis of these long-term observations confirms previously reported features. The paper demonstrates the usefulness of RO data for the study of global distribution of gravity wave activity in the atmosphere. A number of new GPS satellite missions such as COSMIC, GRACE, MetOp, TerraSAR-X, EQUARS, etc., will offer the opportunity for further enhanced space-time resolution and long-term RO measurements. Data sets based on these new missions will further enrich the studies of global wave activity in the troposphere and stratosphere and will also be useful to develop more realistic numerical models that describe gravity wave characteristics.

[17] **Acknowledgments.** The work done by Jonathan Jiang, Chi Ao, and Larry Romans was supported by the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA. Jonathan Jiang thanks D. L. Wu and E. R. Kursinski for support in the initial GPS related studies during 1999–2000. The authors thank the BADC for allowing the use of radiosonde data.

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