A Global Distribution of the Stratospheric Gravity Wave Activity from GPS Occultation Profiles with SAC-C and CHAMP

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Abstract

We have analysed the gravity wave activity using temperature profiles retrieved from the GPS occultation experiments on board the SAC-C and CHAMP satellites. By dividing the latitude and longitude ranges, here considered in individual cells, the variability of wave energy as a function of altitude observed in both hemispheres during October, November and December 2001 is presented. Some features were repeatedly observed during the three months. Nevertheless, as most available occultations were occurred during November, we begin showing results from this month. Significant differences detected during October are only pointed out at midlatitudes, provided that sufficient number of occultations are available. A significantly larger wave activity at 40–60°N with respect to 40–60°S is detected during this month. Differences between both the hemispheres are discussed and compared with previous results. Wave activity enhancements at equatorial regions above Brazil, Indonesia and India are found to be correlated with outgoing longwave radiation data. Vertical fluctuations with lengths above and below 3.5 km are considered separately, in order to identify the contribution of Kelvin and Rossby-gravity waves. In both cases, for long and short fluctuations and at the upper troposphere as well as at the lower stratosphere, there is a height interval of several kilometers where a systematic enhanced wave activity is observed. Its average height is progressively decreasing with increasing latitude, same as the height variation in the tropopause location. Longitudinal enhancements are also detected mainly around the equator and at midlatitudes. A clear signature is observed locally in the Southern Hemisphere (SH) at midlatitudes and 70–65°W, for vertical wavelengths longer than 3.5 km. It corresponds to mountain waves forced by the Andes Range, observed whenever occultations are available in this cell.
1. Introduction

In the last decades, great attention has been paid to the different possible sources of gravity waves in the lower and middle atmosphere. It is now well recognized that these sources have great influence on local meteorology, as well as on the energy and momentum exchange between different altitudes, playing a crucial role in controlling the large-scale circulation of the Earth’s higher troposphere and middle atmosphere. The effects of gravity waves which are not properly parameterized could give rise to simulated winds excessively weak, strong or even wrongly directed. The main tropospheric sources of gravity waves are topographic forcing (e.g., Lott and Teitelbaum 1993), convective and frontal activity in the tropics (Vincent and Alexander 2000) and at middle latitudes (Preusse et al. 2001), wind shear (Murayama et al. 1994), geostrophic adjustment (Fritts and Nastrom 1992), thunderstorms and typhoons (Sato 1993). Among these mechanisms, topographic and deep convection events are of particular relevance near the tropics. In these two cases, the relationship between tropospheric sources and stratospheric wave activity may sometimes be quite obvious, and the interactions between gravity waves are easy to identify (e.g., absorption at critical levels, reflection and breaking). In other cases, the observation of gravity waves mainly related to nonorographic and nonconvective sources are clearly insufficient to produce adjusted parameterizations in the numerical models.

The observation of wave structures in the lower and middle atmosphere are usually performed by means of various ground-based and spaceborne techniques. Satellite measurements involving new techniques and instruments are considerably developed now, with known inherent possibilities and limitations, e.g., limb infrared stratosphere monitor (e.g., Fetzer and Gille 1994), microwave limb sounder (MLS) observations (Wu and Waters 1996a, b) and infrared emission spectra from atmospheric limb scans (Riese et al. 1999).

Within the last few years, the use of occultation measurement principle for observing the Earth’s atmosphere and climate exploit solar, lunar, stellar, navigation and satellite-crosslink signals. The geophysical parameters obtained through the atmosphere extend from temperature, pressure and geopotential and water vapour to particular species such as aerosols, cloud liquid water and electron density. The simultaneous global coverage, sub-Kelvin vertical temperature resolution, long-term stability and the absence of limitations imposed by weather conditions make the GPS radio occultation technique unique among spaceborne atmosphere measurements (e.g., Kursinski et al. 1997; Wickert et al. 2001). GPS radio occultation for remote sensing of the Earth’s atmosphere was pioneered by the U.S. American GPS/MET (GPS/Meteorology) experiment (Ware et al. 1996) and successive studies based on its measurements (e.g., Kuo et al. 2000; Hocke et al. 2002 and references therein) have demonstrated the potential ability in, for example, i) improving numerical weather forecasts, ii) predict future changes in the global radiative budget of the atmosphere and iii) atmospheric dynamic studies in the mesoscale. In the last case, a new and important facility is available for wave generation and propagation studies along with electron density global distributions. The LEO (Low Earth Orbit) satellites CHAMP and SAC-C launched in 2000, carry a new generation of Global Positioning System (GPS) receivers to perform radio occultation soundings of the ionosphere and neutral atmosphere. Up to date, occultations in the order of $10^5$ have been gathered (see e.g., Ao et al. 2003).

Useful information of the gravity wave activity in the upper troposphere and stratosphere is provided by horizontal wind and temperature variances (e.g., Alexander 1998). Tsuda et al. (2000) have extracted mesoscale temperature perturbations from vertical wavelengths ranging from 2 to 10 km, using temperature profiles obtained by the GPS/MET experiment. They calculated the global potential energy, assumed to be caused by atmospheric gravity waves at 20–45 km height, during NH winter. The highest values were found around the equator with considerable longitudinal variations. Longitudinal energy variations in the same height range and midlatitudes yielded higher energy values over the continents than over the oceans. Latitude variations largely concentrated around the equator at 20–30 km, in addition to local enhancements at midlati-
tudes, were observed in winter months in both hemispheres. Using same observations, Hocke and Tsuda (2001) found enhanced gravity wave activity of the lower stratosphere at a height of 22–28 km, associated to areas of increased tropospheric water vapour pressure at 4–6 km, a measure of tropical convection activity. Recently, Hocke et al. (2002) studied stratospheric gravity wave fluctuations at midlatitudes, observing significant asymmetries in their longitudinal dependences between both hemispheres, well correlated in SH with the topographic morphology.

In section 2, we present the data of temperature profiles retrieved by the GPS occultation experiments aboard SAC-C and CHAMP satellites and analyse the gravity wave activity as a function of altitude, latitude and longitude during October, November and December, 2001. In section 3, some conclusions are drawn.

2. SAC-C and CHAMP GPS occultation data and analysis

We analyse the gravity wave activity using temperature, $T$, profiles retrieved by the GPS occultation experiments on board SAC-C and CHAMP satellites. We note that no wind data may be obtained from this technique. Nevertheless, from linear theory of gravity waves, the ratio of kinetic to potential energy is constant (e.g., Fritts and VanZandt 1993). This has been confirmed and extensively discussed from experimental evidence under different atmospheric conditions and wavelength ranges (e.g., de la Torre et al. 1999). Thus, it is possible to estimate the wave energy variability by the calculation of the potential energy or the temperature variance alone, from temperature profiles. We will use the temperature variance to detect growing wave activity. We examine its global variability with altitude, during three months in which a considerable convective activity has been observed near the equator during October, November and December, 2001. About 14,876 occultation temperature profiles were successfully retrieved from both the satellites during this period across the globe around the Earth.

We subdivided both hemispheres in independent, adjacent cells of 5 per 10 degrees in longitude and latitude respectively, making a total of $72 \times 9 \times 2 = 1,296$ cells. The occultation events are rather sparse at equatorial latitudes, in comparison with middle and high latitudes. The distribution of occultation events is considerably denser during November than in October and December. In December, for example, several consecutive cells remain empty. As several main features that could be observed during October and December are better appreciated during November too, we focus our description on this month. We point out here that a compromise between latitudinal, longitudinal and temporal resolution should be specified, in order to get information about seasonal and geographical variability of wave activity. With an average number of $T$ profiles per cell and month near to 4, the estimated statistical uncertainty in the potential energy in each cell is $4^{-1/2}$ times the standard deviation. Satellite missions scheduled in the near future are expected to increase in an order of magnitude the number of available occultation events per day, so decreasing accordingly the associated statistical error. In addition to the statistical error, the standard GPS retrieval techniques which are usually implemented suffer from a high sensitivity to measurement noise (see e.g., Marquardt, et al. 2003a). This makes difficult to distinguish gravity wave signal and instrumental noise. High-resolution variational retrieval of radio occultation data which allows the estimation of gravity wave parameters in the lower stratosphere is at present being developed (Marquardt 2003b). Compared to the standard approach, the variational framework could provide a more detailed understanding of the signal-to-noise issue. In the data set here considered and previously processed at JPL (Jet Propulsion Laboratory), bias in the temperature fluctuations greater than 3 K are frequently observed above and below 29 and 8 km respectively, and sometimes even within this range (see below at the discussion of Figs. 1 and 6). Nevertheless, as our main interest here is the upper troposphere and lower stratosphere regions, we will concentrate our studies within 10–28 km altitude only.

In recent GPS/MET stratospheric studies, normalized temperature fluctuations $(T'/T_f)^2$ were used, where $T'$ is the difference between the retrieved temperature $T$ and its lowpass filtered profile $T_f$ (Preusse et al. 2000; Tsuda
et al. 2000; Hocke et al. 2002). In the present study, we will define the function $F \equiv (g/N)^2 \cdot (T'/T)^2$. The gravity wave fluctuations are modulated here by the factor $(g/N)^2$. $g$ and $N$ are, respectively, the acceleration due to gravity and the mean buoyancy frequency as a function of altitude $z$. Note the difference between $F$ and the specific potential energy, defined by $E_p = \frac{g^2}{N^2(z)} \int(z_2-z_1)T' dz$. In our calculation, the available vertical resolution in $T'$ from temperature data is retained. This is not the case with $E_p$, in which the integral tends to smooth out small-scale fluctuations.

The temperature profiles, after the spline process, were high-pass filtered with a cutoff at 3.5 km. The filter applied is non-recursive, and to avoid Gibbs effects, a Kaiser window was used. Vertical fluctuations with lengths above and below 3.5 km are separately considered, to discard in the later case, the contribution of Kelvin and Rossby-gravity waves.

In Fig. 1, the mean wave activity as a function of height during November is shown, for the cells corresponding to the equatorial region between 10 S and 10 N. The subdivision in adjacent and non overlapping longitude cells instead of applying a sliding window of several degrees of width, have two advantages, as it may be seen from an inspection of Fig. 1: 1) Several isolated cells exhibiting anomalous and periodic high $F$ values ranging from the bottom to the top of the plate are easy to identify (see i.e. cell number 16, corresponding to occultation events produced between 105 W and 100 W). These should be interpreted as bias or spurious enhancements generated at an earlier stage during the retrieval process, as mentioned before. Their localization offers no difficulty as their neighbouring cells differ considerably.
If instead, a sliding window has been applied, the spurious data corresponding to a given cell would have contaminated the wave activity exhibited in a wider and diffuse region around it. By the same reason, the “empty” cells including no occultations at all are clearly identified by a narrow and single white band between 10 and 28 km. On the other hand, real gravity wave signals are usually rapidly attenuated above the lower stratosphere, as it may be appreciated in the majority of the cells. In all of them, the oscillating behaviour of \( F \) with height derives directly from \( (T^0)^2 \). The contrast between successive maxima and minima tends to disappear as the number of occultation events per cell increases, due to the random relative phase shifts of the averaged \( F \) profiles. There are systematic energy enhancements between 15 and 20 km height. As expected, these enhancements are particularly strong at longitudes corresponding to Indonesia, Brazil and India, because during these months large-scale convection activity usually exists. We may discard contributions from Kelvin and Rossby-gravity waves as the filtering applied in Figure 1 considers vertical wavelengths below 3.5 km. Nevertheless, possible contributions from tropical planetary scale waves cannot be discarded.

A horizontal belt of apparent enhanced wave activity is observed at all longitudes around 14 km, due to the tropospheric minimum in the buoyancy frequency. This feature is systematically observed at all latitudes (see below) and may be attributed to an anomalous systematic underestimation of \( N^2 \) from \( T \) profiles, usually 1 or 2 km below the tropopause. The \( N^2 \) influence in Figure 1, or equivalently in the \( E_p \) variability, was confirmed by plotting only the temperature variance, observing that this effect disappears. This enhancement has been equally observed for wavelengths longer than 3.5 km.

In Fig. 2, the outgoing longwave radiation (OLR) data averaged during an arbitrary period (November 14–21, 2001), between 10 N and 10 S, 13th and 18th degree polynomial regressions are included.

Fig. 2. Outgoing longwave radiation (OLR) data averaged during an arbitrary period (November 14–21, 2001), between 10 N and 10 S. 13th and 18th degree polynomial regressions are included.

In Fig. 3, we have integrated the temperature variance \( (T'/T_f)^2 = F/(g/N)^2 \) between 18 and 25 km observed during November 14–21, 2001. 13th and 18th degree polynomial regressions are included.

Fig. 3. Integrated temperature variance \( (T'/T_f)^2 = F/(g/N)^2 \) between 18 and 25 km observed during November 14–21. It provides a quantitative measure of the potential energy content in the lower stratosphere during this period. Due to the sharp fluctuations exhibited in OLR and principally in \( F \), we tested two polynomial regressions of 13th and 18th degree in both variables. In both cases, it was observed that OLR and \( (T'/T_f)^2 \) are negatively correlated, as expected. The cross-correlation from the smooth-
ing with 18th degree polynomials is shown in Fig. 4.

In Figs. 5 and 6 we show the gravity wave energy distribution in November separated in S–N Hemispheres respectively, for vertical wavelengths below 3.5 km. Occultations registered within 8 successive and adjacent latitude intervals of 10 degrees belonging to each hemisphere were considered. In both hemispheres, the enhancement at 15–20 km observed around the equator in Figure 1 is further observed at all latitudes. From 10–20° to higher latitudes, the height interval of several kilometers above the tropopause, where enhanced wave activity is observed, appears progressively decrease with increasing latitude. The same variation with latitude is identically observed near the tropopause. At 70–80° and 80–90° this effect is not evident in Figs. 5–6.

Fig. 4. Cross-correlation between OLR and $F$ (see Figs. 2–3) after smoothing the sharp fluctuations exhibited in both variables with 18th degree polynomials.

Fig. 5. Same as Fig. 1, but for Southern Hemisphere. Occultations registered within 8 successive and adjacent latitude intervals of 10°, belonging to this hemisphere and symmetrically away from the equator, were considered. The mean land features at 50–60° are represented by the (^^^) lines over the corresponding plate.
as far as the minimum height considered here (10 km) lies at or even well above the tropopause. This latitudinal variation of the wave activity was pointed out by Tsuda et al. (2000) from GPS/MET data, from vertical fluctuations between 2 and 10 km. They found latitude variations largely concentrated around the equator at 20–30 km, in addition to longitudinal enhancements at midlatitudes in winter months in both the hemispheres.

The observed differences observed in Figures 5–6 between both hemispheres, are:

1) Depicting the arbitrary distribution of empty cells in both hemispheres, In general larger wave activity at 10–20° in SH is seen at all longitudes. For example, the integrated F between 18 and 22 km, yields the zonal mean values 29.6 and 25.1 Joule km/kg in 10–20 S and 10–20 N, respectively.

2) At 10–20°, the observed enhancements at Indonesia (Brazil) are relatively larger in NH (SH) and reach higher altitudes.

3) In Figs. 5–6, a general enhancement at midlatitudes (40–70°) in NH respect to SH is observed, already detected by Tsuda et al. (2000). The longitudinal distribution in NH shows at 50–60° a maximum at around 120 W above North America, and another region of enhanced wave activity between 20 W and 130 E. These features are observed for vertical wavelengths above 3.5 km, too. A tendency of wave activity to be larger over continents than over oceans is seen (i.e. observe the low F values in the region over the ocean between 130 E and 130 W). At 60–70° in NH the enhancements above North America is quite obvious with respect to SH, depicting the spurious enhancements, like those present in three cells near to 0° longitude. The mean land features at that latitudes are represented by the (^^^) lines over the 50–60° plate in both hemispheres. Finally, it is noticeable the lack of occultation events (white bars) for latitudes above 70°, mainly in NH.
In Fig. 7, two additional features are presented. In Figure 7a, we show the wave activity in October. The symmetry detected by Tsuda et al. (2000) between both hemispheres during this month for wavelengths between 2 and 10 km is not seen here. The wave activity at 40–60°N is considerably larger than in SH, independent of the longitude. We remark that this feature is not seen for wavelengths longer than 3.5 km. In Fig. 7b (left), we show the wave activity at midlatitudes (30–40°S) during November, for wavelengths longer than 3.5 km. A clear enhancement at 75–80°W reaching heights above 20 km is observed. As reflected in Figure 5, this feature does not appear for wavelengths below 3.5 km. This may be explained by the generation of mountain gravity waves of high intrinsic frequency and vertical wavelength of 5–6 km, forced by the Andes Range. These waves have large amplitudes and long vertical wavelengths, as usually reported in this region from balloons and spaceborne observations (see e.g., Eckerman and Preusse 1999). Vertical wavelengths above 5 km are clearly detected from SAC-C and CHAMP GPS occultation data. In December, this enhancement is, with less intensity, present again in the same cell, and shown in Figure 7b (right). Note from the corresponding scale, that the wave activity values for these last two plates are one order of magnitude greater than those at Fig. 7a. Unfortunately in October this cell is empty and no occultation events may account for mountain waves effects there.

In Fig. 8, a quantitative description of latitude and longitude distribution of gravity wave activity represented by the integrated $F$
content between 18 and 25 km height during November above the tropopause, is shown. Note that this tomographic view is different from that shown in Fig. 1, for the same month. It may be observed enhancements around the equator, over Brazil, India and Indonesia, as well as the rapid diminution of wave activity with increasing latitude. The considerably lower intensity at midlatitudes with respect to that observed at the equator results more evident here. It may be seen the considerable large wave activity in the winter (northern) hemisphere respect to the summer hemisphere, already detected by Tsuda et al. (2000).

3. Conclusions

The zonal and meridional gravity wave activity variability has been analysed during three months (October–December 2001) from GPS occultation experiments on board SAC-C and CHAMP satellites. Results are compared with previous works, and a general agreement with observations from GPS/MET observations is found. A considerable wave activity in equatorial areas above Indonesia, Brazil and India, well correlated with outgoing longwave radiation data is observed. There is a height interval of several kilometers above the tropopause where enhanced wave activity is observed. This interval appears progressively lower with increasing latitude. Additional features arising from the separation between wavelengths above and below 3.5 km and between both hemispheres were found. Enhancements above continental areas in NH midlatitudes are observed. In SH, a clear signature of mountain waves around 5–6 km above the Andes Range.
is observed. A considerable large wave activity in the winter (northern) hemisphere respect to the summer hemisphere is observed.

In order to study the seasonal evolution of wave activity from SAC-C and CHAMP data on a global scale, the periods considered should not be shorter than those here selected, as the equatorial region coverage would result too sparse respect to midlatitudes. The choice made in this manuscript to show the energy distribution in adjacent and not overlapping cells, results convenient in order to localize and discard spurious features, although it requires a considerable number of occultations to obtain a reasonable zonal and meridional resolution.

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