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Gravity Waves and Ionospheric Irregularities over Tropical Convection Zones observed by GPS/MET Radio Occultation

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Abstract. GPS/MET observations of the tropical atmosphere of the southern hemisphere (5°S to 25°S) during February 1997 are analysed, when a high amount of convective tropospheric water vapor is at these latitudes. Enhanced gravity wave activity of the lower stratosphere at h=22-28 km is associated to areas of increased tropospheric water vapor pressure at h=4-6 km, regarded as a measure of tropical convection. Sporadic E and other ionospheric irregularities (vertical scales less than 7 km) of the mesosphere/lower thermosphere are observed to be highly correlated to gravity wave activity in the lower stratosphere and to tropical convection zones. We find 4 areas of enhanced ionospheric irregularities and stratospheric wave activity over Pacific (around 140°W), Brazil (50°W), Africa (40°E), and Indonesia/Australia (110°E).

Introduction

Various observations by lidars, radars, rockets, and satellite limb sounding have provided evidence that gravity waves transport energy and momentum from the troposphere up to the mesosphere/lower thermosphere (MLT region). Recent studies on gravity waves in the tropical lower stratosphere over Indian Ocean (12°S, 97°E) show that upward gravity wave flux is predominantly in zonal direction against the prevailing westward mean wind in this region. The wave phase speeds relative to the earth are centered at 0 m/s [*Vincent and Alexander*, 2000; *Alexander and Vincent*, 2000]. Vincent and Alexander observe largest momentum and energy densities of gravity waves during the wet season and find a QBO-like variation (quasi-biennial oscillation) in time series of wave energy in the lower stratosphere. A long-term study by *Tsuda et al.* [2000a] finds a semiannual oscillation (SAO) in wind variance at mesospheric heights over Jakarta (Indonesia). A QBO variation in the stratosphere and a SAO variation in the mesosphere is also present in long-term observations of equatorial zonal wind by the UARS satellite [*Burrage et al.*, 1996]. Simulation studies by *Mayr et al.* [1998] indicate that nonlinear interaction between gravity waves (Doppler spreading) generates a QBO-like variation of the stratospheric zonal wind and a SAO-like variation of the mesospheric zonal wind in the tropics. These observations and simulations suggest a close coupling of troposphere, stratosphere, and mesosphere by upward gravity wave flux from tropical convection zones.

Bistatic radio sounding of the earth's atmosphere by a transmitting GPS satellite and a receiving low earth orbit (LEO) satellite such as GPS/MET Microlab-1 offers the opportunity to observe water vapor profiles in the troposphere and temperature profiles in the troposphere/stratosphere during a radio occultation event [*Rocken et al.*, 1997]. (Radio occultation event refers to the setting of a GPS satellite at the earth's horizon as observed from the place of the LEO satellite.) Approximately at the same time and geographic place the ionospheric plasma distribution of the mesosphere/lower thermosphere region is scanned with a vertical resolution of less than 1 km in height by the GPS-LEO radio link. Because of the strong coupling between ions and neutrals at these heights, the observed ionospheric irregularities are related to gravity wave activity and neutral turbulence of the MLT region [*Hines*, 1960; *Gurevich et al.*, 1997]. In the following the longitudinal distributions of tropospheric water vapor, stratospheric temperature variance, and small-scale plasma irregularities of the MLT region are presented at tropical latitudes of the southern hemisphere derived from GPS/MET radio occultation data.

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Data Analysis

Data Selection and Neutral Atmosphere

We use the temperature profiles of the GPS/MET data base at UCAR (Boulder). *Tsuda et al.* [2000b] show that the relative temperature fluctuations as observed by GPS/MET are appropriate for global studies on wave activity in the stratosphere. Preusse et al. [2000] compare stratospheric fluctuations obtained by active GPS-MET limb sounding with those of passive limb sounding (CRISTA infrared spectrometer on Shuttle pallet satellite and microwave limb sounder on UARS) and find agreement for the measured global distributions of fluctuations.

The mean temperature profile $\bar{T}$ is estimated by averaging the observed temperature profile with a sliding window of 7 km in height. The profiles of relative temperature fluctuations (vertical wavelength less than 7 km) are estimated by $\Delta T/\bar{T} = (T - \bar{T})/\bar{T}$. For the February 1997 *prime time* (1997/2/2-1997/2/16) the average field of relative temperature variance $(\Delta T/\bar{T})^2$ is calculated as function of height and longitude by using all occultation events within the latitude range 5°S to 25°S and by averaging with a sliding window of 10° in longitude and a longitude step of 0.6°. *Prime time* means that antispoofing of the GPS system has been turned off for the GPS/MET experiment in order to enable a higher precision of GPS atmosphere profiling [*Rocken et al.*, 1997]. The GPS/MET mission has been mainly a proof-of-concept, and its data base contains only three prime time intervals (of around 10 days) which have a sufficient number of occultation events for meteorological studies on global scale (around 1000-2000 occultations within a prime time).

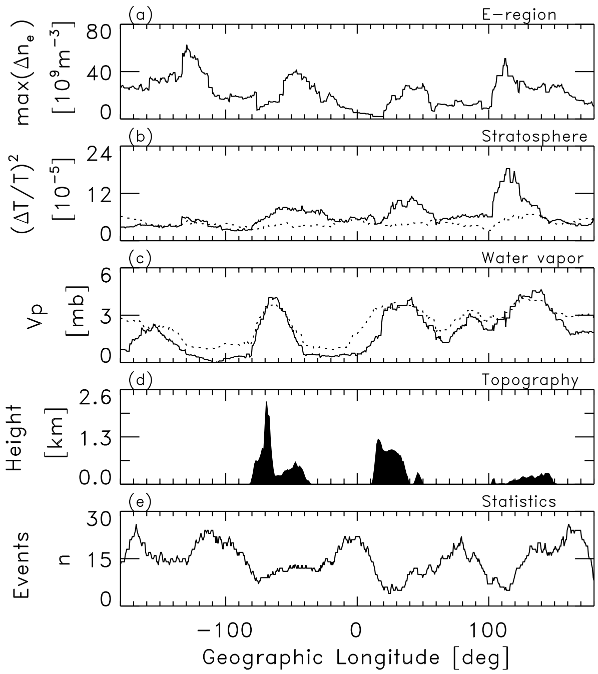

Figure 1. Various parameters of the southern tropics (5°S-25°S) as function of geographic longitude, during GPS/MET prime time February, 1997, 2-16: **(a)** maximum of small-scale (vertical scales < 7 km) fluctuation amplitude of electron density in the MLT region (h=80-120 km); **(b)** stratospheric relative temperature variance (solid line for h=22-28 km, dotted line for h=32-38 km); **(c)** water vapor pressure averaged over h=4-6 km (solid line for GPS/MET, dotted line for ECMWF); **(d)** surface topography; **(e)** number of occultation events. The curves in a, b, c, and e) are averaged by a sliding window with a window length of 10° in longitude. Please note the correlations and slight displacements of maxima in panels (a), (b), and (c). Negative (positive) longitude corresponds to West (East) respectively.

The latitude range 5°S to 25°S has been selected because of the high amount of convective water vapor at these latitudes during February 1997 (as seen in the global map of water vapor pressure at around h=5 km provided by GPS/MET). In particular the tropical convection zone over Africa is centered at 15°S during this time. Our latitude range is compatible to the study by *McLandress et al.* [2000] who selected 15°S for the longitudinal distribution of stratospheric wave activity during Dec.-Feb. in the tropics observed by UARS.

The NetCDF/CMP files of the GPS/MET data base contain for each occultation the profile of water vapor pressure observed by GPS/MET and the corresponding profile determined by ECMWF analyses (European Center for Medium-Range Weather Forecast) [*Rocken et al.*, 1997; *Kursinski et al.*, 1995]. For the present study the average value of water vapor pressure between 4 and 6 km height is calculated from each profile.

Lower ionosphere

Analysed ionospheric observations are not available at the GPS/MET data base. However the analysis is already possible if one has GPS/MET data (50 Hz sampling rate) of transmitter/receiver positions and phase path delays of the GPS L1 and L2 carrier frequencies ($f_1 = 1575.42$ MHz, $f_2 = 1227.6$ MHz). One aim of the present study is to find out, in an empirical manner, if GPS/MET has been able to measure a global small-scale fluctuation field of the lower ionosphere or not. This question is of high interest, since GPS radio occultation may have a new important application for atmospheric research: high resolution global observation of neutral wave/turbulence, plasma irregularities, and electric current system within the MLT and dynamo region. The four main steps of the data analysis of our present study are:
i) Calculation of tangent point height h of GPS-LEO ray by using positions of GPS, LEO, and earth center (straight line is assumed for the ray). **ii)** Derivation of total electron content (TEC) along GPS-LEO ray. Because of the ionospheric dispersion effect, the difference of GPS L1 and L2 phase path excesss is linearly proportional to TEC. Because of limb sounding geometry, we call it horizontal TEC (hTEC). During a radio occultation hTEC is measured as function of ray tangent point height h. **iii)** The profile hTEC(h) is decomposed into a small-scale fluctuation profile ΔhTEC (vertical scales < 7 km) and into an average profile (7-km sliding window average). **iv)** ΔhTEC(h) is transformed into an electron density fluctuation profile Δn_e(h) by dividing with a constant factor s ($s = 2\sqrt{2r\Delta r}$; $r = 6470$ km; $\Delta r = 0.6$ km).

The last step iv) requires the assumption that the small-scale perturbation of hTEC is generated at or near to the tangent point in the lower ionosphere. This can only be fulfilled in a statistical sense, since the ionospheric F2 region also has plasma irregularities. At least three facts are on our side:
(1) Because of limb sounding geometry the phase path delay (or hTEC contribution) of the ray path segment around the tangent point has the maximum weight.
(2) Irregularities of the D, E, and F1 region generally have smaller vertical scales than those of the F2 region. The average vertical scale of fluctuations decreases with decreasing height in the ionosphere. **(3)** Enhanced aspect sensitivity of GPS-LEO radar for atmospheric irregularities at the earth's limb: usually the irregularities of the MLT region are hor-

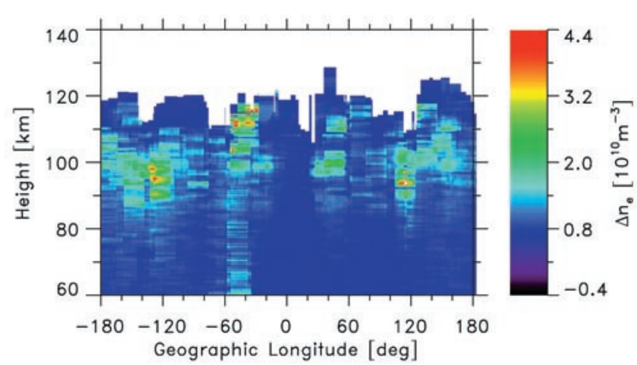

Figure 2. Longitude-height section of electron density fluctuation (vertical scales < 7 km) amplitude of the MLT region, averaged for GPS/MET radio occultation events within the southern tropical latitude range 5°S-25°S during February, 1997, 2-16. A sliding window with 10° in longitude has been applied. Vertical distances of maxima may be interpreted as half of the vertical wavelengths of neutral waves. (Data gaps at higher altitudes are due to lack of GPS/MET data of 50 Hz sampling rate at these heights, since the upper ionosphere has only been measured with 1 Hz sampling.)

izontally layered in the atmosphere (e.g., thin sporadic E layers). The observed ΔhTEC(h) fluctuation is maximal if the GPS-LEO radio ray sounds such a structure at the earth's limb, since in this case the refractivity gradient of the structure, as seen from the place of the LEO satellite, is steepest.

In a case study, *Sokolovskiy* [2000] shows a possibility for localization of a plasma irregularity by using phase and amplitude data of GPS radio occultation. Implementation and test of this alternative method for automatic data processing may be a task for the future. Geomagnetic activity has been low during the selected time interval in Feb. 1997 (Kp $\sim$ 2-3).

Results and Discussion

The correlation of longitudinal distributions of ionospheric irregularities Δn_e, relative temperature variance $(\Delta T/\bar{T})^2$, and surface topography is depicted in Figure 1. The time interval is 2-16 February 1997, and occultation events within the latitude range 5°S to 25°S have been extracted from a total of worldwide around 2000 GPS/MET occultations during this time. The statistics curve (Figure 1e) shows the number of occultation events within this latitude range as function of longitude. This curve and the curves in Figure 1a, b, c) are averaged by a sliding window of 10° in longitude and with a longitudinal step of 0.6°. The surface topography (Figure 1d) is obtained from an elevation data set of 1° resolution (Rand map provided by NCAR, Boulder) and has been only averaged over the latitude range from 5°S to 25°S. The number of occultation events depends on the constellation of GPS and LEO satellites but also on the distribution of the ground stations of the fiducial GPS network which is required for precise phase path determination.

The average water vapor pressure of the height interval h=4-6 km (Figure 1c) and observed by GPS/MET (solid line) agrees well with the corresponding water vapor pressure predicted by ECMWF (dotted line). The only significant difference may be the first maximum at -160 longitude (160°W) over the Pacific which is not resolved by ECMWF. In the following we take the solid curve of GPS/MET water vapor pressure as a measure of intensity of tropical convection and convectively generated gravity waves, since an increase of tropical convection causes an increase of water vapor clouds at higher tropospheric altitudes. Alternatively, the outgoing longwave radiation can be taken which is inverse proportional to high clouds and deep convection [*McLandress et al.*, 2000]; both measures agree well.

The gravity wave activity of the height range h=22-28 km is shown by the solid line in Figure 1b) while the dotted line corresponds to the wave activity at h=32-38 km. The wave activity of the lower stratosphere (solid line) over Brazil, Africa, and Indonesia/Australia correlates well to the water vapor pressure in the panel below. The maximum over the Pacific is maybe shifted by 20° in eastward direction, and the peak form is changed in the lower stratosphere. There is also a slight shift of the maximum over Brazil by 10-20° eastward, while the maximum over Indonesia/Australia is moving westward by around 10-20°. The maximum over Africa remains at the same longitude position of around 40°E. A minor maxima at 90°E occurs in the water vapor pressure but not in the stratospheric temperature variance curve. According to *Alexander* [1998], wave activity of the lower stratosphere in the tropics can be better attributed to tropospheric sources than at higher stratospheric altitudes. This is in agreement with the dotted line (h=32-38 km) of Figure 1b) which shows not much correlation to the curve of water vapor pressure.

For the MLT region the maximum of fluctuation amplitude Δn_e of the height range 80-120 km is determined for each occultation. The average longitudinal distribution of Δn_e in Figure 1a) shows a high correlation to the lower stratospheric temperature variance at h=22-28 km. In particular the positions and shapes of the peaks are similar for the stratosphere and MLT region. In the tropics this correlation is usually explained by gravity waves with upward energy propagation from tropospheric convection zones.

Since the ionospheric irregularities occur over regions of tropical thunderstorms, lightning (electric gas discharge) between the top of a tropospheric thundercloud and the lower ionosphere may be considered for enhanced generation of irregularities in the lower ionosphere [*Volland*, 1996]. However ionospheric irregularities due to lightning possibly occur, in average, at the same geographic place beyond the tropical convection zone and cannot explain the slight shift between the observed maxima of tropospheric water vapor pressure, gravity wave activity, and ionospheric irregularities (Figures 1a,b,c). So we favour a coupling of troposphere and ionosphere by upward propagating gravity waves as interpretation of the high correlation of Figures 1a,b,c). Interaction between gravity waves, tides, planetary waves, and mean flow occurs in the middle atmosphere, and processes such as wind filtering, Doppler-shifting, dissipation, and secondary generation of gravity waves are certainly involved in the transport of energy and momentum from the lower into the upper atmosphere.

Finally we discuss the longitude-height section of the average fluctuation amplitude Δn_e which is depicted in Figure 2. The regions of the 4 maxima of Figure 1 are also clearly separated in Figure 2. The peak over the Pacific is broader than the 3 peaks over the continents. It is remarkable that enhanced fluctuations above Indonesia/Australia and Pacific start at around 85 km height which is around 10 km lower than the start heights of enhanced fluctuations over Brazil and Africa. In case of Brazil, there are faint enhancements at heights h=60-80 km which may be due to strong gravity waves and enhanced ionization degree of the middle atmosphere over tropical convection zones. On the other hand, our assumption (irregularity is located near to the tangent point) may not be appropriate at these heights.

Vertical distances between maxima of the fluctuation amplitude Δn_e (absolute values have been averaged) correspond to the half of the vertical wavelengths of possible neutral waves which may form the plasma irregularities by ion-neutral coupling and $E \times B$ drift [*Whitehead*, 1960]. Looking at Figure 2, we may find vertical wavelengths of neutral waves of around 5-12 km.

Concluding Remarks

The longitudinal distributions of water vapor pressure (h=4-6 km), stratospheric temperature variance (h=22-28 km), and small-scale plasma irregularities (h=80-120 km) show a remarkable high correlation during the wet season of February 1997 at southern, tropical latitudes (5°S to 25°S).

The maxima of enhanced tropical convection, stratospheric wave activity, and ionospheric irregularities are localized over Brazil, Africa, Indonesia/Australia, and Pacific. The slight displacement (0-20° in longitude) of the intensity maxima in the lower stratosphere and ionosphere compared to the maxima of tropospheric water vapor pressure indicates a coupling of troposphere, stratosphere, and MLT region by gravity waves. This is supported by the longitude-height section of the average fluctuation amplitude of electron density which shows features of neutral waves with vertical wavelengths of around 5-12 km. Finally our preliminary analysis of GPS/MET data has given the important result that 50 Hz GPS occultation data obtained during two weeks by just one LEO satellite are already sufficient to provide a reasonable fluctuation field of small-scale ionospheric irregularities (vertical scales $<$ 7 km) of the MLT region. Thus, global observation of dynamics and electrodynamics of the MLT region with a vertical resolution of less than 1 km is a promising task for GPS radio occultation.

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