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Two-day wave observations over the middle and high latitudes in the NH and SH using COSMIC GPSRO measurements

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Abstract

The characteristics of the quasi-2-day wave (QTDW) in the upper stratosphere and lower mesospheric (USLM) altitudes over the northern hemisphere (NH) and southern hemisphere (SH) have been studied by using Global Positioning Radio Occultation (GPSRO) Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) temperature data from November 2006 to December 2010. We studied the seasonal, latitudinal, and interannual variability of the westward-propagating 2-day wave coincident with zonal wave number 3 in both hemispheres in the altitude range of 20–60 km. The Lomb–Scargle periodogram (LSP) analysis indicates the dominance of the QTDW in the USLM in both the hemispheres. The observed amplitude of the wave is maximum during the winter season in middle and higher latitudes, with monthly mean amplitudes being as high as ~ 8 K. These amplitudes are found frequently during the late fall and peak to a maximum in the NH winter season. In the SH, QTDW amplitudes are found in the early winter season and appear till the early fall months. The QTDW varies from 49 ± 3 to 48 ± 1 h in the NH and SH, respectively, with westward-propagating wave number 3. The amplitudes of the wave are large during winter in both the hemispheres, and, comparatively, the NH amplitudes are larger than those of the SH in higher latitudes.

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Keywords: Middle atmosphere dynamics; COSMIC GPSRO; Stratosphere and mesosphere; Quasi 2-day wave; Temperature

1. Introduction

Planetary waves are a part of global-scale oscillations, which play a significant role in the middle atmosphere dynamics. The primary periods of the planetary waves contain quasi 2-day, quasi 5-day, quasi 10-day, and quasi 16-day waves (Jacobi et al., 1998; Wang et al., 2010). Among these planetary waves, the quasi 2-day wave (QTDW) is predominantly necessary due to its relevance

in interactions with the mean flow and other planetary waves including solar tides (Mitchell et al., 1996). Muller (1972) attempted to study the QTDW in the upper mesosphere with zonal and meridional winds observed from a meteor radar over a mid-latitude site. Subsequently, using ground-based radars and satellite data sets, the QTDW was studied extensively (Wu et al., 1996; Rodgers and Prata, 1981; Manson et al., 2004; Riggins et al., 2004; Limpasuvan et al., 2005). In particular, meteor and medium-frequency (MF) radars were used to investigate the vertical structure and climatology of the 2-day wave at middle and high latitudes (e.g., Manson et al., 2004; Riggins et al., 2004; Sandford et al., 2008). Most of the previous studies showed the presence of the QTDW as bursts during the solstice and 1 month after the solstice lasting for

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a few weeks. Salby (1981) suggested that the observed QTDW of a period of 2.1 days is actually a manifestation of the Rossby-gravity normal mode of zonal wave number 3 in an isothermal windless atmosphere.

At mid-latitude locations, only summer activity is usually reported (Thayaparan et al., 1997a; Lima et al., 2004). However, recent studies (Jacobi et al., 1998; Nozawa et al., 2003a) showed that QTDW could be found in other times of the year as well. Jacobi et al. (1998) showed the presence of QTDW throughout the year but with smaller amplitudes and less regularity compared to the summer months. Namboothiri et al. (2002) also noted some increase in amplitudes (up to 15 m/s) in the winter months at Yamagawa (31°N) and Wakkanai (45°N) during 1997–1999 (see their Figs. 8 and 9). Later, Nozawa et al. (2003b) found that the QTDW amplitudes were larger in winter than in summer in the region of 70–91-km height for the high-latitude stations at Tromso (69°N) and Poker Flat (65°N). In the southern hemisphere (SH), the 2-day wave is primarily composed of zonal wave number 3, while the northern hemisphere (NH) wave is a mixture of wave numbers 2, 3, and 4 (Meek et al., 1996). However, ground-based radar measurements are limited to a particular latitude and longitude, to determine the zonal structure of the QTDW, and it is difficult to determine the zonal wave number.

The QTDW has been studied by using satellite measurements in the upper stratosphere and the lower mesosphere (USLM) region by using wind (Wu et al., 1993; Limpasuvan and Leovy, 1995), temperature data from Nimbus 7 (Rodgers and Prata, 1981), the Upper Atmosphere Research Satellite (UARS) (Limpasuvan and Wu, 2003), TIMED (Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics) (Garcia et al., 2005), and EOS Aura Microwave Limb Sounder (MLS) (Limpasuvan et al., 2005; Sandford et al., 2008; Tunbridge et al., 2011). All these studies showed temperature amplitudes up to ~11 K in the SH and weaker amplitudes in the NH.

Huang et al. (2013) studied the characteristics of QTDW between 52°S and 52°N using SABER (Sounding of the Atmosphere using Broadband Emission Radiometry) temperature data sets. Limpasuvan et al. (2005) reported 2-day waves in the upper stratosphere and mesosphere heights during December 2004–March 2005 using MLS water vapor, carbon monoxide, temperature, and line-of-sight wind measurements. Their results suggested that the 2-day wave appears in early January, peaks at the end of January, and persists until late February using MLS water vapor and temperature measurements. They also noted the simultaneous existence of the 2-day wave in the winter hemisphere mainly trapped in the stratosphere and lower mesosphere. Alexander and Shepherd (2010) showed the distribution and variability of planetary wave activity in the low to mid-stratosphere of the Arctic and Antarctic using Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) Global Positioning Radio Occultation (GPSRO) temperature measurements. However, these planetary wave studies have ~16–20-day periodicity mainly; measurements on QTDW from GPSRO observations have not been paid much attention. Therefore, in the present study, we attempted to investigate the QTDW by using GPSRO COSMIC satellite temperature data in both hemispheres. The GPSRO satellite technique provides highly accurate temperatures and has long-term stability, global coverage, <1-km vertical resolution, and all-weather capability (Kursinski et al., 1997; Anthes et al., 2008).

The objective of this article is to present the monthly, seasonal, and climatological latitudinal and geographical distribution of westward-propagating zonal wave number 3 QTDW by using the COSMIC GPSRO temperature data during the period of November 2006–December 2010 in the altitude range of 10–60 km in both NH and SH. The next section deals with the data and analysis procedure adopted for the present study. Results and discussion are given in Section 3. Finally, the summary and conclusions are presented in Section 4.

2. Data analysis

GPSRO COSMIC is a joint Taiwan–US mission and the satellite (Rocken et al., 2000) launched successfully on 14 March 2006 on a circular orbit with an inclination of 72° at an altitude of ~750 km (Cheng et al., 2006). Under the assumption of geometric optics and the local spherical symmetry of the atmosphere, the phase delay measurements can be directly inverted to yield an index of refraction profile with a vertical resolution of about 500 m in the lower troposphere to about 1 km in the upper stratosphere. The “dry” temperature data product obtained from the COSMIC/FORMOSAT-3 mission is computed from the observed refractivity under the assumption that the water vapor pressure is negligible in the lower troposphere. It provides ~1500 radio occultations on the vertical profiles of atmospheric air density, temperature, and water vapor as well as ionospheric electron density per day (Anthes

Fig. 1. Histogram of the number of occultations for 2007 over 90°S to 90°N for every 10° interval.

Fig. 2. Frequency-wave number spectrum of temperature at altitude ranges from 52 to 56 km over latitudes between 50° and 60°S estimated using COSMIC RO observations during the SH winter (JJAS) 2008 season.

Fig. 3. Temperature amplitude spectra of GPSRO for days 345–354 during the year 2007 at a height of 58 km over 60–65°N. The significance level (90%) is indicated by a horizontal dashed line.

et al., 2008). COSMIC data sets are available from the surface to 60 km; however, for the purpose of our analysis, we consider altitudes above 10 km to avoid the effects of humidity in the lower troposphere.

This study considers a data sample of 51 months, which begins from November 2006 to December 2010. As a polar-orbiting satellite, COSMIC makes about 15 orbits per day in a ~ 750 -km and 72° inclination orbit. Considering that COSMIC takes 50 days to cover 24 h local time at each latitude band (Wu et al., 2009), at each hour at every altitude, COSMIC temperature data are binned into grid cells with latitude 10° and longitude 10° . For calculating the hourly means, we adopted the criterion that there should be more than three temperature values per hour at each longitude–latitude grid. Fig. 1 shows the histogram of the number of occultations for each grid of COSMIC for the year 2007. From the figure, we can see that occultations in the high latitudes (80 – 90° N and 80 – 90° S) and tropics (10° S– 10° N) were lower in density than in the mid-latitudes. It is due to the high inclination of COSMIC and their viewing geometry relative to GPS (Haji et al., 2004). The highest latitude accessible to the satellite is just over 85° in both the hemispheres (NH and SH). The advantage of the GPSRO data is that they can have a longer temporal

coverage, roughly evenly distributed in space, and their latitude routinely reaches within 2° of the poles so the GPSRO data are useful for studying the global planetary wave phenomena such as QTDW. In addition, the GPS data can have longer temporal coverage than many other satellites (Wang and Alexander, 2009). The temperature precision of 0.5 K or better between the radiosonde and COSMIC at 25-km altitude was observed by Hayashi et al. (2009). The validation of GPSRO temperature has been studied extensively recently by Kishore et al. (2008) and Rao et al. (2009). Recently, Madhavi et al. (2013) observed that the precision is about ~ 1.5 K at 35 km; degrading to ~ 3 K was observed in USLM (40–60 km) using different satellite measurements (MLS and SABER) and COSMIC RO temperatures. Recently, Das and Pan (2014) compared COSMIC temperature profiles with satellites (MLS and SABER); the COSMIC temperature is observed to be 2 K less than SABER at 50 hPa and ~ 5 K higher than SABER at 0.3 hPa. The GPS temperatures are higher than the MLS temperatures by 0–2 K from 50 to 2 hPa and 6–8 K higher at 0.3 hPa.

During the analysis of temperature data, we noticed data gaps, which were filled by using linear interpolation. However, the data gaps, which are longer than 1 day (i.e., greater than one-fourth of the period of interest), were left unfilled and no further analysis was conducted with the data. In this study, the Lomb–Scargle periodogram (LSP) method (Scargle, 1982) is used to obtain estimates of the spectral amplitudes and confidence levels as well as phase information. In our analysis, we used 4-day groupings of temperature data in each time series, and the intervals were shifted by 1 day. The LSP method is equivalent to pure harmonic least-square analysis. This method is useful to estimate the amplitude or power spectra of the time series, which are unevenly spaced (Press et al., 1992). The LSP weights the data by each point rather than by each time interval. The standard method of calculating the LSP significance levels employed in the present study is only appropriate for the most significant peak in a spectrum (Horne and Baliunas, 1986).

Fig. 4. Seasonal variations of temperature amplitudes for the COSMIC QTDW from 48 to 58 km at every 2 km for latitude bins 40–50°N, 50–60°N, 60–70°N, and 70–80°N.

3. Results and discussion

Fig. 2 shows the distribution of power over a range of frequencies and wave numbers. This spectrum was computed from the temperature data in the altitude range of 52–56 km and 50–60°S latitude bins during winter (JJAS) of 2008. A positive (negative) wave number indicates eastward (westward) propagation. The presence of a westward-propagating wave with zonal wave number 3 for a period of 2 days is clearly observed. The 2-day wave is dominant in the period of 43–52 h as seen in the spectrum (see Fig. 2). In addition, a secondary component is seen in the spectra with a period of ~ 46 h with zonal wave number 2. This is beyond the scope of our present study. This study completely deals with only wave number 3 in both the hemispheres.

In order to identify the dominant periodicities, which are present in the time series of the temperature data, the data were subjected to LSP analysis. Fig. 3 shows the LSP spectra of the temperature data during the month of December 2007 in the latitude band of 60–65°N at an altitude of 58 km. The amplitude spectra of temperature show the

2-day dominant peak along with the diurnal, semidiurnal, and terdiurnal tides at frequencies 0.5, 1.2, and 3 cycles/day (cpd), respectively. Although the diurnal, semidiurnal, and terdiurnal tides are observed clearly, the 2-day peak is broad, ranging from roughly 42 (0.0238 cpd) to 58 h (0.0172 cpd). The horizontal dotted line corresponds to the 90% significance level. The probability level indicates the confidence with which one may reject the null hypothesis. The spectral amplitudes occur because of random-noise fluctuation in the time-domain data.

3.1. Monthly variation of QTDW

Fig. 4 shows the seasonal variations of temperature amplitudes of the westward-propagating QTDW of wave number 3 from November 2006 to December 2010 in the height range of 48–58 km with 2-km intervals. The amplitudes are calculated by using LSP analysis with a time window of 4 days with a progressive advancement of 1 day for those cases where the data coverage is at least three-fourth the window width, that is, ≥ 36 h. The QTDW temperature amplitudes are calculated corresponding to a 2-day period

Fig. 5. Seasonal variations of temperature amplitudes for the COSMIC QTDW from 48 to 58 km at every 2 km for latitude bins 40–50°S, 50–60°S, 60–70°S, and 70–80°S.

(0.5 cpd) at each altitude for different latitude bands, 40–50°N, 50–60°N, 60–70°N, and 70–80°N. A similar method applied by [Thayaparan et al. \(1997a,b\)](#) and [Namboothiri et al. \(2002\)](#) showed that a 4-day fit is enough to obtain reasonable significance. We estimated the confidence levels of the periodograms containing spectral peaks with >90% significance. From [Fig. 4](#), it can be seen that from the 48- to 58-km range, the QTDW temperature amplitude during the winter months (November–February) is significantly stronger and comparatively less prominent in summer months. The QTDW amplitudes increase with latitude and a strong-wave amplitude appears at the mid- and high-latitude regions. A clear seasonal variation is noticed in QTDW activity from November to February and weak activity from May to August. The winter amplitudes are higher by a factor of 1.5 than in summer at all the altitude levels. The winter amplitudes are approximately constant in the 70–80°N latitude with an amplitude of about 9–10 K. During NH winter (70–80°N), the amplitudes are higher by a factor of 2–2.25 than those in winter at 40–50°N. The 2-day wave maximum amplitudes are

observed at about 56-km altitude level using MLS temperatures over a high-latitude (63–73°N) region with zonal wave numbers 2 and 3 ([Sandford et al., 2008](#)).

The seasonal variations of QTDW amplitudes at different altitudes are shown in [Fig. 5](#) for SH. The 2-day wave amplitudes are dominant from June to the end of September. The secondary maximum amplitude of about 6–7 K appears at the end of August and early September. The maximum amplitude of the 2-day wave occurs during November 2006–January 2007. Wave amplitudes during the summer are smaller than during the winter season, but they occasionally reached up to ~6 K during the summer month of January 2007. The SH winter maximum amplitude reached about 8 K during 2007. The wave period also varies between the two hemispheres.

3.2. Latitudinal, temporal, and height variations of 2-day wave and their interannual behavior

To provide a more quantitative description of the QTDW activity as a function of height and time, the

Fig. 6. Time–height contours of COSMIC QTDW amplitudes during November 2006–December 2010 for 50–60°N, 60–70°N, and 70–80°N (left side) and for 50–60°S, 60–70°S, and 70–80°S (right side).

Fig. 7. Time–latitude contours of COSMIC QTDW amplitudes during November 2006–December 2010 at height 56 km.

temperature amplitudes of QTDW at three different latitude ranges of NH (50–60°N, 60–70°N, and 70–80°N) and SH (50–60°S, 60–70°S, and 70–80°S) from November 2006 to December 2010 are shown in Fig. 6. The left panel corresponds to the NH and right panel represents the SH latitude region. The spectral amplitudes in the contour panels are calculated by LSP analysis with a 4-day window, and the window is shifted by a 1-day increment. The periodogram analysis conducted for the time series from various altitudes reveals a prominent component centered

at 2 days. The QTDW amplitudes observed in both the hemispheres have certain similarities as well as differences. The annual variations of QTDW amplitudes are found almost regularly in late NH winter. In the SH, the wave activity appears during early winter and extends up to the early spring months. Note that the NH winter months are from November to February and from June to August for the SH. The wave amplitudes are stronger at higher altitudes compared to the lower altitudes suggesting that the wave amplitudes increase with altitude. In the latitude

Fig. 8. (a) Period, (b) phase, and (c) amplitude profiles of COSMIC QTDW in the northern hemisphere for latitude bins 40–50°N, 50–60°N, 60–70°N, and 70–80°N for the period November 2006–December 2010 during the winter (NDJF) months.

Fig. 9. (a) Period, (b) phase, and (c) amplitude profiles of COSMIC QTDW in the southern hemisphere for latitude bins 40–50°S, 50–60°S, 60–70°S, and 70–80°S for the period November 2006–December 2010 during the winter (JJAS) months.

band of 50–60°N, the 2-day wave amplitudes increase with height and reach a peak amplitude at an altitude level of around 57 km. The wave amplitude reaches 7–9 K above the altitude level of 48 km in mid and high-latitude regions. An earlier study by [Limpasuvan and Leovy \(1995\)](#) showed a maximum amplitude above 0.465 hPa (~ 53 km) in the USLM altitude region using temperature and H₂O measurements from the UARS MLS data sets. In both the hemispheres (NH and SH), the QTDW peaks exist 2007, 2008, and 2010 at middle and high latitudes; this means that the interannual variations are evident in both hemispheres.

[Fig. 7](#) shows the latitude–time cross section of the Q2DW amplitudes estimated by LSP analysis at an altitude of 56 km during the period from November 2006 to December 2010. From the figure, it is evident that the QTDW reveals consistent characteristics of the wave and the amplitudes are more at the mid- and high-latitude regions. In both the hemispheres, the QTDW winter amplitudes reach a maximum up to ~ 10 K in January for NH latitudes, whereas in SH latitudes the maximum amplitudes are at ~ 9 K and extend up to solstice. In mid-latitudes, the SH enhancement in winter is more robust and repeatable

than the NH winter enhancement. In low latitudes (30°S–30°N), the QTDW amplitudes look similar in both hemispheres. However, it is noteworthy that the height–time structure demonstrates some differences in their interannual variations. From [Fig. 7](#), the QTDW exhibits strong year-to-year variations in amplitude and time of occurrence. In spite of this, there is an apparent seasonal variation with maxima in winter and minima during summer especially in the USLM region. These results are consistent with a previous study by [Sandford et al. \(2008\)](#). [Patra \(1984\)](#) reported 2-day wave amplitudes to be stronger in the polar winter stratosphere observations at a height of around 45 km. In the SH, their periods and wave numbers are about 48 h and -3 (minus means westward propagation), respectively. On the other hand, in the NH, the periods range between 42 and 56 h, with corresponding wave numbers -2 , -3 , and -4 ([Craig et al., 1980](#); [Pancheva et al., 2004](#); [Malinga and Ruohoniemi, 2007](#)).

Figs. 8(a–c) and 9(a–c) show the height variations of the mean period, phase, and amplitudes of the QTDW observed during the winter months at the NH and SH over four different latitude bands. By using the LSP analysis, the mean period, amplitude, and phase of the QTDW were

determined at a specified time interval. A minimum period of 47 h is observed over 40–50°N from 44 to 56 km, and above 56 km the observed period is 48 h. A maximum period of 51 h is observed in 60–70°N. The error bars (solid horizontal lines) indicate that the monthly variations are of the order of 45 min from the mean value. A consistently evident picture of a 2-day wave with 48 ± 1 h is observed between 50° and 60°N at all heights from 46 to 58 km. The QTDW amplitudes increase from middle to higher latitudes (40–50°N–70–80°N), the range of amplitudes varies from 5 to 6 K, and the phase profiles show a clear downward propagation in all latitude bands. In the SH, the phase profile shows less variation (see Fig. 9(a)). The observed minimum period is 47 h in 40–50°S and the maximum period is about 49 h in 70–80°S. A consistently evident picture of 2-day wave periods with 48 ± 1 h can be seen in the case of 50–60°S and 60–70°S at all heights from 46 to 60 km. The observed SH QTDW period is consistent with earlier reports of Lima et al. (2004) that the periods are almost close to 48 ± 1 h. The wave periods also vary between the two hemispheres. It is clear that the period

of the 2-day wave varies between 49 ± 2 and 48 ± 1 h in the NH and SH, respectively. In the SH, at low and middle latitudes, the wave period is often observed to be very close to 2 days (e.g., Craig et al., 1980; Wu et al., 1996). In the NH, the observed wave period varies between 1.8 and 2.2 days. The vertical wavelength is measured by the rate of change of the phase with height, that is, in the altitude regions of downward phase propagation. The observed wavelength lies in the range 12–16 km in both hemispheres of QTDW. These vertical wavelengths are small compared to the theoretical estimates for QTDW in the USLM region. Our present study, on the QTDW in NH middle and high latitudes, exhibits clear amplitude maxima during winter, although the peaks show significant differences in periods (47 ± 2 h). These differences in periods are due to modulation of the wave amplitude which tends to spread energy over a range of frequencies, further accounting for the shift in periods (Vincent, 1984).

To deduce more information on the height dependence of the QTDW, monthly amplitude profiles are estimated from the temperature measurements over three different

Fig. 10. Mean height profiles of COSMIC temperature QTDW amplitudes for 50–60°N, 60–70°N, and 70–80°N during November 2006–December 2010.

Fig. 11. Mean height profiles of COSMIC temperature QTDW amplitudes for 50–60°S, 60–70°S, and 70–80°S during November 2006–December 2010.

latitude bands of the winter months in both the hemispheres as shown in Figs. 10 and 11. During each month of winter, the maximum QTDW amplitudes are observed over 70–80°N and 70–80°S in both the hemispheres. The height profiles of amplitude show features more prominently than those seen in the contour plots (see Fig. 6). The maximum amplitudes are observed around the upper stratopause region in the NH of about ~ 10 K during the month of December, whereas in the SH the maximum amplitude occurs at about ~ 7 K in September every year. The maximum amplitudes are observed at the end of the winter months in both hemispheres, and sometimes they extend to the beginning of the next season. Comparatively large variations are seen in the NH amplitudes than the SH amplitudes. From Figs. 10 and 11, we conclude that the QTDW amplitudes are maximum at 56 km with a peak value near 55 km, in all the three latitude bins of the NH and SH, respectively.

4. Summary and conclusions

In the present study, we examined the global QTDW structure at middle and high latitudes in the USLM region using high-resolution temperature data collected by the COSMIC/FORMOSAT 3 satellite mission during the period of November 2006–December 2010. The climatology of QTDW shows the strongest amplitude occurring in winter and low amplitudes during the summer season. Significant interannual variability was observed in both the hemispheres. In NH winter, the wave amplitudes were about ~ 8 K, but weakly present in the summer season.

The COSMIC GPSRO temperature data reveal the regular presence of a westward-propagating QTDW with zonal wave number 3. Maximum wave amplitudes are observed during winter in middle to high latitudes in both hemispheres. However, there are some hemispherical differences in QTDW characteristics such as amplitude, occurrence, and time periods.

The QTDW exhibits strong interannual variations in amplitude and time of occurrence. In spite of this, there exist clear seasonal variations with maxima during winter in both hemispheres. The maximum amplitudes are observed around 56 km in both hemispheres.

The period and amplitude of the 2-day wave are determined at all heights using LSP analysis. The vertical phase structure shows a descending phase and the magnitude of the vertical wavelengths is smaller than theoretical values, whereas the phase values show little variation with height when the amplitude is large. The periods of QTDW vary between 49 ± 2 and 48 ± 1 h in the NH and SH, respectively. These results are consistent with the previous studies, but some differences are apparent in high latitudes (50 – 60° and 60 – 70°) in both the hemispheres.

In order to understand the generation mechanism and tidal interaction, the characteristics of the QTDW over middle and high latitudes in the USLM region need further investigation.

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