Global Distribution and Inter-annual Variations of Mesospheric and Lower Thermospheric Neutral Wind Diurnal Tide.

Part 2: Nonmigrating Tide

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Abstract

Based on TIDI mesosphere and lower thermosphere neutral wind observations from 2002 to 2005, we analysis the interannual variations of nonmigrating diurnal tides from eastward zonal wavenumber 3 (E3) to westward zonal wavenumber 3 (W3). We focus

on possible QBO related variations in these nonmigrating diurnal tide components. We found: 1) strong reverse QBO effect on the W2 meridional diurnal tide in fall and winter, suggesting a W2 source of nonlinear interaction between planetary wave 1 and migrating diurnal tides; 2) QBO effect on the peak height was observed during the summer solstice on the E3 zonal diurnal tide; 3) several nonmigrating tide components (E3, E2, E1, W3 meridional and W3 zonal) show similar eastward phase QBO enhancement during the spring equinox as the migrating diurnal tide did, though to a less degree.

1. Introduction

Besides the migrating diurnal tide, the nonmigrating diurnal tides are also significant at times. Nonmigrating diurnal tides are suggested to be caused by latent heat release [e.g., *Hagan and Forbes,* 2002; 2003], nonlinear interaction between the migrating tide and planetary wave [e.g., *Hagan and Roble,* 2001; *Mayr et al.*, 2003; *Lieberman et al.*, 2004; *Mayr et al*., 2005a; 2005b; *Forbes et al.*, 1995; *Teitelbaum and Vial*, 1991], sea-land and orographic distributions [*Tsuda and Kato*, 1989; *Kato et al*., 1982]. Other sources are also suggested [*Oberheide et al*., 2002; 2006].

Based on UARS HRDI observations *Talaat and Lieberman* [1999], *Forbes et al.* [2003], and *Huang and Reber* [2006] examined the seasonal variations of various nonmigrating diurnal tides. Using TIDI observations *Oberheide et al.* [2005a; 2006] studied the nonmigrating diurnal tides and compared the observations with TIME-GCM model results. Ground based observations of the nonmigrating tide are difficult and require multiple stations often with only limited resolution for zonal wavenumbers. When the nonmigrating tide become significant (e.g. at high latitudes), ground based observations are able to provide good nonmigrating tide results [e.g., *Murphy et al.*, 2003; *Baumgaertner et al.,* 2006]. Recently, MLT nonmigrating tide has been attributed to the longitudinal variations in the equatorial ionosphere anomaly [*Sagawa et al.,* 2005; *England et al.,* 2006a; 2006b; *Immel et al*. 2006;]. Hence there is a renewed interest for a better understanding of the MLT nonmigrating tides.

In general, there have been very few systematic nonmigrating tide observations. Modeling efforts have progressed in recent years on nonmigrating tides [*Hagan and Forbes,* 2002; 2003; and *Grieger et al.*, 2004]. While we know more about the seasonal and latitudinal variations of the nonmigrating diurnal tide, very little has been shown about their interannual variabilities [*Hagan et al.*, 2005; *Oberheide et al.*, 2005b].

In this paper, we focus on the interannual variation of the nonmigrating diurnal tide. This is a continuation of the effort to examine the diurnal tides (migrating and nonmigrating) using the TIDI observations. In *Wu et al*. [2007, hereafter Part I] paper, we examined the migrating diurnal tide. As in Part I, we are particularly interested in the QBO effect. The QBO effect on migrating diurnal tide is strongest during the northern spring equinox because the stratospheric winds are at their peaks possibly inducing maximum gravity wave filtering effect [Part I]. Hence, we will mostly perform the interannual comparison of the northern spring equinox diurnal tide amplitude. However, if other seasons also show possible QBO related variation, we may examine these seasons instead. Since the data set and processing method are the same as those used in the [Part I], we will not repeat those descriptions here. More details about the data set, stratospheric QBO wind condition, and analysis method can be found in Part I.

One of the intriguing problems is how the nonmigrating diurnal tides react to the QBO. For the westward propagating nonmigrating, we would expect similar behaviors. For the eastward nonmigrating tides, we expect different interaction with gravity waves. Hence, these results may shed light on how the gravity waves interact with tides propagating in different directions. We do not include the NCAR TIME-GCM 1.2 annual results for this nonmigrating tide analysis, because the TIME-GCM 1.2 annual runs were based on only GSWM migrating tide components at 10 hPa. We plan to perform new annual runs with nonmigrating tides at 10 hPa in the future.

The paper is organized as follows. In Section 2, we describe the nonmigrating diurnal tides of various modes in spring equinox meridional and zonal winds during the four years 2002 to 2005 based on the TIDI observations. We discuss the results in Section 3 and summarize our findings in Section 4.

2. TIDI Nonmigrating Diurnal Tide in Neutral Winds

The diurnal tide has several prominent nonmigrating components based on past observations [e.g., *Forbes et al.*, 2003]. We examined nonmigrating diurnal tide from eastward zonal wavenumber 4 (E4) to westward zonal wavenumber 4 (W4). Because both the E4 and W4 are too small to be included in the discussion, we limited our analysis to components from E3 to W3. For each nonmigrating diurnal tide component, we will start with the latitudinal and daily variations at 95 km. Then, we will show the most QBO affected seasons with a latitude and vertical variation plot.

2.1 Eastward Zonal Wavenumber 3 (E3)

Figure 1 shows the E3 in meridional winds at 95 km for the four years (2002 – 2005). The E3 meridional tide is limited to the region close to the equator. We see very almost no activity at this altitude in 2002. In other years, the amplitudes tend to peak during spring and fall seasons. Since the amplitude at 95 km gives no obvious QBO effect, we examine the amplitude profiles during spring equinox when the migrating diurnal tide shows largest QBO effect. Figure 2 plots the E3 meridional amplitude vertical profiles during spring equinox. We see slightly stronger amplitude during the eastward phase of the stratosphere QBO (2002 and 2004).

Figure 3 is for the zonal wind E3 amplitude. The zonal wind amplitude is also limited to the low latitudes. But the region is wider than of the meridional winds. The maximum amplitude tends to occur in the summer. The amplitude is stronger during the eastward phase of the stratosphere QBO (2002 and 2004). To examine the amplitude change more closely, we plot the amplitude profiles of summer solstice in Figure 4. There is no clear peak amplitude difference between the eastward and westward phase of the QBO. There is a small difference in altitude of the E3 active region. During the eastward phase of the QBO (2002 and 2004), the region appears to be lower in altitude.

Consequently, the 95 km amplitudes show an increase for the 2002 and 2004 summer season (Figure 3).

2.2 Eastward Zonal Wavenumber 2 (E2)

The diurnal E2 component at 95 km is much weaker than that of the E3 in general (Figure 5). It is centered near the 10°S. No clear QBO effect can be seen. Figure 6 shows the E2 vertical profiles during the northern spring equinox. In this plots, we can see enhancement during the eastward phase of the stratosphere QBO (2002 and 2004). The E2 amplitude during these two years (2002 and 2004) peaked at 10°S. Figure 7 shows E2 in the zonal winds at 95 km. There is a slight increase in amplitude in the winter season at 50°S during the westward phase of the QBO (2003 and 2005). Figure 8 illustrates the vertical profiles of the E2 zonal amplitude during winter solstice. A narrow region of the enhanced amplitude can be seen during the westward phase of the stratosphere QBO (2003 and 2005).

2.3 Eastward Zonal Wavenumber 1 (E1)

The E1 meridional component peaks at 20°S most of the time (Figure 9). Two strong peaks in 2002 and 2003 fall equinox. There is a small increase in spring equinox during 2002 and 2004. The vertical profile of the meridional amplitude for spring equinox shows a small increase around 20°S for the eastward stratosphere QBO phase. The E1 in the zonal winds at 95 km is shown in Figure 11. We see no consistent seasonal pattern. The vertical profiles during spring equinox (not shown) also have no identifiable features.

2.4 Stationary Zonal Wavenumber 0 (S0)

The meridional wind S0 component has two tracks at 20°S and 20°N (Figure 12). The amplitude has tendency to maximize near day 200. We may say that the maximum in the fall equinox tend to larger at 20°N (near day 200) for the westward phase of the QBO, whereas the maximum in the 20°S (near day 200) show no such regularity. Figure 13 shows the spring equinox vertical profiles. For the eastward phase QBO (2002 and

2004), the S0 peaks at 20°S around 87 km, whereas for the westward phase QBO (2003 and 2005) the S0 peaks at 10°S around 92 km.

The zonal wind S0 component at 95 km does not have well defined pattern (Figure 14). Most of its activities are in the southern hemisphere near 50°S.

2.5 Westward Zonal Wavenumber 2 (W2)

The meridional wind W2 component has well defined pattern with amplitude crests at 20°S and 20°N (Figure 15). The amplitude has two peaks on day 230 and 300. The amplitude is quite significant, particularly in 2005, reaching ~ 30 m/s. The QBO effect is very pronounced, with larger amplitude in fall and winter season during the westward phase of the QBO (2003 and 2005). Strong inter-hemispheric differences are also seen. Figure 16 is the vertical and latitude variations of the meridional wind W2 amplitude. Stronger amplitude in 2003 and 2005 is quite apparent. The amplitude is also much stronger in the northern hemisphere at this time of the year.

Relative to the meridional winds, the zonal wind W2 component is much less well organized (Figure 17). At 30°N near day 300 during 2003 and 2005, we see a small region of the enhancement. At 53S near day 200, a persistent active region appeared in 2003, 2004 and 2005. The rest of active regions scattered across the southern hemisphere throughout the years.

2.6 Westward Zonal Wavenumber 3 (W3)

Although, the amplitude is not strong the meridional W3 has a clear annual pattern with peak at 20°S near day 230 (Figure 18). Less noticeable are the enhancements near day 50 between 50°S and 10°S during 2002 and 2004. Figure 19 shows the vertical and latitudinal variations of the W3 during spring equinox. The enhancement is mostly in the between 50°S and 10°S during eastward phase of stratosphere QBO (2002 and 2004).

The zonal winds W3 component pattern is less clear at 95 km (Figure 20). Most active regions are in the southern hemisphere. Small enhancements are seen at 50°S near day

70. The vertical and latitudinal variation plot for spring equinox show an increase near 50°S during the eastward phase of the QBO.

3. Discussions

There are not many systematic analyses of interannual variations of the diurnal nonmigrating tides. TIDI instrument provides the opportunity with consistent and dedicated MLT neutral wind observations. Moreover, the TIDI coverage is identical year after year. The strongest reaction to QBO is that of meridional diurnal W2 during the fall equinox. We see a reversed QBO on the meridional diurnal W2 with enhancement in the westward phase of the QBO during the fall equinox. QBO effect on the meridional E3 is also noticeable in terms of altitude shift in the summer solstice.

Some changes are very subtle. For the S0 meridional wind component, we see changes in latitude and altitude of the large amplitude during different phases of the QBO. Whether that is due to excitations of different modes is a question needs further studies.

For most of the other components, we see a smaller enhancement in spring equinox during eastward phase of the QBO. Even for some eastward propagating components, we also see increase in the eastward phase of the QBO. One would expect that the QBO affects tides through filtering of gravity waves. Such mechanism should not be isotropic, gravity waves may interact with nonmigrating tides propagating in the eastward direction differently compared to westward migrating diurnal tide. Yet, we see similar QBO modulation on these eastward propagating tides as to the westward migrating tides. This result seems to suggest that the nonmigrating diurnal tides may be related to the migrating tide. Although there have been in depth discussions about the nonlinear interaction between the migrating diurnal tide and planetary waves causing the nonmigrating tides [e.g., *Mayr et al*. 2005a; 2005b], such discussions have not extended to the eastward propagating nonmigrating diurnal tides. It is worth to look into the contribution from the migrating diurnal tide to eastward propagating nonmigrating diurnal tides.

The W2 component peaks in the fall and winter seasons. The QBO modulation is reversed. If we consider the W2 as the result of nonlinear interaction between the migrating W1 and planetary wave 1 as suggested by *Lieberman et al.* [2004], this reserved QBO modulation then may be traced to QBO modulation of the planetary wave 1 in the stratosphere. *Hu and Tung* [2002] have noted such reversed QBO modulation stratosphere planetary wave 1 during the northern winter. Hence, our results seem to lend more credence to the notion that the W2 diurnal tide is caused by the nonlinear interaction between the migrating W1 and planetary wave 1.

4. Summary

We give only a brief overview of the interannual variation of the nonmigrating diurnal tide in this paper. Some of nonmigrating diurnal tides show significant interannual variabilities, some may be QBO related and some may be not. We are far from understanding these variations at this point. Future studies with sophisticated models with proper QBO and stratosphere-mesospheric interactions are needed. In summary, we found 1) strong reverse QBO effect on the W2 meridional diurnal tide in fall and winter, suggesting a source of nonlinear interaction between planetary wave 1 and migrating diurnal tides; 2) QBO effect on the peak height was observed during the summer solstice on the E3 zonal diurnal tide; 3) several nonmigrating tide components (E3, E2, E1, W3 meridional and W3 zonal) show similar eastward phase QBO enhancement during the spring equinox as the migrating diurnal tide did, though to a less degree.

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Figure Captions

Figure 1. Diurnal E3 in meridional winds at 95 km.

The plot is based on analysis with a 60-day sliding window; the date in vertical direction marks the beginning of the 60-day window. For comparison with monthly average, a shift of 30 days is recommended. The left side is for the eastward phase of the stratosphere QBO (2002 and 2004) whereas the right side is for the westward phase. The contour level step is 4 m/s.

Figure 2. Diurnal E3 merdional during northern spring equinox.

The latitudinal and vertical variations of the meridional E3 diurnal tide amplitude during northern spring equinox. Again the left side is for the eastward phase of the stratosphere QBO (2002 and 2004) and the westward phase is on the right side (2003 and 2005). The contour level step is 2 m/s.

Figure 3. Diurnal E3 in zonal winds at 95 km.

Same as Figure 1 for E3 merdional winds.

Figure 4. Diurnal E3 zonal during northern fall equinox.

Same as Figure 2 for E3 zonal winds during northern fall equinox.

Figure 5. Diurnal E2 in meridioal winds at 95 km

Same as Figure 1 for E2 meridional winds.

Figure 6. Diurnal E2 meridional during northern spring equinox

Same as Figure 2 for E2 meridional winds during northern spring equinox.

Figure 7. Diurnal E2 in zonal winds at 95 km

Same as Figure 1 for E2 zonal winds.

Figure 8. Diurnal E2 in zonal winds during northern winter solstice

Same as Figure 2 for E2 zonal winds during northern winter solstice.

Figure 9. Diurnal E1 in meridional winds at 95 km

Same as Figure 1 for E1 meridional winds.

Figure 10. Diurnal E1 meridional during northern spring equinox

Same as Figure 2 for E1 meridional winds during northern spring equinox.

Figure 11. Diurnal E1 in zonal winds at 95 km

Same as Figure 1 for E1 zonal winds.

Figure 12. Diurnal S0 in meridional winds at 95 km

Same as Figure 1 for S0 meridional winds.

Figure 13. Diurnal S0 in meridional winds during northern spring equinox

Same as Figure 2 for S0 meridional winds during northern spring equinox.

Figure 14. Diurnal S0 in zonal winds at 95 km

Same as Figure 1 for S0 zonal winds.

Figure 15. Diurnal W2 in meridional winds at 95 km

Same as Figure 1 for W2 meridional winds.

Figure 16. Diurnal W2 in merdional winds during northern spring equinox

Same as Figure 2 for W2 meridional winds during northern spring equinox.

Figure 17. Diurnal W2 in zonal winds at 95 km

Same as Figure 1 for W2 zonal winds.

Figure 18. Diurnal W3 in merdional winds at 95 km

Same as Figure 1 for W3 meridional winds.

Figure 19. Diurnal W3 in meridional winds during northern spring equinox

Same as Figure 2 for W3 meridional northern spring equinox.

Figure 20. Diurnal W3 in zonal winds at 95 km

Same as Figure 1 for W3 zonal winds.

Figure 21. Diurnal W3 in zonal winds during northern spring equinox

Same as Figure 2 for W3 zonal northern spring equinox.