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

Part 1: Migrating Tide

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Abstract

Using the TIMED Doppler interferometer (TIDI) mesospheric and lower thermospheric neutral wind multiyear data set (2002 – 2005) and NCAR TIME-GCM 1.2 annual run results at the TIDI sampling points, we study the migrating diurnal tide global distribution, interannual, and seasonal variations in connection with the mean zonal wind interannual and seasonal variations. Strong quasi-biennial oscillation (QBO) effect on the diurnal tide was observed in the TIDI data and reproduced to a less degree in the TIME-GCM run. The migrating diurnal tide amplitude is larger during the eastward phase of the stratosphere QBO and weaker during the westward phase. Westward mesosphere equatorial mean zonal winds appeared during the eastward phase of the stratosphere QBO (2002 and 2004). The strongest QBO effect on both the migrating diurnal tide and mean zonal winds were observed during the northern spring equinox. We believe that is because both the stratosphere winds and diurnal tide amplitude reach their maximum magnitudes during northern spring equinox. The stratospheric QBO winds apply the maximum filtering effect on the gravity waves, which in turn strongly modulate the diurnal and mean zonal winds at higher altitudes. The TIDI data also exhibit large inter-hemispheric asymmetry. The westward mean zonal winds in the mesosphere appeared to be associated with the enhanced diurnal tide. The TIME-GCM 1.2 diurnal tide amplitudes are in general smaller than that observed by TIDI. Limited vertical spatial resolution for the TIME-CGM 1.2 is suggested as the cause. Future improvements are expected with higher spatial resolution in the model.

1. Introduction

Diurnal tide is the most prominent dynamics feature of the mesosphere and lower thermosphere (MLT) region. The MLT diurnal tide has both significant migrating and nonmigrating components. The migrating tide is sun synchronous caused by solar UV radiation absorption by stratosphere ozone and troposphere water vapor. Studies of the MLT migrating tides have a long history [e.g., *Chapman and Lindzen*, 1970; *Forbes*, 1982a; 1982b; *Vial*, 1989]. Due to strong forcing, the migrating diurnal tide is much stronger than the nonmigrating tide in most cases.

Both ground based and satellite observations have revealed many important features of the diurnal tide. Ground based observations have established seasonal and interannual variations of the MLT diurnal tide at various latitudes [e.g., *Manson et al.*, 1988; 1989;

1999; *Vincent et al.*, 1989; *She et al.*, 2004; *Yuan et al.*, 2006]. By combining observations from various locations, *Pancheva et al.*, [2002] were able to assemble a global picture of the diurnal tide. But some large gaps in coverage remain.

Satellite observations such HRDI and WINDII from UARS satellite and TIDI from TIMED satellite have been able to provide a global view of the diurnal tide [*Burrage et al.*, 1995; *Wu et al.*, 1995; *Hays et al.*, 1994; *Morton et al.*, 1993; *McLandress et al.*, 1994; 1996; *Lieberman et al.*, 1994; *Khattatov et al.*, 1997a; 1997b; *Yudin et al.*, 1998; *Wu et al.*, 2006; *Killeen et al.*, 2006]. More significantly, satellite observations also were able to separate the nonmigrating tide from the migrating tide [e.g., *Forbes et al.*, 2003; *Oberheide et al.*, 2005; 2006].

Migrating diurnal tide has a strong seasonal variation. The tide reaches large amplitudes during spring and fall equinoxes and smaller values during summer and winter solstices. Both ground and satellite observations show this consistent behavior. Various tide models, such as the Global Scale Wave Model (GSWM) also show the same seasonal changes in tidal amplitude [*Hagan et al.*, 1999a; 2002; 2003].

Moreover, the diurnal tide also exhibits a strong interannual variation closely related to the stratosphere quasi-biennial oscillation **(**QBO) [*Burrage et al.*, 1995; *Hagan et al.*, 1999b, *Lieberman*, 1997; *Vincent et al.*, 1998]. Recently using TIMED SABER temperature data, *Huang et al.* [2006] and *Xu et al.* [2007] have examined the QBO effects on diurnal tide in temperature. It has long been suggested that the diurnal tide QBO effect is related to the mean zonal wind QBO like variations because of the direct link via the advection terms in the tidal equation [*Mayr and Mengel*, 2005]. Observations have shown that the migrating diurnal tide increases (decrease) when the equatorial mean zonal winds are westward (eastward) [*Hagan et al.*, 1999b, *Mayr and Mengel*, 2005]. Nevertheless, it has been hard to pin down the causal relationship between the tidal amplitude variations and mean zonal winds. *Hagan et al.* [1999] used the observed mean zonal winds to simulate the tidal variations and obtained opposite effect on the tidal amplitude using GSWM, whereas, *McLandress* [2002] was able to obtain consistent migrating diurnal tide amplitude with observed mean zonal winds. *McLandress* [2002] attributed the tidal amplitude increase to the increase of the meridional gradient in the mean zonal winds. *Mayr and Mengel* [2005] suggested that the vertical gradient in the mean zonal wind could also be important in modulating the diurnal tide.

It has been shown that gravity wave filtering variation due to the stratosphere QBO of zonal winds can generate QBO with opposite phase in the mesospheric zonal winds [*Mayr et al*., 1997]. *Lieberman* [1997] also suggested that the momentum flux of migrating diurnal tide (1, 1) mode contribute to the maintenance of time-mean westward winds in 90 – 105 km range. Perhaps, the momentum flux from (1,1) mode may also be partly responsible for the QBO related variations into the westward winds. Obviously, QBO alters the gravity wave filtering pattern and leads to QBO related variations in the migrating diurnal tide and mean zonal winds at high altitudes. Gravity waves may modulate the tide amplitude directly or indirectly through the mean zonal winds. It may also be possible that the gravity wave may interact with the mean zonal wind indirectly through the tide. Thus, it is unclear that the interaction between the tide amplitude and mean zonal winds is one-way or two-way. It will require more observations and model simulation to resolve these issues.

In this paper, we use recent mesosphere neutral wind data from the TIMED instrument TIDI in combination with the NCAR TIME-GCM 1.2 model annual-run results to examine the QBO effect on the migrating diurnal tide and mean zonal winds. In a companion paper [*Wu et al.*, 2007, hereafter Part II], we will examine the QBO effect on the nonmigrating diurnal tides. We hope to shed some light on this very complex relationship between the diurnal amplitude and mean zonal winds under the influence of the QBO.

Since its launch on December 7, 2001, the TIMED satellite has been in orbit for over 5 years. The TIDI instrument is a new generation of spaceborne interferometer, and it provides wider latitudinal and nighttime altitudinal coverage compared to the UARS

HRDI instrument. Furthermore, TIDI is a dedicated mesosphere and lower thermosphere instrument with more completed and consistent coverage of the MLT region. Because of the 24 hour local time coverage, the mean zonal wind results are less likely to be affected by diurnal tide aliasing. Of course the 24-hour local time coverage is achieved by combining data sampled over 60 days. We also sampled the TIME-GCM 1.2 [*Roble and Ridley*, 1994] annual run at the TIDI data points and analyzed the TIME-GCM 1.2 results in the same manner. In this way, we eliminate any differences between the observations and model due to sampling differences. The TIME-GCM 1.2 model is driven by NCEP data (winds and temperature) at 10 hPa (roughly 30 km). Even though the TIME-GCM does not have the explicit QBO, the NCEP data will contain its effect, particularly in the stratosphere neutral winds. These QBO signatures, in turn, may manifest into the mesosphere and lower thermosphere region. Thus give us an opportunity to study the interaction between the diurnal tide and mean zonal winds. This is probably the first attempt to use the TIME-GCM to study inter-annual variations.

The paper is organized as follows. In Section 1, we give a brief description of the stratosphere environment for the time period of interest and information about the instrument. Section 2 describes data analysis method. Section 3 shows the analysis results of the migrating diurnal tide in both the meridional and zonal winds. Section 4 is devoted to the mean zonal winds. We discuss the results in Section 5 and summarize our findings in the Section 6.

2. TIDI Data

2.1 Background Information

TIDI data from 2002 day 051 (February 20) to the end of 2005 are used in the study, which roughly cover four year time period. Over that time period, the stratosphere zonal winds have experienced roughly two QBO cycles. Figure 1 shows the stratosphere zonal wind over Singapore from 2002 to 2005. The QBO cycles are apparent. During the years of 2002 and 2004 the stratosphere zonal winds are in the eastward phase, while during 2003 and 2005 in the westward phase. The westward phase winds are usually stronger than that during the eastward phase.

2.2 Brief Instrument Description and Data Sampling Distribution

TIDI instrument is a limb-scan Fabry-Perot interferometer, which monitors the Doppler shift in the airglow emissions due to the neutral winds. The details of the instrument can be found in papers by *Killeen et al.* [1999; 2006] and *Skinner at al.* [2003]. In short, the instrument samples neutral winds on two sides of the satellite track. While one sampling track on one side reaches the North Pole, the other flies over the South Pole. Because the TIMED satellite precesses slowly in local time (3 deg/day) or 12 hours in 60 days, the local time of the sampling points do not change much during a day. On the other hand, the satellite has ascending and descending nodes, which are separated close to 12 hours. Therefore, the satellite can cover 24 hour in local time for every 60 days with combined ascending and descending node data. The satellite orbits the Earth 15 times per day. Figure 2 plots the local times and latitudes of TIDI sample for day 2004080. The red track goes to the North Pole (northern track) whereas the blue track (southern track) passes over the South Pole. The solid dots are for the daytime and hollowed dots for the nighttime. Over a day, the whole sampling pattern will go over the Earth 15 times above different longitudes without drifting much in local time. Over a 60-day period, the whole sampling pattern will shift in local time by 12 hours. One thing should be noted is overlapping of the sampling region. Because both sides make measurements between 60°S and 60°N, there are four local times coverage in this region. Outside this latitude region, the coverage is limited to one track with two local times. This coverage difference will have an impact on precision of the tidal analysis as we will show later on. In the vertical direction, the TIDI instrument scans from 70 to 115 km during the day and 80 to 105 km during the night. We selected the wind data from 85 to 107.5 km in our analysis, the data values at these lower and higher boundaries tend to have larger uncertainties due to the lack of airglow emission from these heights. The NCAR processed O2 (0-0) P9 line TIDI data version 0307 are used in this analysis.

3. Data Analysis Method

Because of TIDI's limited local time coverage during a day, it is impossible to calculate the tidal amplitude and phase without making assumptions about the latitudinal and vertical variations of the tide. Indeed, one can obtain daily variations of the diurnal and semidiurnal tides by assuming that tides have only the most dominant Hough modes [*Hays et al.*, 1994, *Lieberman and Hays,* 1994]. In another approach, one would assume nothing about the latitudinal and vertical variations, yet imply that the tide does not change much over a period (60 days in case of TIDI). One can use least square method for spectral analysis of space-time series to extract tidal amplitudes and phases at different latitude and altitude [*Wu et al.*, 1995]. This spectral method was also used to extract quasi-two day wave from the TIDI data [*Limparsuvan et al.*, 2005]. Both methods have their limitations and advantages. In this study, we use the second approach. We analyzed the TIDI data based on a 60-day sliding window. Space-time series spectral analysis is performed to both the southern and northern tracks, respectively, to obtain tidal amplitudes and phases of both migrating and nonmigrating tides. The results from the southern and northern tracks are then combined to form a global view of the tidal amplitudes and phases. The final result will have a horizontal resolution of 6 degree in latitude and a vertical resolution of 2.5 km.

Based on the random statistical error of the wind measurements, we estimate the precision of the tidal amplitude calculation during spring time of each of the four years (2002 – 2005). The results are shown in Figure 3. The precision has improved from 2002 to 2005 due to the reduction of ice on TIDI optics through the two roll maneuvers in 2003 and gradual sublimation over the years [*Skinner et al.*, 2003]. The vertical variations are mostly due to the O_2 (0-0) band airglow emission profile. The O_2 (0-0) band peaks near 94 km, consequently, the wind error is smallest at that height. Above 105 km, only daytime data are available, hence, the error increases. The latitudinal variations are caused by the distribution of sampling point. As we have pointed out that both the southern and northern tracks cover the region between 60°S and 60°N latitudes resulting more data points and smaller statistical errors. In the high latitude regions (> 60 degree latitude), only one track passes over with fewer sampling points causing higher statistical errors. While it is easier to compute the statistical errors, systematic errors are much difficult to ascertain. Hence, the tidal amplitudes may contain some systematic biases, which will gradually reduce with improvement of data in the future. At this point, it appears that we still have some noticeable bias at high latitude region affecting the migrating tide analysis. For that reason, we limit our discussion about mid and low latitude regions for migrating tide results. Because of high precision, the analysis result should provide mostly reliable relative changes for inter-annual comparisons.

4. Diurnal Tide in Mesospheric Winds

4.1 Migrating Diurnal Tide in Merdional Winds

4.1.1 TIDI Results

The migrating tide amplitudes of meridional winds for each season during the four years from 2002 to 2005 are plotted in Figure 4. To highlight the inter-annual variations we plotted the same season of different years side by side. Figure 4a is for the spring equinox. The time period of 60 day starts from day 51 (February 20). The years on the left side (2002 and 2004) are in the eastward phase of the stratosphere QBO. The right side (2003 and 2005) is for the westward phase. The contrast between the left and right is quite apparent. Stronger diurnal tide amplitudes are observed during the eastward phase of the stratosphere QBO. Besides the inter-annual variations, inter-hemispheric differences are also quite noticeable. The amplitude peak altitudes in the two hemispheres have offset in height and the southern hemisphere tends to have double peaks. The large tidal amplitudes at northern high latitude and high altitudes appear to be a result of bias in the winds, which tend to affect the migrating tide results. For this reason, we have limited our analysis of migrating tide to 70 degree latitude. To examine the seasonal variation, we use Figure 4b to show the tidal amplitude variations at 95 km for each of the four years. The vertical coordinate marks the beginning of the 60 day sliding window upon which the space-time series spectral analysis was performed. For comparison with monthly values a upward shift of 30 days is needed. The 2002 data starts at day 51 (02/20/02). Peaks at spring and fall equinoxes are visible. The spring equinox diurnal tide amplitudes are larger during 2002 and 2004. Because of the late start in data set, the increase in 2002 is not as obvious as that in 2004. The amplitude in the northern hemisphere show consistent larger values than that in the southern hemisphere. Figure 4c displays the diurnal tide amplitude at 21° N for the four years. The spring equinox maximum is apparent for all four years. The amplitude of the migrating diurnal tide appears to shift upward during the spring equinox for all four years. Again because of the late start of the 2002 data, the slightly increase in the 2002 spring equinox is not clearly seen. We should note that the starting point of 2002 is day 51 (February 20). On that day we still see the contour of 60 m/s. In 2003, the same 60 m/s contour line did not appear to extend to day 51. The increase in 2004 is very obvious. There is no clear QBO related variation for the fall equinox peaks.

4.1.2 TIME-GCM Results

Figure 5a is for the spring equinox results from TIME-GCM annual run. There is a very small increase in the tide amplitude during the eastward phase (2002 and 2004). Both hemispheres show multiple peaks at similar heights with varying amplitudes. The amplitudes are in general smaller than that from the TIDI observations. Figure 5b shows the migrating diurnal tide amplitude at 95 km. We can hardly identify the increase during the spring equinox. Figure 5c illustrates the diurnal tide amplitude at 21° N. The spring equinox amplitude in 2002 is only slightly larger noting the small 40 m/s contour line near 100 km. The increase is more obvious in 2004. The peak amplitude also appears to shift upward during the spring equinox for all four years.

4.2 Migrating Diurnal Tide in Zonal Winds

4.2.1 TIDI Results

Figure 6a illustrates the spring equinox zonal wind diurnal amplitudes. The inter-hemisphere distance between the peak latitudes are larger in the zonal winds than in the meridional winds which is consistent zonal wind Hough mode configuration. The amplitude tends to peak near 30°N in the northern hemisphere. In the southern hemisphere, the peak amplitude is much widely distributed into the mid latitude region (50°N). We also see a tendency to have larger amplitudes during the eastward phase of the stratosphere QBO (2002 and 2004). The amplitude at 95 km also show large spring equinox peaks during 2002 and 2004 in the southern hemisphere (Figure 6b).

4.2.2 TIME-GCM Results

The spring equinox amplitudes in the southern hemisphere are larger during the eastward phase of QBO (Figure 7a). The zonal wind amplitude in general is smaller than that of the meridional winds. We also see peak height offsets between the two hemispheres. The amplitudes at 95 km are displayed in Figure 7b. The increase in 2002 spring equinox is less obvious. The spring equinox amplitude in 2004 is larger as shown by larger area of the 25 m/s contour line. There is clear fall equinox peak during all four years, but no apparent QBO related variation for the fall equinox season.

5. Mean Zonal Winds

5. 1 TIDI Results

The mean zonal winds from a 60-day window during spring equinox are displayed in Figure 8. The distinction between the two phases of QBO is very obvious. During the eastward phase of QBO, there is a large region of westward zonal winds centered at the equator and extended to about 100 km, whereas the westward zonal wind region is smaller and wind magnitude is smaller during the westward phase of QBO. We also noticed enhancements of the eastward wind near 30°N and 40°S during the eastward phase of the QBO. Hence, there is a further increase of the meridional gradient of the mean zonal wind during the eastward phase of QBO. There is a strong eastward wind region in the southern hemisphere during 2002.

5. 2 TIME-GCM Results

The simulation from the NCAR TIME-GCM for spring equinox is shown in Figure 9. Even though the westward wind region is much weaker and smaller, it also appears during the eastward phase of the QBO as the TIDI observational results had shown. The large eastward region in the southern hemisphere is present as in the case of the TIDI observations, though with smaller wind magnitude. The TIME-GCM diurnal tide amplitudes range from 60 to 70 percent of that observed by TIDI.

6. Discussions

6.1 March Equinox Season

During this season, we see strong QBO dependence in TIDI data and TIME-GCM runs. The westward zonal winds at the equator coincide with the enhanced the meridional and zonal wind migrating tide. That should not be a surprise. The northern spring equinox coincides with the peak stratospheric zonal wind magnitude (westward and eastward) of the stratosphere QBO. Therefore, we should see the maximum filtering effect of the gravity waves. Moreover, equinox is also the season when the migrating diurnal tide peaks. Combining these two factors, we should expect the maximum QBO modulation on the migrating diurnal tide during this season.

The TIME-GCM results are interesting because it reproduces the TIDI mean zonal wind pattern, although to a lesser extent. At the same time the TIME-GCM diurnal tide increase during the eastward phase of the QBO is also smaller (barely noticeable). It is worth pointing out that both the enhancements in the tide and the westward zonal wind region near the equator during the eastward phase of QBO are generated by the TIME-GCM based on the NCEP data at 10 hPa, while the tidal amplitudes at 10 hPa from the GSWM remain the same for all four years. Compared to TIDI observations (~30 m/s), the TIME-GCM mean westward winds near the equator is small (< 10 m/s), so are the increase in the tide amplitude. The TIME-GCM tide amplitude is small in general. That is likely because the spatial resolution (half of the scale height in vertical and 5x5 degrees in horizontal) of the model is not sufficient for migrating diurnal tide with vertical wavelength of ~ 20 km. A new double resolution TIME-GCM 1.3 (under testing) is able to produce more comparable amplitude. The TIDI mean zonal wind result can be a reference for future tuning of the TIME-GCM. It will be interesting to see after adjustment to the TIME-GCM model to better match the mean zonal wind, would the tidal amplitude also match well.

6.2 Tidal Amplitudes and Mean Zonal Winds

The TIDI data show a strong connection between the tidal amplitude and mean zonal winds associated with QBO as observed in the past by HRDI. Large tidal amplitude is observed when the westward zonal wind appeared near the equator. The QBO effect on the mean zonal wind is not limited in the lower latitudes; we also noticed increase of the eastward zonal wind in the mid-latitudes during eastward phase of QBO (spring equinox).

6.3 Inter-hemispheric Asymmetry

There is a large asymmetry in tidal amplitude. Moreover, the mean zonal wind also exhibits asymmetry between the two hemispheres even during spring equinox. The eastward wind in the southern mid-latitudes is particularly during 2002 spring equinox. The mean wind is more symmetric during the fall equinox. It is possible the QBO may be asymmetric and leads to asymmetries in the mesospheric zonal winds. On the other hand, the TIME-GCM results tend to be more symmetric in tidal amplitude peak altitude location. The asymmetry in the model mean zonal wind has the same general features observed by TIDI.

7. Summary

The TIDI data provide a global view of the meridional and zonal wind migrating diurnal tide and mean zonal winds. The data show strong seasonal variations of the migrating tide with the strongest amplitude in spring equinox. In addition, the migrating diurnal tide also is strongly affected by the QBO, the strongest effect is during the spring equinox in connection with a large westward zonal wind region near the equator in the mesosphere, associated with the large eastward zonal wind in the stratosphere. Given that the stratospheric wind magnitudes are stronger during the spring equinox, we believe that it is reasonable to expect a stronger QBO modulation during that season. The QBO effect on the mean zonal wind appears to extend into the mid-latitude region by increase the eastward wind during the spring equinox. The TIME-GCM driven by the NCEP data at 10 hPa was able to reproduce the QBO effect on the diurnal tide and mesospheric zonal wind, although to a less extend. Since the TIME-GCM is driven by tidal amplitudes from the GSWM output at 10 hPa without inter-annual variations, a small mesospheric QBO effect is not unexpected. We expect to see future TIME-GCM produce even better agreement with observations.

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Figure Captions

Figure 1 Stratosphere Zonal Winds over Singapore

Daily stratospheric winds over Singapore from 2002 to 2005. Clear quasi-biennial oscillation can be seen. The contour step is 5 m/s.

Figure 2 TIDI Sampling Points in Local Time

The blue track (southern) is for the coldside of TIMED satellite (away from the sun) whereas the red track (northern) is for the warmside (towards the sun). The solid dots are for daytime and hollow dots for nighttime. The ascending (nighttime) and descending (daytime) nodes are plotted.

Figure 3 TIDI Tide Analysis Precision

The horizontal grid size is 6 degree and vertical is 2.5 km. Each sampling will have about 900 raw data point from a 60 day slighting window. Precisions are estimated for the four years during the northern spring equinox. The gradual improvement of the precision from 2002 to 2005 is due to reduction of the ice on the TIDI optics. The contour step is 0.5 m/s.

Figure 4 TIDI Migrating Diurnal Tide Westward one (W1) in Meridional Winds

The migrating diurnal tide amplitude altitude and latitude variations based on 60-day period observations starting at day 51 (February 20). For easier comparison, the data from the same season of the four different years are plotted on the same page. The altitude and latitude variations during northern spring equinox are plotted in Figures 4a. The latitude and seasonal variation at 95 km are plotted in Figure 4b. The altitude and seasonal variation at 21°N are shown in Figure 4c. The contour step is 10 m/s.

Figure 5 TIMEGCM Migrating Diurnal Tide W1 in Meridional Winds

Same as Figure 4 for the TIME-GCM results at the TIDI sampling points. The contour step is 5 m/s for 4a and 4b. The color scale is different for the two plots. Figure 4c uses contour step 10 m/s.

Figure 6 TIDI Migrating Diurnal Tide W1 in Zonal Winds

The spring equinox altitude and latitude variations of the diurnal tide amplitude are plotted in Figure 6a (contour step 10 m/s). The latitudinal and seasonal changes at 95 km are shown in Figure 6b (contour step 15 m/s).

Figure 7 TIMEGCM Migrating Diurnal Tide W1 in Zonal Winds

Same as Figure 6 for the TIME-GCM zonal winds. The contour step for Figure 7a and 7b is 5 m/s.

Figure 8 TIDI Zonal Mean Winds

Mean zonal winds from 60-day slighting window for the northern spring equinox season (starting on day 51, February 20). The contour step is 10 m/s.

Figure 9 TIMEGCM Zonal Mean Winds

Same as Figure 8 for the mean zonal winds from the TIME-GCM runs.