DW1 Tidal Enhancements in the Equatorial MLT During 2015 El Niño: The Relative Role of Tidal Heating and Propagation

Masaru Kogure and Huixin Liu

1Department of Earth and Planetary Science, Kyushu University, Fukuoka, Japan

Abstract

Ground-based and satellite observations have shown that the tidal component DW1 in the equatorial mesosphere and lower thermosphere (MLT) was enhanced in July–October 2015, which was an intense El Niño year. This enhancement is reproduced in the 21 years reanalysis-driven model simulation by the Ground-to-topside model of Atmosphere and Ionosphere for Aeronomy (GAIA). Our analysis shows the (1,1) Hough mode dominates this tidal enhancement, and its peak amplitude was 7.4 K (74%) higher than that under neutral (non-ENSO) conditions at 90 km. The corresponding tidal heating was found to increase by 0.4 mWkg\(^{-1}\) (5%), which can explain 0.5 K (7%) of the (1,1) enhancement. To explain the remaining 6.9 K (93%) of the enhancement, we quantitatively examined the upward propagation condition by calculating the vertical wavenumber and the latitudinal shear of the zonal wind. The analysis reveals that the vertical wavenumber between 18 and 60 km was one standard deviation smaller than that under neutral conditions. The latitudinal zonal wind shear also decreased at 18 N/S° in 18–30 km. These results suggest smaller dissipation and damping of the (1,1) mode during its upward propagation, which dominantly contributed to the tidal enhancement at 90 km altitude. This decrease in the vertical wavenumber and the wind shear can be reasonably explained by the eastward phase of the quasi-biennial oscillation (QBO) in the lower stratosphere. This study suggests that the overlapping of the 2015 El Niño with the eastward phase of the QBO induced the large enhancement of the DW1.

Plain Language Summary

A thermal tide is caused by atmospheric heating, conveys its momentum vertically, and causes the circulation in the mesosphere and lower thermosphere (MLT). Additionally, thermal tides control a small-scale wave (atmospheric gravity wave) and cause instability. A thermal tide is classified by its period, zonal wavenumber, and phase velocity direction. The tide with a 24 h period and westward zonal wavenumber 1 (DW1) is mainly exited by heating caused by tropospheric water vapor and propagates to the MLT. This study found that DW1 was enhanced in the MLT during the El Niño event (2015/2016) in the Ground-to-topside model of Atmosphere and Ionosphere for Aeronomy reanalysis data. This enhancement was very likely caused by an increase in the tropospheric heating and a decrease in the tidal reduction. The tropospheric heating can be enhanced by El Niño, and this enhancement can explain 0.5 K (7%) of the tidal enhancement. The decrease in the tidal reduction can explain the remaining 6.9 K (93%). The decrease in the tidal reduction could be caused by a small vertical wavenumber and the small meridional zonal wind shear at 18 N/S°. These small values could be caused by the quasi-biennial oscillation (QBO) eastward phase in the lower stratosphere.

1. Introduction

Thermal tides are excited by atmospheric heating, propagate vertically, and attain large magnitudes in the upper atmosphere. Tides are classified into different components based on their zonal wavenumber, period, and phase velocity direction (Chapman & Lindzen, 1970; Vincent, 2015). It is well known that a tide with a diurnal period (24 h) and westward zonal wavenumber 1 (DW1) is dominant in the equatorial mesosphere and lower thermosphere (MLT) (Forbes & Vincent, 1989; Zhou et al., 2018). DW1 can be decomposed into different Hough modes, and DW1 in the equatorial MLT region is mostly composed of (1,1) mode (Burrage et al., 1995). This mode has a latitudinal symmetric structure and propagates vertically. The (1,1) mode of DW1 is excited by water vapor absorption of solar radiative and latent heat in the troposphere and then propagates into the MLT (Chapman & Lindzen, 1970; Zhang et al., 2010). The water vapor distribution is modulated by El Niño-Southern Oscillation (ENSO), which implies that ENSO modulates the DW1.
Lieberman et al. (2007) found the enhanced diurnal tide's amplitude during the 1997/98 El Niño phase in equatorial MLT by using meteor radars. They showed DW1 component of equatorial radiative heating was enhanced in the 1997/98 El Niño phase and concluded that this heating enhancement caused the observed tidal enhancement. Model simulation work on ENSO supported the enhancement of DW1 during El Niño in the equatorial MLT (Liu et al., 2017; Pedatella & Liu, 2012).

The DW1 is also modulated by the background fields in the middle atmosphere while it propagates from the troposphere to the MLT. Forbes and Vincent (1989) demonstrated that the (1,1) mode is dissipated more in the westward wind than in the eastward wind. Because dissipation due to eddy diffusion is approximately proportional to the squared vertical wavenumber of the (1,1) mode, which becomes larger in the westward wind due to Doppler shift, the dissipation increases consequently. McLandress (2002a) found that tropospheric heating and the latitudinal shear of zonal wind in the subtropical mesosphere strongly control the (1,1) mode seasonal variation (its maximum at equinox and its minimum at solstice) in the MLT. The large wind shear due to the mesospheric summer jet reduces the (1,1) mode amplitude. From these wind impacts on the DW1, it can be expected that the zonal wind quasi-biennial oscillation (QBO) in the lower stratosphere modulates the DW1 in the equatorial MLT, and several studies indeed showed robust QBO variation in DW1 with larger amplitude during the eastward QBO phase (Hagan et al., 1999; Liu et al., 2017; Mayr & Mengel, 2005; McLandress, 2002b; Sun et al., 2018; Xu et al., 2009). However, the physical process remains unclear (Smith, 2012).

The present work focuses on the enhanced DW1 in the equatorial MLT during the 2015 El Niño event, which was revealed by Liu et al. (2017), Figure 2 in a 21 years simulation using the Ground-to-topside model of Atmosphere and Ionosphere for Aeronomy (GAIA) during 1996–2016. This enhancement lasted from July to October 2015 and is also confirmed by Zhou et al. (2018), using the combination of wind observations from ground-based radars and the Thermosphere, Ionosphere, Mesosphere, Energetics, and Dynamics (TIMED) satellite. The purpose of this study is to investigate the physical mechanisms for this tidal enhancement. In particular, we quantitatively examine the relative contributions from tropospheric heating and the background zonal wind which causes tidal dissipation and reduction during its upward propagation to the MLT region.

2. Data and Methods

2.1. Reanalysis Data-Driven GAIA Simulation

GAIA is a whole atmosphere-ionosphere coupled model. This model simulates the neutral atmosphere in an altitude range of the surface to the exobase and the ionosphere up to ~3,000 km. The distributions of water vapor and cloud (which influence thermal tide's intensity) were calculated with the cumulus parameterization developed by Kuo (1974). The distribution of ozone is prescribed as the monthly mean zonally symmetric values. It should be noted that the DW1 (1,1) mode in the MLT is non-sensitive to the ozone variation (Hagan et al., 1999). Jin et al. (2012) described details about GAIA model. GAIA model performed a 21 years simulation between January 1, 1996, and December 31, 2016. The output variables below 30 km altitude (e.g., the temperature, pressure, winds, and water vapor) are constrained with the reanalysis data Japanese 25 years Japanese Reanalysis (JRA-25) up to the end of 2013 and JRA-55 in 2014–2016 (Kobayashi et al., 2015; Onogi et al., 2007).

We derived the DW1 components for temperature and wind from the GAIA simulation results using Fourier analysis. To examine tidal changes during 2015 El Niño from tides under neutral (non-ENSO) conditions, tidal anomalies were then obtained by subtracting tides averaged under neutral conditions whose the absolute Oceanic Niño Index (|ONI|) is less than 0.4.

2.2. Calculation of Tropospheric Tidal Heating

To compare the DW1 components and tropospheric heating, we used radiative and latent heating derived from the data set, fct_phy3m125, produced by JRA-55. The data are provided in a 6 h time-averaged. Its horizontal resolution is 1.25° × 1.25° with a coverage height of 1,000–1 hPa in 37 pressure levels. The radiative heating was calculated from a sum of solar radiative heating rate and longwave radiative heating.
The latent heating was calculated from a sum of large-scale condensation heating rate and convective heating rate. These heating values were integrated in 800–200 hPa with a density weighting function in accordance with Lieberman et al. (2007). Then, the DW1 components of the tropospheric radiative and latent heating were derived with the same Fourier analysis used to derive tidal amplitudes.

3. DW1 Enhancement in the MLT and Heating Variability During the El Niño 2015

Figure 1 shows that the anomalies of DW1 for the temperature at 90 km altitude (a), radiative heating (b), and latent heating (c). The amplitudes of the temperature, radiative, and latent heating are shown in Figure S1 in the supporting information. The tidal amplitude for temperature in Figure 1a was enhanced by...
2–7 K around 0°N/S and 1–3 K around 30°N/S in July–October 2015 (the red box) during the El Niño phase, which implies an enhancement of the symmetric (1,1) mode. The tidal anomalies for zonal and meridional winds were also enhanced consequently (see Figure S3 in supporting information). Such enhancements have also been reported by Zhou et al. (2018). They showed DW1 zonal and meridional wind amplitudes in 2013–2015 from a combination of ground-based radars and the TIMED Doppler Interferometer, which showed clear enhancement around July–October 2015 (see Figure 6 in Zhou et al., 2018).

To examine the cause of the DW1 enhancement, we calculated both the radiative heating and latent heating and obtained the DW1 component of the heating (see Figures S1b and S1c). Figures 1b and 1c shows heating anomalies, and Figure 2 shows heating anomalies averaged in the tidal enhancement period (the red box in Figures 1b and 1c). We see that both the radiative anomaly around 0°N and latent heating anomaly around 10°N were positive (0.21 mWkg⁻¹ and 0.57 mWkg⁻¹ at maxima, respectively). On the other hand, both heatings show a negative anomaly in the southern hemisphere around 10°S. To take into account the latitudinal distribution, in the following section, we will focus on the (1,1) Hough mode of heating, which generates the (1,1) mode of DW1 tide. From the latitudinal structure shown in Figure 1a, we have seen that (1,1) mode dominates the enhancements during July–October 2015.
Effects of the Tropospheric Heating and Background Wind on Thermal Tides in the MLT

4.1. DW1 (1,1) Mode Amplitude for the Temperature and Heating

The (1,1) mode amplitude was derived by convoluting the DW1 perturbation and its Hough function. This function was calculated from the normalized ALP expansion method (Groves, 1981) using a program developed by Wang et al. (2016). Figure 3a shows that the (1,1) mode anomalies for the temperature at 30 and 90 km altitudes, respectively. The (1, 1) mode contributes 70%–90% of the DW1 amplitude at 90 km altitude, which is well known (Baldwin et al., 2019).

**Figure 3.** (a) Monthly mean DW1 (1,1) mode anomaly for the temperature at 30 km (blue line) and 90 km (red line) in 2010–2016. (b) The same as (a), but for the radiative heating (red line) and the latent heating (blue line). (c) The (1,1) mode vertical wavenumber anomalies averaged over 18–30 km (blue line), 30–60 km (red line), and 60–90 km (black line), respectively. Error bars in (a) and (b) indicate the standard deviations in the neutral conditions. The red boxes indicate the tidal enhancement period (July–October 2015). The purple lines indicate the beginning of the (1,1) mode enhancement for the temperature at 30 km (May 2015) in (a) and the latent heating (April 2015) in (b), and the decrease of the vertical wavenumber in 30–60 km in (c), respectively. The red and blue arrows in (a) roughly indicate the timing for maxima and minima for the quasi-biennial oscillation (QBO) of the (1,1) mode amplitude. The amplitudes for the temperature, the heating, and magnitudes of the vertical wavenumber (wavelength) are shown in Figure S3 in the supporting information.

4. Effects of the Tropospheric Heating and Background Wind on Thermal Tides in the MLT

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The classical tidal theory is widely used in the theoretical analysis and can explain tides in the real middle atmosphere and MLT, although it assumes an isothermal atmosphere without background wind (Sakazaki et al., 2013; Zhou et al., 2018). According to the classical tidal theory, the temperature amplitude of a thermal tide for each Hough mode in the heating altitude is projected to the heating amplitude for that Hough mode (Chapman & Lindzen, 1970; Lindzen, 1967).

In Figure 3a, the tidal anomalies at both 30 and 90 km altitudes were in phase with each other, with a magnitude ratio of ~1/20. The tidal anomalies exhibit a quasi-biennial cycle (the red and blue arrows roughly indicate the maxima and minima for the tidal QBO) suggesting strong influence from the QBO. On top of this, the anomaly at 90 km altitude exhibits large positive values exceeding the standard deviations (1.2–2.1 K) of the tidal amplitudes in the neutral conditions during July–October 2015 (the red box in Figure 3a), demonstrating strong enhancement of the (1,1) mode during this period. Actually, the amplitude at 20–110 km altitudes were all enhanced (the one at 30 km is shown in Figure 3a) during this period. The tidal anomaly at 30 km altitude started to exceed the standard deviation (~0.04 K) in May 2015 (purple line in Figure 2a), but both anomalies at 30 and 90 km disappeared in the same month (October 2015).

The latent heating anomaly in Figure 3b started to exceed the standard deviation in the neutral conditions (0.13 mW/kg) in April 2015 (the purple line) at a similar time for the tidal enhancement at 30 km (the purple line in Figure 3a). It reached the maximum (1.1 mW/kg) in February 2016. The radiative heating anomaly also enhanced from June 2015 to March 2016, with the maximum in February 2016, exceeding the standard deviations (0.15–0.33 mW/kg) in June–July 2015, November–December 2015, and February–March 2016. Being the tidal generation sources, enhancement in radiative and latent heating can directly lead to tidal enhancement (Chapman & Lindzen, 1970). However, the heating enhancement found in Figure 3b is clearly not sufficient to explain the tidal enhancement quantitatively. For instance, the tidal amplitude at 90 and 30 km in September 2015 were 7.4 K (74%) and 0.22 K (47%) larger than those under the neutral conditions (10.0 K at 90 km and 0.47 K at 30 km), but the heating increase is only 0.4 mW/kg (5% of non-ENSO's ~8 mW/kg). This 5% enhancement in heating should increase the tidal amplitudes by 5% (i.e., 0.5 K at 90 km and 0.02 K at 30 km) according to the linear theory of tidal generation (Chapman & Lindzen, 1970, page 161) along with neglection of changes in wave dissipation rate during upward propagation. In other words, the enhanced heating can explain 7% (=0.5 K/7.4 K) of the tidal enhancement at 90 km.

The possible mechanism to explain the rest of the enhancement is that the metrological condition in the middle atmosphere was favorable for the (1,1) mode DW1 during July–October 2015; that is, its dissipation and reduction during upward propagation need to be smaller than that under the neutral conditions. In the following, we examine two aspects that are related to the tidal dissipation and reduction: (a) The tidal vertical wavenumber (b) The latitudinal zonal wind shear.

4.2. Vertical Wavenumber of the DW1 (1,1) Mode

Forbes and Vincent (1989) pointed out that tidal dissipation is approximately proportional to their squared local vertical wavenumber when applying a Newton cooling parameterization. Therefore, the tidal vertical wavenumber is one critical factor to consider for tidal dissipation. The GAIA model applies the Newton cooling parameterization (Miyahara et al., 1993), and thus the tidal vertical wavenumber should be one of the factors for tidal dissipation in the GAIA model. We derive the tidal vertical wavenumber for the (1,1) mode from its tidal phase with the least-square method in a range of 2 scale heights (~14 km) by 0.2 scale height steps. The vertical wavenumbers were then averaged in three regions; the QBO zonal wind height range (18–30 km), Stratospheric Semi-Annual Oscillation zonal wind height range (30–60 km), and Mesospheric Semi-Annual Oscillation zonal wind height range (60–90 km) (Baldwin et al., 2001; Garcia et al., 1997).

Figure 3c shows the averaged vertical wavenumber anomalies. The negative anomaly in 18–30 km was smaller between July and October 2015 by over the standard deviations of the vertical wavenumber under the neutral conditions (0.0033–0.0055 km⁻¹). The one in 30–60 km was also smaller between May (purple dashed line in Figure 2c) and October 2015 by over the standard deviation (0.0052–0.0078 km⁻¹). The negative vertical wavenumber anomalies at both altitudes had minima in August 2015. These decreases in
the vertical wavenumbers correspond to increases in the vertical wavelengths by 1.6 km in 18–30 km and 2.7 km in 30–60 km (wavelengths under natural conditions in August are 20.1 km between 18 and 30 km and 28.3 km between 30 and 60 km, respectively). These results suggest that the dissipation in 18–60 km became smaller during July–October 2015. The anomaly in 60–90 km also decreased in September–October 2015, although it was large in July–August 2015. The decreases in vertical wavenumbers indicate less dissipation during the upward propagation of DW1 (Forbes & Vincent, 1989), thus contributing to the MLT tidal enhancement in July–October 2015.

According to Forbes and Vincent (1989), the local vertical wavenumber at a latitude, \( k_{z(z,\theta)} \), is described as

\[
k_{z(z,\theta)} = \frac{N^2(z,\theta)}{gh(z,\theta)^2} - \frac{1}{4H^2(z,\theta)}
\]

where \( N, g, H, \) and \( \theta \) are the buoyancy frequency, gravitational acceleration, scale height, and colatitude, respectively. \( h' \) is the Doppler-shifted equivalent depth written as

\[
h'_z(z,\theta) = h \left( 1 + \frac{u(z,\theta)}{C_0 \sin \theta} \right)^4
\]

where \( h, C_0, \) and \( u \) are the equivalent depth under the non-background wind, the eastward phase speed of the diurnal tide at the equator (~465 ms\(^{-1}\)), and the background zonal wind, respectively. It should be noted that Equation 1 assumes the tidal local dispersion relation and also neglects the influences of gravity wave drag.

According to Equations 1 and 2, the tidal vertical wavenumber decreases when the background zonal wind is eastward, and the buoyancy frequency is small. Figure 4 shows the anomalies in the zonal wind and \( N^2 \) at each altitude range. The zonal wind and \( N^2 \) are shown in Figures S4 and S5 in supporting information. The zonal wind anomalies around the equator in 18–30 km were eastward and westward during the positive and negative tidal anomalies, respectively (compare Figures 3a and 4a). The zonal wind anomaly during July–October 2015 (the red box) was eastward (10–30 ms\(^{-1}\)) suggesting that the eastward phase of the stratospheric QBO decreases the tidal vertical wavenumber. The zonal wind anomaly in 30–60 km was positive, by more than 20 ms\(^{-1}\), around 40°S (nearby 30°S, i.e., the second peak of the (1,1) Hough mode function) in July–October 2015, which suggest that stronger polar night jet. These eastward winds possibility contributed to the decrease of the vertical wavenumber in 30–60 km. The zonal wind anomaly in 60–90 km was smaller than those in 18–60 km. The buoyancy frequency, \( N^2 \) shows slight negative anomalies at 18–30 km altitudes, which could also contribute to the wavenumber decrease at those altitudes according to Equation 1 during the tidal enhancement period (July–October 2015). However, above 30 km, no negative anomalies in the buoyancy frequency is found, indicating the smaller wavenumbers are dominantly caused by the eastward zonal wind in that period.

4.3. Effect of Latitudinal Shear in Zonal Wind

Several studies showed that the latitudinal shear of zonal wind at lower latitudes strongly affects the DW1. For instance, McLandress (2002b) and Mayr and Mengel (2005) found that the large wind shear around 18°N / S (where are the peaks of the (1,1) Hough mode function for the meridional wind) reduces the DW1 amplitude. To explain the DW1 enhancement during the 2015 El Niño, we further examine changes in the latitudinal shear of the zonal wind during this period. Figure 5 shows the anomalies of the absolute latitudinal zonal wind shear \(|\partial u / \partial y|\) at 18°N / S averaged in 18–30 km (a), 30–60 km (b), and 60–90 km (c) (the latitudinal shear itself is shown in Figure S6 in the supporting information). Roughly speaking, the \(|\partial u / \partial y|\) anomalies at 18°N / S in 18–30 km were larger during the westward QBO phase than those during the eastward QBO phase. The year July–October 2015 in the eastward phase of QBO, which leads to relatively small \(|\partial u / \partial y|\) and hence larger tidal amplitude there according to Mayr and Mengel (2005). On the other hand, \(|\partial u / \partial y|\) anomalies between 30-90 km (Figures 5b and 5c) show no clear QBO variation, indicating
Figure 4. Monthly mean zonal wind anomalies averaged in 18–30 km (a), 30–60 km (b), and 60–90 km (c) in 2011–2016, respectively. (d), (e), and (f) are the same as (a), (b), and (c) but $N^2$ anomalies, respectively. The red boxes indicate the tidal enhancement period (July–October 2015). The red and blue arrows in (a) roughly indicate the timing of maxima and minima for the quasi-biennial oscillation (QBO) of the zonal wind anomaly.
Thus, we conclude that the small latitudinal shear in the zonal wind in 18–30 km due to the eastward phase QBO is probably one of the primary factors for the tidal enhancement in July–October 2015.

5. Conclusions

DW1 in the equatorial MLT at 90 km was enhanced in July–October 2015, which was an intense El Niño year. This enhancement was found to be largely due to the enhancement of the (1,1) Hough mode which amounts to 7.4 K. To quantitatively explore the physical mechanisms for the enhancement, we analyzed the vertical structure between 18-90 km and the temporal variation of the dominant (1,1) mode in negligible QBO in 30–90 km influence on the (1,1) mode amplitude via latitudinal shear of the zonal wind.
terms of amplitude and vertical wavenumber. We also calculated the (1,1) mode of the tidal heating in the troposphere. The results show that the total heating for the (1,1) mode during the period of the DW1 enhancement increased by 0.4 mW kg$^{-1}$ (5%). According to the linear theory of tidal generation (Chapman & Lindzen, 1970), this can explain only 0.5 K (7%) of the tidal enhancement at 90 km altitude, which suggests that the tidal propagation process contributed to the remaining tidal enhancement. For the latter, we found the vertical wavenumber between 18 and 60 km altitude. Furthermore, the latitudinal zonal wind shear between 18 and 30 km altitudes also weakened. These changes suggest that the dissipation and reduction of the (1,1) mode in the middle atmosphere were smaller during July and October 2015. This favorable propagation condition can be attributed to the eastward QBO phase overlapping the 2015 El Niño. Thus, we conclude that 0.5 K (7%) of the DW1 (1,1) mode enhancement in the equatorial MLT was caused by the tropospheric heating enhanced by the El Niño itself, while the remaining 6.9 K (93%) is due to smaller dissipation and reduction in the (1,1) mode due to the eastward QBO phase.

Finally, we would like to point out that the cause of the unprecedented QBO anomaly (i.e., early shift to eastward phase) during 2015–2016 itself has been attributed to tropospheric heating associated with the strong El Niño 2015 (Coy et al., 2017; Newman et al., 2016; Osprey et al., 2016). In this sense, El Niño-driven changes in tropospheric heating contributed to both enhancements in tidal forcing and background atmospheric conditions favorable for tidal propagation.

Data Availability Statement

The GAIA data set supporting the conclusions of this article is available in the 21 years GAIA reanalysis data repository, https://gaia-web.nict.go.jp/data_e.html. The data set used for this study is from the Ground-to-topside model of Atmosphere and Ionosphere for Aeronomy (GAIA) project carried out by the National Institute of Information and Communications Technology (NICT), Kyushu University, and Seikei University. The JRA-55 data set supporting the conclusions of this article is available from the JMA Data Dissemination System, http://jra.kishou.go.jp/JRA-55/index_en.html.

References

Baldwin, M. P., Birner, T., Brasseur, G., Burrows, J., Butchart, N., Garcia, R., et al. (2019). 100 years of progress in understanding the stratosphere and mesosphere. Meteorological Monographs, 59, 1–62. https://doi.org/10.1175/AMSMONOGRAPHS-D-19-0003.1

Baldwin, M. P., Gray, L. J., Dunkerton, T. J., Hamilton, K., Haynes, P. H., Randel, W. J., et al. (2001). The quasi-biennial oscillation. Review of Geophysics, 39(2), 179–229. https://doi.org/10.1029/1999RG000071

Burrage, M. D., Hagan, M. E., Skinner, W. R., Wu, D. L., & Hays, P. B. (1995). Long-term variability in the solar diurnal tide observed by HRDI and simulated by the GSWM. Geophysical Research Letters, 22, 2641–2644. https://doi.org/10.1029/95GL02635

Chapman, S., & Lindzen, R. S. (1970). Atmospheric tides. New York: Gordon and Breach.

Coy, L., Newman, P. A., Pawson, S., & Lait, L. R. (2017). Dynamics of the disrupted 2015/16 quasi-biennial oscillation. Journal of Climate, 30(15), 5651–5674. https://doi.org/10.1175/jcli-d-16-0663.1

Forbes, J. M., & Vincent, R. A. (1989). Effects of mean winds and dissipation on the diurnal propagation tides, Planet. Space Science, 37, 197–209. https://doi.org/10.1016/0032-0633(89)90007-x

Garcia, R. R., Dunkerton, T. J., Lieberman, R. S., & Vincent, R. A. (1997). Climatology of the semiannual oscillation of the tropical middle atmosphere. Journal of Geophysical Research, 102(D22), 26019–26032. https://doi.org/10.1029/97JD00207

Groves, G. (1981). Notes on obtaining the eigenvalues of laplace’s tidal equation. Planetary and Space Science, 29, 1339–1344. https://doi.org/10.1016/0032-0633(81)90100-8

Hagan, M. E., Burrage, M. D., Forbes, J. M., Hackney, J., Randel, W. J., & Zhang, X. (1999). QBO effects on the diurnal tide in the upper atmosphere. Earth Planets and Space, 51, 571–578. https://doi.org/10.1186/BF03352126

Jin, H., Miyoshi, Y., Panccheva, D., Mukhtarov, P., Fujiwara, H., & Shinagawa, H. (2012). Response of migrating tides to the stratospheric sudden warming in 2009 and their effects on the ionosphere studied by a whole atmosphere-ionosphere model GAIA with COSMIC and TIMED/SABER observations. Journal of Geophysical Research, 117, A10323. https://doi.org/10.1029/2012JA017650

Kobayashi, S., Harada, Y., Ibata, A., Moriya, M., Onoda, H., Onogi, K., et al. (2015). The JRA-55 reanalysis: General specifications and basic characteristics. Journal of the Meteorological Society of Japan, 93, 5–48. https://doi.org/10.2151/jmsj.2015-001

Kuo, H. L. (1974). Further studies of the parameterization of the influence of cumulus convection on large-scale flow. Journal of the Atmospheric Sciences, 31(5), 1232–1240. https://doi.org/10.1175/1520-0469(1974)31<1232:FSOTPO>2.0.CO;2

Lieberman, R. S., Riggin, D. M., Orland, D. A., Nesbitt, S. W., & Vincent, R. A. (2007). Variability of mesospheric diurnal tides and tropospheric diurnal heating during 1997–1998. Journal of Geophysical Research, 112, D20110. https://doi.org/10.1029/2007JD008578

Lindzen, R. S. (1967). Thermally driven diurnal tide in the atmosphere. Journal of Geophysical Research, 72, 5605–5614. https://doi.org/10.1029/JC072i022p05605

Osprey, E. M., Baldwin, M. P., & Newell, R. E. (2017). ATMOSpheric tides. Journal of Geophysical Research: Space Physics, 122, 5359–5549. https://doi.org/10.1002/2016JA024011

Mayr, H. G., & Mengel, J. G. (2005). Interannual variations of the diurnal tide in the mesosphere generated by the quasi-biennial oscillation. Journal of Geophysical Research, 110, D10111. https://doi.org/10.1029/2004JD005055
McLandress, C. (2002a). Interannual variations of the diurnal tide in the mesosphere induced by a zonal-mean wind oscillation in the tropics. *Geophysical Research Letters*, 29(9), 19–21. https://doi.org/10.1029/2001GL014551

McLandress, C. (2002b). The seasonal variation of the propagating diurnal tide in the mesosphere and lower thermosphere. Part I: The role of gravity waves and planetary waves. *Journal of the Atmospheric Sciences*, 59, 893–906. https://doi.org/10.1175/1520-0469(2002)059<0893:TRODTI>2.0.CO;2

Miyahara, S., Yoshida, Y., & Miyoshi, Y. (1993). Dynamic coupling between the lower and upper atmosphere by tides and gravity waves. *Journal of Atmospheric and Terrestrial Physics*, 55, 1039–1053. https://doi.org/10.1016/0021-9169(93)90096-h

Newman, P. A., Coy, L., Pawson, S., & Lait, L. R. (2016). The anomalous change in the QBO in 2015–2016. *Geophysical Research Letters*, 43, 8791–8797. https://doi.org/10.1002/2016GL070373

Onogi, K., Tsutsui, J., Koide, H., Sakamoto, M., Kobayashi, S., Hatsushika, H., et al. (2007). The JRA-25 reanalysis. *Journal of the Meteorological Society of Japan*, 85, 369–432. https://doi.org/10.2151/jmsj.85.369

Osprey, S. M., Butchart, N., Knight, J. R., Scaife, A. A., Hamilton, K., Anstey, J. A., et al. (2016). An unexpected disruption of the atmospheric quasi-biennial oscillation. *Science*, 351, 1424–1427. https://doi.org/10.1126/science.aab4156

Pedatella, N. M., & Liu, H.-L. (2012). Tidal variability in the mesosphere and lower thermosphere due to the El Niño–Southern Oscillation. *Geophysical Research Letters*, 39, L19802. https://doi.org/10.1029/2012GL053383

Sakazaki, T., Fujiwara, M., & Zhang, X. (2013). Interpretation of the vertical structure and seasonal variation of the diurnal migrating tide from the troposphere to the lower mesosphere. *Journal of Atmospheric and Solar-Terrestrial Physics*, 105, 66–80. https://doi.org/10.1016/j.jastp.2013.07.010

Smith, A. K. (2012). Global dynamics of the MLT. *Surveys in Geophysics*, 33, 1177–1230. https://doi.org/10.1007/s10712-012-9196-9

Sun, Y. Y., Liu, H., Miyoshi, Y., Liu, L., & Chang, L. C. (2018). El Niño–Southern Oscillation effect on quasi-biennial oscillations of temperature diurnal tides in the mesosphere and lower thermosphere. *Earth Planets and Space*, 70, 85. https://doi.org/10.1186/s40623-018-0832-6

Vincent, R. A. (2015). The dynamics of the mesosphere and lower thermosphere: A brief review. *Progress in Earth and Planetary Science*, 2, 4. https://doi.org/10.1186/s40645-015-0035-8

Wang, H., Boyd, J. F., & Akmaev, R. A. (2016). On computation of Hough functions. *Geoscientific Model Development*, 9, 1477–1488. https://doi.org/10.5194/gmd-9-1477-2016

Xu, J., Smith, A. K., Liu, H.-L., Yuan, W., Wu, Q., Jiang, G., et al. (2009). Seasonal and quasi-biennial variations in the migrating diurnal tide observed by thermosphere, ionosphere, mesosphere, energetics and dynamics (TIMED). *Journal of Geophysical Research*, 114, D13107. https://doi.org/10.1029/2008JD011298

Zhang, X., Forbes, J. M., & Hagan, M. E. (2010). Longitudinal variation of tides in the MLT region: 2. Relative effects of solar radiative and latent heating. *Journal of Geophysical Research*, 115, A06317. https://doi.org/10.1029/2009JA014898

Zhou, X., Wan, W., Yu, Y., Ning, B., Hu, L., & Yue, X. (2018). New approach to estimate tidal climatology from ground-and space-based observations. *Journal of Geophysical Research: Space Physics*, 123, 5087–5101. https://doi.org/10.1029/2017JA024967