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Key Points:
- Eighteen years of SABER diurnal temperature tides show a statistically significant response to the MJO on the order of ±10%.
- Convectively forced nonmigrating tides respond more strongly to the MJO than the migrating tide.
- Sign and magnitude of the tidal response depend on the location of MJO-convection (phase of the MJO index).

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The Tidal Response in the Mesosphere/Lower Thermosphere to the Madden-Julian Oscillation Observed by SABER

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Abstract A statistical study of 18 years of diurnal temperature tides observed by the SABER instrument on board the TIMED satellite reveals a substantial response of the tides in the upper atmosphere (>60 km) to the Madden-Julian Oscillation (MJO) in the tropical troposphere. Nonmigrating tidal amplitudes are modulated at the intraseasonal MJO periods up to ~25% relative to the seasonal mean, twice as much as for the migrating tides (~10%). We fully characterize the tidal response for active MJO days as a function of season and MJO location as prescribed by the MJO index. The MJO modulation of the tides was predicted by models but could not be unequivocally observed before. Our results further point to an important role of background winds that partly cause a different response for equatorial and nonequatorial tidal modes in different seasons, which has implications for the MJO imprint on the ionospheric dynamo region.

Plain Language Summary Tides are key to understanding the connection between tropospheric weather/climate and space weather/climate. Tropospheric convection associated with the Madden-Julian Oscillation (MJO) has been known to modulate the intensity of upward-propagating gravity waves and Kelvin waves. An impact on tides was already proposed over two decades ago, but only recent progress in data analysis now allows one to quantify the effect from observations. Eighteen years of daily atmospheric tidal diagnostics (observed by the SABER instrument onboard the TIMED satellite) at altitudes 60–105 km reveal statistically significant intraseasonal tidal modulation as a response to the MJO. The magnitude of the response is on the order of ±20% (~0.5–2 K) of the seasonal mean depending on the MJO phase during active conditions. The tidal response to the MJO is present across all seasons. Tides can also couple the response on MJO timescales in the mesosphere/lower thermosphere to the ionosphere through E-dynamo processes, which has further implications in the F-region of the ionosphere.

1. Introduction

The Madden-Julian Oscillation (MJO) (Madden & Julian, 1971) is the dominant mode of intraseasonal variability in tropical convection and circulation and has been extensively studied since its discovery (~50 years ago) due to its importance for medium-range weather forecasting. It is an eastward moving disturbance near the equator (±30°) that typically recurs every ~30–90 days in tropical winds, clouds, rainfall, and many other variables (Zhang, 2005). The MJO is known to generate a spectrum of global-scale waves, for example, Kelvin waves (Wheeler & Kiladis, 1999), and modulate stratospheric gravity waves (GW), GW drag, and zonal winds (e.g., Alexander et al., 2018). Studies of MJO signals in the mesosphere/lower thermosphere (MLT) are sparse and mostly based on radar wind observations. Eckermann et al. (1997) suggested that tropospheric convection associated with the MJO modulated the intensity of upward-propagating GWs and tides. These observations were consistent with 70–110 km equatorial daytime HRDI zonal winds that showed strong signals within the range of MJO periods (Lieberman, 1998). More recently, Gasperini et al. (2020) found evidence for an MJO effect in ultrafast Kelvin waves in the thermosphere from GOCE data, and one can expect MJO impacts on the mean state of the thermosphere through changes in the wave driving of the mean circulation, similar to sudden stratospheric warming effects but on a regular basis (Oberheide et al., 2020). Note that while Gasperini et al. (2020) performed analysis of GOCE winds, the main results presented in their study used SD/WACCM-X. Liu et al. (2018) reported on MJO signals in wave-3 and wave-4 tidal proxies near the mesopause in local time locked MLS data. However, insufficient time-resolution in satellite-borne tidal diagnostics has prevented the extraction of MJO signals in the tidal spectrum from spectral space/time fits. Only the recent advent of daily tidal diagnostics using "tidal
deconvolution” techniques (section 2) allows one to resolve tidal variability on MJO timescales. Kumari and Oberheide (2020), while studying tidal/planetary wave interactions, already suggested the presence of large intraseasonal variations in SABER tidal temperatures caused by the MJO. Any MJO modulation of the MLT tides can be imposed by an MJO in tropospheric forcing, stratospheric/mesospheric wind filtering, GW momentum forcing, and possibly other effects. The exact mechanisms and their relative importance are topics for dedicated model studies in future work.

In this paper, we focus on two important diurnal tides: (i) the prominent migrating diurnal tide DW1 due to radiative and—to some extent—latent heating forcing in the troposphere and (ii) the convectively forced nonmigrating diurnal tide DE3, which is an eastward propagating diurnal tide with zonal wavenumber 3. The latter is particularly effective in modulating the E region dynamo and mapping tropospheric convection into the ionospheric plasma and can directly propagate into the upper thermosphere (e.g., Chang et al., 2013; Hagan et al., 2009; Oberheide et al., 2009). Sassi et al. (2019) suggest that MJO-related intraseasonal variations in the ionosphere are integral to improving space weather modeling and forecasting. On the observational side, Gasperrini et al. (2017) found a 90-day signal in zonal mean winds and a DE3 proxy (“wave4”) derived from CHAMP and GOCE in the thermosphere but could not conclusively relate the signal to the MJO. García (2000); Isoda et al. (2004); Kumar et al. (2007) suggested that the intraseasonal oscillations in the MLT zonal winds are possibly due to the intraseasonal variabilities in nonmigrating tides as a response to MJO-related convective forcing. In a statistical sense, Yang et al. (2018) found a clear connection between intraseasonal signals in DW1 from SD-WACCM and the MJO: Depending on the MJO phase (its location), convective anomalies lead to an enhanced/reduced DW1 forcing with temperature and wind amplitude differences of about 20% (peak-to-peak) around the mesopause in boreal winter. Briefly, the increased/decreased moisture over the enhanced/suppressed deep convection at a MJO phase leads to stronger/weaker radiative DW1 forcing by increased/decreased water vapor in the middle and upper equatorial troposphere (5–13 km, 10°S–10°N). MJO-modified GW momentum forcing on the DW1 also plays a role, according to the model.

The SABER data (section 2) now allow us to statistically characterize and quantify the MJO effect on MLT diurnal tidal variability, to test the model predictions of Yang et al. (2018) and to get a first assessment of the role of background winds in understanding the seasonal variation of the tidal response to the MJO through tidal mode coupling (section 3).

2. Data and Analysis

2.1. SABER Temperature Tides

The tidal baseline data from 2002 to 2019 used for the analysis are constructed from SABER (version 2.07) short-term tidal diagnostics (20–105 km, 50°S–50°N) followed by projection into symmetric and antisymmetric Hough Mode Extensions (HMEs). Unlike spectral Fourier fits which require combined 60 days of SABER (Russell III et al., 1999) observations to obtain full local time coverage due to the TIMED satellite orbit precession of 12 min/day, we employ daily tidal diagnostics from “tidal deconvolution” (Oberheide et al., 2002) that has proven its usefulness for studying the short-term variability of various diurnal tides using HRDI, WINDII, and SABER data (e.g., Kumari & Oberheide, 2020; Lieberman et al., 2013, 2015; Pedatella et al., 2016; Vitharana et al., 2019). See Oberheide et al. (2002) for complete mathematical details of the deconvolution method which essentially takes differences of observations on the ascending and descending orbit nodes at various altitudes to obtain amplitudes and phases with a time resolution of 1 day. The SABER tidal deconvolution error is ~0.5 K (Lieberman et al., 2015).

Figure 1a exemplifies the DE3 daily amplitudes for the year 2009 and 95 km. The year 2009 was chosen since it is the so-called year of tropical convection with several strong MJOs (Waliser et al., 2012). The observed short-term amplitude variability frequently reaches ~10 K within a few days. Most of the salient features of upward propagating tides are well described by fitting Hough Mode Extensions (HMEs) to diurnal tides (e.g., Oberheide et al., 2011). Basically, HMEs are extensions of classical Hough functions in that they account for tidal dissipation (Lindzen et al., 1977). See Oberheide and Forbes (2008) for a detailed discussion and the numerical HME computation. Each HME is a self-consistent latitude versus height set of amplitudes and phases in tidal temperature, winds, and density, from pole-to-pole, 0–390 km, and time-independent. The HMEs for each tidal component can be least squares fitted to the observed tides in the MLT region,
and tidal amplitudes and phases corresponding to each of the HMEs are obtained as function of latitude, altitude, and days. Usually, the first two HMEs, that is, HME1 (first symmetric) and HME2 (first antisymmetric) are important. Adding higher-order HMEs would result in a closer match to the observations, but their contribution is comparatively small, and they do not pose a problem as HMEs are orthogonal to each other. As such, the DE3 tide is largely a superposition of a symmetric (HME1, vertical wavelength $\lambda_z \approx 56$ km, peak altitude ~110 km) and an antisymmetric (HME2, $\lambda_z \approx 30$ km, peak altitude ~90 km) mode with respect to the equator (e.g., Oberheide & Forbes, 2008). DW1 is dominated by HME1 (symmetric with respect to the equator), and only this mode is used in the following. The HMEs projections are shown in Figures 1b–1d, reconstructed using HME fit coefficients and corresponding HMEs (latitude-altitude, as shown in Oberheide & Forbes, 2008). Figure 1 depicts the seasonal variation (winter/summer) and the latitude structure (symmetric/antisymmetric) of the HMEs amplitudes. An 11-day running mean smoothing is applied for illustration purposes.

Using HME projections instead of the observed amplitudes to study short-term variations is important because zonal mean (background) wind variations in different seasons can impact the symmetric and antisymmetric modes quite differently, along with tidal heating variations. For example, the DE3 antisymmetric mode (HME2) dominates in winter while the symmetric mode (HME1) dominates in summer and fall, as a consequence of tropospheric heating and mean zonal wind variations in the stratosphere and lower

**Figure 1.** An 11-day running mean of (a) the SABER DE3 daily amplitudes in Kelvin at 95 km altitude for the year 2009, the corresponding (b) HME1 and (c) HME2 projections of DE3, and (d) the HME1 projection of DW1 daily amplitudes. (e) The Fourier spectrum of HME fit coefficients for the year 2009 corresponding to DW1 HME1 (green), DE3 HME1 (blue), and DE3 HME2 (red) from 10–100 days. The 95% significance levels are shown as dotted lines in green, blue, and red, respectively.
mesosphere resulting in mode coupling (Oberheide & Forbes, 2008; Zhang et al., 2012). The HMEs are fitted to the observations in the latitude range 30°S–30°N and the height range 85–105 km. Since the latitude/height information is completely contained in the HMEs (in the sense of a tensor basis), the fit coefficients are latitude and altitude independent and only depend on time. Therefore, HMEs greatly simplify the spatial complexity, and the full temporal information is contained in the one-dimensional fit coefficients, which are used for the further analysis.

Figure 1e shows the Fourier spectra of all three fitting coefficient time series. The variability covers a wide range of temporal scales, from planetary wave timescales to intraseasonal to seasonal. An intraseasonal peak at 30–50 days period is present in all three fit coefficients. DW1 HME1 and DE3 HME1 have another broad peak at 60–73 days. Careful examination of wavelet spectra (Kumari & Oberheide, 2020; Vitharana et al., 2019) found this peak not to be an artifact of the 60-day TIMED yaw cycle. The peak at 92 days in nonmigrating tides (DE3 HME1 and DE3 HME2) is the fourth annual harmonic and most likely not related to the MJO. We thus have a short-term tidal data set (DW1 HME1 and DE3 HME1&2, 2002–2019) that can be further investigated for the tidal response to the MJO activity through the MJO index.

2.2. Real-Time Multivariate MJO Index

The RMM (real-time multivariate MJO) index by Wheeler and Hendon (2004) is widely used for monitoring the strength and location of the MJO-convection. Available from 1974 to present, it is based on a pair of empirical orthogonal functions (EOFs) of the combined fields of near-equatorially (15°N–15°S) averaged 850 hPa zonal wind, 200 hPa zonal wind, and satellite observed outgoing longwave radiation (OLR) data. The projection of observed daily data onto the EOFs, with annual cycle and interannual variability removed, yields principal components (PC) time series that vary mostly on the intraseasonal timescale of the MJO only. The RMM index time series includes RMM (or MJO) amplitudes and phases which are based on the first two orthogonal PC time series RMM1 and RMM2. MJO phases generally coincide with locations along the equator around the globe. For convenience, one defines eight different MJO phases, that is, location of MJO-convection, numbered 1 through 8 (8&1: western hemisphere and Africa, 2&3: Indian Ocean, 4&5: maritime continent, 6&7: western Pacific). We use the RMM index to locate active MJO events and its phase location in order to compare the tidal variability with respect to the MJO phases for active MJO events.

2.3. Analysis

We use the same approach as Yang et al. (2018) to compare our results with the model simulation. Note that Yang et al. (2018) used 1979–2015 (~35 years) SD-WACCM simulation for their statistical study, while we use 2002–2019 (~18 years) SABER observations. We first estimate the seasonal mean from each of the DW1 HME1, DE3 HME1, and HME2 amplitude time series (reconstructed using HME fit coefficients) for each season, that is, northern hemisphere (NH) winter (December-January-February, DJF), NH spring (March-April-May, MAM), NH summer (June-July-August, JJA) and NH fall (September-October-November, SON). In order to extract/filter the MJO signal (i.e., MJO anomalies) in MLT diurnal tides, we then apply a band-pass filter of 30–100 days upon the tidal time series (latitude averaged HMEs amplitudes) at each of the altitudes between 80 and 100 km. The next step is to identify active MJO events in each season using MJO amplitudes from the RMM index. Similar to Yang et al. (2018), an RMM index greater than 1.5 for at least five consecutive days is identified as an active MJO event. We only use days corresponding to active MJO events in each season for further analysis. We then group the remaining set of MJO-filtered tides in eight bins corresponding to eight MJO phases, using the phase information of active-MJO days. This allows one to relate the intraseasonal variability in tidal amplitudes with the MJO phases. We also calculate percent deviations from the seasonal mean in order to quantify the MJO signal in diurnal tidal variability at each MJO phase. See Figure 2c and section 3 for details.

Note that there are other ways to extract MJO anomalies in tides. One approach is filtering 30–100 days on anomalies (rather than amplitudes) calculated as deviations from the 91-day running mean of the amplitudes (as a proxy for seasonal mean which is used to minimize the interannual variability effect), and the results are very similar. One can also compute the percent deviation relative to a multyear climatology in order to study interannual variability. Detrending before band-pass filtering is necessary to study MJO effects for individual years. However, the Yang et al. (2018) approach is adequate for a statistical study.
3. Results and Discussion

Figure 2a shows the altitude structure of variations in DW1 HME1 amplitude with MJO phases in winter (DJF). The percent deviation (Figure 2b, shown for completeness) from the seasonal mean, however, is independent of altitude as the altitude and latitude structure is fully contained in the HME basis functions. It yields identical results to the percent deviations of the fit coefficients (Figure 2c). We therefore use HMEs coefficients as a proxy for HME amplitudes (in Kelvin) for the rest of the analysis for all seasons.

The range of percent deviation values during the boreal winter for DW1 HME1 (peak-to-peak difference in Figure 2c) attributed to the MJO response is ~10%. This MJO response is somewhat smaller compared to the 15–20% reported by Yang et al. (2018) in their model study. Nonetheless, the sign of the response that we found for the various MJO phases largely agrees with their findings. Yang et al. (2018) also found that the amplitude shows a positive anomaly during MJO phases 1 through 4 with a maximum of ~10%, while a negative anomaly is seen during MJO phases 5 through 8 with a minimum of ~5%. Thus, their peak-to-peak difference is ~15%, larger than our corresponding value of ~10%. In our result, the maximum positive anomaly in amplitude is ~6%, while the minimum anomaly is ~4%. As such, the 35 years of SD-WACCM in Yang et al. (2018) succeed in reproducing a realistic MJO dependence but overestimates the relative magnitude of the MJO signal in DW1. Note that Yang et al. (2018) only show DW1 DJF results and do not provide DE3 model results.

We now examine the seasonal variation of the MJO signal in both migrating and nonmigrating tides using the HME fit coefficients as a basis, similar to Figure 2c. The results are summarized in Figure 3 that shows a comprehensive view of the MLT diurnal tidal response to the tropical MJO as a function of season. We use 50 Monte Carlo simulations to calculate the uncertainty based on a tidal amplitude error (~1 K) estimated during the tidal deconvolution followed by HMEs projections of SABER temperatures. Note that the uncertainties obtained from the simulations are the statistical errors shown as the red bars in Figure 3 which represents the uncertainties of the line plots (black) up to one (±) standard deviation. The length of the error bars is <1% (equivalent to 0.02 K) for Figures 3a–3h and does not exceed 9% (~0.12 K) for Figures 3i–3l. Overall, the error bars are smaller than the change of percent deviation values in between MJO phases, which highlights the statistical significance of the tidal response. Clearly, there is a significant response to the tropical MJO in the MLT diurnal tides in all seasons with percent deviations of 7–10% in DW1 (Figures 3a–3d) and 15–25% in DE3 (Figures 3e–3l).

Note that the number of active MJO days differ from one season to another. Winter (DJF ~648 days) has nearly twice the MJO activity of summer (JJA ~353 days). The spring (MAM ~578 days) and fall (SON ~442 days) have less MJO activity than winter. The larger number of data points in winter provides a better statistical estimate of the MJO response. Hence, the error estimate in the season of summer (e.g., Figure 3k)
is larger. The error bars for DE3 HME2 (Figures 3i–3l) are significantly larger than those for DW1 HME1 and DE3 HME1, due to the generally smaller amplitudes of DE3 HME2 (Figure 1). The migrating diurnal tide has significant MJO responses in spring (MAM, ~15%) and fall (SON, ~11%), while the response is smallest in summer (JJA, ~7%). Evidently, both the migrating and nonmigrating tides are considerably modulated by the MJO phase with the details of the responses varying from one season to another.

The peak-to-peak difference between the positive and negative percent deviations for phases 1 through 8 is taken as a measure of the strength of the tidal MJO signal. As such, the nonmigrating tidal responses to MJO in winter (Figures 3e and 3i) and summer (Figures 3g and 3k) are twice as strong as their respective counterparts for the migrating tides in winter (Figure 3a) and summer (Figure 3c), possibly due to enhanced eastward drag to DE3 by MJO-related stratospheric GWs. This is because MJO-born GWs in the stratosphere, that is, away from source region, are found to cause larger eastward anomalies globally in stratospheric zonal winds (Alexander et al., 2018). As DE3 HME1 dominates in summer and fall, we also looked into percent deviations in August-September-October (Figure 4). The MJO response in DE3 HME1 in summer is significant (~20%, small error), and most features of Figures 3g and 3h are contained in Figure 4 except the prominent peak at phase 4 in Figure 3g, likely related to a MJO response in June-July that is not present in August.

Figure 3. Statistical tidal response to the MJO (a–d; DW1 HME1, e–h; DE3 HME1, and i–l; DE3 HME2) in each season (DJF, MAM, JJA, and SON), computed with respect to the corresponding seasonal mean. Red bars are the corresponding error estimates.

Figure 4. The percent deviations at each MJO phase for DE3 HME1 in August-September-October (ASO).
It is surprising that DE3 HME1 has a strong response in winter (DJF) and DE3 HME2 has a strong response in summer (JJA) as DE3 HME2 dominates in winter while DE3 HME1 dominates in summer and fall (Oberheide & Forbes, 2008). Also, the DE3 HME2 mode peaks at midlatitudes (~20°) with small amplitudes at the equator, while MJO-related convective variations are centered at the tropics. This raises the question of the cause of the significant DE3 HME2 response to the MJO. As mentioned above, the seasonal variation of HMEs in DE3 comes as a consequence of tropospheric heating and mean zonal wind variations in the stratosphere and lower mesosphere (Oberheide & Forbes, 2008; Zhang et al., 2012). Yang et al. (2018) attempted to explain the physical mechanism behind the increase/decrease of DW1 amplitudes anomalies with MJO phases and found it to be a response of enhanced-suppressed convection attributed to MJO effects in the tropics. MJO-related GW disturbances also play an important role in enhancing the DW1 tide during strong MJO events. While an enhanced convective forcing in winter (DJF) must also enhance DE3 HME1 amplitude anomalies, our observations (Figure 3) show an anticorrelation between the percent deviations of DE3 HME1 and DW1 HME1 for various MJO phases. Moreover, DE3 HME2 amplitudes are enhanced in winter mainly due to mode coupling, that is, energy transfer between modes arising from mean wind variations in the stratosphere and lower mesosphere with convective forcing playing a lesser role (Zhang et al., 2012). A possible explanation is as follows: We perform our HME fits of DE3 above the mode coupling region, that is, above 85 km. The negative DE3 HME1 response (Figure 3e) and positive DE3 HME2 (Figure 3i) response in MJO phases 1 through 5 is possibly an indication of the energy transfer due to the mode coupling. This would explain the similar responses of DE3 HME2 (antisymmetric) and DW1 HME1 (symmetric) in winter. The role of mean wind variations in the MJO response is clearly key to understanding the percent deviation variations with MJO phases. An interesting observation from Figures 3a–3d is that DW1 HME1 has positive MJO responses in phases 2 through 4 during winter and spring, while it has negative responses in phases 7 and 8 during all seasons. In comparison, DE3 HME1&2 shows greater variations in responding to the MJO phases across different seasons. Overall, the seasonal variation in the DW1 migrating tidal response is less variable in comparison to that of the DE3 nonmigrating tide. Gasperini et al. (2020) suggested that the QBO and SAO play a significant role in the MJO-MLT tidal coupling. Analysis that takes into account the phase of the QBO and SAO is needed to better understand seasonal dependencies in the MLT tidal MJO variations.

4. Conclusions

SABER observations allow one for the first time to quantify the MLT tidal response to the Madden-Julian Oscillation and to test model predictions. The latter produce a realistic response depending on the MJO phase but generally overestimate the effect for DW1. Both migrating and nonmigrating diurnal tides respond strongly (~10–25% of seasonal mean) to the MJO during all seasons and have a clear dependence on the location of the MJO, that is, the MJO phase, possibly due to changes in background wind (and additional MJO-derived GW forcing) and convective forcing. Interestingly, the MJO effects in both equatorial nonequatorial modes (HMEs) of the nonmigrating tides can be quite different and are possibly related to mode coupling in the stratosphere/lower mesosphere. The nonmigrating tidal response (~25%) to the MJO is about twice as strong as the migrating tidal response in summer (~8%) and winter (~10%). Moreover, the seasonal variation of the MJO response in nonmigrating tides is more prominent than in the migrating tides. The relatively strong tidal response to the MJO in the low-latitude MLT suggests that similar effects, on the order of 25%, will be found in the F-region plasma due to E-region dynamo modulation. This is important for space weather research and lower atmosphere coupling on intraseasonal timescales as the MJO is a regularly recurring pattern.

Data Availability Statement

SABER Level 2a, version 2.07 data are available throughout the NASA SPDF (http://spdf.gsfc.nasa.gov). The RMM MJO index was obtained online (http://www.bom.gov.au/climate/mjo/).

References

Alexander, M. J., Grimsdell, A. W., Stephan, C. C., & Hoffmann, L. (2018). MJO-related intraseasonal variation in the stratosphere: Gravity waves and zonal winds. Journal of Geophysical Research: Atmospheres, 123, 775–798. https://doi.org/10.1002/2017JD027620
Chang, L. C., Lin, C. H., Yue, J., Liu, J. Y., & Lin, J. T. (2013). Stationary planetary wave and nonmigrating tidal signatures in ionospheric wave 3 and wave 4 variations in 2007–2011 FORMOSAT-3/COSMIC observations. Journal of Geophysical Research: Space Physics, 118, 6651–6665. https://doi.org/10.1002/2013JA019583

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Eckermann, S. D., Rajopadhya, D. K., & Vincent, R. A. (1997). Intraseasonal wind variability in the equatorial mesosphere and lower thermosphere: Long-term observations from the Central Pacific. Journal of Atmospheric and Solar-Terrestrial Physics, 59(6 SPEC ISS.), 603–627. https://doi.org/10.1016/s1364-6826(96)00143-5

Garcia, R. R. (2000). The role of equatorial waves in the semiannual oscillation of the middle atmosphere. In Atmospheric science across the stratosphere, geophysical monograph series (Vol. 123, pp. 161–176). Washington, DC: American Geophysical Union. https://doi.org/10.1029/GM123p0161

Gasperini, F., Hagan, M. E., & Zhao, Y. (2017). Evidence of tropospheric 90 day oscillations in the thermosphere. Geophysical Research Letters, 44, 10,125–10,133. https://doi.org/10.1002/2016GL070545

Gasperini, F., Liu, J., & Minnis, P. (2020). Preliminary evidence of Madden-Julian Oscillation effects on ultrafast tropical waves in the thermosphere. Journal of Geophysical Research: Space Physics, 125, e2019JA027649. https://doi.org/10.1029/2019JA027649

Hagan, M. E., Maute, A., & Roble, R. G. (2009). Tropospheric tidal effects on the middle and upper atmosphere. Journal of Geophysical Research, 114, A01302. https://doi.org/10.1029/2008JA013637

Isoda, F., Tsuda, T., Nakamura, T., Vincent, R. A., Reid, I. M., Achmad, E., et al. (2004). Intraseasonal oscillations of the zonal wind near the mesopause observed with medium-frequency and meteor radars in the tropics. Journal of Geophysical Research D, 109(D21), 35–40. https://doi.org/10.1029/2003JD003378

Kumar, K. K., Antonita, T. M., Ramkumar, G., Deepa, V., Gurubaran, S., & Rajaram, R. (2007). On the tropospheric origin of mesosphere thermosphere: Long term observations from the Central Pacific. Journal of Geophysical Research: Space Physics, 112, A01302. https://doi.org/10.1029/2006JA012058

Lieberman, R. S., Riggin, D. M., Ortland, D. A., Oberheide, J., & Siskind, D. E. (2015). Global observations and modeling of nonmigrating tides generated by tide-planetary wave interactions. Journal of Geophysical Research: Atmospheres, 120, 11,419–11,437. https://doi.org/10.1002/2015JD023739

Lindzen, R. S., Hong, S. S., & Forbes, J. M. (1977). In Semiannual Hough mode extensions in the thermosphere and their application (NRL Memo. Report 3442, pp. 1–28). Washington, DC: Naval Research Laboratory. retrieved from https://apps.dtic.mil/sti/pdfs/ADA038240.pdf

Liu, G., Janche, D., & Lieberman, R. S. (2018). Intraseasonal variations of nonmigrating tides observed near the mesopause. Journal of Geophysical Research: Space Physics, 123, 9921–9931. https://doi.org/10.1029/2018JA025799

Madden, R. A., & Julian, P. R. (1971). Detection of a 40–50 day oscillation in the zonal wind in the tropical Pacific. Journal of the Atmospheric Sciences, 28(5), 702–708. https://doi.org/10.1175/1520-0469(1971)028<0702:DOADTO>2.0.CO;2

Oberheide, J., & Forbes, J. M. (2008). Tidal propagation of deep tropical cloud signatures into the thermosphere from TIMED observations. Geophysical Research Letters, 35, L04816. https://doi.org/10.1029/2007GL032397

Oberheide, J., Forbes, J. M., Hauri, K., Wu, Q., & Bruinsma, S. L. (2009). Tropospheric tides from 80 to 400 km: Propagation, interannual variability, and solar cycle effects. Journal of Geophysical Research, 114, D00D05. https://doi.org/10.1029/2009JD012388

Oberheide, J., Forbes, J. M., Zhang, X., & Bruinsma, S. L. (2011). Climatology of upward propagating diurnal and semidiurnal tides in the thermosphere. Journal of Geophysical Research, 116, A11306. https://doi.org/10.1029/2011JA016784

Oberheide, J., Hagan, M. E., Roble, R. G., & Offermann, D. (2002). Sources of nonmigrating tides in the tropical middle atmosphere. Journal of Geophysical Research, 107(D21), A101–A110. https://doi.org/10.1029/2002JD002220

Oberheide, J., Pedatella, N. M., Gao, Q., Kumari, K., Burns, A. G., & Eastes, R. W. (2020). Thermospheric composition O/N2 response to an altered meridional mean circulation during sudden stratospheric warmings observed by GOLD. Geophysical Research Letters, 47, e2019GL086313. https://doi.org/10.1029/2019GL086313

Pedatella, N. M., Oberheide, J., Sutton, E. K., Liu, H., Anderson, J. L., & Raeder, K. (2016). Short-term nonmigrating tide variability in the mesosphere, thermosphere, and ionosphere. Journal of Geophysical Research: Space Physics, 121, 3621–3633. https://doi.org/10.1002/2016JA022528

Received Russell, J. M. III, Mlynarski, M. G., Gordley, L. L., Tansock, J. J. Jr., & Esplin, R. W. (1999). Overview of the SABER experiment and preliminary calibration results. Optical Spectroscopic Techniques and Instrumentation for Atmospheric and Space Research III, 3756, 277. https://doi.org/10.1117/12.366382

Sassi, F., McCormack, J. P., & McDonald, S. E. (2019). Whole atmosphere coupling on intra- and inter-seasonal time scales: A potential source of increased predictive capability. Radio Science, 54, 913–933. https://doi.org/10.1029/2019RS006847

Vitharanu, A., Zhu, X., Du, J., Oberheide, J., & Ward, W. E. (2019). Statistical modeling of tidal weather in the mesosphere and lower thermosphere. Journal of Geophysical Research: Atmospheres, 124, 9011–9027. https://doi.org/10.1029/2019JD035073

Waliser, D. E., Moncrieff, M. W., Burridge, D., Fink, A. H., Goebis, D., Goswami, B. N., et al. (2012). The “year” of tropical convection (May 2008–April 2010): Climate variability and weather highlights. Bulletin of the American Meteorological Society, 93(8), 1189–1218. https://doi.org/10.1175/2011BAMS3095.1

Wheeler, M., & Kiladis, G. N. (1999). Convectively coupled equatorial waves: Analysis of clouds and temperature in the wavenumber-frequency domain. Journal of the Atmospheric Sciences, 56(2), 374–399. https://doi.org/10.1175/1520-0469(1999)056<0374:CCCEWA>2.0.CO;2

Wheeler, M. C., & Hendon, H. H. (2004). An all-season real-time multivariate MJO index: Development of an index for monitoring and prediction. Monthly Weather Review, 132(8), 1917–1932. https://doi.org/10.1175/1520-0493(2004)132<1917:AMRAAIMM>2.0.CO;2

Yang, C., Smith, A. K., Li, T., & Dou, X. (2018). The effect of the Madden-Julian oscillation on the mesosphere migrating diurnal tide: A study using SD-WACCM. Geophysical Research Letters, 45, 5105–5114. https://doi.org/10.1029/2018GL077956

Zhang, C. (2005). Madden-Julian oscillation. Reviews of Geophysics, 43, RG2003. https://doi.org/10.1029/2004RG000158

Zhang, X., Forbes, J. M., & Hagan, M. E. (2012). Seasonal-latitudinal variation of the eastward-propagating diurnal tide with zonal wave number 3 in the MLT: Influences of heating and background wind distribution. Journal of Atmospheric and Solar-Terrestrial Physics, 78-79, 37–43. https://doi.org/10.1016/j.jastp.2011.03.005