Ionosphere-Thermosphere-Mesosphere Variability imposed by Waves from Below in Future Climates

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The positions, experiences, and viewpoints expressed below are those of the authors as scientists in the space research community and are not the official positions of their employing institutions.

Synopsis: *The structure and dynamics of the Ionosphere-Thermosphere-Mesosphere (ITM) system are significantly influenced by waves from the lower atmosphere. Understanding of the physical mechanisms at play and trends is impaired by data sparsity. This white paper reviews current knowledge in this area and highlights the importance and critical need for new, global, height-resolved observations of the ITM.*

1. INTRODUCTION

Over the past two decades, improved physical understanding of the Ionosphere-Thermosphere-Mesosphere (ITM) system, partly enabled by the development of new observational techniques, advances in the sophistication and computing power of models, and a new generation of tools allowing the relevant processes to be visualized and analyzed, demonstrated unambiguously that much of the terrestrial influences on the ITM is due to ***internal atmospheric waves***. Mostly excited in the troposphere-stratosphere region (ca., 0-50 km), internal atmospheric waves play a key role in the transfer of energy and momentum, mixing of constituents, development of large-scale flows, and generation of ITM variability [e.g., *Liu*, 2016; *Forbes*, 2021]. The components of the atmospheric wave spectrum coupling terrestrial variability with ITM changes are gravity waves (GWs), atmospheric tides, Kelvin waves (KWs), and Rossby planetary waves (PWs), covering a spatial range from a few tens of kilometers to several thousand kilometers [e.g., *Oberheide et al.*, 2015]. Understanding the impacts of vertically propagating waves on ITM variability is fundamental to understanding its thermal, dynamical, and compositional structure and long-term trends [e.g., *Qian et al.*, 2017; *Rezac et al.*, 2018; *Solomon* et al., 2018, 2019]. Recent research [see, e.g., reviews by *Sassi et al.*, 2019; *Ward et al.*, 2021] highlighted the importance of the manner in which waves produced in the troposphere-stratosphere region propagate vertically to influence the dynamics and transport of constituents in the ITM system, the character of the long-term trends in the ITM, and the changes taking place in the thermosphere that may affect the ITM structure, composition, and variability in ***future climates***.

The satellite environment in near-Earth space depends on the complex ITM region as the maintenance of satellite orbits and space debris trajectories require the accurate prediction of neutral atmospheric densities over time and space [e.g., *Emmert*, 2015]. The accurate modeling of neutral atmospheric density requires an understanding of atmospheric waves and dynamics that modulate the neutral density spatially and temporally [e.g., *Leonard et al.*, 2012]. Ionospheric plasma is also significantly influenced by atmospheric dynamics driven by waves [e.g., *Forbes and Zhang*, 1997; *Hocke and Schlegel*, 1996, *Laštovička* et al., 2006; *England et al.*, 2010; *Forbes et al.*, 2018; *Koucká Knížová et al.*, 2021], with direct implications for satellite communication links and GPS-based navigation.

2. INTRA-SEASONAL AND INTER-ANNUAL VARIABILITY IN THE ITM

ITM neutral and electron density variability spanning timescales from months to years have been observed since the 1930s-1960s [e.g., *Appleton and Naismith*, 1935; *Berkner and Wells*, 1938; *Yonezawa*, 1959; *Paetzold and Zschorner*, 1961], yet significant uncertainty still exists on the physical mechanisms responsible for these variations. Attaining a better understanding and characterization of the various modes of variability in the ITM system from intra-seasonal (~30-90 days) to inter-annual timescales and their connections to terrestrial drivers is critical for achieving whole atmosphere predictability [*Sassi et al.*, 2019] and for improving our ability to model changes associated with future climates [*Ward et al.*, 2021]. Modes of intra-seasonal variability include the tropospheric Madden-Julian Oscillation (MJO; *Madden and Julian*, 1971); the stratospheric/mesospheric wind vacillations and global normal modes [*Smith*, 1985]; while modes of inter-seasonal and inter-annual variability include the tropospheric El Nino-Southern Oscillation (ENSO; *Trenberth*, 1997); the stratospheric quasi-biennial oscillation (QBO; *Baldwin et al.*, 2001); the stratospheric/mesospheric annual (AO) and semiannual (SAO) oscillations [*Paetzold et al.*, 1961; *Garcia et al.*, 1997], and the solar cycle (SC) variation [*Oberheide et al.*, 2009]. Figure 1 (from *Sassi et al.*, 2019) illustrates the complexity of the coupling processes affecting the ITM based on their characteristic time scale and vertical domain.

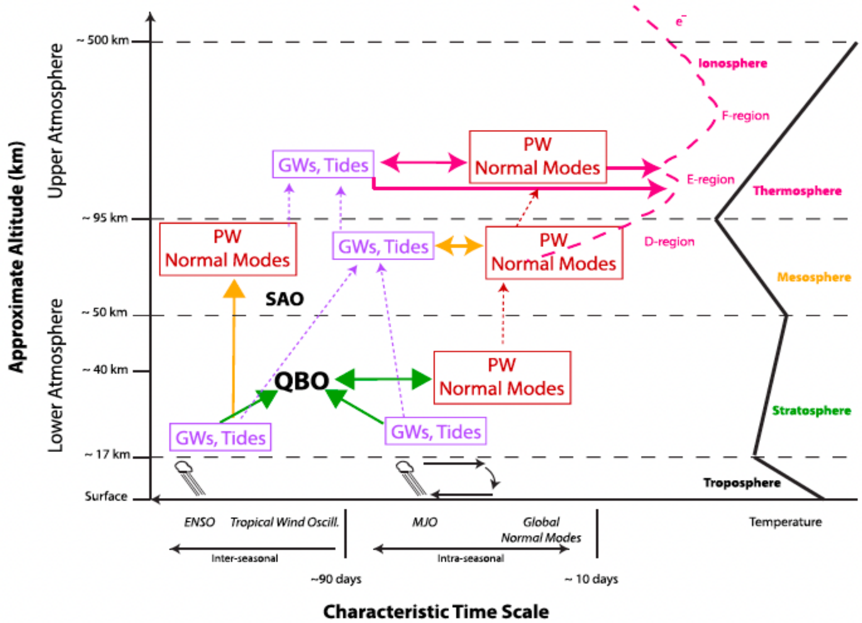

Figure 1 *Illustration of the various processes affecting the ITM as a function of their characteristic time scale and vertical domain. Illustrations (not to scale) of typical temperature (thick black solid) and ionospheric electron density (purple dash) profiles are shown to the right. The solid arrows indicate interaction pathways, while the dashed arrows indicate the propagation directions in the vertical. [Figure from Sassi et al., 2019].*

3. INTRA-SEASONAL ITM VARIATIONS: CONNECTIONS TO THE MJO

The MJO is the dominant mode of intra-seasonal variability in tropical convection and circulation [*Zhang*, 2005] and is known to generate a whole spectrum of global-scale waves mainly through convective forcing [*Wheeler and Kiladis*, 1999]. The MJO was shown to modulate stratospheric GW, GW drag, and mean winds [*Alexander et al.,* 2018] and lower and middle thermospheric tides and UFKWs [*Kumari et al.*, 2020, 2021; *Gasperini et al.*, 2020]. *Li and Lu* [2020] provided observational evidence that an ~15% peak-to-peak MJO-modulation of the GWs extends up to ~100 km altitude and into the extra-tropics, while *Li and Lu* [2021] found large MJO signals in MERRA-2 resolved GWs and parameterized GW drag at high northern latitudes during winter. *Kumari et al.* [2020] demonstrated that the MJO modulates the certain tidal amplitudes in the lower atmosphere by up to 25%, while *Kumari et al.* [2021] revealed that the modulation of tidal heating is comparatively more important than the modulation of background winds to impose the MJO signal on the low latitude E-region tides. The MJO-modulation of tides and UFKW has been shown to extend well into the thermosphere [*Gasperini et al.,* 2017, 2020] with potential effects on the ionosphere either through E-region dynamo or direct upward propagation and/or composition changes. These recent studies suggest that the MJO may be responsible for an important fraction of the intra-seasonal variability observed in the ITM system, although work on this topic is at the very early stages.

4. INTER-SEASONAL ITM VARIABILITY: CONNECTIONS TO QBO, SAO, ENSO, SOLAR CYCLE

The QBO is the largest source of inter-annual variability in the tropical stratosphere [*Baldwin et al.*, 2001], and its influence extends to higher latitudes throughout the lower atmosphere [e.g., *Anstey and Shepherd*, 2014]. Ground- and space-based observations documented the presence of QBO-like oscillations in mesospheric winds over 25 years ago [e.g., *Burrage et al.*, 1996; *Gurubaran and Rajaram*, 1999; *Vincent et al.*, 1998]. There is now substantial observational and modeling evidence indicating that the QBO impacts inter-annual variability in lower thermosphere dynamics by affecting both tidal and GW breaking [*Vincent et al.*, 1998; *Hagan et al.*, 1999; *Wu et al.*, 2008a,b; *Hibbins et al.*, 2007; *Pancheva et al.*, 2009; *Oberheide et al.*, 2009; *Xu et al.*, 2009; *Davis et al.*, 2013; *Gan et al.*, 2014; *Laskar et al.*, 2016; *Dhadly et al.*, 2018]. Recent results by *Yamazaki et al.* [2017] suggest that the variation of atmospheric tides due to the stratospheric QBO could be an important source for inter-annual variability of the ionospheric wind dynamo. Yet, the question remains whether the QBO may have any measurable impact on the ionosphere.

The SAO in the tropical zonal wind is a mode affecting both the stratosphere and the mesosphere [*Ern et al.,* 2021*; Smith et al.*, 2017], with SAO amplitudes and phases varying between these two atmospheric regions. It has been shown that there is a relationship between the QBO and SAO and that at times their phases can align. There is also evidence of the role of the QBO influencing the mesospheric SAO; this is thought to be due to QBO filtering of large equatorial waves and GWs. These changes in the mesosphere map onto changes observed in the D-region ionosphere, where SAO signatures have been observed in Total Electron Content (TEC) and ion temperature observations [*Silber et al.*, 2016].

The ENSO ocean-atmosphere coupling phenomenon is recognized as an important source of inter-annual variability in the lower thermosphere [*Gurubaran et al.,* 2005; *Lieberman et al.,* 2007; *Pedatella and Liu,* 2012, 2013; *Warner and Oberheide,* 2014; *Liu,* 2016; *Liu et al.,* 2017; *Sun et al.,* 2018]. The ENSO-related variation in diurnal tides in the lower thermosphere can modulate the ionospheric wind dynamo, coupling ENSO variability to the ITM system. Studies on the ENSO signature in the ionosphere are rare and challenging [*Pedatella and Forbes*, 2009; *Pedatella and Liu,* 2013; *Chang et al.,* 2018]. *Pedatella and Liu* [2013] simulated the influence of the ENSO-driven tidal variability on the low-latitude ionosphere and showed that the interannual tidal variability in the lower thermosphere can introduce 10-15% variability in the $E \times B$ vertical drift velocity and ionosphere peak density. The ENSO can also modulate the stratospheric QBO [e.g., *Taguchi,* 2010] as well as the QBO components in the temperature DW1 and DE3 in the lower thermosphere [e.g., *Sun et al.,* 2018]. Despite this recent progress, connections between ENSO and the ITM system are not as well established.

Solar cycle effects on tidal dissipation have been demonstrated in various studies [e.g., *Oberheide et al.*, 2009*, Jones et al.,* 2016]. *Oberheide et al.* [2009] (and references therein) showed that tidal dissipation becomes more important as solar activity increases. *Jones et al.* [2016] showed that the solar cycle variability in tidal-induced zonal-mean temperature changes results from tidally driven increases in nitric oxide (NO) infrared radiative (IR) cooling and that tidal modifications to the ionosphere are quite substantial through tidal-induced temperature and constituent changes. *Mlynczak et al.* [2010, 2014] reported strong solar cycle dependence in NO and carbon dioxide (CO_2) IR cooling in the thermosphere implying that the tidal effects on NO and CO_2 IR cooling could modulate its inherent solar cycle behavior with implications for the whole ITM system. More modeling- and observational-based studies are needed to address the physical mechanisms at play.

5. OPEN QUESTIONS

It is now well established that internal waves play a leading role in impressing their long-term variability from the lower and middle atmosphere into the lower thermosphere and ionosphere. A growing body of recent evidence suggests that upward propagating waves may be the leading driver of long-term variability in the whole ITM system. Variability in the wave spectrum can be ascribed to changes in sources associated with tropospheric weather, variable propagation conditions, and nonlinear interactions between different parts of the wave spectrum [*Yigit and Medvedev*, 2015; *Liu*, 2016; *Sassi et al.*, 2019]. As their generation and propagation conditions may be undergoing modifications in a changing climate [*Ward et al.*, 2021], it is critical that we attain a better understanding of the physical mechanisms at play for improving our modeling and predictive capabilities.

Despite recent improved observational capabilities afforded by NASA's Ionospheric Connection Explorer (ICON, *Immel et al.*, 2018) and Global-scale Observations of the Limb and Disk (GOLD, *Eastes et al.*, 2017) missions, our ability to attain a comprehensive physical understanding of the processes at play is significantly impaired by the data sparsity in the ITM. Without global measurements with sufficient temporal and spatial resolution, physics-based models cannot be validated, and data assimilation for these heights remains a tentative venture. The establishment and maintenance of suitable observing capabilities are thus critical to allow for the dynamical conditions to be monitored.

The upcoming Geospace Dynamics Constellation (GDC) mission shall provide critical observations to better understanding long-term ITM coupling processes. Observations from the Dynamical Neutral Atmosphere-Ionosphere Coupling (DYNAMIC) mission will be particularly helpful by providing critical information on the height evolution of the wave spectrum in the thermosphere. GDC and DYNAMIC are expected to provide much-needed day/night wind, temperature, and composition observations throughout the thermosphere and ionosphere that will enable the investigation of wave-mean flow interactions, ion-neutral interactions, and dynamo processes critical for the study of long-term ITM variability in current and future climates.

A few, but not all, of the important open questions that need to be addressed in this area of research include:

1. *What are the physical mechanisms that transmit intra-seasonal, inter-seasonal, and inter-annual variability from the lower and middle atmosphere into the ITM system, and what is their relative importance?*
2. *What are the influences of lower atmospheric waves on the long-term trends of the ITM system? In particular, what are their impacts on eddy diffusion and CO_2 cooling rates that drive variations in O/N_2 and thus thermospheric density?*
3. *How are the influences of lower atmospheric waves on the long-term trends of the ITM system changing with respect to a changing solar energy budget on longer time scales?*

Simultaneous measurements from both GDC and DYNAMIC are critical to answering these outstanding questions along with many others.

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, J. Geophys. Res. Atmos., 123, 775–788, doi:10.1002/2017JD027620.

Anstey, J. A., and Shepherd, T. G. (2014). High-latitude influence of the quasi-biennial oscillation. Quarterly Journal of the Royal Meteorological Society, 140(678), 1–21. https://doi.org/10.1002/qj.2132

Appleton, E. V., and Naismith, R. (1935). Some further measurements of upper atmospheric ionization. Proceedings of the Royal Society of London. Series A - Mathematical and Physical Sciences, 150(871), 685–708. https://doi.org/10.1098/rspa.1935.0129

Baldwin, M. P., Gray, L. J., Dunkerton, T. J., Hamilton, K., Haynes, P. H., Randel, W. J., et al. (2001). The quasi-biennial oscillation. Reviews of Geophysics, 39(2), 179–229. https://doi.org/10.1029/1999RG000073

Berkner, L. V., & Wells, H. W. (1938). Non-seasonal change of f2-region ion-density. Terrestrial Magnetism and Atmospheric Electricity, 43(1), 15–36. https://doi.org/10.1029/TE043i001p00015

Burrage, M. D., Vincent, R. A., Mayr, H. G., Skinner, W. R., Arnold, N. F., & Hays, P. B. (1996). Long-term variability in the equatorial middle atmosphere zonal wind. Journal of Geophysical Research, 101(D8), 12,847–12,854. https://doi.org/10.1029/96JD00575

Chang LC, Chiu PY, Salinas CCJH, Chen SP, Duann Y, Liu JY, Lin CH, Sun YY (2018) On the relationship between E region scintillation and ENSO observed by FORMOSAT-3/COSMIC. J Geophys Res Space Phys 123:4053–4065. https://doi.org/10.1029/2018JA025299

Davis, R. N., Du, J., Smith, A. K., Ward, W. E., & Mitchell, N. J. (2013). The diurnal and semidiurnal tides over Ascension Island (8S, 14W) and their interaction with the stratospheric quasi-biennial oscillation: studies with meteor radar, eCMAM and WACCM. Atmospheric Chemistry and Physics, 13(18), 9543–9564. https://doi.org/10.5194/acp-13-9543-2013

Dhadly, M. S., Emmert, J. T., Drob, D. P., McCormack, J. P., & Niciejewski, R. J. (2018). Short-term and interannual variations of migrating diurnal and semidiurnal tides in the mesosphere and lower thermosphere. Journal of Geophysical Research: Space Physics, 123, 7106–7123. https://doi.org/10.1029/2018JA025748

Eastes, R. W., W.E. McClintock, A.G. Burns, et al. (2017), The Global-Scale Observations of the Limb and Disk (GOLD) Mission, *Sp. Sci. Rev.*, 212, 383, doi:10.1007/s11214-017-0392-2.

Emmert, JT (2015) Altitude and solar activity dependence of 1967–2005 thermospheric density trends derived from orbital drag. J Geophys Res Space 120(4):2940–2950. https://doi.org/10.1002/2015JA021047.

England, S. L., Immel, T. J., Huba, J. D., Hagan, M. E., Maute, A., & DeMajistre, J. (2010). Modeling of multiple effects of atmospheric tides on the ionosphere: An examination of possible coupling mechanisms responsible for the longitudinal structure of the equatorial ionosphere. Journal of Geophysical Research, 115, A05308. https://doi.org/10.1029/2009JA014894

Ern, M., Diallo, M., Preusse, P., Mlynczak, M. G., Schwartz, M. J., Wu, Q., and Riese, M.: The semiannual oscillation (SAO) in the tropical middle atmosphere and its gravity wave driving in reanalyses and satellite observations, Atmos. Chem. Phys., 21, 13763–13795, https://doi.org/10.5194/acp-21-13763-2021, 2021.

Forbes, J. M., and Zhang, X. (1997). Quasi 2-day oscillation of the ionosphere: A statistical study. Journal of Atmospheric and Solar-Terrestrial Physics, 59(9), 1025–1034. https://doi.org/10.1016/S1364-6826(96)00175-7

Forbes, J. M., Maute, A., Zhang, X., & Hagan, M. E. (2018). Oscillation of the ionosphere at planetary-wave periods. Journal of Geophysical Research: Space Physics, 123, 7634–7649. https://doi.org/10.1029/2018JA025720

Forbes, J.M. (2021). Atmosphere-Ionosphere (A-I) Coupling by Solar and Lunar Tides. In Upper Atmosphere Dynamics and Energetics (eds W. Wang, Y. Zhang and L.J. Paxton). https://doi.org/10.1002/9781119815631.ch9

Gasperini, F., M. E. Hagan, and Y. Zhao (2017), Evidence of tropospheric 90 day oscillations in the thermosphere. Geophysical Research Letters, 44, 10,125–10,133, soi: 10.1002/2017GL075445

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

Gan, Q., Du, J., Ward, W. E., Beagley, S. R., Fomichev, V. I., & Zhang, S. (2014). Climatology of the diurnal tides from eCMAM30 (1979 to 2010) and its comparison with SABER. Planets and Space, 66(1), 103. https://doi.org/10.1186/1880-5981-66-103

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), 26,019–26,032. https://doi.org/10.1029/97JD00207

Gurubaran, S., & Rajaram, R. (1999). Long-term variability in the mesospheric tidal winds observed by MF radar over Tirunelveli (8.7N, 77.8E). Geophysical Research Letters, 26(8), 1113-1116. https://doi.org/10.1029/1999GL900171

Gurubaran, S., R. Rajaram, T. Nakamura, and T. Tsuda (2005), Interannual variability of diurnal tide in the tropical mesopause region: A signature of the El Niño-Southern Oscillation (ENSO), *Geophys. Res. Lett.*, **32**, L13805, doi:10.1029/2005GL022928.

Hagan, M. E., M. D. Burrage, J. M. Forbes, J. Hackney, W. J. Randel, and X. Zhang (1999), QBO effects on the diurnal tide in the upper atmosphere, *Earth Planets Space*, **51**, 571– 578.

Hibbins, R. E., Espy, P. J., & Jarvis, M. J. (2007). Quasi-biennial modulation of the semidiurnal tide in the upper mesosphere above Halley,Antarctica. Geophysical Research Letters, 34, L21804. https://doi.org/10.1029/2007GL031282

Hocke, H., and Schlegel, K. (1996). A review of atmospheric gravity waves and traveling ionospheric disturbances: 1982-1995. Annales Geophysique, 14(9), 917–940. https://doi.org/10.1007/s00585-996-0917-6

Immel, T.J., England, S.L., Mende, S.B. et al, (2018), The Ionospheric Connection Explorer Mission: Mission Goals and Design, *Sp. Sci. Rev.*, 214, 13, doi:10.1007/s11214-017-0449-2.

Jones, M., Forbes, J. M., and Hagan, M. E. (2016), Solar cycle variability in mean thermospheric composition and temperature induced by atmospheric tides, *J. Geophys. Res. Space Physics*, 121, 5837– 5855, doi:10.1002/2016JA022701.

Koucká Knížová, P., Laštovička, J., Kouba, D., Mošna, Z., Podolská, K., Potužníková, K., ... & Rusz, J. (2021). Ionosphere influenced from lower-Lying atmospheric regions. *Frontiers in Astronomy and Space Sciences*, *8*, 651445.

Kumari, K., J. Oberheide, and X. Lu (2020), The Tidal Response in the Mesosphere/Lower Thermosphere to the Madden-Julian Oscillation Observed by SABER, Geophys. Res. Lett., 47, e2020GL089172, doi:10.1029/2020GL089172.

Kumari, K., H. Wu, A. Long, X. Lu, and J. Oberheide (2021), Mechanism Studies of Madden-Julian-Oscillation Coupling into the Mesosphere/Lower Thermosphere Tides using SABER, MERRA-2 and SD-WACCMX, J. Geophys. Res. Atmos., 126, e2021JD034595, doi:10.1029/2021JD034595.

Laskar, F. I., Chau, J. L., Stober, G., Hoffmann, P., Hall, C. M., & Tsutsumi, M. (2016). Quasi-biennial oscillation modulation of the middle and high-latitude mesospheric semidiurnal tides during August-September. Journal of Geophysical Research: Space Physics, 121, 4869–4879. https://doi.org/10.1002/2015JA022065

Laštovička, J., Sauli, P., & Krizan, P. (2006). Persistence of planetary wave type oscillations in the midlatitude ionosphere. Annales Geophysicae, 49(6), 1235–1246

Leonard, J. M., J. M. Forbes, and G. H. Born (2012), Impact of tidal density variability on orbital and reentry predictions, Space Weather, 10, S12003, doi:10.1029/2012SW000842.

Li, J., and X. Lu (2020), SABER observations of gravity wave responses to the Madden-Julian Oscillation from the stratosphere to the lower thermosphere in tropics and extratropics. Geophysical Research Letters, 47, e2020GL091014, doi: 10.1029/2020GL091014.

Li, J., and X. Lu (2021), Global Responses of Gravity Waves and Zonal Mean Winds to the Madden-Julian Oscillation and the Latitudinal Dependence of Their Relations using MERRA-2, Geophysical Research Letters, 48, e2021GL094717, doi:10.1029/2021GL094717.

Lieberman RS, Riggin DM, Ortland DA, Nesbitt SW, Vincent RA (2007) Variability of mesospheric diurnal tides and tropospheric diurnal heating during 1997-1998. J Geophys Res 112:D20110. https://doi.org/10.1029/2007JD008578

Liu, H-L (2016) Variability and predictability of the space environment as related to lower atmosphere forcing. Space Weather 14(9):634–658. https://doi.org/10.1002/2016SW001450.

Liu H, Sun Y, Miyoshi Y, Jin H (2017) ENSO effects on MLT diurnal tides: a 21 year reanalysis data-driven GAIA model simulation. J Geophys Res. https://doi.org/10.1002/2017ja024011

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

Mlynczak, M. G., et al. (2010), Observations of infrared radiative cooling in the thermosphere on daily to multiyear timescales from the TIMED/SABER instrument, J. Geophys. Res., 115, A03309, doi:10.1029/2009JA014713.

Mlynczak, M. G., L. A. Hunt, C. J. Mertens, B. T. Marshall, J. M. Russell, T. Woods, R. E. Thompson, and L. L. Gordley (2014), Influence of solar variability on the infrared radiative cooling of the thermosphere from 2002 to 2014, Geophys. Res. Lett., 41(7), 2508-2513, doi:10.1002/2014GL059556.

Oberheide, J., J. M. Forbes, K. Hausler, Q. Wu, and S. L. Bruinsma (2009), Tropospheric tides from 80 to 400 km: Propagation, interannual variability, and solar cycle effects,J . Geophys. Res.,114, D00I05, doi:10.1029/2009JD012388.

Oberheide, J, Shiokawa K, Gurubaran S, Ward WE, Fujiwara H, Kosch MJ, Makela JJ, Takahashi H (2015) The geospace response to variable inputs from the lower atmosphere: a review of the progress made by Task Group 4 of CAWSES-II. Prog Earth Planet Sci 2(1):2.

Paetzold, H. K., and Zschorner, H. (1961). An annual and a semiannual variation of the upper air density. Annual Review of Astronomy and Astrophysics, 48(1), 85–92. https://doi.org/10.1007/BF01992371

Pancheva, D., Mukhtarov, P., Andonov, B., Mitchell, N. J., & Forbes, J.M. (2009). Planetary waves observed by TIMED/SABER in coupling the stratosphere-mesosphere-lower thermosphere during the winter of 2003-2004: Part 2—Altitude and latitude planetary wave structure. Journal of Atmospheric and Solar - Terrestrial Physics, 71(1), 75–87. https://doi.org/10.1016/j.jastp.2008.09.027

Pedatella NM, Forbes JM (2009) Interannual variability in the longitudinal structure of the low-latitude ionosphere due to the El Niño-Southern Oscillation. J Geophys Res 114:A12316. https://doi.org/10.1029/2009JA014494

Pedatella NM, Liu HL (2012) Tidal variability in the mesosphere and lower thermosphere due to the El Niño-Southern Oscillation. Geophys Res Lett 39:L19802. https://doi.org/10.1029/2012GL053383

Pedatella NM, Liu HL (2013) Influence of the El Niño Southern Oscillation on the middle and upper atmosphere. J Geophys Res Space Phys 118:2744–2755. https://doi.org/10.1002/jgra.50286

Qian, L, Burns AG, Solomon SC, Wang W (2017) Carbon dioxide trends in the mesosphere and lower thermosphere. J Geophys Res Space 122(4):4474 4488. https://doi.org/10.1002/2016JA023825.

Rezac, L, Yue J, Yongxiao J, Russell JM, Garcia R, López-Puertas M, Mlynczak MG (2018) On long-term SABER CO 2 trends and effects due to nonuniform space and time sampling. J Geophys Res Space 123(9):7958–7967. https://doi.org/10.1029/2018JA025892.

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

Silber, I., Price, C., and Rodger, C. J.: Semi-annual oscillation (SAO) of the nighttime ionospheric D region as detected through ground-based VLF receivers, Atmos. Chem. Phys., 16, 3279–3288, https://doi.org/10.5194/acp-16-3279-2016, 2016.

Smith, A. K. (1985). Wave transience and wave-mean flow interaction caused by the interference of stationary and traveling waves. Journal of the Atmospheric Sciences, 42. https://doi.org/10.1175/1520-0469(1985)042<0529:WTAWMF>2.0.CO;2

Smith, A. K., Garcia, R. R., Moss, A. C., & Mitchell, N. J. (2017). The Semiannual Oscillation of the Tropical Zonal Wind in the Middle Atmosphere Derived from Satellite Geopotential Height Retrievals, *Journal of the Atmospheric Sciences*, *74*(8), 2413-2425.

Solomon, SC, Liu H-L, Marsh DR, McInerney JM, Qian L, Vitt FM (2018) Whole atmosphere simulation of anthropogenic climate change. Geophys Res Lett 45(3):1567 1576. https://doi.org/10.1002/2017GL076950.

Solomon, SC, Liu H-L, Marsh DR, McInerney JM, Qian L, Vitt FM (2019) Whole atmosphere climate change: dependence on solar activity. J Geophys Res Space 124(5):3799–3809. https://doi.org/10.1029/2019JA026678.

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

Taguchi M (2010) Observed connection of the stratospheric quasi-biennial oscillation with El Niño-Southern Oscillation in radiosonde data. J Geophys Res 115:D18120. https://doi.org/10.1029/2010JD014325

Trenberth, K. (1997). The definition of El Nino. Bulletin of the American Meteorological Society, 78(12), 2771–2777. https://doi.org/10.1175/ 1520-0477(1997)078<2771:TDOENO>2.0.CO;2

Vincent, R. A., Kovalam, S., Fritts, D. C., & Isler, J. R. (1998). Long-term MF radar observations of solar tides in the low-latitude mesosphere: Interannual variability and comparisons with GSWM. Journal of Geophysical Research, 103(D8), 8667–8683. https://doi.org/10.1029/98JD00482

Ward, W., Seppälä, A., Yiğit, E. *et al.* Role Of the Sun and the Middle atmosphere/thermosphere/ionosphere In Climate (ROSMIC): a retrospective and prospective view. *Prog Earth Planet Sci* **8,** 47 (2021). https://doi.org/10.1186/s40645-021-00433-8

Warner K, Oberheide J (2014) Nonmigrating tidal heating and MLT tidal wind variability due to the El Niño-Southern Oscillation. J Geophys Res Atmos 119:1249–1265. https://doi.org/10.1002/2013JD020407

Wheeler, M. and G. N. Kiladis (1999), Convectively Coupled Equatorial Waves: Analysis of Clouds and Temperature in the Wavenumber-Frequency Domain, J. Atmos. Sci., 56, 374-399, doi: 10.1175/1520-0469(1999)056%3C0374:CCEWAO%3E2.0.CO;2

Wu, Q., Ortland, D. A., Killeen, T. L., Roble, R. G., Hagan, M. E., Liu, H. L., et al. (2008a). Global distribution and interannual variations of mesospheric and lower thermospheric neutral wind diurnal tide: 1. Migrating tide. Journal of Geophysical Research, 113, A05309. https://doi.org/10.1029/2007JA012542

Wu, Q., Ortland, D. A., Killeen, T. L., Roble, R. G., Hagan, M. E., Liu, H. L., et al. (2008b). Global distribution and interannual variations of mesospheric and lower thermospheric neutral wind diurnal tide: 2. Nonmigrating tide. Journal of Geophysical Research, 113, A05309. https://doi.org/10.1029/2007JA012543

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

Yamazaki, Y., Liu, H., Sun, Y.-Y., Miyoshi, Y., Kosch, M. J., and Mlynczak, M. G. (2017), Quasi-biennial oscillation of the ionospheric wind dynamo, *J. Geophys. Res. Space Physics*, 122, 3553– 3569, doi:10.1002/2016JA023684.

Yigit, E., and A. S. Medvedev (2015), Internal wave coupling processes in Earth's atmosphere, Adv. Space Res., 55, 983–1003, doi:10.1016/j.asr.2014.11.020.

Yonezawa, T. (1959). On the seasonal and non-seasonal annual variations and the semi-annual variation in the noon and midnight electron densities of the f2 layer in middle latitudes. ii. Journal of the Radio Research Laboratories, 6(28), 651–668. Retrieved from http://www.nict.go.jp/publication/journal/06/028/Journal_Vol06_No028_pp651-668.pdf

Zhang, C. (2005), Madden-Julian Oscillation, Rev. Geophys., 43, RG2003, doi: 10.1029/2004RG000158.