Importance of the semidiurnal tide, and future measurements needed to improve its characterization

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Synopsis

Interactions between lower atmosphere and space is an exciting new frontier in geospace science. We recommend that the community should emphasize understanding of semidiurnal tidal variations and their impact on the ionosphere-thermosphere-mesosphere (ITM) system as a major component of lower/upper atmosphere coupling studies. Many factors about tidal influence on the ITM system remain unknown, primarily due to the lack of observations in the critical altitude region between 90-200 km, where waves reach their peak amplitudes and are damped. We propose multi-pronged solution that consists of several components: 1) investment in advanced ground-based observational capabilities, including networks of instrumentation; 2) further investments in incoherent scatter radars capabilities for understanding tidal dynamics above ~105km altitude; 3) implementation of DYNAMIC-like mission to obtain global, day and night wind and temperature observations, with further expansion to a more comprehensive DYNAMIC+ mission; implementation of GDC mission to understand global ionospheric response; 4) strengthening of inter-division (within single agency), inter-agency, and international collaboration to maximize return on investment in research infrastructure.

1. Background and motivation

Atmospheric solar thermal tides are global-scale oscillations with a period equal to one day or an integer fraction of one day. Tides play a key role in coupling lower, middle, and upper atmosphere, and have profound effects on Earth's thermospheric and ionospheric parameters through a number of mechanisms still under extensive and vigorous community frontier research.

Solar thermal tides are excited primarily by the diurnal cycle in the solar heating of water vapor and ozone in the troposphere and stratosphere and the release of latent heat in deep tropospheric convection. As the tides propagate upwards from their source regions, their amplitudes increase and reach several 10s of m/s in the mesosphere and lower thermosphere (MLT) region. Atmospheric tides cause large variations in many atmospheric parameters, including winds, temperature, density, and others. The largest amplitude tides are the 24-hr diurnal tide and the 12-hour semidiurnal tide, although 8-hr and 6-hr tides also exist with smaller amplitudes. Generally, diurnal tides reach maximum at low latitudes and at ~100km altitude, while semidiurnal tides reach maximum at middle to high latitudes (~40-60^{o}) and at ~110-115km.

Oberheide et al. [2015] provided a broad overview of all aspects of atmospheric tides including progress over the prior decade. Most recently, Forbes [2021] provided a comprehensive review of mechanisms, observations, and modeling pertinent to the topic of atmosphere-ionospheric coupling by tides, and outlined open science questions and avenues of future research.

Observations have shown that tidal signals can extend into the upper thermosphere, including the ionospheric dynamo region [e.g., Hausler et al., 2007; Hausler and Lühr, 2009; Forbes et al., 2008, 2009; Oberheide et al., 2009; Hausler et al., 2010], in spite of the strong molecular damping of the waves in the thermosphere. Tidal winds affect ion-neutral coupling through the ionosphere E and F region wind dynamo [Richmond et al., 1976; Forbes and Lindzen, 1976; Richmond and Roble, 1987; Millward et al., 2001; Liu et al., 2010a; Liu and Richmond, 2013], by modulating thermospheric composition [Yamazaki & Richmond, 2013; Yamazaki et al., 2016], as well as by modulating plasma transport and ion-neutral collisions in the F region [Wan et al., 2012; Lei et al., 2014; Liu 2016]. The relative importance of the E and F region wind dynamo can be affected by solar activity, which determines the damping and penetration height of tidal waves [Oberheide et al., 2009; Liu et al., 2010b], as well as the critically important Pederson and Hall conductivities [Liu and Richmond, 2013]. Tides with large amplitudes at middle to high latitudes (such as migrating and nonmigrating semidiurnal components) can strongly contribute to the modulation of ionospheric electrodynamics [e.g., Liu and Richmond, 2013; Liu 2016] and are considered the primary source of quiet-time low-latitude electric fields in the ionosphere [Millward et al., 2001; Yamazaki et al., 2016].

Apart from the general behavior of tides and their effects on middle and upper atmosphere, the role of diurnal and semidiurnal tides in changing the mesosphere and ionosphere at low, middle and high latitudes is of great importance during Sudden Stratospheric Warmings (SSW) [e.g., Chau et al., 2012; Eswaraiah et al., 2018; Forbes 2021; Goncharenko et al., 2021, 2022]. Better understanding of tidal modulation of mesosphere, lower thermosphere, and ionosphere dynamics during SSWs (and other meteorological disturbances) will illuminate numerous coupling mechanisms that are still not fully resolved.

Despite accumulated body of knowledge, **many factors about tidal influence on the ITM system remain unknown, primarily due to the lack of observations in the critical altitude region between 90-200 km, where waves reach their peak amplitudes and are damped.**

The goal of this white paper is to draw community attention to important unresolved questions related to the observations of semidiurnal tides. We also outline potential solutions to resolving these questions that can provide tangible scientific benefits on medium-term scales (3-7 years) and longer-term scales (10+ years). To remain compact and actionable, this paper focuses on only several selected issues out of a broad range of interlocked topics related to the significant impacts of upward propagating waves (gravity waves, various tides, planetary waves) on the ionosphere and thermosphere.

2. Current state of knowledge and unresolved issues

2.1 Observational limitations

Challenge: Available wind/temperature observations are very limited in what tides they can resolve (in altitude, latitude, time). Although understanding of semidiurnal tides and their impact on ITM is significantly improved due to the availability of TIMED SABER and TIDI data, it remains limited due to the lack of global tidal observations above ~105-110km. High-resolution observations can be obtained from MLT radars [Chau et al., 2015], but their number is quite limited. Observations of semidiurnal tides at altitudes of their peak amplitudes (~110-120km) can be provided by incoherent scatter radars, but this information is also limited due to observational constraints of these radars (currently of the order of several days per year, depending on the radar operation mode) and the fact that only several radars are capable of such observations. In-situ data from the ICON MIGHTI instrument is collected in a limited range of latitudes (~20S – 40N) and is not available at the key latitudes of peak semidiurnal tides. The limitations of current community understanding of tidal winds and their impacts on the ITM system are also highlighted by the most recent studies that leverage availability of ICON data [Immel et al., 2021; Forbes et al., 2022; Oberheide 2022].

2.2 Unresolved issues in tidal studies

2.2.1. Discrepancies between available observations

Challenge: Significant discrepancies currently exist between available observations of MLT region tides. Limited comparisons between different observational platforms show that the satellite and ground-based tidal signatures in the mesosphere and lower thermosphere are in generally good agreement. These studies demonstrate that the tidal wind fields observed by both types of observations are consistent with each other [Zhang et al., 2003; Ward et al., 2010; Harding et al., 2021]. However, available tidal climatology at middle latitudes above the Millstone Hill location [Goncharenko and Salah, 1998; Zhang et al., 2003] is drastically different from tidal behavior determined from meteor wind, MF, and SuperDARN radars [He and Chau, 2019, Hibbins et al., 2019, Stober et al., 2021]. Specifically, Millstone Hill observations have the largest tidal amplitudes in the spring and summer seasons (Figure 1, left panel), while other radars show largest amplitudes in the autumn (Figure 1, right panels). It is not yet clear if these differences are related to differences in altitudes, differences in latitudes, differences in the time over which data was collected, or other unknown factors.

Furthermore, daytime winds observed by the MIGHTI instrument on NASA's ICON satellite are ~15-25% higher than winds observed by meteor radars [Harding et al., 2021]. These discrepancies are similar to previously reported differences between space-based and ground-based observations [Burrage et al., 1996; Forbes et al., 2004; Wu et al., 2006]. To the best of our knowledge, the cause of these discrepancies is still not understood. It is also not known how and to what extent short-term (day-to-day to < 1 month) variations in tidal amplitudes and phases in the MLT region impact the I-T system both locally and remotely through dynamo electric fields. Tide-related research has been hindered by the so-called "thermospheric gap" in the data [Oberheide et al., 2011], referring to the altitude range between 120 and 400 km, for which global tidal measurements are currently sparse. As a result, recent studies using various types of measurements have focused on either the lower thermosphere (below 120 km) or the upper thermosphere (above 400 km) or have used data sets covering short time intervals or limited altitude ranges. ***Resolving these discrepancies and understanding tidal impacts on the ionosphere/thermosphere forms a key set of questions for ITM research.***

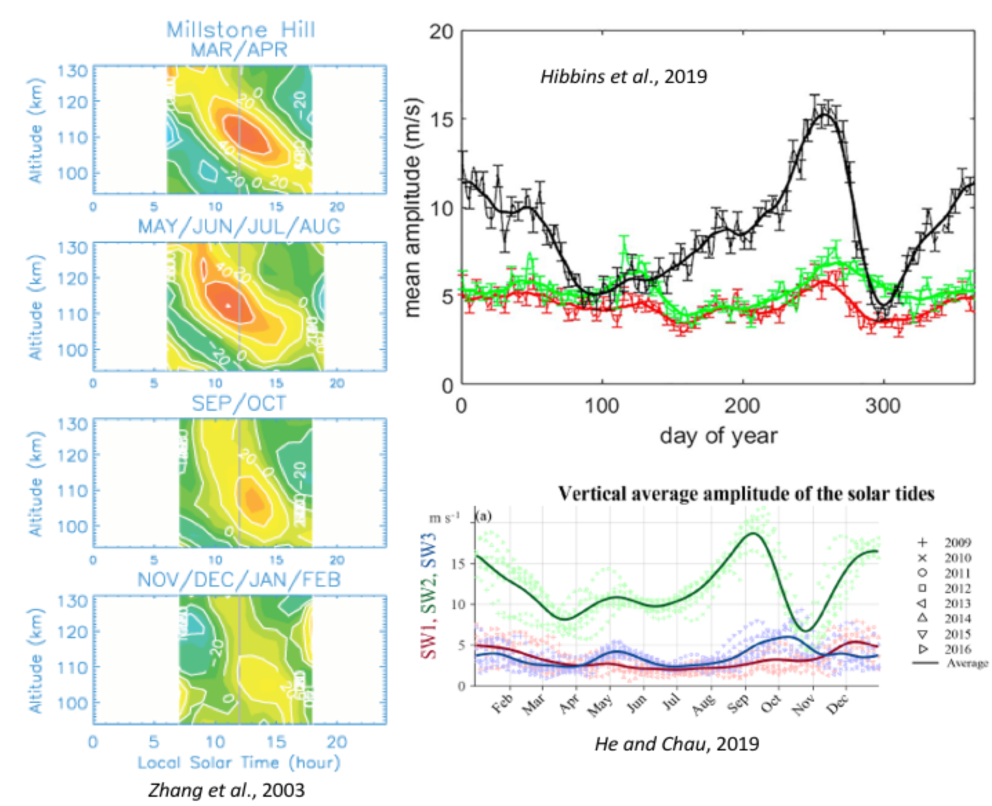

Figure 1. MLT climatology of neutral wind at 100-130 km above Millstone Hill (42°N) indicates that strongest winds and tides occur during the spring equinox and summer (left panel, from Zhang et al. [2003]). However, MLT radars located at similar latitudes show different seasonal features, including largest amplitudes in September equinox instead (right panel, from Hibbins et al., [2019] and He and Chau, [2019]).

2.2.2 Separation of solar and lunar semidiurnal tides and their effects on the ionosphere/thermosphere

Challenge: Separation of different tidal types and their system effects represents another unresolved problem. One of the unexpected advances of the last decade is a growing understanding that the lunar semidiurnal tide can play a prominent role in the variability of the ITM system, in particular when it is strongly amplified due to sudden stratospheric warmings [Fejer et al, 2010; Forbes & Zhang, 2012]. Limited observational evidence to date shows that both solar and lunar semidiurnal tides are amplified during SSW events. However, some observations demonstrate that lunar tides have lower amplitudes than solar tides in the MLT region [Sathiskumar and Sridharan 2013], and some show that lunar tides exceed solar tides [Chau et al., 2015; Siddiqui et al., 2018]. This issue is further complicated by longitudinal variations in the lunar tide itself and longitudinal variations in ionospheric response to both solar and lunar tides [Yamazaki et al., 2017]. Furthermore, holographic analysis of global meteorological analysis data and local meteor radar observations of the semidiurnal tide suggests that the general assumption of phase stability does not hold, posing an additional issue to separate a lunar from a solar driven tide at the MLT (Stober et al., 2020). Another key aspect is that the comprehensive models often are driven by reanalysis data collected every 6 hours, which limits a realistic forcing of the 12-hour tide for the nudging and can lead to underestimation or misattribution of tidal effects on ITM in simulations.

2.2.3 Separation of upward propagating tides from in-situ generated tides

Challenge: Separating impacts of tides propagating from the stratosphere and impacts of tides generated in the thermosphere also poses a current unresolved problem in studies of variability. Upward propagating semidiurnal tides generated by heating of stratospheric ozone are expected to peak at ~45-60^o latitudes, but remain significant at higher latitudes. Absorption of EUV by molecular oxygen and nitrogen leads to peak dissociative heating between ~100 and 200 km, and day-to-night changes in absorption lead to in-situ generation of tides (both diurnal and semidiurnal) that also propagate upward. Separating impacts of these tides is a challenging task. At high latitudes, the situation becomes even more complex, as high-latitude plasma convection can generate in-situ tides (primarily diurnal) through ion drag and frictional heating. Limited observational evidence suggests that transition from predominantly semidiurnal to predominantly diurnal oscillations occurs between ~115-120km [Nozawa et al., 2010], but semidiurnal oscillations have been reported in observations at much higher altitudes [Jin et al., 2012; Wu et al., 2017]. It is not known what portion of 12-hr oscillations in the F-region results from upward propagating tides generated below MLT and what portion results from in-situ generated tides.

Understanding tides in MLT and their impacts on ITM at polar latitudes is an extremely challenging task due to the complexity of lower/upper atmosphere coupling processes and solar-magnetosphere-ionosphere coupling processes. Recent studies emphasized the role of tides in changing the polar upper atmosphere during SSWs [Eswaraiah et al., 2018; Liu et al., 2021; Goncharenko et al., 2022], but overall this complicated problem cannot not be comprehensively addressed due to the lack of sufficient observational data.

3. Proposed solutions

3.1 *Ground-based observations*

Recommendation: investment in advanced ground-based observational capabilities, including modern networked instrument configurations, is needed and is essential for forward progress. Ground-based observations can provide key high temporal resolution data in ways that are needed to resolve short-term variability in tidal modes, separate solar and lunar semidiurnal tides, and assess the impact of tides on the short-term variations in the ITM system. Although observations from a single location cannot separate migrating and non-migrating components of tides, a joint analysis of observations from several locations well separated in longitudes can resolve different tidal modes, as already demonstrated in several studies [He and Chau, 2019; He et al., 2020]. Furthermore, modern radar practices like spread-spectrum and MIMO (multiple-input, multiple-output) remote sensing enable inexpensive, robust and easy to operate meteor radar systems that are easy to scale to form regional or continental-scale networks [Stober and Chau, 2015, Stober et al., 2018, Chau et al., 2019; Chau et al., 2021]. Investment in such systems to build a network of meteor radars within the US can provide a relatively inexpensive solution to directly address tidal questions in the MLT region (in addition to numerous other MLT science topics). Moreover, as such systems have been already successfully demonstrated in several locations [Chau et al., 2019; Conte et al., 2021; Volz et al., 2021], deployment of such a network within the US is a relatively low-risk investment that can provide a significant scientific yield in a short time frame (~3-7 years). Recent state-of-the-art multi-static meteor radar networks such as the Chilean Observation Network De Meteor Radars and the Nordic Meteor Radar Cluster are suitable to apply tomographic approaches using 3DVAR and 3DVAR+Div retrievals (Stober et al., 2021), which permit to investigate the spatial variability of atmospheric tides and their interaction with gravity waves on regional scales and are even sensitive enough to obtain robust and reliable vertical winds. Furthermore, passive microwave radiometers leveraging modern receiver chains provide a sufficient temporal resolution to provide temperature and trace-gas soundings up to the MLT (Schranz et al., 2019, Krochin et al., 2022a, Krochin et al., 2022b).

An extremely cost-effective way to "fill" the gap for tidal measurements at higher altitudes, in the thermosphere, is to use Dynasonde data [Negrea et al., 2016]. The Dynasonde technique allows almost continuous measurements of the altitude and phase profiles for diurnal, semidiurnal, and terdiurnal tidal harmonics in a broad altitude range covering the entire bottom-side ionosphere. The tilt measurement provided by the Dynasonde is particularly useful in detecting tidal and wave features, as it is sensitive to wave-like perturbations. A Transportable Dynasonde System, operating together with stationary ones, can provide a tool for distinguishing migrating and non-migrating tides at the thermospheric altitudes. The methodology of tidal measurements used in [Negrea et al., 2016] should be extended for the entire network of Dynasonde-capable instruments.

Furthermore, Fabry-Perot or Scanning Doppler Interferometer is a cost-effective instrument for wind observations for the ITM system (Dhadly et al., 2015, Wu et al., 2022), and enhanced networks of such instruments can be efficiently utilized to bring closure to tidal science questions.

Recommendation: Further investment in incoherent scatter radar (ISR) capability and infrastructure is required for adequate knowledge of tidal dynamics > 110 km altitude. To understand tidal modes in the altitude region above ~105-110km (upper limit of meteor radars) and study their impact on the ionosphere/thermosphere, the community needs better data availability from incoherent scatter radars through the following strategies: 1) ***Modernization and additional operations support for existing ISRs*** to enable operation of instruments for longer periods of time; 2) ***Coordinated multi-radar studies*** to emphasize lower thermosphere wind data collection (similar to LTCS-type campaigns practiced in 1980-1990s); 3) ***Increase in support for studies of MLT winds*** and their impact on the short-term variability of ionosphere/thermosphere.

3.2. Space-based observations

Recommendation: move to global observations of multiple ionosphere and thermosphere state parameters, with a particular emphasis on wind and temperature, in the altitude range from MLT to the upper thermosphere. It is clear from the literature that full characterization of different tidal modes can be achieved only with global, day and night, high resolution ***wind and temperature observations*** that cover all latitudes and altitudes from ~90km to ~200-250km. To understand the impact of tides on the ITM system (i.e. response of the system), both locally and globally, it is also critical to collect ***concurrent observations of major thermospheric and ionospheric parameters*** (thermospheric winds, thermospheric composition, electric fields, profiles of electron density). Such observations were envisioned by the Decadal Survey of 2013 and recommended for the DYNAMIC and GDC missions. The general progress made since 2013, already mentioned in this white paper, has only strengthened community arguments for the urgent and sustained need of these missions. However, a constellation of 2 spacecraft (as envisioned for DYNAMIC) is still not sufficient to fully resolve dynamic forcing. We recommend that ***further expanded multi-spacecraft missions should be planned*** in order to provide key information in a more comprehensive way (DYNAMIC+).

3.3. Need for inter-division, inter-agency, and international cooperation

Recommendation: Interactions between lower atmosphere and space is an exciting new frontier in geospace science that requires strong community emphasis in the next decade. To achieve breakthrough science, we need to strengthen inter-division, inter-agency and international collaboration and cooperation for mesosphere, thermosphere and ionosphere joint studies.

As lower/upper atmosphere coupling research lies in the intersection between Earth Science and Heliophysics, it needs close collaboration between different divisions of each agency (NASA, NSF, NOAA). Further progress in rapidly growing understanding of multiple pathways connecting troposphere/stratosphere to the ITM system also requires coordinated multi-agency effort and coordinated use of space-based and ground-based assets. To maximize return on investment in research infrastructure supported by different agencies (NSF, NASA, NOAA, DoD), it is critical to significantly strengthen collaboration and cooperation between different agencies. Specific examples include development of multi-agency support for joint observations and data analysis, multi-agency lines of funding, data fusion from multiple instruments, data assimilation efforts, and development of new data products based on data fusion and machine learning.

Geospace science requires an international perspective and participation, as it needs to include observations from around the globe to achieve breakthrough science. ***We urge the heliophysics community to support and advocate for international collaborations, including close collaborations with Canadian Space Agency, European Space Agency, and Japan Aerospace Exploration Agency.***

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