Wind and Temperature Variations of Wave-4 Terdiurnal Tides at E- and F-region Altitudes seen with MIGHTI in 2020

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Abstract

The Earth's upper atmosphere is highly dynamic, serving as a crucial interface between tropospheric weather processes and the exosphere. Understanding its variability is essential for assessing its impact on lower atmosphere and its response to space weather. A comprehensive approach to the exploration of the features of the ionosphere is to observe the global-scale waves known as atmospheric tides and planetary waves which influence and also generate similar wave-like disturbances in the E- and F-region altitudes. While previous studies suggest that tides migrate upwards and cause changes in the ion production, loss and transport in the ionosphere, further investigation is necessary to quantify these effects. The MIGHTI instrument aboard the ICON satellite provides three years of global wind and temperature data (2019-2022) spanning altitudes from 90-300 km and latitudes from 6°S to 42°N during day and night local times. Using this dataset, the study examines the effects of terdiurnal tides on the ionosphere and its seasonal and annual patterns are observed.

A key enabling factor for this objective is to use tidal fits to a wave model which assists in simulating various ionospheric regions so that different tidal patterns can be observed. The structural approach for the study involves developing an elaborate wave model which is a sine wave with amplitude and phase components of each tide that have temporal periods of 24, 12 and 8 hours, (n), and zonal wavenumbers ranging from -6 to 6, (s). Further computation involves reconstructing the desired tides from the obtained values and analyzing them along varying times, altitudes and latitudes. The results are compared with previous studies and conclusions are drawn. Uncertainty in amplitudes and phases are also accounted for to explain potential variations in observations or digressions from anticipated results. Initial findings indicate that the bulk of the E-region altitudes consist of diurnal and semidiurnal tides with the zonal wind amplitudes peaking at 50 m/s near the equator. Preliminary analysis for the migrating terdiurnal tide (TW3) reveals well-defined structures in the F-region with zonal wind amplitudes reaching up till 25 m/s. This suggests that these might be generated somewhere in the mid-altitudes. Ongoing work addresses altitude-dependent variations and discrepancies, considering factors such as limited nighttime data at high altitudes and dominance of other tides at low altitudes which possibly cause terdiurnal tides to be more sensitive to minor amplitude fluctuations and therefore harder to extract. Further research aims to refine these conclusions and enhance our understanding of terdiurnal tidal variability in the ionosphere, aiding space weather forecasting, satellite operations, and communication reliability. Refined tidal models that provide reliable results benefit scientists, space agencies, and navigation experts in mitigating ionospheric disturbances, improving GPS accuracy, and optimizing satellite performance, ultimately contributing to advancements in atmospheric science and space technology.

1. Background and Introduction

What are tides and planetary waves?

These are global scale wave-like disturbances in winds and temperature in the MLT region that generate at lower altitudes and propagate upwards, causing changes in the ion production, loss and transport. They are caused by solar heating, in combination with processes such as cloud formation, and have a lot for variability year round and under all geophysical conditions. Tides can also be produced in the thermosphere by absorption of ionospheric radiation, and by wave-wave interactions involving tides and planetary waves. Tides can interact with one another and create more tides, thus making the simulation of atmospheric layers more complex and necessary.

Significance of atmospheric tides

- Potential drivers of ionospheric variability originating from the troposphere and stratosphere.
- They create a dynamo effect with the electric fields between altitudes 100-300 km, thus significantly influencing the plasma distribution in the ionosphere.
- They redistribute solar energy between different atmospheric layers.
- Key characteristics for studying atmosphere-space coupling of Earth and other planets.

Tidal Harmonics:

Temporal period: n = [1,3] - signify 24, 12 and 8 hour period respectively

Zonal wavenumber: s = [-6,6]

Diurnal, Semidiurnal and Terdiurnal tides correspond to n = 1,2,3 respectively. When n = 0, they are called Stationary Planetary Waves (SPWs). Migrating tides refer to a same (n,s) pair such as (3,3). When s < 0, the tides are Eastward and when s > 0, they are Westward.

What are the missing pieces that this research is tending to?

- Many studies highlighted that non-migrating tides are much larger in the MLT region with a focus on diurnal and semidiurnal tides, it was required to look at the same for terdiurnal tides in both E- and F-region.
- Since terdiurnal tides are studied the least due to their weaker presence in the atmosphere generally, this study provides a deeper insight into the wave-4 terdiurnal tides.
- Visualizing the difference of tidal amplitudes at E- and F-region altitudes in 2020 for terdiurnal tides within the northern low to mid-latitudes.
- Exploring the dynamical consequences of non-linear coupling between SPW4 and the migrating terdiurnal tide (TW3), with an emphasis on their joint influence on middle and upper atmospheric variability.

2. Data Sources and Instrumentation

Ionospheric Connection, ICON, performs a scientific investigation to understand the fundamental question of atmosphere-ionosphere coupling. Through magnetically connected remote and in-situ measurements, ICON measures quantities such as neutral wind, temperature and ion density profiles. The explorer has an instrument on board - Michelson Interferometer for Global High-resolution Thermospheric Imaging, MIGHTI, that provides limb observations of altitude profiles of the mentioned quantities during day and night time. This instrument is dedicated to address the science question of the ICON mission to identify the source of strong ionospheric variability.

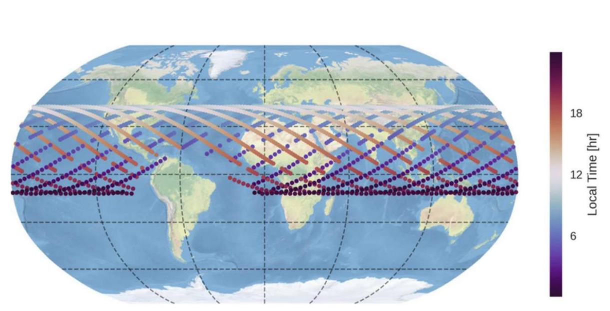


Fig. 1: Geographic coverage of MIGHTI observations, after Englert et al. 2017a; Harding et al. 2017a.

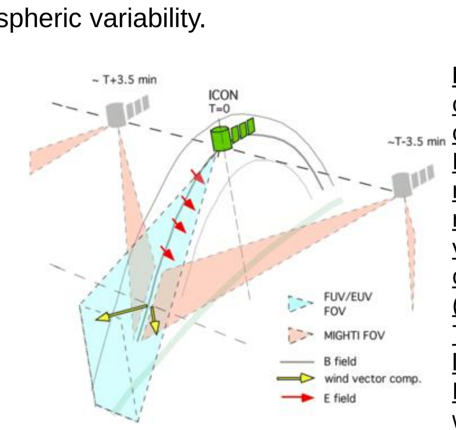


Fig. 2: Geometry of ICON observations. MIGHTI measures the relevant wind vector components (yellow arrows). The tangent point locations where MIGHTI samples wind filed vary with altitude

- Nearly circular orbit; Altitude ~ 600 km; 27° inclination (provides a rapid precession rate required for sampling at all locations and LTs in a month); Latitudes 12° South - 42° North
- MIGHTI A and B's phase of observed interference fringes, factored by oxygen red (λ=630 nm) and green line (λ=557.7 nm) emission.
- Vertical profiles of horizontal thermospheric winds are measured with resolution of 10km over the complete range of altitudes.
- Measures winds with per-sample precision better than 20 ms-1.
- MIGHTI measures O_2 with 762 nm band emission from which the neutral temperature can be derived in the 91–109 km altitude range.

3. Tidal Modeling and Analytical Methods

MIGHTI Dataset Visualization

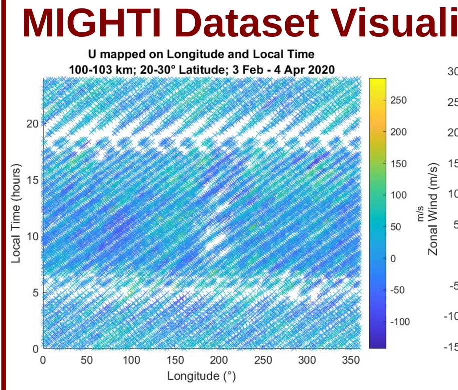


Fig. 3: U on LT vs Lon at Lower Alt

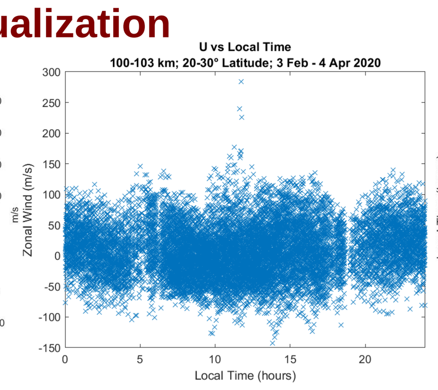


Fig. 4: U vs LT at Lower Alt

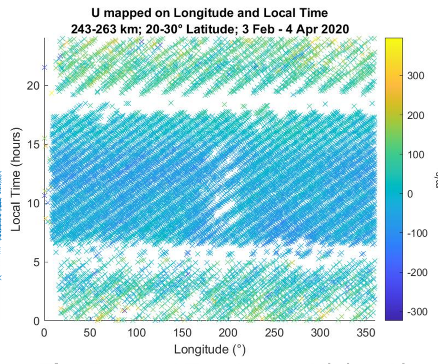


Fig. 5: U on LT vs Lon at Higher Alt

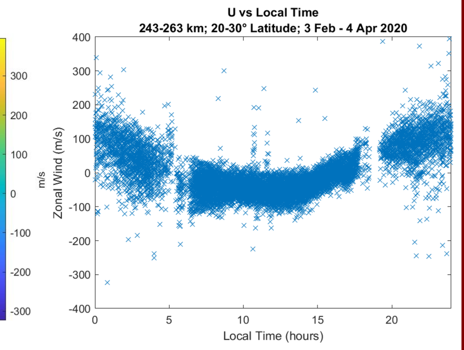


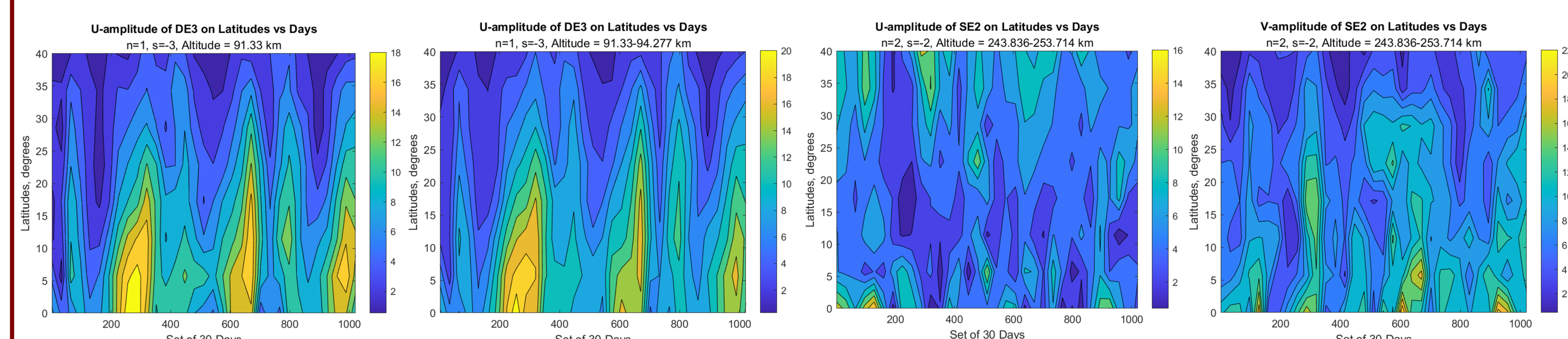
Fig. 6: U vs LT at Higher Alt

- We illustrated the unprocessed zonal wind data (U) along space and time dimensions at the E- and F-region altitudes, which highlight the nature of the dataset - signatures of upward propagating waves and tides with clear variability of data density along LT.
- Figures 3 and 5 exhibit higher concentrations of data in the day time in both the altitude regions, which verifies the data collection process of MIGHTI and also suggests that F-region data might require additional processing to produce comparable results to the E-region, given that it has lesser data points.

Data Processing – Wave Model, Tide Fitting and Reconstruction

- We applied two levels of processing the data, first of which is averaging the data set into 60-day bins with a step size of 30 days and 10° latitude bins (-5° S to 45° N). For the E-region, each bin of data consists of values from ~3 km altitude range and F-region has values from ~20 km altitude range which is the additive data from two consecutive ~10 km altitude ranges. This results in more definitive features in the F-region because there are lesser recorded data points at those levels.
- The second step was to fit the entire data set to the wave model considered for this study, which in its elaborate version, expands from n = [0,3] and s = [-6,6]. Each data point is averaged into bins before it enters the fit. The figures are the reconstruction of wave-4 tides for E- and F- regions with and without adding data from two consecutive altitude ranges.

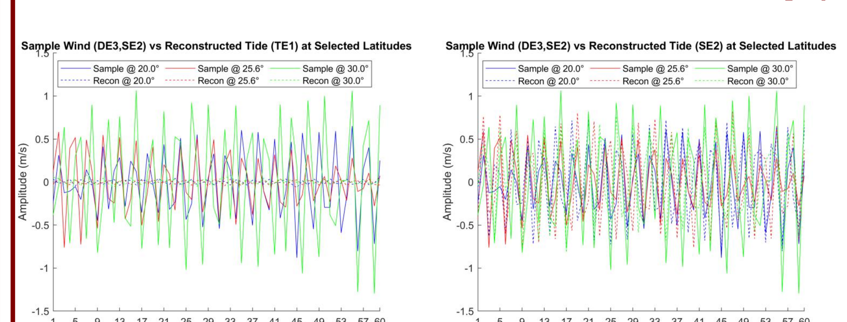
$$A0 + A\cos\left(nt\frac{2*pi}{24} + (s-n)\lambda\frac{2*pi}{360} - \phi\right) \qquad \text{[Eq. 1]}$$



Figs. 7-8: [First two] U-amp of DE3 on Lat vs Days in E-region from 2019-2022 w/o and with consecutive altitudes appended respectively
Figs. 9-10: [Second two] U- and V-amp of SE2 on Lat vs Days in F-region from 2019-2022 with consecutive altitudes appended

Nonlinear Interaction of Wave-4 Tides and Aliasing Test Signatures

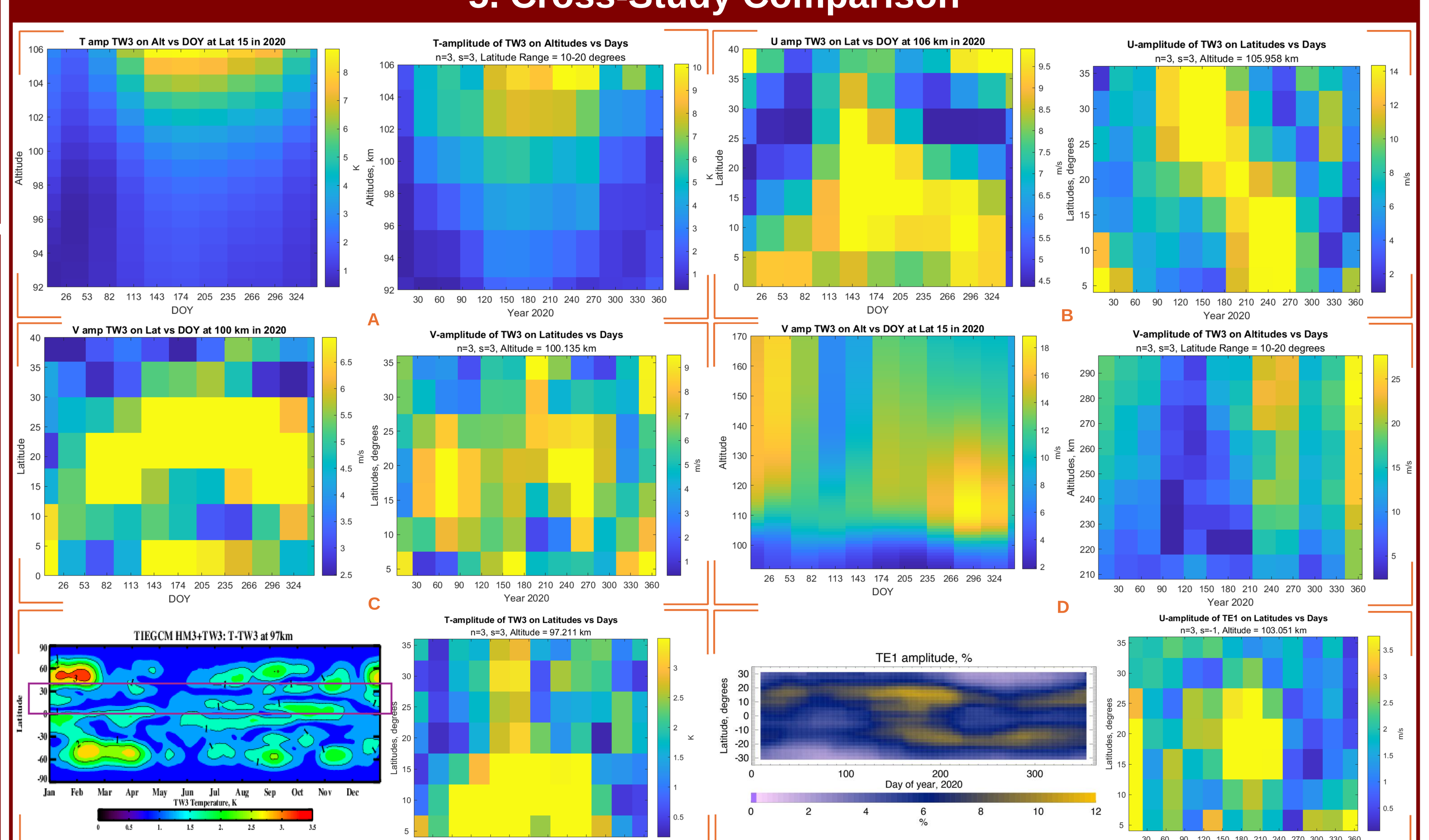
$$\underbrace{\cos(4\lambda)}_{\text{SPW4}}\underbrace{\cos(3\Omega t + 3\lambda)}_{\text{TW3}} \rightarrow \underbrace{\cos(3\Omega t - \lambda)}_{\text{TE1}} + \underbrace{\cos(3\Omega t + 7\lambda)}_{\text{TW7}} \qquad \text{[Eq. 2]}$$



Figs. 11-12: Reconstruction of TE1 and SE2 respectively in a sample environment of DE3 and SE2 to test the signal dependency of TE1 on high-magnitude Wave-4 tides

- To test any susceptibility to aliasing from the high amplitude DE3 and SE2, we performed some idealized tests where the inputs were known.
- Through previous studies, it is known that DE3 and SE2 U-amplitudes are strong in the E-region which makes it extremely likely that other wave-4 tides (e.g. TE1) could be (potentially) identified when DE3 and or SE2 are present.
- In Figure 11, the dotted lines signify the U-amplitude of TE1, which, evidently, is very small as compared to high U-amplitudes of DE3 and SE2 suggesting that TE1 is not directly affected by DE3 and SE2. Figure 12 is the reconstruction of SE2 and it closely aligns with the wave structure of the sample wind, verifying our testing methodology for aliasing. Hence, this test validates our approach to study the nonlinear interaction for TW3 and SPW4 to see their impact on TE1 and TW7 tidal structures.

5. Cross-Study Comparison

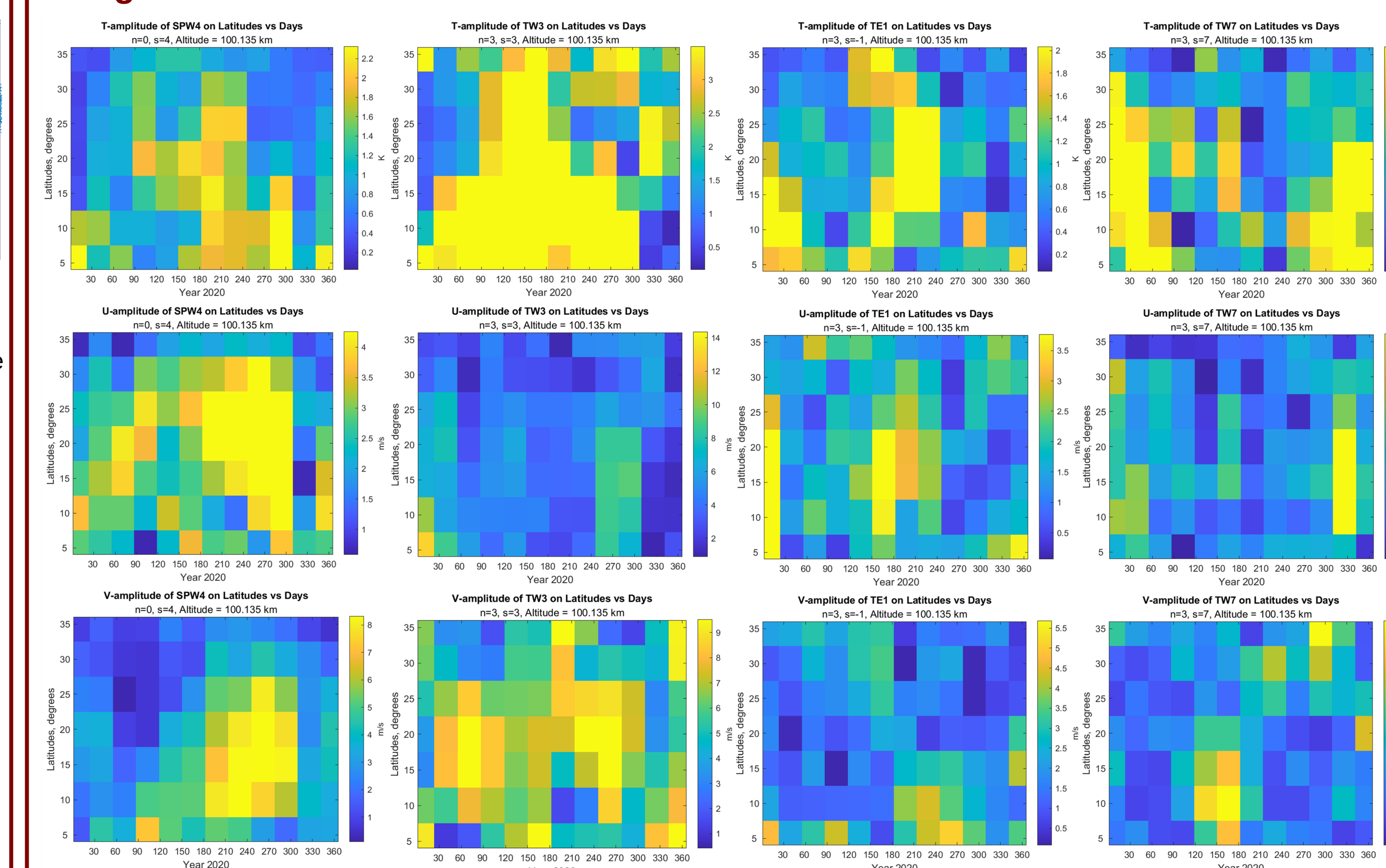


Figs. 38-49: [Panels A-D] Comparison with Dr. Cullens' T,U,V for TW3, [Panel E] Comparison with Dr. Maute's T for TW3, [Panel F] Comparison with Dr. England's electron density for TE1; For all panels, my plots are on the right and the compared work is on the left.

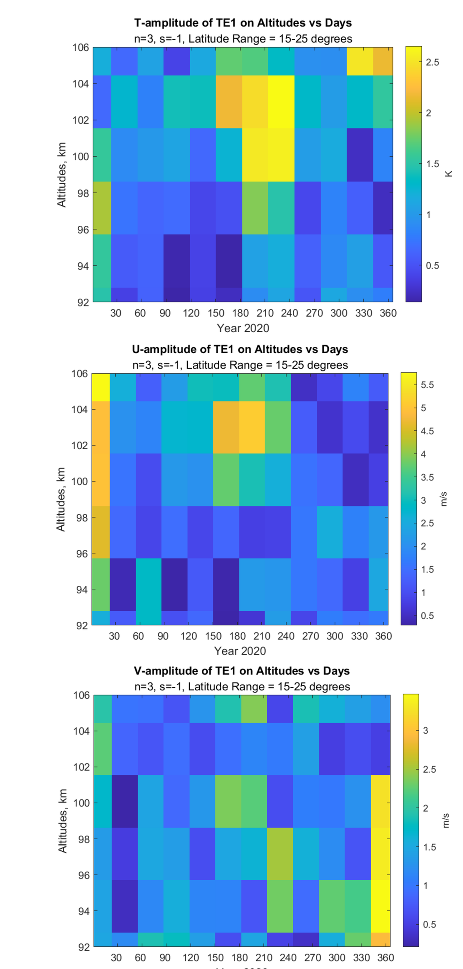
- In the first 4 panels, we compare our tidal fits to HME fits that use both MIGHTI and SABER data. Very close agreement can be seen between T-amplitude and V-amplitude in the E-region. V-amplitudes have similar signatures in the F-region too, although the time stamps have a minor shift. On the contrary, U-amplitudes show less agreement in terms of the tidal structure. These differences are noted in both lower and higher altitude ranges.
- Panel E shows a comparison of our fits to the lower boundary of TIEGCM-ICON. It shows how T-amplitudes have peaks at the lower boundary of the E-region in the middle of the year, but not in the end of the year which is shown by Dr. Maute's work. Panel F is a comparison between COSMIC-2 GIS electron density plot of TE1 at 360 km close to the F-region peak. We noted a similarity in the tidal structure in U in the middle of the year and a little in the beginning and end of the year (Jan and Dec).

4. Results from Current Analysis

E-region Wave-4 tides



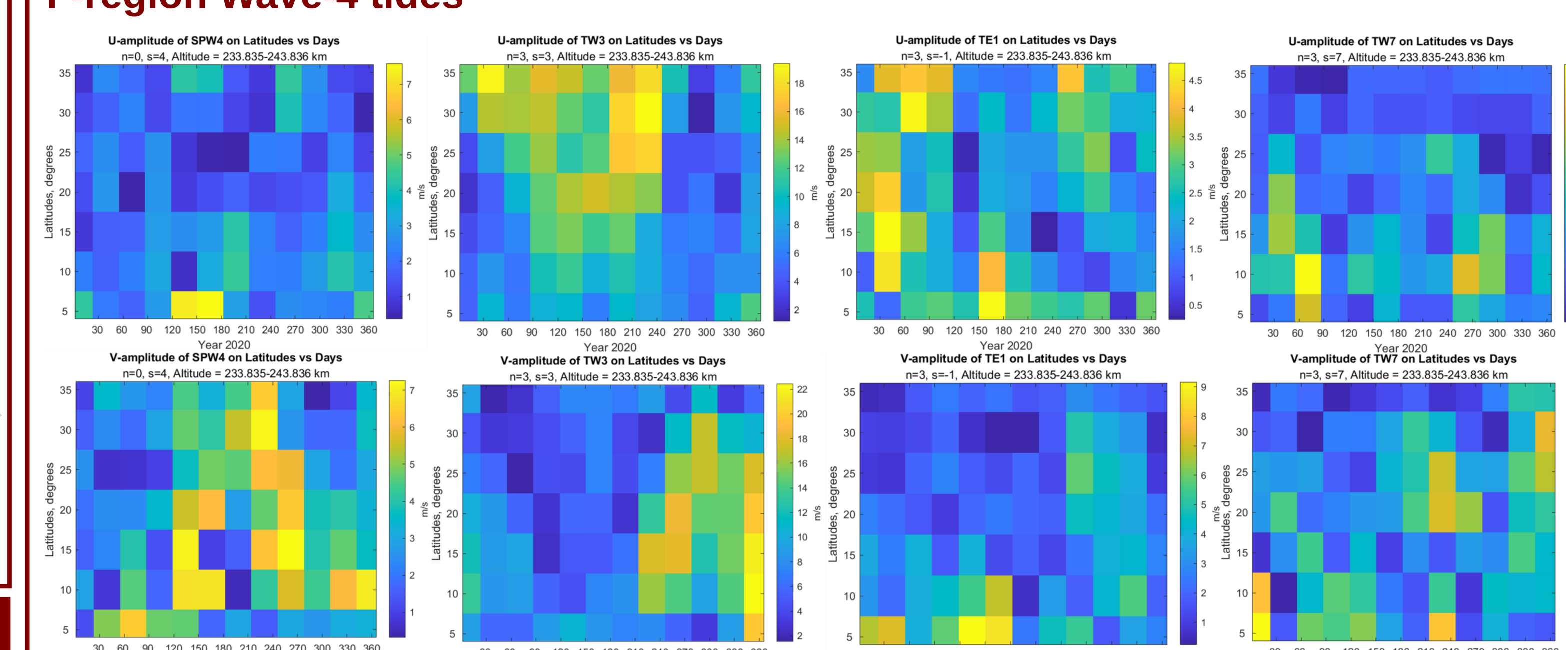
Figs. 13-16: [Top row] T-amp in K; **Figs. 17-20:** [Middle row] U-amp in m/s; **Figs. 21-24:** [Bottom row] V-amp in m/s; All plots in Lat vs DOY. Each column pertains to a single kind of atmospheric tide or planetary wave based on the order they appear in Equation 2.



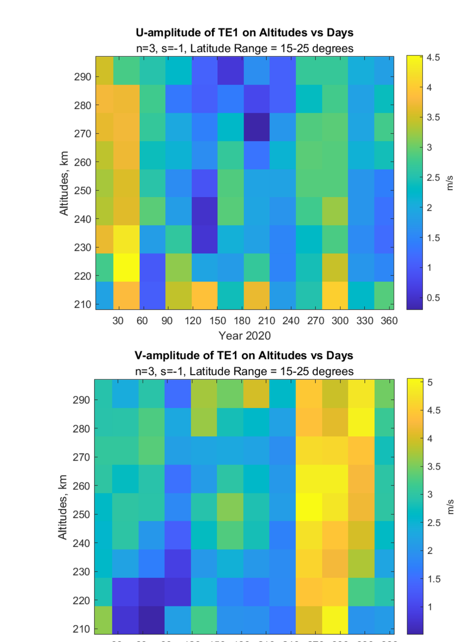
Figs. 25-27: T-amp in K and U,V amp in m/s for TE1; All plots in Alt vs DOY

- According to Forbes et al 2008, wave-4 tides are prominent in the bulk of the MLT region (equatorial and tropical), more specifically DE3 and SE2. The terdiurnal counterparts of the same are TE1 and TW7, hence we expected an exhibit of strong activity. In Row 1, T is stronger for TW3 compared to SPW4 and has a peak throughout a major portion of the year, but TE1 and TW7 have lower amplitudes than TW3 and peak in different months. Both TE1 and TW7 reach maximum values in the beginning of the year, but then TE1 has a second peak in Jul-Aug while TW7 peaks at the end of the year.
- U and meridional wind (V) also have elevated values for TW3 than SPW4, due to which the tides generated by their interaction have lower amplitudes and also amplify in different areas from one another. SPW4 seems to have maximum activity from Jul-Oct. TW3 also has enhanced activity in the same window (Sep-Oct) and also earlier in the year (Jan-Apr).
- T and U in the terdiurnal tides elevate around the same time in the year whereas V is inconsistent with this observation.
- In Figures 25-27, stronger signatures are observed in Jan, Jun-Jul and Nov-Dec in almost all the quantities.

F-region Wave-4 tides



Figs. 28-31: [Top row] U-amp in m/s; **Figs. 32-35:** [Bottom row] V-amp in m/s; All plots in Lat vs DOY. Each column pertains to a single kind of atmospheric tide or planetary wave based on the order they appear in Equation 2.



Figs. 36-37: U,V amp in m/s for TE1; All plots in Alt vs DOY

- In the F-region, there are steep amplitude differences in SPW4 and TW3. From column 2, we can see that U winds have amplified activity in the first half of the year (Jan-Aug) in the upper latitudes but V-winds have it in the end of year (Aug-Dec) in the low latitudes for TW3.
- It appears that due to SPW4, the amplitudes of TE1 and TW7 are not as strong as TW3, while TW3 impacts the longitudinal and time variability in the wave-4 tides.
- It is also observed that the wind values for TW3 have a big rise from the E- to the F-region, whereas there is a comparatively lesser elevation in the values for TE1 and TW7. SPW4 wind values are about the same.
- In figures 36-37, the winds have the region of maximum values for TE1 across the complete altitude range during a specific part of the year. For U, it is Jan-Feb and for V, it is Sep-Nov. Their secondary peaks are during the same times as the other's primary peak occurs. Thus, there appears to be a complimentary primary and secondary peak pair-when U is dominant at a particular time in the year, V is not as much strong and vice-versa.

6. Conclusion and Future Work

Conclusion:

- Our tests show that the sampling we have done for testing aliasing means we have little, if any, aliasing of DE3 or SE2 into our computed TE1.
- In the E-region, given SPW4 and TW3, they may generate TE1 and TW7. We see some evidence that this may be true with TE1 as some signatures are visible around the same months as they are in the tides that are interacting, but TW7 does not show those features clearly at 100 km.
- Looking at the wave-4 tides, we see a lot of change from E- to F- region altitudes. In the F-region, looking at the meridional winds, there is some similarity between the SPW4 and TW3. To be more definite about the results, more quantitative analysis is required. A timeline of amplitudes can be looked at for each of the tides and their signatures can be compared to see if nonlinear interaction is also visible through numbers.
- The TE1 tide in the Altitude vs DOY plots at the MLT altitudes shows signs of upward propagating tide which we may expect.
- At the F-region altitudes, we see little systematic variation in amplitude with height for TE1.
- Our analysis vs the HME (Dr. Cullen's work) shows good agreement at low altitude where the upward propagating tides are strong, but these are not independent datasets, so this is maybe expected. At higher altitudes, we differ much more, suggesting especially TW3 is being generated above 100 km (in addition to any upward propagating component).
- Our comparison to GIS TE1 shows that the seasonal pattern in the ionosphere reflects the E-region TE1 winds.

Future Work:

- Year to year comparison for ICON winds and temperature data will provide deeper insights into seasonal and annual patterns of wave-4 tides.
- Quantitative analysis of the values in terms of a timeline will help verify the nonlinear interaction between SPW4 and TW3.
- Phase and uncertainty values' analyses are due for wind and temperature data in the E- and F-regions for three years (2019-2022).

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