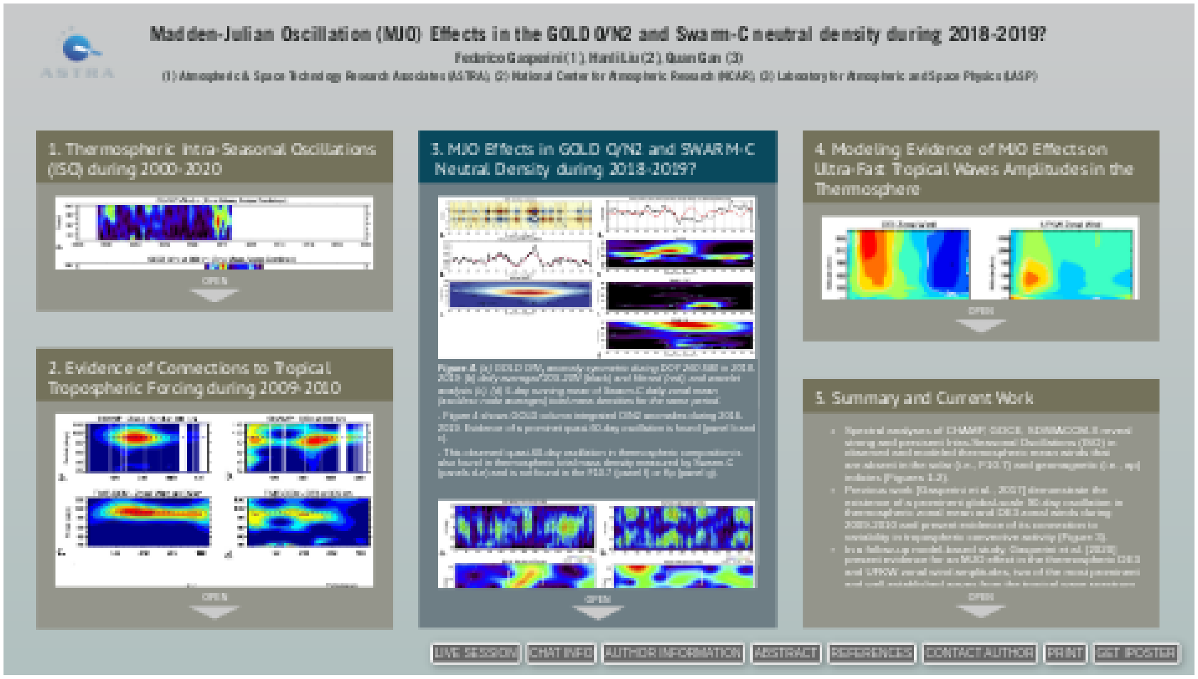
Madden-Julian Oscillation (MJO) Effects in the GOLD O/N2 and Swarm-C neutral density during 2018-2019?



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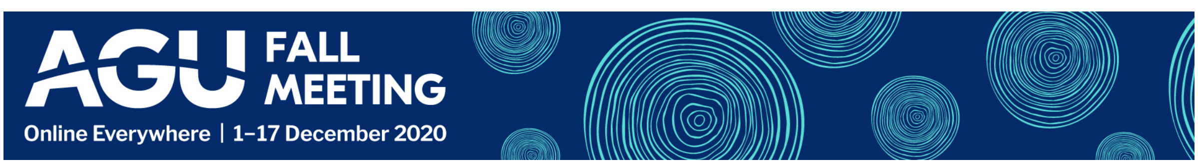

1. THERMOSPHERIC INTRA-SEASONAL OSCILLATIONS (ISO) DURING 2000-2020

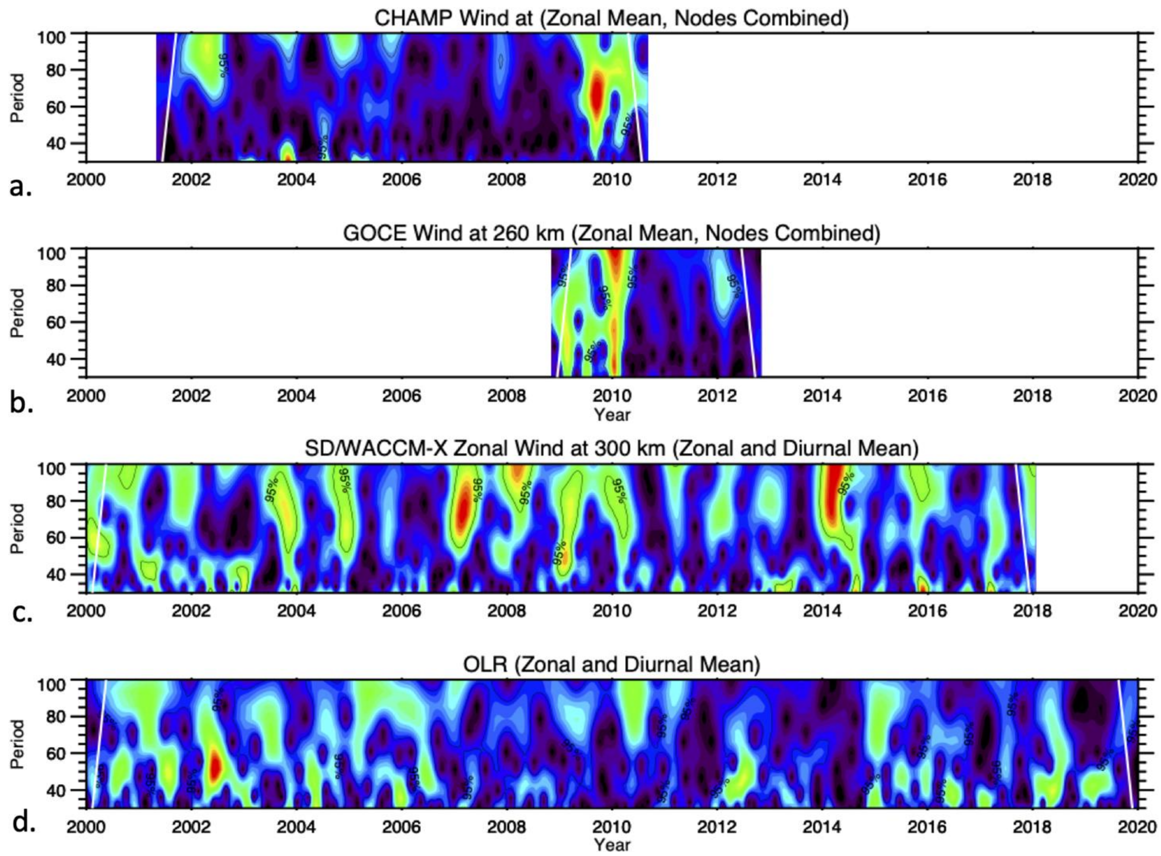

Figure 1. *Morlet wavelets of zonal mean zonal wind from CHAMP (a), GOCE (b), SD/WACCM-X (c), and OLR (d) during 2000-2020.*

- Significant ISO is found in CHAMP and GOCE zonal mean winds (Figure 1a-1b).

- SD/WACCM-X nudged with MERRA-2 data shows similar ISO variability near 300 km (Figure 1c), while OLR demostrates that similar and concurrent variations are present in tropical troppsheric convection (Figure 1d)

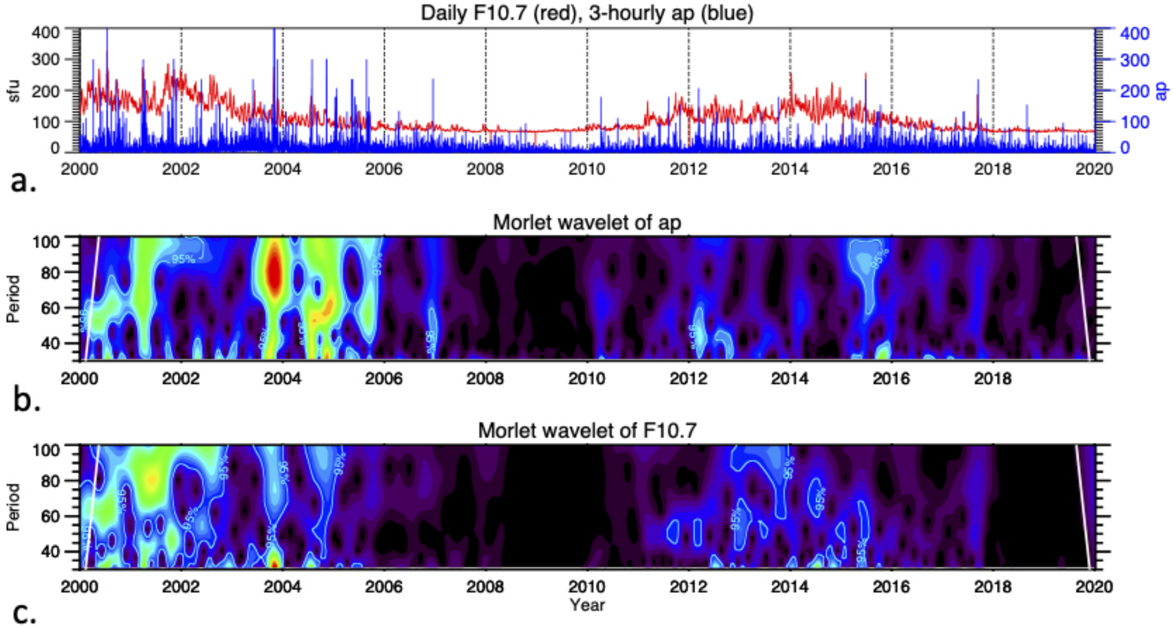

Figure 2. *(a) Time series of F10.7 (red) and 3-hourly ap (blue), and Morlet wavelets of ap (b) and F10.7 (c) during 2000-2019.*

- Wavelet analyses of daily F10.7 (Figure 2c) and 3-hourly ap (Figure 2b) shows little ISO variability during 2005-2020, despite evidence of significant ISO variability in satellite observations (Figures 1a-1b) and SD/WACCM modeling results (Figure 1c).

- Is this observed ISO variability in the thermospheric mean winds (Figure 1a-1b) connected to tropical tropospheric convection (Figure 1d)?

2. EVIDENCE OF CONNECTIONS TO TROPICAL TROPOSPHERIC FORCING DURING 2009-2010

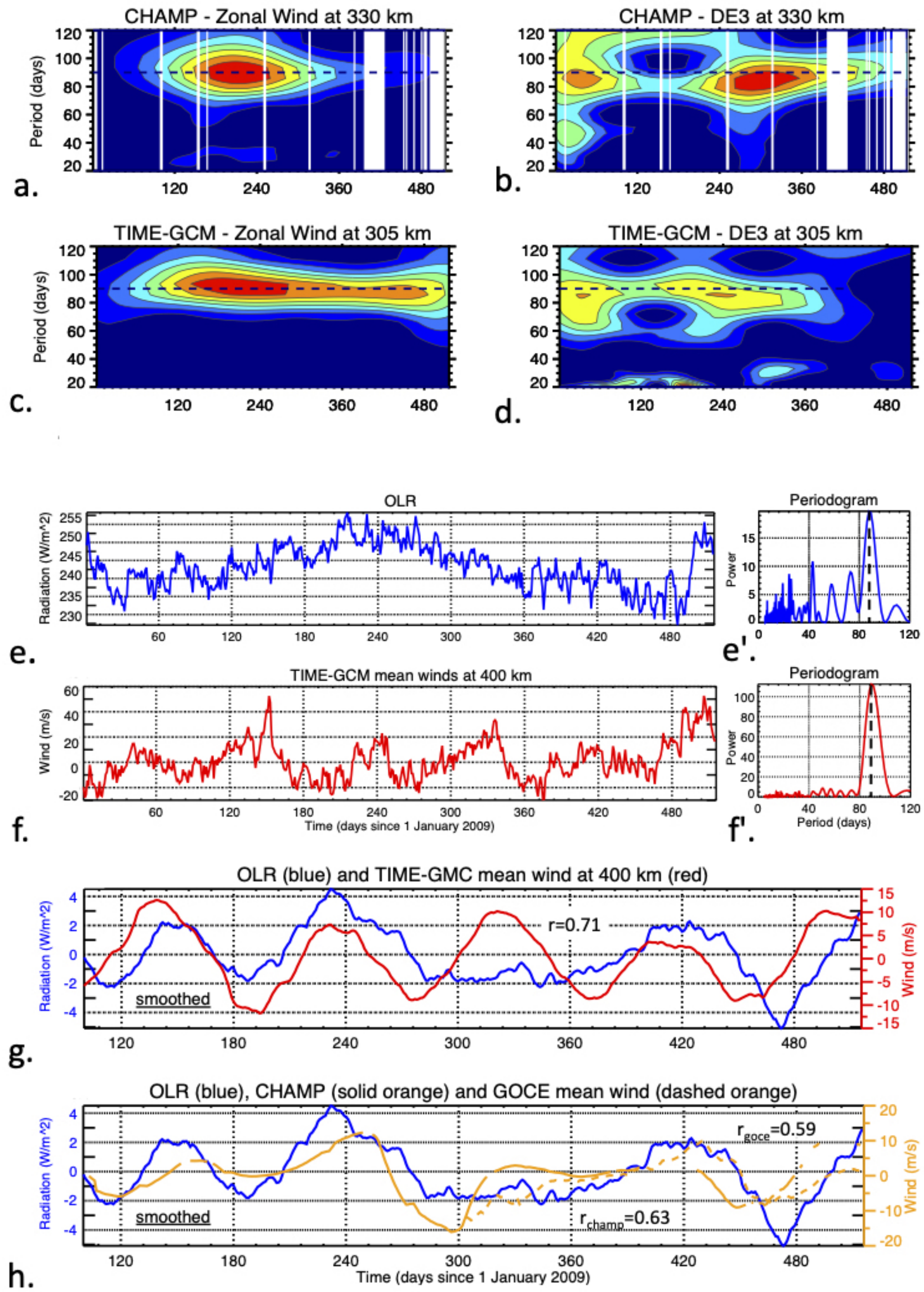

Figure 3. Wavelet of CHAMP and TIME-GCM zonal mean wind (a, c) and DE3 (c, d) during 2009-2010 showing strong 90-day oscillations. Time series of OLR (e), TIME-GCM mean winds (f), and their running means (g and h). Striking 90-day peaks in both OLR and thermospheric mean winds and their correlation [Gasperini et al., 2017].

- Results above (from Gasperini et al. [2017]) demonstrate the existence of a prominent global-scale 90-day oscillation in thermospheric zonal mean and DE3 zonal winds during 2009-2010 using CHAMP and GOCE observations, a TIME-GCM simulation forced with MERRA reanalysis data, and interpolated OLR estimates.

- Figure 3 shows wavelets of zonal mean zonal winds and DE3 wind perturbations from CHAMP (panels 1a and 1b) and TIME-GCM (panels 1c and 1d) averaged over ±30° latitude that indicate the existence of a strong and persistent 90-day oscillation during 2009 and early 2010. This 90-day oscillation is coherent with height and possesses amplitudes up to ±20 m/s in the zonal mean wind and ±3 m/s in DE3 amplitude.

- Figure 3e-f shows the time series of ±30° latitude averaged daily OLR values (panel e) and model mean winds at 400 km (panel f) with their respective periodograms (panels e' and f'). The latter display striking 90-day peaks in both OLR and mean winds.

-To isolate this 90-day oscillation and gain insights into its amplitude and variation over time, for each day residuals are created by removing 90-day running means to the raw data. To reduce noise, a 20-day running mean is then applied to the residuals. The time series of these mean residuals are shown in Figure 3g for OLR (blue curve) and model mean winds at 400 km (red curve), while a comparison among OLR, CHAMP mean winds (orange solid curve), and GOCE mean winds (orange dashed curve) is contained in Figure 3h. Significant correlation is also found between OLR and mean winds as evidenced by the correlation coefficients included in panels c and d: r=0.71 for OLR-model; r=0.63 for OLR-CHAMP; r=0.59 for OLR-GOCE. Striking is also the phase relationship between OLR and correspondent thermospheric wind variations. Comparatively smaller correlations for the OLR-satellite data analyses are likely caused by SW2 aliasing in the mean winds and errors and gaps in the raw wind data.

-The results in Figure 3 demonstrate that strong coupling between the troposphere and the thermosphere takes place at ISO timescales during 2008-2019 - rasing the question: how many such events exist?

3. MJO EFFECTS IN GOLD O/N2 AND SWARM-C NEUTRAL DENSITY DURING 2018-2019?

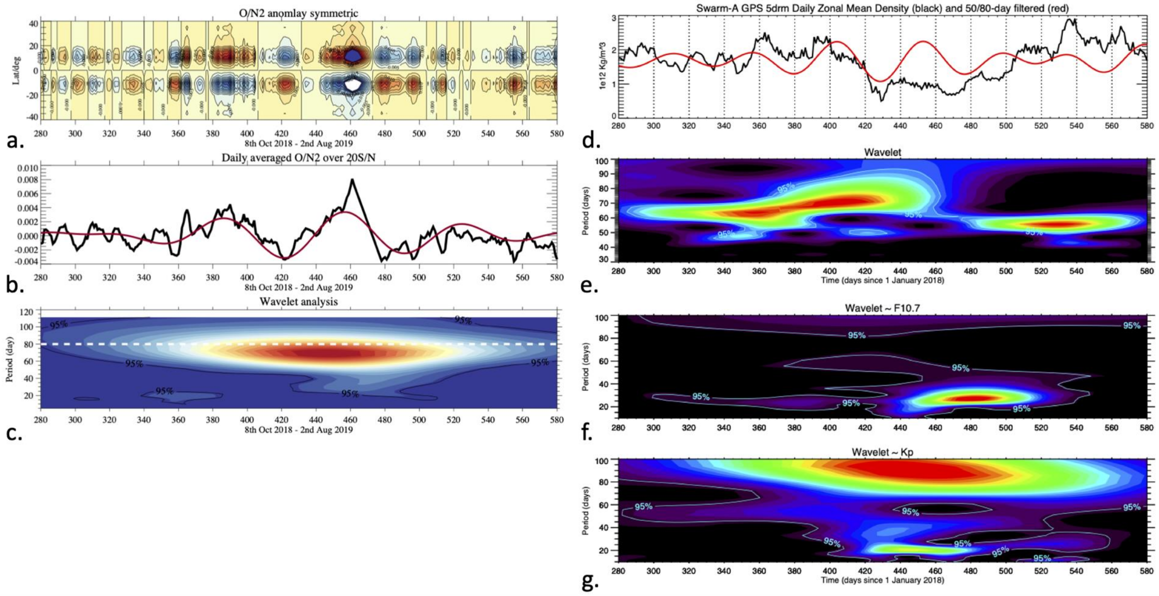

Figure 4. *(a) GOLD O/N$_2$ anomaly symmetric during DOY 260-580 in 2018-2019; (b) daily averaged 20S-20N (black) and filtered (red), and wavelet analysis (c). (d) 5-day running mean of Swarm-C daily zonal mean (asc/desc node averages) total mass densities for the same period.*

- Figure 4 shows GOLD column integrated O/N2 anomalies during 2018-2019. Evidence of a prominet quasi-60-day oscillation is found (panel b and c).

- This observed quasi-60-day oscillation in thermospheric composition is also found in thermospheric total mass density measured by Swarm-C (panels d-e) and is not found in the F10.7 (panel f) or Kp (panel g).

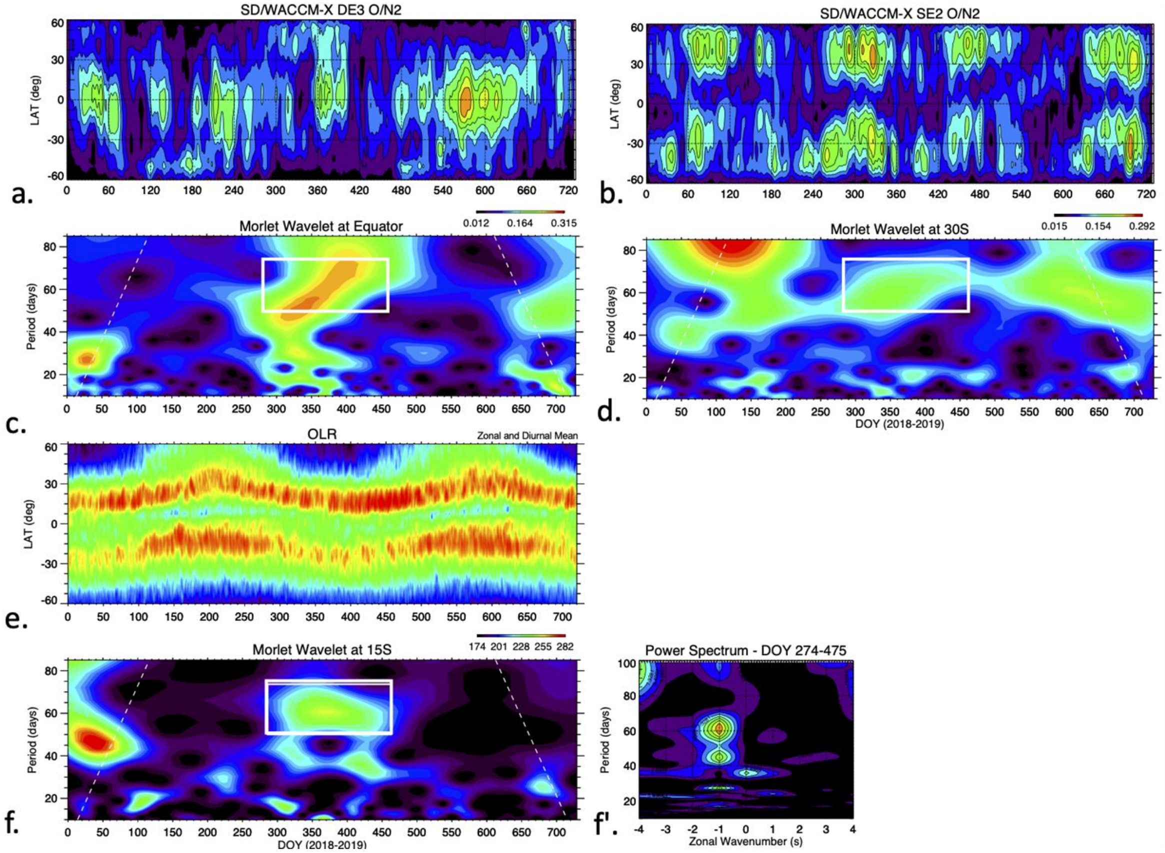

Figure 5. *Latitude-time depiction of SD/WACCM-X DE3 (a) and SE2 (b) O/N$_2$ during 2018-2019 and their wavelets (c) and (d), respectively. (e) and (f), similar to (a) and (c) b*ut for OLR. (f') Period-zonal wavenumber spectrum for DOY 274-475.

- SD/WACCM-X analyses of DE3 and SE2 in column integrated O/N2 reveals similar and concurrent ~60-day oscillations (Figure 5a-d).

- Anallysis of interpolated OLR reveals a concurrent ~60-day oscillation in tropical tropospheric convection (panels e-f). This variation is found to be eastward propagating and to possess zonal wavenumber -1 (panel f') and thus is consistent with an MJO event.

- Results in Figures 4 and 5 suggest that a strong quasi-60-day MJO event observed in OLR around DOY 300-450 in 2018-2019 may be imparting a similar variability in thermospheric composition and total mass desnity measured concurrently by GOLD and Swarm-C - *is this due to tidal/wave amplitude modulation in the lower and/or middle atmosphere?*

4. MODELING EVIDENCE OF MJO EFFECTS ON ULTRA-FAST TROPICAL WAVES AMPLITUDES IN THE THERMOSPHERE

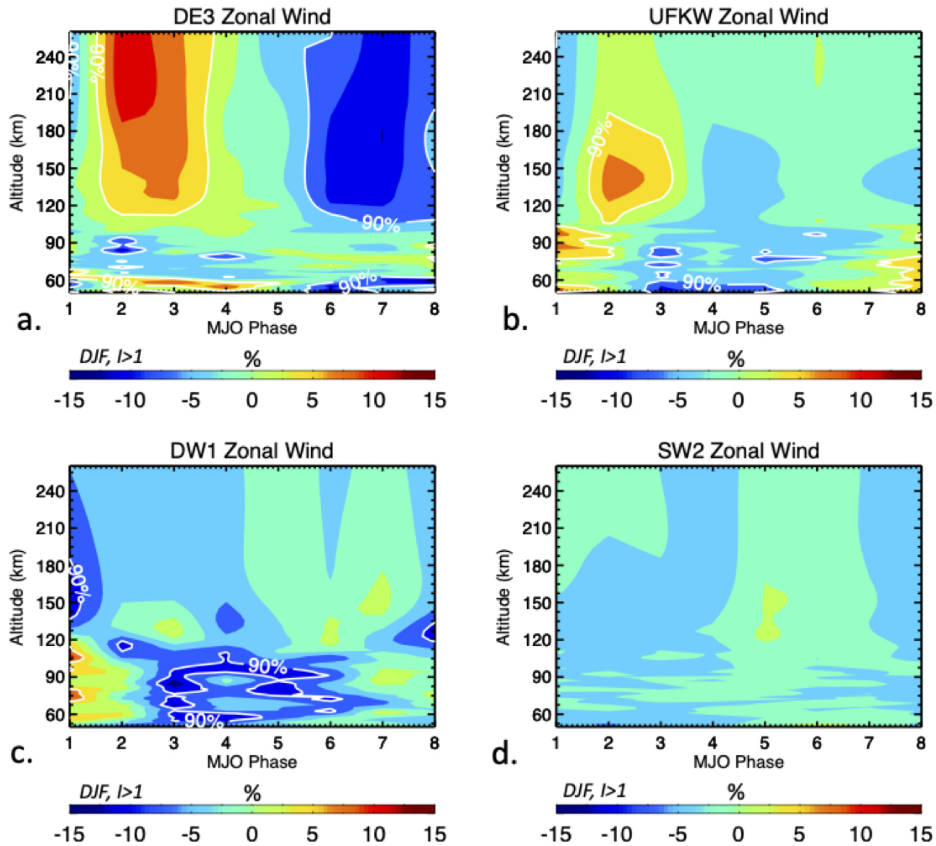

Figure 6. Height (50–260 km) versus MJO phase depiction of DE3 (a), UFKW (b), DW1 (c), and SW2 (d) low-latitude (±40◦) zonal wind amplitudes obtained applying the composite analysis method to 3-hourly SD/WACCM-X output for 1980–2017. The white contour line indicates a 90% confidence level [Gasperini et al., 2020].

- The Madden-Julian Oscillation (MJO) is the dominant mode of intra-seasonal variability in tropical convection and circulation and has been extensively studied since its discovery due to its importance for medium-range weather forecasting.

- The MJO is an eastward moving low-latitude (±30°) disturbance that typically recurs every ~30-90 days in tropical winds, clouds, rainfall, and many other variables. The MJO is known to generate a spectrum of global-scale waves, and modulate stratospheric GW, GW drag, and zonal winds.

- The MJO attenuates rapidly above the tropopause due to its low−frequency and slow zonal propagation speed. MJO events are commonly identified using Real-time Multivariate MJO series 1 (RMM1) and 2 (RMM2). MJO events are grouped into eight active phases according to the amplitude and phase information obtained by combining the RMM1 and RMM2 values. In Phase 1, convection of a decaying MJO event is found in the central Pacific, while enhanced convection for a growing event is centered over Africa and the western Indian Ocean. Over subsequent phases, convection in the Indian Ocean grows and moves eastward, and as it reaches Australia, shifts southward to be most concentrated at about 15°S in Phase 5.

- In a recent model-based study, Gasperini et al. [2020] present statistical evidence for strong MJO effects in the thermospheric amplitudes of DE3 and UFKW, two of the most prominent and well-established tropospherically-generated global-scale waves that preferentially propagate to the thermosphere/

- By employing a 38-year SD/WACCM-X simulation, daily zonal wind DE3 and UFKW amplitudes are calculated for all latitudes and pressure levels. The December-January-February seasonal mean tidal amplitudes is computed for each year of the simulation by applying Fourier analysis to the full model output. The ISO period is isolated in the daily amplitude data by applying a 10- to 100-day band-pass filter. The anomalies in the filtered data are obtained on a daily basis as the difference of the daily amplitude from the seasonal mean amplitude. Using a method similar to Yang et al. [2018], for days that correspond to an active MJO period the anomalies are composited by binning together all cases having the same MJO phase. The anomalies are presented as percent differences from the seasonal mean. By removing the mean state of each year from the composite the influence of interannual variations is minimized.

- Figure 6 shows the height (50-260 km) versus MJO phase depiction of DE3 (panel a), UFKW (panel b), DW1 (panel c), and SW2 (panel d) low-latitude (+/-40 deg.) zonal wind anomalies obtained by applying the composite analysis method described above to daily SD/WACCM-X wave amplitudes for 1980-2017. Striking MJO phase dependencies exist in DE3 (panel a) and UFKW (panel b) anomalies above ~120 km, with enhanced amplitudes (compared to the seasonal mean) of ~5-15% during MJO phases 2 and 3 (red contours) and reduced amplitudes of ~3-10% during MJO phases 6-8 (blue contours). The migrating DW1 (panel c) and SW2 (panel d) tides show comparatively smaller MJO phase effects above ~110 km (only up to +/-2%). Further analysis (not shown here) also reveal strong SAO and QBO phase influences. Thermospheric DE3 and UFKW amplitudes are larger (up to ~15%) during westward SAO and QBO phases and smaller (up to ~6%) during eastward SAO and QBO phases.

5. SUMMARY AND CURRENT WORK

- Spectral analyses of CHAMP, GOCE, SD/WACCM-X reveal strong and persisent Intra-Seasonal Oscillations (ISO) in observed and modeled thermospheric mean winds that are absent in the solar (i.e., F10.7) and geomagnetic (i.e., ap) indicies (Figures 1-2).
- Previous work [Gasperini et al., 2017] demonstrate the existence of a prominent global-scale 90-day oscillation in thermospheric zonal mean and DE3 zonal winds during 2009-2010 and present evidence of its connection to variability in tropospheric convective activity (Figure 3).
- In a follow-up model-based study, Gasperini et al. [2020] present evidence for an MJO effect in the thermospheric DE3 and UFKW zonal wind amplitudes, two of the most prominent and well-established waves from the tropical wave spectrum that preferentially propagate into the thermosphere (Figure 6).
- New analyses of GOLD O/N2 and Swarm-C total mass density reveal evidence of strong and persistent quasi-60 day oscillations in thermospheric composition and density during DOY 300-450 in 2018-2019 (Figure 4).
- Similar and concurrent oscillations are observed in the DE3 and SE2 column integrated O/N2 tidal amplitudes from SD/WACCM-X (Figure 5a-d).
- Spectral analysis of OLR for this period reveals a similar oscilation in tropical tropospheric convection that is shown to be eastward propagating with s=-1 and is thus consistent with an MJO event (Figure 5e-f').
- Further work will be geared toward better understanding and characterizing the thermospheric impacts of this MJO event.

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ABSTRACT

The extent to which terrestrial weather below 30 km in altitude can influence the dynamics and mean state of the thermosphere (ca., 100-500 km) is a fascinating discovery of the last two decades or so. Waves that are excited by deep convection in the tropical troposphere and propagate vertically into the thermosphere are responsible for much of this influence. Tropospheric convection associated with the Madden−Julian Oscillation (MJO), the dominant mode of intra-seasonal variability in tropical convection and circulation, has been known to modulate the intensity of upward−propagating gravity waves and Kelvin waves. An MJO impact on tides was already proposed over two decades ago, but only recent gains in satellite observational capabilities allows one to quantify their effect from observations. Previous work by Gasperini et al. [2017a] demonstrate that a 90-day oscillation in tropospheric convection during 2009-2010 is imprinted on both thermospheric mean winds and the eastward propagating wavenumber 3 diurnal (DE3) tidal amplitudes observed by the GOCE and CHAMP satellites and modeled with the TIME-GCM. In a follow-on modeling-based study, Gasperini at al. [2020] present statistical evidence for a strong connection (+/-12%) between the phase of the tropospheric MJO and the amplitudes of the thermospheric DE3 and 3-day ultra-fast Kelvin wave (UFKW), two of the most prominent and well-established waves from the tropical wave spectrum that preferentially propagate into the thermosphere. These recent studies demonstrate that strong coupling between the troposphere and the thermosphere occurs on intra-seasonal timescales, raising important questions that have implications for the whole atmosphere system. In this work, we present evidence for a strong quasi-60 day oscillation in GOLD column-integrated O/N2 and Swarm-C total mass density during 2018-2019. A similar and concurrent oscillation is observed in the DE3 and SE2 tidal ampltiudes derived from SD/WACCM-X. Spectral analysis of OLR reveals a similar oscilation in tropical tropospheric convection that is shown to be eastward propagating with s=-1 and is thus consistent with an MJO event.

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Gasperini, F, M. E. Hagan, and Y. Zhao (2017), Evidence of tropospheric 90-day oscillations in the thermosphere, Geophys. Res. Lett., doi:10.1002/2017GL075445.

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