Long-Term Variability in the Ionosphere-Thermosphere-Mesosphere (ITM) System Imposed by Waves

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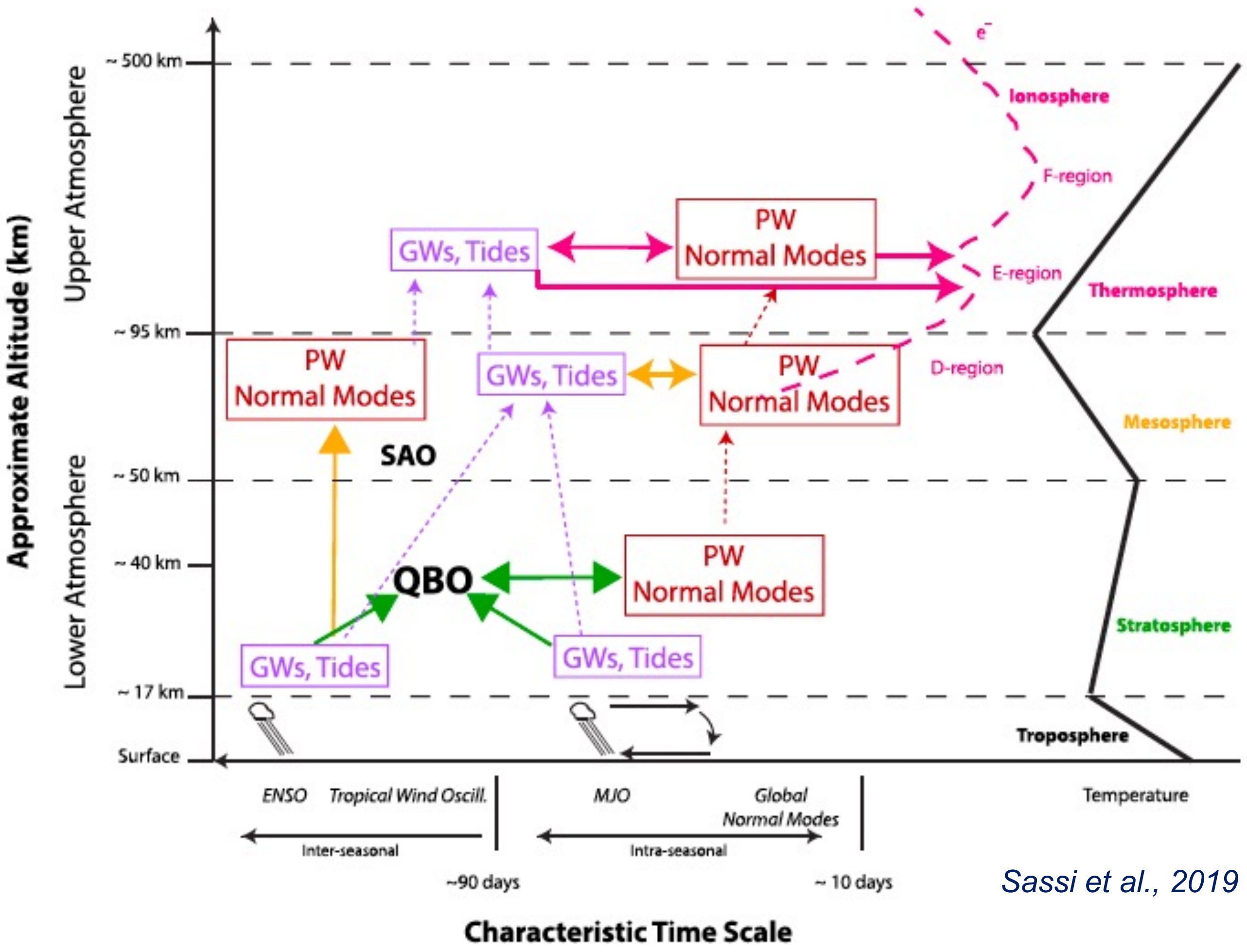
L1.1 Long Term Events

OUTLINE

1.1 Long-Term ITM Variability from Waves

- Most of the ***day-to-day and longitudinal variability*** of the ITM not associated with solar/geomagnetic effects can be ***attributed to internal waves originating in the lower atmosphere*** including tides, KWs, PWs, and GWs (see reviews by *Liu*, 2016*; Yiğit and Medvedev, 2015*).
- Understanding and characterizing long-term (>10-day) ITM variability and its connections to terrestrial drivers is critical for ***achieving whole atmosphere predictability*** (*Sassi et al.*, 2019).
- ITM impacts of lower atmospheric variability over long-term time scales have received little attention, despite clear evidence since the 30s-50s.
- Challenges:
  - (a) there is abundant evidence of *long-term variations of wave amplitudes in the ITM*, but how and why such variations occur still remain unclear;
  - (b) long-term ITM variations due to *major tropospheric and stratospheric variability* have been observed but the physical pathways are still poorly understood;
  - (c) PW-scale oscillations couple the lower and upper atmospheres, but *it remains unclear to what extent they impact the ionosphere* directly via wind-dynamo coupling, or indirectly via modulation of waves.
- Modes of ***inter-annual variability*** include the stratospheric ***QBO***; the tropospheric ***ENSO***, and the ***Solar Cycle*** variation.
- Modes of ***intra-annual variability*** include the stratospheric and mesospheric ***SAO*** and ***AO***, and the tropospheric ***MJO.***



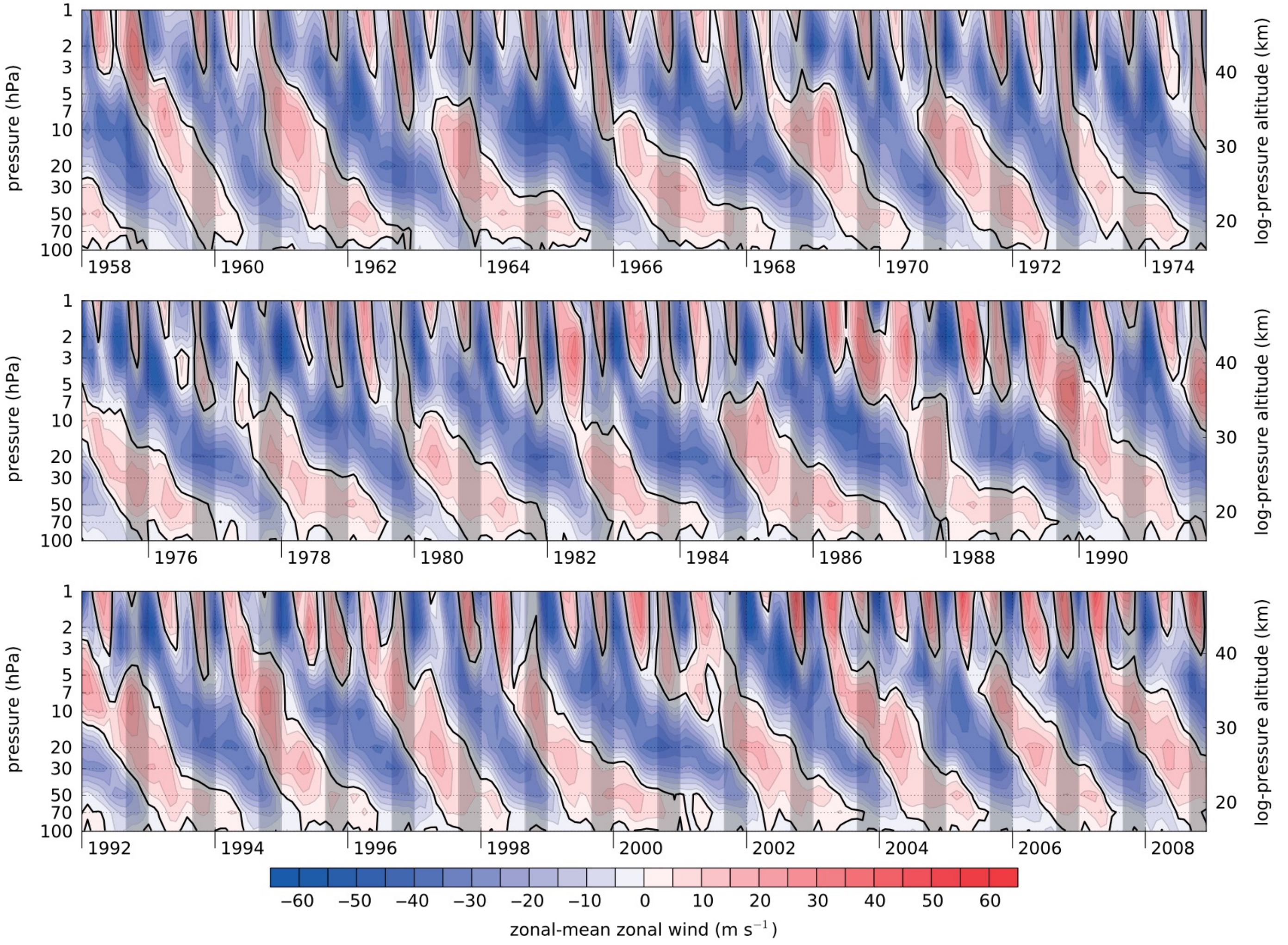
Sassi et al., 2019

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.

2.1 Inter-Annual ITM Variations: *QBO*

- The QBO is an ***alternating westerly and easterly zonal wind regime*** that descends from the tropical upper stratosphere to the tropical tropopause with a ~28-month cycle (*Baldwin 2001*).
- The QBO is the ***largest source of inter-annual variability in the tropical stratosphere***, and its influence extends to higher latitudes throughout the lower atmosphere.
- Ground/space-based observations show large QBO-like oscillations in a number of ITM parameters.
- QBO background wind variations extend well into the MLT where they are out of phase with the stratospheric QBO.
- Several pathways have been proposed to explain QBO-ITM coupling, but there is yet no scientific consensus regarding the main physical processes responsible for this coupling.
- QBO influences on upward-propagating waves include Doppler shifting effects and wave filtering in the stratosphere and mesosphere, e.g., higher-frequency waves are harder to dissipate than lower-frequency waves of comparable wavelength.
- The QBO-ITM connections are not well established due to:
    - (a) limited observational record across altitudes.
    - (b) unrealistic LB forcing in ITM models and shortcomings of physical parameterizations (e.g., GW drag).
    - (c) aliasing from 26- to 28-month variations in solar UV/EUV.
    - (d) complexity of solar cycle-QBO-ENSO coupling.

Anstey and Shepherd, 2014

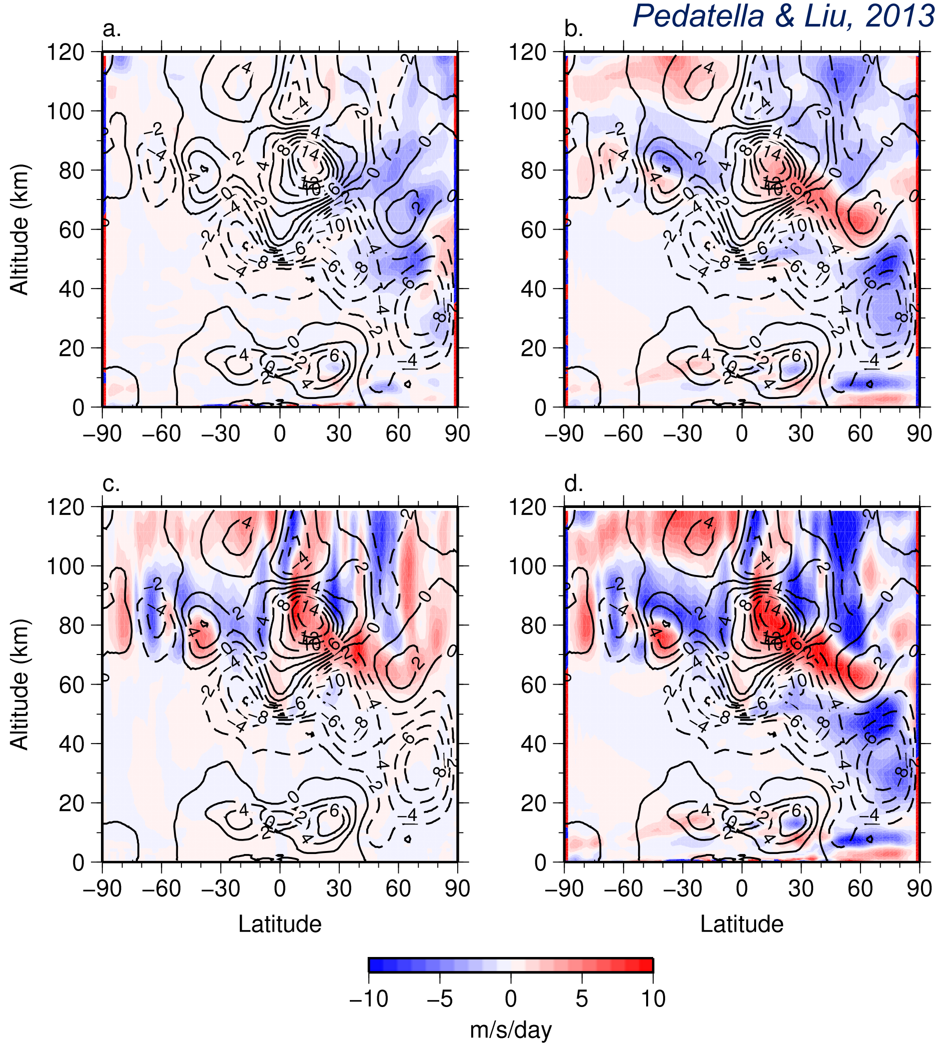


Time series of 1958-2008 equatorial monthly-mean zonal-mean zonal wind averaged over 2S-2N from ECMWF and ERA reanalyses.

2.2 Inter-Annual ITM Variations: *ENSO*

- The ENSO is an ***irregular periodic variation in winds and sea surface temperatures over the tropical eastern Pacific Ocean*** affecting the climate of much of the tropics and subtropics, with the warming (cooling) phase of sea temperature known as El Niño (La Niña).
- Changes in the horizontal distribution, vertical penetration, or intensity of ***convection in the tropical Pacific Ocean from ENSO impact the ITM***.
- Large-scale convection from ENSO can ***facilitate the excitation of nonmigrating tides*** through latent heat release, nonlinear interaction with PWs, and the background atmospheric changes.
- Numerical simulations (e.g., *Pedatella & Liu, 2012, 2013*) suggest that ***ENSO-induced MLT variability is ~10-30% and ionospheric variability is ~10-15%***.
- DW1 enhancement is most notable during El Niño time periods and DW1 is only slightly decreased during La Niña, with enhancements driven by anomalously large tropospheric radiative forcing
- The nonmigrating DE3 and DE2 are the most affected by ENSO exhibiting enhancements during La Niña (and are only a slight response to El Niño) driven by large tropospheric latent (and radiative) heating forcing.
- Effects from the coupling between ENSO, the QBO, and the solar cycle are aspects that require further research.

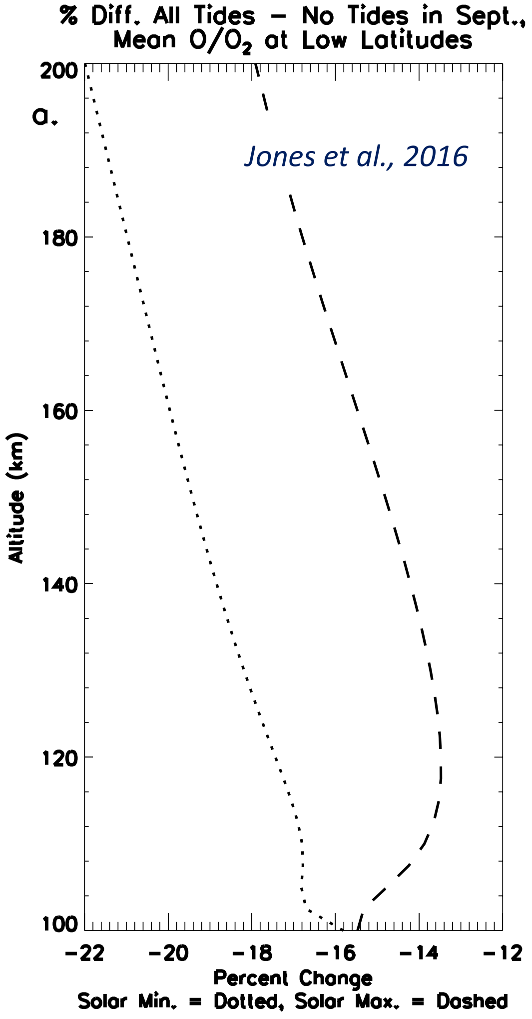
Pedatella & Liu, 2013



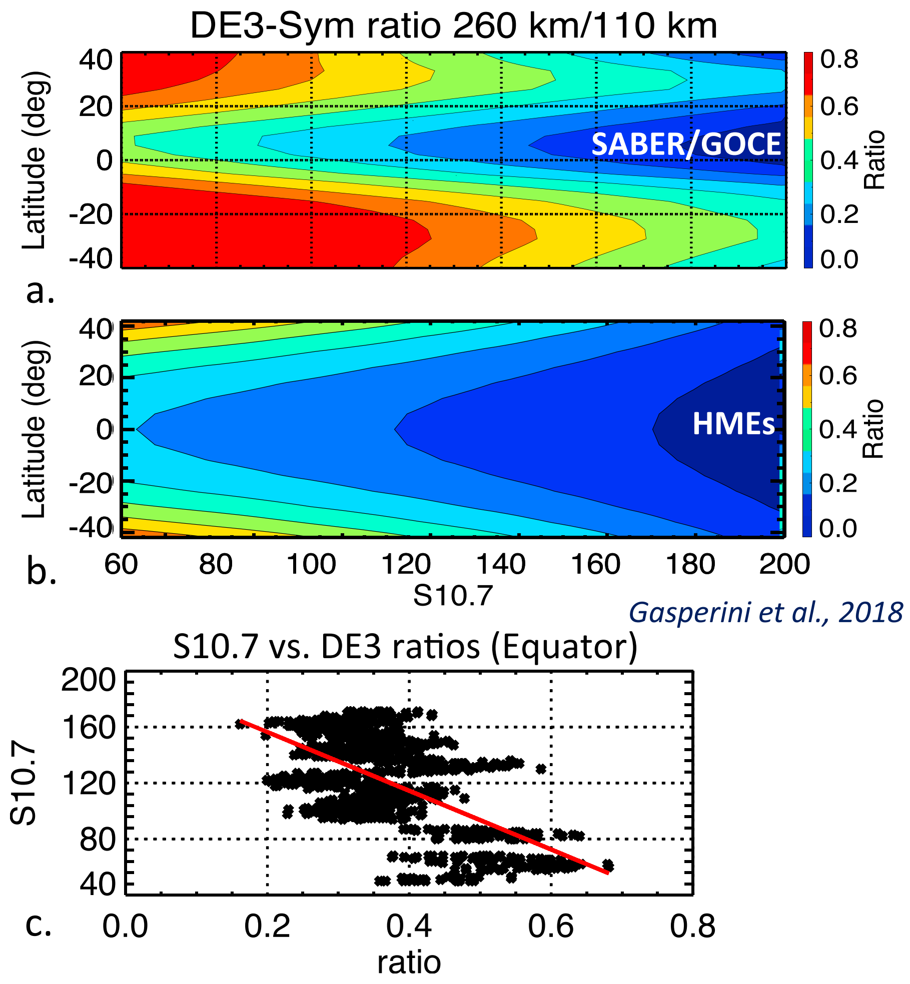
Changes in the zonal mean zonal wind for January during El Niño time periods. Colors represent the anomalous forcing due to (a) EP flux divergence, (b) meridional and vertical advection, (c) gravity waves, and (d) the sum of the forcing in a-c.

2.3 Inter-Annual ITM Variations: *Solar Cycle*

- Solar cycle variations in ITM tidal temperature, density, horizontal and vertical winds have been long reported (*Oberheide et al., 2009*).
- NO and CO_2 radiative cooling rates in the thermosphere have a strong solar cycle dependence (*Mlynczak et al., 2010, 2014*).
- Solar cycle effects can be associated with ***tidally induced modulation of mean thermospheric temperatures and composition***, with up to a ~20% decrease in the electron density in *NmF*2 driven by decreases in [O] and increases in [O_2] due to the tides at solar medium from TIE-GCM simulations (*Jones et al., 2016*).
- Tidal/KW dissipation becomes more important as solar activity increases, with **reduced** (increased) ***amplitudes in the middle thermosphere for increased*** (decreased***) solar activity***. This response can be explained as due to the effect of molecular dissipation below ~200 km and the hydrostatic law above ~200 km (*Gasperini et al., 2018*).



Percent changes in zonal-mean O/O2 ratio averaged over low latitudes from TIE-GCM including CTMT lower boundary tidal forcing between 100 and 200 km during September under solar min (dotted line) and max (dashed line) conditions.

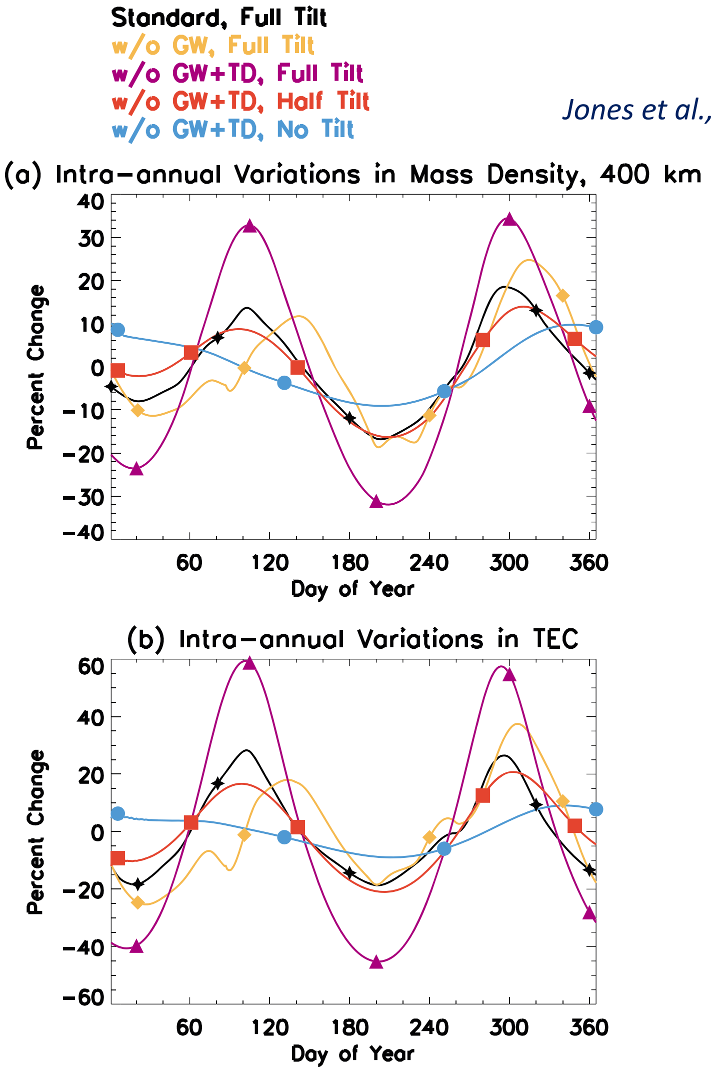


Ratios of symmetric DE3 density as a function of lat. and S10.7 calculated linearly fitting S10.7 and the ratios from SABER/GOCE data (a) and from HMEs (b). Panel c shows the scatter plot of S10.7 versus DE3 ratios at the equator and the linear fit used to derive the ratios in (a).

3.1 Intra-Annual ITM Variations: *AO & SAO*

- AO and SAO variations have been observed in globally averaged thermospheric mass density since the early 1960s but their origin is still not well understood.
- The Earth's elliptical orbit around the Sun introduces a ~ 7% difference in the solar irradiance that reaches the Earth's thermosphere between early July (aphelion) and early January (perihelion), causing an ***annual variation*** in the ITM.
- The ***SAO*** is the second-largest fluctuation in global average density, after the solar cycle, and is characterized by ***maxima near the equinoxes and minima near the solstices*** and solar minimum amplitudes of ~15% at 400 km (increasing with altitude and solar flux level).
- Various other mechanisms have been proposed to explain the global ITM SAO, including:
    - geomagnetic activity (e.g., *Walterscheid, 1982*)
    - the thermospheric-spoon mechanism (TSM, e.g., *Fuller-Rowell, 1998*)
    - the seasonally varying eddy mixing (Kzz) hypothesis (e.g., *Qian et al., 2009, 2013, 2022*)
- The TSM is an internal, large-scale meridional and vertical circulation of constituents due to the latitudinal gradient in radiative forcing driving stronger interhemispheric transport at the solstices. The ***summer-to-winter circulation causes stronger mixing of the thermosphere during solstices***, and thus smaller neutral density scale height and mass density.
- Recent numerical results (*Jones et al., 2018, 2021*) suggest that the primary source of the global ITM SAO is the changing solar illumination due to the Earth's obliquity, i.e., the TSM.

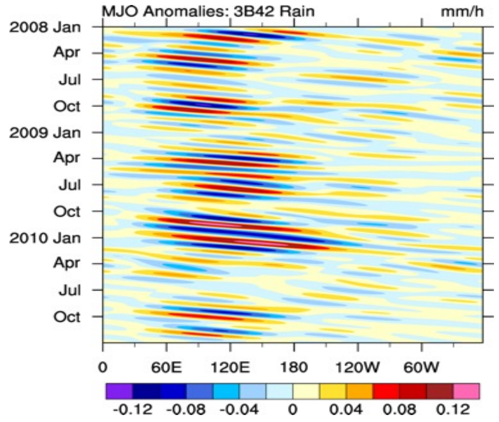
Jones et al., 2018



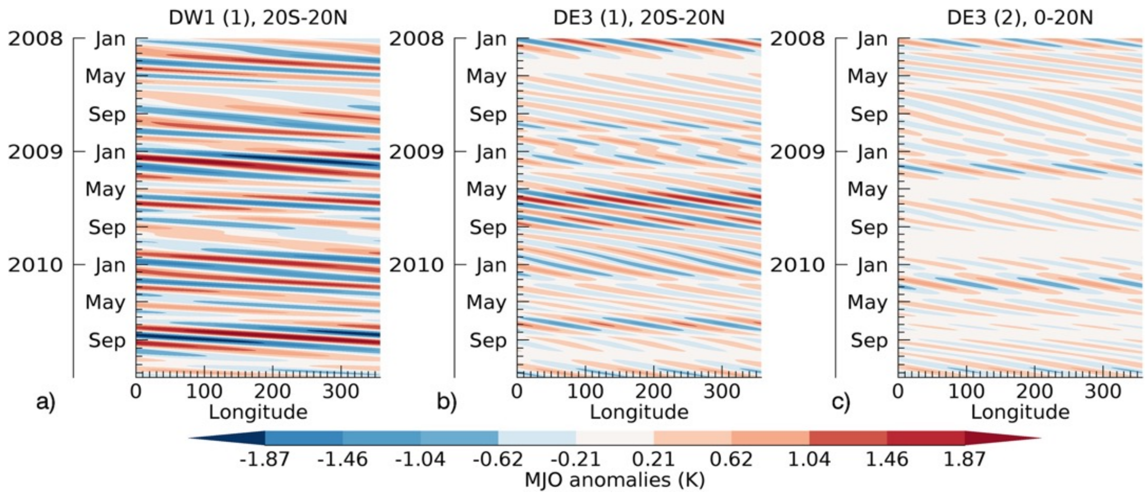
Intra-annual variations in (a) globally averaged mass density at 400 km and (b) TEC in % relative to their global and annual averages from TIME-GCM from the Standard, Full Tilt (black stars); w/o GW, Full Tilt (orange diamonds); w/o GW+TD, Full Tilt (purple triangles); w/o GW+TD, Half Tilt (red squares); and w/o GW+TD, No Tilt (cyan circles) simulations.

3.2 Intra-Annual ITM Variations: *MJO*

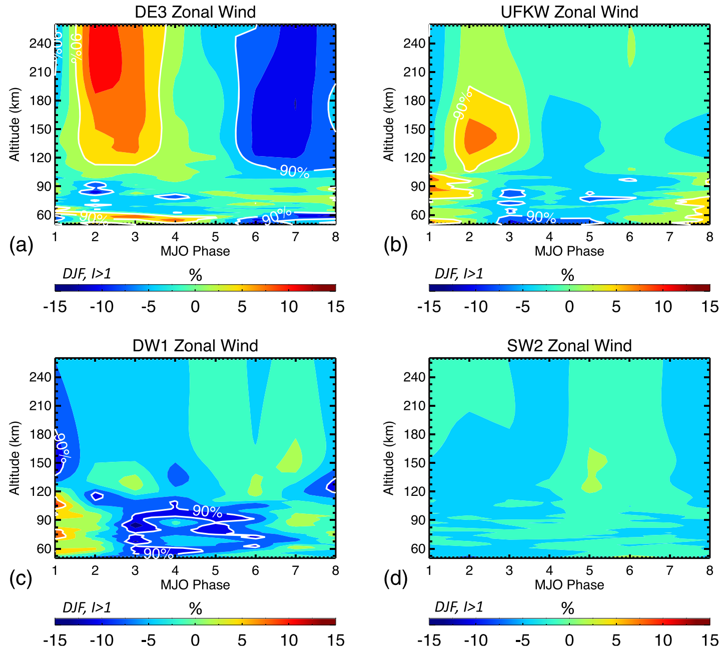
- The ***MJO*** is a prominent low latitude tropospheric eastward moving disturbance recurring every ~30-90 days in winds, clouds, rainfall and other variables and is the ***dominant mode of intra-seasonal variability in tropical convection and circulation***.
- The MJO generates a whole spectrum of global-scale waves, and modulates stratospheric GW, GW drag, and mean winds, depending on its magnitude and phase (i.e., location).
- ***Non-migrating tidal amplitudes*** are modulated at the intra-seasonal MJO periods ***up to ~25%*** relative to the seasonal mean, twice as much compared with the migrating tides (~10%) in the MLT region (*Kumari et al., 2020*).
- The ***modulation of tidal heating*** was shown to be comparatively ***more important*** than the modulation of background winds for non-migrating tides (*Kumari et al., 2021*).
- The MJO-modulation of tides and UFKW extends well into the middle thermosphere, with evidence for an MJO-modulation of DE3 and UFKW and the thermospheric zonal mean winds (~20 m/s peak-to-peak; *Gasperini et al., 2017, 2020*).
- *A* ~15% peak-to-peak MJO-modulation of GWs up to 100 km and into the extra-tropics was recently found (*Li & Lu, 2020, 2021*).



MJO-modulation of rainfall (Wang et al., 2014).



MJO-modulation (Hovmoeller analysis) at 95 km of (a) DW1 averaged over the equator, (b) DE3 symmetric mode (c) DE3 asymmetric model from SABER temperatures (Kumari et al., 2021).

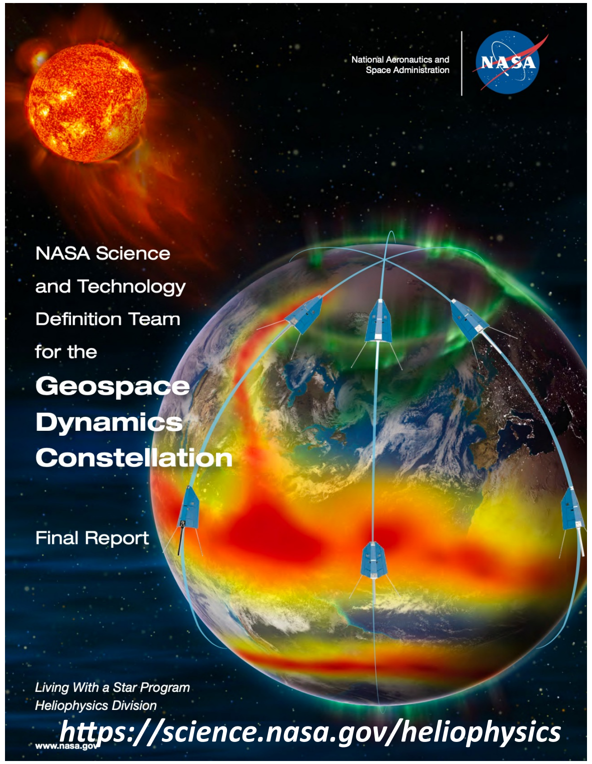


- Global-scale thermospheric impacts from the MJO and effects on the ionosphere are yet to be determined.
- Models and observational efforts are needed to address issues related to this coupling.

Height-MJO phase depiction of DE3 (a), UFKW (b), DW1 (c), and SW2 (d) low-latitude (±40°) zonal wind amplitudes using a composite method and SD/WACCM-X output for 1980–2017 (Gasperini et al., 2020).

Summary & Open Questions

- Upward propagating waves are a leading driver of long-term variability in the whole ITM system.
- Variability in the wave spectrum can be ascribed to *(a)* lower/middle atmospheric weather, *(b)* variable propagation conditions, and *(c)* nonlinear interactions between different parts of the wave spectrum.
- It is critical that we attain a better understanding of the physical mechanisms at play for improving modeling/predictive capabilities.
- The Ionospheric Connection Explorer (ICON) and Global-scale Observations of the Limb and Disk (GOLD) missions offer new insights, yet our understanding is impaired by the ***poor observational record*** of 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 upcoming ***Geospace Dynamics Constellation (GDC)*** mission shall provide very ***well-needed observations*** that will be critical to better understanding ITM coupling sources.
- Observations from the ***Dynamical Neutral Atmosphere-Ionosphere Coupling (DYNAMIC)*** mission would be particularly helpful by measuring the ***height evolution of the wave spectrum in the thermosphere*** and providing the much-needed day/night wind throughout the thermosphere to study wave-mean flow interactions, ion-neutral interactions, and dynamo processes.
- Important open questions that need to be addressed in this area of research include:
    1. *What are the **physical mechanisms** that transmit **long-term variability** from the lower/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?*



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