Back to Basics: Planetary Waves and Tides

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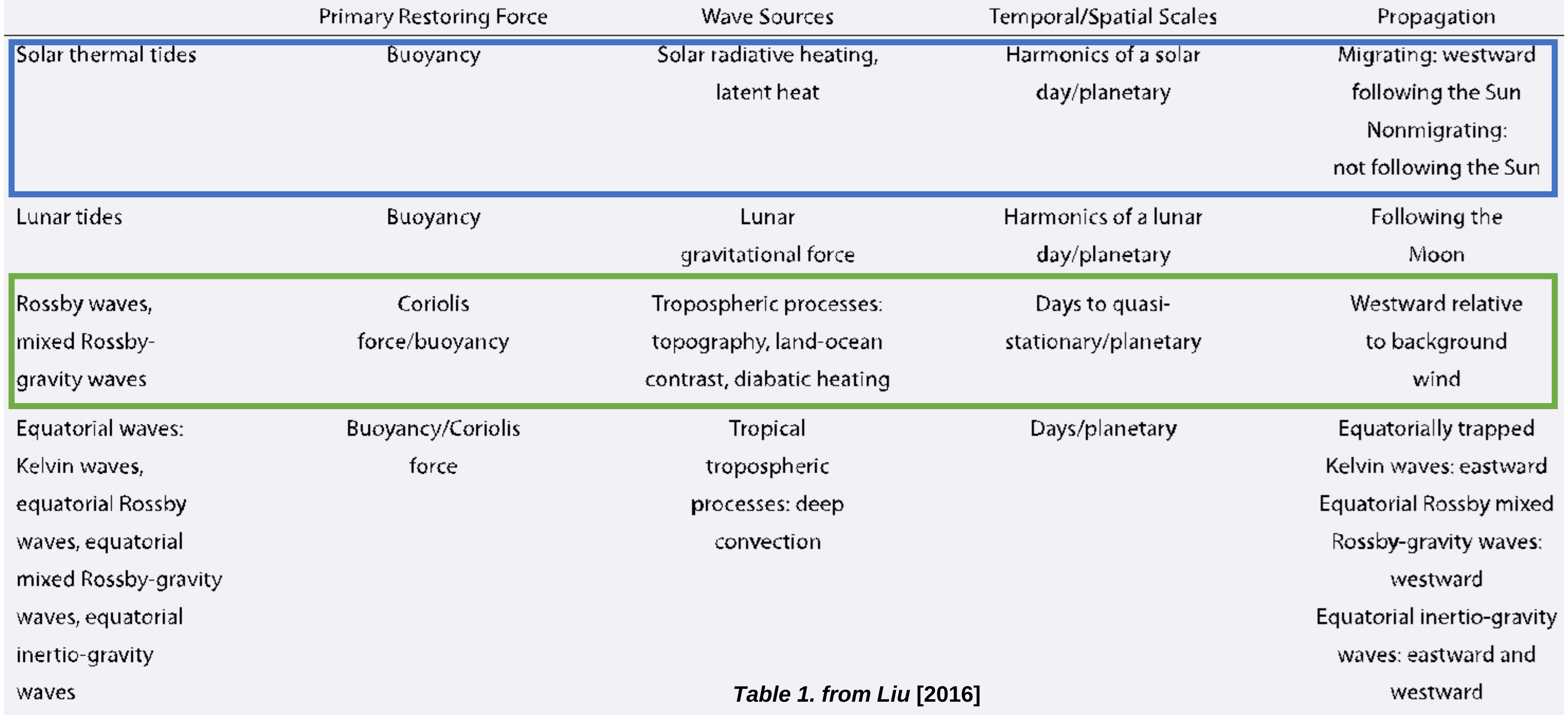


	Primary Restoring Force	Wave Sources	Temporal/Spatial Scales	Propagation
Solar thermal tides	Buoyancy	Solar radiative heating, latent heat	Harmonics of a solar day/planetary	Migrating: westward following the Sun Nonmigrating: not following the Sun
Lunar tides	Buoyancy	Lunar gravitational force	Harmonics of a lunar day/planetary	Following the Moon
Rossby waves, mixed Rossby-gravity waves	Coriolis force/buoyancy	Tropospheric processes: topography, land-ocean contrast, diabatic heating	Days to quasi-stationary/planetary	Westward relative to background wind
Equatorial waves: Kelvin waves, equatorial Rossby waves, equatorial mixed Rossby-gravity waves, equatorial inertio-gravity waves	Buoyancy/Coriolis force	Tropical tropospheric processes: deep convection	Days/planetary	Equatorially trapped Kelvin waves: eastward Equatorial Rossby mixed Rossby-gravity waves: westward Equatorial inertio-gravity waves: eastward and westward

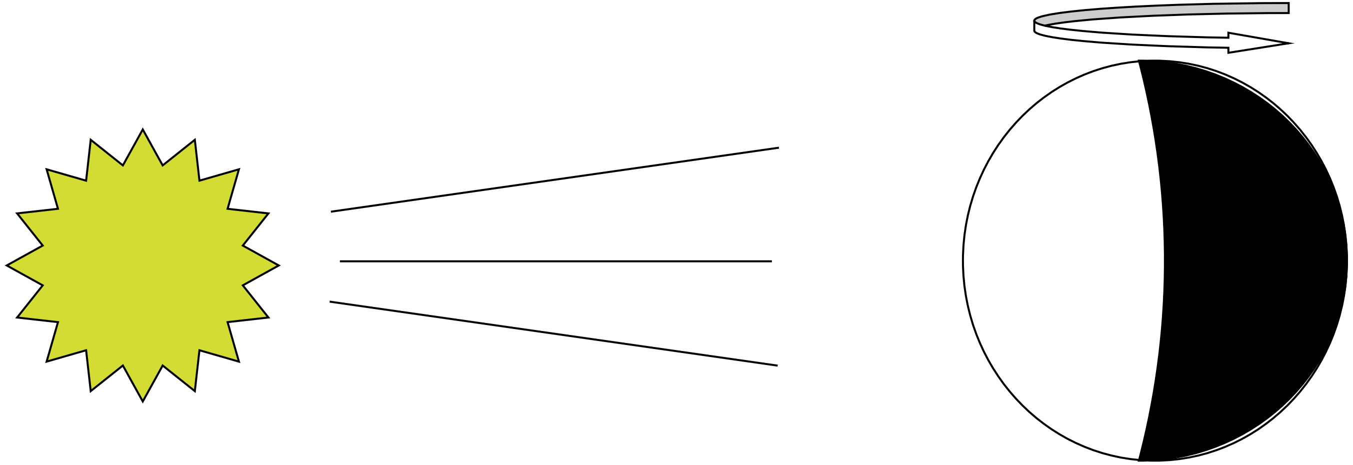
Table 1. from Liu **[2016]**

Tides
24, 12, 8 hours
1000's to 10,000 km

Planetary Waves
2-20 days
1000's to 10,000 km

Acknowledgement: This work was sponsored by NASA Early Career Investigator (ECI) Program.

Global distribution of solar heating from a space-based perspective

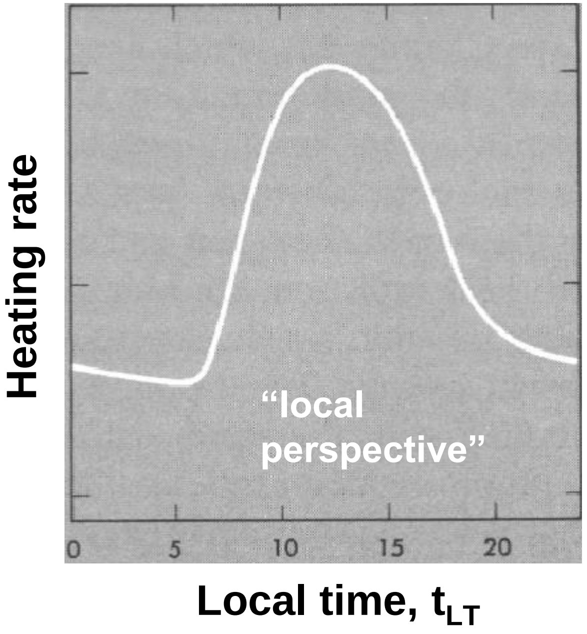


To an observer in space, it looks like the bulge is fixed with respect to the Sun, and the planet is rotating beneath it.

In the local (solar) time frame, the heating may be represented as

$$\text{heating} = Q_o + \sum_{n=1}^{N} a_n \cos n\Omega t_{LT} + b_n \sin n\Omega t_{LT}$$

$$= Q_o + \sum_{n=1}^{N} A_n \cos(n\Omega t_{LT} - \phi) \qquad \Omega = \frac{2\pi}{24}$$



diurnal, (n = 1), semidiurnal (n = 2), etc. tides

Slide provided and adapted from Jeff Forbes

Global distribution of solar heating from a space-based perspective

Converting to universal time $t_{LT} = t + \lambda/\Omega$, we have

$$\text{heating} = Q_o + \sum_{n=1}^{N} A_n \cos(n\Omega t + n\lambda - \phi)$$

Implying a zonal phase speed $$C_{ph} = \frac{d\lambda}{dt} = -\frac{n\Omega}{n} = -\Omega$$

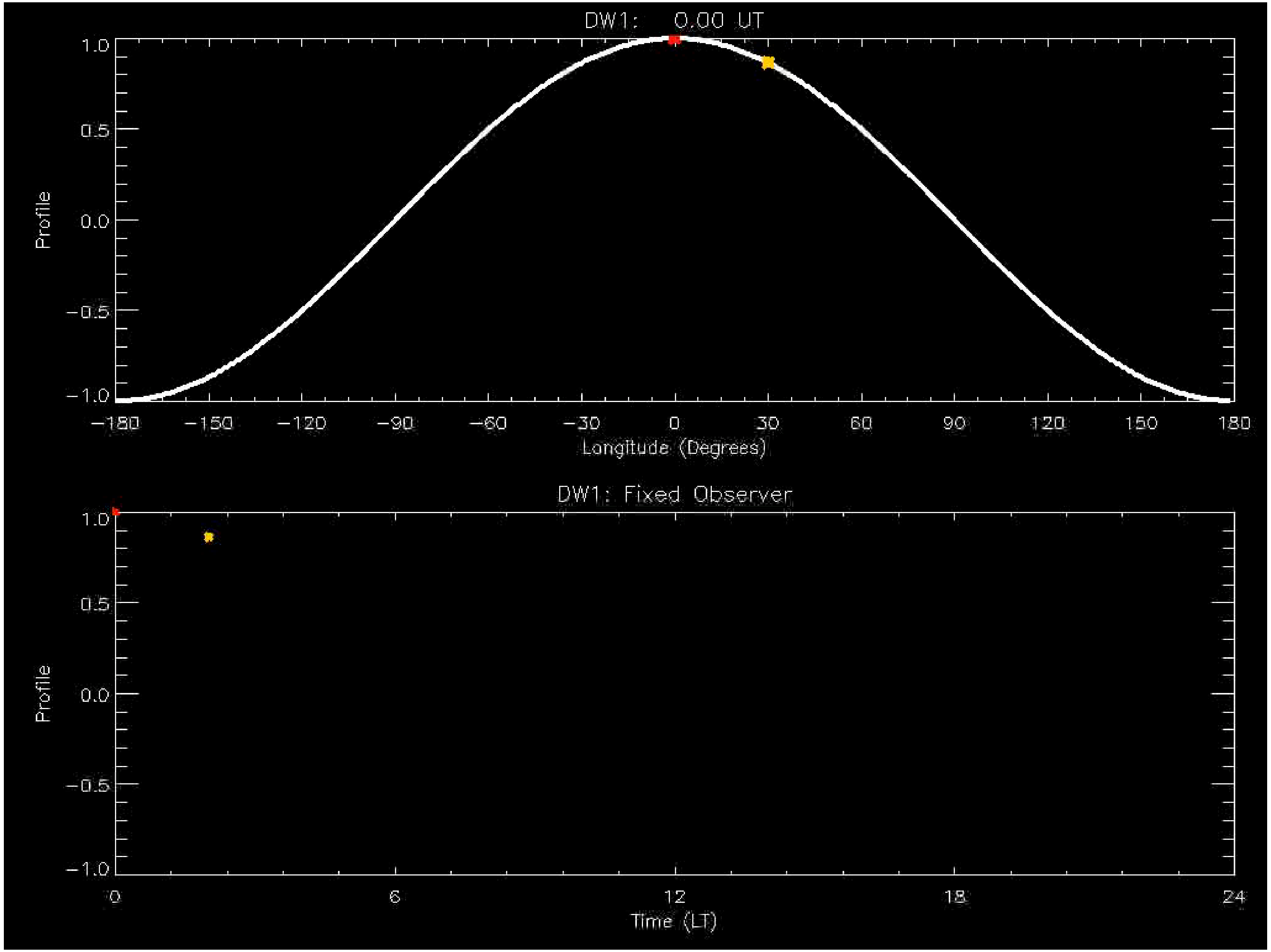
To an observer in space, it looks like the bulge is fixed with respect to the Sun, and the planet is rotating beneath it.

To an observer on the ground, the bulge is moving westward at the apparent motion of the Sun. It is sometimes said that the bulge is 'migrating' with the apparent motion of the Sun with respect to an observer fixed on the planet.

Since this thermal forcing is periodic, it can excite a wave, called a "thermal tide", that can propagate from the lower atmosphere up into the upper atmosphere where it is dissipated.

Slide provided and adapted from Jeff Forbes

Migrating Diurnal Tide (DW1) Example



Animation provided by Loren Chang

Global distribution of solar heating from a space-based perspective

For solar heating that varies with longitude, a spectrum of tides is produced that consists of a linear superposition of waves of various frequencies (n) and zonal wavenumbers (s):

$$\sum_{s=-k}^{s=+k}\sum_{n=1}^{N} A_{n,s}(z,\theta)\cos\left(n\Omega t + s\lambda - \phi_{n,s}(z,\theta)\right)$$

implying zonal phase speeds

Similarly, at any given local time, we have a sum of waves that defines the longitude dependence of heating at that local time.

At any given longitude, we have a sum of waves that defines the local time pattern of heating, as before; however, this pattern now changes with longitude.

The waves w … respect to the Sun to a planetary-fixed observer.

Transforming back to local time:

$$\sum_{s=-k}^{s=+k}\sum_{n=1}^{N} A_{n,s}(z,\theta)\cos\left(n\Omega t_{LT} + (s-n)\lambda - \phi_{n,s}(z,\theta)\right)$$

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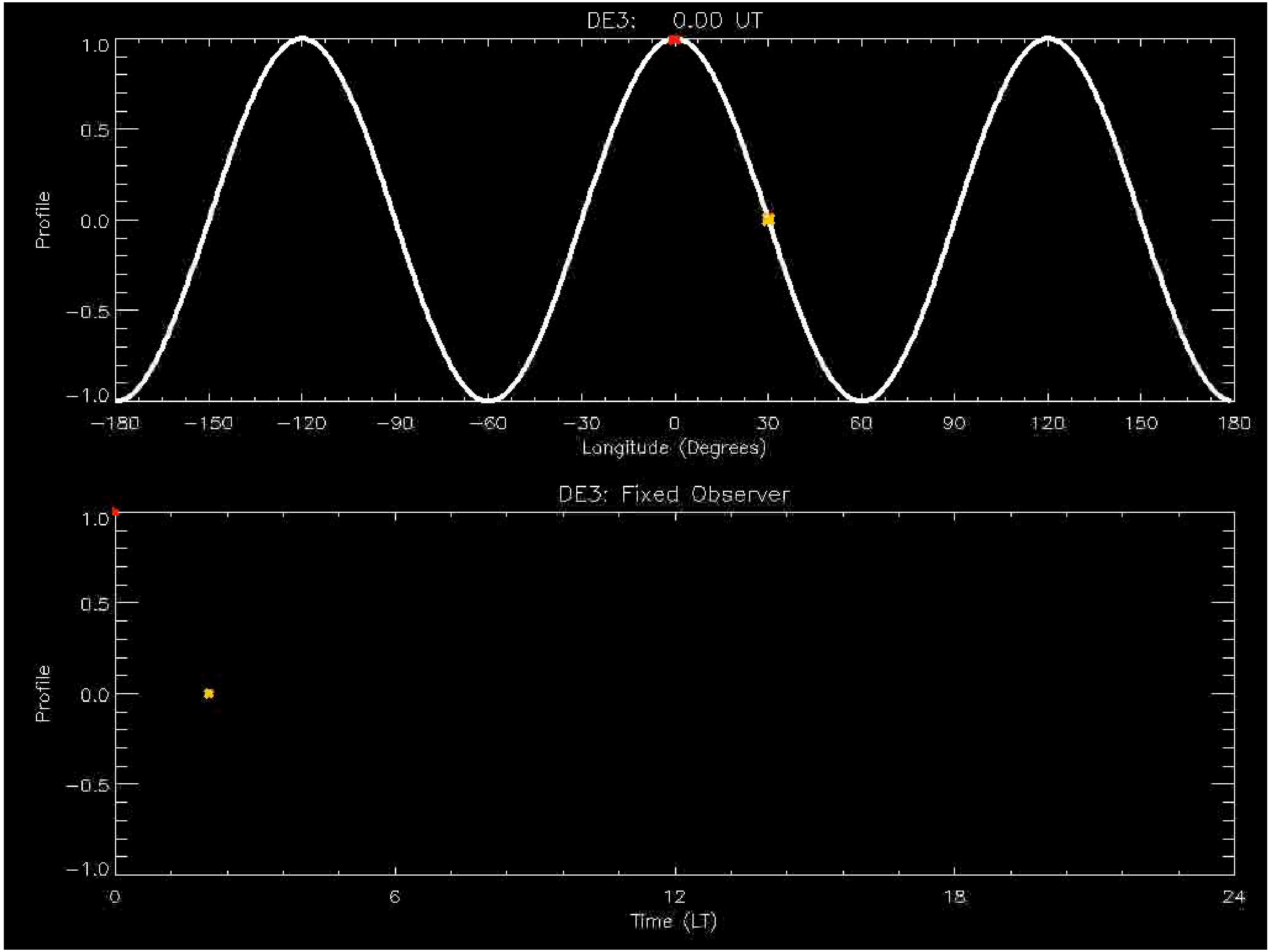
Diurnal eastward propagating tide with zonal wavenumber 3 (DE3) example



Animation provided by Loren Chang

Examples of atmospheric tidal impacts on the thermosphere-ionosphere system you might hear about this week

1. Alter the mean state of the thermosphere-ionosphere system

1. Drive spatiotemporal variability in the thermosphere-ionosphere system

1. **Modulate the E-region ionosphere dynamo and drive longitudinal variability in F-region/topside ionosphere**

1. Can force distinct features, e.g., midnight temperature maximum and midnight density modulation

1. Non-linearly interact with other tides, gravity and planetary waves

1. Modulate ion-neutral interactions, e.g., equatorial ionization anomaly and equatorial electrojet

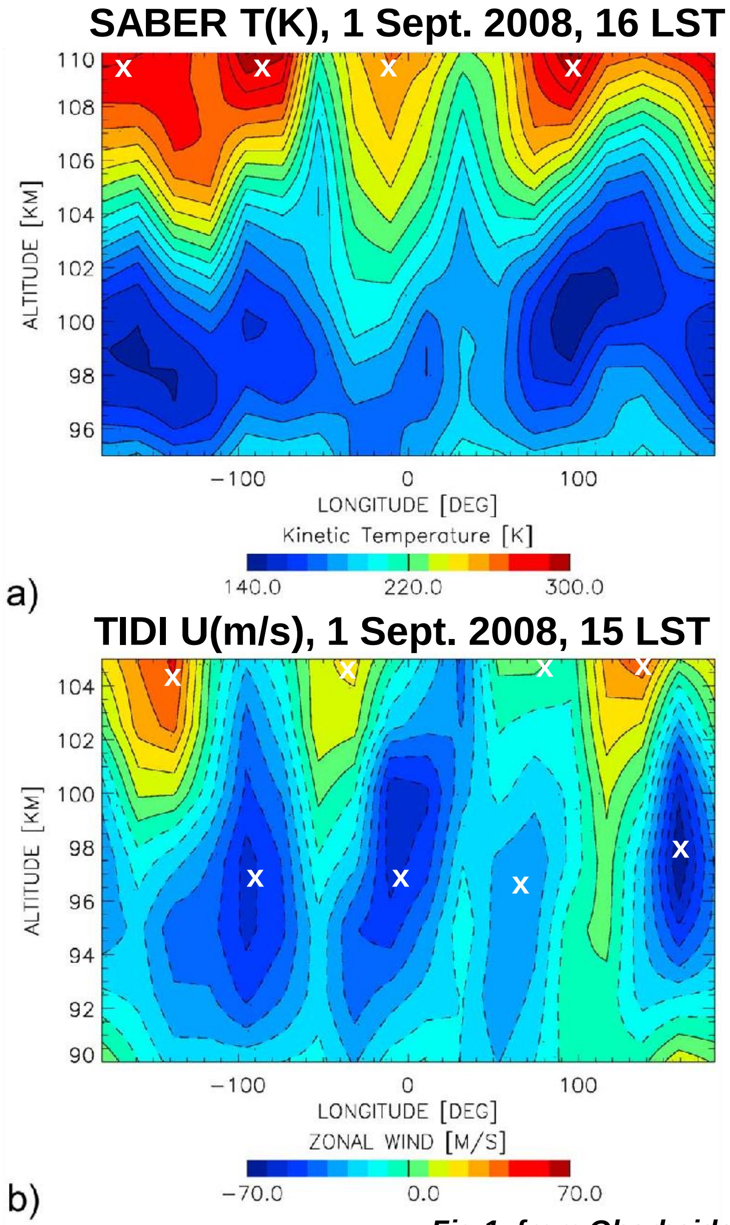
1. Play a large role in the ionospheric responses to sudden stratospheric warmings

1. Modulate global intra-annual variations, e.g., thermosphere-ionosphere semiannual oscillation

1. Force day-to-day variations in the thermosphere-ionosphere important for forecasting space weather

1. A number of other processes ….

Example of tides modulating the E-region ionospheric dynamo and its impact on the upper F-region ionosphere


SABER T(K), 1 Sept. 2008, 16 LST

TIDI U(m/s), 1 Sept. 2008, 15 LST

Fig 1. from Oberheide et al. [2011]

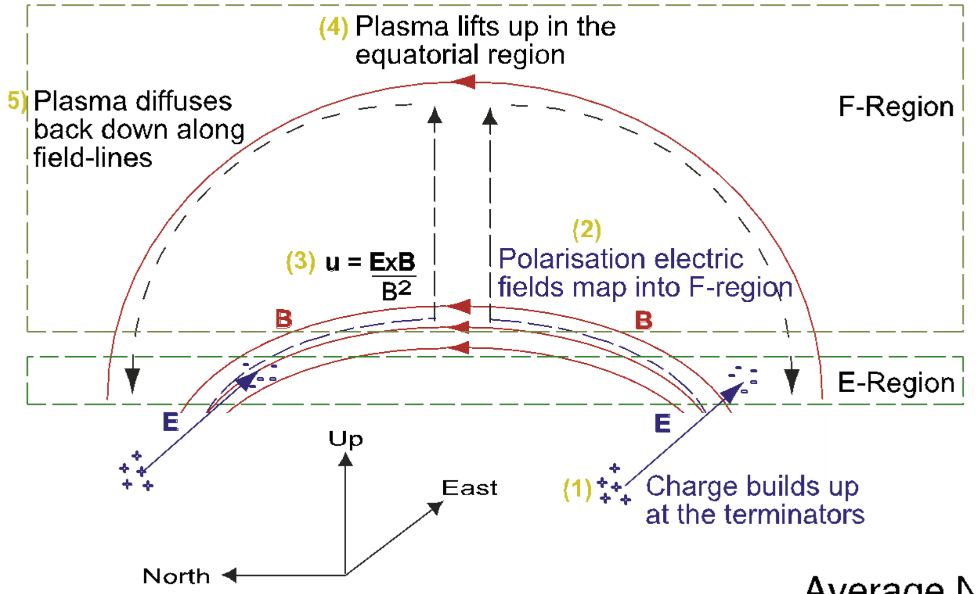


Fig 2. from Immel et al. [2006]

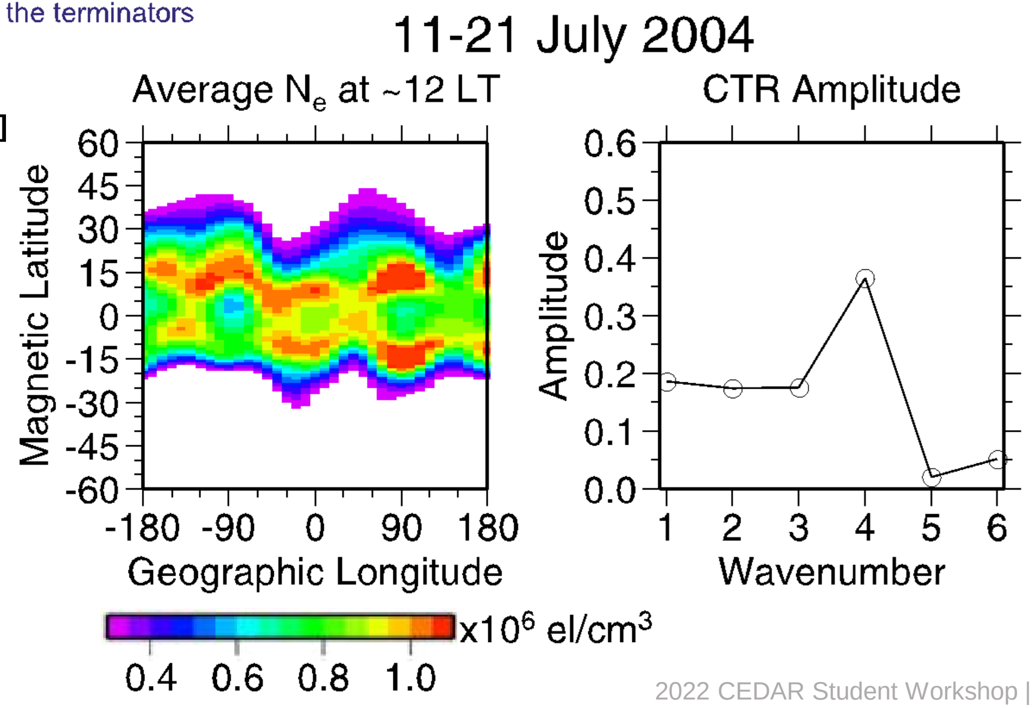
$$(s-n)\lambda$$

DE3: s=-3, n=1

SE2: s=-2, n=2

SPW4: s=4, n=0

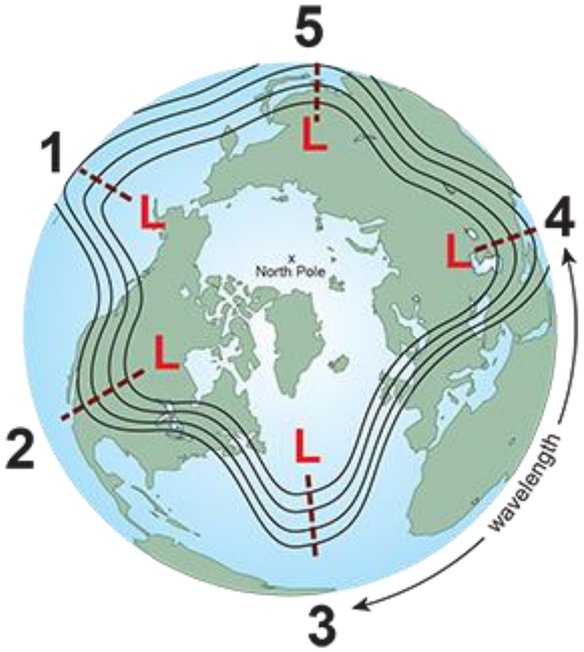
from Fig. 2 of Pedatella et al. [2008]


11-21 July 2004

Rossby (Planetary) Waves

- When we typically think of Rossby (planetary) waves we think of large-scale peaks and troughs in the jet stream (or “longwaves”) ….
- Rossby waves can travel both eastward and westward, but they always flow westward relative the mean flow.

- In the upper atmosphere, Rossby (planetary waves) generally refer to westward propagating rotational modes with periods ranging from longer than 1 day to around 20 days or so.



Example of a planetary wave pattern from weather.gov

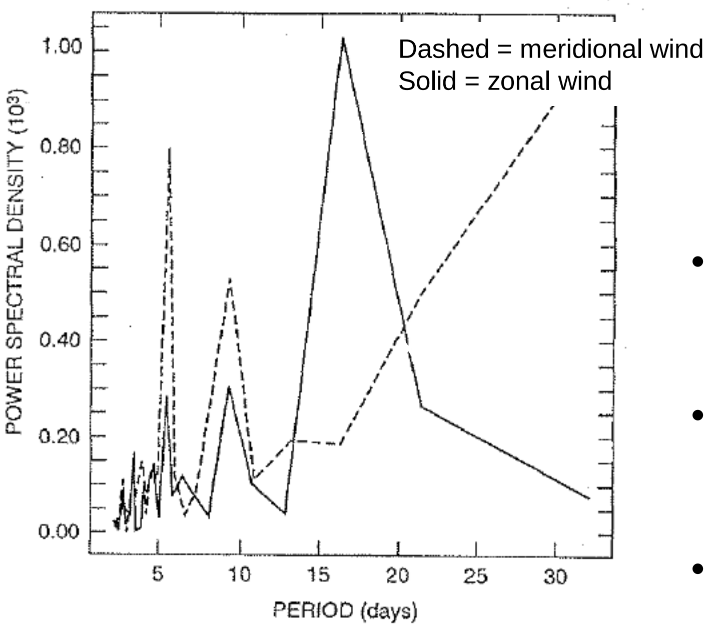

Dashed = meridional wind
Solid = zonal wind

***Fig 2. from Forbes* [1995]**

- A specific set of planetary waves, known as Rossby normal modes because of the similarities w/meteorological forced waves, are of great interest in MLT and TI system.

- **Rossby normal modes** (or more commonly just planetary waves or normal modes) are a special, forced-free solution to the primitive equations with some assumptions.

- Theory predicts normal mode frequencies to appear at 2, 5, 8, and 12 days, but at MLT and TI altitudes, these waves typically occur at periods near ~**2,~5**,~**10**, and ~**16** days. Why?

Rossby (Planetary) Waves □ Normal Modes

- **Rossby normal modes** are global solutions to Laplace’s tidal equation, assuming a isothermal, windless, and dissipationless atmosphere.

- What happens though in the real atmosphere that is not isothermal, windless, or dissipationless?

- **Main Takeaway: Meridional temperature gradients, latitudinally-varying mean winds, and dissipative processes cause Rossby normal mode periods to shift from the 2, 5, 8, 12 day periods to Quasi-2,5,10,16 day waves in the upper atmosphere.**

- A series of comprehensive work by *Salby* [1979], [1981a,b,c], [1984] provided a in-depth look in these effects.

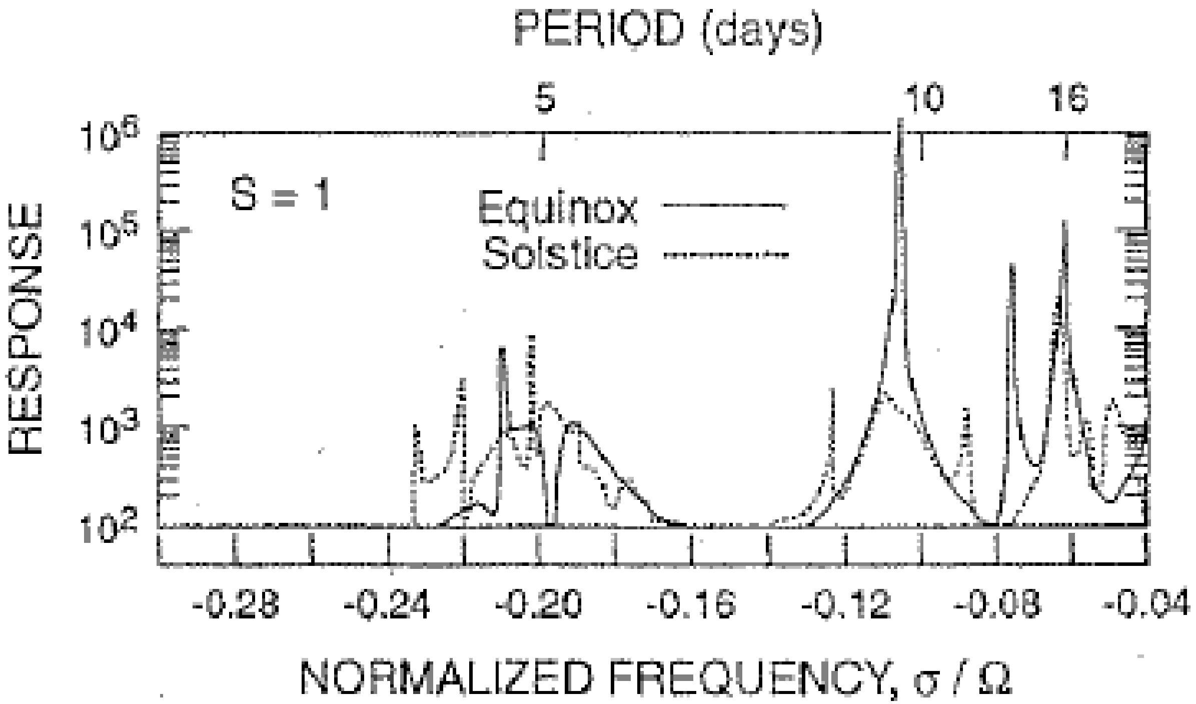


Fig 15. from Forbes **[1995] and adapted from *Salby* [1981b]**

Example of Normal Modes in the F-region Ionosphere

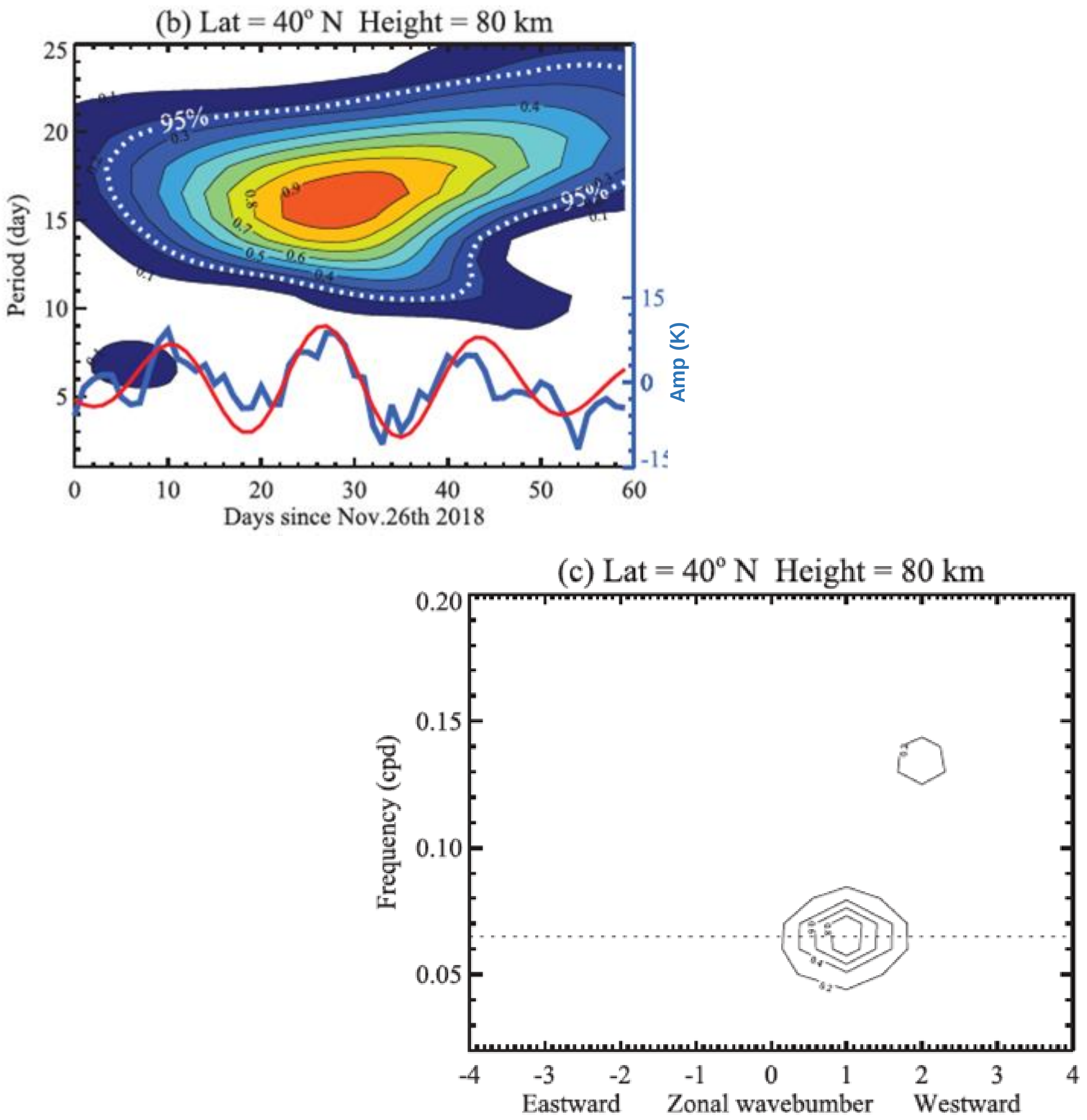


Fig 4b and 4c. from Gan et al. [2020]

SABER observed Q16DW signature in the mesosphere during the northern winter of 2018/2019 during a sudden stratospheric warming

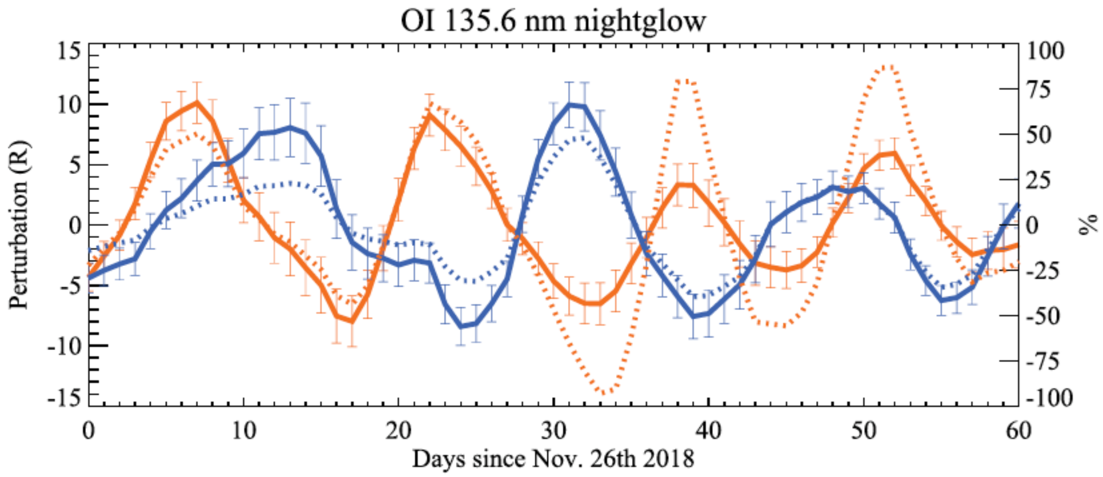


Fig 3. from Gan et al. [2020]

At the same time GOLD observed Q16D oscillations in the equatorial ionization anomaly □ Could be forced by 16d modulation of the tides …

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EXTRA SLIDE(S)

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Tidal Nomenclature

- The positive integer n = 1, 2, ... corresponds to oscillation periods of 24h, 12h, ... and are referred to as diurnal and semidiurnal tides, respectively.
- s > 0 (s < 0) corresponds to a westward (eastward) propagating tides.
- When s = n in there is no longitudinal variability around a constant latitude circle and thus these tides are said to be migrating (i.e., Sun-synchronous).
- When s ≠ n, a given tide with a frequency nΩ and zonal wavenumber s has a longitudinal variation of |s-n| (i.e., |s-n| maxima and minima observed in longitude). These are non-migrating tides.
- DWs (SWs) or DEs (SEs) to signify westward or eastward propagating diurnal (semidiurnal) tide, respectively, with zonal wave number s.
- Standing oscillations (i.e., s = 0) are denoted as D0 and S0.
- Waves with n = 0 are referred to as stationary planetary waves (SPW), with zonal wave number s and are denoted as SPWs.

Definition of an Atmospheric Solar Tide in Words

Solar thermal tides are global-scale perturbations in temperature, wind, pressure, and density, with frequencies that are harmonics of a solar day and are excited due to the absorption of solar radiation throughout the atmosphere.

Tides excited in the lower and middle atmosphere propagate upward and grow in amplitude becoming large until they dissipate, depositing their energy and momentum in the upper mesosphere and thermosphere.