Impact of Lower Atmosphere Waves on the Thermosphere and Ionosphere

Not a conventional CEDAR tutorial – what we do know
A Grand-Challenge tutorial – what we don't know

Tim Fuller-Rowell,

CIRES University of Colorado and
NOAA Space Weather Prediction Center

With contributions from Mariangel Fedrizzi, Mihail Codrescu, Jack Olsen, Tzu-Wei Fang, Fei Wu, Rashid Akmaev, Xian Lu, Gonzalez Hernandez, Xinzhao Chu, John Retterer, Roland Tsunoda, Miguel Larsen, F. Djuth, Hanli Lu, Larisa Goncharenko, Koki Chau, Jeff Forbes, Mike Taylor, Dominique Pautet, Karen O'Loughlin, Liying Qian, Stan Solomon, Eduardo Araujo, Tom Immel, Dave Hysell, Klemens Hocke, Simone Studer

Theme: The role of lower atmosphere waves on the thermosphere and ionosphere variability (80 to 200 km)

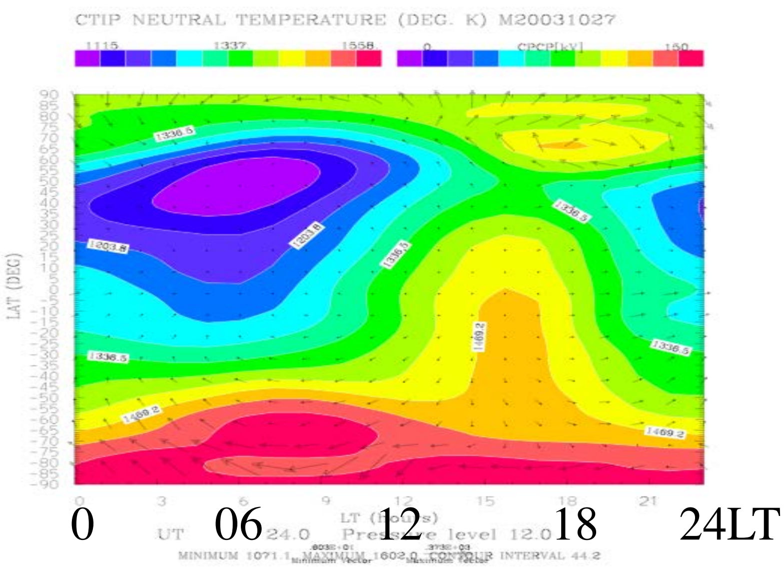
Context: Whole atmosphere modeling, and the impact of the whole spectrum of these waves

- What mixes the lower thermosphere? (turbulence, global circulation, tides, gravity waves, the whole spectrum of waves)?
- What is the day-to-day variability of tidal amplitude and phase, what is its impact on the thermosphere and ionosphere, and what causes it?
- What is the nature, characteristics, and source of non-tidal thermosphere and ionospheric variability, and what is its dependence on seasonal, latitude, region, time, etc.?

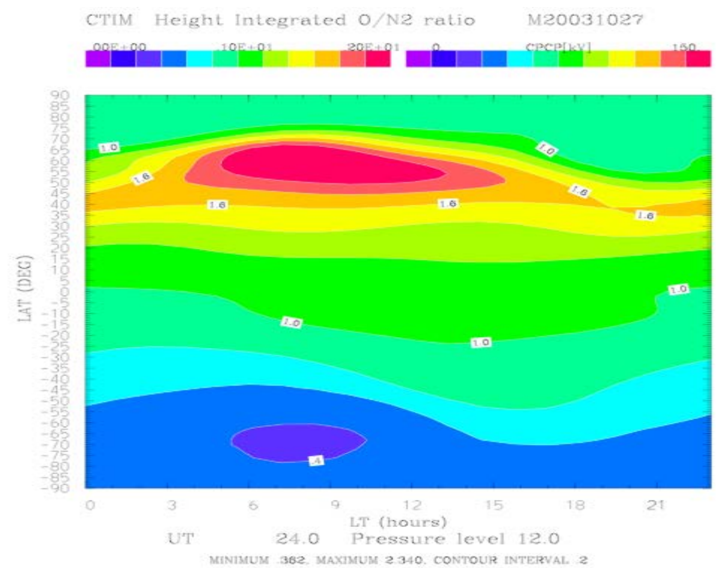
CTIPe model global thermosphere-ionosphere: is this reality?

00UT

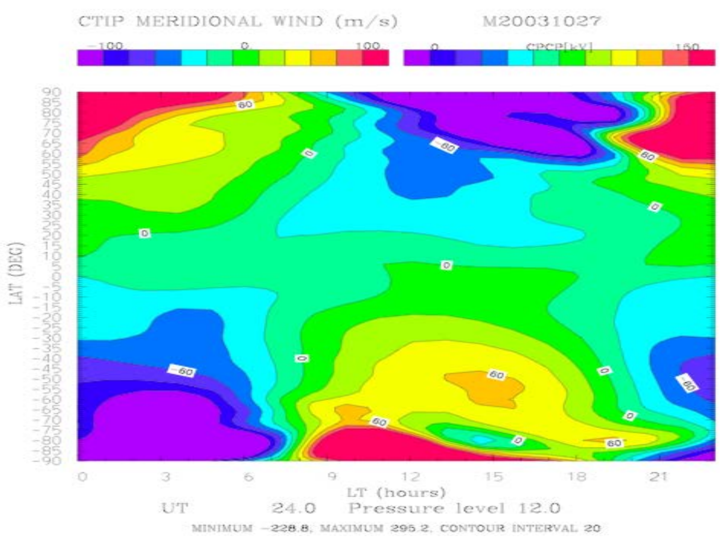
Temperature



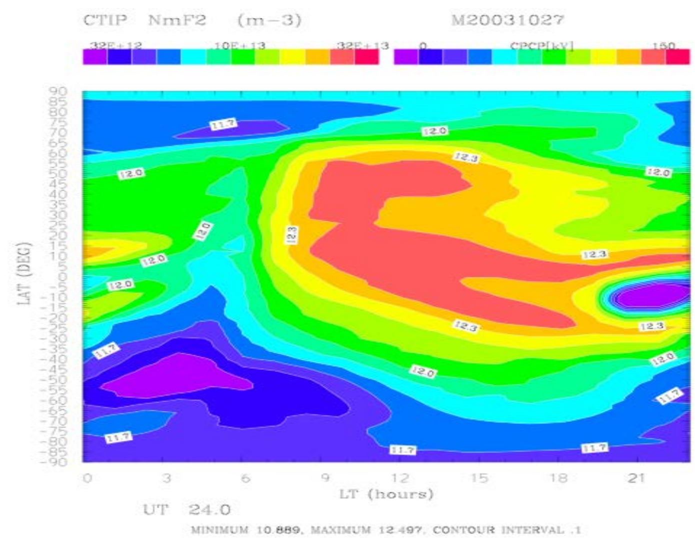
Height-integrated O/N_2 ratio



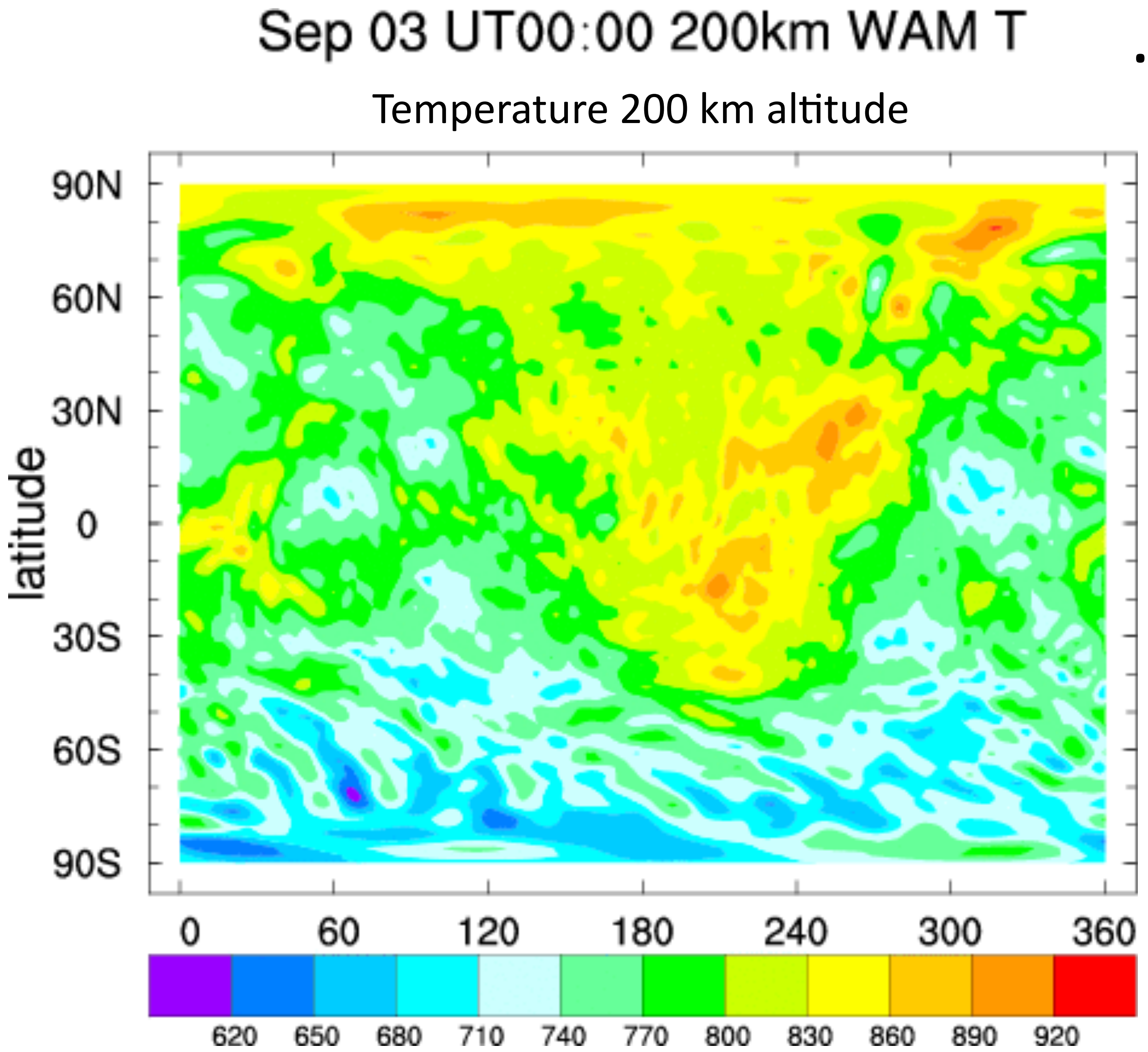
Meridional wind



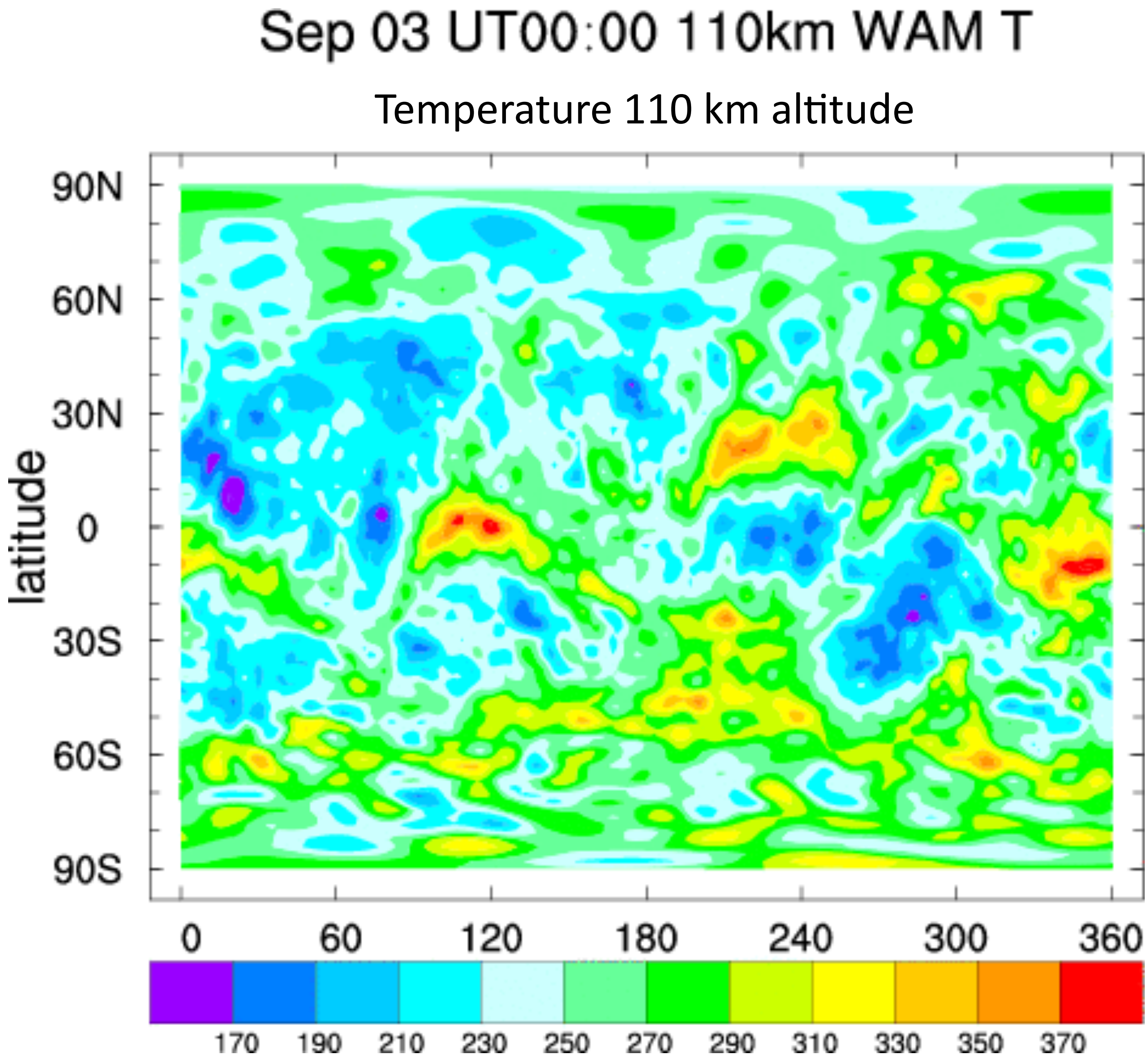
Ne



….or is this reality?

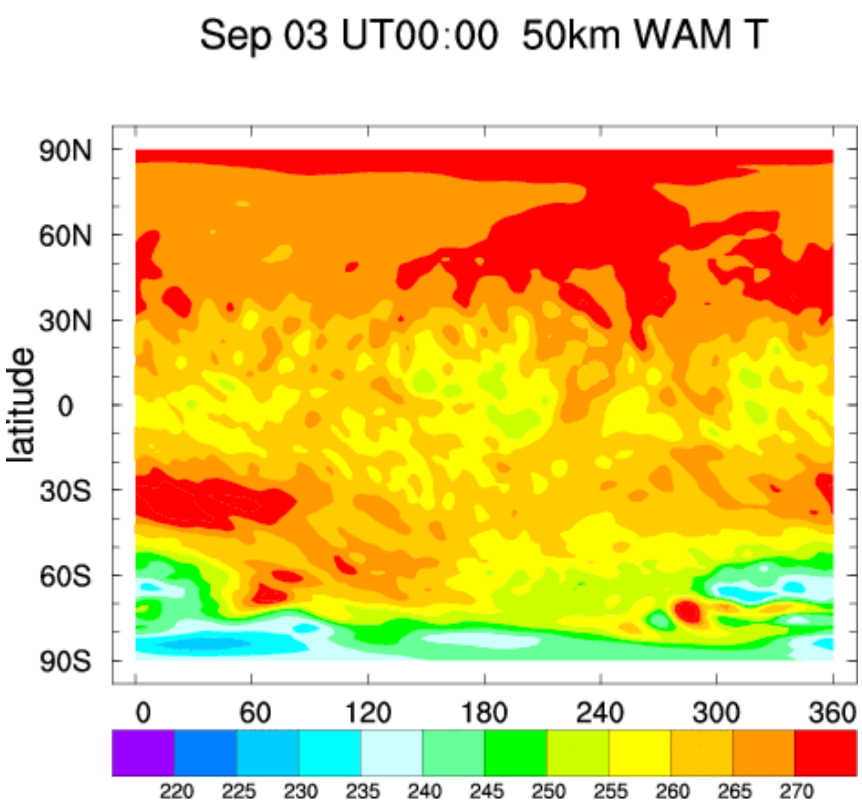


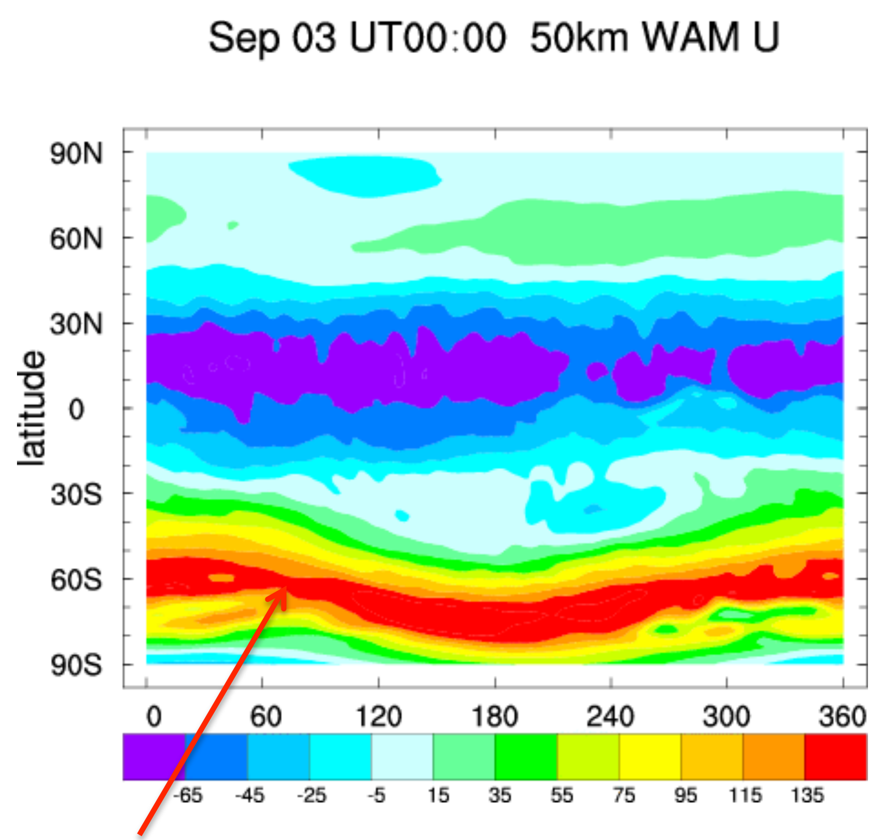
Can you see DE3?



Where and what is the source of waves?

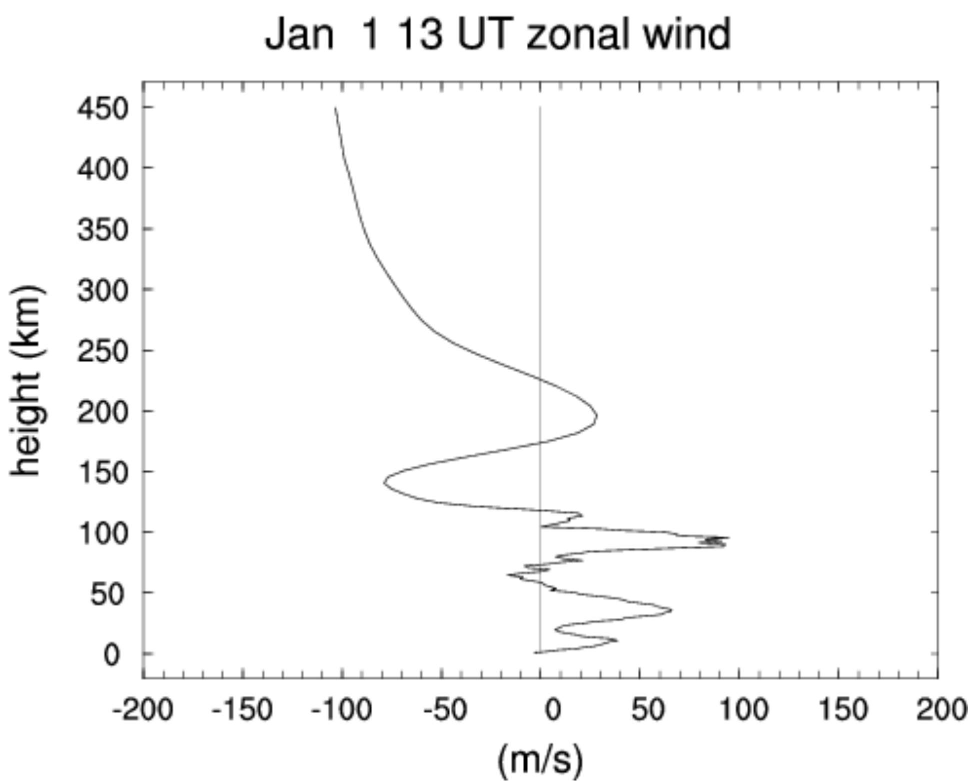
Temperature and Zonal wind 50 km altitude

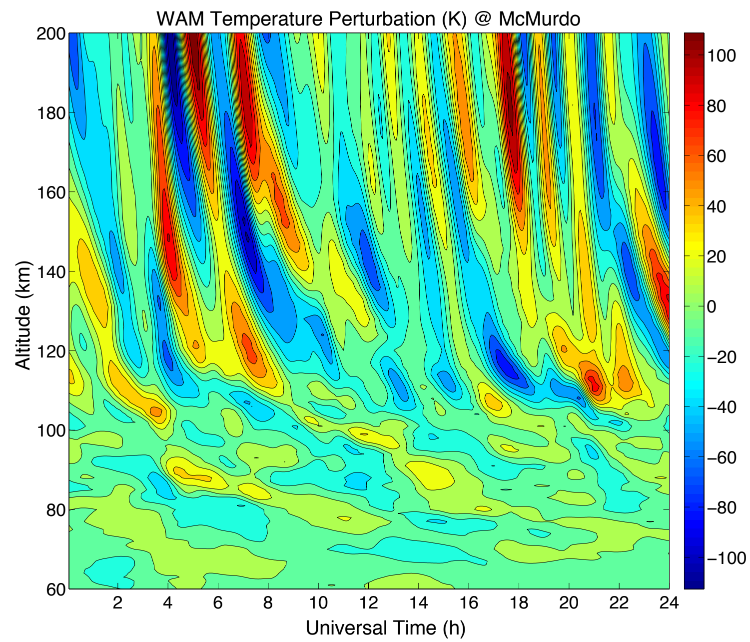




strong polar vortex
one of the many possible sources

What does it look like from a particular location?



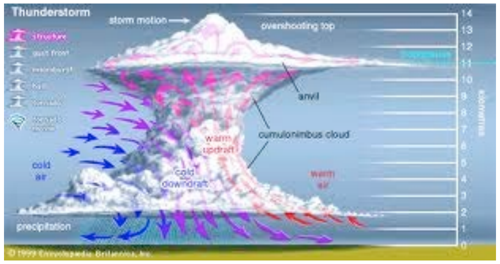


zonal (east/west) wind

neutral temperature

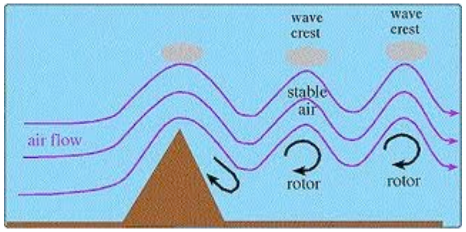
Some Lower Atmosphere Sources of Waves

- Tropical convection
- Hurricanes, tornados, thunderstorms



- Wind shear, frontal systems
- Large-scale ocean swell

- Orographic effects such as airflow over mountains



- Jet stream, polar stratospheric vortex
- Equatorial Kelvin waves
- Ozone and water vapor absorption of solar radiation
- etc., etc., …………………………

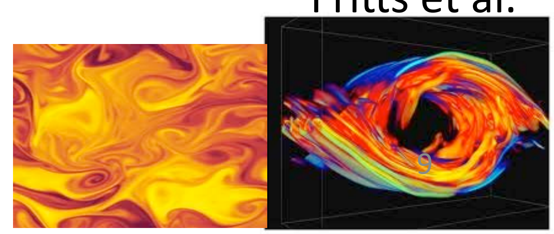
Some of the types of waves in the thermosphere

- Migrating and non-migrating tides
- Stationary planetary waves (and "normal modes" 2, 5, 10, 16 days?)
- Gravity waves (or buoyancy waves, restoring force is gravity)
- Inertial gravity waves (restoring force Coriolis C, geostrophic adjustment)
- Waves launched by meandering Rossby waves (latitude gradient in Coriolis)
- Acoustic waves (or sound waves)

Waves that can propagate vertically grow in amplitude in the increasingly rarified atmosphere

Some waves that get to the thermosphere have sufficiently large amplitudes that they can break causing mixing, and deposit heat and momentum.

Fritts et al.

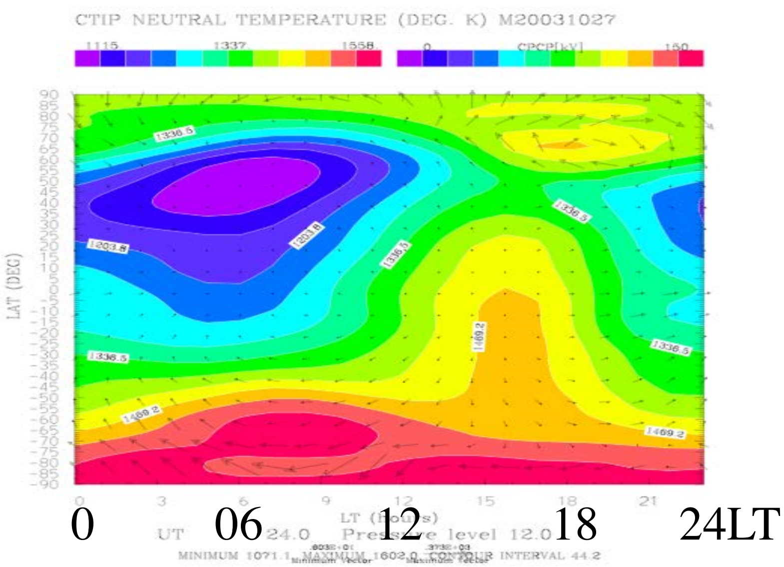


Traditionally these breaking gravity waves are the source of turbulence and the main source of mixing in the thermosphere

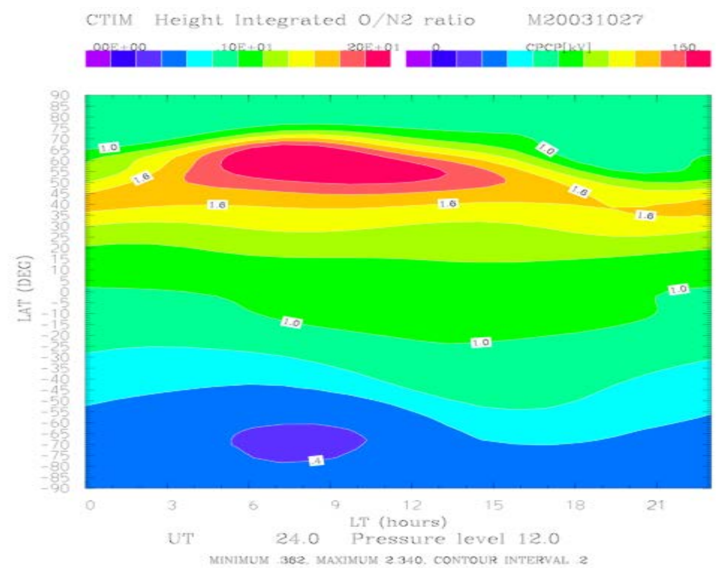
What mixing processes are in T-I models?

00UT

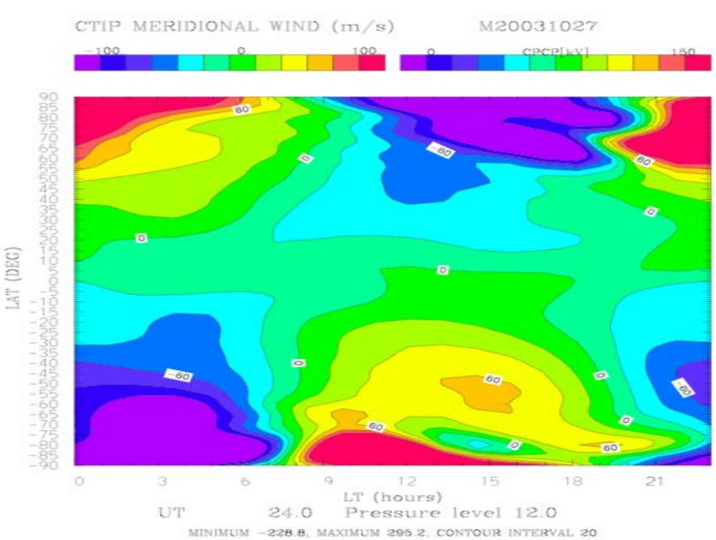
Temperature



Height-integrated O/N_2 ratio



Meridional wind



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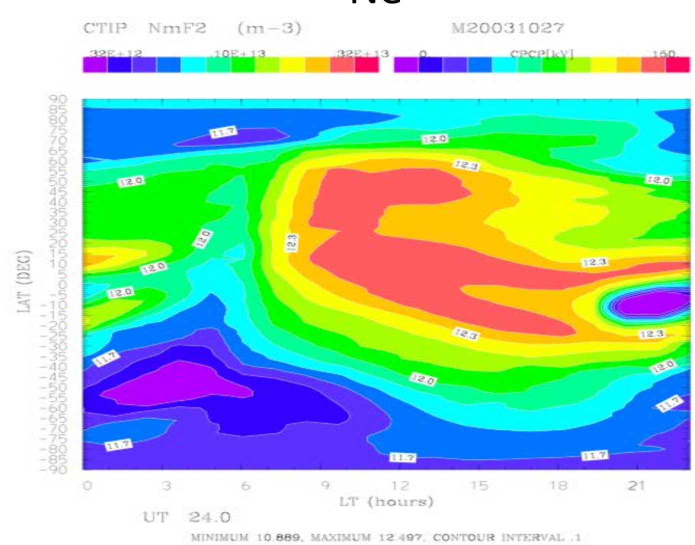
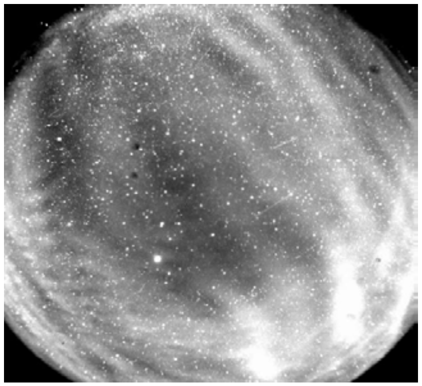
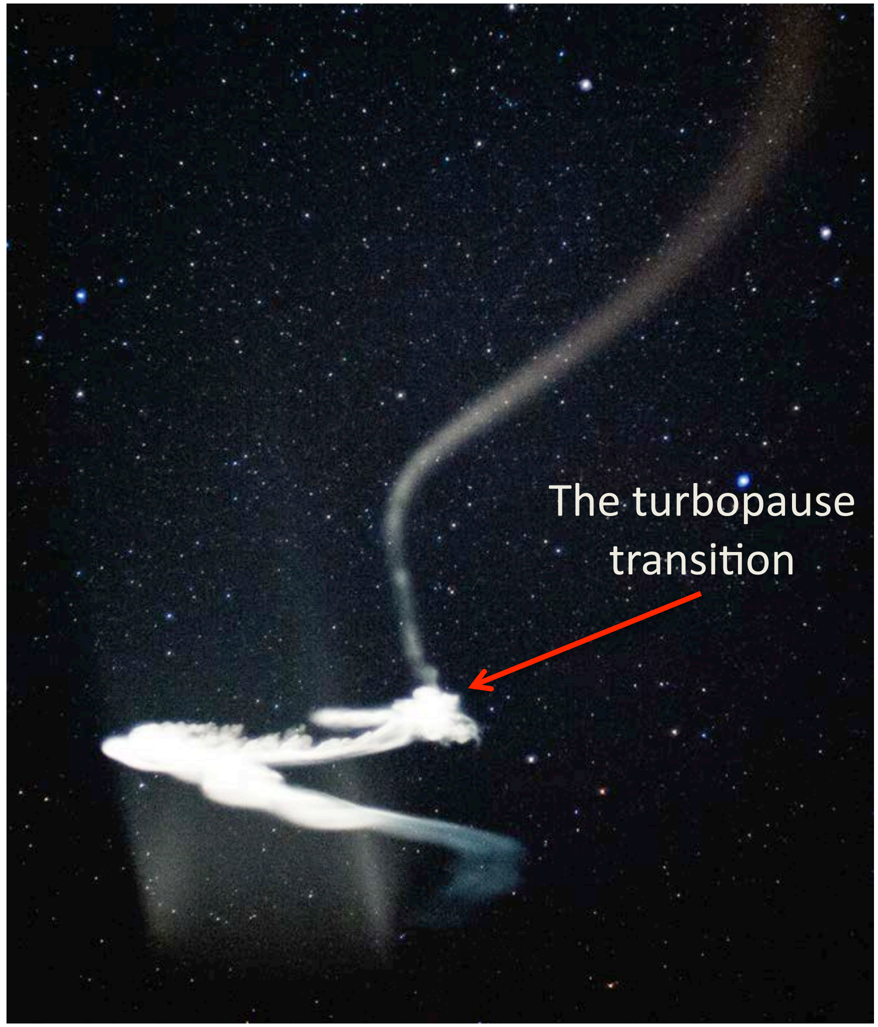


The Turbopause Transition



All-sky movie of gravity waves from Bear Lake Observatory. The night sky as seen in near-infrared OH emission showing bands and ripples rolling by at ~90 km altitude, and the Milky Way rising.

Courtesy: Mike Taylor and Dominique Pautet



Trimethyl aluminum trail released by rocket launched from Wallops Island.

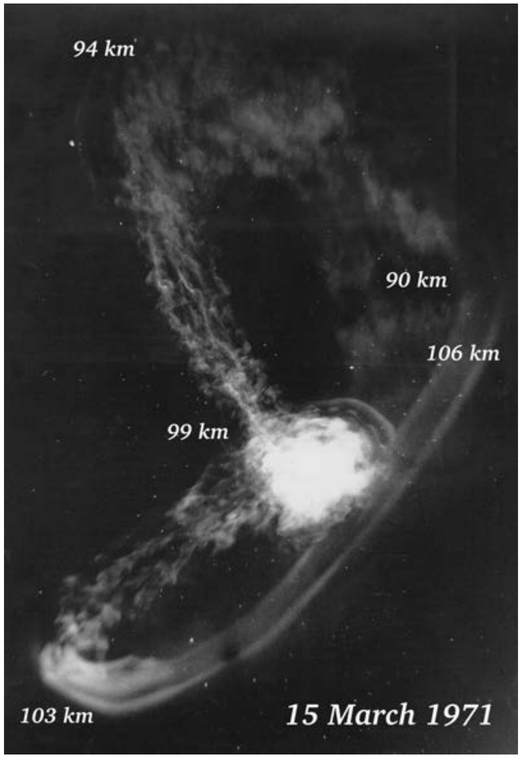
Courtesy Miguel Larsen

Conventional wisdom:

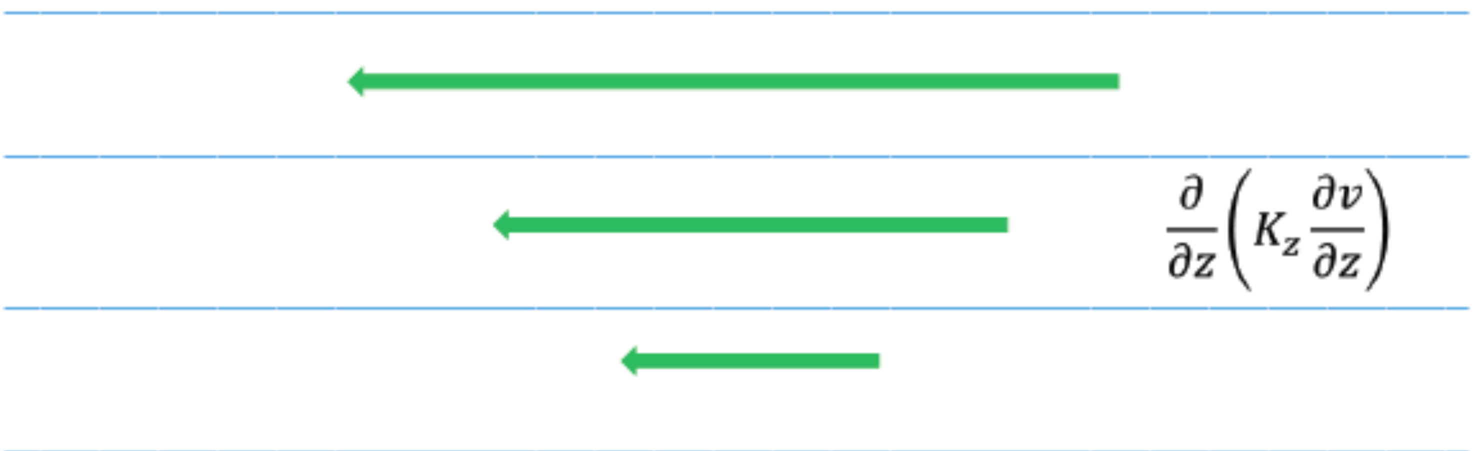
Gravity wave breaking and mixing below the turbopause height near ~110 km

Laminar flow above the turbopause with molecular diffusion - separation of heavy and light species in altitude

Transition from turbulent to laminar flow



Eddy Diffusion



$$K_z \frac{\partial v}{\partial z}$$

$$\frac{\partial}{\partial z}\left(K_z \frac{\partial v}{\partial z}\right)$$

$$K_z \frac{\partial v}{\partial z}$$

K_z

- Rate at which momentum, energy, or species diffuse between layers
- Parameterization of mixing processes (e.g., turbulence, gravity wave breaking)
- Can be different for each parameter
  - Schmidt # —ratio of momentum to mass diffusivity
  - Prandtl # —ratio of momentum to heat diffusivity
- K_z is not a physical process

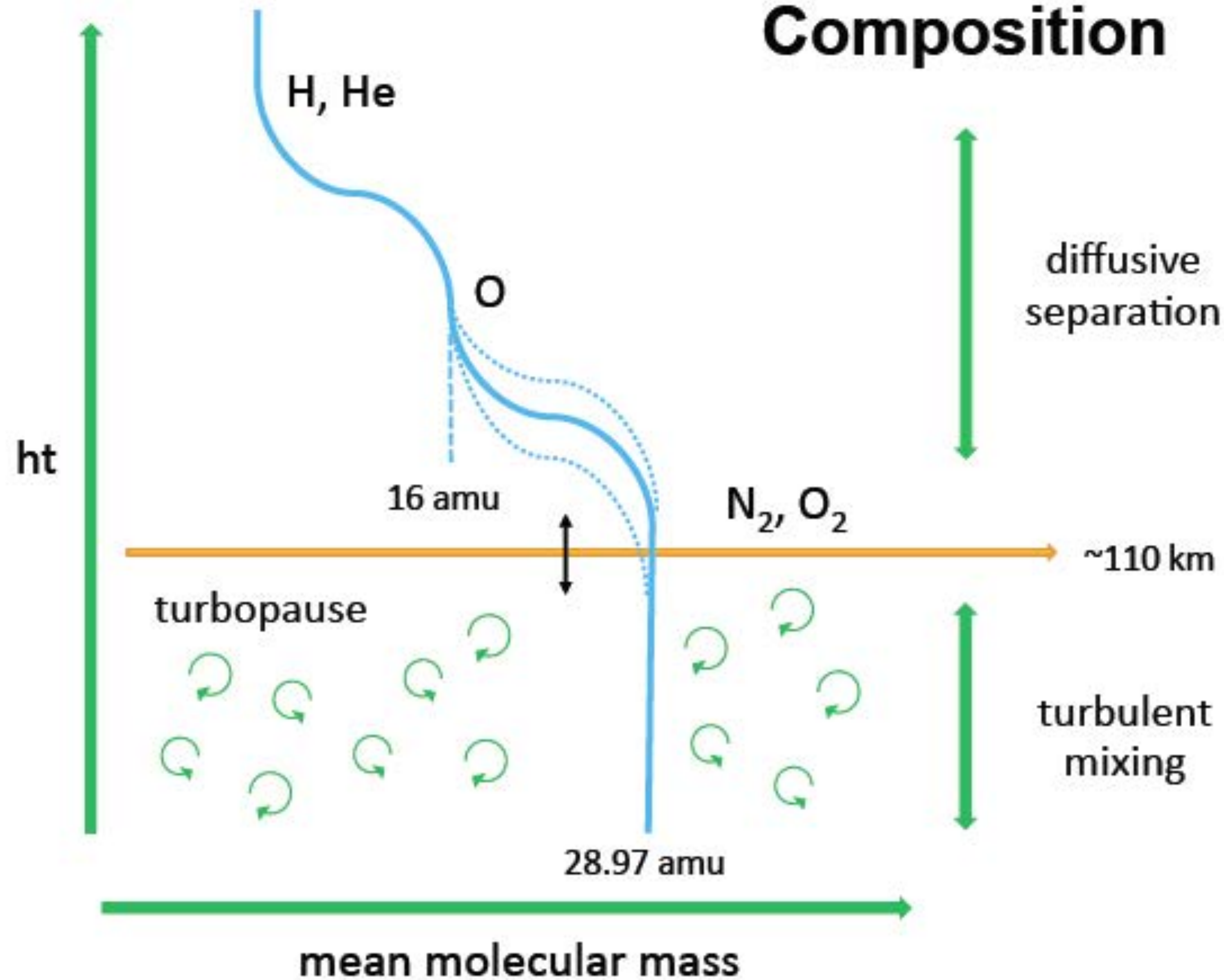
$$g \frac{\partial}{\partial p}\left[(\mu_m + \mu_T) \frac{p}{H} \frac{\partial}{\partial p} V_\theta \right]$$

vertical viscosity

$$\frac{\partial \psi_i}{\partial t} = \frac{1}{\rho} m_i S_i - \overline{V} \cdot \nabla p \psi_i - \omega \frac{\partial}{\partial p} \psi_i - \frac{1}{\rho} \nabla \cdot (n_i m_i C_i) + \frac{1}{\rho} \frac{\partial}{\partial p} \left(K_T \frac{\partial}{\partial p} m \psi_i \right)$$

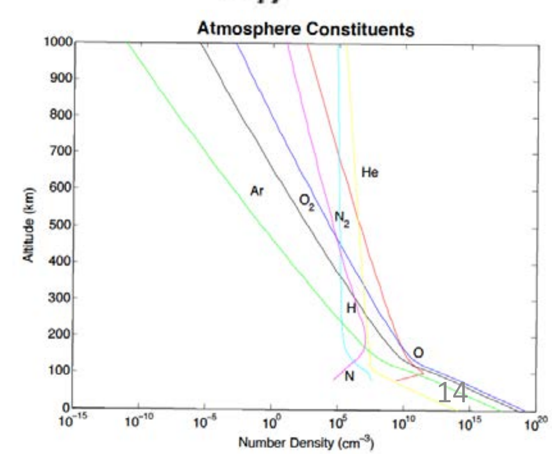
Ψ_i – species mixing ratios

eddy mixing



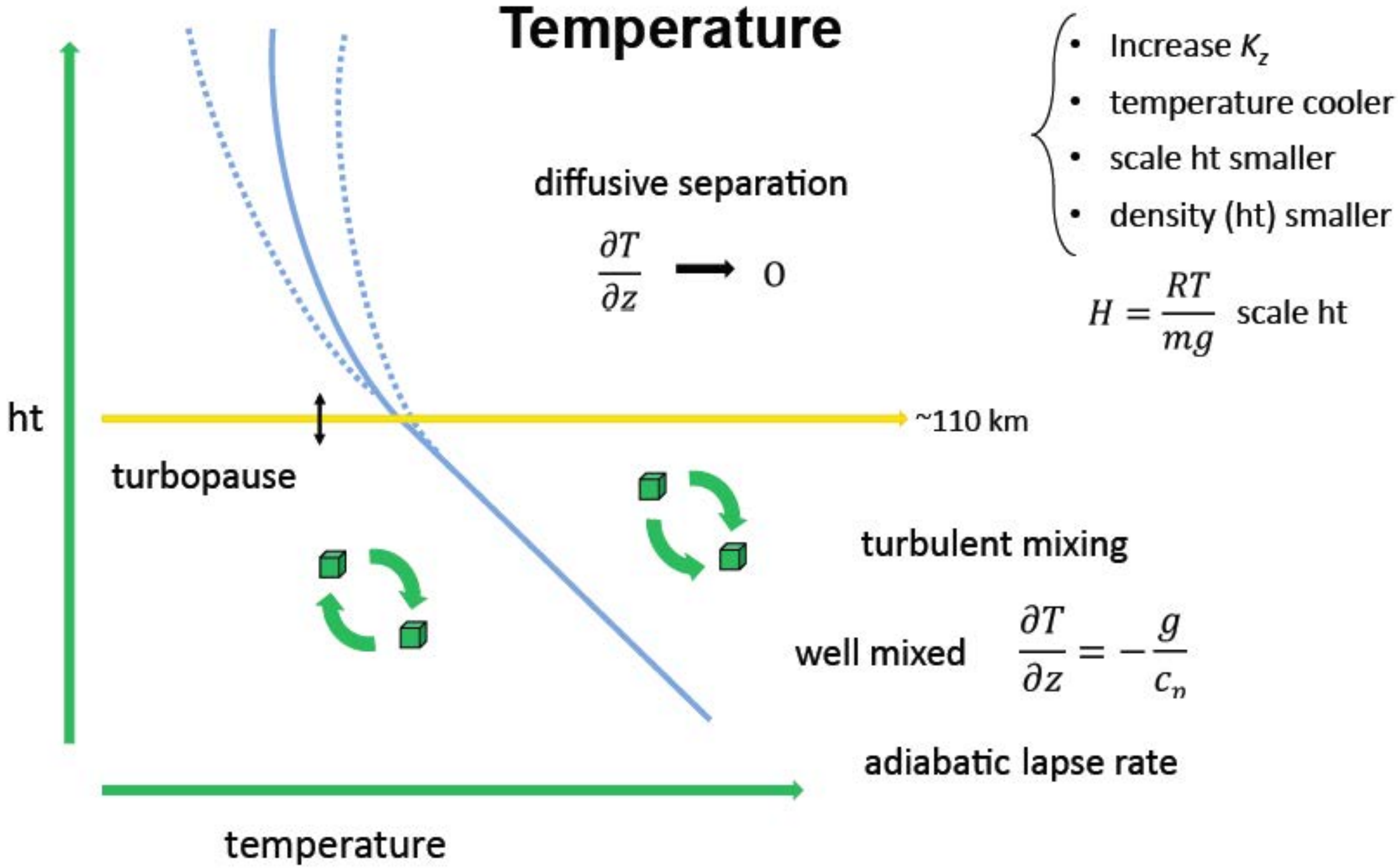
- Increase K_z
- Turbopause higher
- More mixing
- O/N_2 small
- Scale ht smaller
- Density (ht) smaller

$$H = \frac{RT}{mg} \quad \text{scale ht}$$



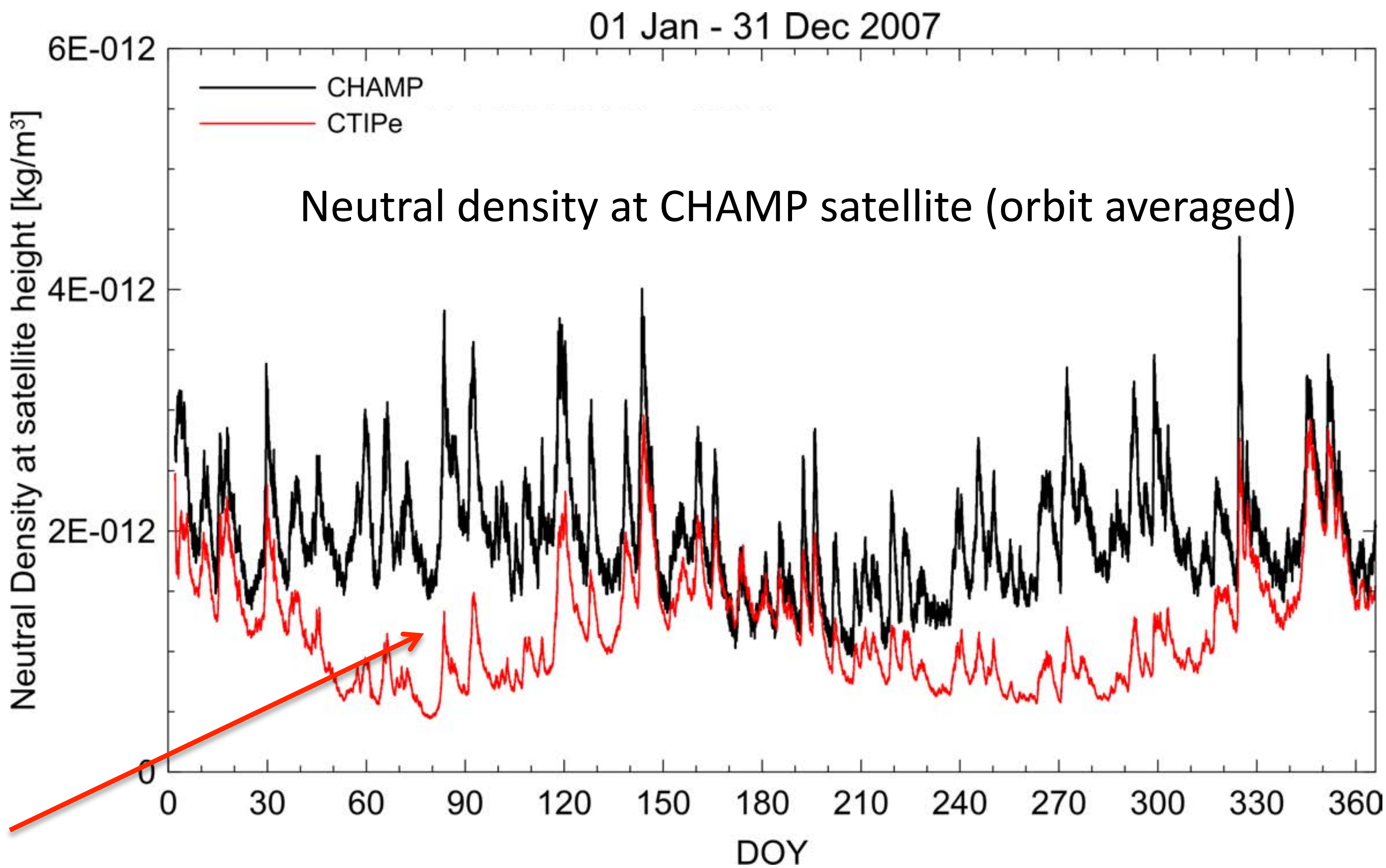
Vertical heat conduction

$$g\frac{\partial}{\partial p}\left[\left(\kappa_m+\kappa_T\right)\frac{p}{H}\frac{\partial}{\partial p}T\right]-g\frac{\partial}{\partial p}\frac{g\kappa_T}{c_p}$$



Challenge of the semi-annual variation

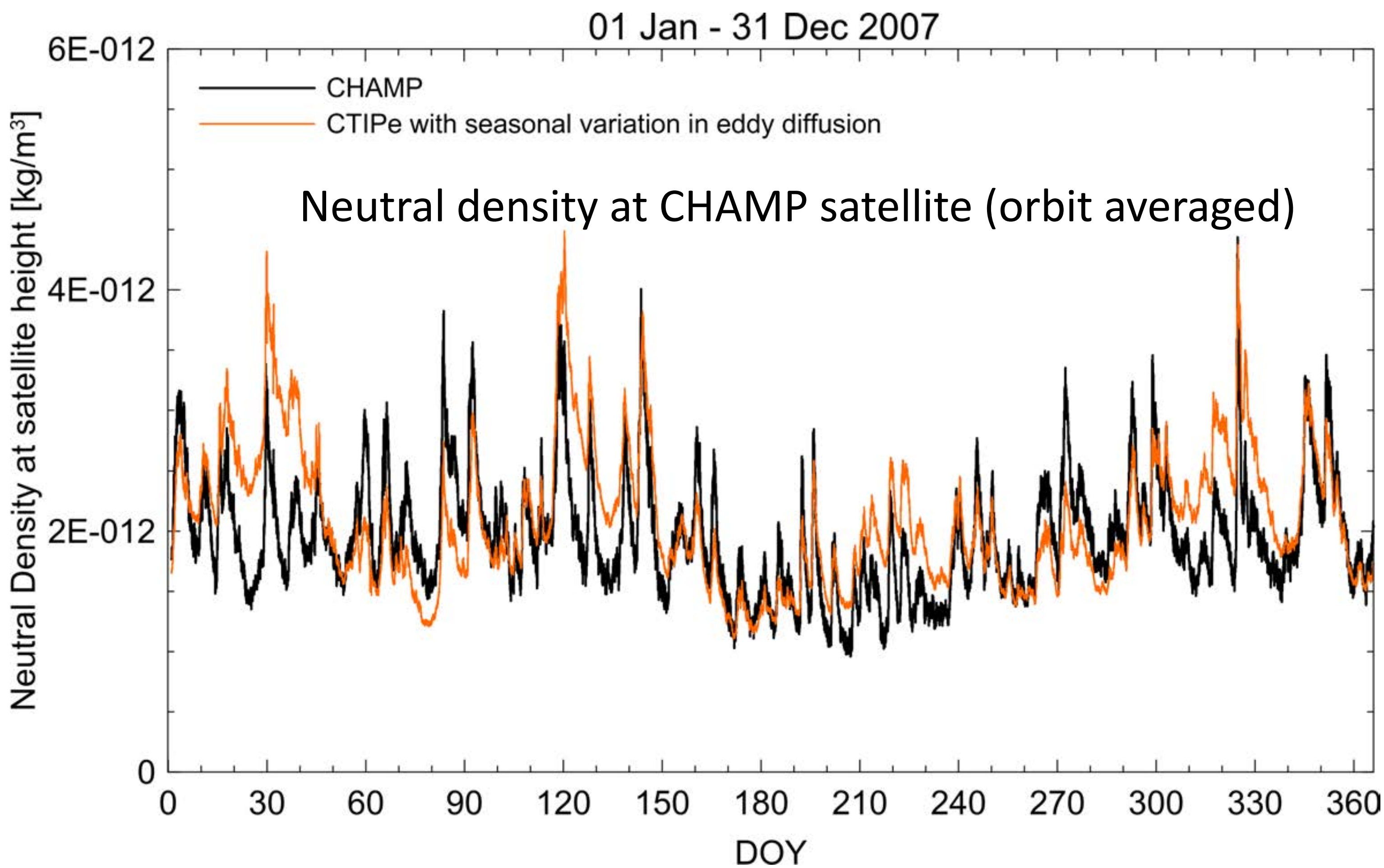
underestimate at equinox same magnitude as response to a storm



Discrepancy, after accounting for solar UV and EUV radiation and geomagnetic activity (magnetospheric sources)

Seasonal variation in eddy diffusion

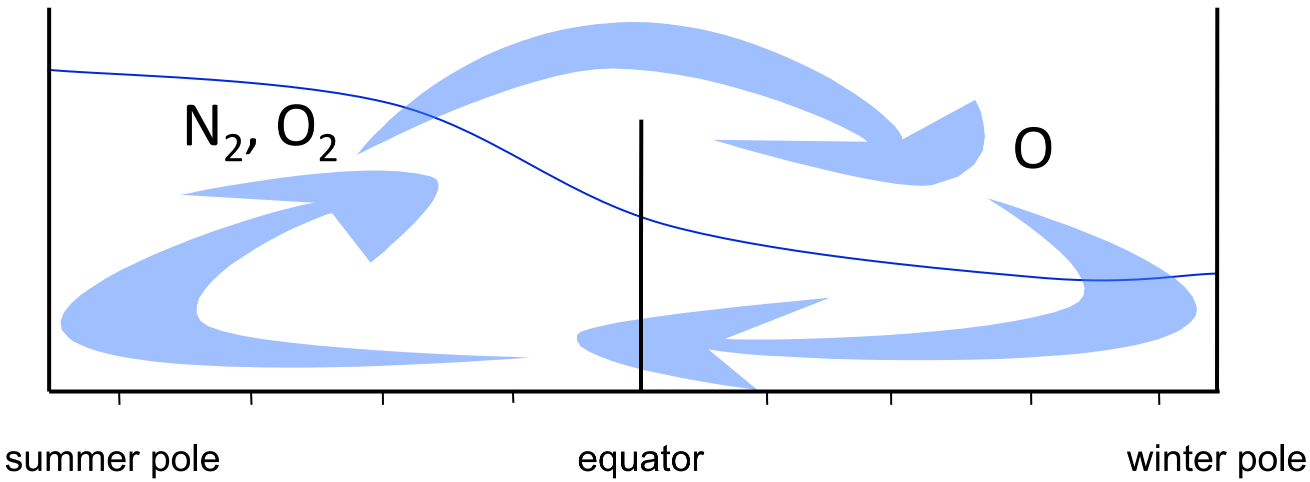
Mariangel Fedrizzi

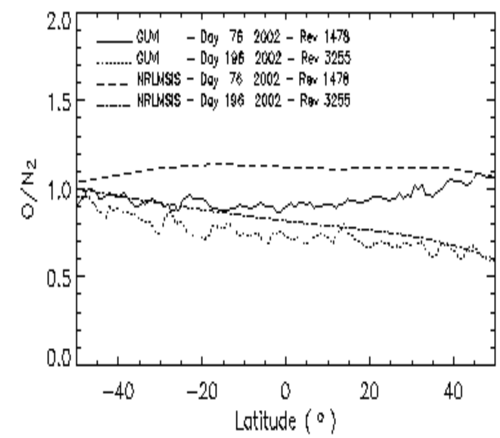


Liying Qian and Stan Solomon used same method used in TIE-GCM (with more harmonics)

Global Scale

Circulation at solstice mixes thermosphere like a global-scale eddy has the equivalent impact of turbulent eddies mixing N_2 and O_2 through the thermosphere (partially), mean mass (m) increases, O/N_2 ratio decreases, scale height H=RT/mg decreases density at fixed height decreases





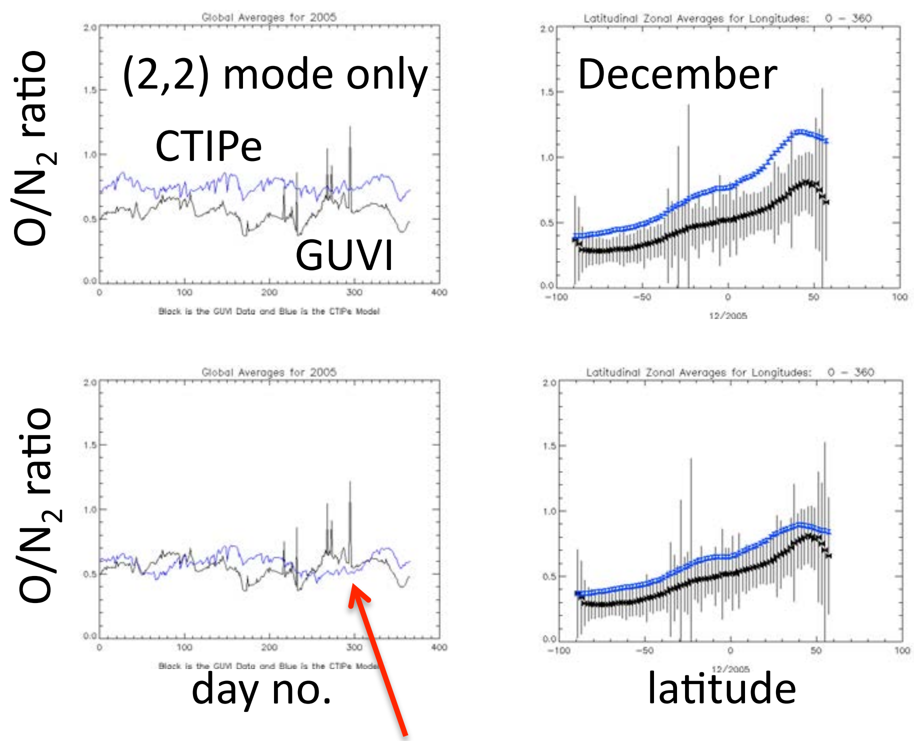
Thermospheric spoon: possible source of semi-annual variation
Shows you don't have to have "breaking waves" to mix

Impact of tides

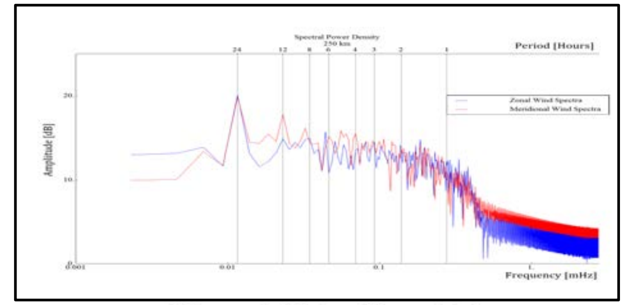
Impact of increasing the spectrum of tides in CTIPe on O/N_2 ratio (Olsen et al., 2013)

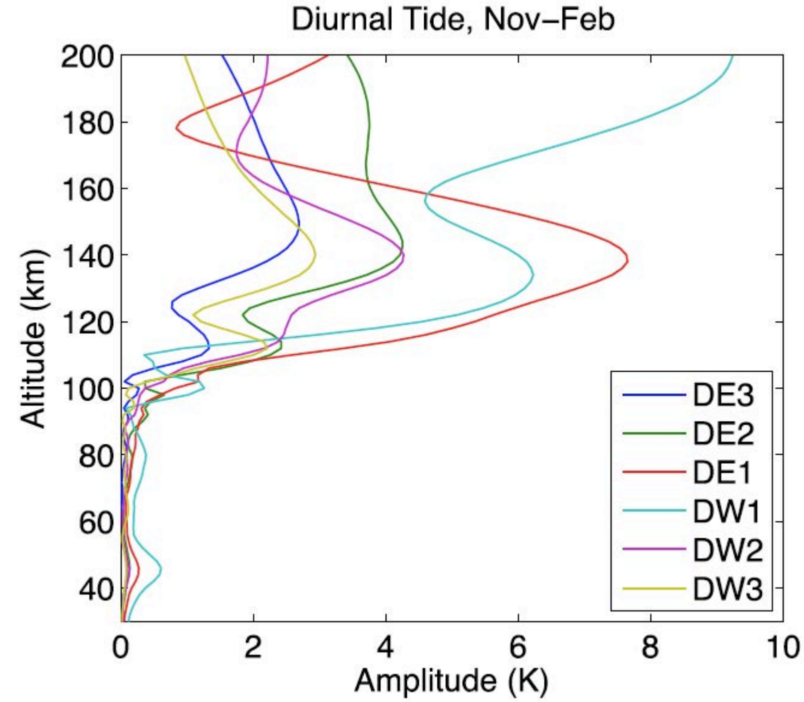
global mean

latitude structure



Uses (1,1), (2,2), (2,3), (2,4) and (2,5) modes from Global Scale Wave Model-09 (GSWM-09) Maura Hagan



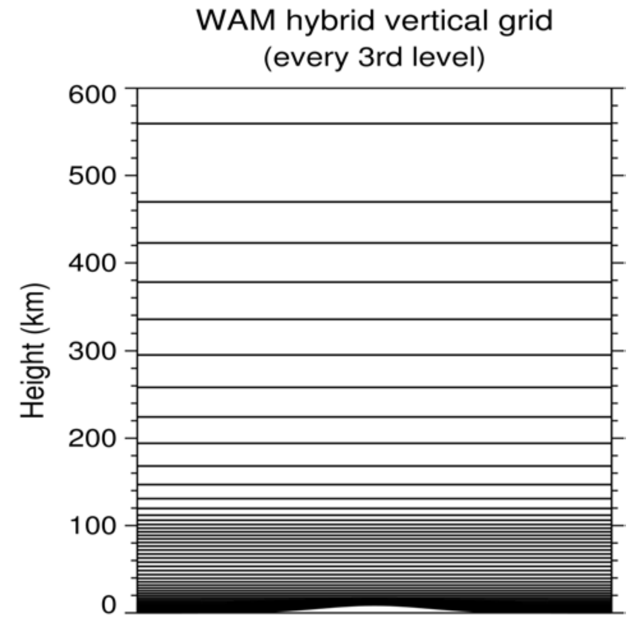


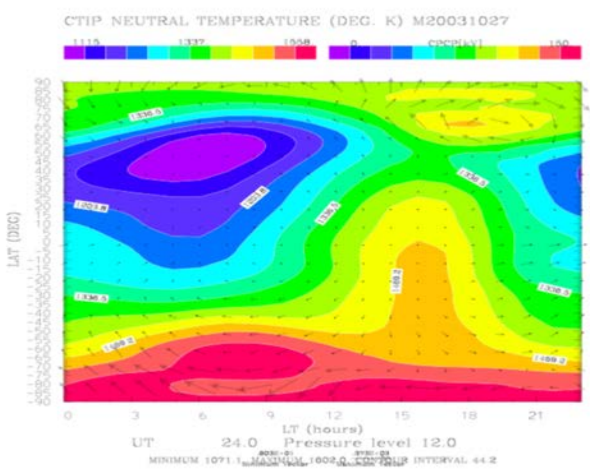
In reality spectrum is actually much richer, and many of the tidal modes peak in the lower thermosphere: What is the impact on thermospheric mixing?

Note: Siskind et al., (2013) showed that you could reduce K_z by a factor of 5 when the NOGAPS spectrum of non-migrating tides were introduced into TIEGCM

Whole Atmosphere Model (WAM)

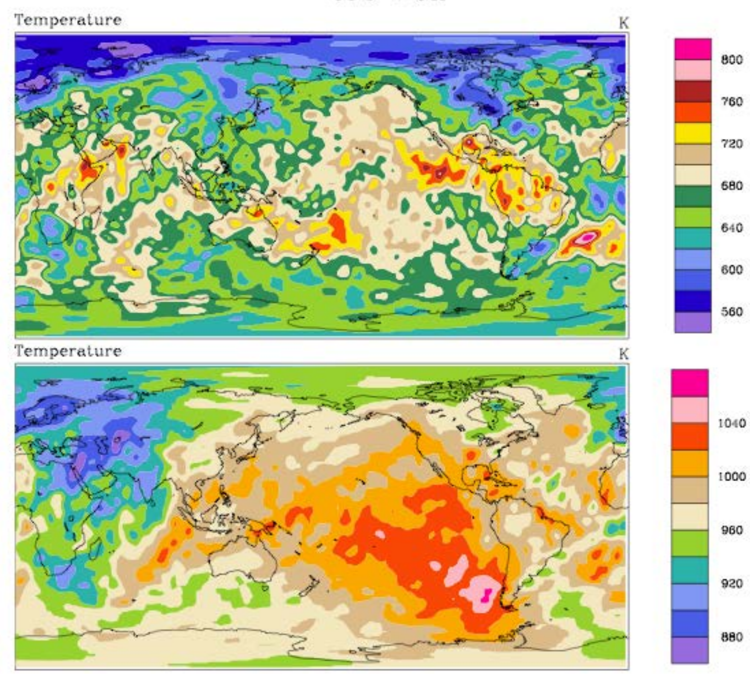
- Global seamless whole atmosphere model (WAM) 0-600 km, 0.25 scale height, 2° x 2° lat/long, T62, hydrostatic, 150 levels, 10-fold extension of Global Forecasting System (GFS) US weather model.
- O_3 chemistry and transport
- Radiative heating and cooling
- Cloud physics and hydrology
- Sea surface temperature field and surface exchange processes
- Orographic gravity waves parameterization
- Diffusive separation, ion drag, Joule heating, etc.,





CTIPe thermospheric temperature (like MSIS)

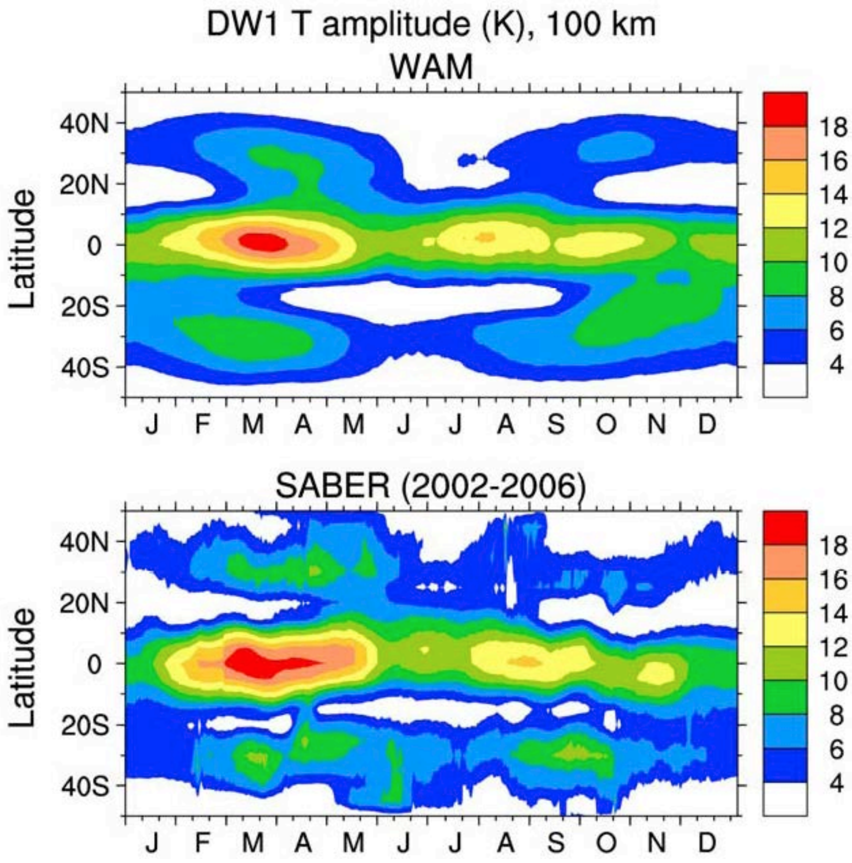
WAM
150 and 300
km altitude

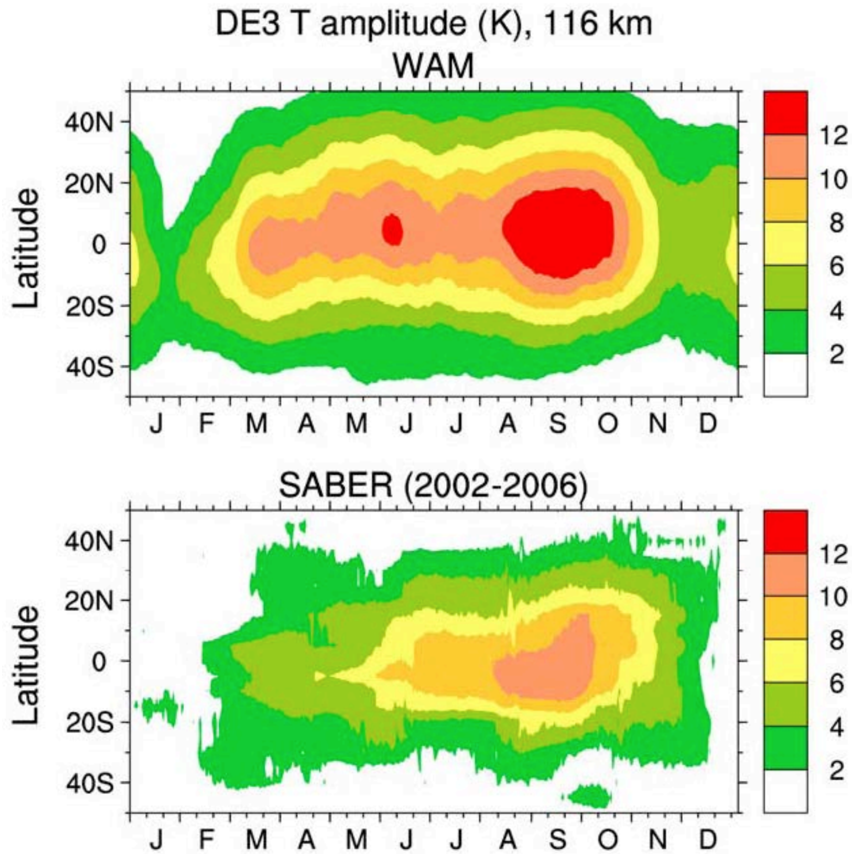


WAM global temperature

WAM agrees well with the diurnal migrating tide DW1 and the famous DE3

WAM model top: Akmaev et al. 2008





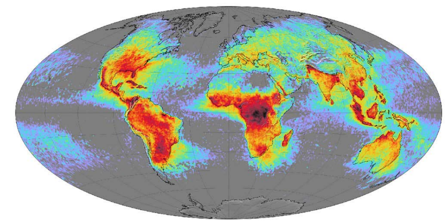
DW1

SABER observations below: Forbes et al. 2008

DE3

Tidal Nomenclature

Zonal wave number (number of waves around the Earth in longitude frame): Wave 1, 2, 3, etc.
Period (time to go through one cycle): Diurnal (D), Semi-diurnal (S), Ter-diurnal (T), etc.
harmonics of the 24 hour fundamental
Direction of propagation with respect to longitude:
eastward (E), westward (W), or stationary (fixed in in longitude)

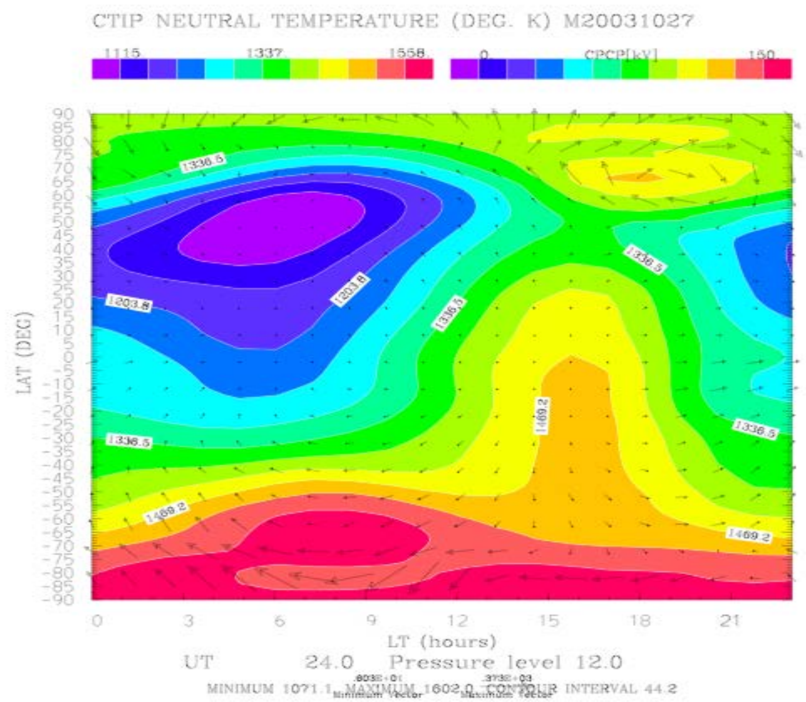


Planetary waves: W1, W2, W3, etc.
These make sense, e.g., topography, weather system move quite slowly in longitude, offset of geographic and geomagnetic poles generates a Wave 1 in longitude

Migrating tides: follow the motion of the Sun e.g., DW1, SW2, TW3

These make sense physically too and are intuitive, but the nomenclature is cumbersome.

In a local-time frame it is simply a diurnal variation, or semi-diurnal, or ter-diurnal, etc.

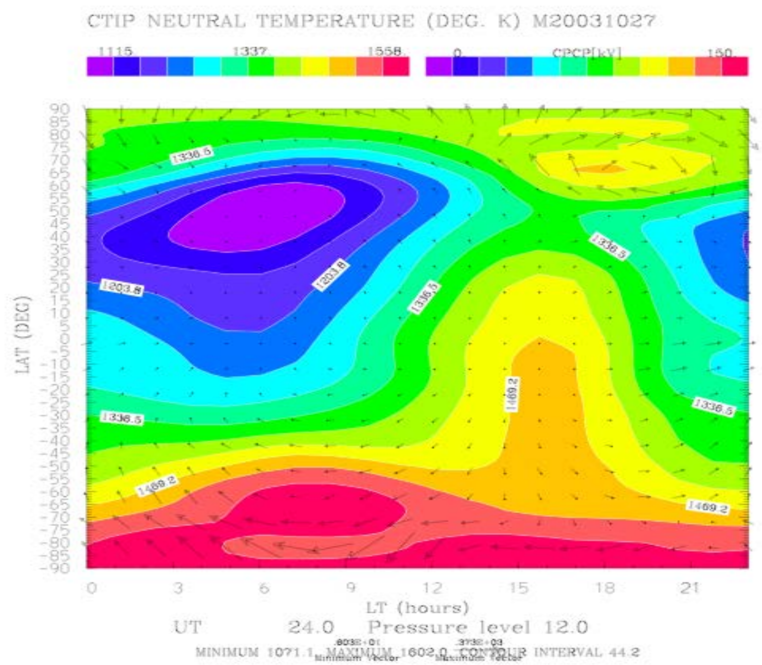


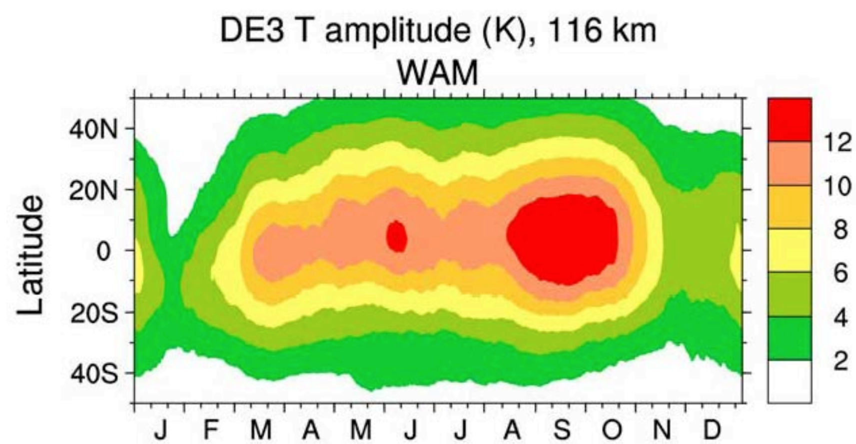
“Migrating” tidal nomenclature

Migrating tides, follow Sun: DW1, SW2, TW3

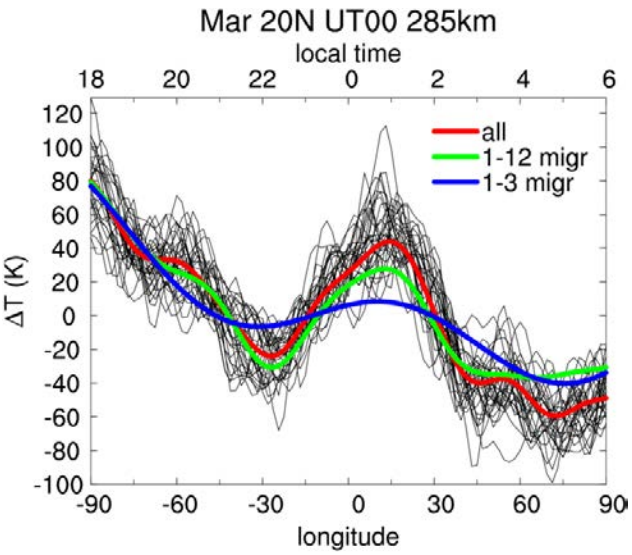
In tidal nomenclature: “Normal” or migrating diurnal tide, wave has one peak and trough, tied to local time, e.g., thermosphere temperature, peak ~4pm every day, minimum at ~4am
Wave 1 moves with the Sun, so it has to propagate or “migrate” westward to follow Sun as Earth rotates once every 24 hrs, therefore has to be DW1 in tidal nomenclature
“Normal” semi-diurnal tide, wave has 2 peaks, moving westward every 12 hours to keep up with the apparent motion of the Sun, so has to be SW2, same for TW3 etc.

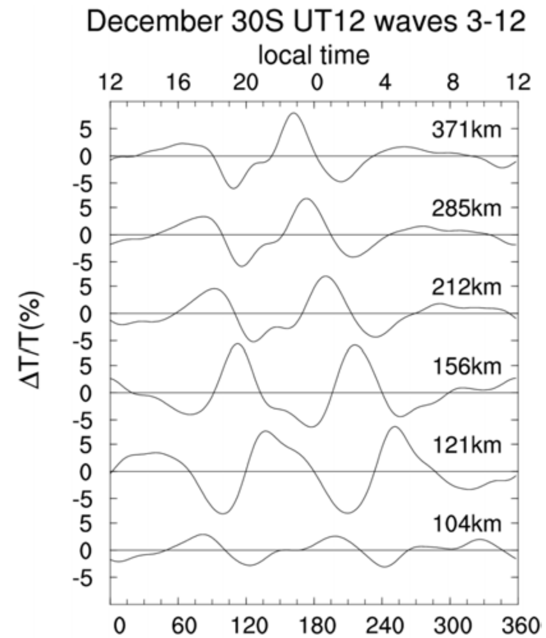
Non-migrating tides: all the others, not always intuitive, e.g., DE3: Why would a wave propagate eastward?

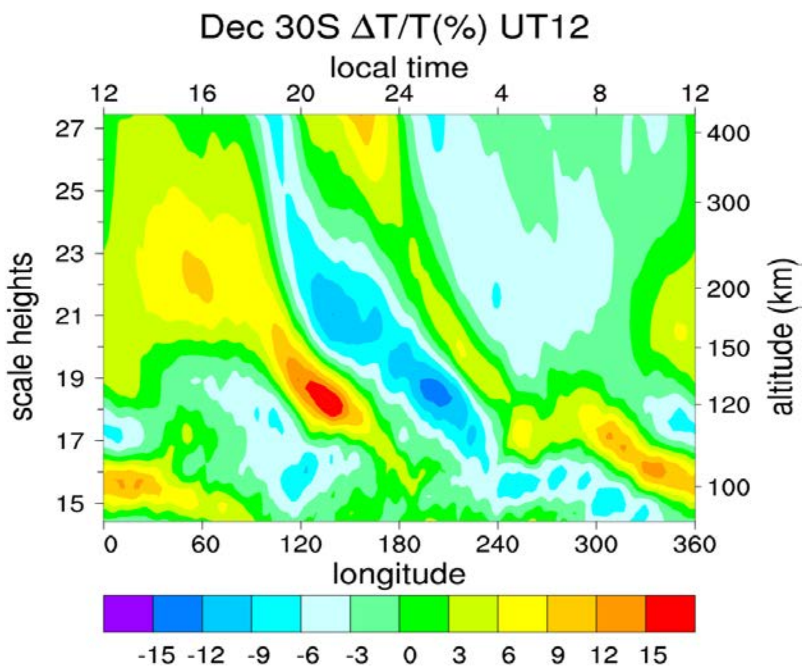


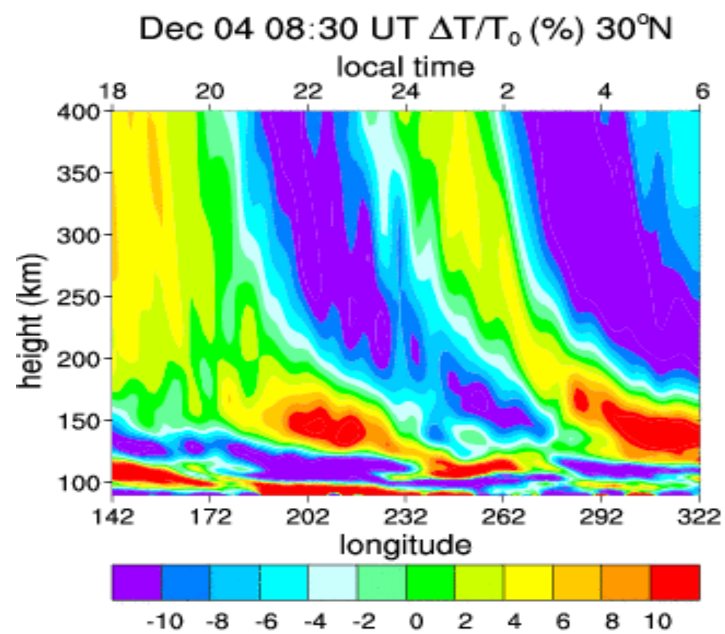


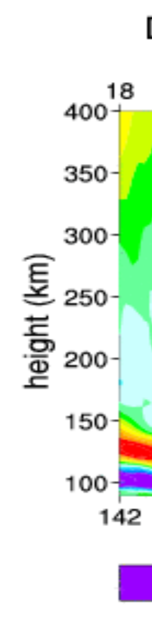
WAM produces the Midnight Temperature Maximum



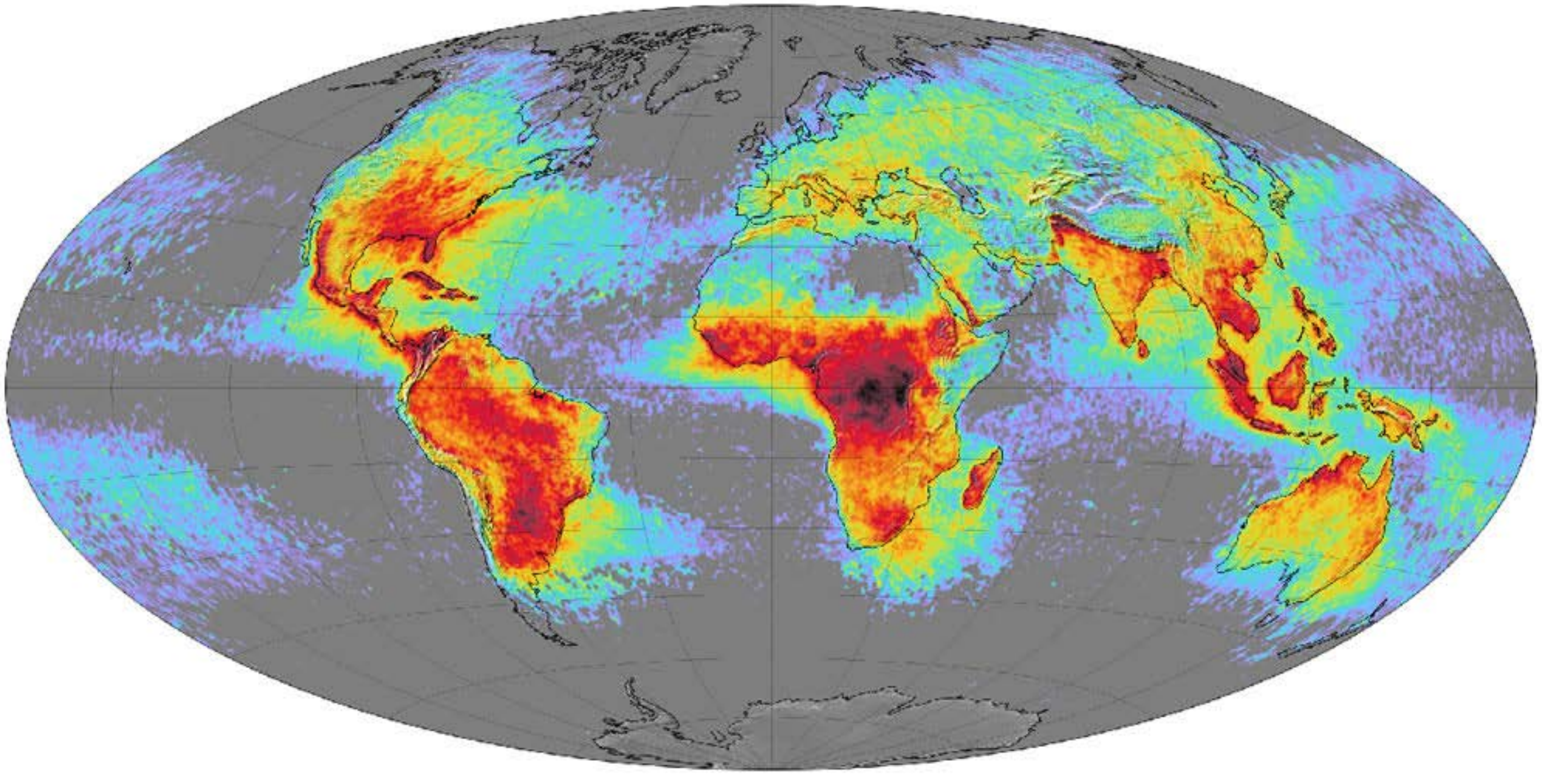








So what about the famous DE3



Lightning strikes from convective storms, signature of latent heat release:
Looks like three peaks in longitude: wave 3
Illuminated/modulated by the Sun every 24 hours: diurnal

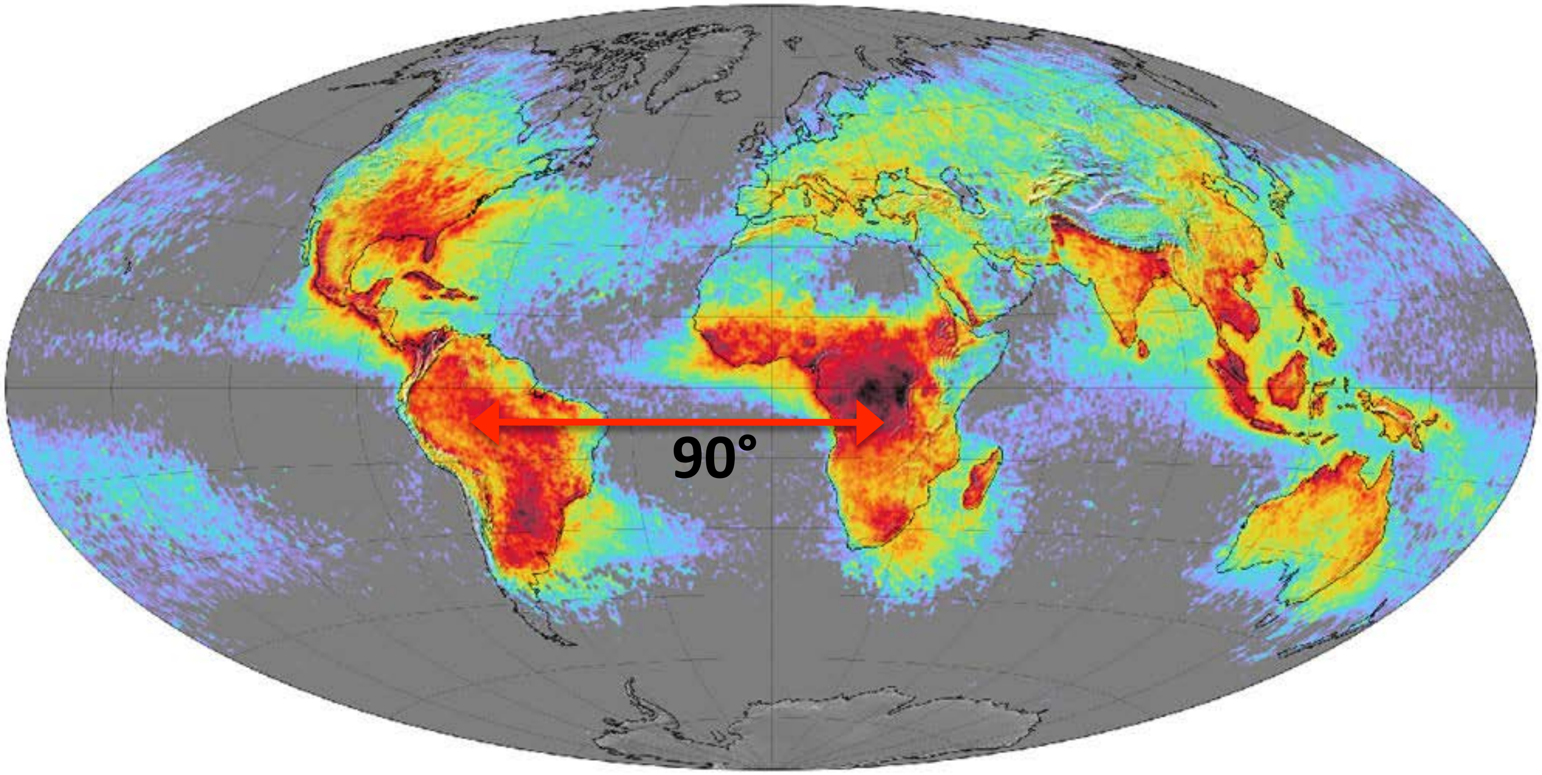
Therefore might expect D*3 Why DE3

$\Omega = 2\pi/24$ $\cos(\Omega t + \lambda)\cos 3\lambda$ ---> $\cos(\Omega t + 4\lambda) + \cos(\Omega t - 2\lambda)$

Forbes Nicolet Lecture

eastward propagating W2 diurnal DE2
not DE3

So what about the famous DE3



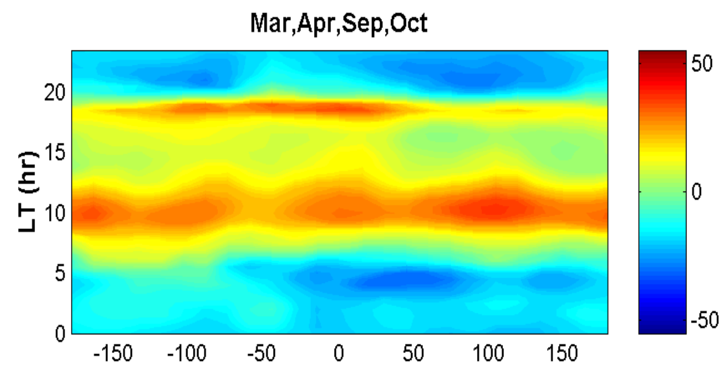
Lightning strikes from convective storms, signature of latent heat release:
Maybe four (not three) peaks in longitude: wave 4?
Illuminated by the Sun every 24 hours: diurnal

Now we can see where a DE3 might come from:

$$\cos(\Omega t + \lambda)\cos 4\lambda \quad \text{--->} \quad \cos(\Omega t + 5\lambda) + \cos(\Omega t - 3\lambda)$$

eastward propagating W3 diurnal DE3

DE3 winds drives E-region dynamo to produce tidal signatures in nightside Equatorial Ionospheric Anomaly (EIA) Why 4 peaks at fixed local time?



3 peaks of wave 3
Move one peak eastward in 24 hours

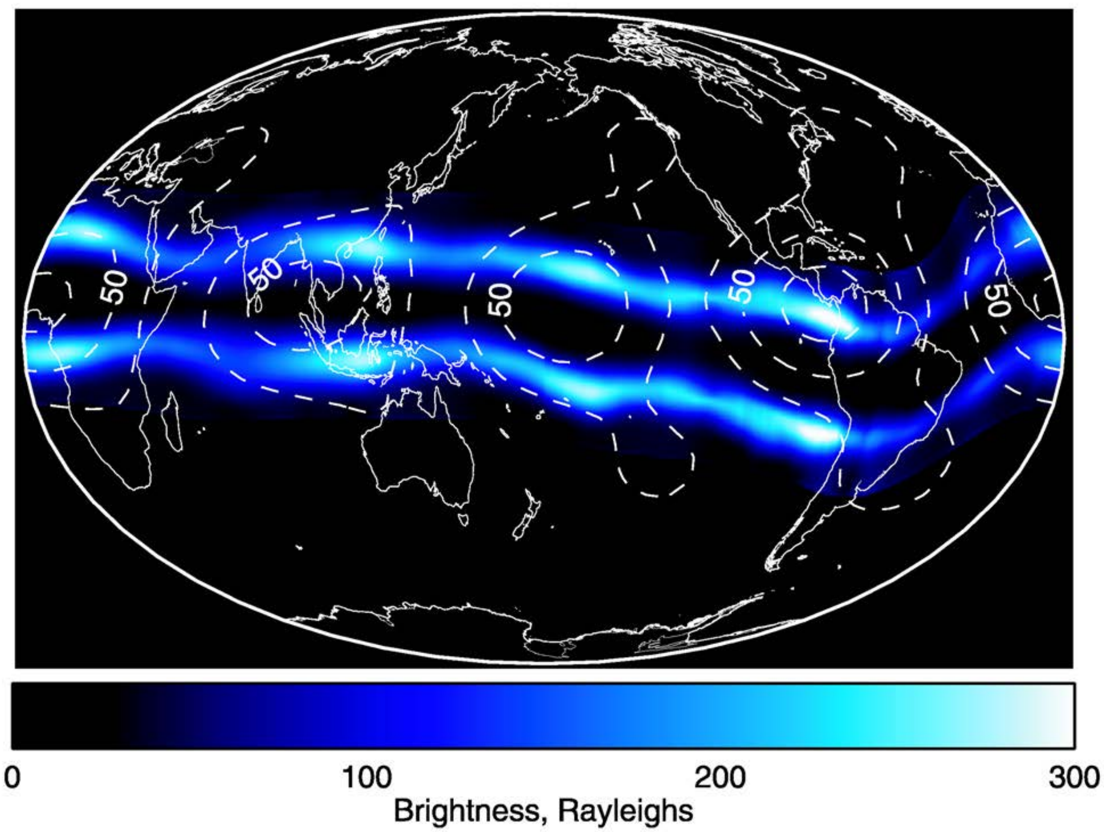
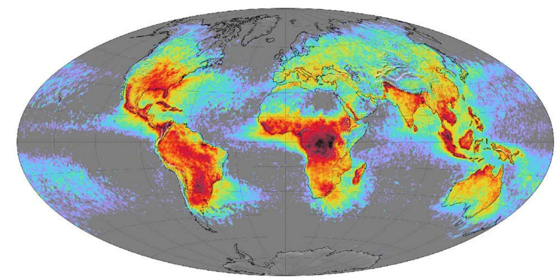
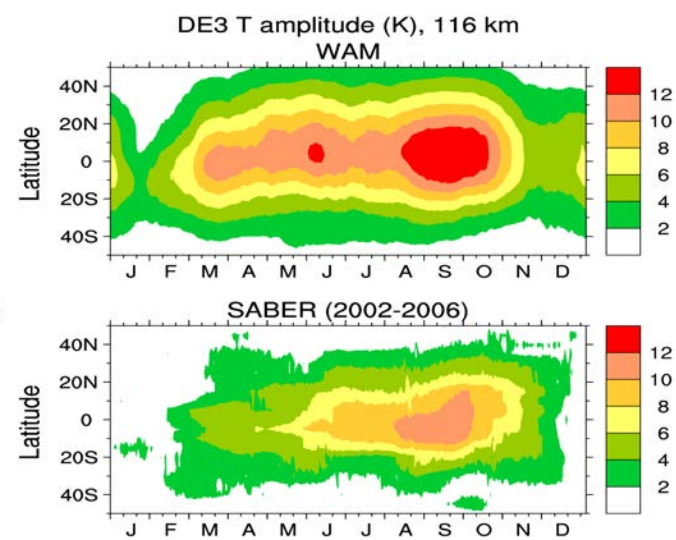
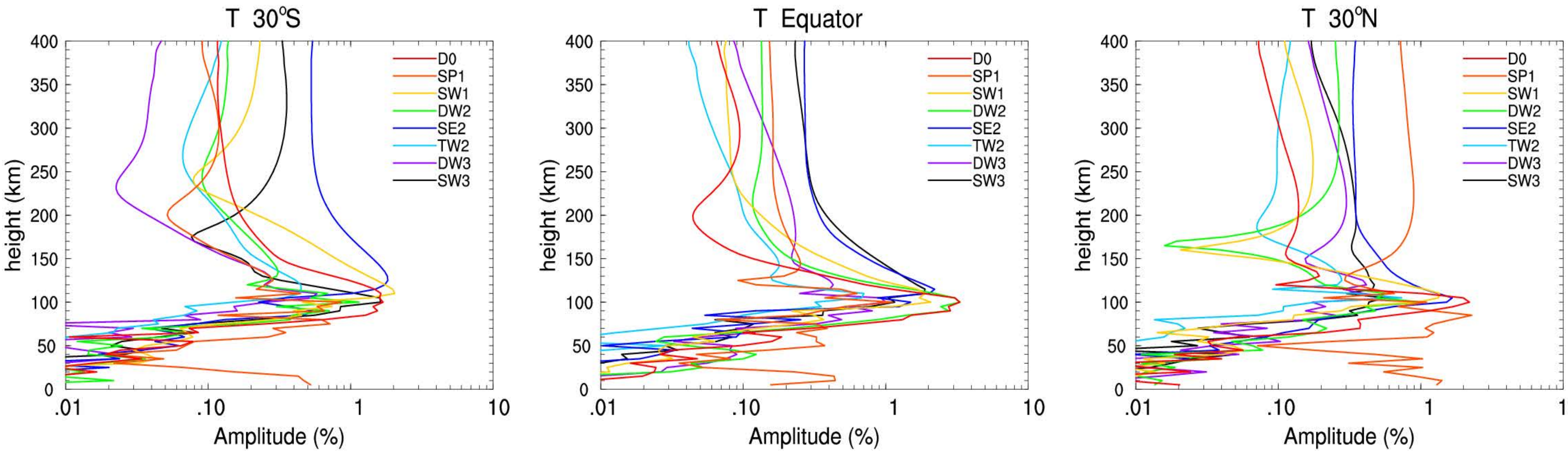


IMAGE composite of 135.6-nm O airglow (350-400 km) for March-April 2002 and magnitude of tidal temperature oscillations at 115 km (Immel et al., 2006).

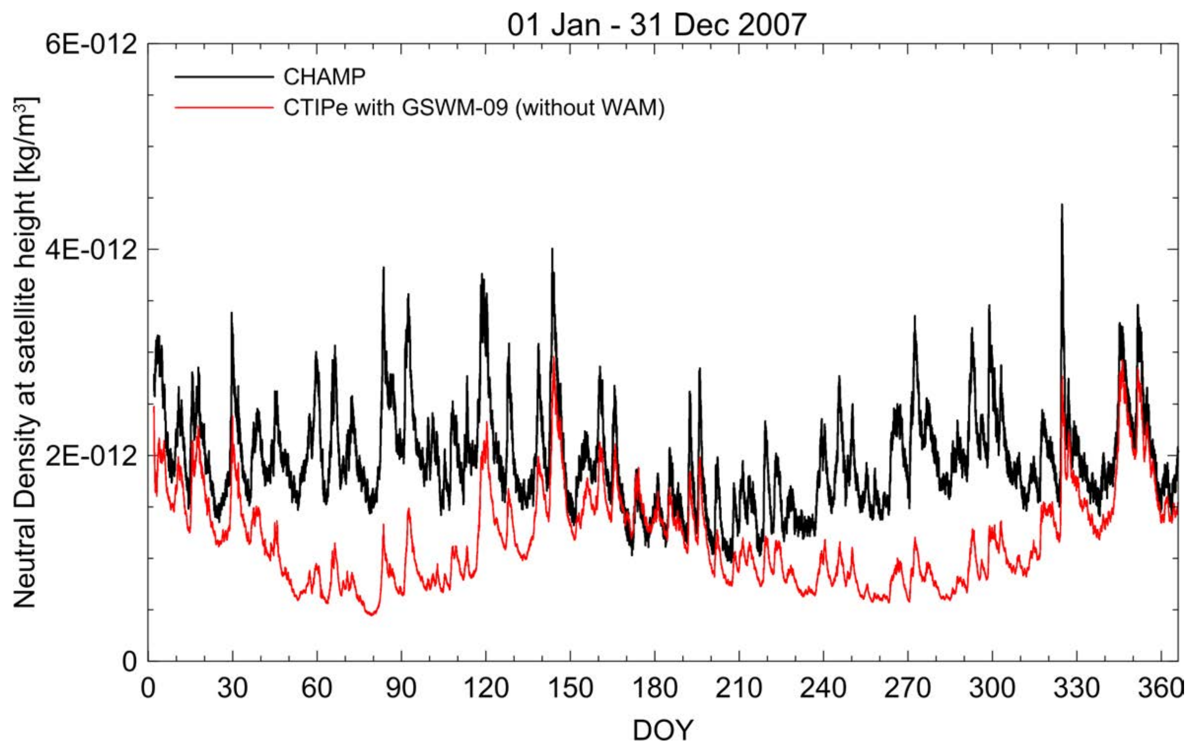




Back to the semi-annual variation

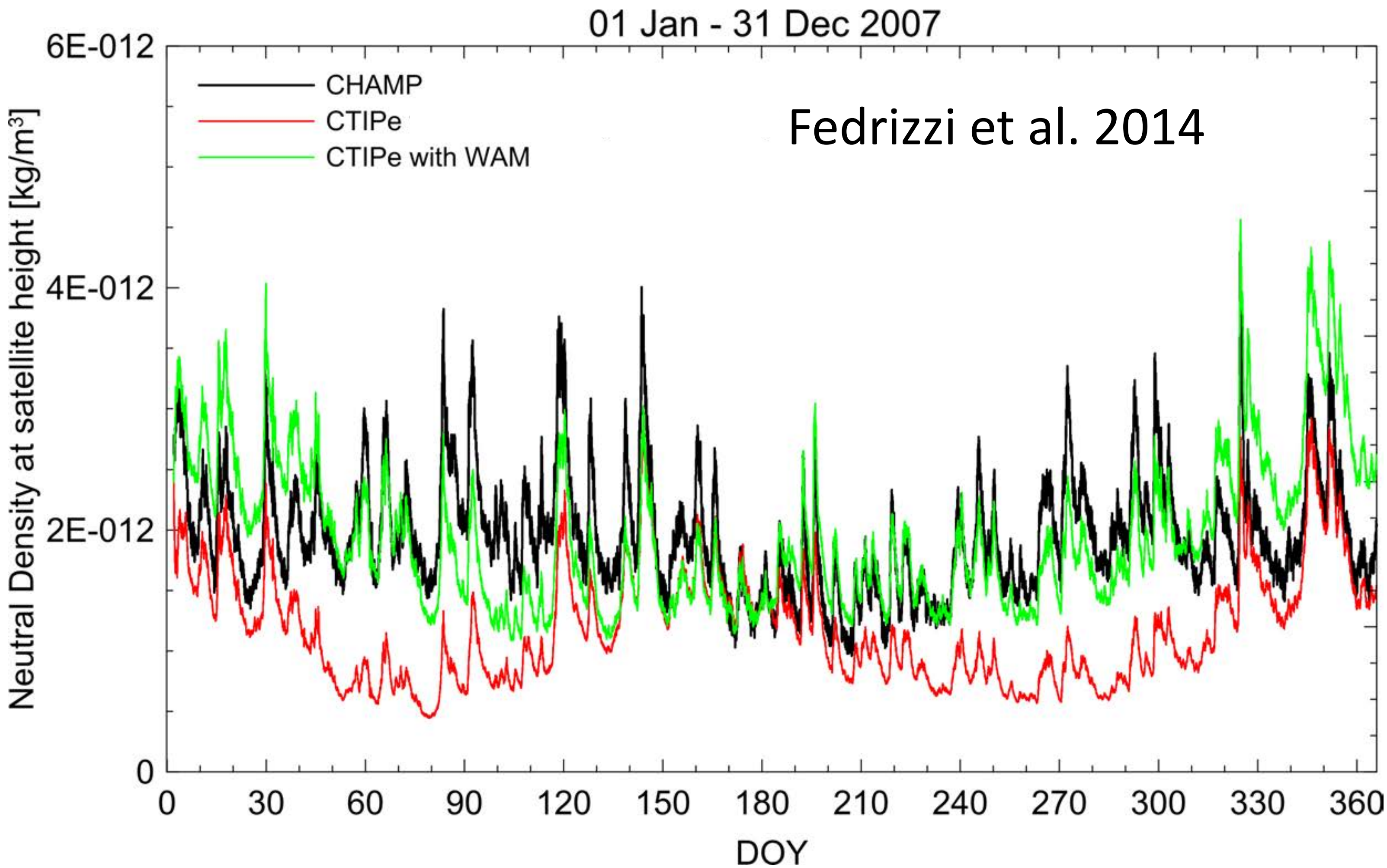


What is the impact of this more complete spectrum of migrating and non-migating tides?

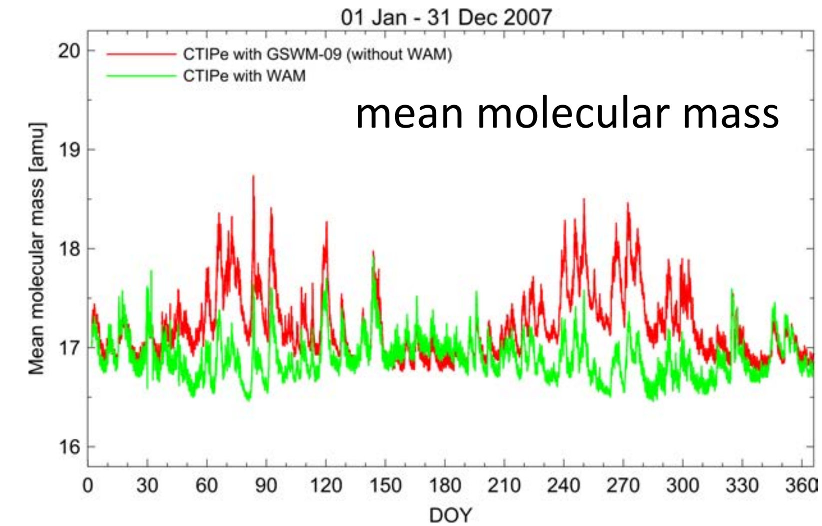


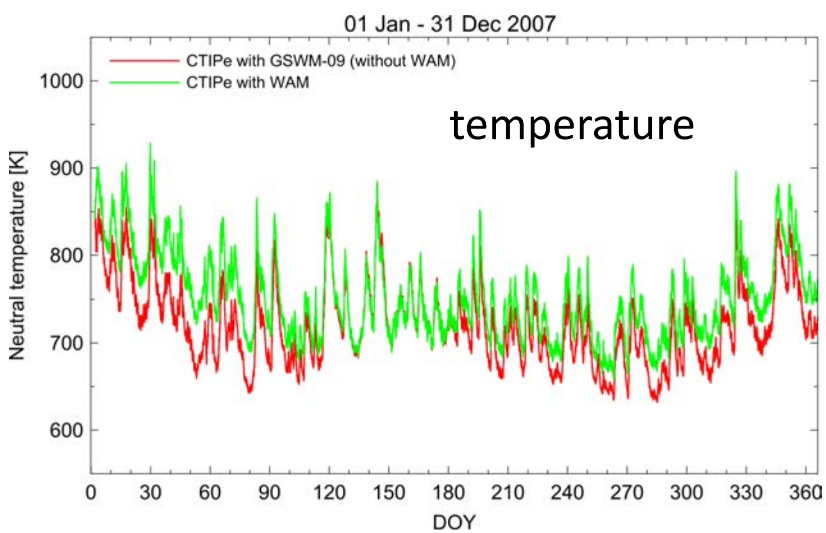
CTIPe driven by WAM fields below 97 km

replace limited set of basic climatological tides at lower boundary with monthly mean WAM fields of T, U, V, ht at each UT hour (zonal means + tides)

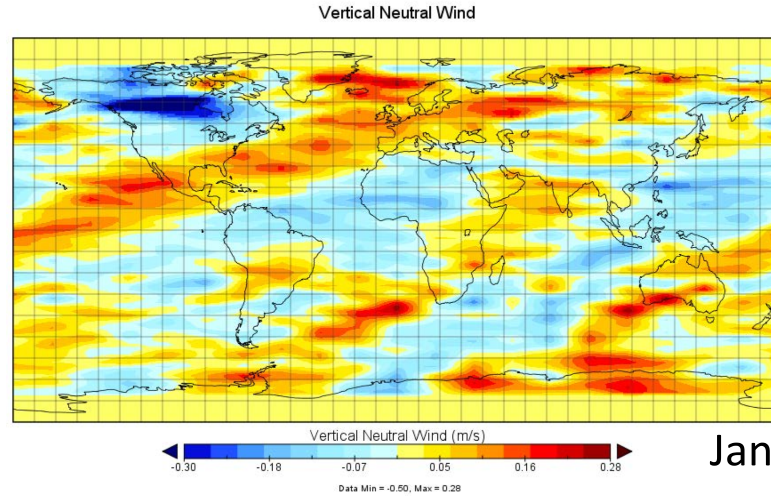


orbit average

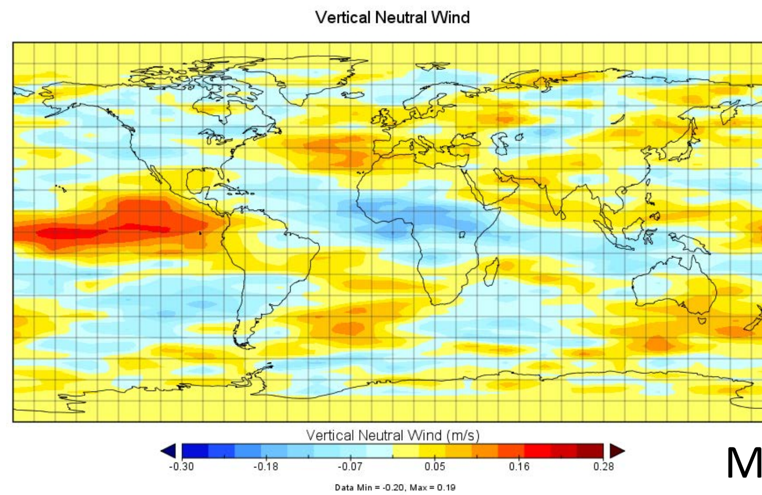




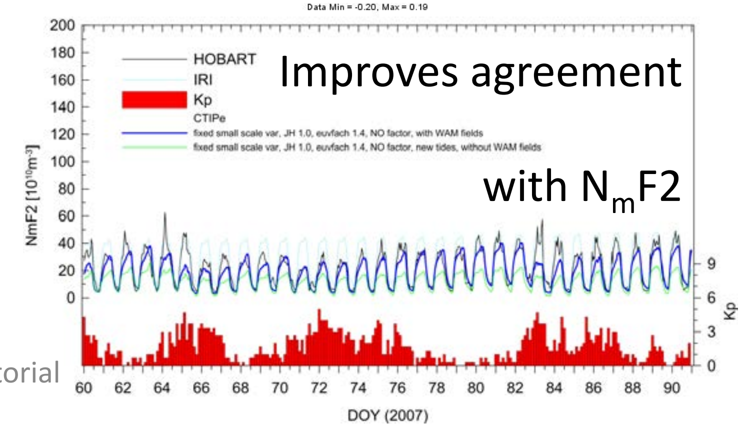
along champ orbit



January



March

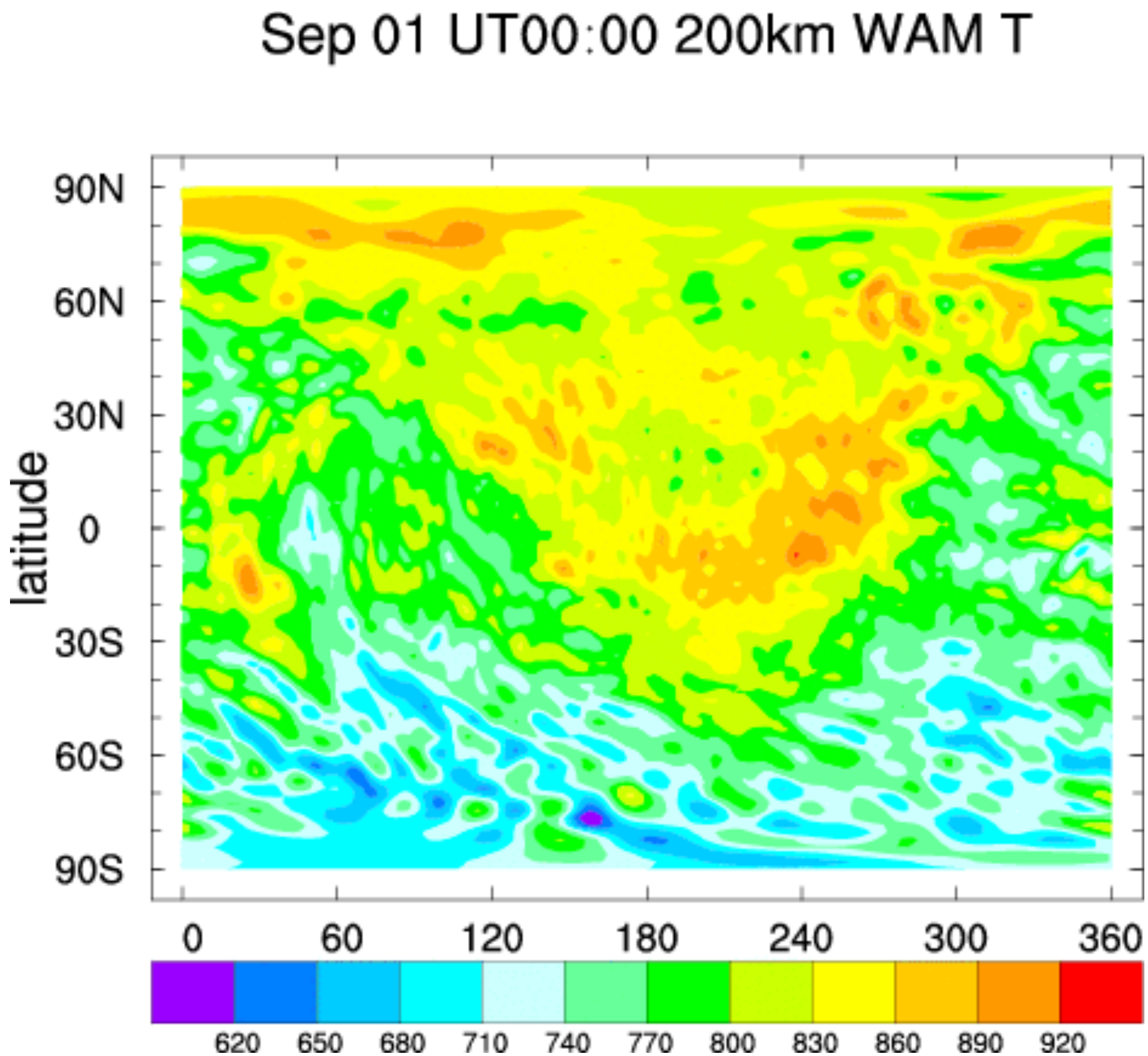


Types of Mixing in the Thermosphere

Question: Which ones dominate, where and when?

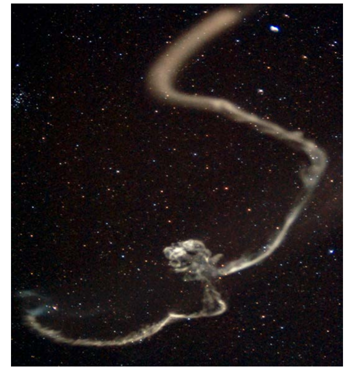
- Turbulence (physical breaking of small-scale gravity waves, *advective*, deterministic, chaotic) parameterized as "eddy diffusion" (which is not the actual physical process)
- Molecular diffusion
- Wave induced chemical transport (Akmaev and Shved, 1980)
- Dissipating large-scale waves (tidal, gravity waves, etc.,) driving circulation and advective transport (Yamazaki and Richmond, 2013)
- Non-linear interaction (not dissipating) of the wave field driving localized circulation and again advective transport?
- Circulation driven by zonal mean structure imposed from below, by lower atmosphere (Jones et al., 2014)
- Global seasonal and geomagnetic storm circulation

What is impact of non-tidal wave spectrum

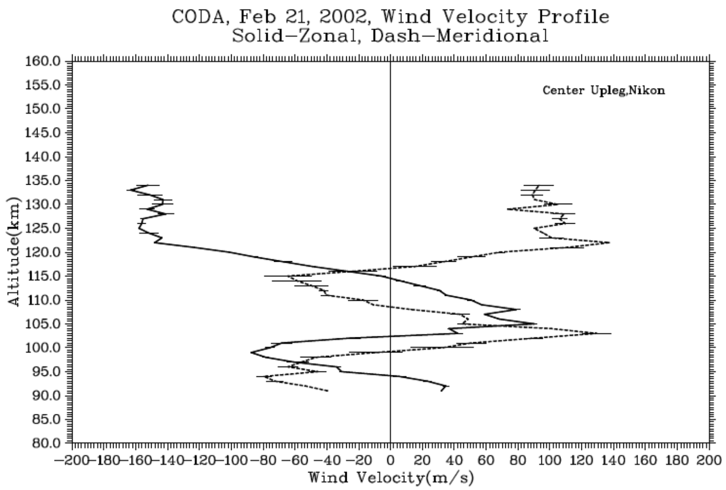


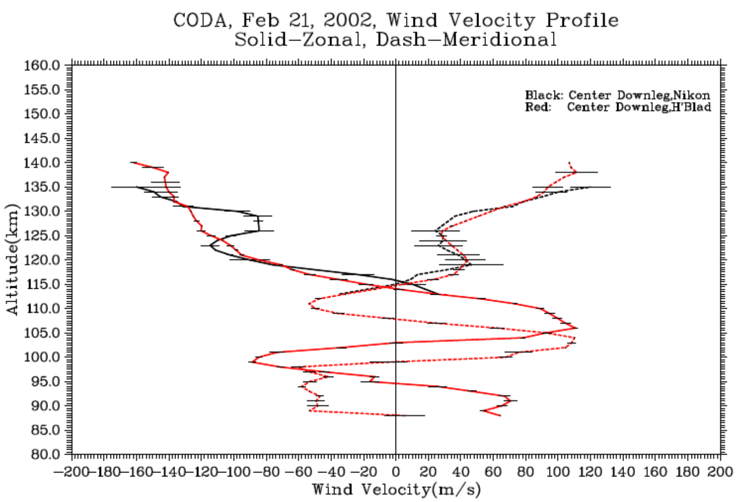
Chemical trails also provide horizontal winds

courtesy Miguel Larsen, Tianyu Zhan

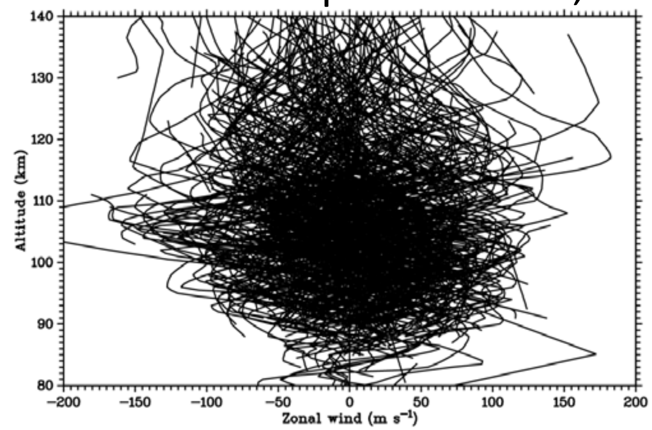


Laminar flow in lower thermosphere - “dissipating” but maybe not “breaking” waves?

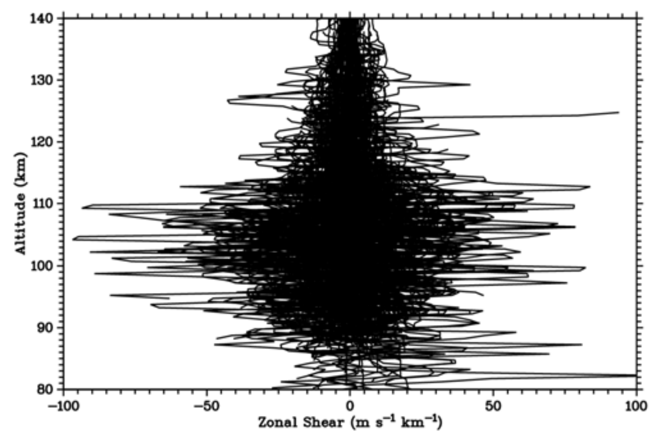




Four decades of wind measurements in lower thermosphere Larsen, 2002

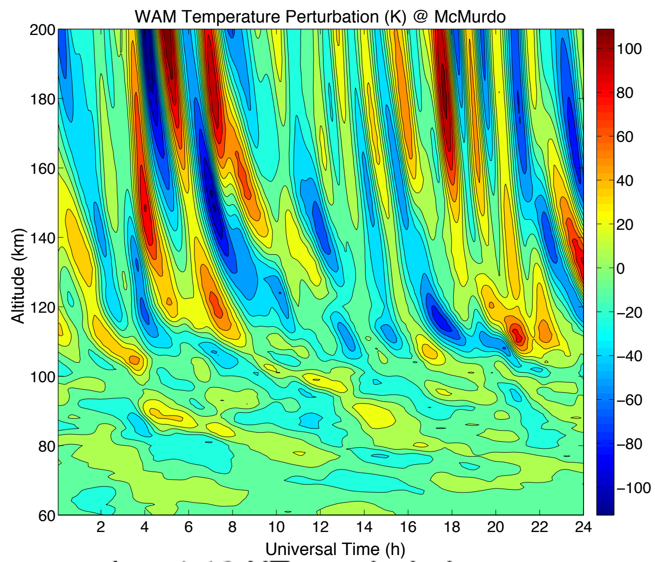


Typical peak zonal wind +/- 100 m/s

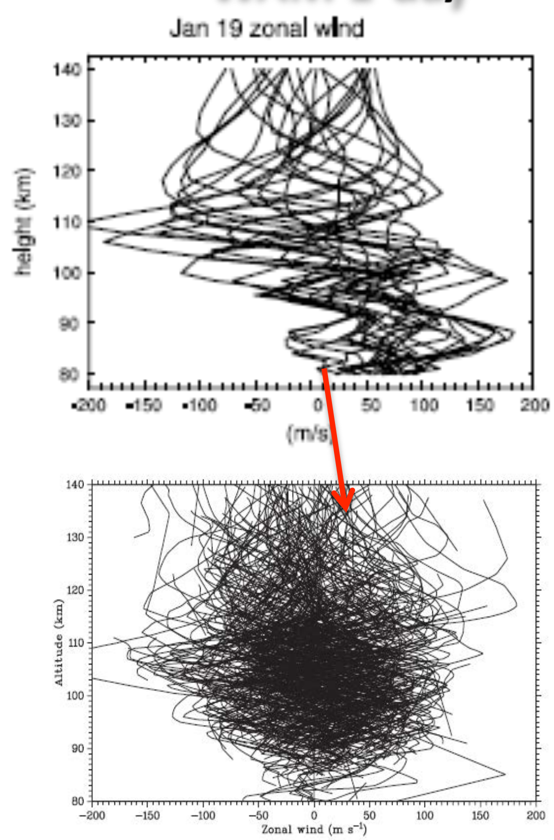


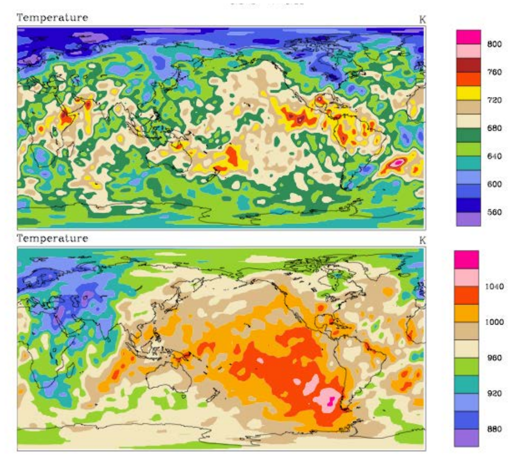
wind shear +/- 50 m/s/km

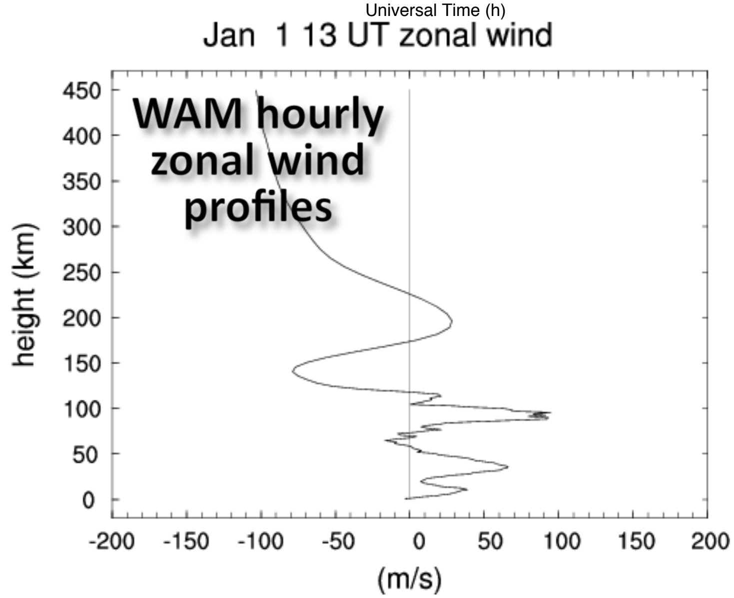
A rich spectrum of waves propagate from the lower atmosphere impacting the thermosphere and ionosphere



WAM 1-day

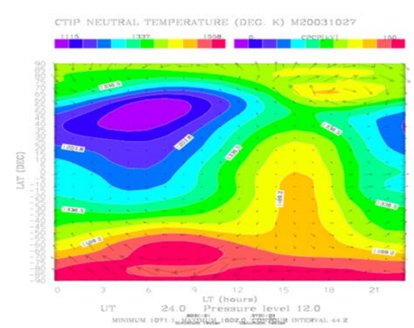






Observed mid and low latitude zonal winds Larsen (2002)

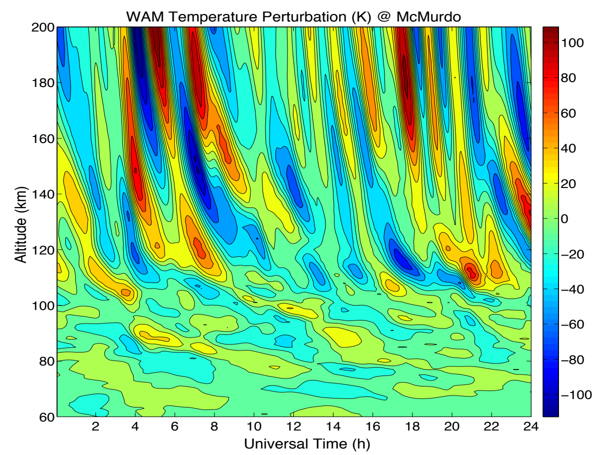
A new paradigm in thermosphere-ionospheric modeling



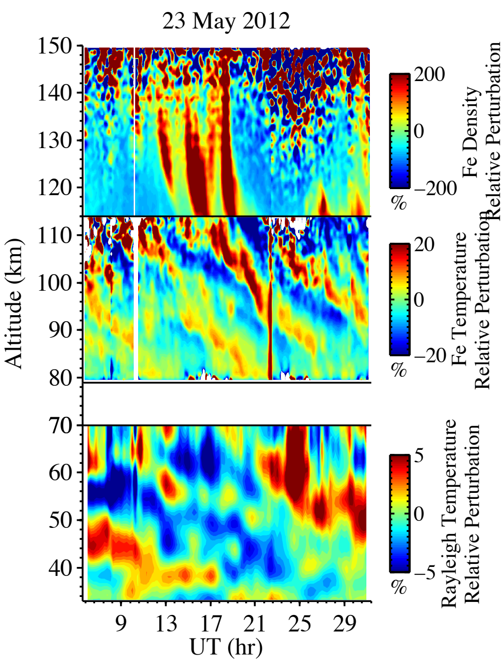
Validation: Fe LIDAR and vertical and horizontal winds

- WAM structure agrees well with ground-based LIDAR observations in the mesosphere and lower thermosphere
- WAM vertical winds consistent with FPI at 240 km
- Consistent with observed winds in lower thermosphere

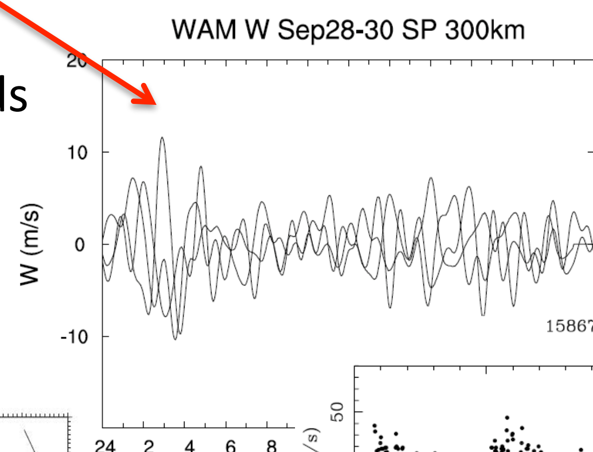
WAM temperature

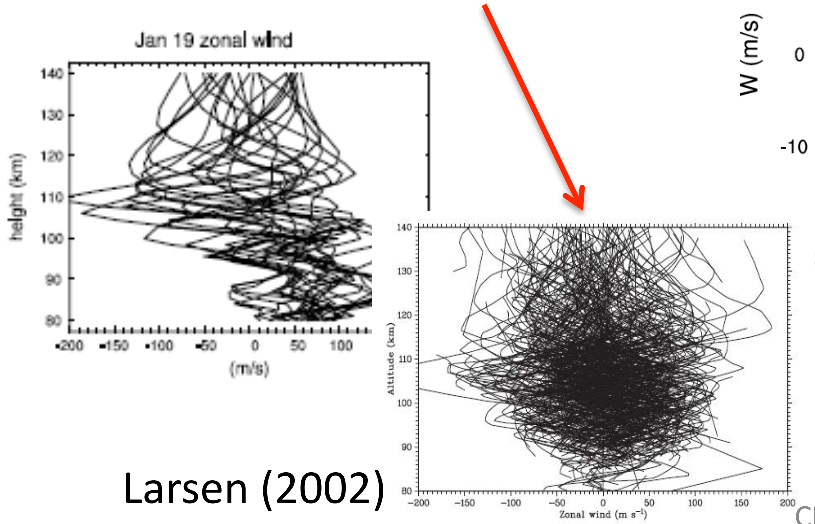


Fe LIDAR

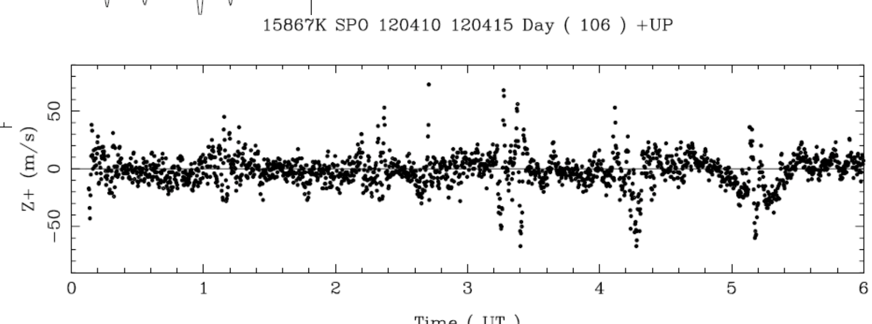


LIDAR (X. Chu and X. Lu)





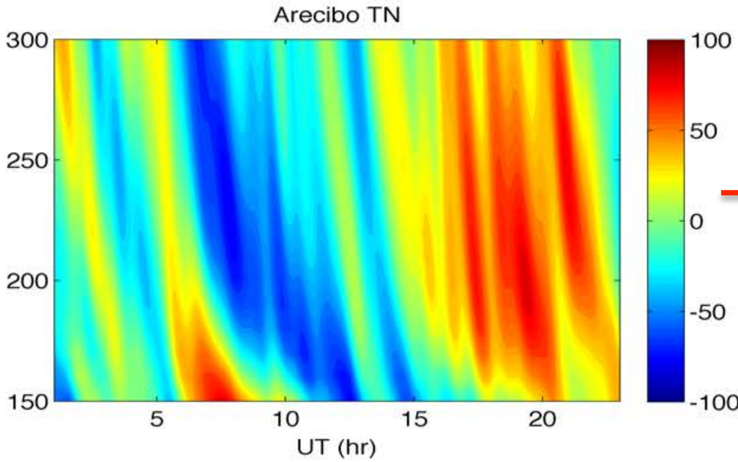
Larsen (2002)



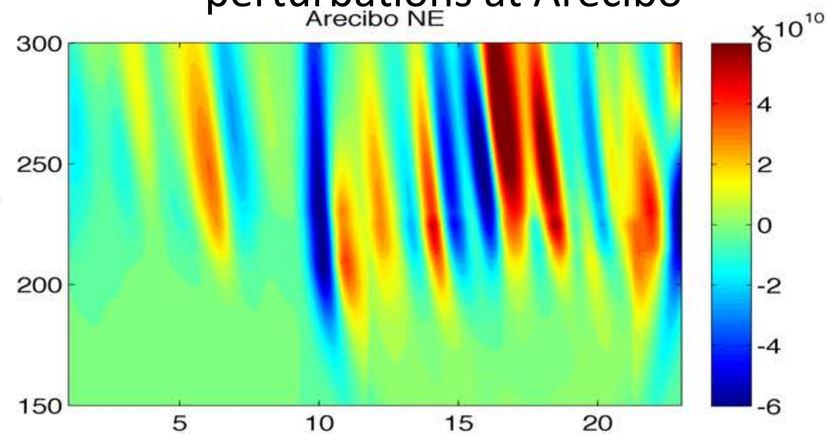
Fabry-Perot bi-static south pole vertical winds (Gonzalez Hernandez)

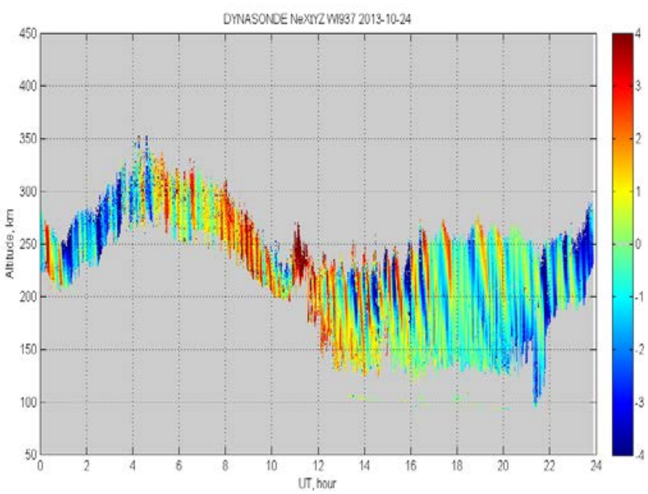
Use WAM winds, composition, density to drive GIP plasma density
- agrees well with Arecibo ISR observations by Djuth et al. -

WAM temperature perturbations at Arecibo

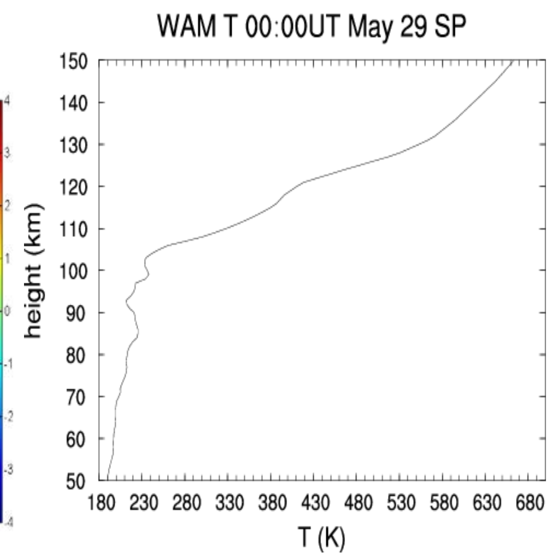


WAM-GIP ~20% plasma density perturbations at Arecibo

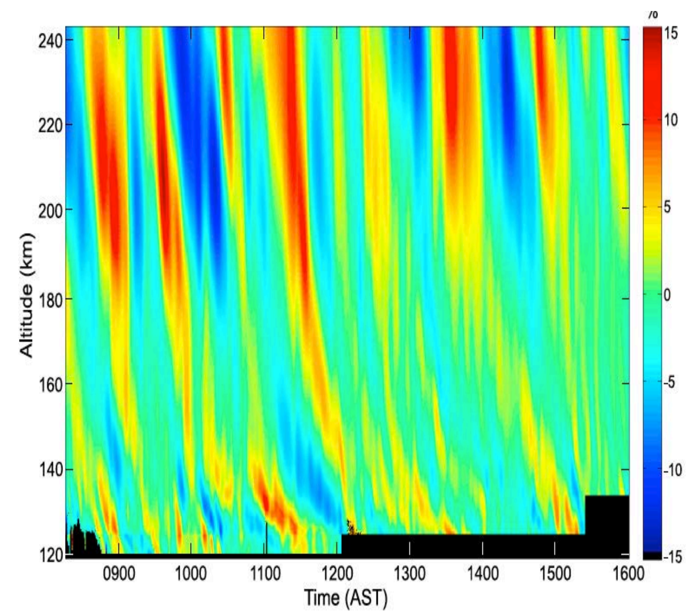




Dynasonde - vertical velocity and tilts, Nikolay Zabotin

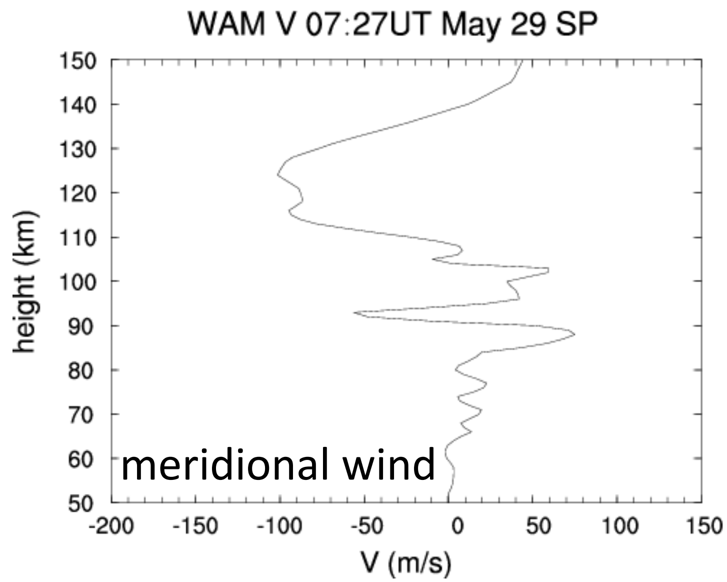


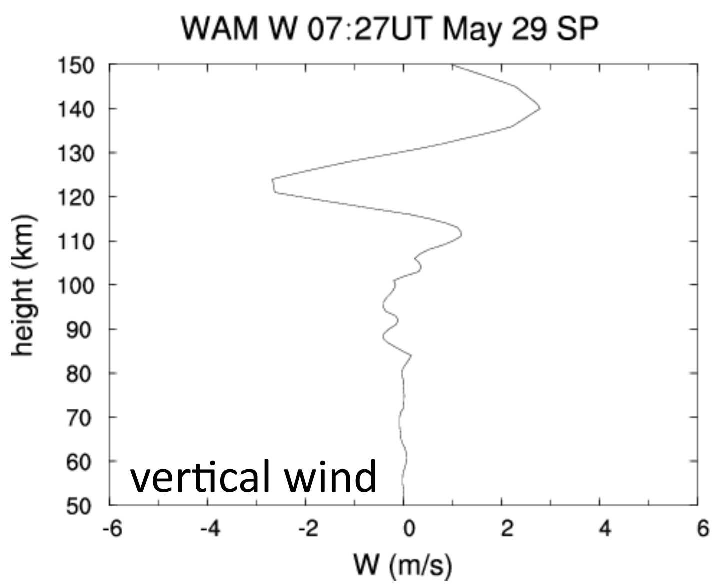
WAM tmeperature

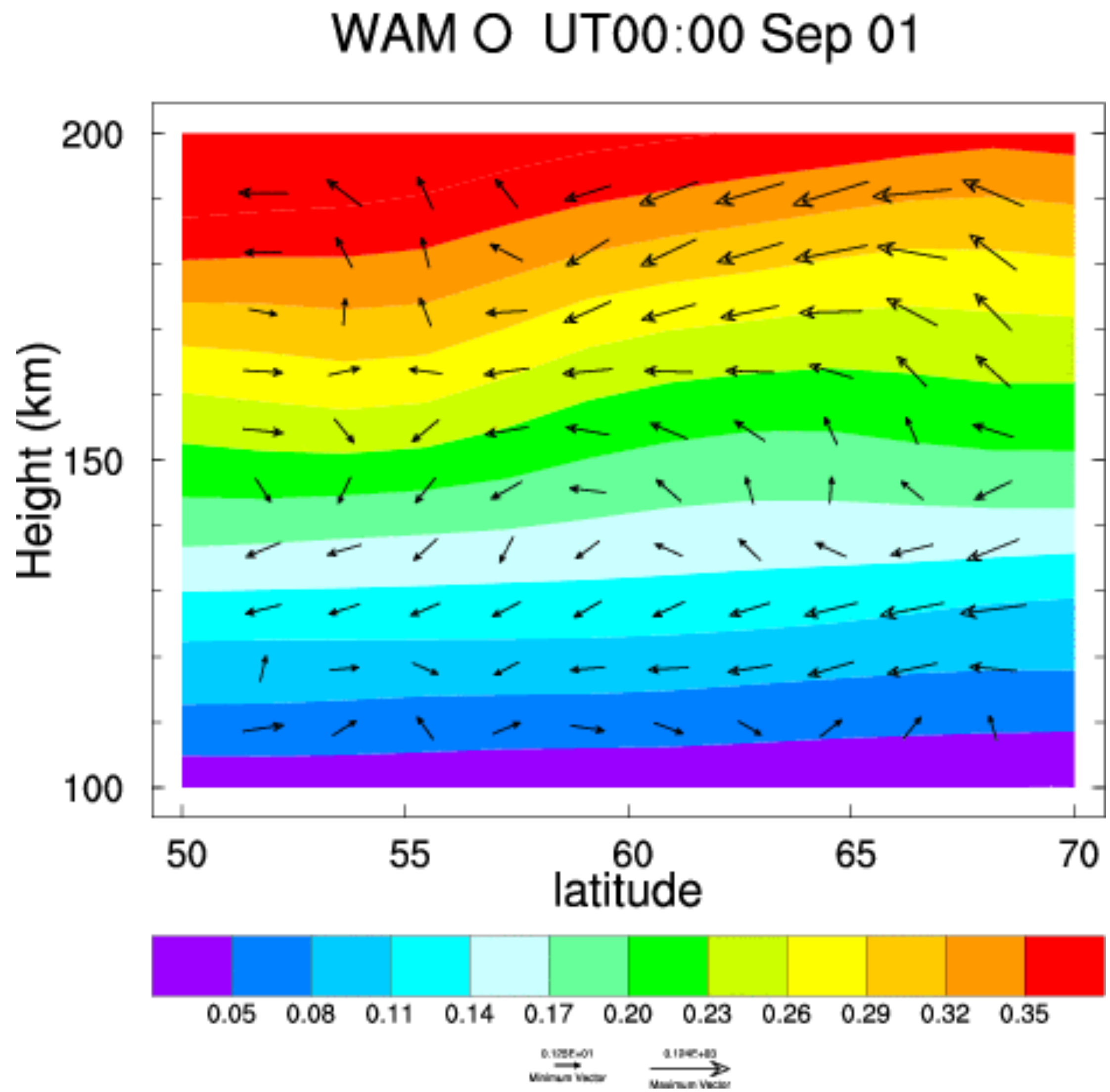


ISR observations of N_e perturbations, Djuth et al.

Mixing in the lower thermosphere

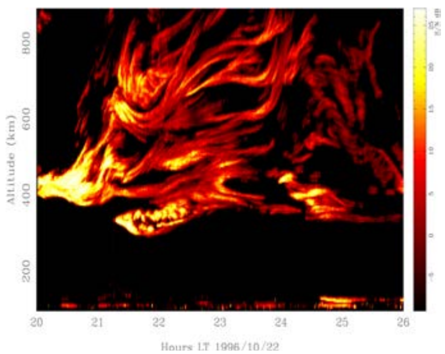




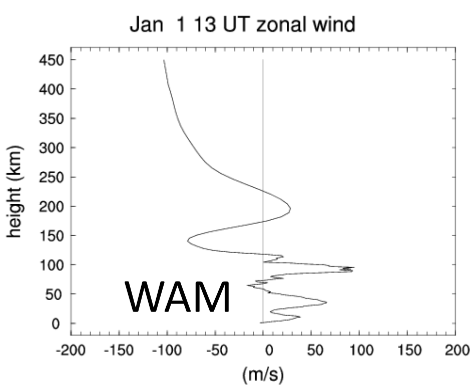


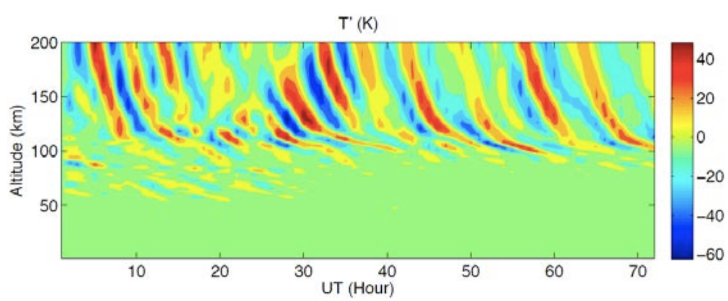
atomic oxygen mixing ratio and winds

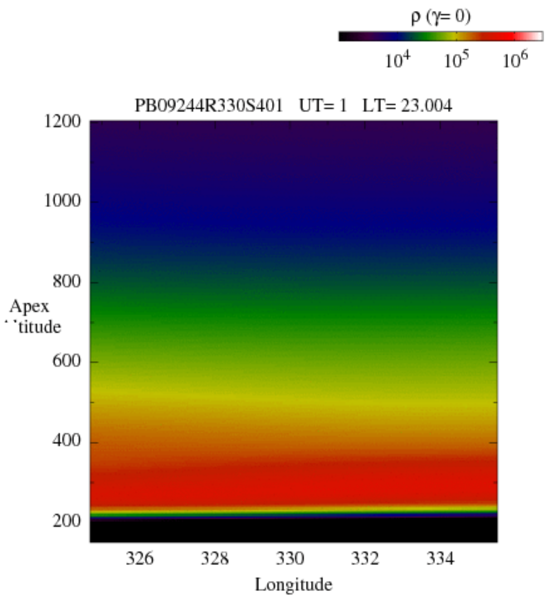
Bubble development in physics-based irregularity model (PBMOD) with WAM fields (180 km horizontal. resolution, ¼ scale-height vertical, ~2-5km) with no additional seeding Retterer et al.

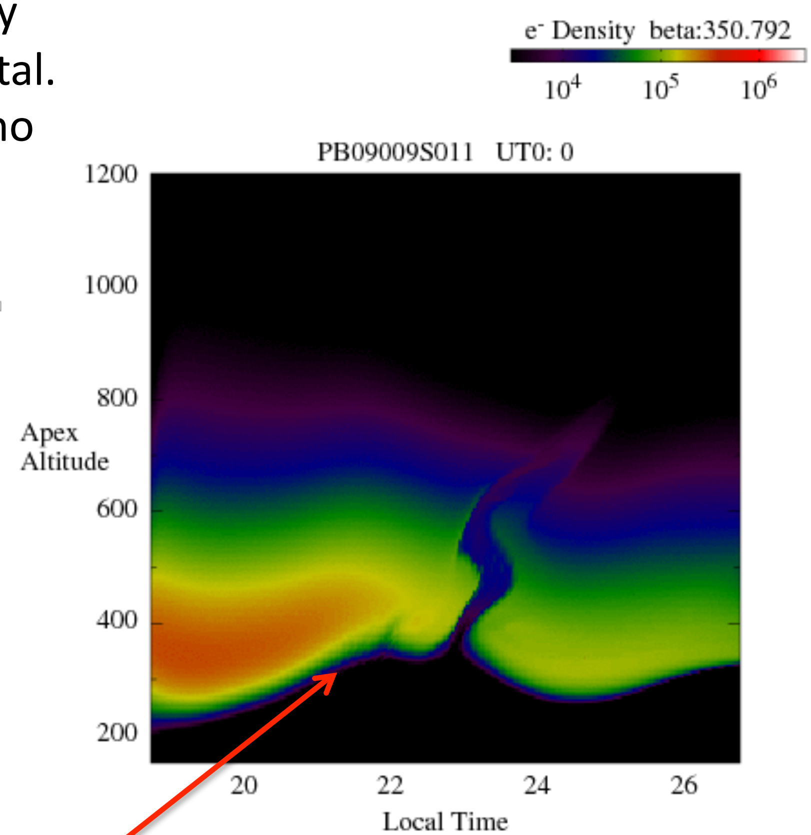


JULIA radar (Hysell)

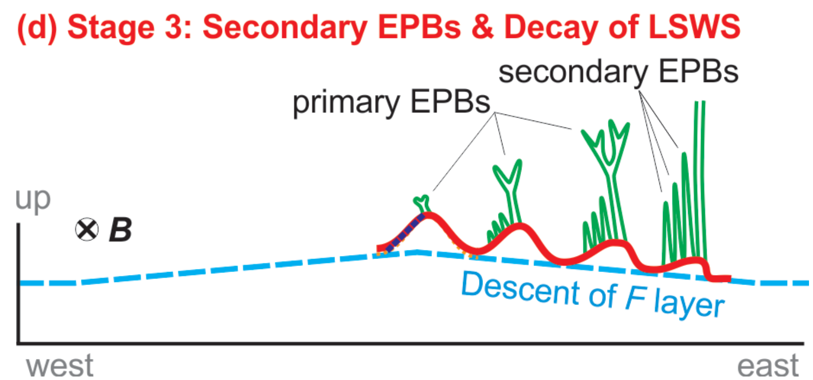






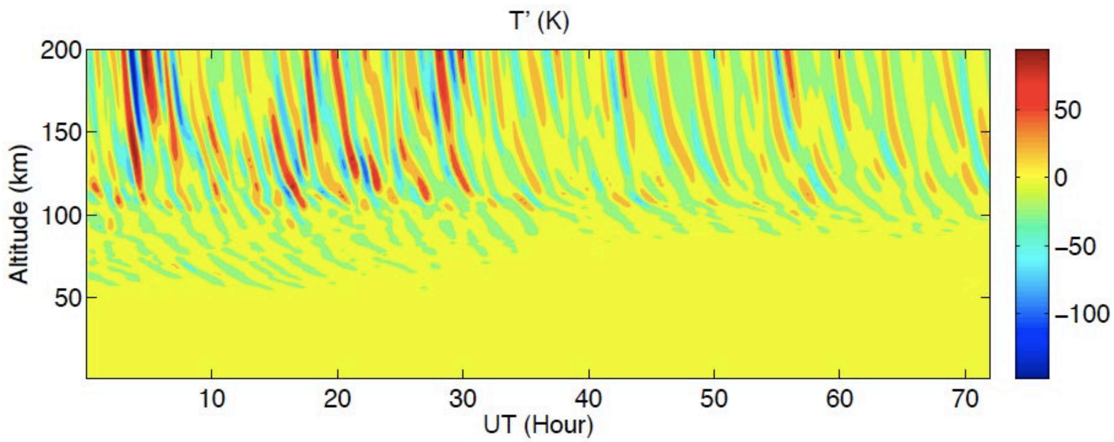


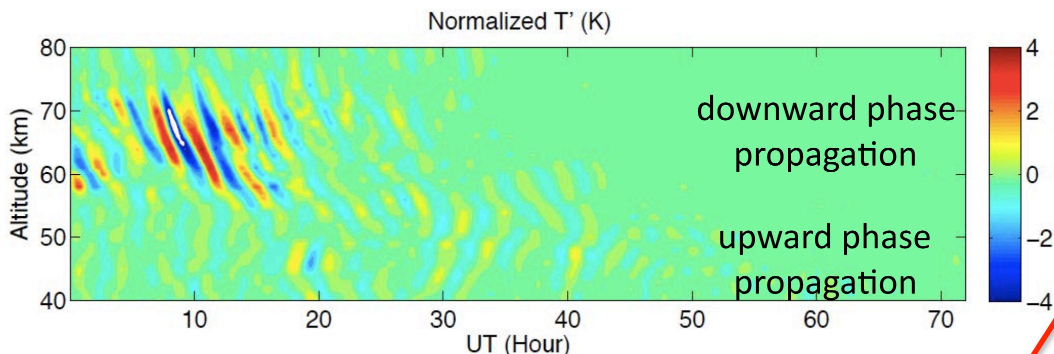
forecasting large scale wave structure, (LSWS) on bottomside

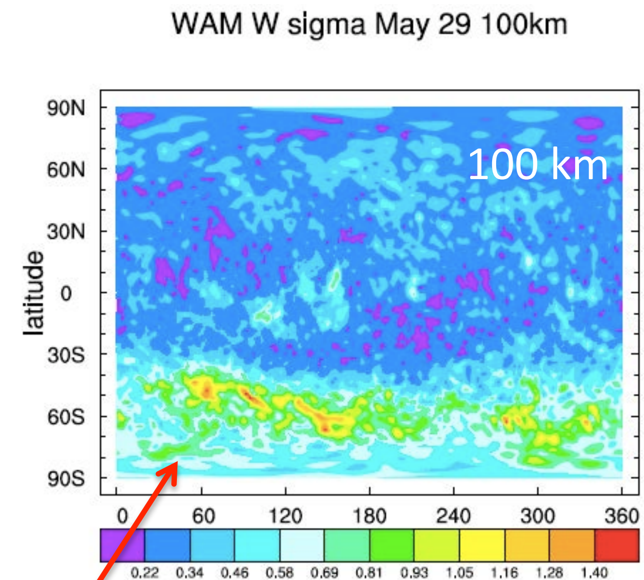


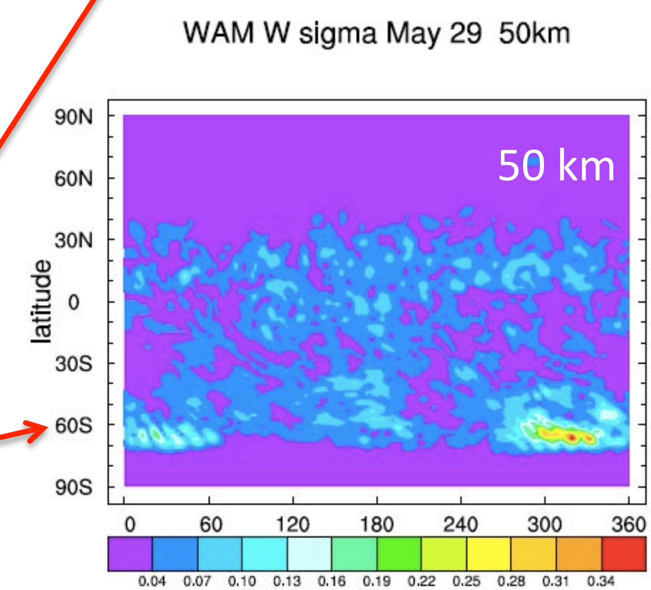
Roland Tsunoda

Tracing the origin of one of the many source of waves – unbalance flow of stratospheric jets –









Scaled in altitude by exp(-(z-40)/2H)

Instabilities in strong stratospheric jets in winter high latitudes at 50 km growing in amplitude into the lower thermosphere (100 km)

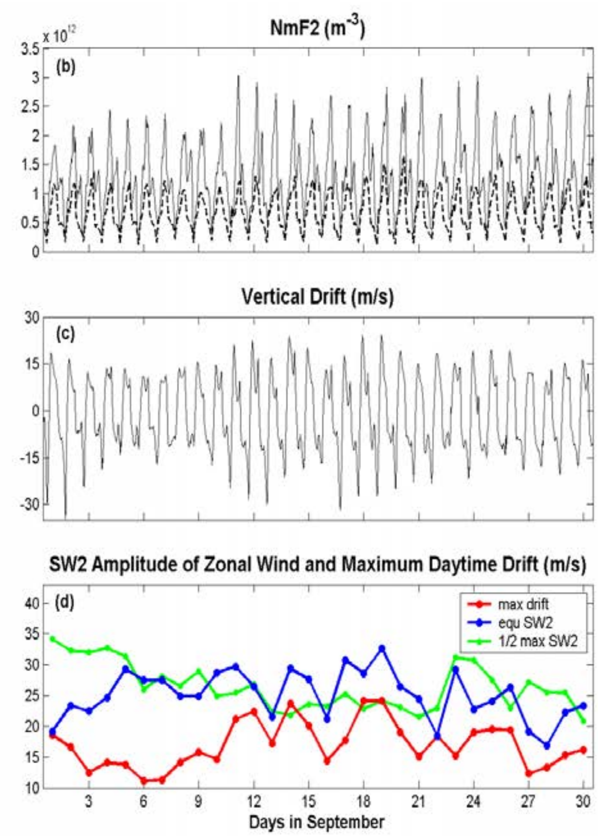
What are the consequences of tidal variability, and what drives it?

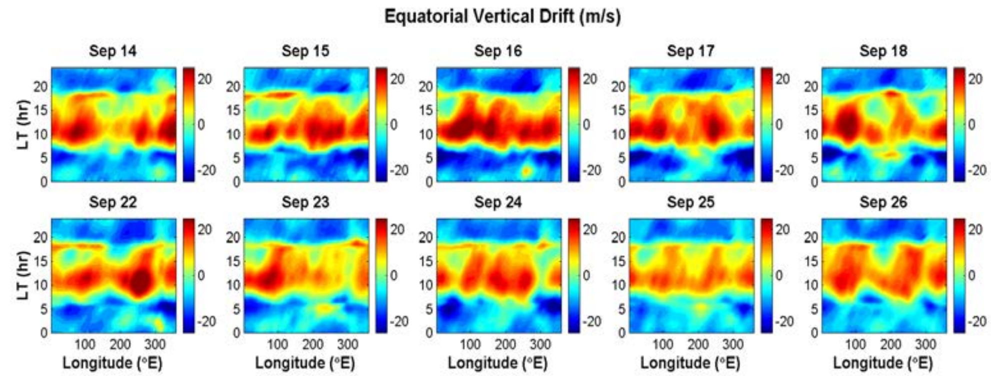
- Variations in tidal mixing will affect O/N_2 ratios in the thermosphere and hence plasma loss rates and neutral density.
- Tides in the lower thermosphere dynamo region (100 to 150 km on dayside) drive electrodynamics, which controls the strength of the F-region equatorial ionization anomaly.
- These competing mechanism work on different time-scales
- We don't have measurements of the rapid changes in tidal amplitude and phase. SABER takes more than 30 days to sample all local time sectors to estimate amplitude of SW2, for instance

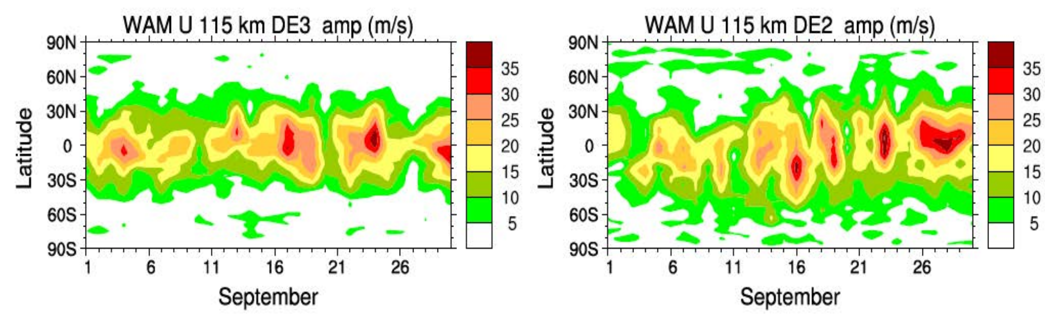
- What is tidal variability in lower thermosphere controlled by?
  - changes in the sources (e.g., H_2O and O_3 distribution)? (Larisa Goncharenko)
  - possible changes in atmospheric resonance of lunar tide? (Forbes and Zhang)
  - propagation of solar tide through different background wind fields, changing amplitude and phase?

Example of impact of tidal variability

Tzu-Wei Fang et al. 2013 from WAM-GIP model simulation





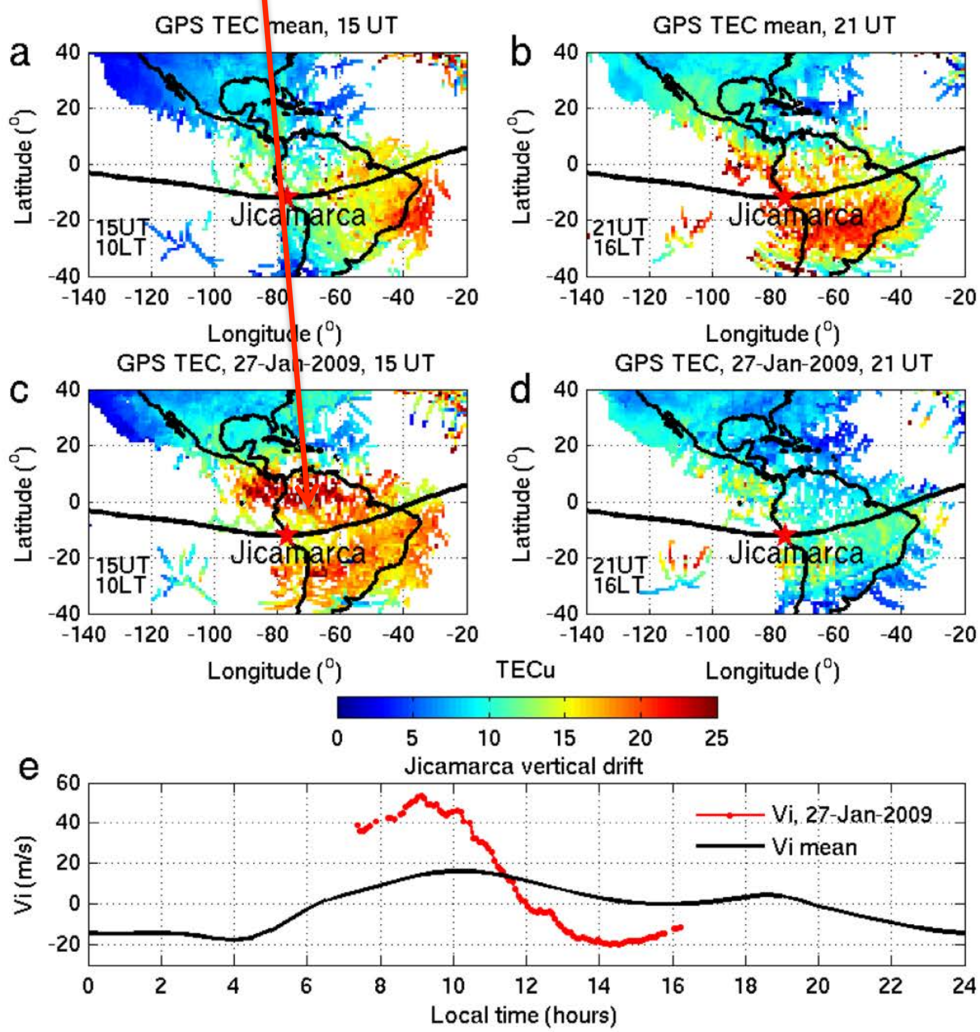


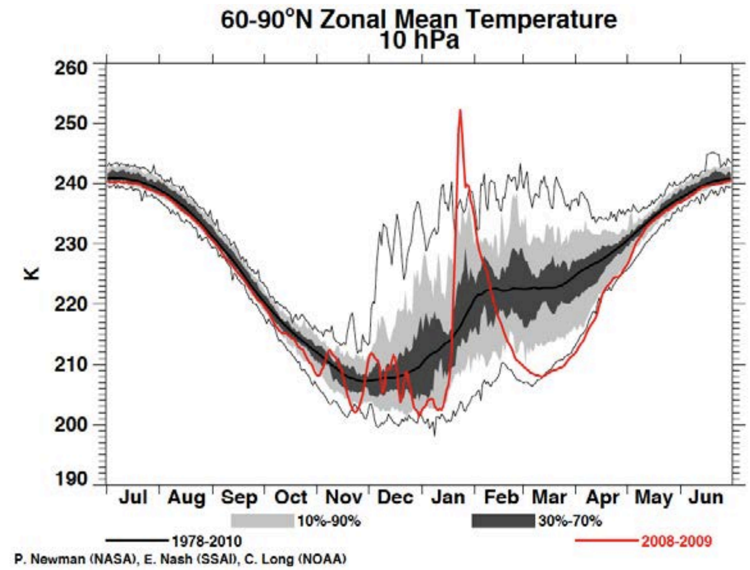
Modulation of semi-diurnal tide SW2 correlates with increases in peak vertical plasma drift and N_mF2

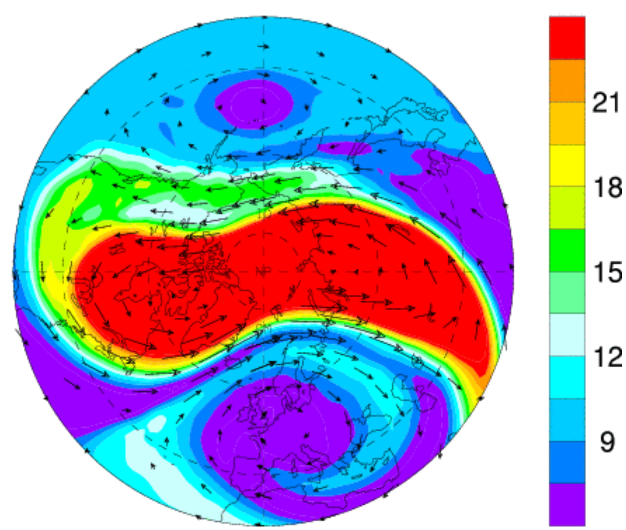
Modulation of DE3 and DE2 tidal amplitudes correlates with number of peaks in longitude structure of vertical plasma drift

Other examples: 50% increase in TEC in January 2009 when solar and geomagnetic activity were very low

Goncharenko et al. 2010



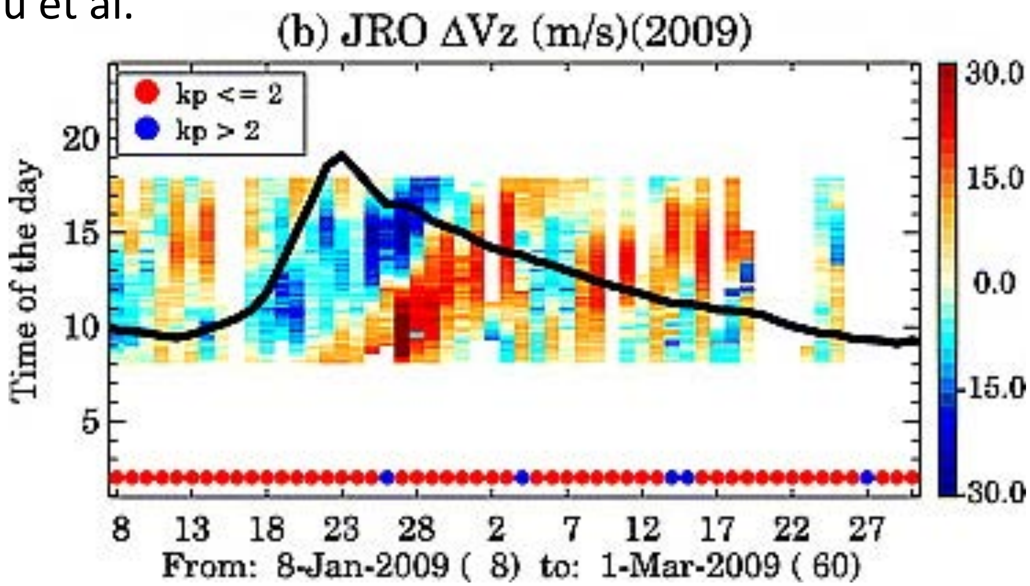




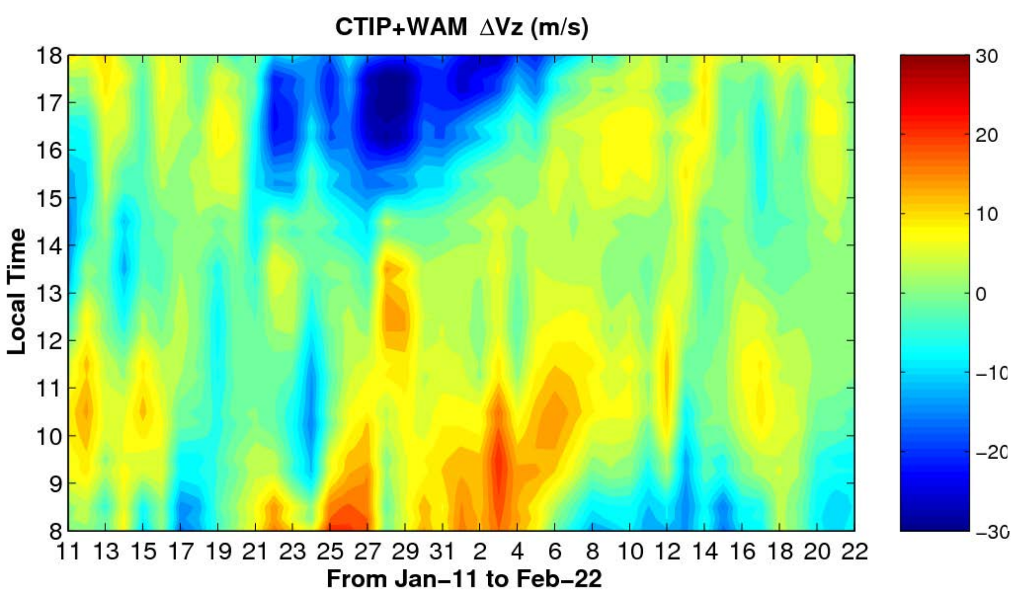
Is this also a response to changing tidal amplitudes?

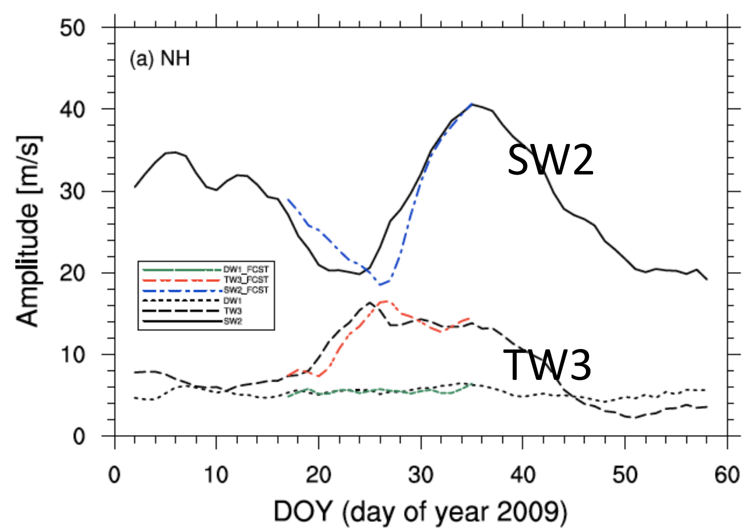
Electrodynamic comparison JRO vs WAM-CTIPe

Chau et al.



- CTIPe simulations with WAM winds (lower panel) appear to reproduce the main features in the observed vertical plasma drift (upper panel) during a SSW, including the stronger upward drift early in the morning and reversal to downward in the afternoon
- Largest tidal changes during interval are in SW2 and TW3

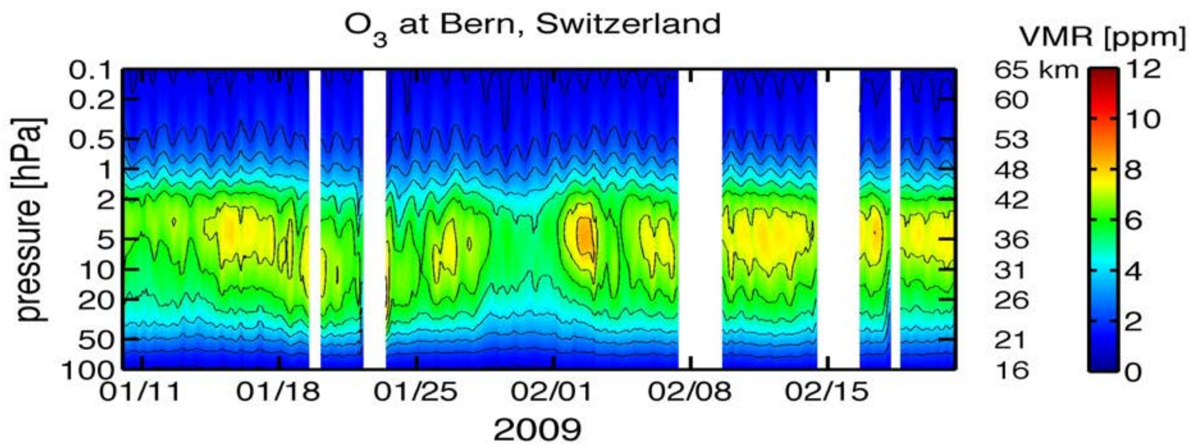




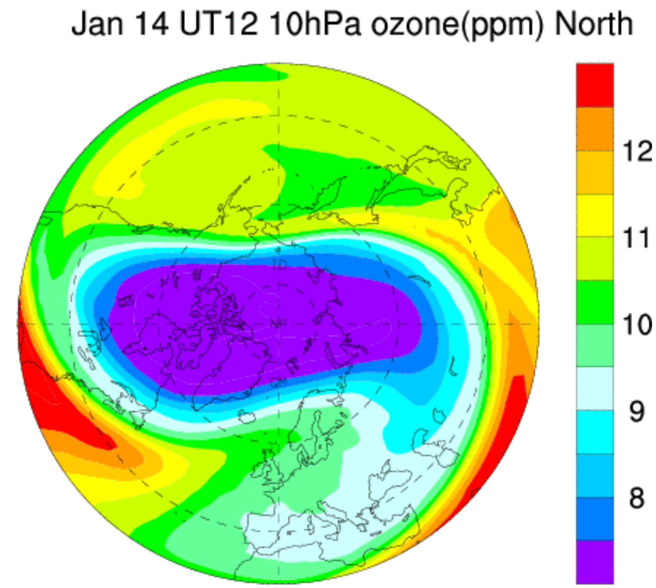
average 95-155km, 20 – 60° north

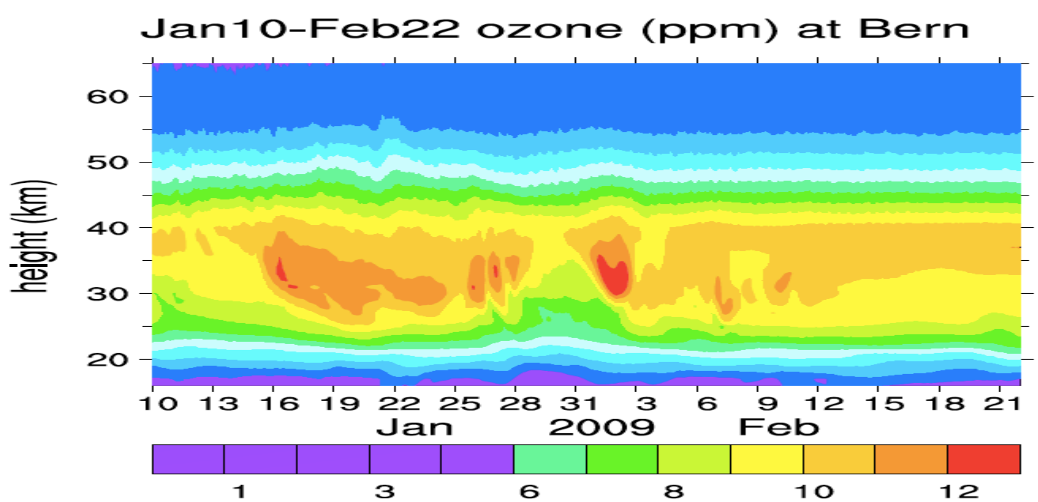
Fuller-Rowell et al. 2011

1. Changes in ozone drives changes in source function for SW2 tide

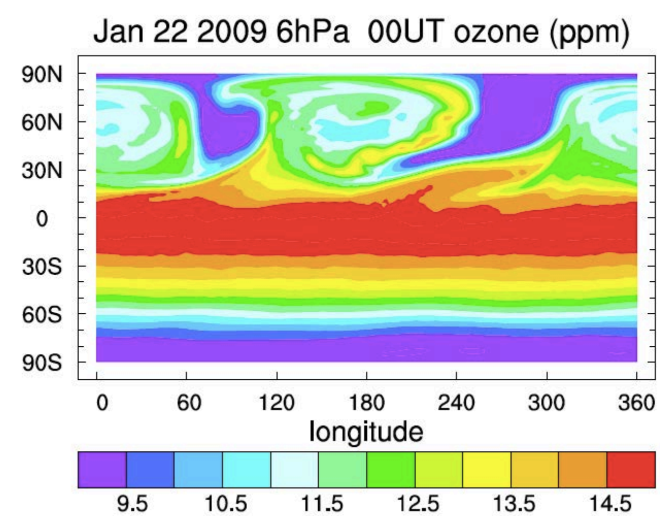


Observations: Klemens Hocke, Simone Studer, Bern





Modeling: WAM

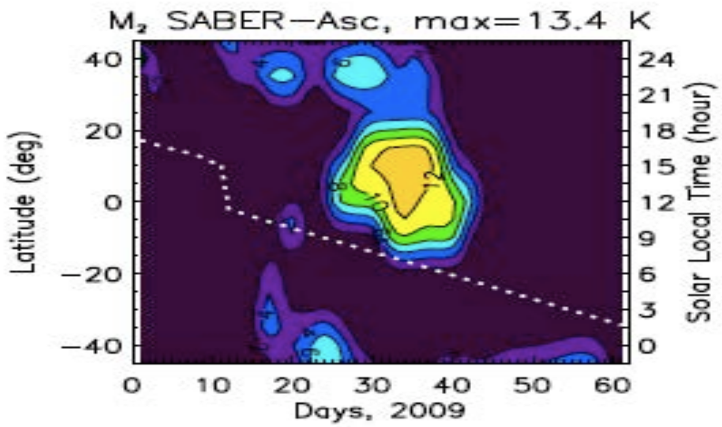


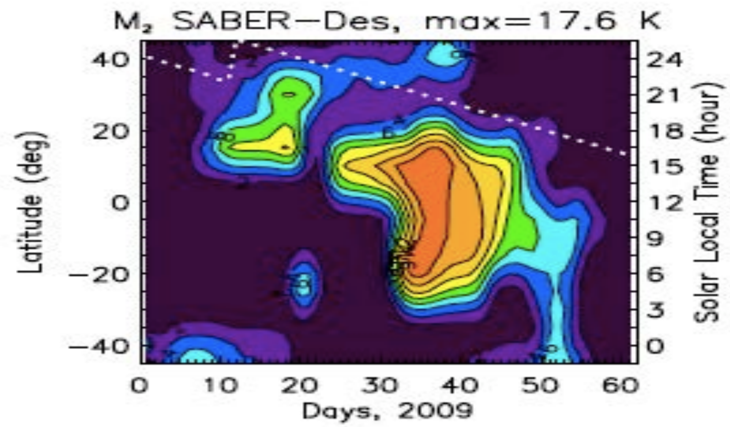
Ozone redistribution at 6 hPa
~30 km altitude

2. Forbes and Zhang (2012) theory:

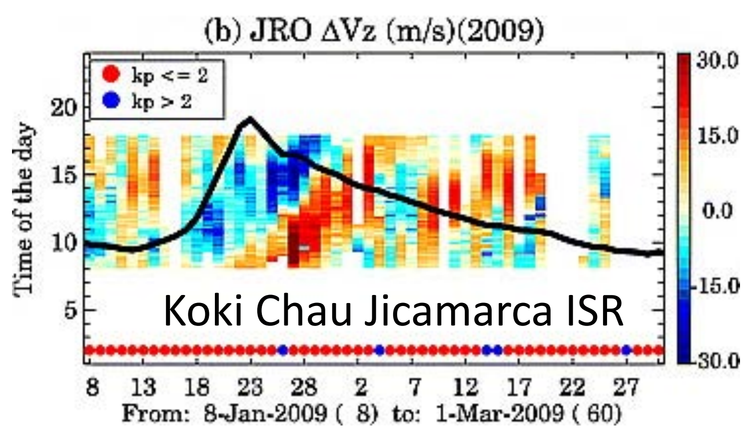
Change in the dynamics shifts the natural atmospheric Pekeris resonance close to the lunar quasi-semidiurnal tide (M2, period 12.42 hrs)
Increase in lunar tidal amplitude by factor of three.

SABER: increase in amplitude of lunar M2 tidal mode





Phase change of electrodynamics signature of lunar tide



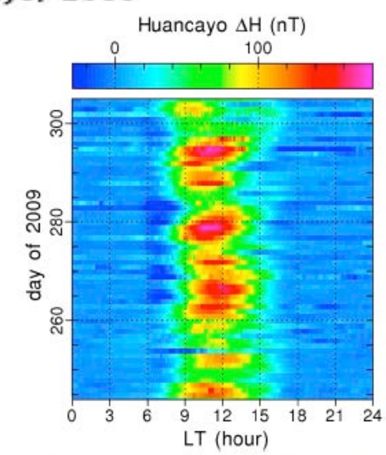
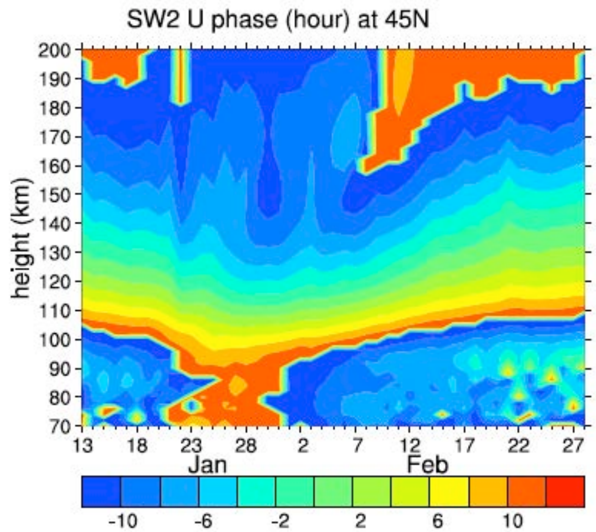


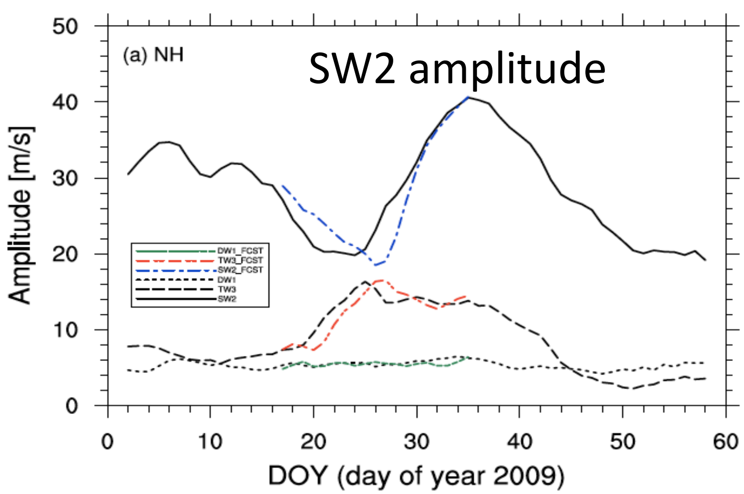
Figure 3. The magnitude of the quiet day variation of the horizontal component (ΔH) of the Huancayo Observatory magnetometer. The EEJ zonal current is closely related to the ΔH variation and the zonal electric field.

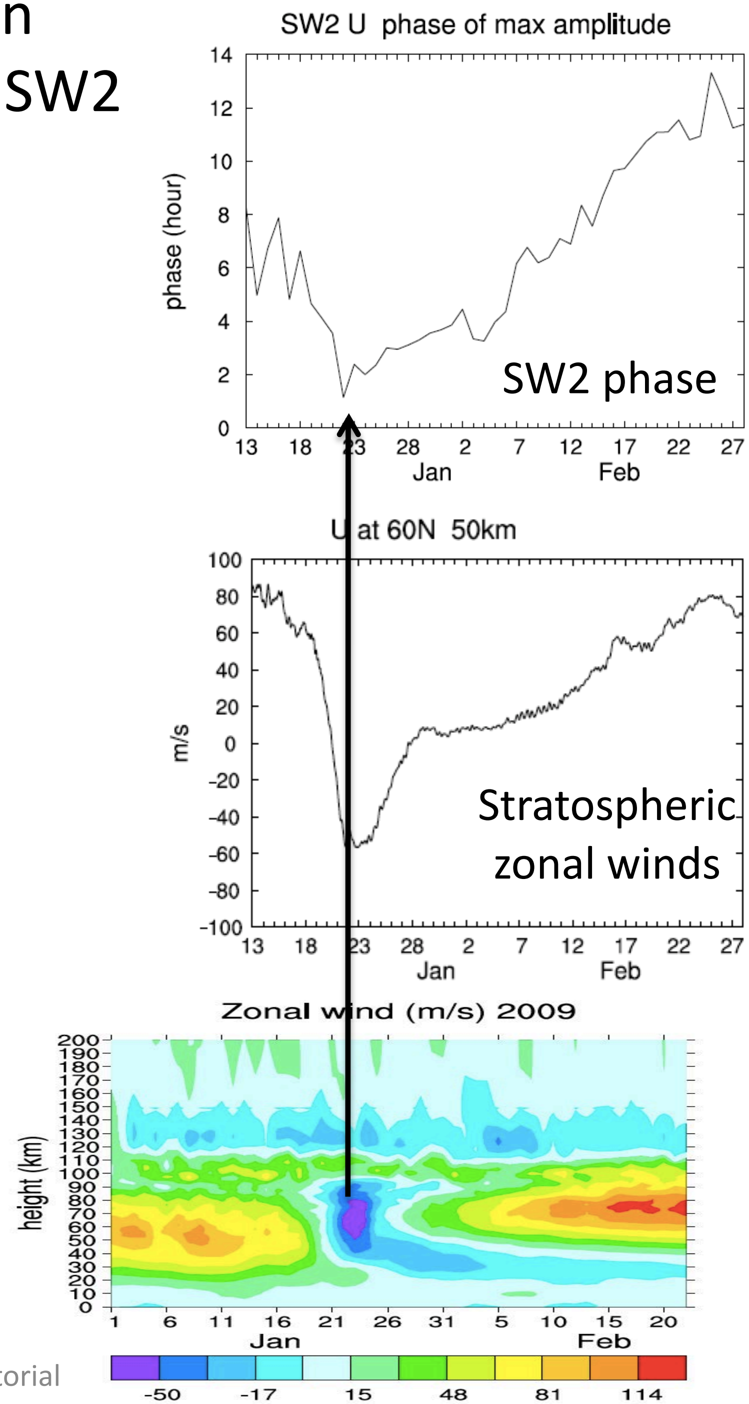
Eccles et al., 2010

Ground-based magneto-meter

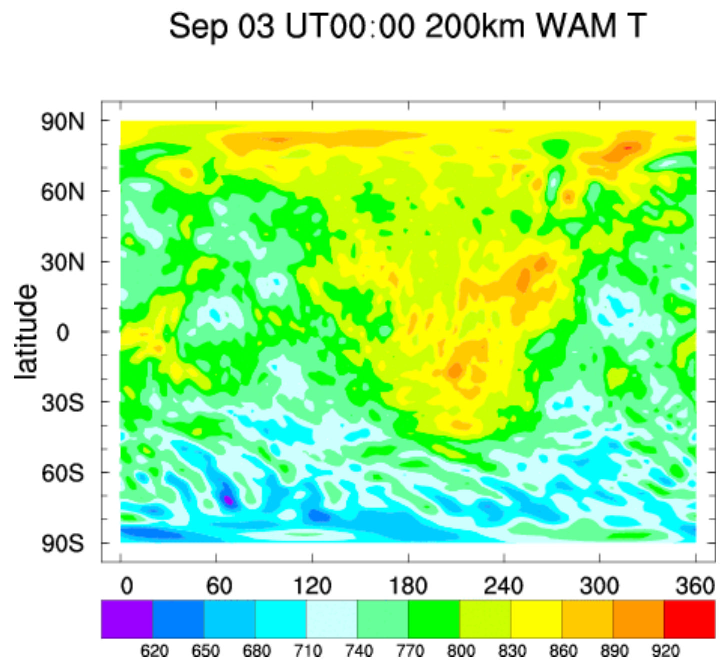
3. Change in tidal propagation
Amplitude and phase change of SW2 vs zonal winds

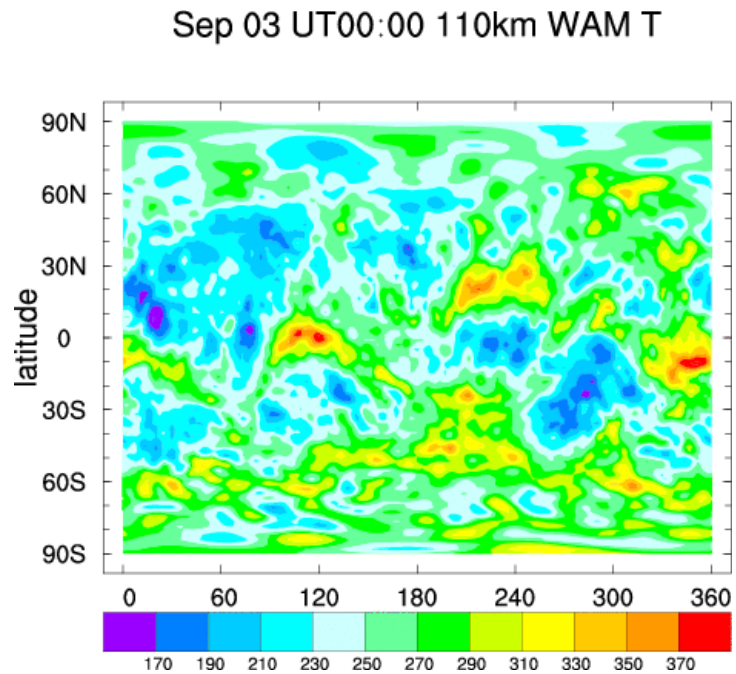


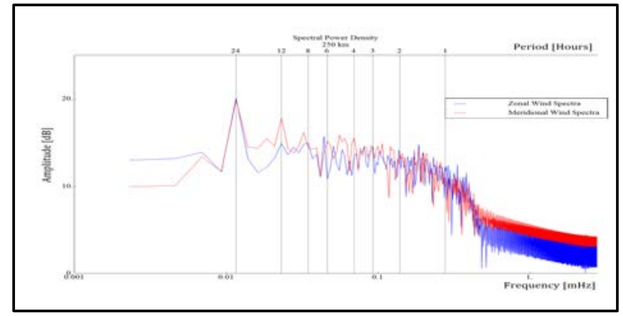


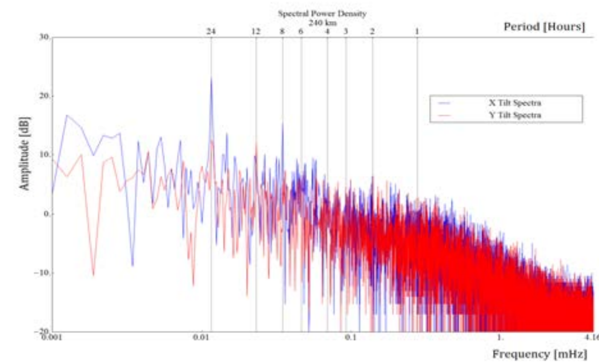


WAM spectrum with 180 km grid – cuts off at about 25 minute period

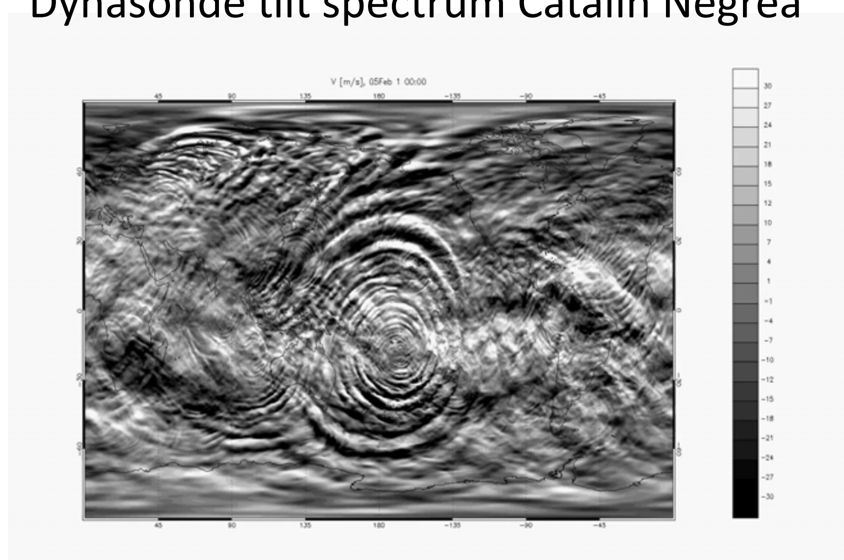








Dynasonde tilt spectrum Catalin Negrea



WACCM spectrum 25 km grid

Conclusion

Theme: The role of lower atmosphere waves on the thermosphere and ionosphere variability (80 to 200 km)

- It now appears there may be multiple sources of mixing in the lower thermosphere (turbulence, global circulation, tides, the whole spectrum of waves, etc.) and the challenge is to determine their relative contributions and their impact.
- We have little observational knowledge of the day-to-day variability of tidal amplitude and phase, or what drives it, or the impact on the thermosphere and ionosphere.
- We don't know the nature, characteristics, and source of all the frequencies in the non-tidal wave spectrum, their contribution to thermosphere and ionospheric variability, or their dependence on season, latitude, region, time, etc.