Atmospheric Tides and their Roles in Vertical Coupling

Ruth S. Lieberman
GATS, Inc.
Boulder, CO

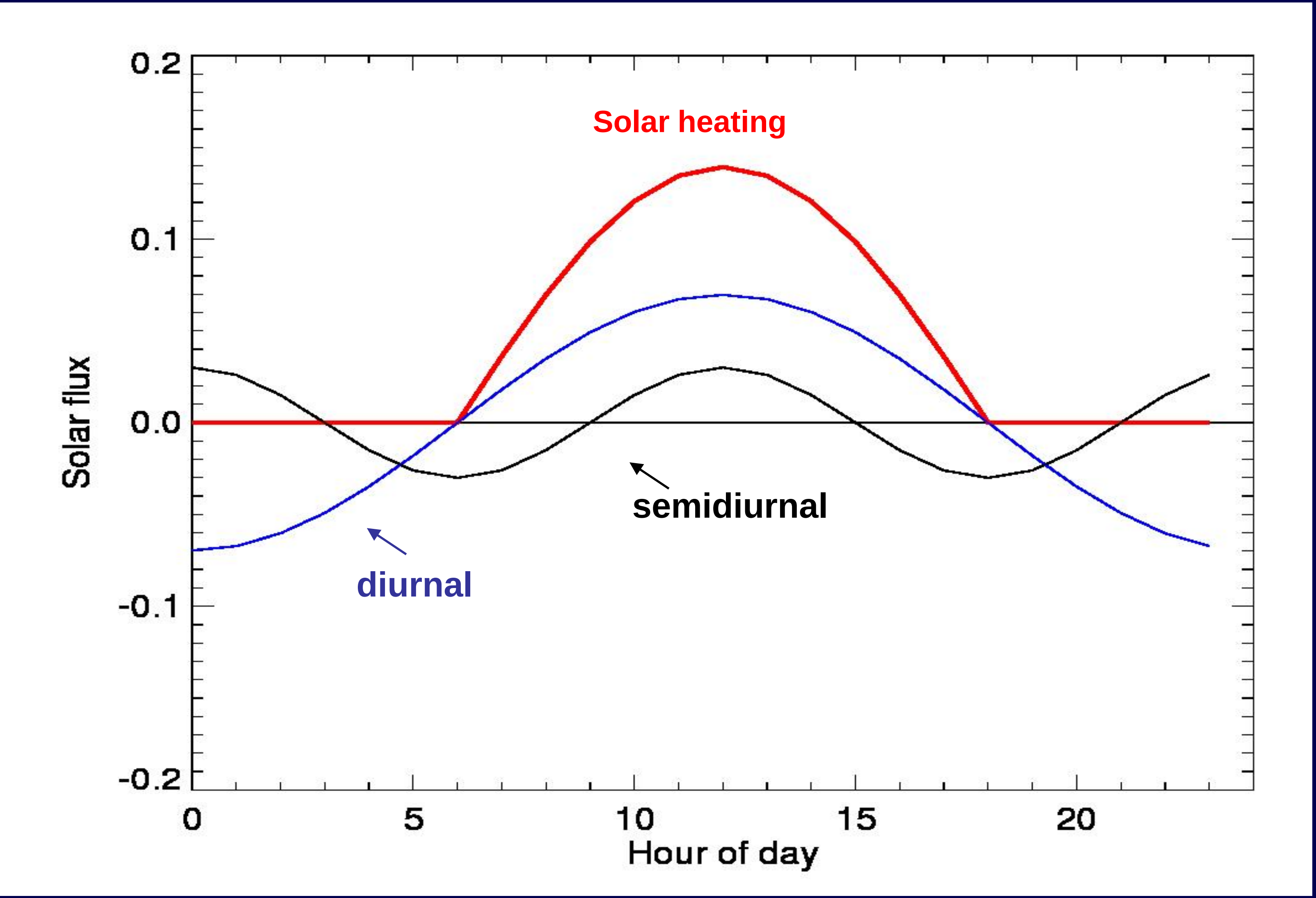
Outline

1. Definitions and sources of tides.
2. Tidal theory (very simplified).
3. Interpreting observations.
4. Importance of middle/upper atmosphere tides.
5. Tides as vertical and horizontal coupling agents.

Definitions

Atmospheric thermal tides are global-scale oscillations whose periods are fractions of a solar day:

- **24 hours (diurnal).**
- **12 hours (semidiurnal).**
- **8 hours (terdiurnal)**
- **6 hours**
- **And so on…..**



Tides occur because the sun illuminates the Earth only during daylight hours.

Additional useful nomenclature

***Migrating tides*:**

Angular phase speed c = Ω (2π/24, Earth rotation).

For diurnal tide, m = 1 westward (c = Ω/1).

For semidiurnal tide, m = 2 westward (c = 2Ω/2).

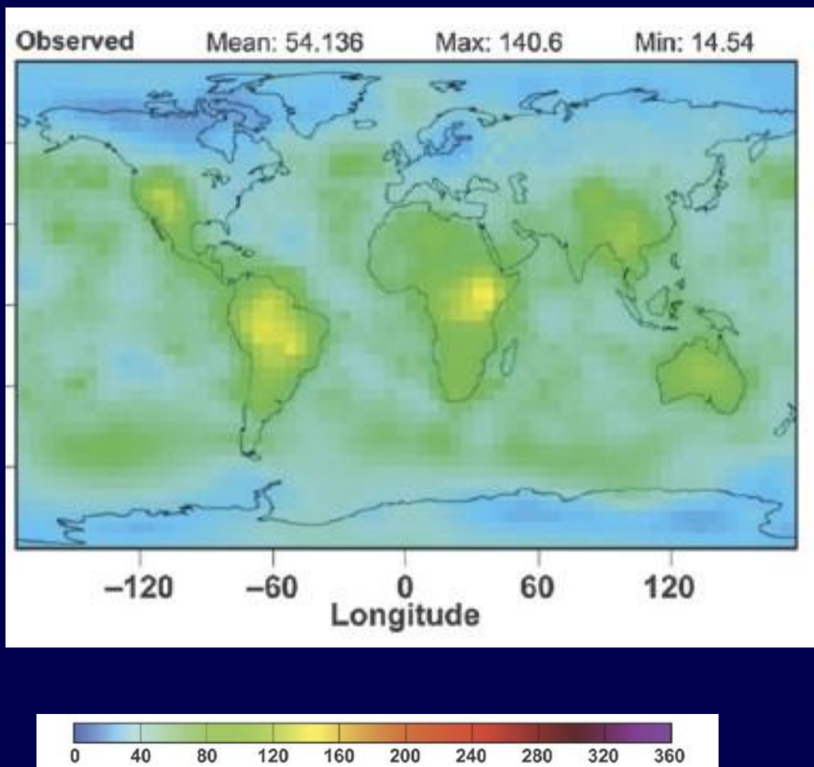
***Nonmigrating tides*:**

Angular phase speed c $\neq$ Ω.

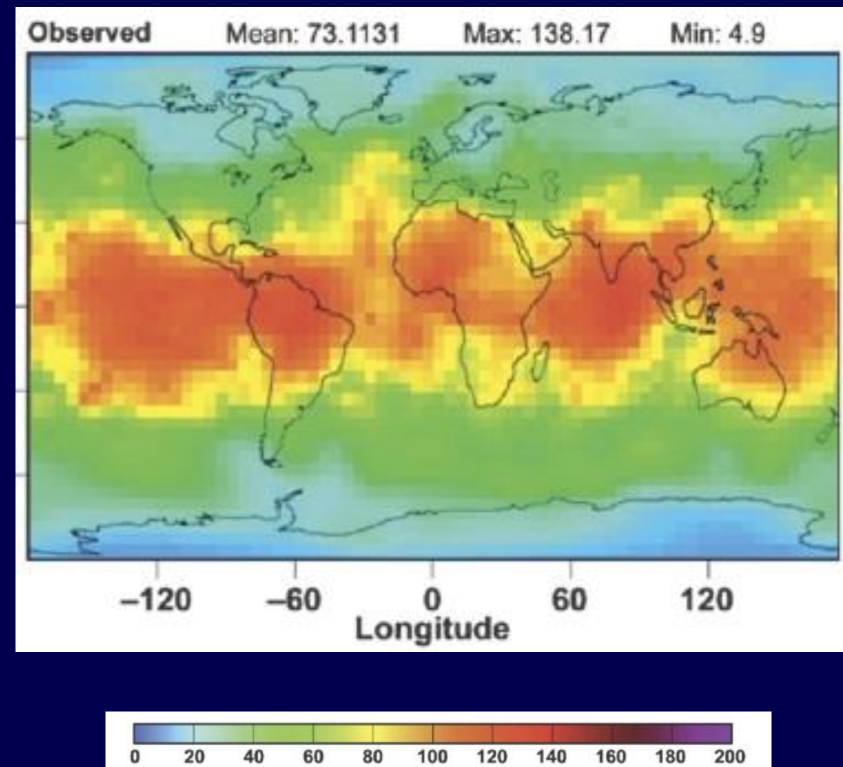
For diurnal tide, westward m $\neq$ 1, and all eastward-propagating waves.

For semidiurnal tide, westward m $\neq$ 2, and all eastward-propagating waves.

Surface Pressure Tides
(Dai and Wang, 1999; Covey et al., 2011)



Diurnal (Pa)

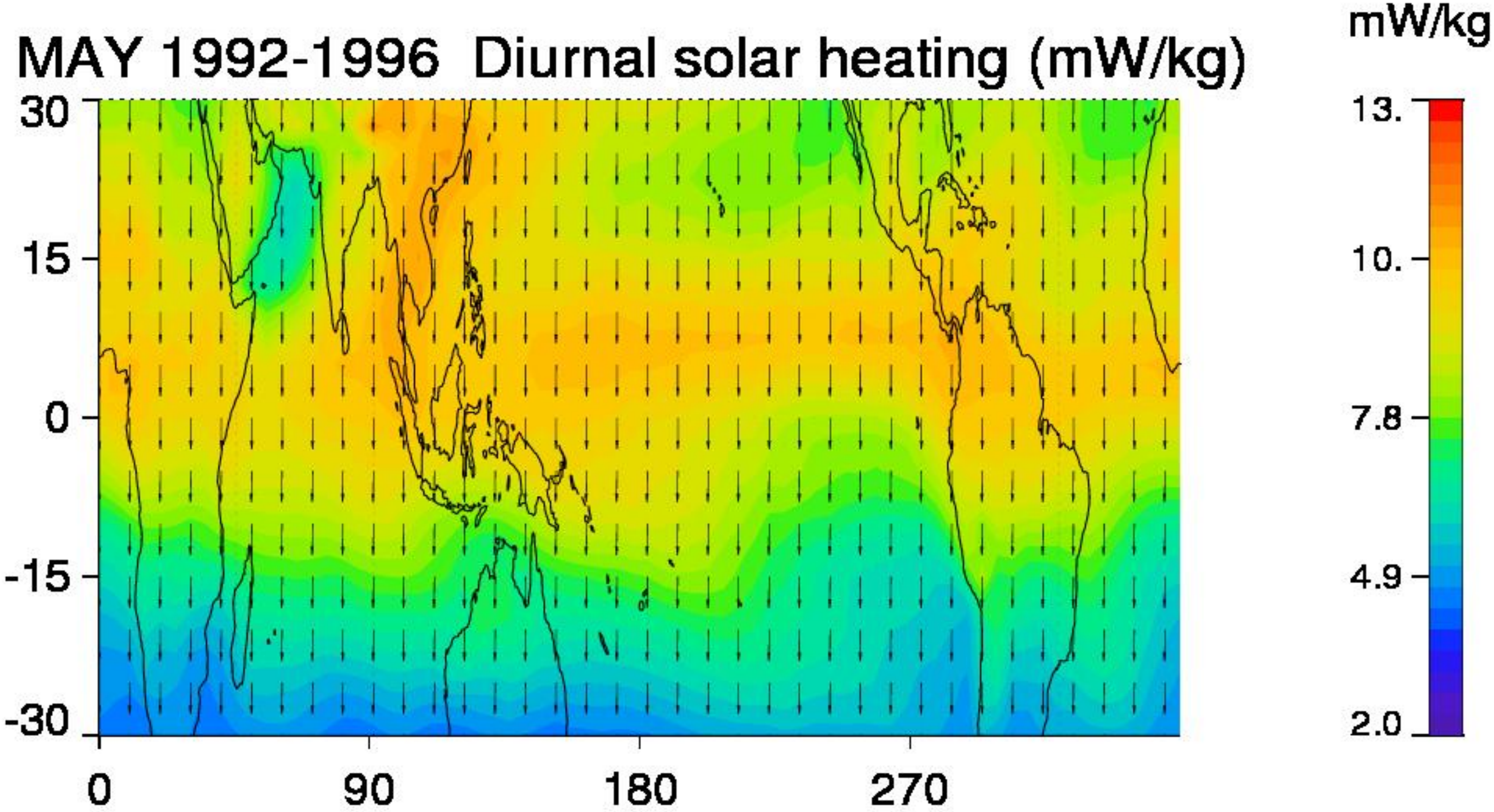


Semidiurnal (Pa)

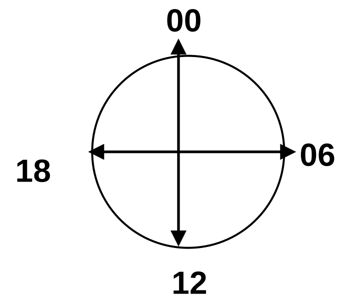
Note: Typical values of atmospheric surface pressure are ~101325 Pa.
At the surface, tidal oscillations are .1% of background pressure.

Atmospheric Tidal Forcing

- Near-IR radiation absorbed by H_2O_v in the lower troposphere.
- Release of latent heat by deep tropical convection.
- UV radiation absorbed by O_3 (stratosphere) and O_2 (thermosphere).
- EUV absorption and exothermic thermospheric reactions involving O recombination.



Mean tropospheric H_2O tropospheric heating



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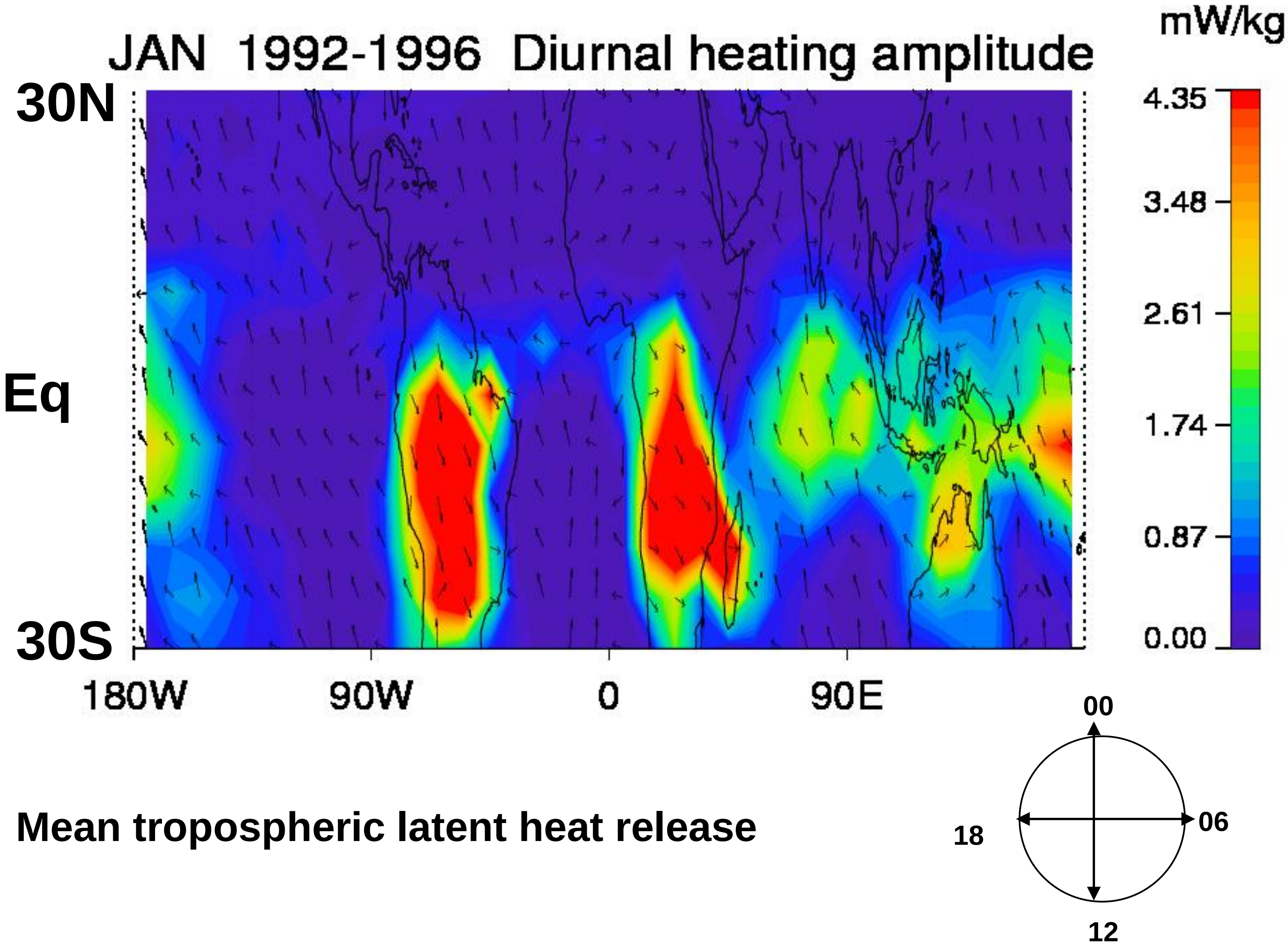

Mean tropospheric latent heat release

Atmospheric Tidal Forcing

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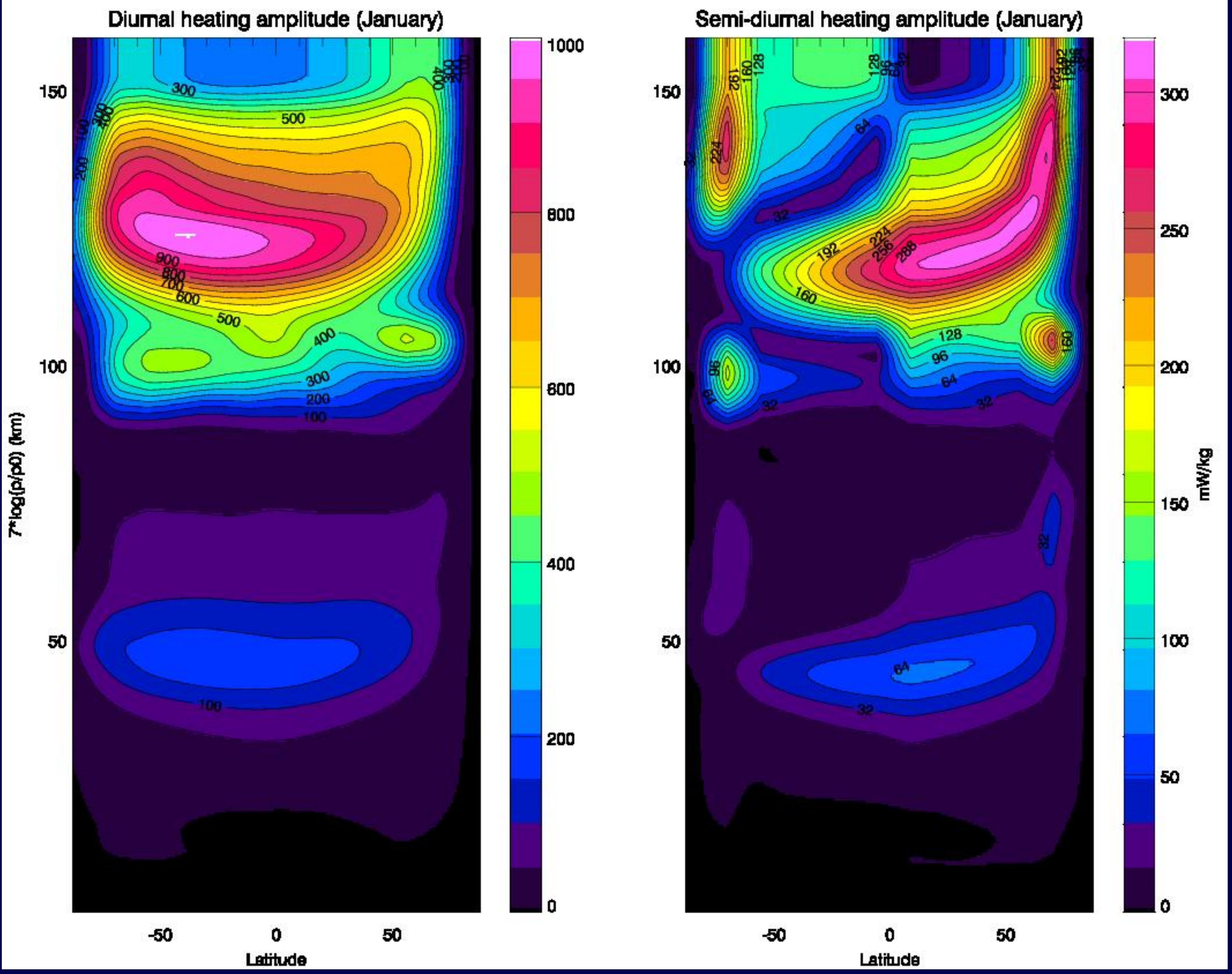

Diurnal heating amplitude (January)
Semi-diurnal heating amplitude (January)
7*log(p/p0) (km)
Latitude
Latitude
mW/kg

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TIMED-GCM thermospheric heating

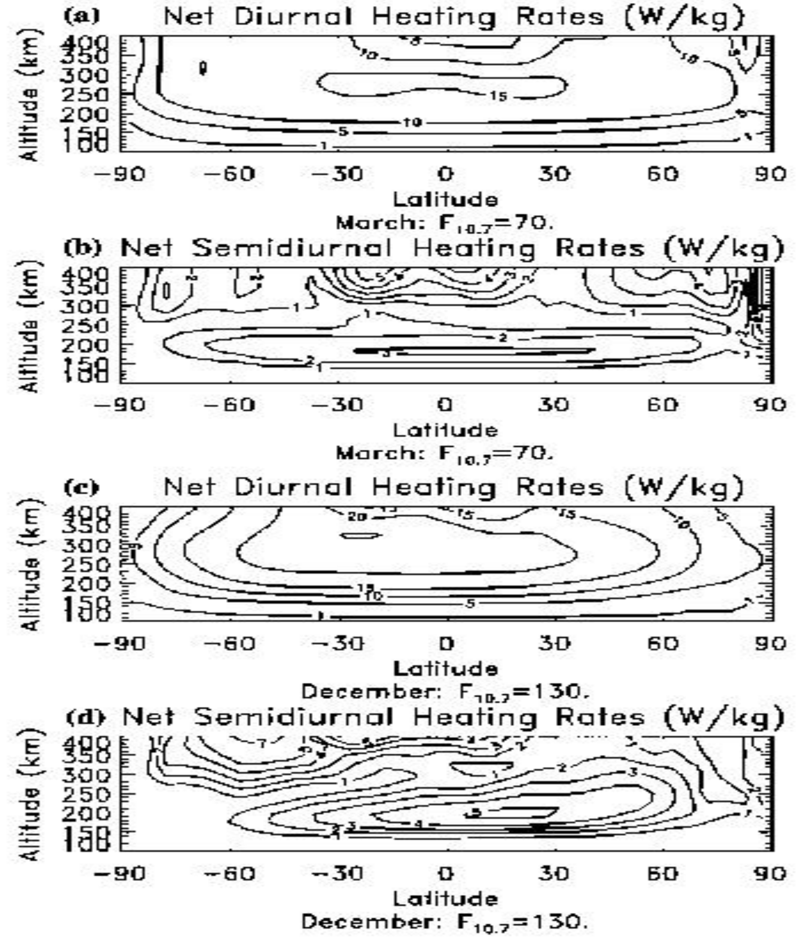
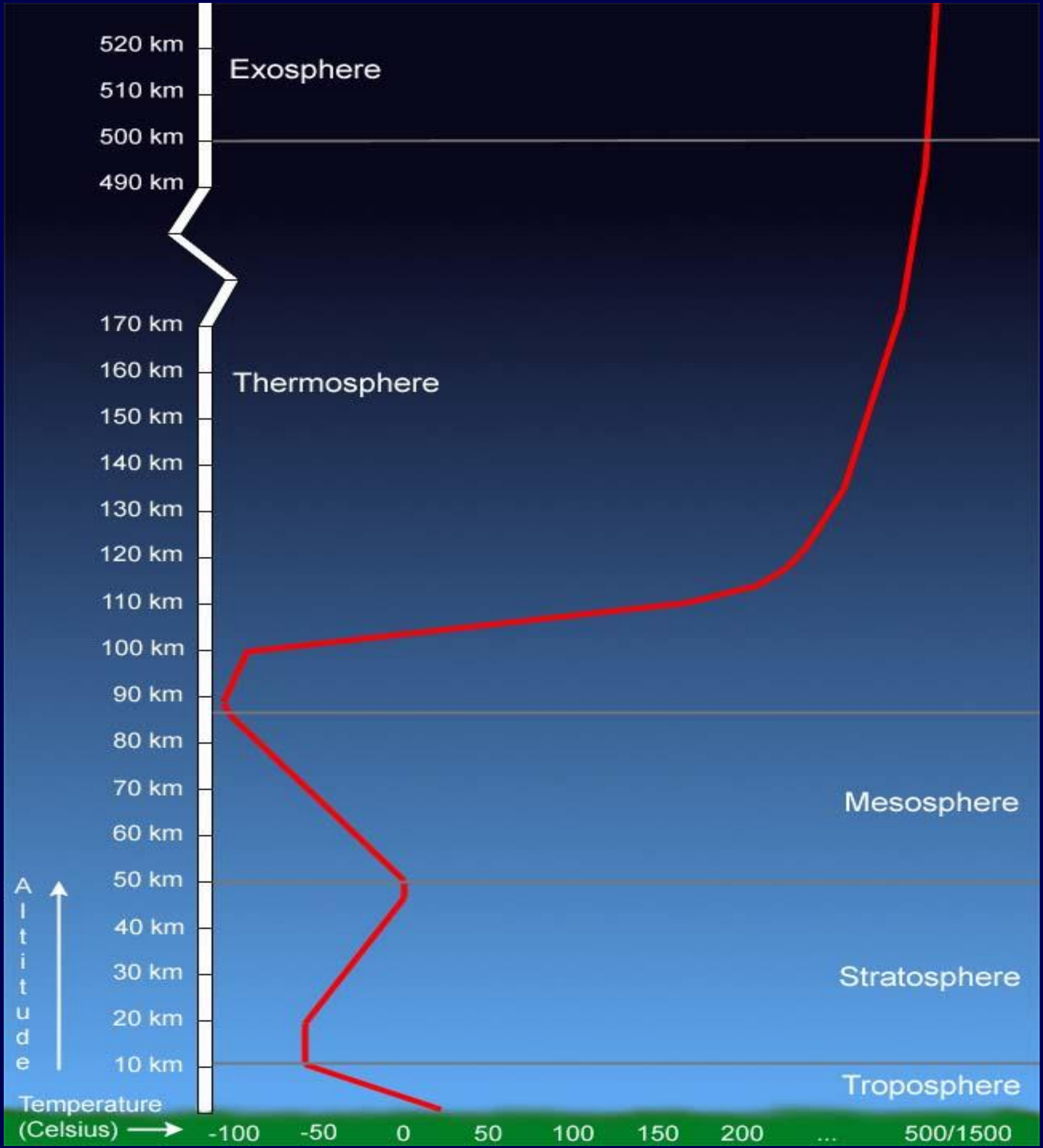


Figure 1. GSWM thermospheric heating rates (W kg^{-1}) as a function of geographic latitude and altitude (km) based on TIE-GCM neutral gas heating for the diurnal (a) and semidiurnal (b) tide during March solar minimum conditions and for the diurnal (c) and semidiurnal (d) tide during December solar moderate conditions.

Hagan et al., 2001



EUV heating: 10 W/kg

O_2 heating: 1W/kg

O_3 heating: 0.1 W/kg

H_2O_v + LH: 0.01 W/kg

Dynamics of Atmospheric Tides

Tides are inertia-gravity waves on a sphere

$$\partial u'/\partial t - f v' + (a\cos\varphi)^{-1}\Phi'_\lambda = 0$$

$$\partial v'/\partial t + f u' + a^{-1}\Phi'_\varphi = 0$$

$$\left(a\cos\varphi\right)^{-1}\left(u'_\lambda + (v'\cos\varphi)_\varphi\right) = \rho_0^{-1}(\rho_0 w')_z$$

$$\Phi'_{zt} + N^2 w' = Q'$$

Heuristic view of low-latitude semidiurnal tides: 2Ω >> f

$$\partial u'/\partial t + \Phi'_x = 0$$

$$\partial v'/\partial t + \Phi'_y = 0$$

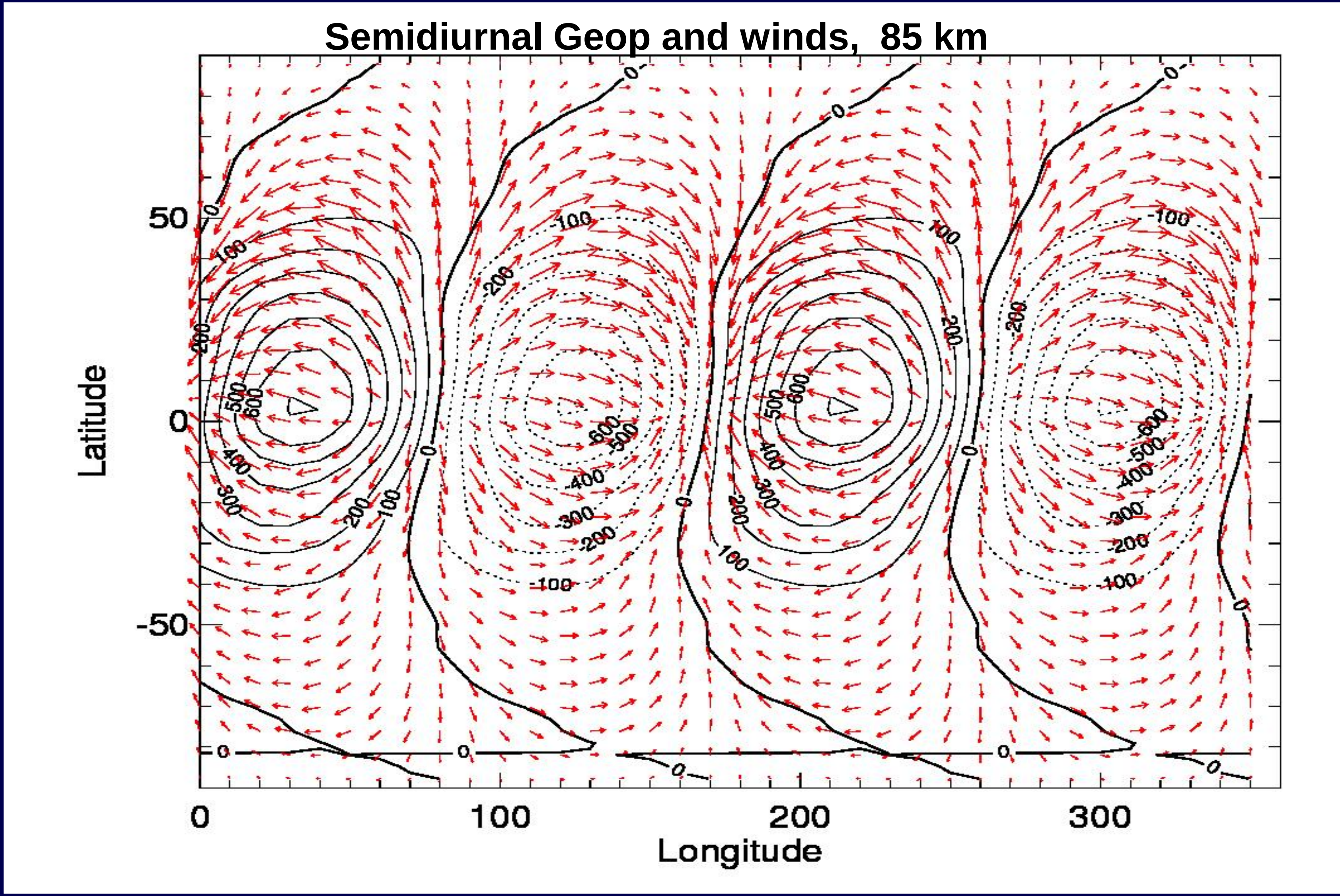
Divergence

$$\delta = u'_x + v'_y$$

$$\partial \delta / \partial t = -\nabla^2 \Phi' \quad \alpha \quad \Phi'$$

At low latitudes, migrating semidiurnal tides are internal gravity waves (horizontal restoring force is the pressure gradient).

Source: Ortland's tide model



At low latitudes, maximum convergence leads the high pressure by ¼-cycle.

Heuristic view of midlatitude semidiurnal tides ($f \Rightarrow 2\Omega$)

$$\partial u'/\partial t - f v' = 0$$

$$f = 2\Omega \sin \varphi$$

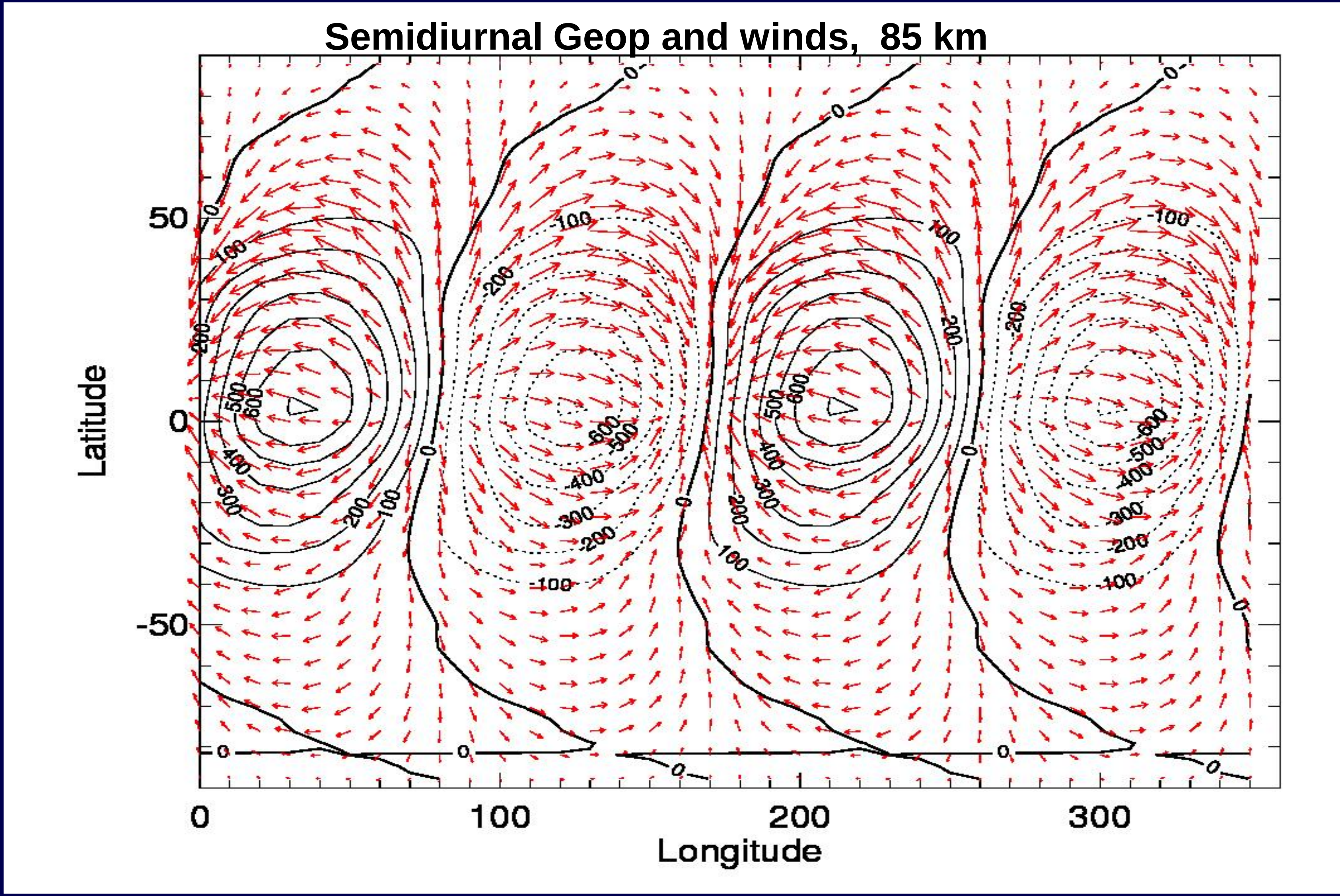
$$\partial v'/\partial t + f u' = 0$$

$$\zeta' = \partial v'/\partial x - \partial u'/\partial y$$

$$\partial \delta'/\partial t = f \zeta'$$

At higher latitudes, migrating semidiurnal tides are inertial oscillations (restoring force is the Coriolis acceleration).

Source: Ortland and Alexander, 2006



At middle and high latitudes, Coriolis effect rotates winds rightward (NH) into inertial circulations.

Heuristic view of low-latitude diurnal tides: Ω ≥ f

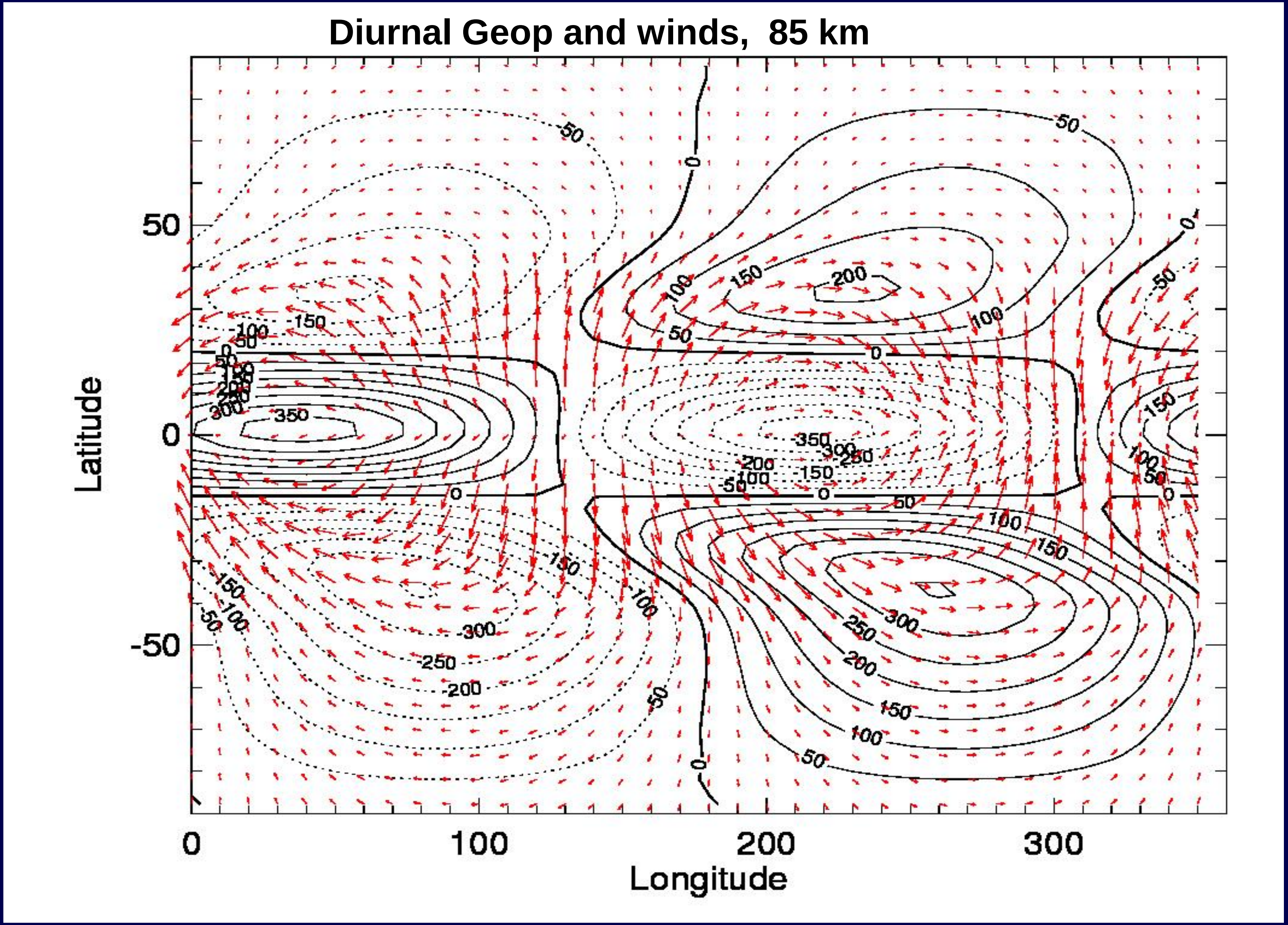
$$\partial u'/\partial t - fv + \Phi'_x = 0$$

$$\partial v'/\partial t + fu + \Phi'_y = 0$$

$$f = 2\Omega \sin\varphi$$

- Pure gravity waves at the equator (like semidiurnal).
- But inertial (Coriolis) effects "kick in" by 10°; note that $f = \Omega$ at 30°.

Diurnal tide (Ortland and Alexander, 2006)



Heuristic view of mid-high latitude diurnal tides: f > Ω

$$\partial u' / \partial t - f v' + \Phi'_x = 0$$

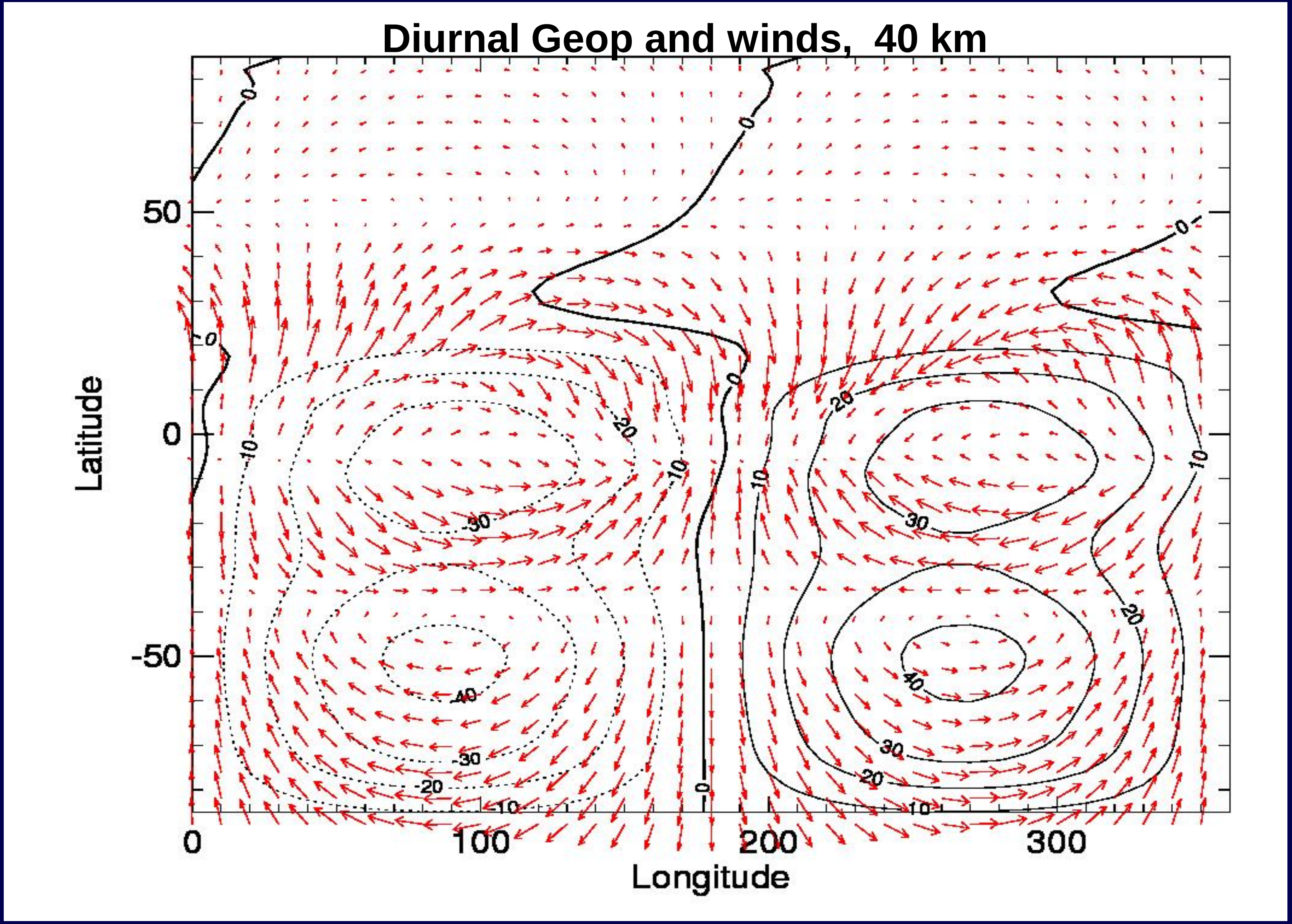
$$\partial v' / \partial t + f u' + \Phi'_y = 0$$

$$f = 2\Omega \sin\varphi$$

$$u'_g = -\Phi'_y / f$$

$$v_g' = \Phi'_x / f$$

Source: Ortland and Alexander, 2006



At very high latitudes, diurnal exhibits approaches quasigeostrophic flow in SH (opposite to NH conventions).

Vertical propagation

At latitudes where tides are internal gravity waves ($f \ll \Omega$) they propagate vertically.

$\lambda_z \sim 27$ km (main diurnal).
$\lambda_z \sim 60$ km (main semidiurnal).

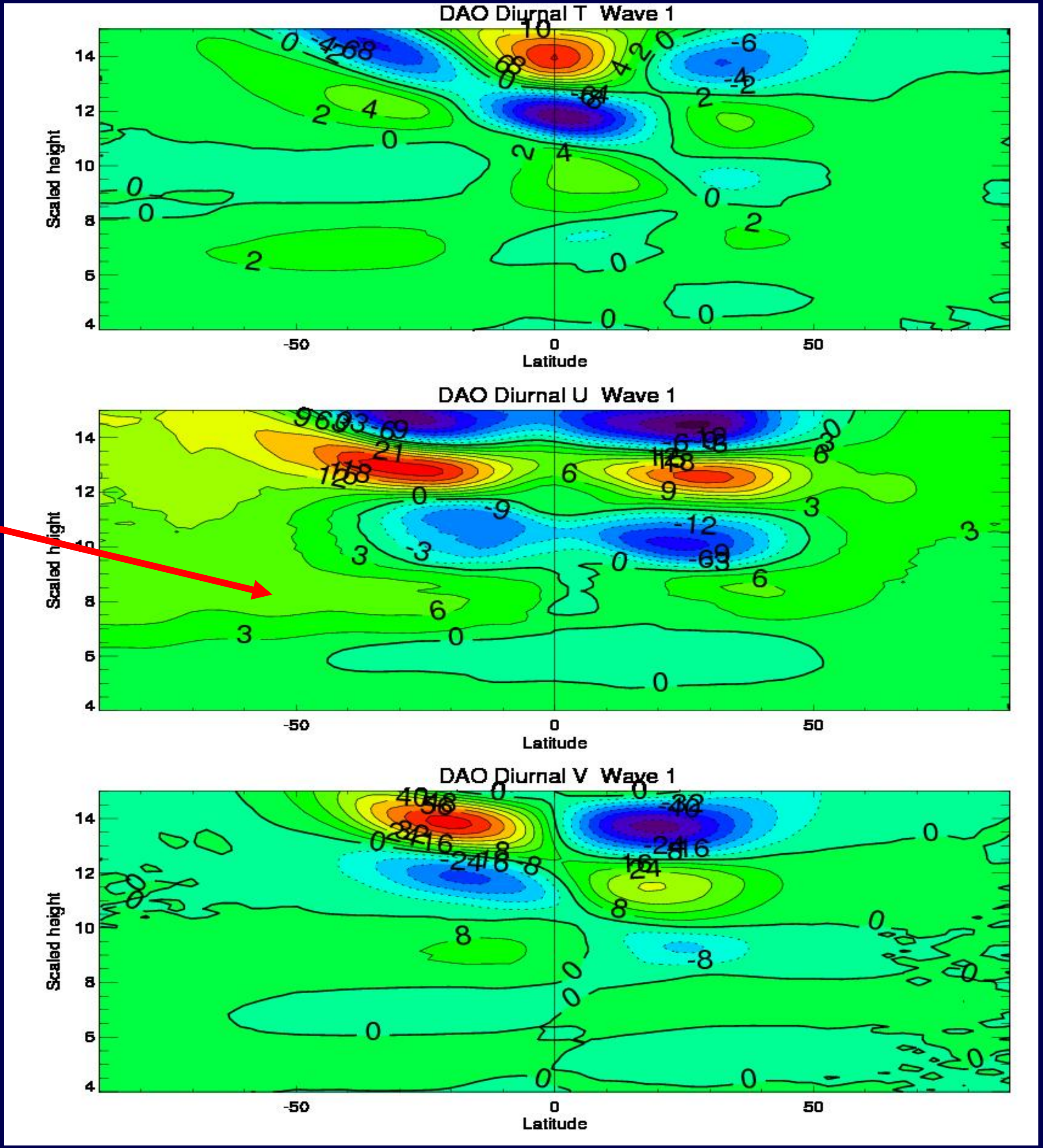
Amplitudes increase exponentially with altitude to stratopause; above that growth becomes linear, then breaking and decaying.

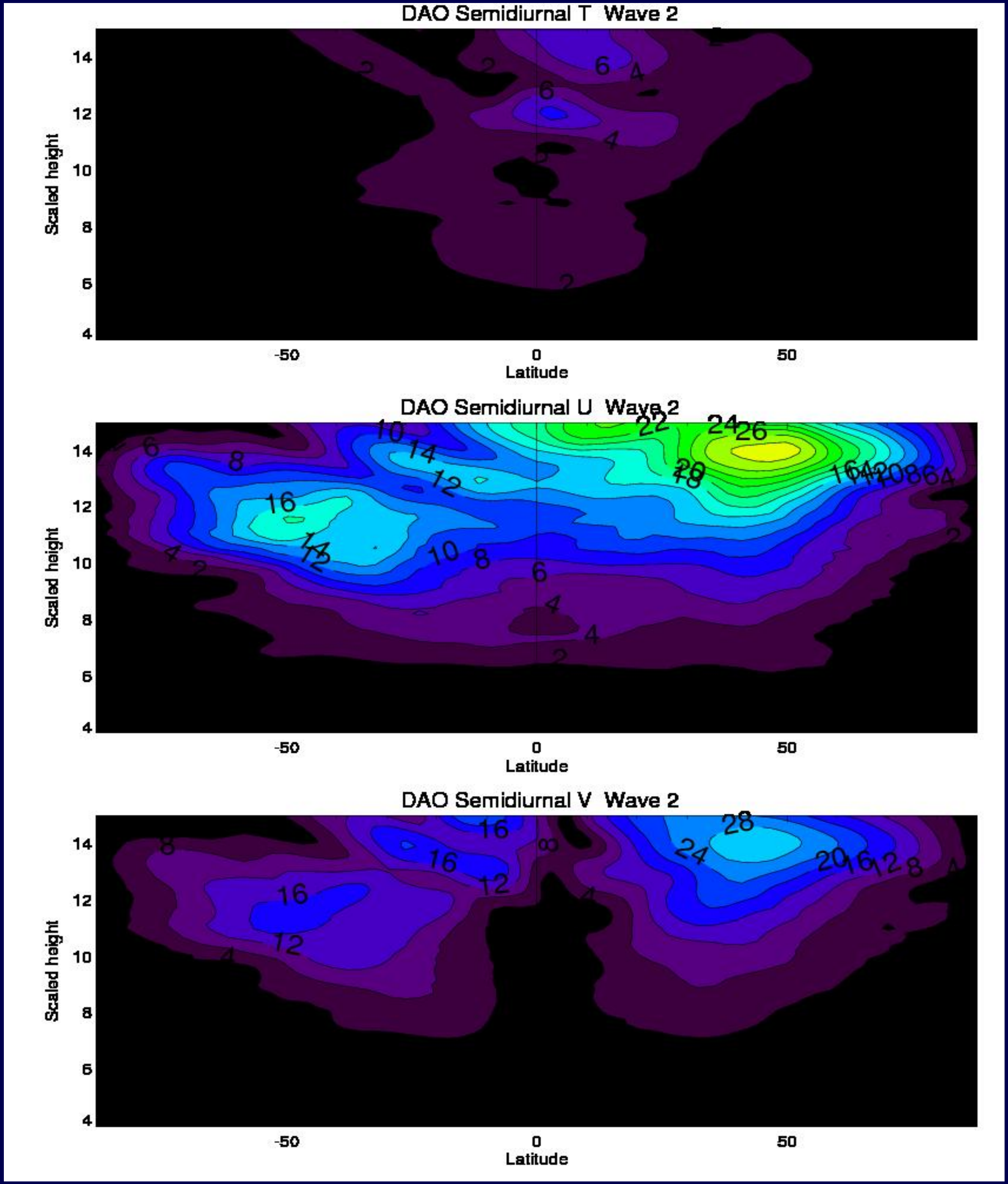
At higher latitudes ($f \geq \Omega$) *diurnal tides do not propagate vertically.* Amplitudes are highest in the region of forcing, and decay exponentially in altitude.

Diurnal tides propagate vertically between 30ºS-30ºN.

Vertically trapped response to ozone heating.

Diurnal tides acquire strongest amplitudes at ~95 km.



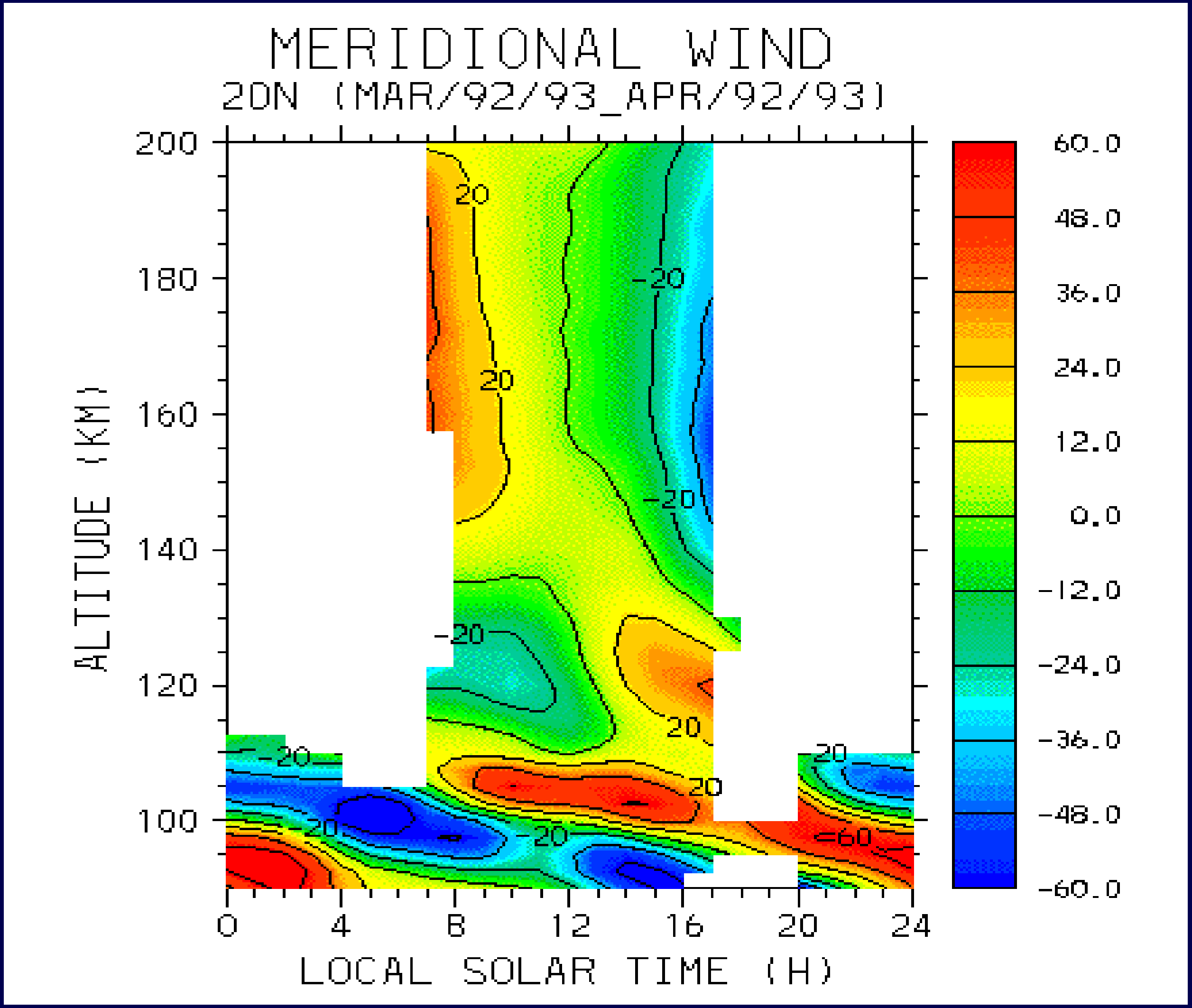


Semidiurnal tides acquire strongest amplitudes above 100 km.

Semidiurnal tides extend to higher latitudes.

Semidiurnal tides propagate vertically at all latitudes.

Thermospheric tides



Migrating diurnal tides attenuate above 120 km.

Migrating semidiurnal tide dominates above 120 km.

McLandress et al., 1996

Atmospheric tidal theory

Tidal theory pulls together the "f-plane" behaviors summarized in previous slides into a global solution.

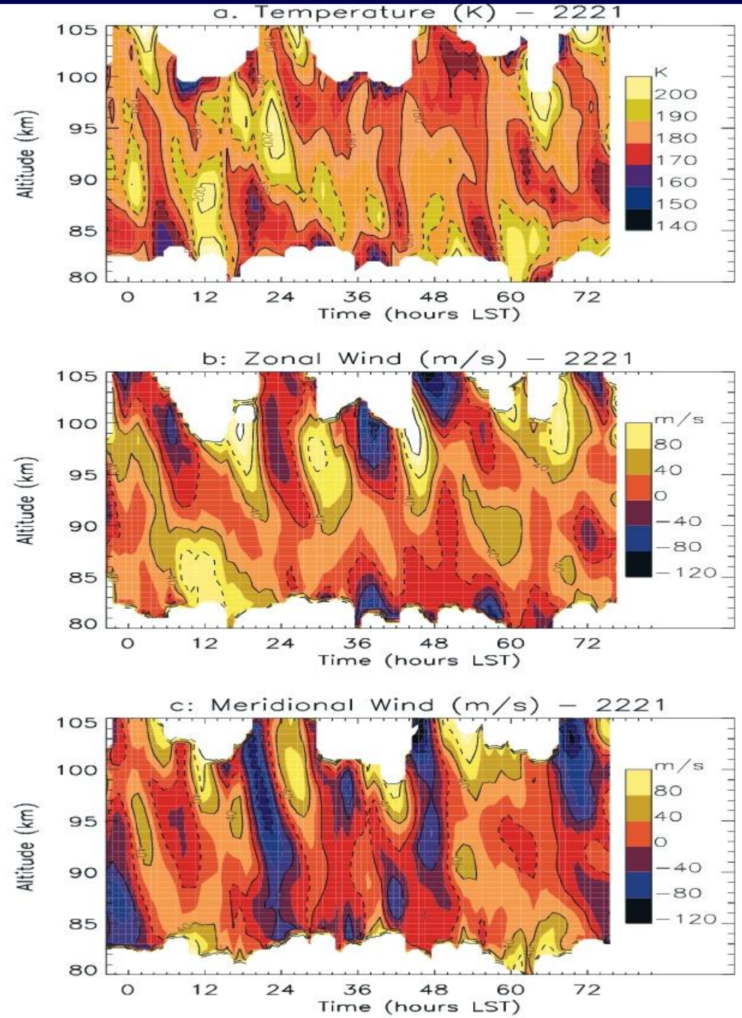
The primitive equations are most tractable for a *nonviscous* atmosphere with *zero background wind* (Chapman and Lindzen 1970, Kato 1966).

Under these circumstances, PE system are *linear*, and their horizontal and vertical structures are *separable*.

The separability property leads to the solution of the tidal system as a series of spherical harmonics known as *Hough functions*.

Observing the tides

Single point 24-hour coverage



Na lidar at Fort Collins, August 9-12, 2002.

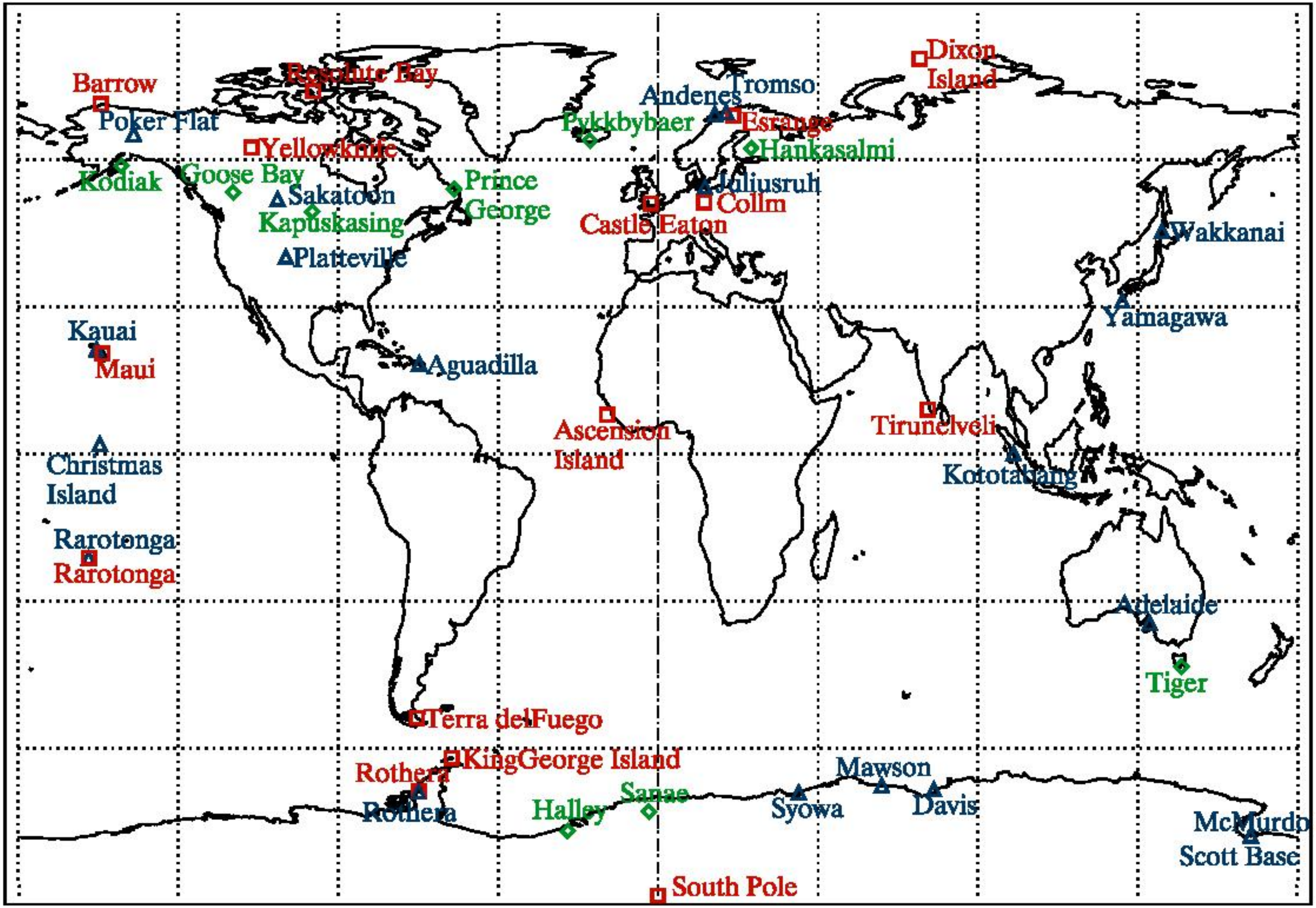
15

Sampling illustrated in this plot shows clear diurnal and semidiurnal variations, that can be isolated with Fourier methods.

Ideally, this sampling of tides would be mimicked over the entire globe.

Unfortunately, full local time coverage above the surface is rare, and confined to ground-based sites.

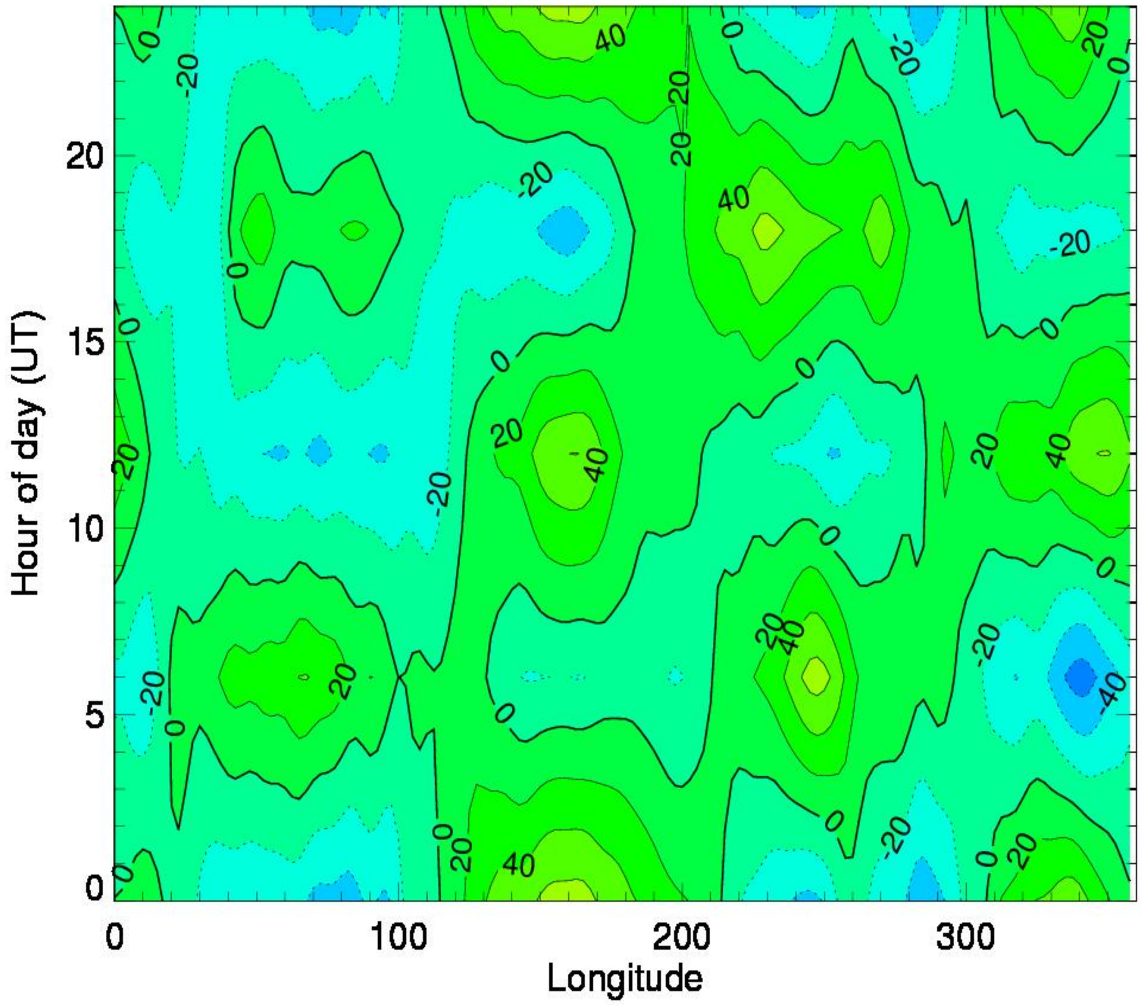
Figure: She et al., 2004.



Barrow
Resolute Bay
Poker Flat
Yellowknife
Kodiak
Goose Bay
Sakatoon
Kapuskasing
Platteville
Prince George
Pykkbybaer
Andenes
Tromso
Esrange
Hankasalmi
Juliusruh
Collm
Castle Eaton
Dixon Island
Wakkanai
Yamagawa
Kauai
Maui
Aguadilla
Ascension Island
Tirunelveli
Kototabang
Christmas Island
Rarotonga
Rarotonga
Adelaide
Tiger
Terra delFuego
KingGeorge Island
Rothera
Rothera
Halley
Sanae
Syowa
Mawson
Davis
McMurdo
Scott Base
South Pole

Global 4x/day Reanalysis

Equatorial NCEP 2004 Φ’at 10 hPa (~30 km)

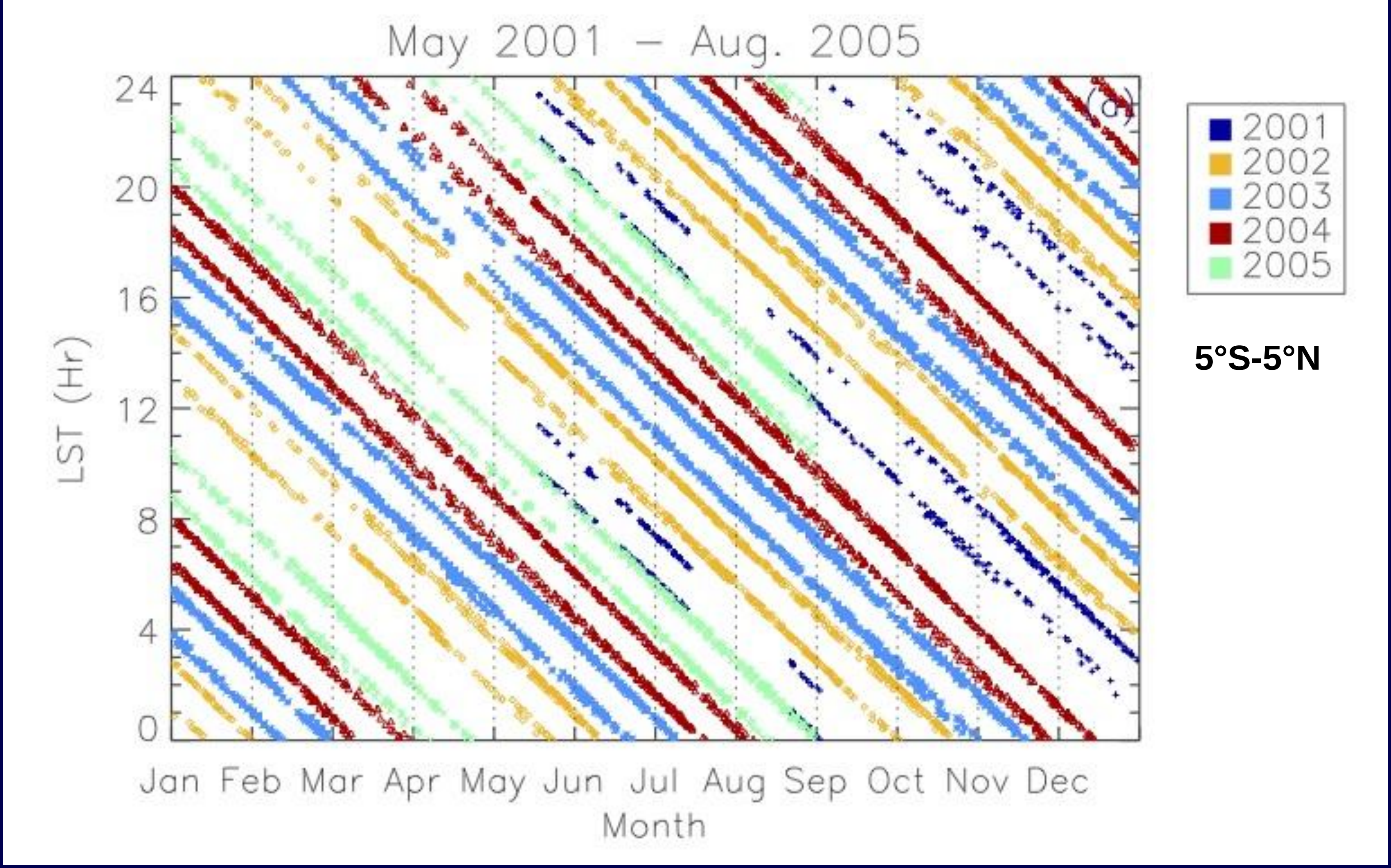


Global analysis at spaced 6 hours apart reveals diurnal semidiurnal variations.

Unfortunately, most reanalyses only reach the stratospheric levels, well below where strongest amplitudes are found.

See Sakazaki et al. (2012) to learn about tides in reanalyses.

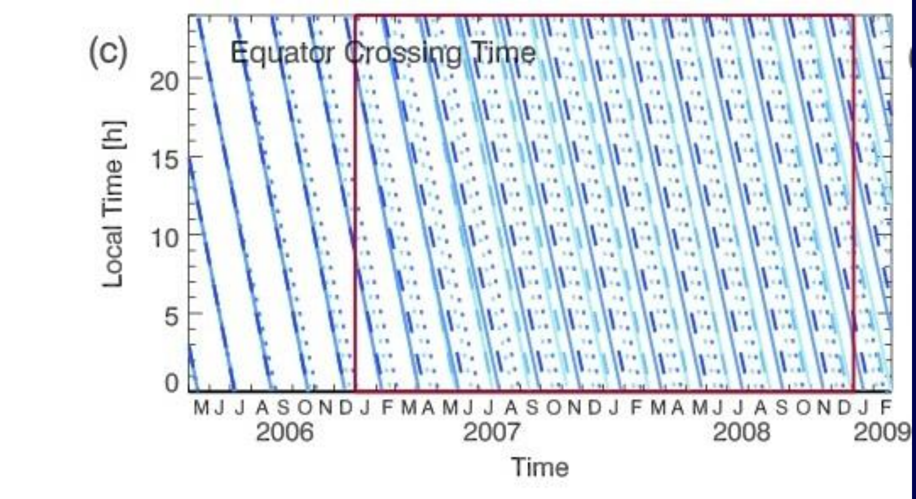
CHAMP RO T (Zeng et al., 2008)



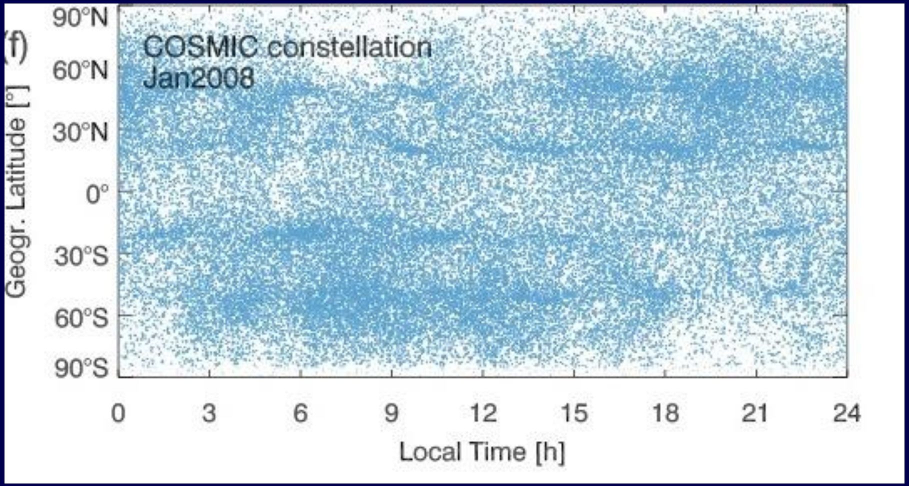
5°S-5°N

Altitude range of GPS T: 10—30 km

COSMIC RO T (Pirscher et al., 2010)

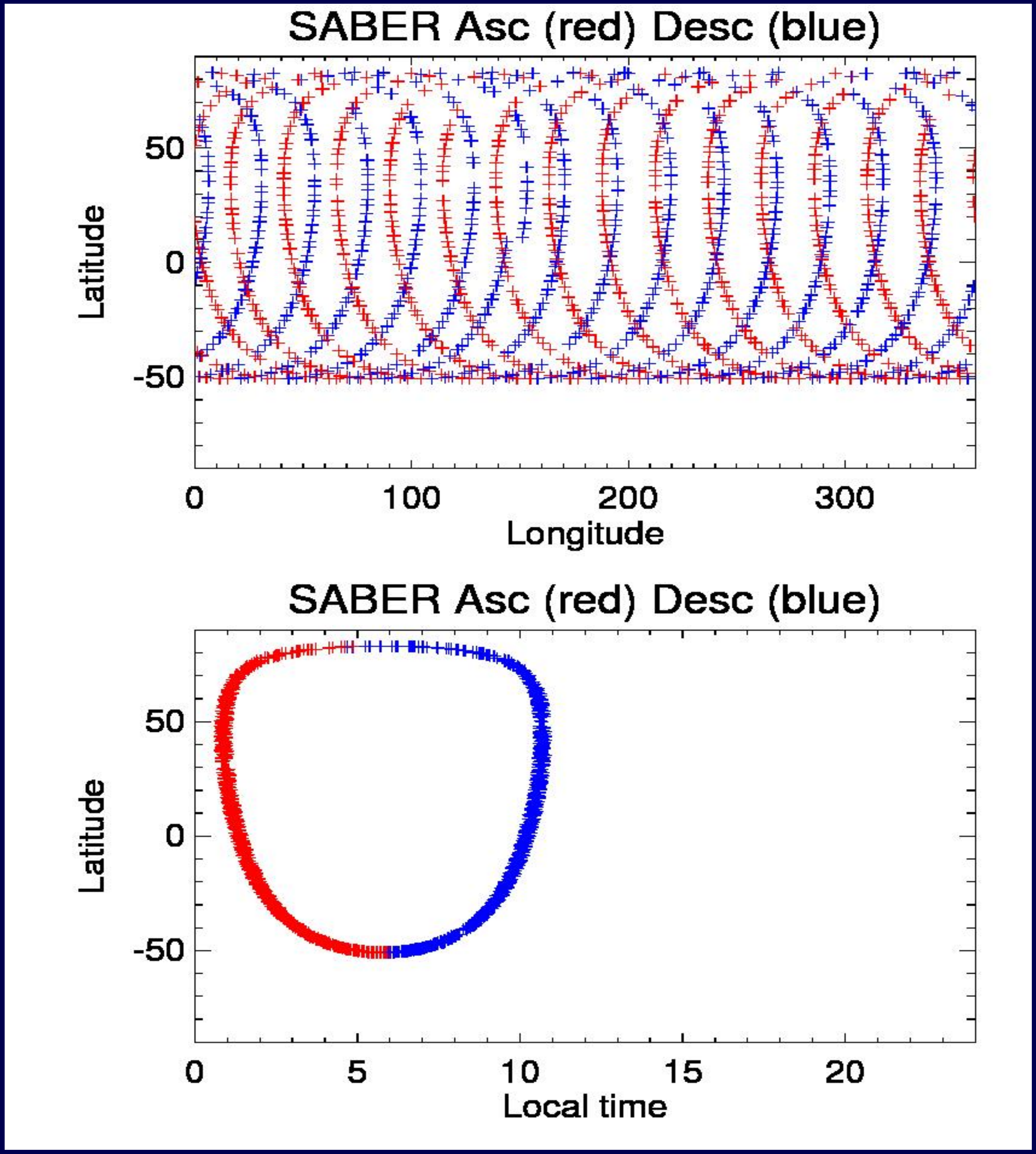


Sampling by constellation of 6 satellites



Altitude range of GPS T: 10—30 km

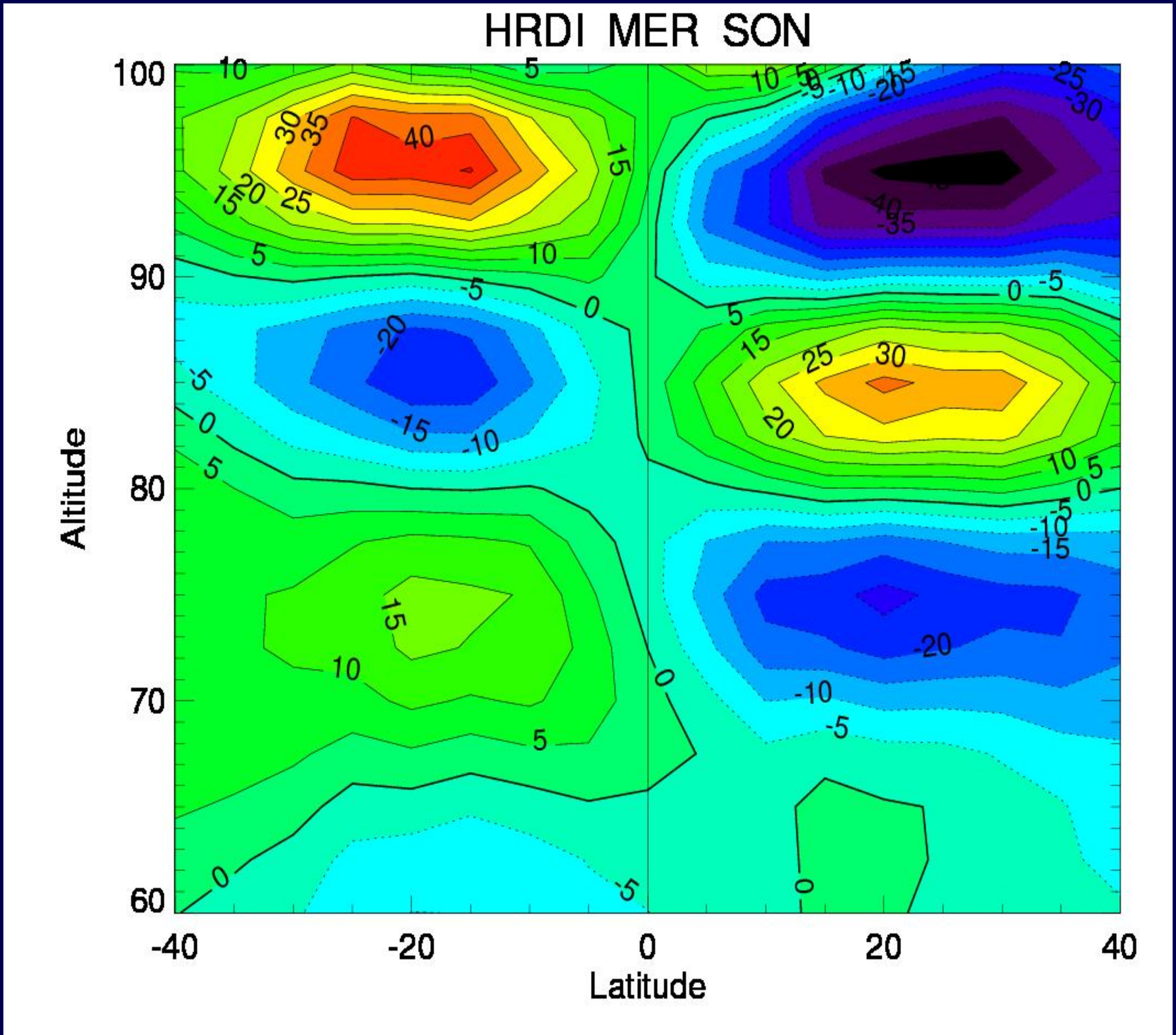
Satellite Sampling



Satellites provide global, latitude-longitude coverage.

But *local time sampling is very limited.*

Zonal mean V at fixed local time

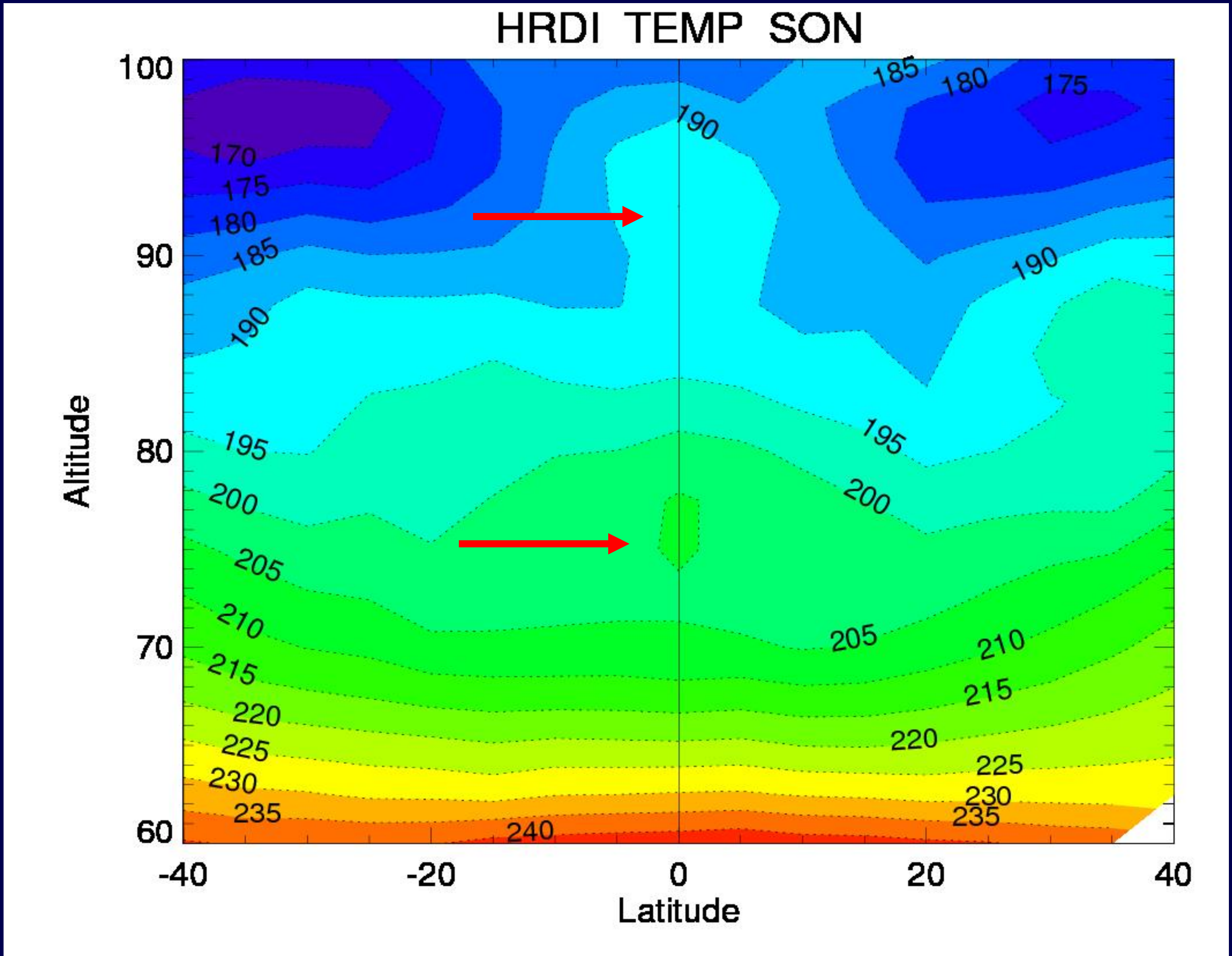


Satellites provide global, latitude-longitude-altitude coverage.

But *local time sampling is very limited.*

V tides show up well in a single local time (0900) because of weak background…

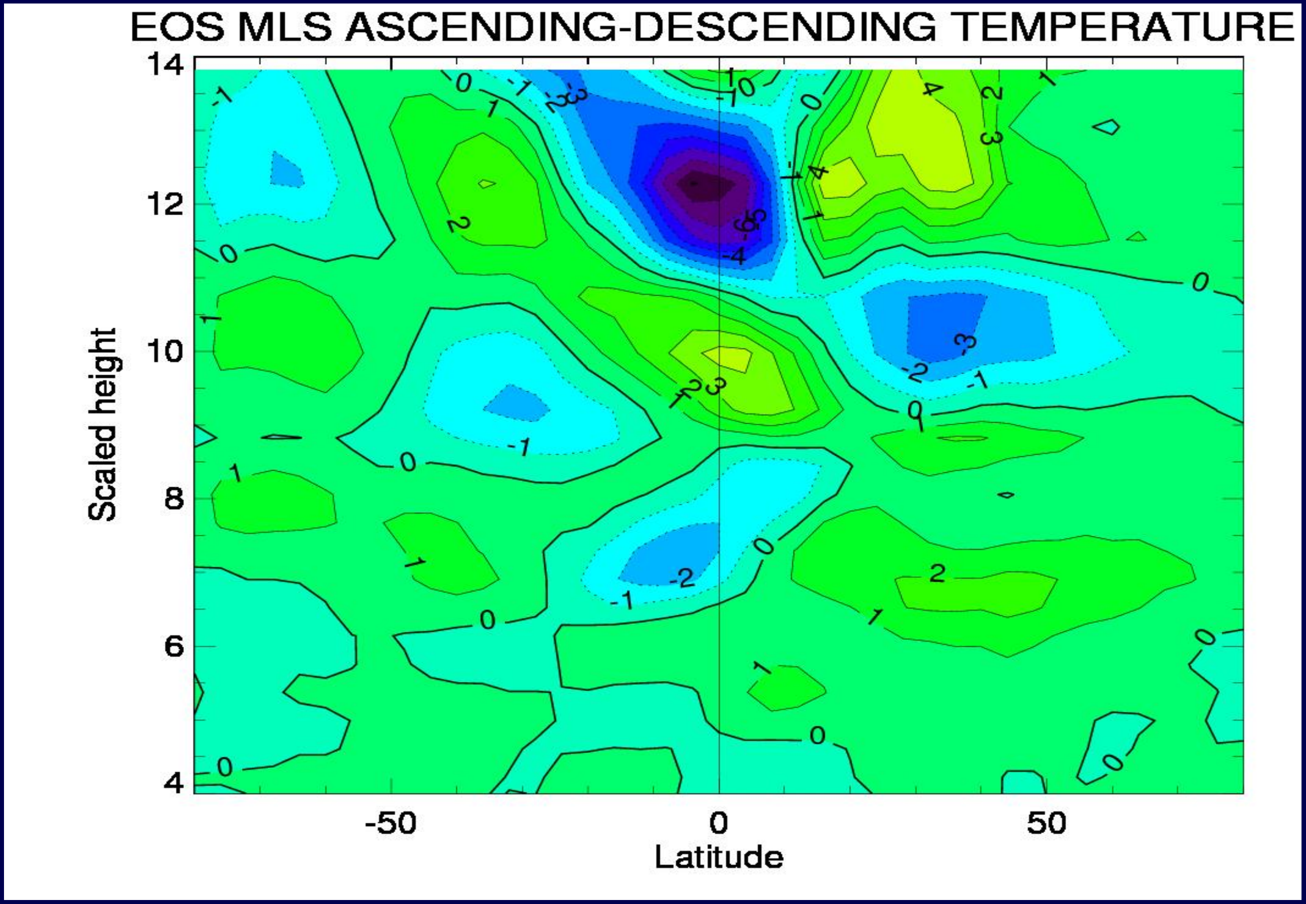
T at fixed local time



Tides can be much harder to discern at a single local time when there is a strong background, such as T.

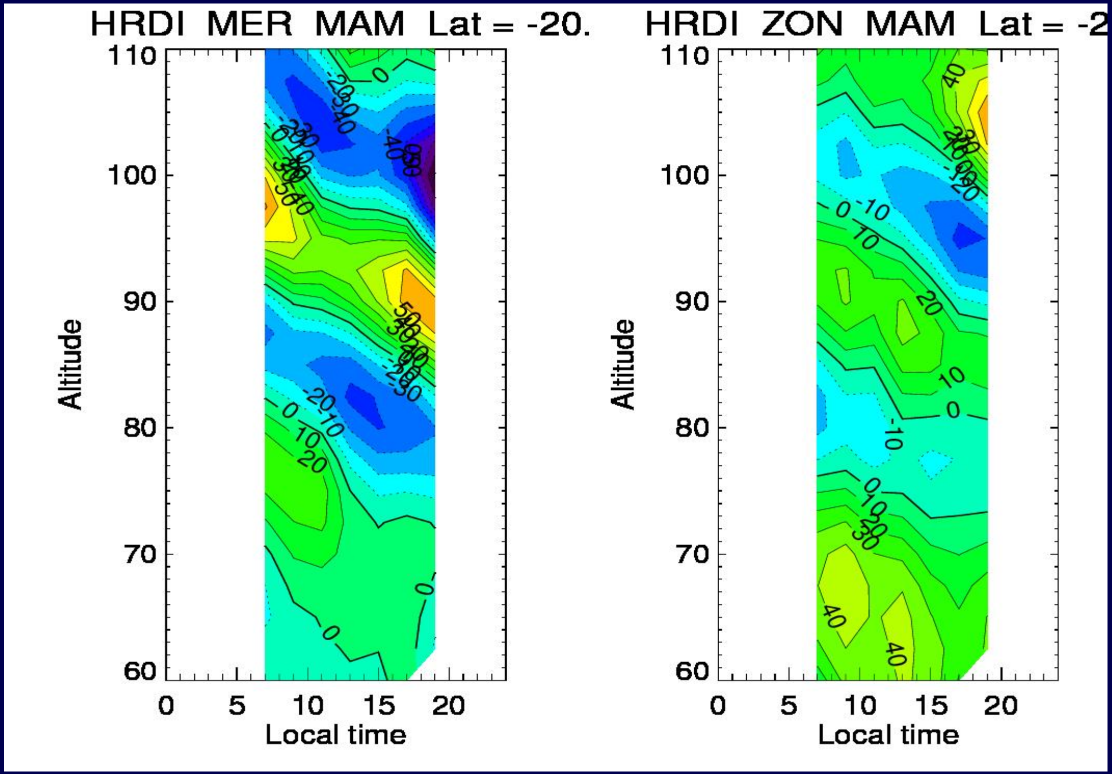
Need more local times!

Tides: Sun-synchronous satellites



Diurnal variation can be observed from ascending-descending node differences (Hitchman and Leovy, 1985; Ward, 1999).

Tides: Satellite with precessing orbit



UARS: 12 daytime hours sampled over 36 days (Hays et al., 1994)

TIMED: 24 hours sampled over 60 days (Zhang et al, 2006; Oberheide et al., 2006; Wu et al., 2008)

CHAMP: 24 hours sampled over 140 days (Zheng et al, 2008; Hausler and Luhr, 2009).

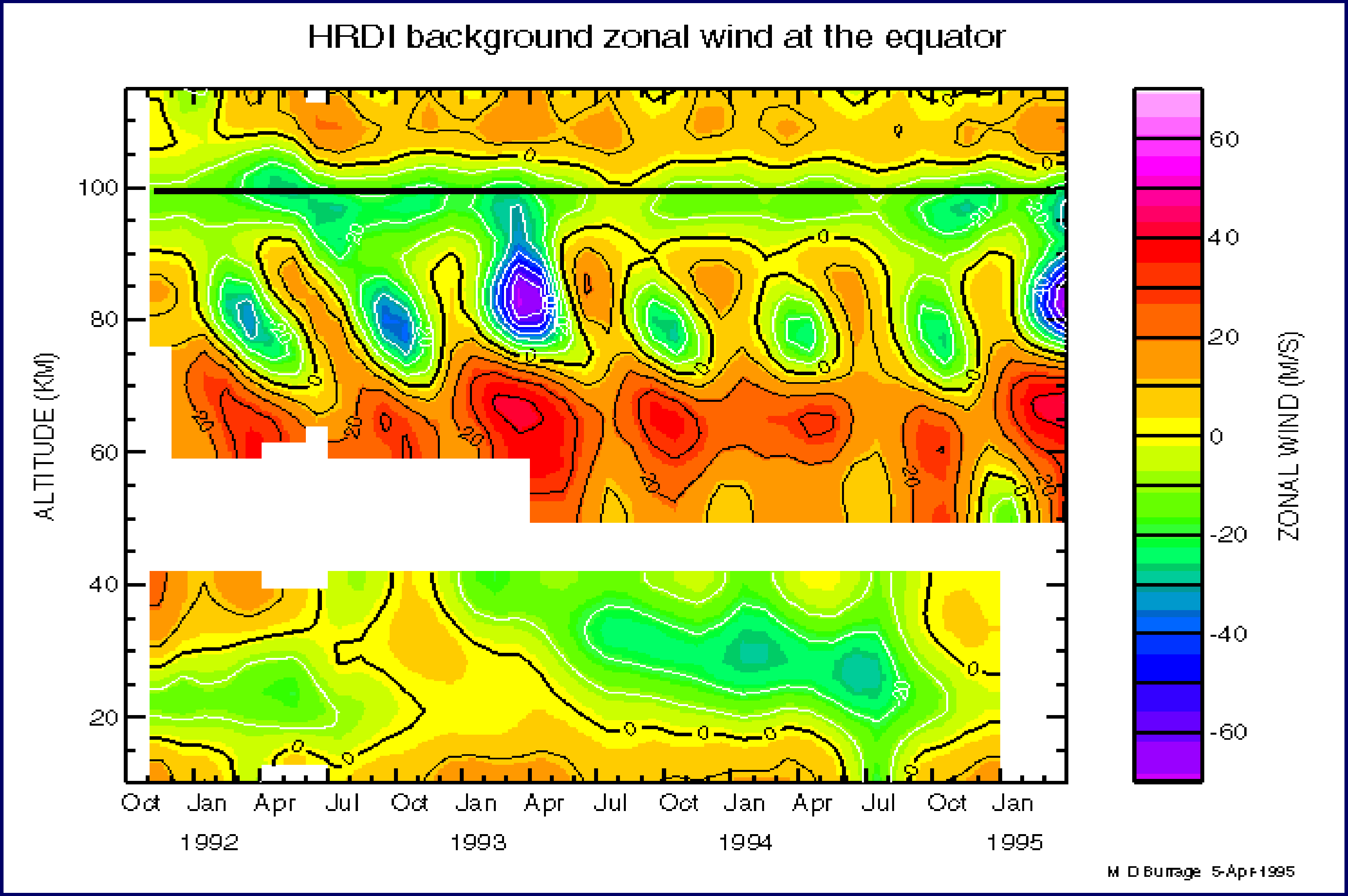
Why are tides important?

•In the MLT tidal winds are as large as zonal mean winds. Wave saturation transfers westward momentum to the zonal mean flow (5-15 m/s/day).

•Tides modulate aeronomical species (OH, O_2).

•Long vertical wavelengths (27-60 km) makes the tides efficient agents of vertical coupling, and transmission of tropospheric variability into the ITM.

•Global structure of tides may facilitate cross-equatorial and ionospheric coupling through nonlinear tide-PW interaction.



Zonal mean westward winds above MSAO levels (90-100 km) maintained in part by dissipating diurnal tides.

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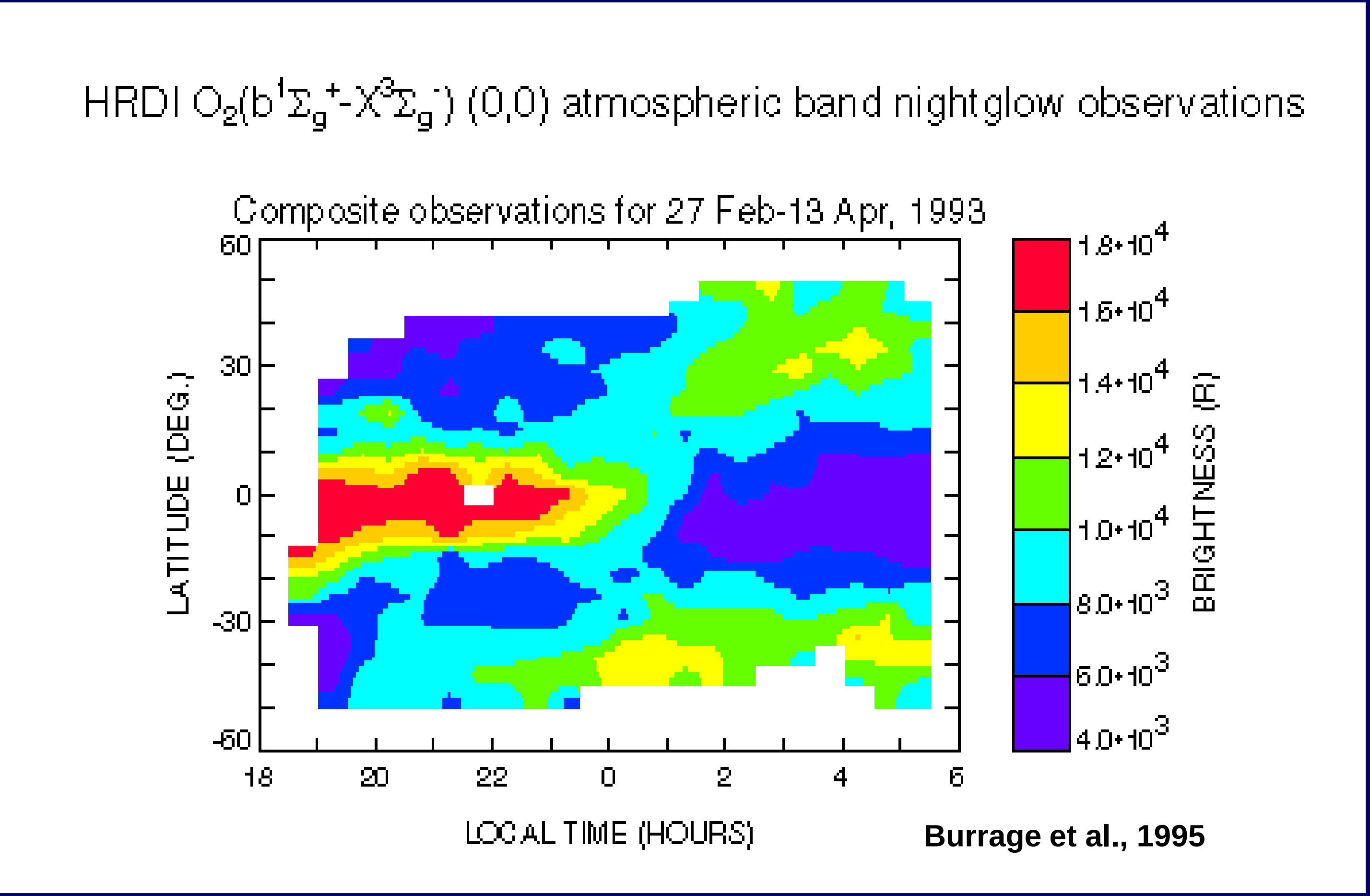
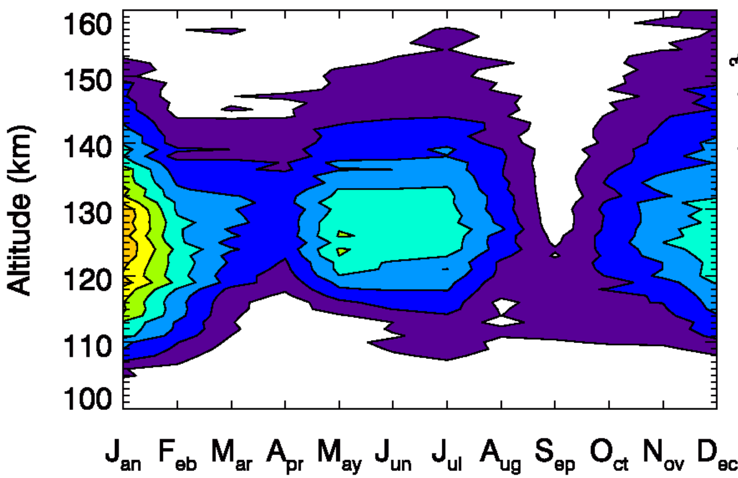


Tidal w' moves O abundance up and down, influencing OH and O_2 recombination (Marsh et al, 1999).

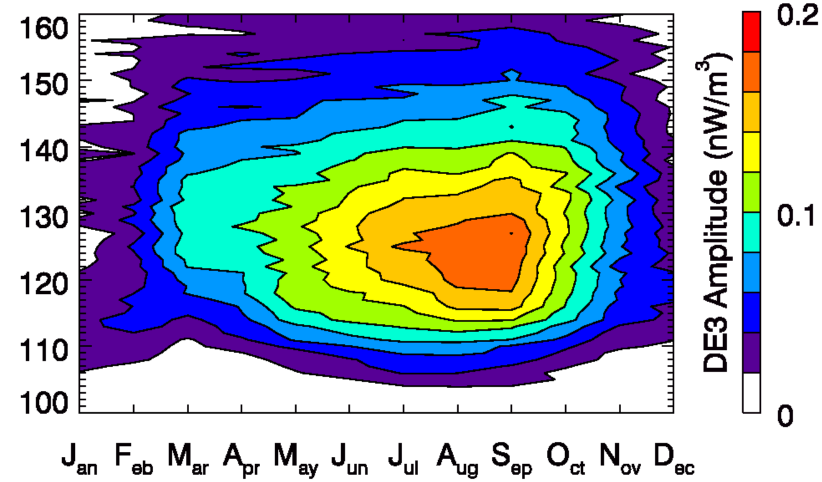
Tidal T' modulates the rates of OH and O_2 production and loss.

SABER, 2008, equator, NO 5.3 µm volume emission rates

DE2



DE3



NO 5.3 µm infrared emissions key cooling mechanism for the thermosphere.

Background value @equator, solar min is about 0.8 nW/m3 around 130 km.

Optically thin: energy escapes thermosphere completely

Acts as the thermosphere's "natural thermostat".

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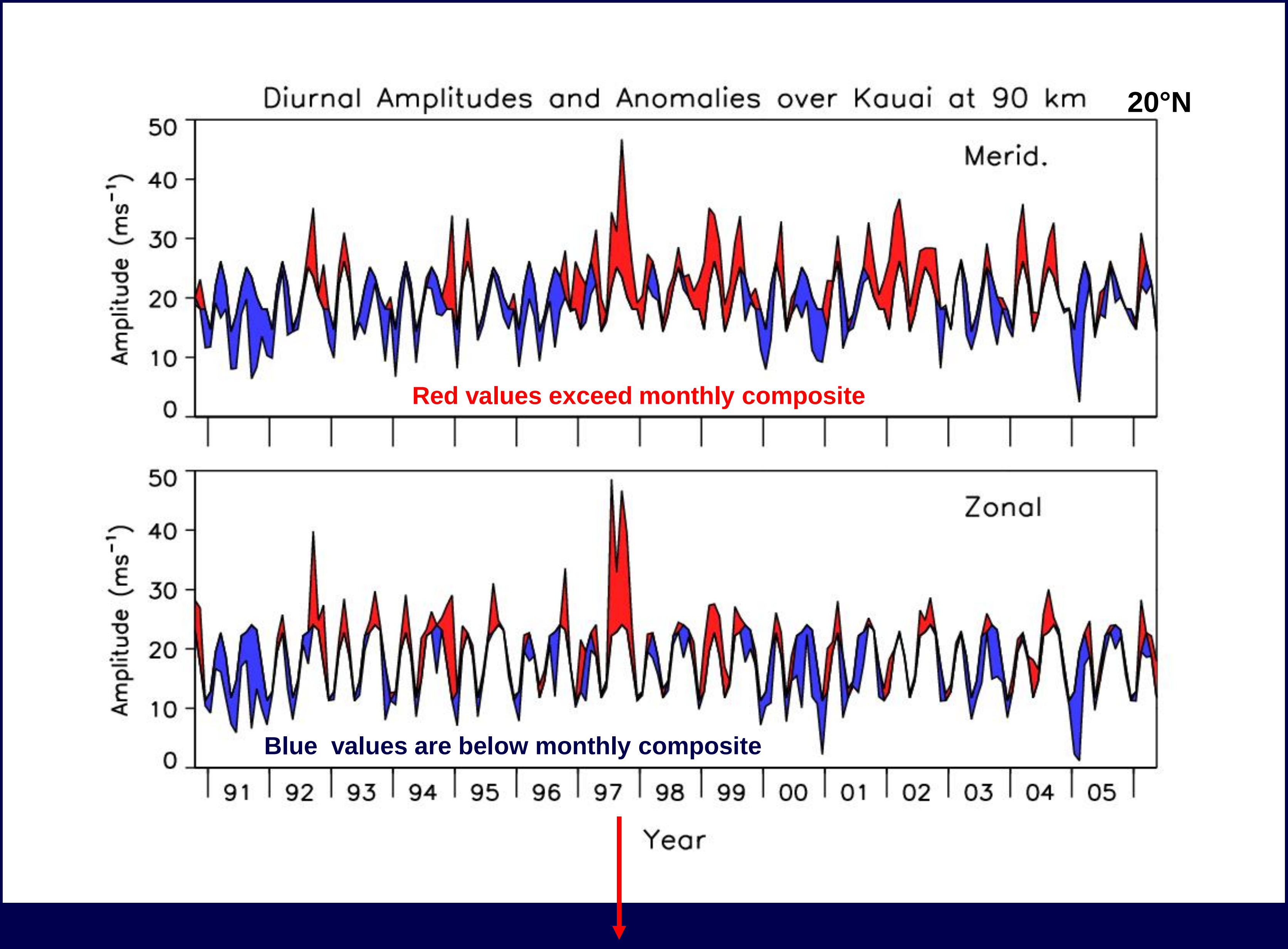
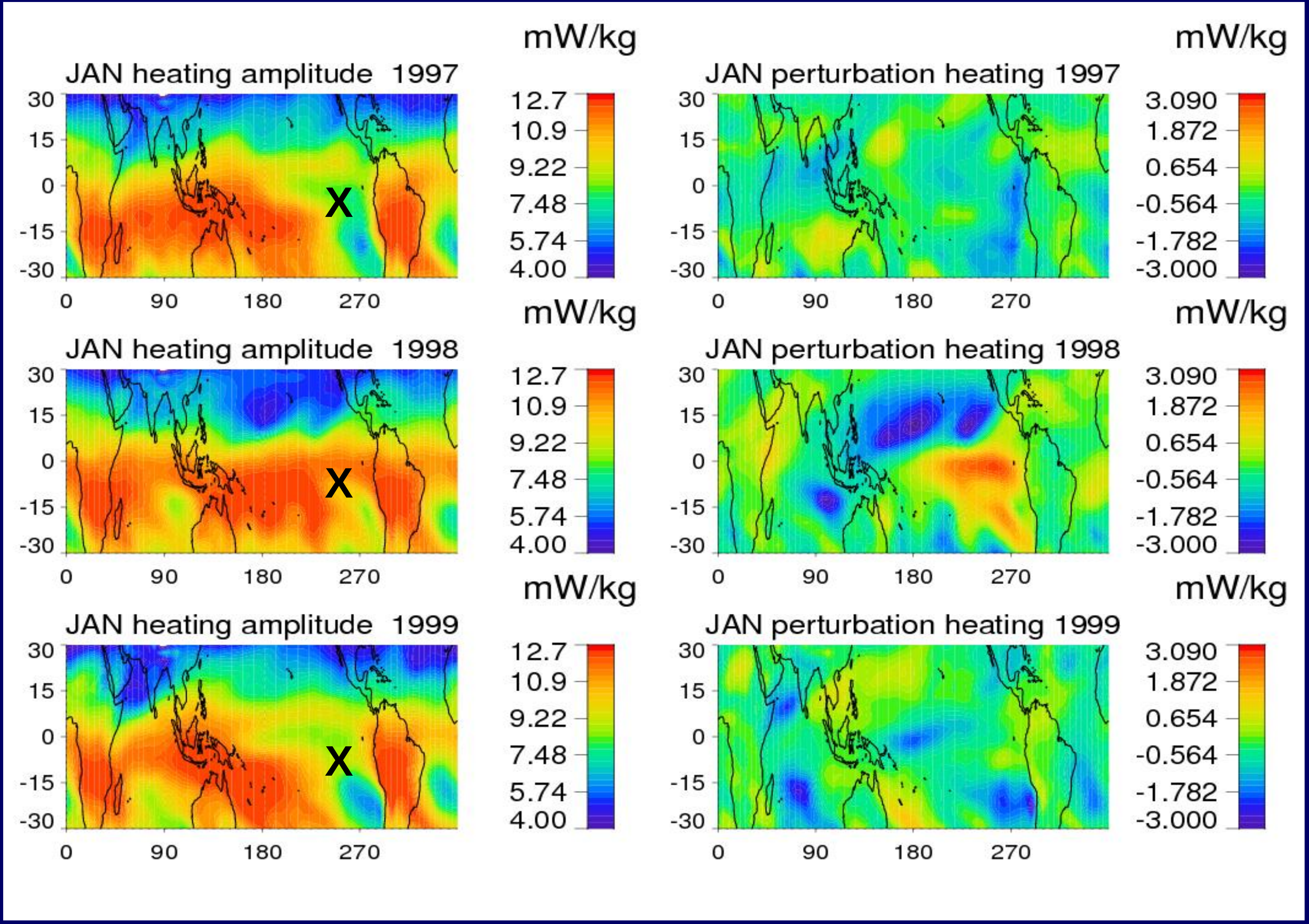
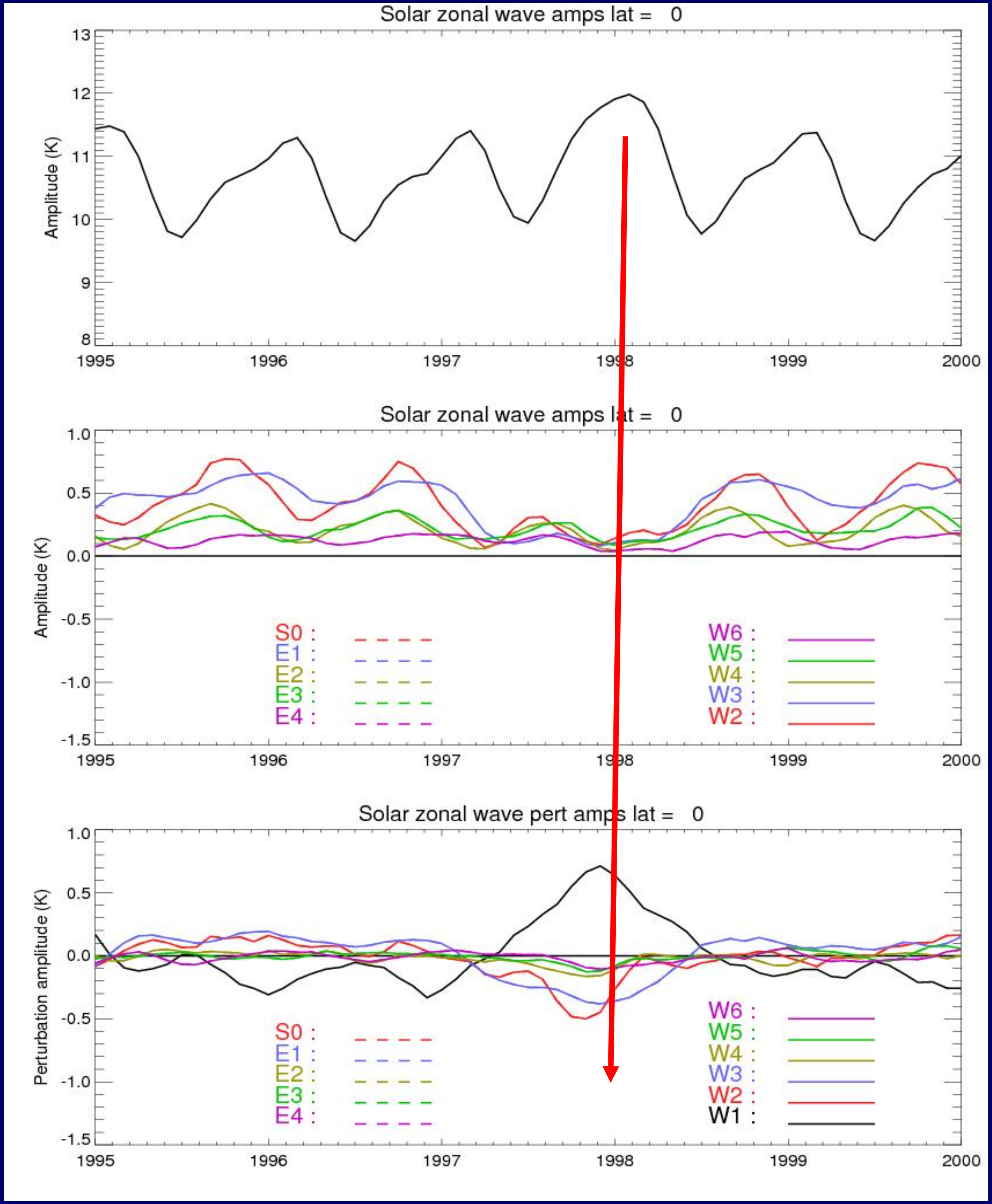


ENSO enhanced forcing of migrating diurnal tide by H_2O_v heating (Lieberman et al., 2007).

Diurnal water vapor heating

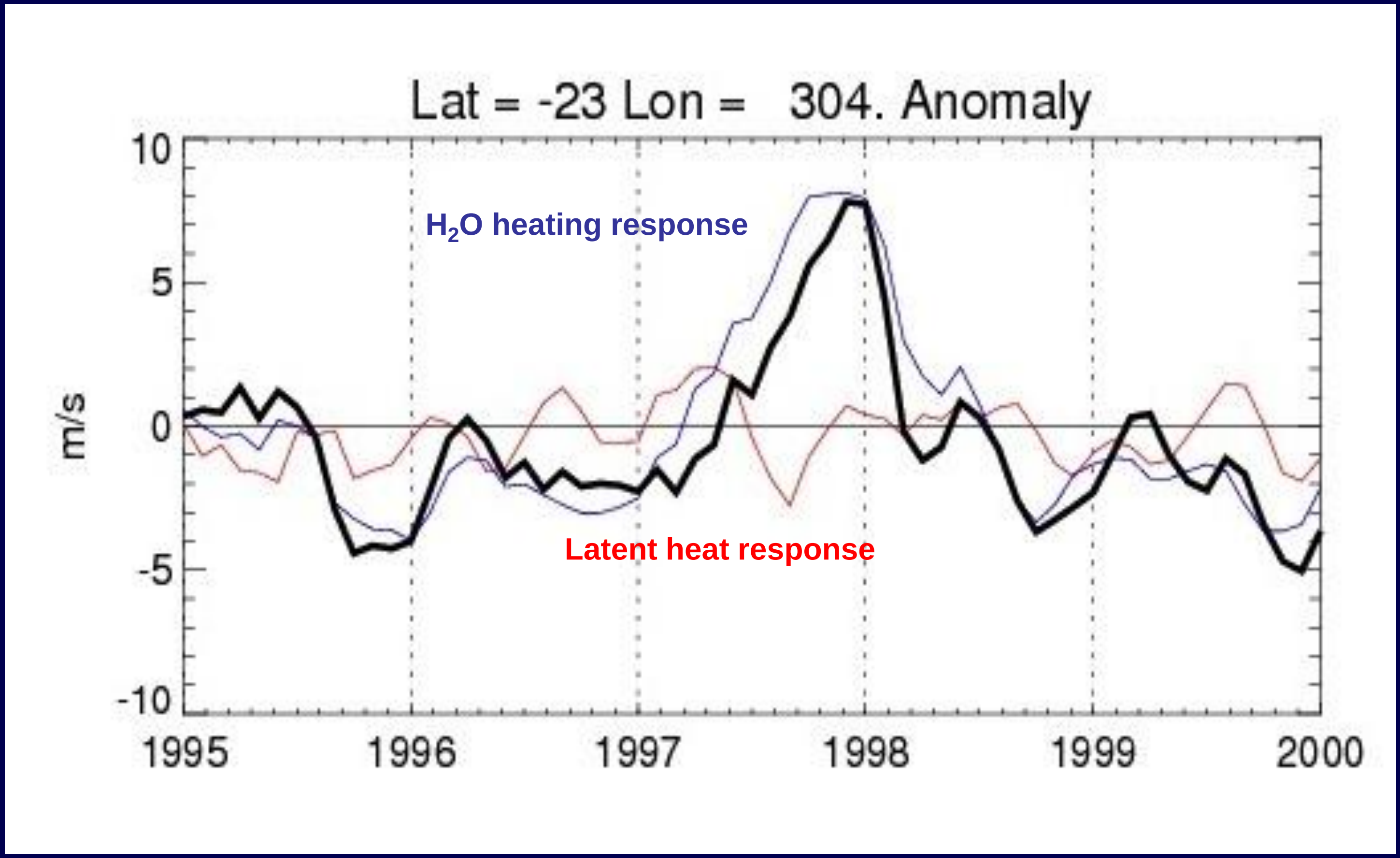




Diurnal water vapor heating at equatorial latitudes is dominated by a large migrating (W1) component…

And several much-weaker nonmigrating components.

During 1997-98 W1 increased while nonmigrating tide is nearly nonexistent.



V response to H_2O_v heating is much stronger than LH release.
LH response is out of phase with H_2O_v response.
Net response to anomalously high H_2O_v heating is stronger in SH.

Warner and Oberheide (2013); Petadella et al. (2012).

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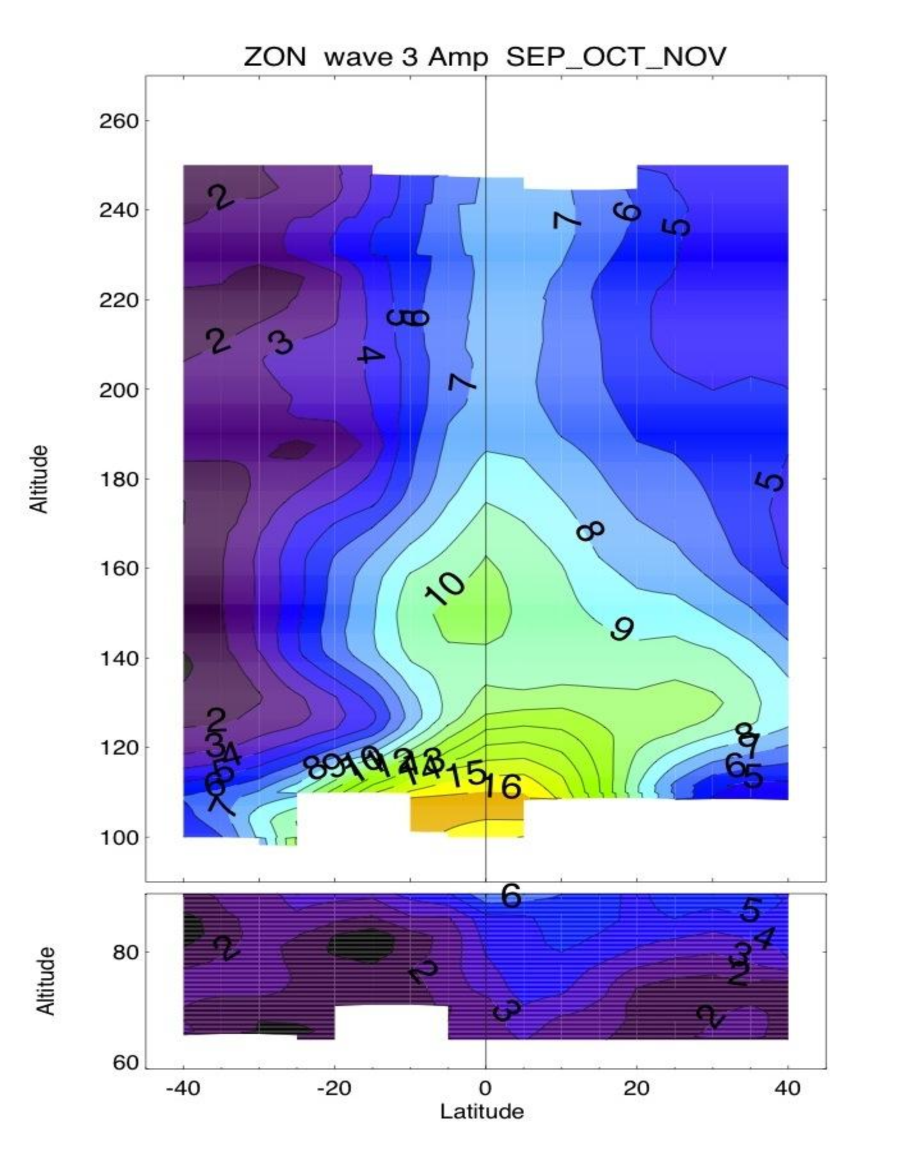
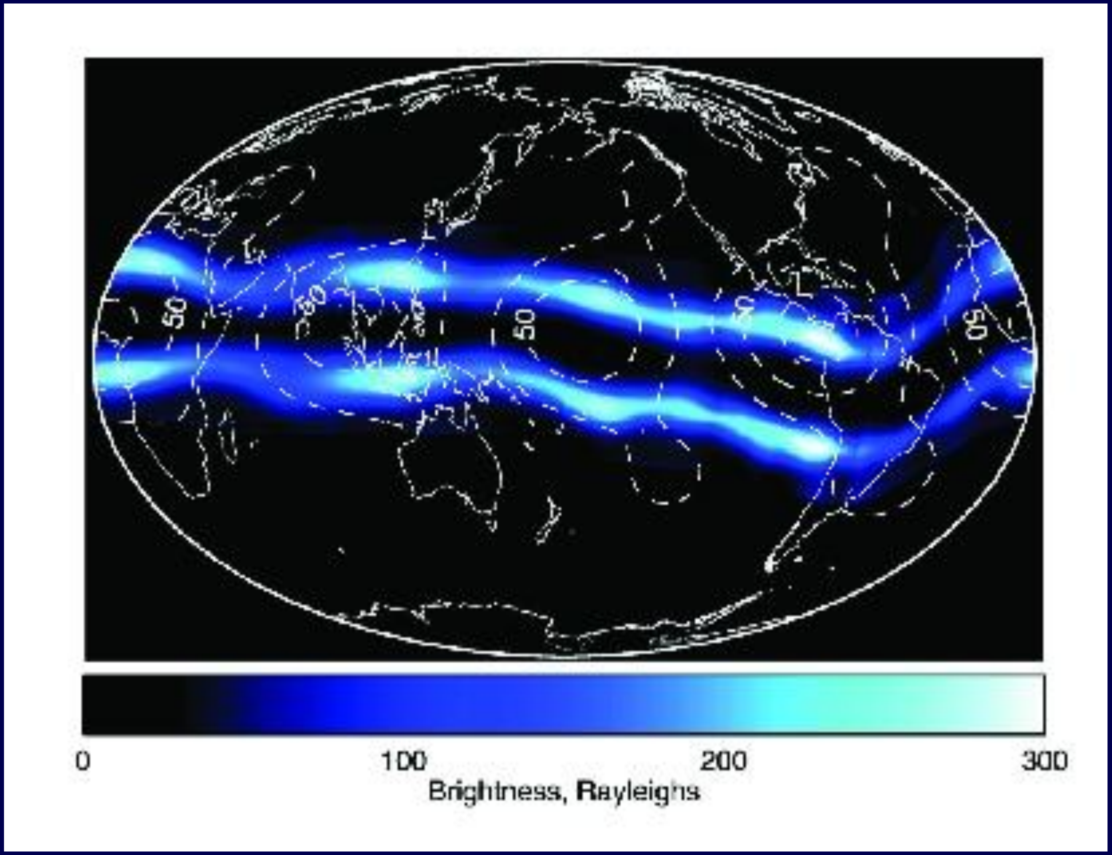
UARS/WINDII Diurnal E3



Deep tropical convection projects strongly onto an eastward-propagating zonal wavenumber 3 component (DE3).

DE3 has a long vertical wavelength (~56 km) and propagates into the thermosphere.

IMAGE Far UV Imager ionosphere nightglow



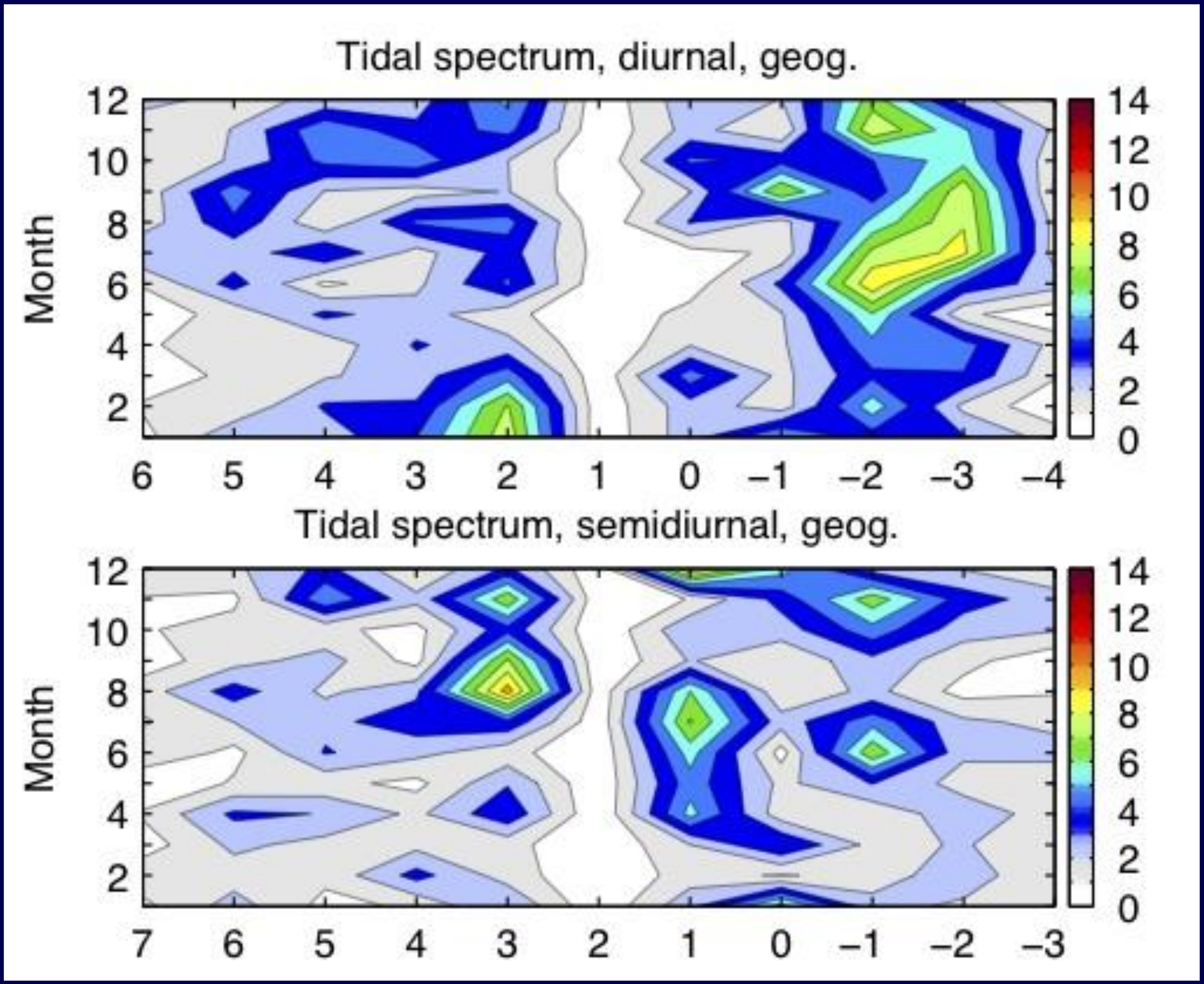
2000 LT IMAGE-FUV brightness (O^+ recombination), ~350 km.

A wavenumber-4 pattern is discernible.

This pattern corresponds to DE3 (Doppler-shifted by the motion of the satellite).

Immel et al., 2006

Thermospheric nonmigrating tides



CHAMP U (~400 km) (Hausler and Luhr, 2009)

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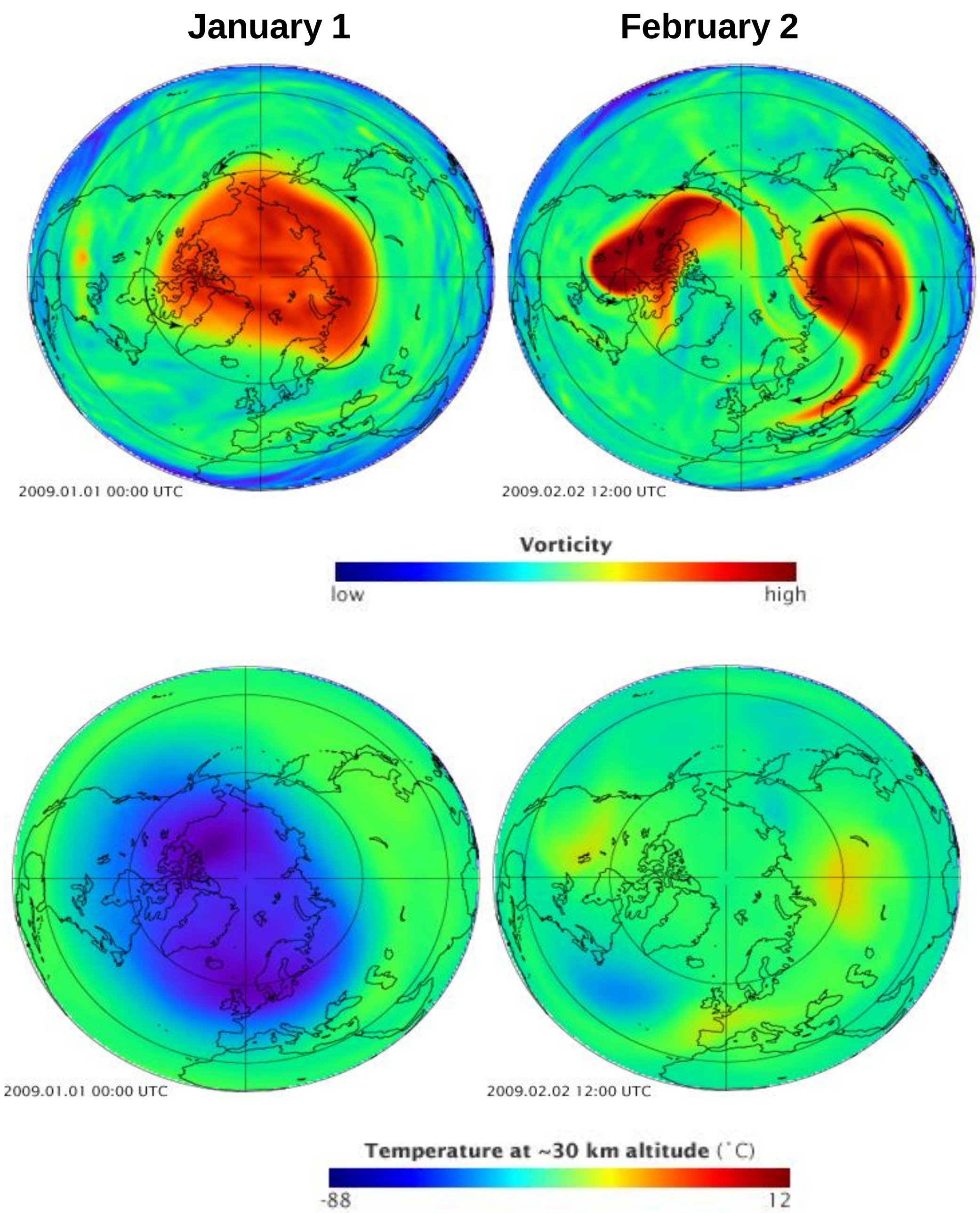
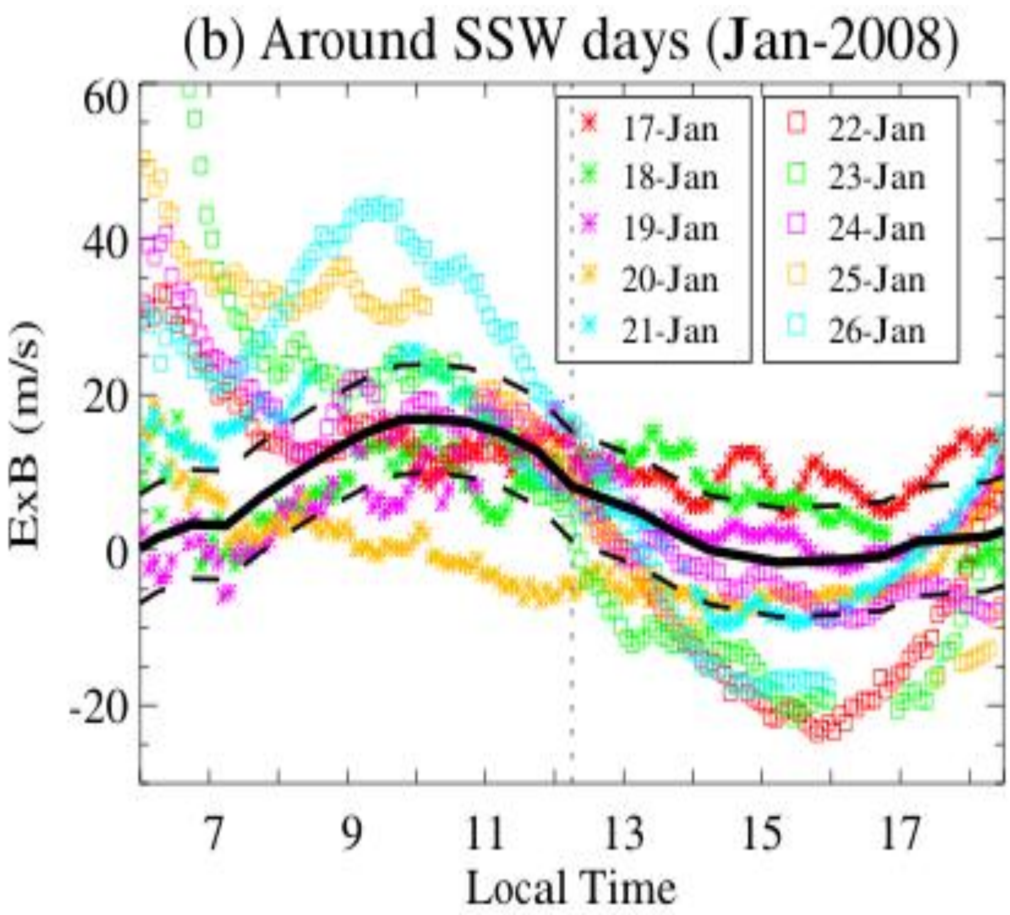
Example of sudden warming and vortex splitting in 2009



Rapid amplification of PW 1 and 2 displace or even "split" the polar vortex.

Transience and dissipation of PW 1 and 2 result in westward momentum flux divergence, that warms the higher latitudes.

January 2008 SSW & Jicamarca ISR

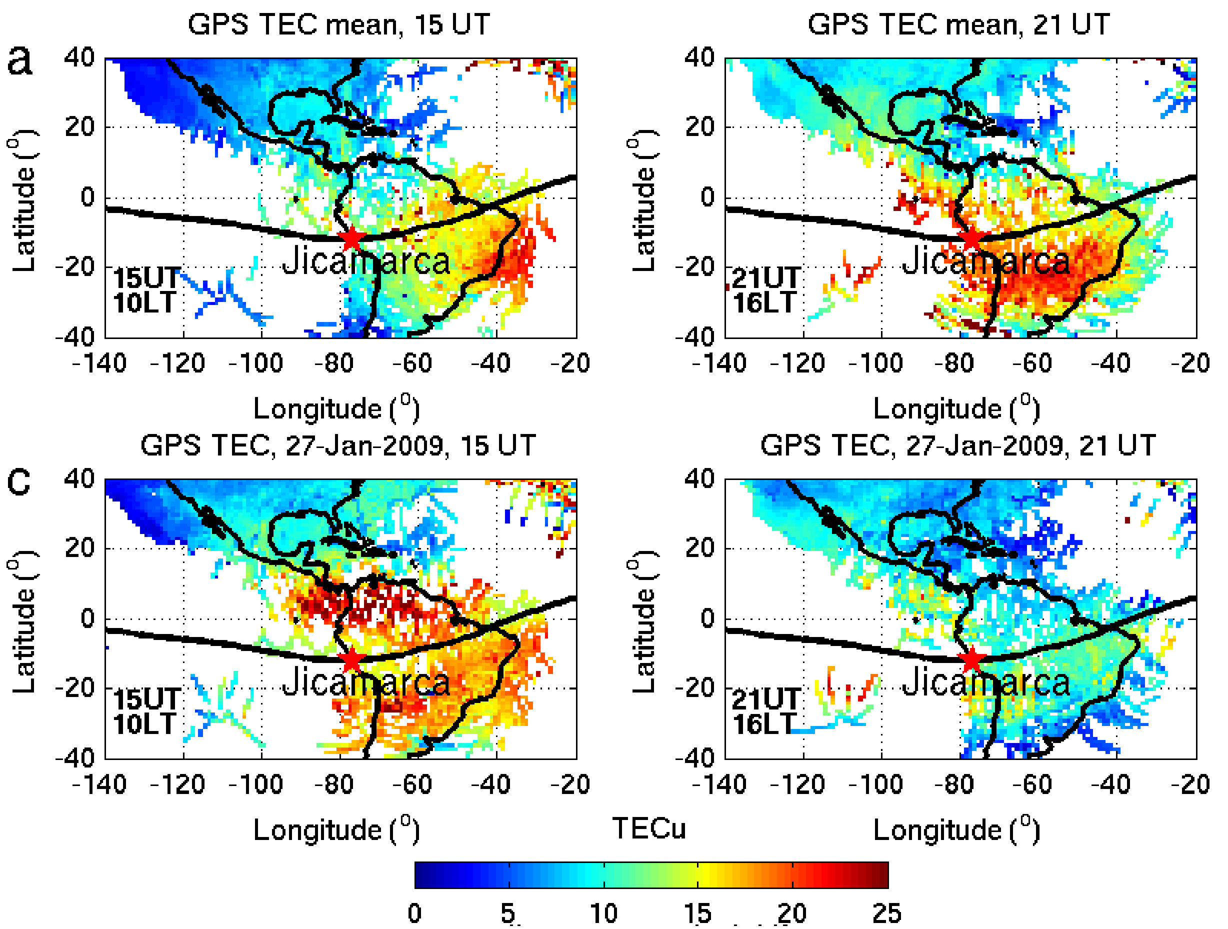


Chau et al., 2009

- Upward drift in the morning, downward in the afternoon -12-h wave
- Interpreted as evidence of enhanced 12-tide & E-region dynamo
- Upward drift leads to plasma transport to higher altitudes with low recombination rates and plasma density increase; opposite for the downward drift

January 2009 SSW: GPS TEC

15 UT **21 UT**



Total Electron Content change 50-150%

Goncharenko et al., 2010

Suggested mechanisms for ionospheric modification during SSW

- Amplification of migrating 12-h tide, due to O_3 increase during SSW.
- Amplification of lunar 12-h tide (Fejer et al., 2010; Pedatella et al., 2012).
- Non-linear interaction of planetary wave with 12-h and 24-h tides resulting in:
    - Generation of non-migrating 12-h and 24-h tides (DW2, DS0, SW1, SW3), modulation of the 12-h and 24-h wave amplitudes, and E-region dynamo (Liu et al., 2010).

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Earth-to-space weather

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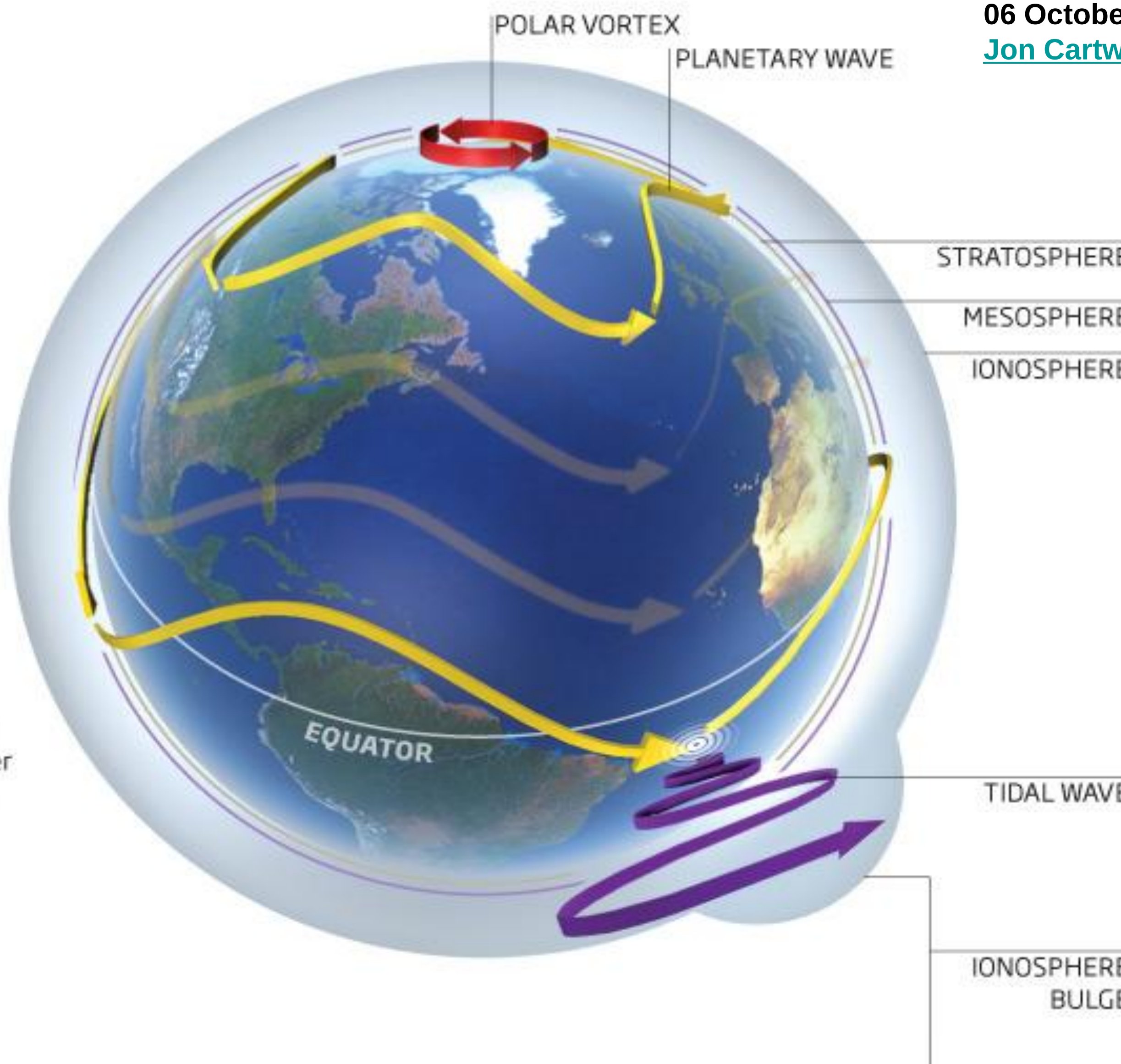
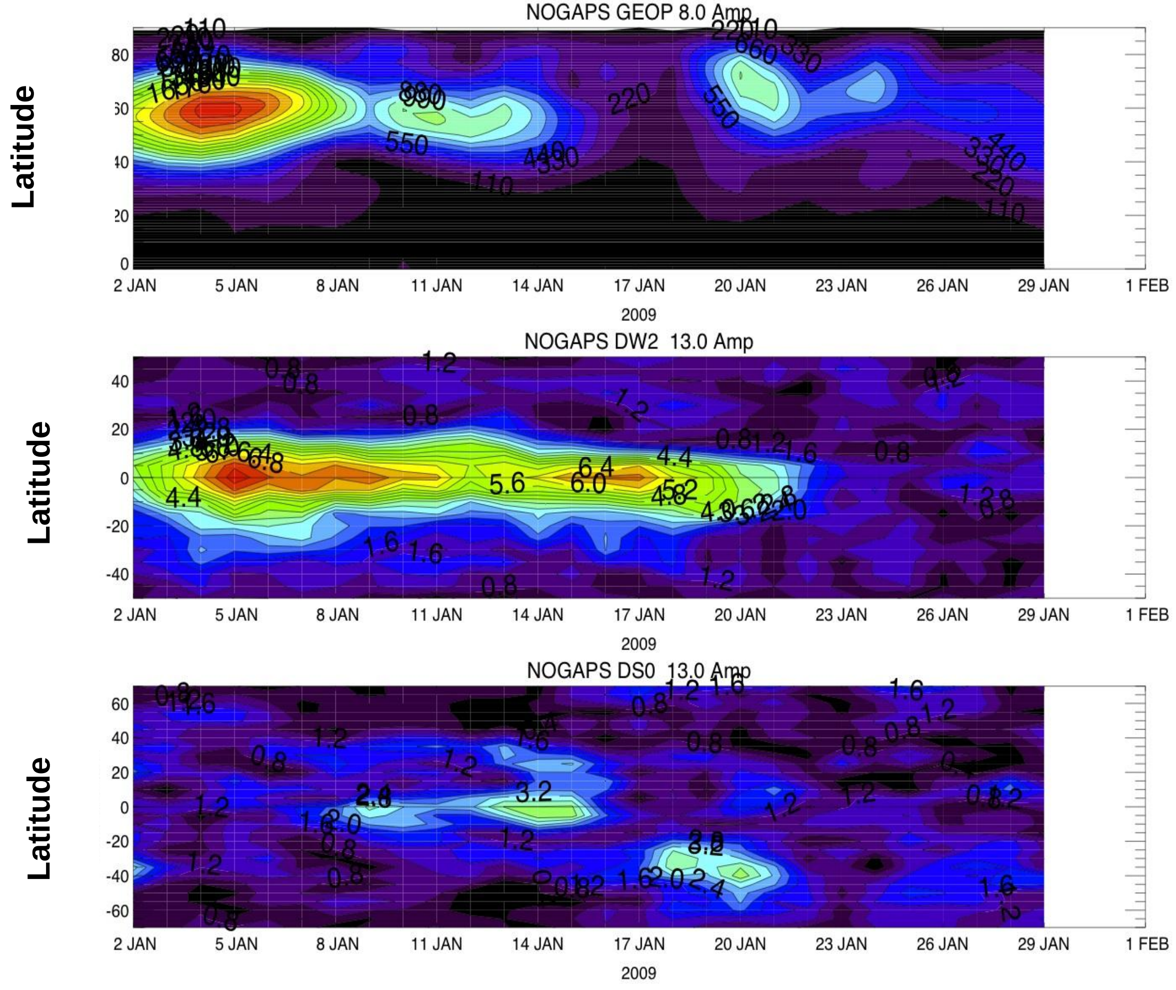
How terrestrial weather events may affect and shape the upper atmosphere

***"Phantom storms: How our weather leaks into space"*,** **06 October 2009 by** **Jon Cartwright**

The planetary wave, a natural oscillation in the stratosphere, interrupts the polar vortex in the stratosphere above the North Pole, leading to a predictable terrestrial weather event - a "stratwarm"



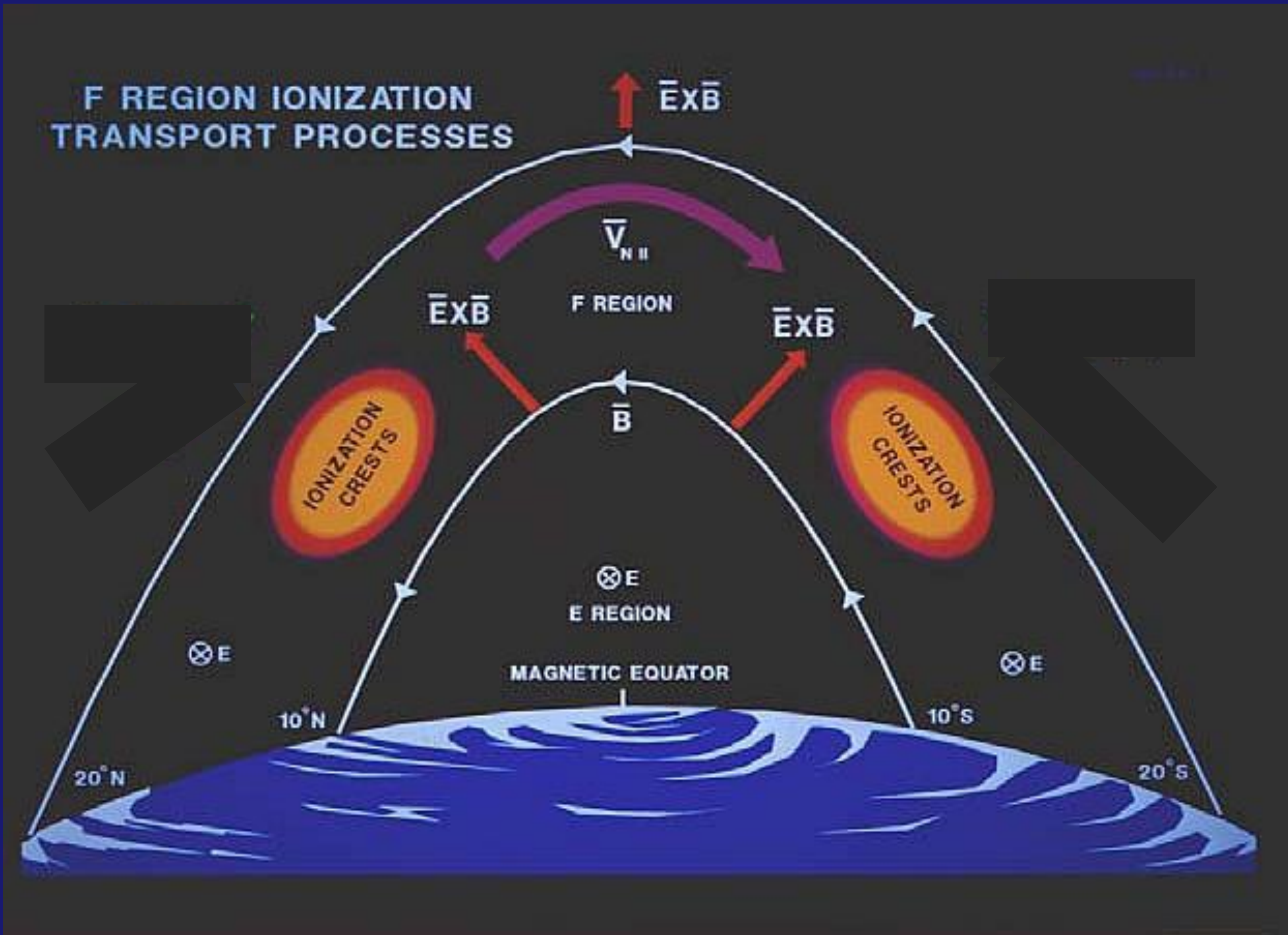
As the planetary wave travels southwards, it meets and amplifies another type of atmospheric wave, known as the tidal wave, which propagates up through the mesosphere to the ionosphere



Strong PW1 amplification in early January.

DW2 amplitude at the equator is strong through January 20, 2009.

DS0 has a weaker signature.


F REGION IONIZATION
TRANSPORT PROCESSES
$\overline{E}\mathrm{x}\overline{B}$
$\overline{V}_{N\parallel}$
$\overline{E}\mathrm{x}\overline{B}$
F REGION
$\overline{E}\mathrm{x}\overline{B}$
IONIZATION CRESTS
$\overline{B}$
IONIZATION CRESTS
⊗E
E REGION
⊗E
MAGNETIC EQUATOR
⊗E
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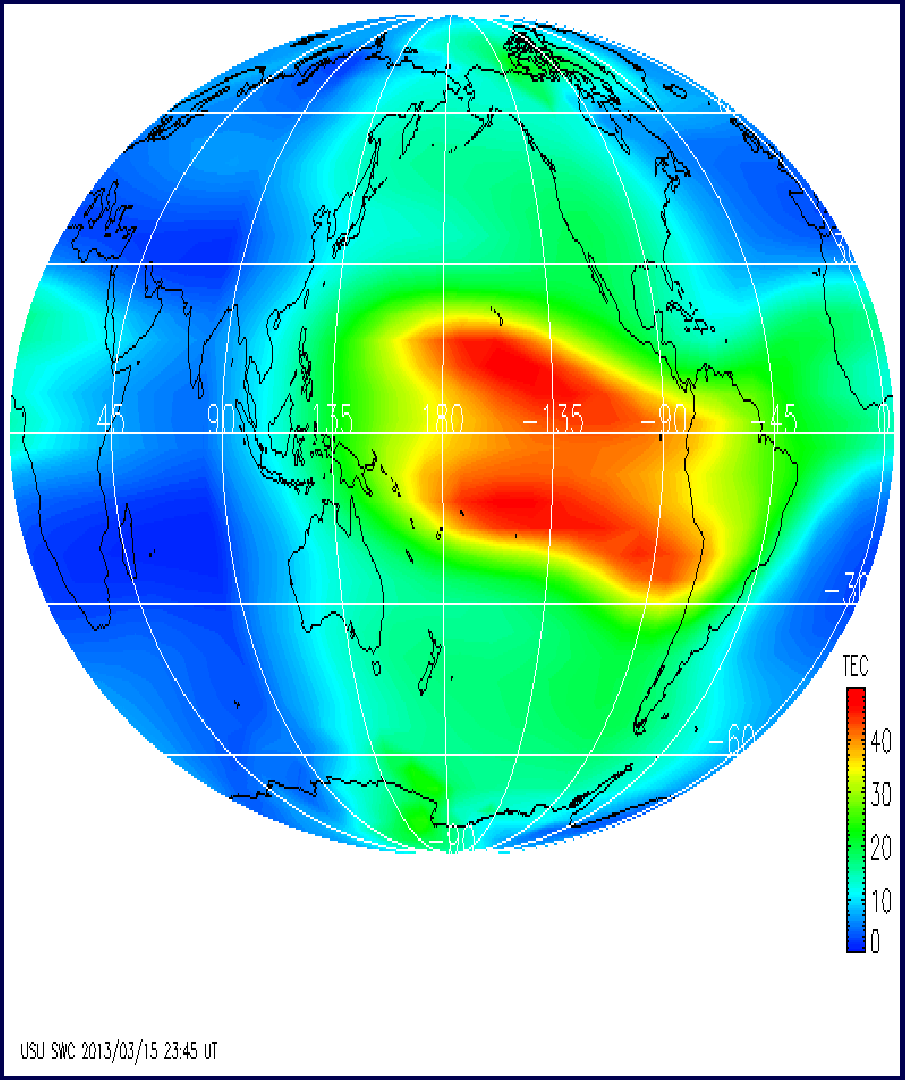
10°S
20°N
20°S



Liu et al . (2010) have examined the ionospheric response in TIME-GCM to a PW at bottom boundary)30 km).

Predicted nonmigrating diurnal and semidiurnal tides were generated.

Vertical plasma drifts and TEC patterns were modified (from quiet-time control).

Significant longitudinal variations were observed.

Effects of tides on drift depend strongly on phase.

Additional Challenges for Tidal Research

- **Sampling tidal parameters (neutral and charged) globally between surface-IT. Currently it is necessary to patch together assimilated or modeled data.**
  ICON and GOLD missions will measure thermospheric V, T, and plasma emissions.

- **Understanding seasonal/QBO/interannual variability.**
  What are the roles of background U vs. forcing?

- **Numerical modeling of the vertical wavelength of the diurnal tide.**
  Role of tide-GW interaction.

Thank you for your attention

Additional slides

Classical tidal theory (Chapman and Lindzen, 1970)

$$\partial u'/\partial t - f v' + (a\cos\varphi)^{-1}\Phi'_{\lambda} = 0$$

$$\partial v'/\partial t + f u' + a^{-1}\Phi'_{\varphi} = 0$$

$$(a\cos\varphi)^{-1}\left(u'_{\lambda} + (v'\cos\varphi)_{\varphi}\right) = \rho_0^{-1}(\rho_0 w')_z$$

$$\Phi'_{zt} + N^2 w' = \kappa J'/H$$

Express

$$(u', v', \Phi', Q') = \exp^{z/2H} U(z)[\tilde{u}, \tilde{v}, \tilde{\Phi}, \tilde{Q}](\varphi)\exp(i(s\lambda + \sigma t))$$

$$w' = \exp^{z/2H} W(z)\tilde{w}(\varphi)\exp(i(s\lambda + \sigma t))$$

Equations collapse into a horizontal structure equation

$$\Im\Theta_n^{(\sigma,s)} = \frac{4\Omega^2 a^2}{gh_n}\Theta_n^{(\sigma,s)}$$

$\Theta(y)$ ("Hough" functions) and eigenvaues h_n are solved for each σ and s.

and a vertical structure equation

$$\frac{d^2W}{dz^2} + \left(\frac{N^2}{gh_n} - \frac{1}{4H^2}\right)W = \frac{kJ_n(z)e^{-z/2H}}{gh_n H}$$

Tidal solutions

$$T(y,z)=\sum_n T_n e^{z/2H} e^{mz} \Theta_n^{(1,1)}$$

$$m^2=\frac{N^2}{gh_n}-\frac{1}{4H^2}$$

Vertical structure depends on h_n!

For semidiurnal tides of all s, h_n> 0.

For diurnal tides, h_n> 0 associated with equatorial modes.

h_n< 0 associated with mid-high latitude modes.

For h_n > 0, m is imaginary; tide propagates vertically.
For h_n < 0, m is real and negative; solutions are trapped in z.

Tide-PW interaction

Nonlinear interaction between large-amplitude PW (m_p) and diurnal tide (m_t,Ω) expressed as

$T_d \cos(m_d \lambda + \Omega t) * T_p \cos(m_p \lambda) \Rightarrow$ yielding ”product waves”

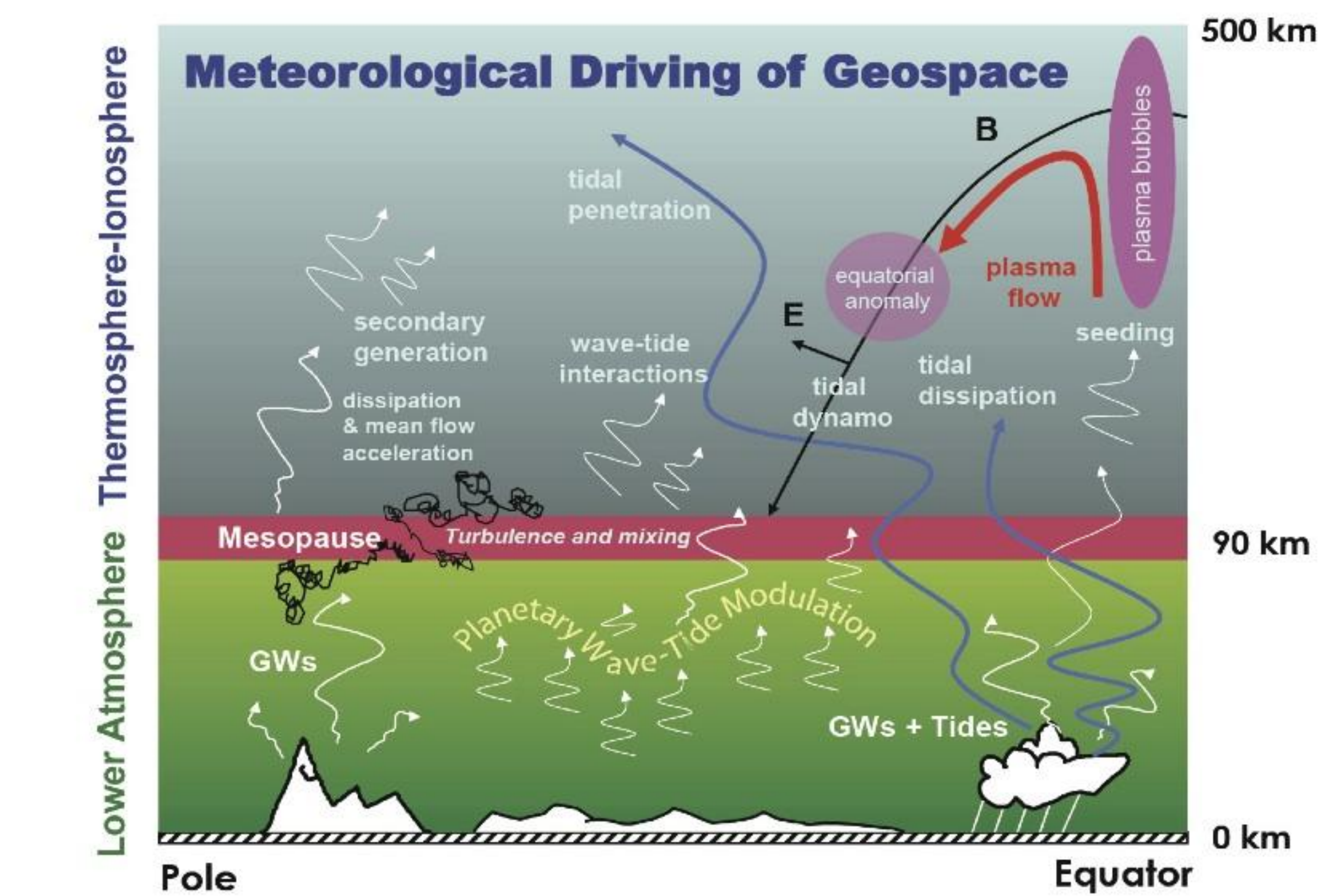
($m_d + m_p$,Ω) and ($m_d - m_p$,Ω).

Stationary PW 1 and migrating diurnal tide (m=1) interaction $\Rightarrow$
diurnal m = 0 and m = 2.

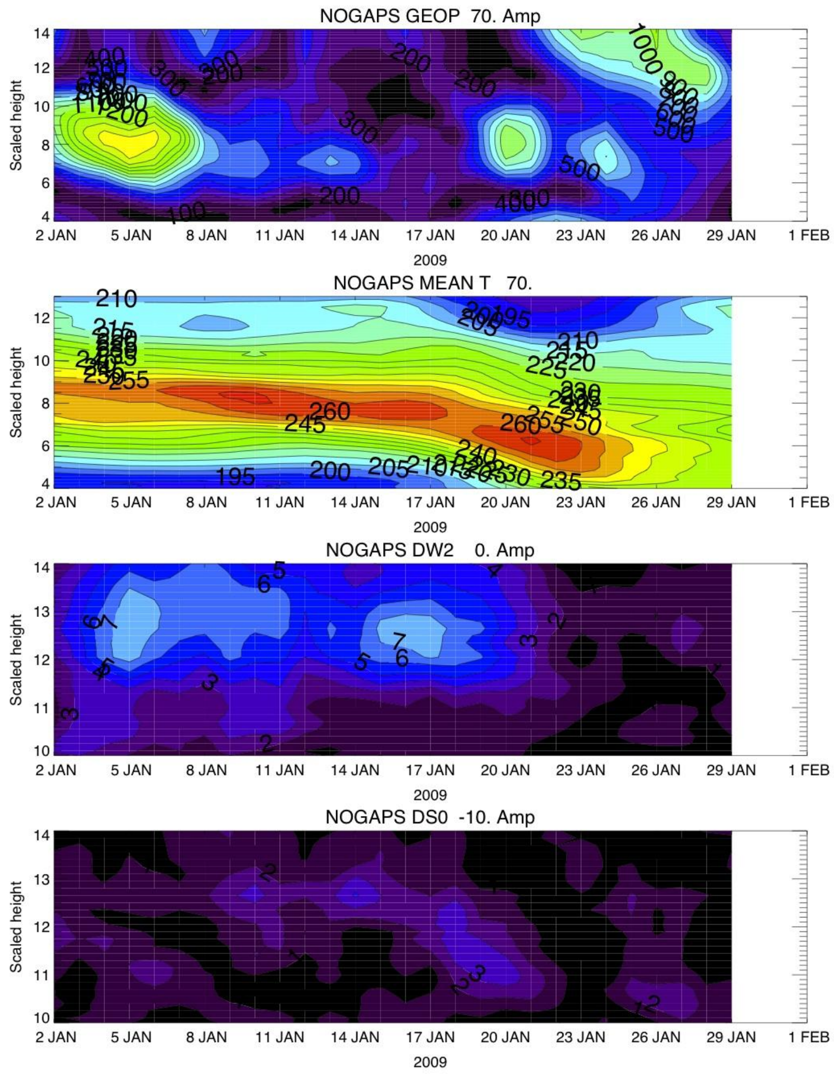
Stationary PW 1 and migrating semidiurnal tide (m=2) interaction $\Rightarrow$
semidiurnal m = 1 and m = 3.

Support for these interaction seen in TIME-GCM (Hagan and Roble 2001), mechanistic models (Angelats i Coll and Forbes , 2002) and ground-based observations (Smith et al., 2007).

Can we observe the nonlinear wavenumber products?



Meteorological Driving of Geospace
500 km
90 km
0 km
Thermosphere-Ionosphere
Lower Atmosphere
B
E
plasma bubbles
plasma flow
equatorial anomaly
seeding
tidal penetration
tidal dissipation
tidal dynamo
secondary generation
wave-tide interactions
dissipation & mean flow acceleration
Mesopause
Turbulence and mixing
Planetary Wave-Tide Modulation
GWs
GWs + Tides
Pole
Equator

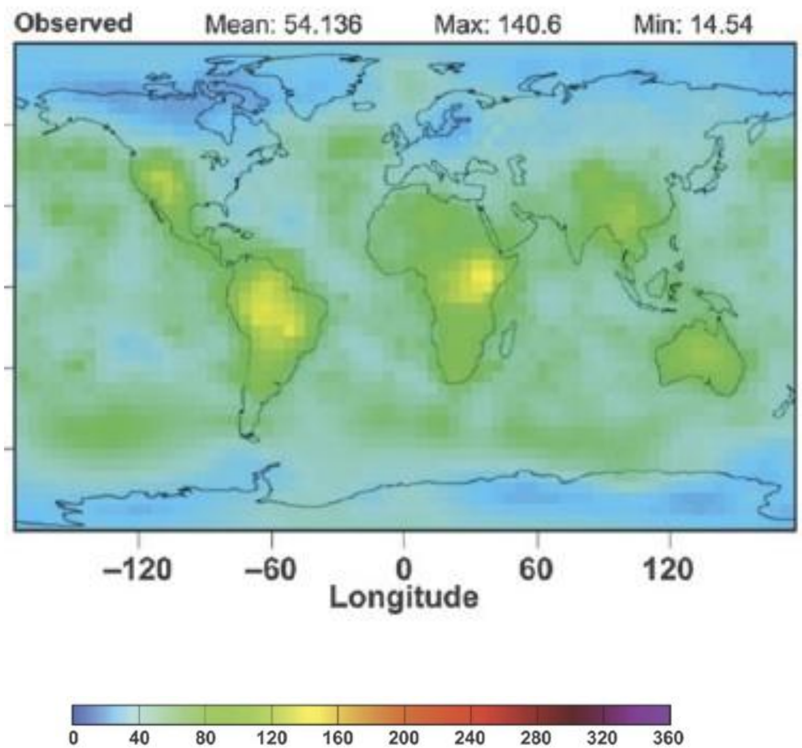


Strong PW1 amplification in early January.

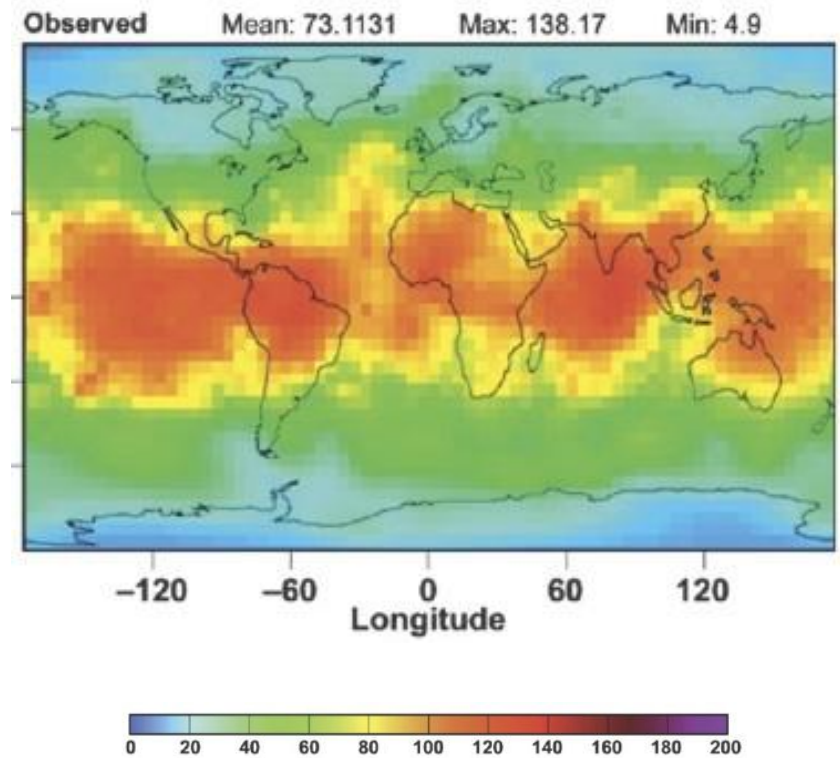
Warming response occurs about a week following.

DW2 amplitude at the equator is strong through January 20, 2009.

DS0 has a weaker signature.

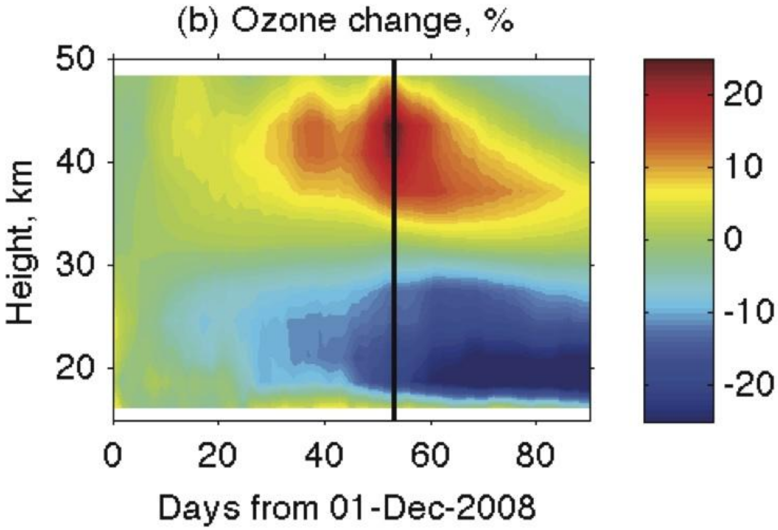


Diurnal (Pa)



Semidiurnal (Pa)

Ozone variations in the low-latitude stratosphere during SSW



Goncharenko et al., 2012

- Increase in the zonal mean ozone mass mixing ratio due to cooling and vertical transport
- Implications: amplified 12-h migrating tide

- Longitudinal distribution of ozone becomes strongly asymmetric
- Implications: amplified semiduirnal non-migrating tide of *stratospheric* origin