The Role of Tides and Planetary Waves in Atmospheric Vertical Coupling

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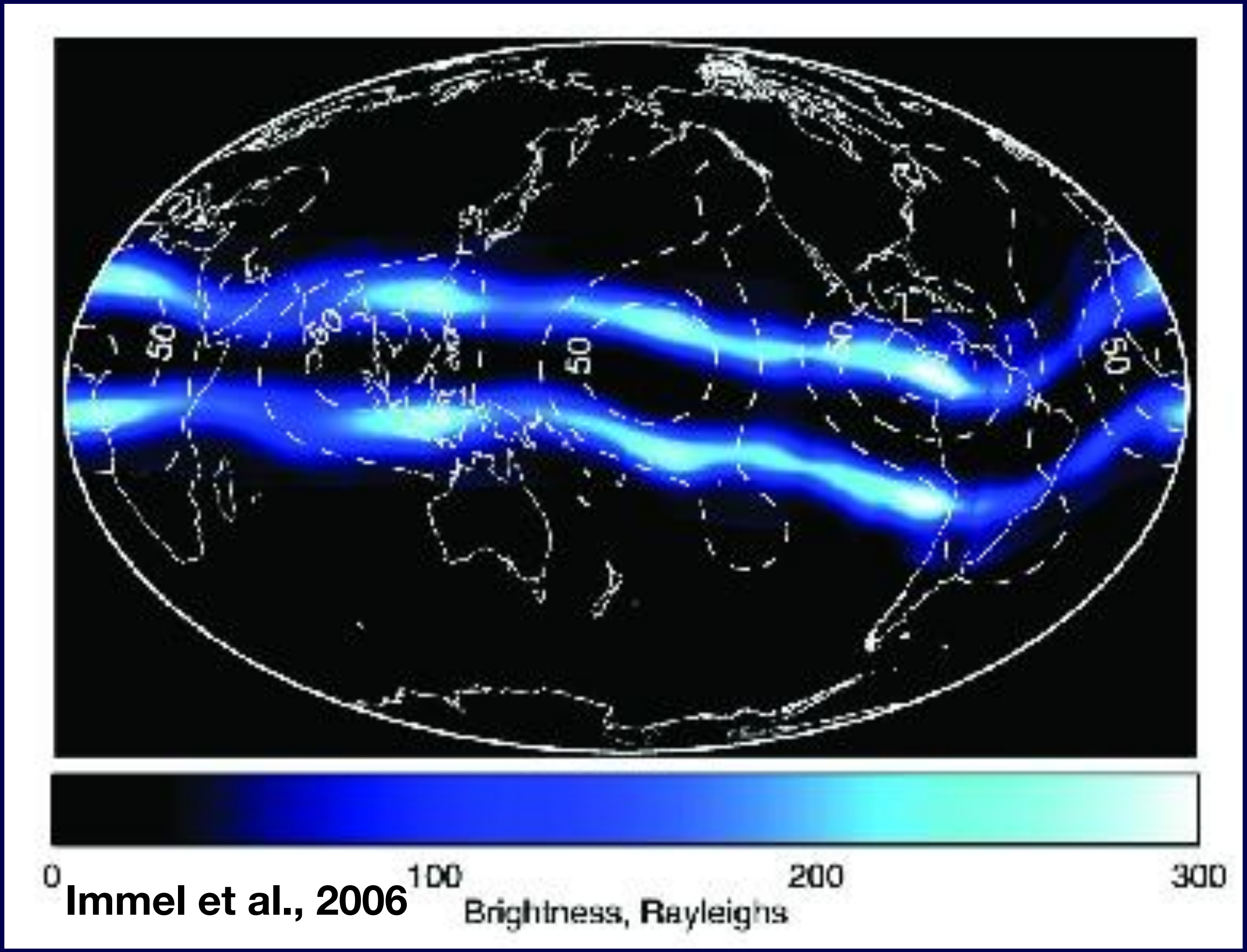
Quiet-time ionospheric variability

Major variations in ionospheric parameters are assumed to be related to solar and geomagnetic activity.

However, persistent, 50-100% deviations from background occur due to the influences from the lower atmosphere:

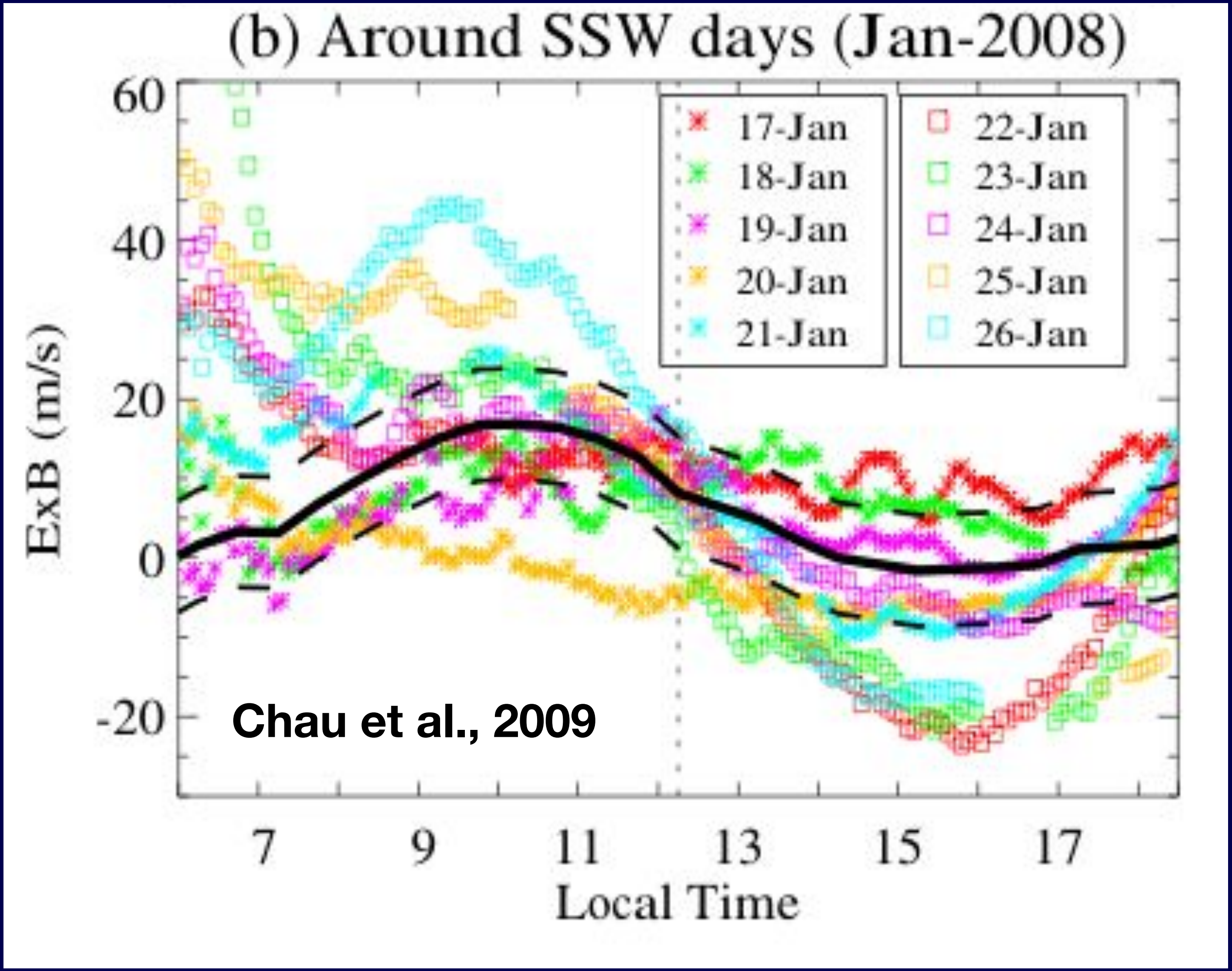
- Tides.
- Planetary and gravity waves.
- Sudden stratospheric warmings
- Impulsive events (tsunamis, volcanoes).

Immel et al., 2006



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

4-peaked pattern corresponds to an atmospheric tide.



Enhanced vertical plasma drifts (200-400 km) over Jicamarca (8ºS)

This presentation

1. How do tides and planetary waves couple the atmosphere vertically?

2. How does the neutral atmosphere imprint upon the F-region?

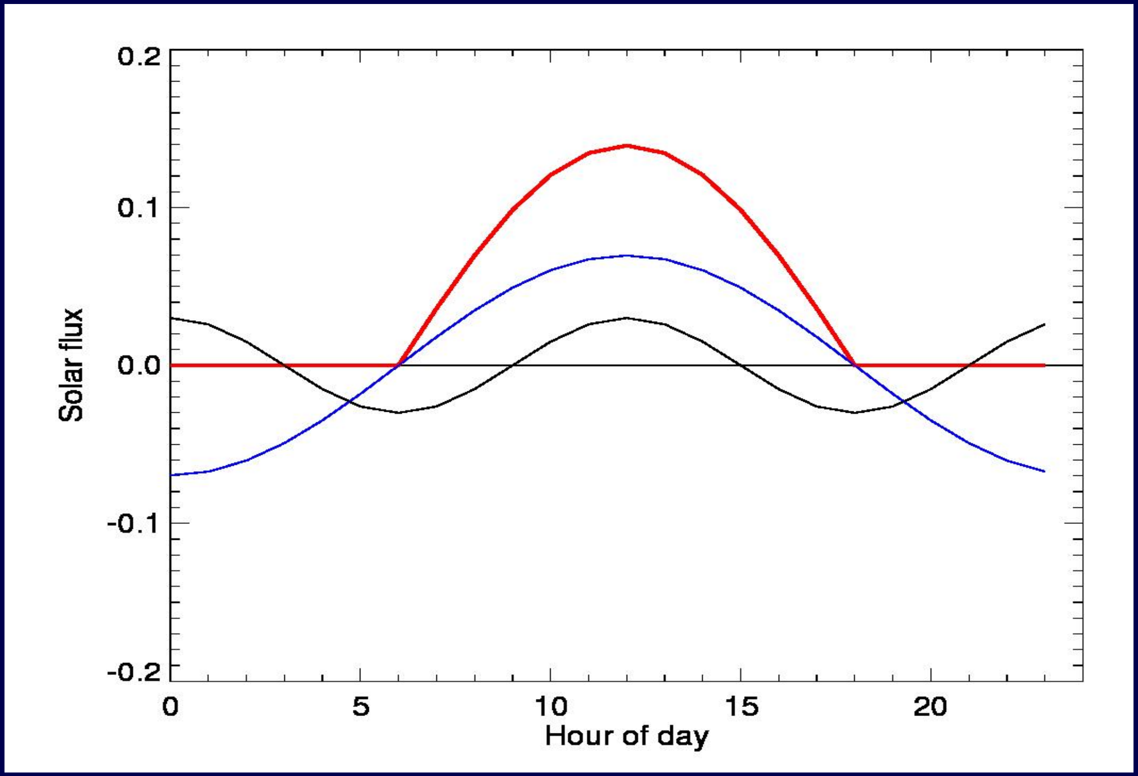
3. How are recent missions helping us to meet the goals for A-I coupling articulated in the DS?

4. Challenges, observing needs, and future missions.

Atmospheric thermal tides

Solar heating of the neutral atmosphere (O_3 absorption in the stratosphere, H_2O_v absorption near surface).

Latent heat release in daily tropical convection.



Periods: 24, 12, 8… hours. (Frequencies: Ω, 2Ω, 3Ω…)

$U = (u,v,w)$

3-D wind

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

E-W momentum

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

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

N-S momentum

$$(a\cos\varphi)^{-1}(u'_{\lambda} + v'\cos\varphi)_{\varphi} = -\varrho_0^{-1}(\varrho_0 w')_z$$

Mass conservation

$$\Phi'_{zt} + N^2 w' = 0$$

First law thermodynamics

Tropical waves: *f ~ 0*

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

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

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Tropical waves: *f ~ 0*
Semidiurnal tide: 2Ω >> f

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

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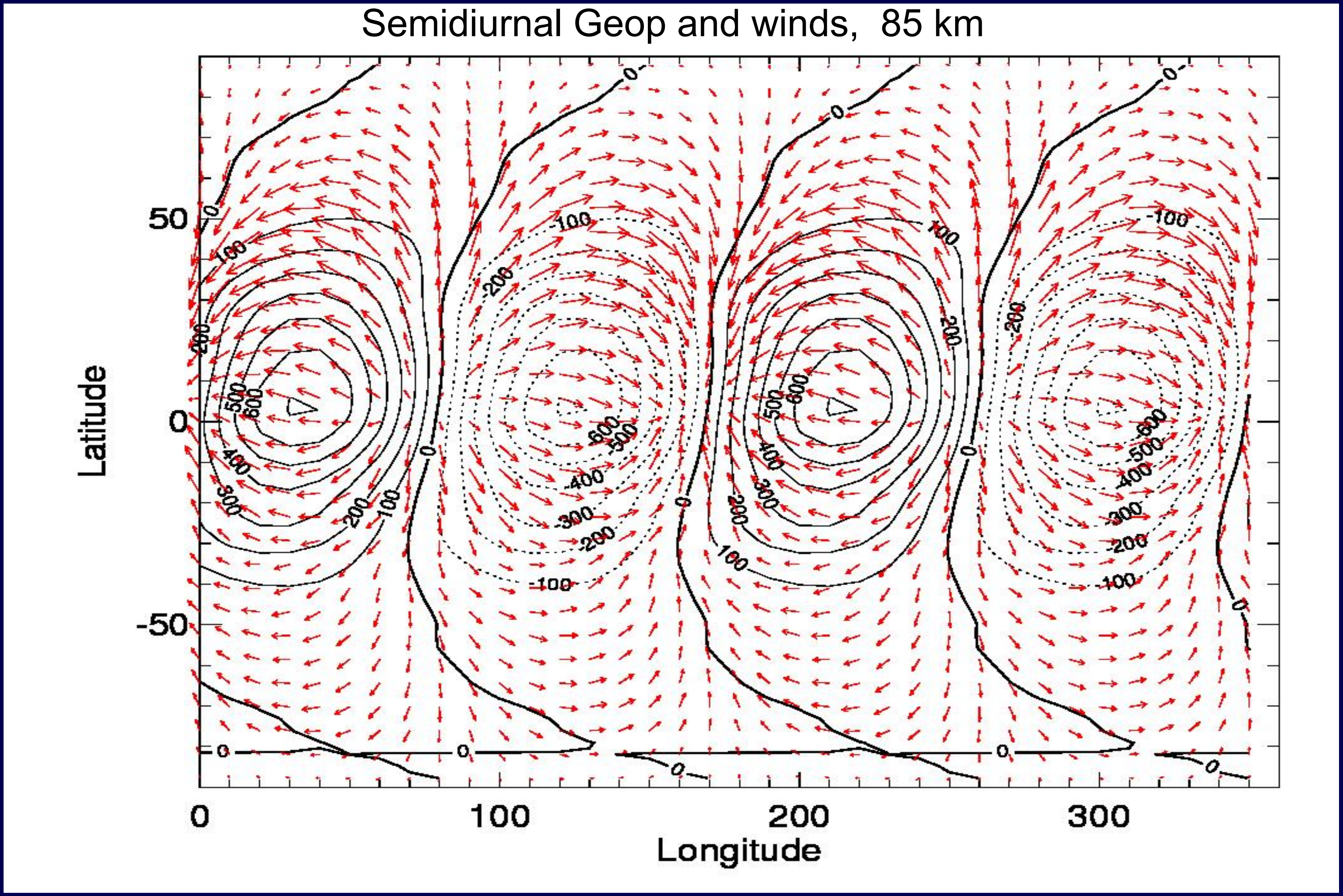
$$(a\cos\varphi)^{-1}(u'_{\lambda} + v'\cos\varphi)_{\varphi} = -\rho_0^{-1}(\rho_0 w')_z$$

$$\Phi'_{zt} + N^2 w' = 0$$

Source: Ortland's tide model



"Gravity wave" behavior in the tropics

High latitude semidiurnal tide: $\partial / \partial t \sim 2\Omega \sim f$

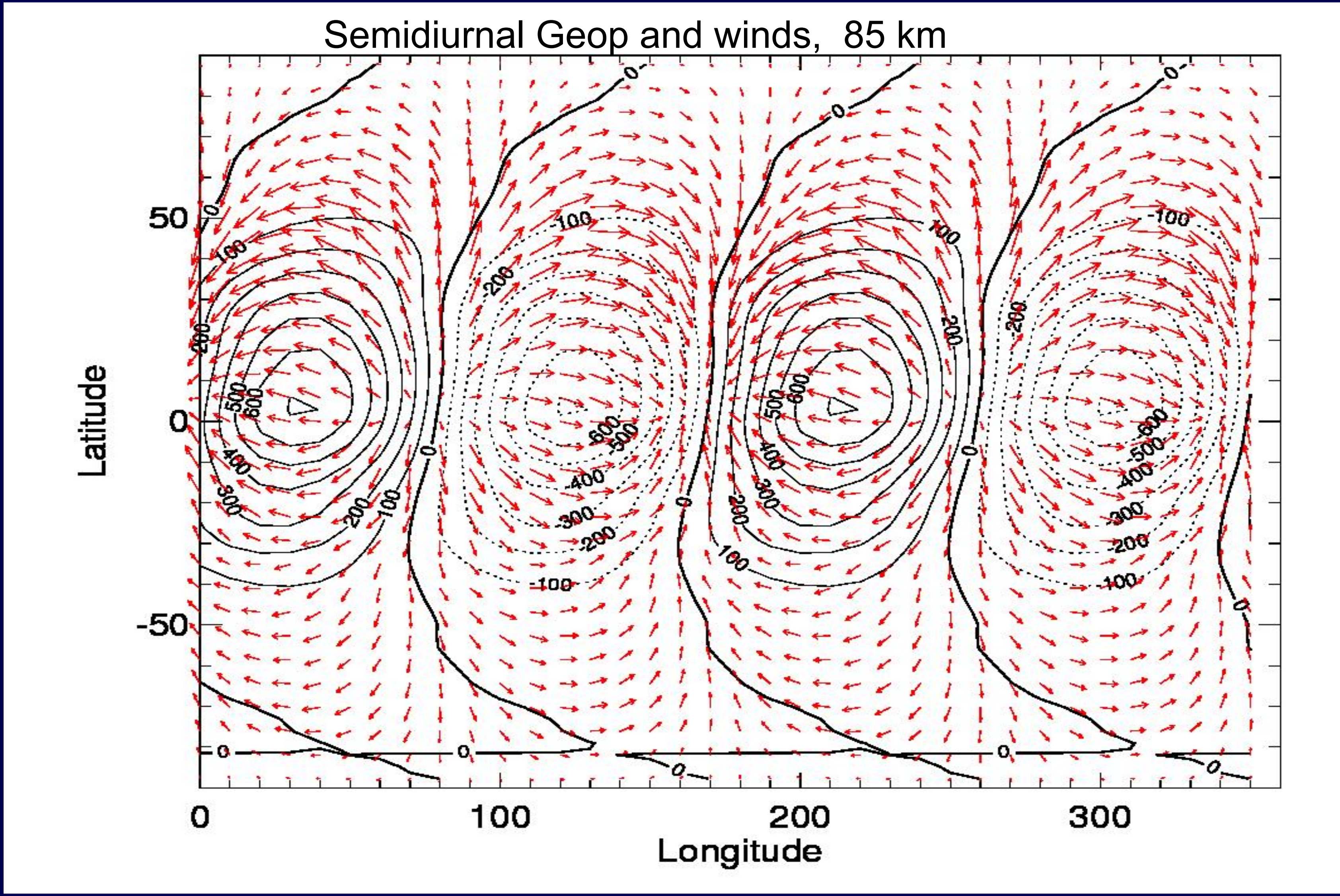
$f = 2\Omega \sin\varphi$

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

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

At higher latitudes, migrating semidiurnal tides are inertial oscillations (horizontal 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.

Low-latitude diurnal tides:
Ω >> f

$f = 2\Omega \sin\varphi$

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

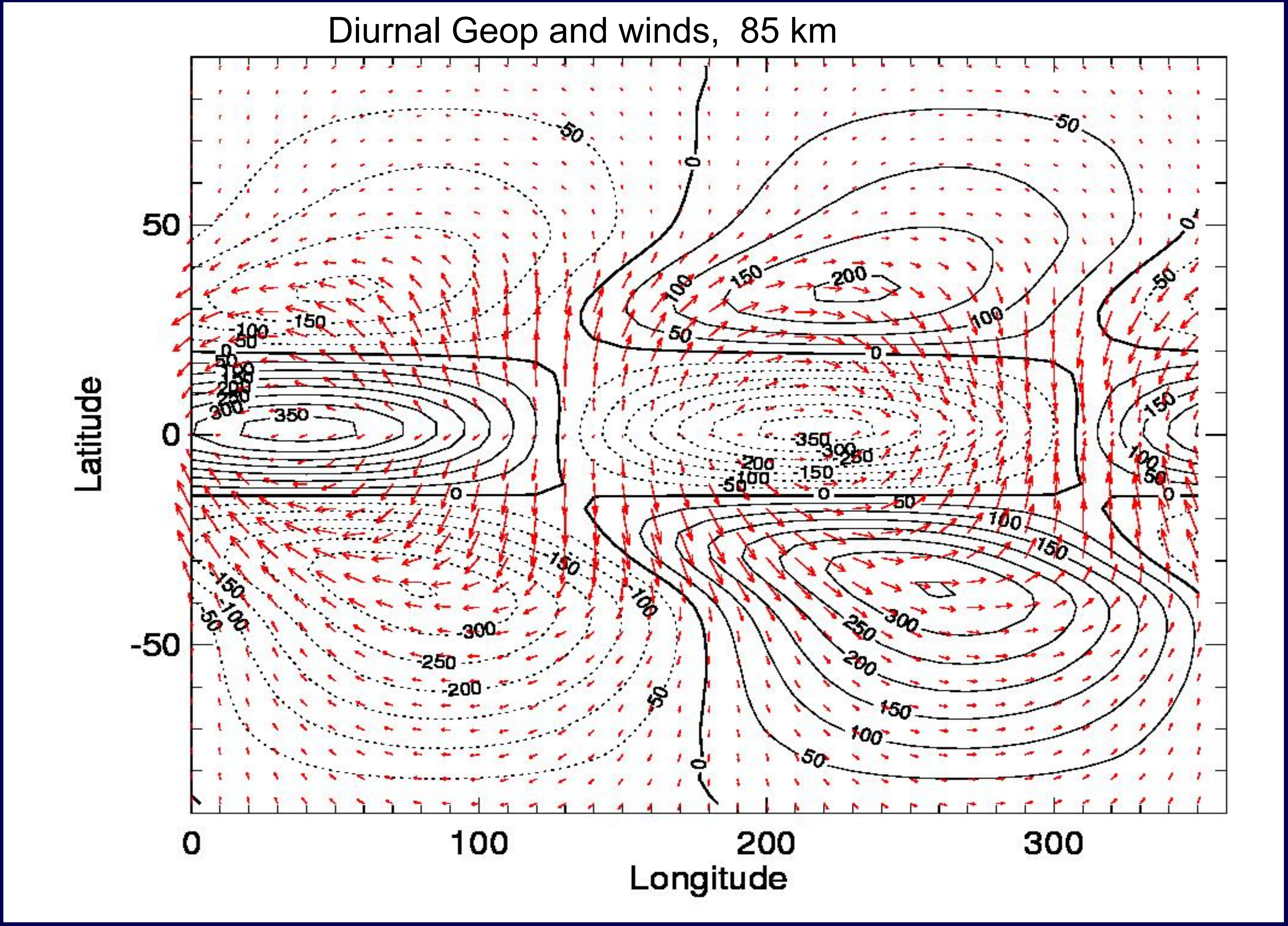
$$\partial v'/\partial t + f u' + \Phi' = 0$$

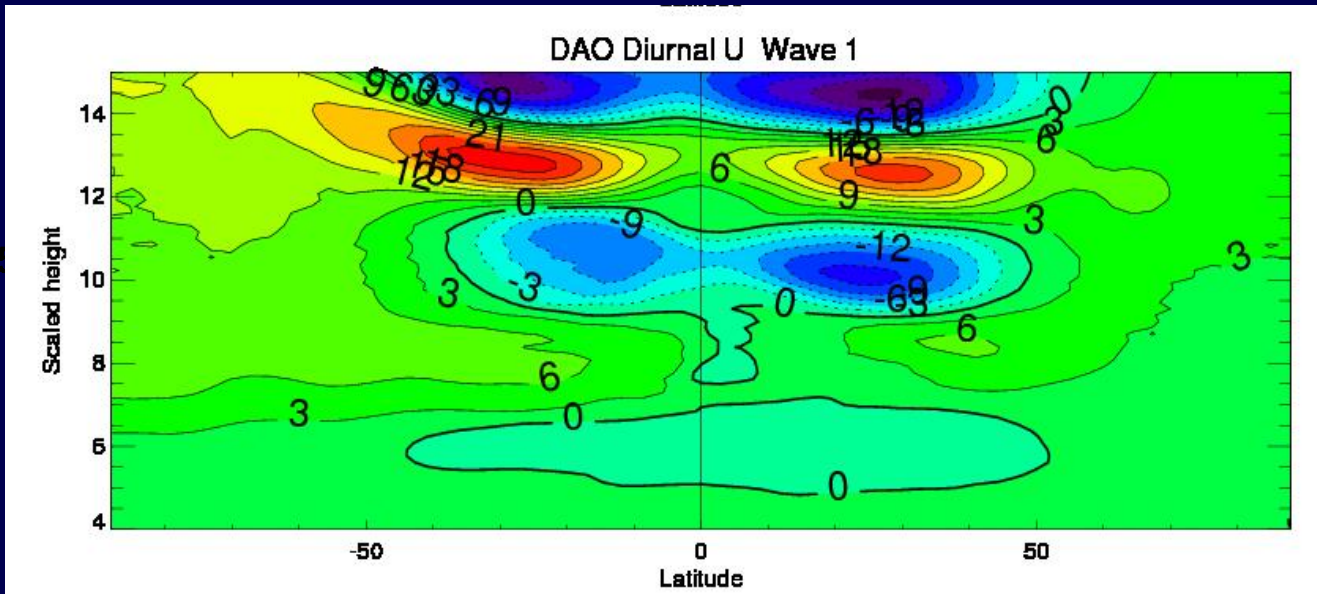
$$(a\cos\varphi)^{-1}(u'_{\lambda} + v'\cos\varphi)_{\varphi} = -\varrho_0^{-1}(\varrho_0 w')_z$$

Pure gravity waves at the equator.

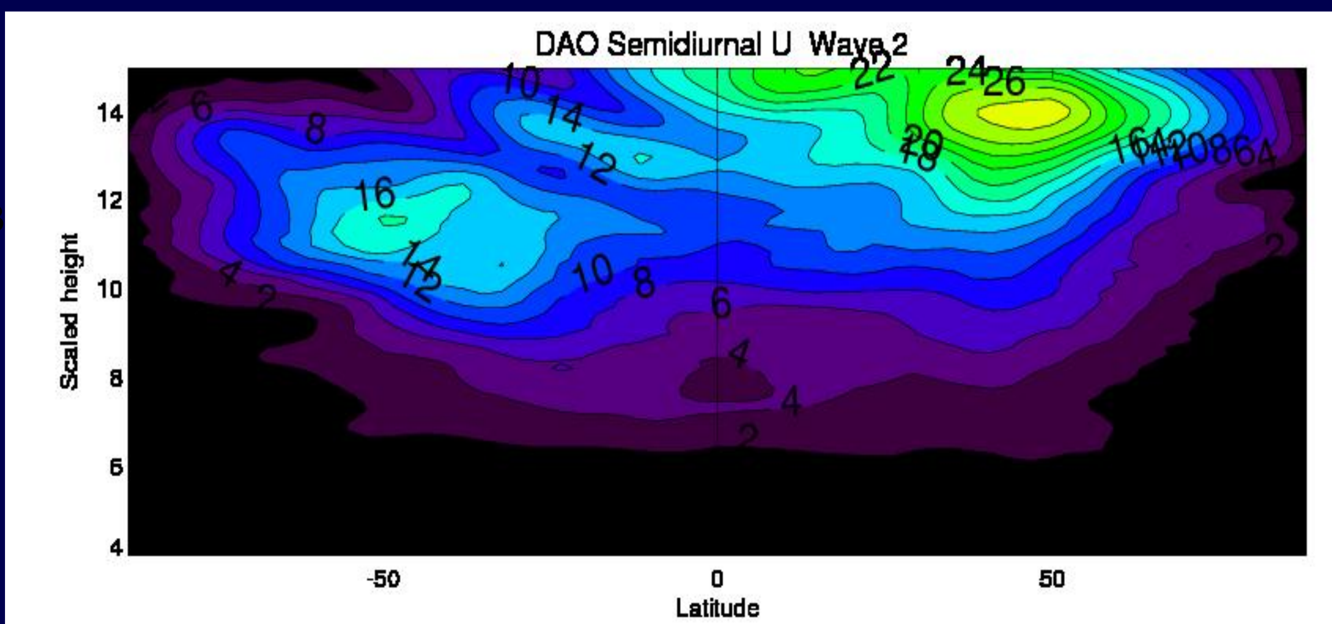
But inertial (Coriolis) effects kick in by 10°; Note that $f = \Omega$ at 30°

Diurnal tide (Ortland and Alexander, 2006)





Diurnal tide vertically propagates at low latitudes.



Semidiurnal tide vertically propagates at all latitudes. High-latitude maximum.

Midlatitude Planetary Waves

Slow waves arising from quasi-stationary sources (topography, differential land-sea heating).

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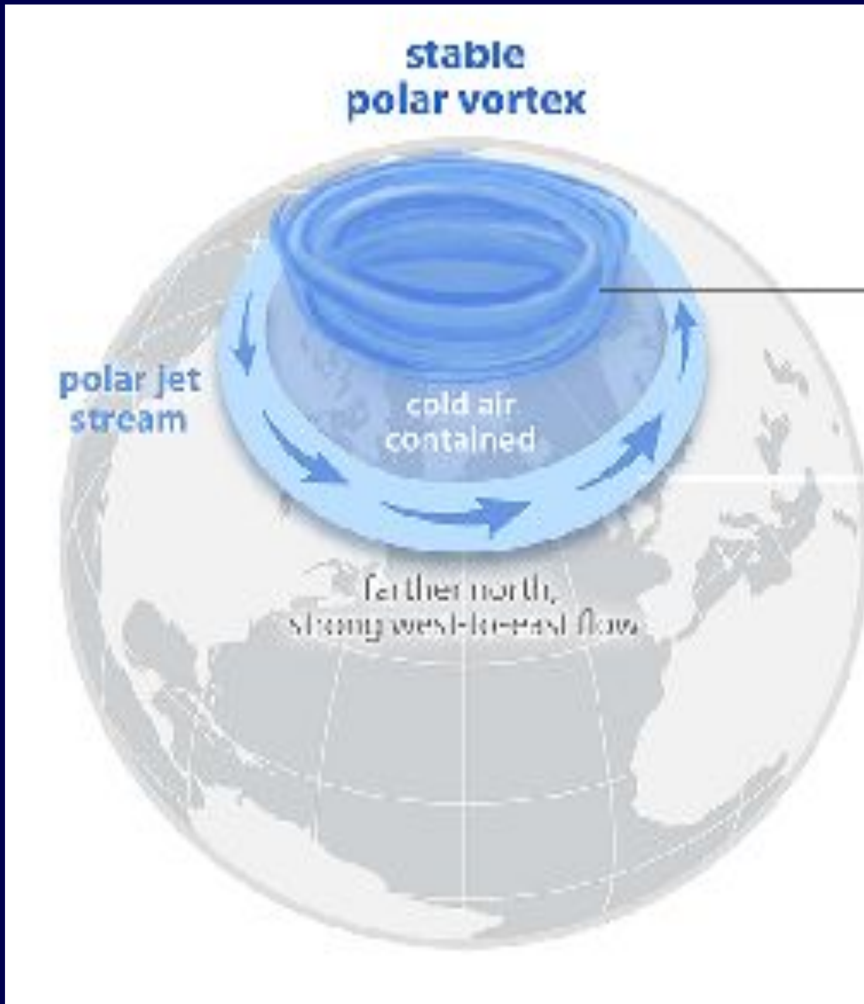

Steady state polar vortex

Geostrophic wind

$$u_g = -1/f\, \Phi_y$$

$$v_g = 1/f\, \Phi_x$$

V_g flows parallel to height (or pressure) contours. (High pressure to the right.)

Non-divergent.

Readily calculated (and visualized) from observed Φ.

Quasi-stationary, midlatitude planetary waves most readily analyzed as tendency of vorticity (wind curl).

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$$\zeta = (\nabla \times V)_z = \partial v/\partial x - \partial u/\partial y \sim (\nabla^2_H \Phi/f_0)$$

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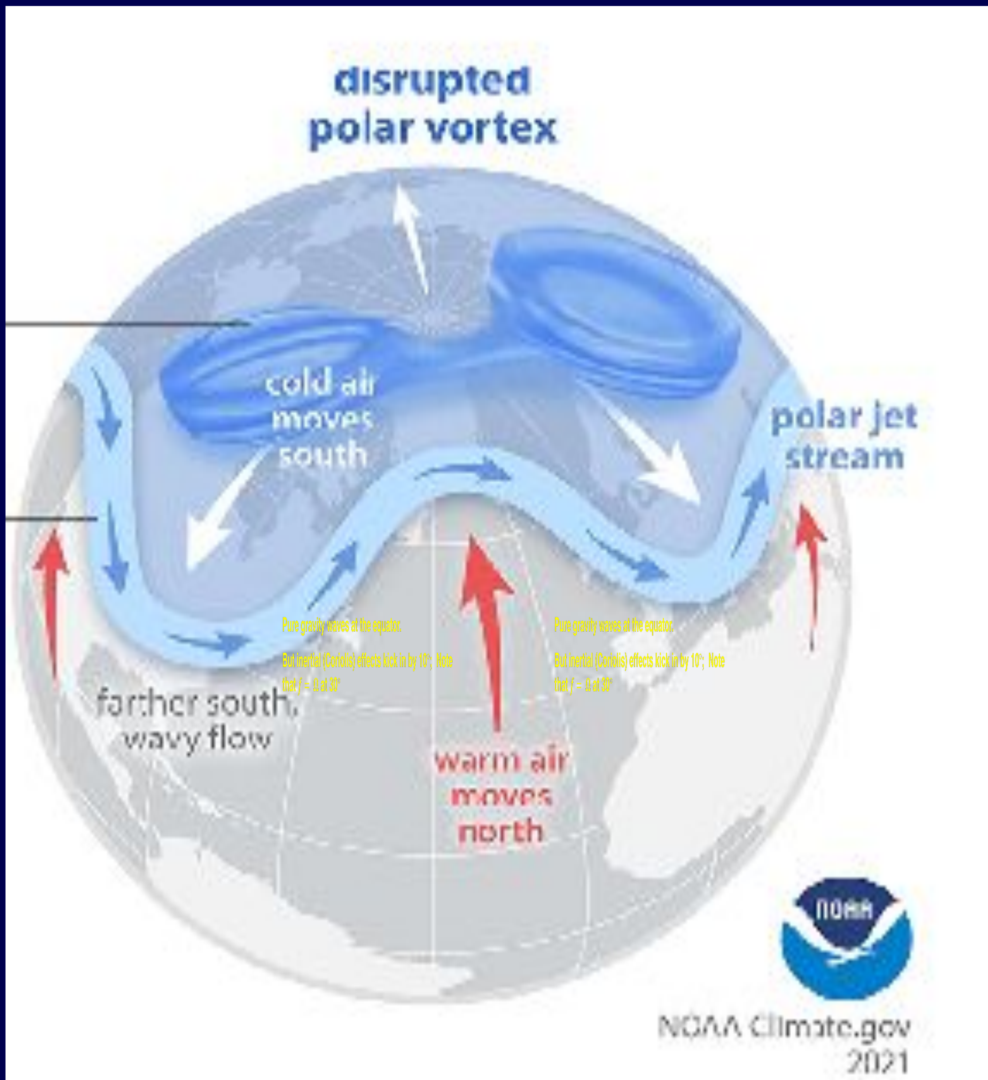
$$D/Dt\,(\nabla^2_H \Phi/f_0) + v_g\, df/dy = 0$$

$$D/Dt\,(\nabla^2_H \Phi/f_0) + v_g\, df/dy = D/Dt\,(\zeta + f) = 0$$

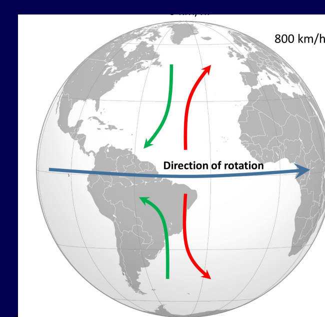
Rossby wave



Propagation is controlled by the y-gradient of f $(=2\Omega \sin\varphi)$.

Propagation is *westward* relative to the background wind.

Wave dynamics easy to visualize in patterns of geopotential Φ.



Goncharenko et al., 2021

Quasi-geostrophic wave facts

Waves propagate upward and equatorward along U < 25 m s^{-1}.

Waves saturate in upper stratopause; transfer *westward* momentum to the mean flow.

Extreme situations result in breakdown of polar vortex and sudden warming.

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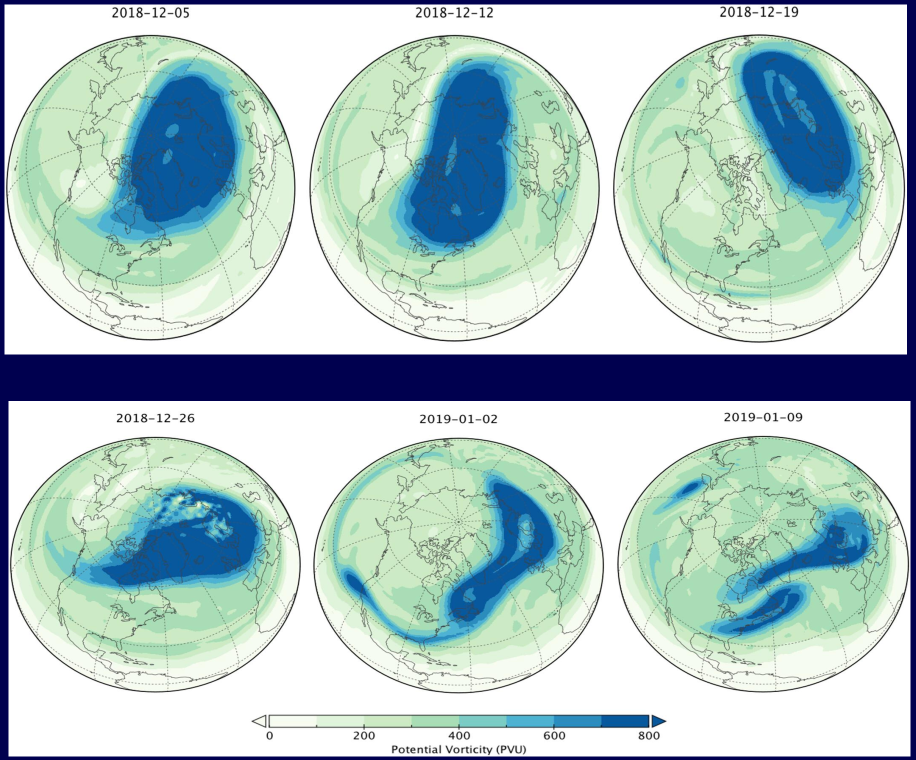

Baldwin et al., 2021

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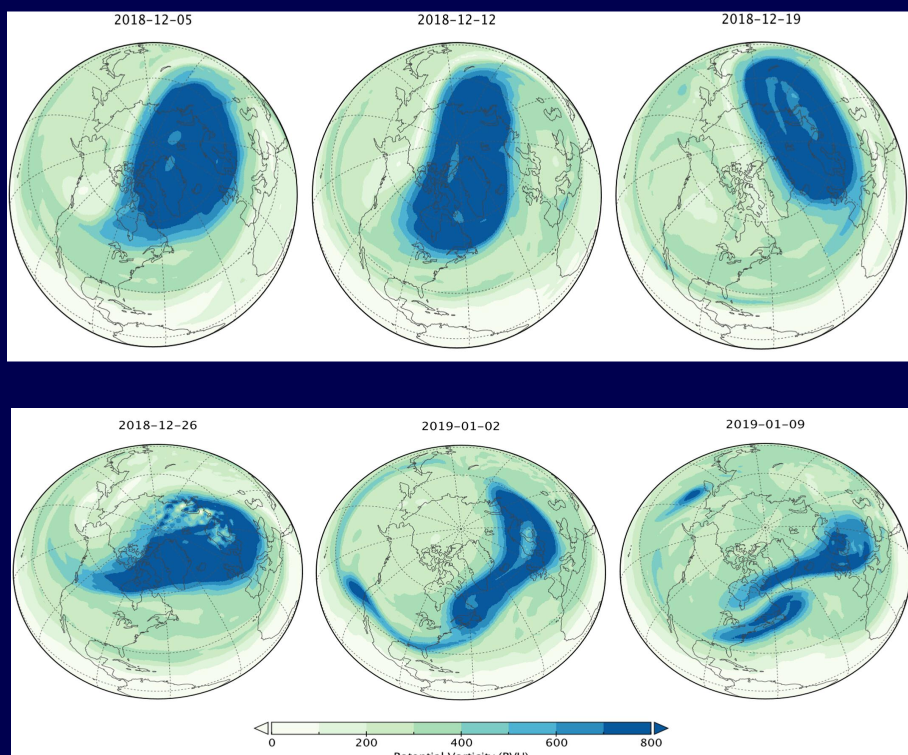
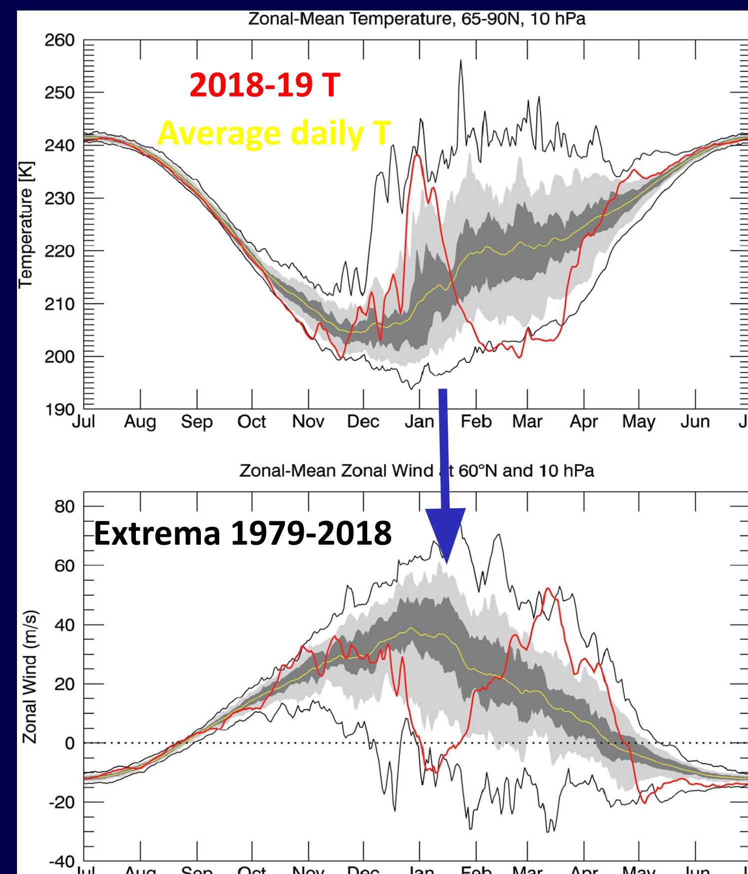
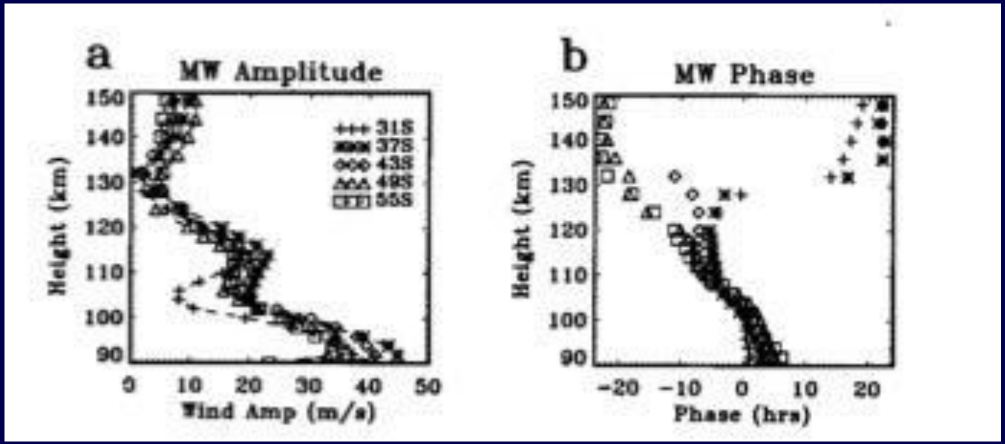


Baldwin et al., 2021

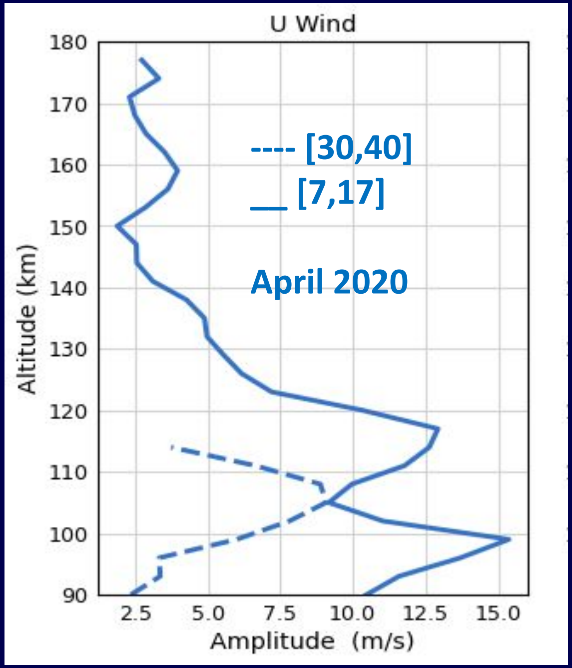


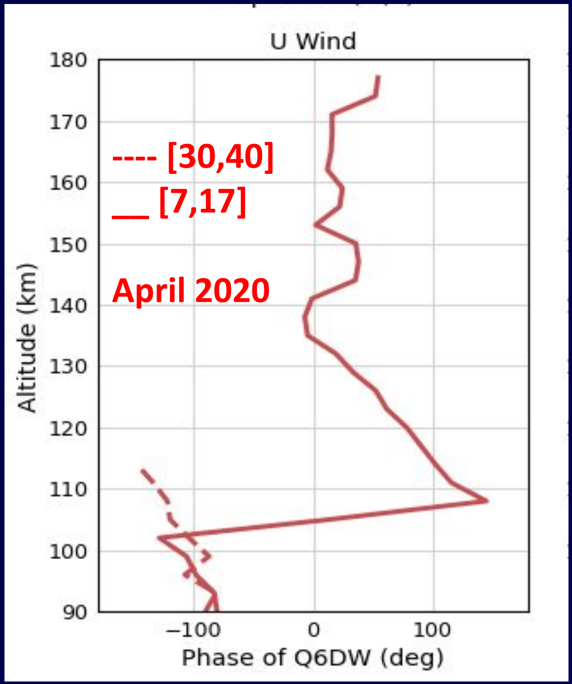
Traveling planetary waves

Two-day wave: Ward et al., 1996



Six-day wave: Wu et al, 2023





This presentation

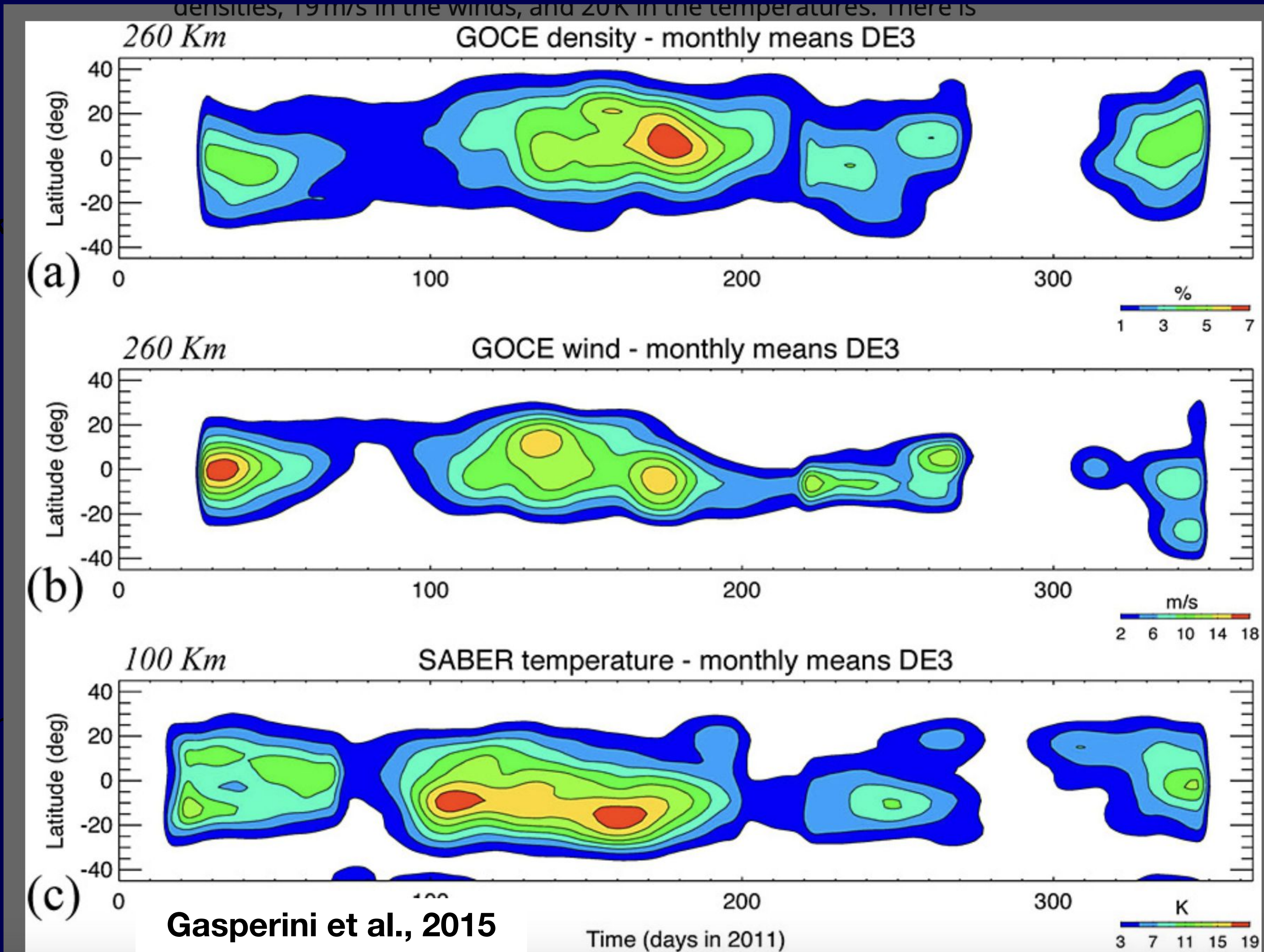
How do tides and planetary waves couple the atmosphere vertically?

- **Direct propagation: transmits variability in H_2O_v and latent heating.**
- **Interactions with PWs: transmit polar vortex distortion, breakdown.**

How does the neutral atmosphere imprint upon the F-region?

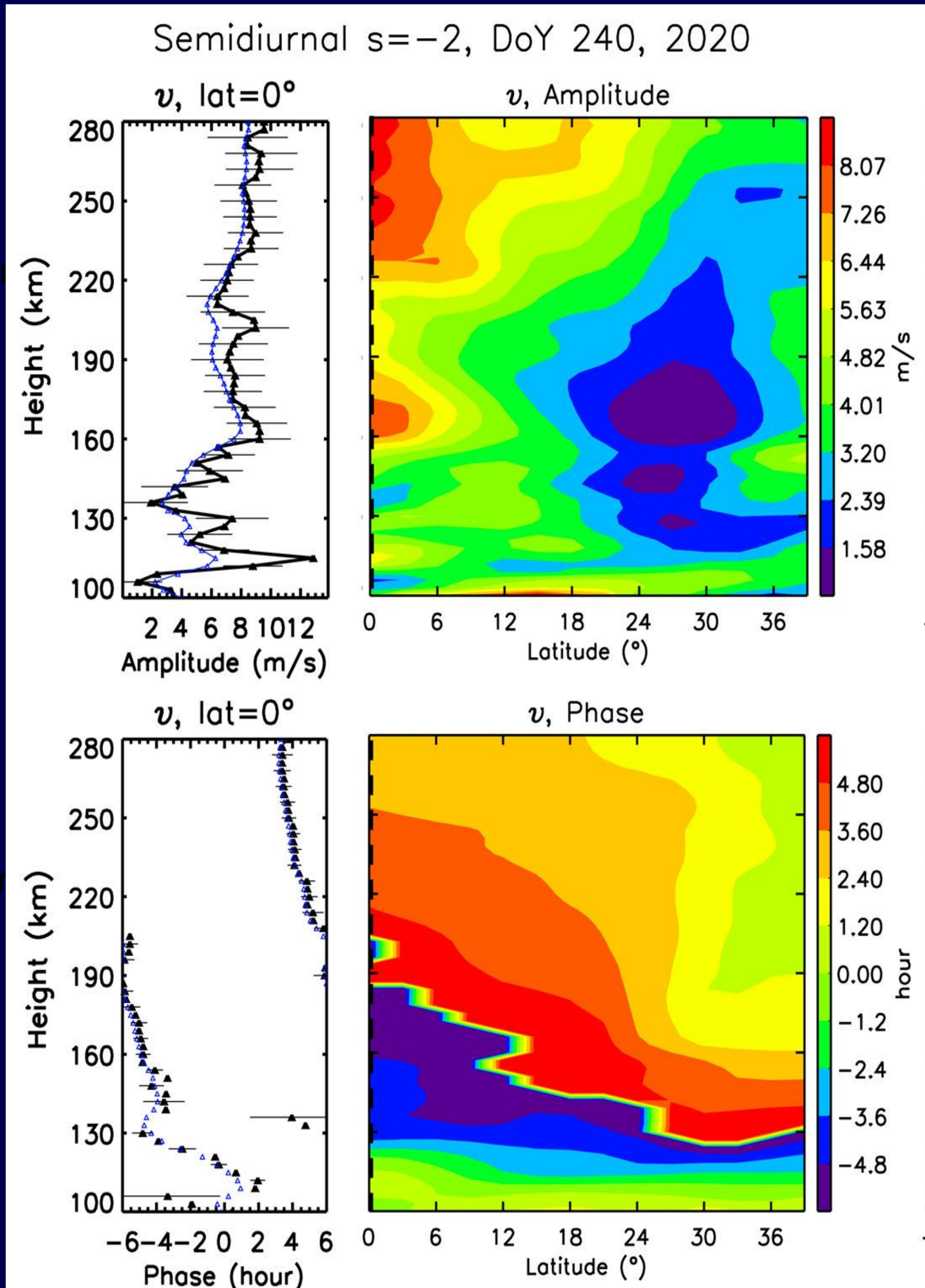
How are recent missions helping us to meet the challenges articulated in DS?

Future missions, observing and analysis strategies.



Gasperini et al., 2015

Direct vertical propagation of tides to F-region.



Forbes et al., 2022

Direct propagation of SE2 to 280 km.

SE2 forced by tropical convection.

Also nonlinear interactions among DW1 and UFKW.

This presentation

How do tides and planetary waves couple the atmosphere vertically?

- **Direct propagation: transmits variability in H_2O_v and latent heating, including ENSO, IS, and QBO effects.**
- **Interactions with PWs: transmit polar vortex distortion, breakdown.**

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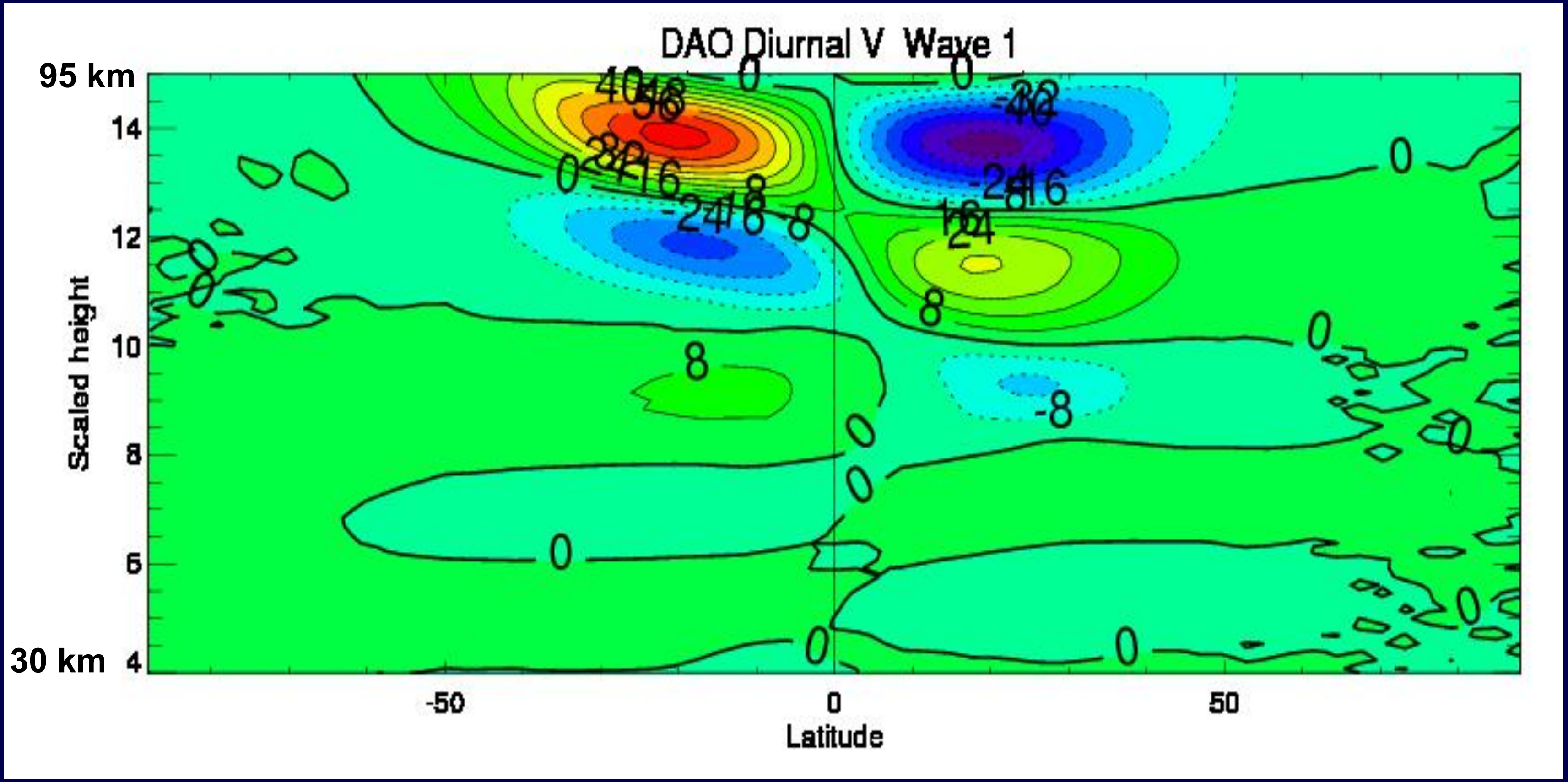
Rossby waves are stratospheric, high winter latitude features.

Tides are *global*, and propagate into the thermosphere.

Waves transport momentum and energy between themselves.



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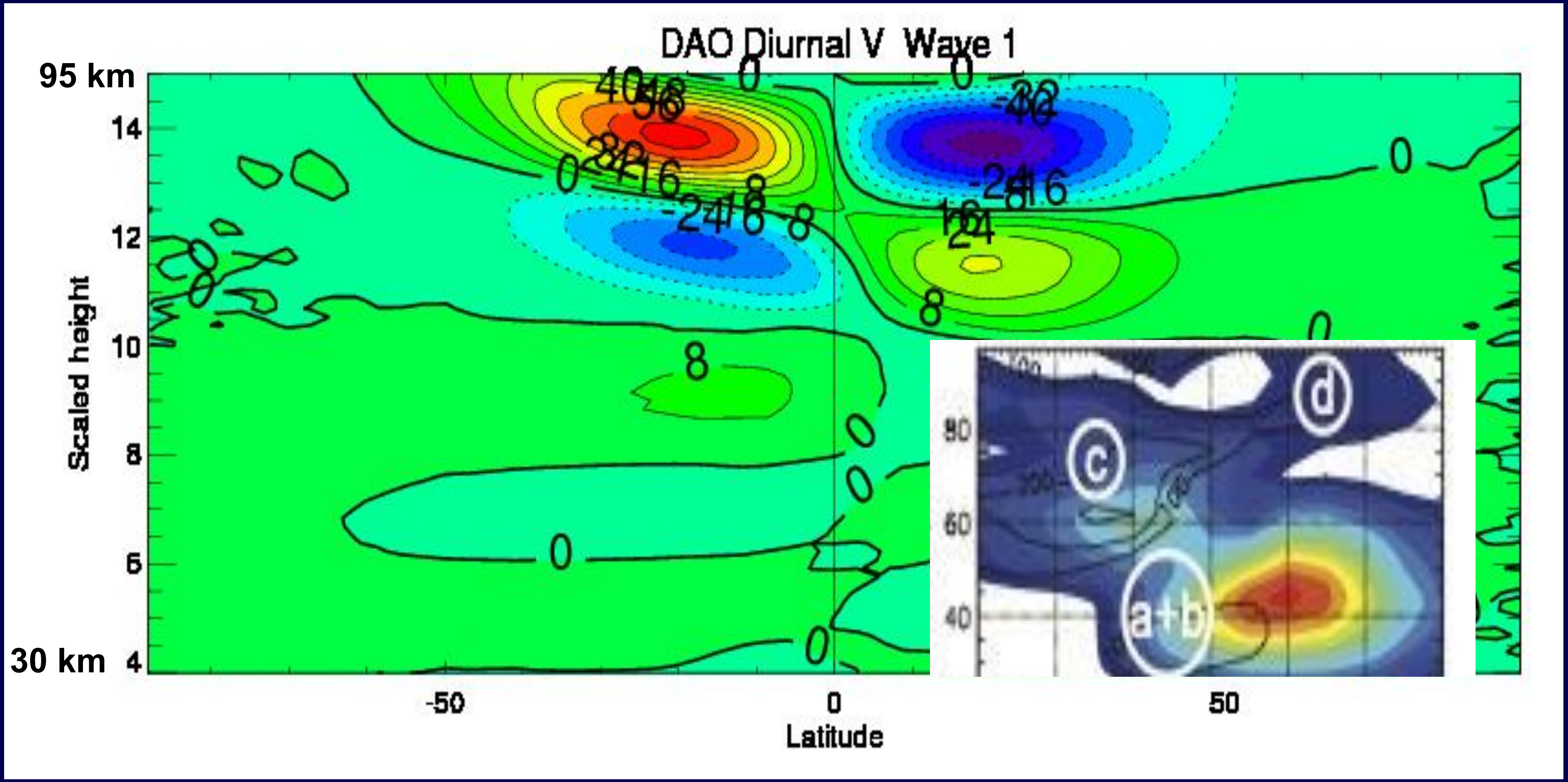
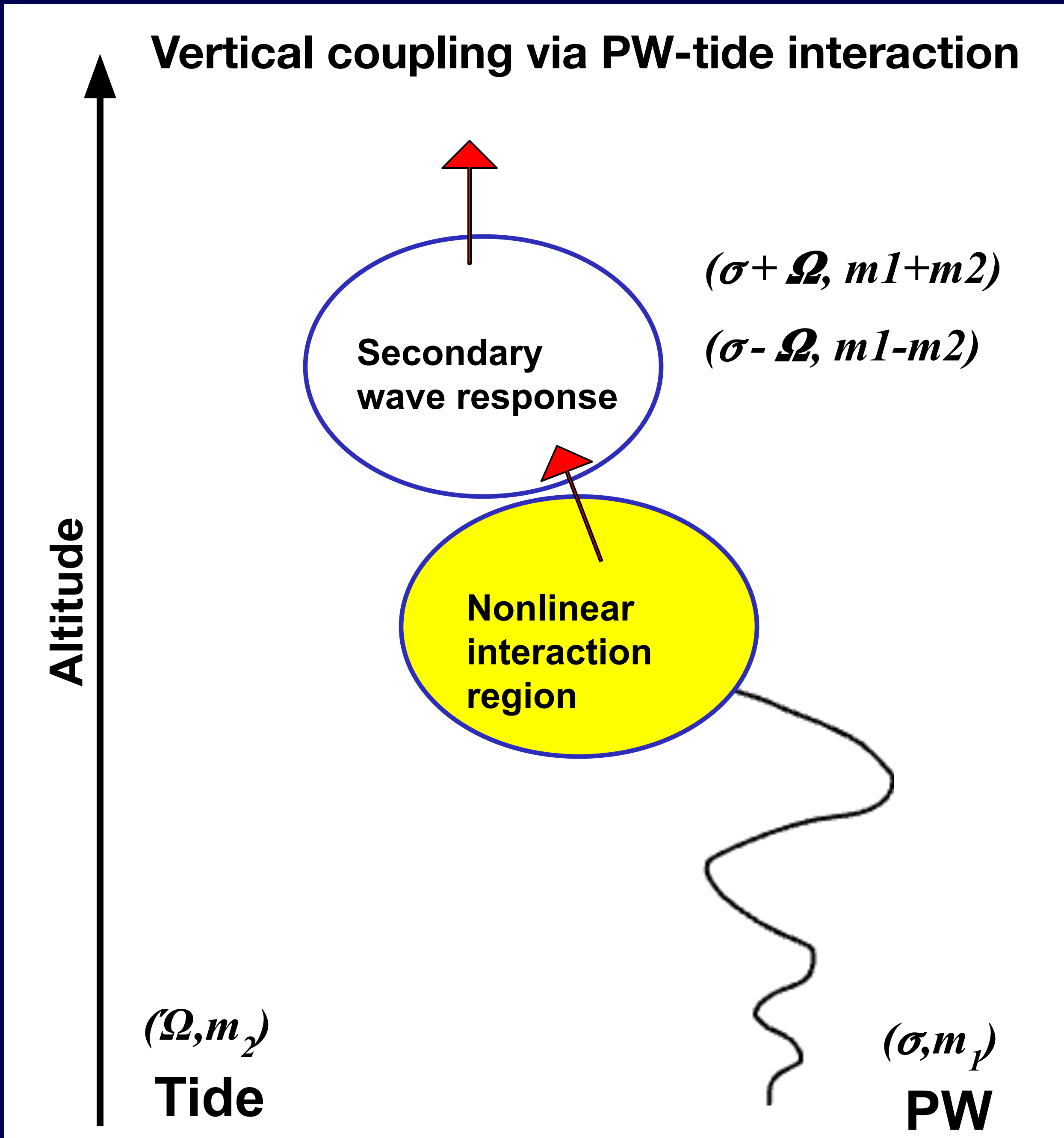




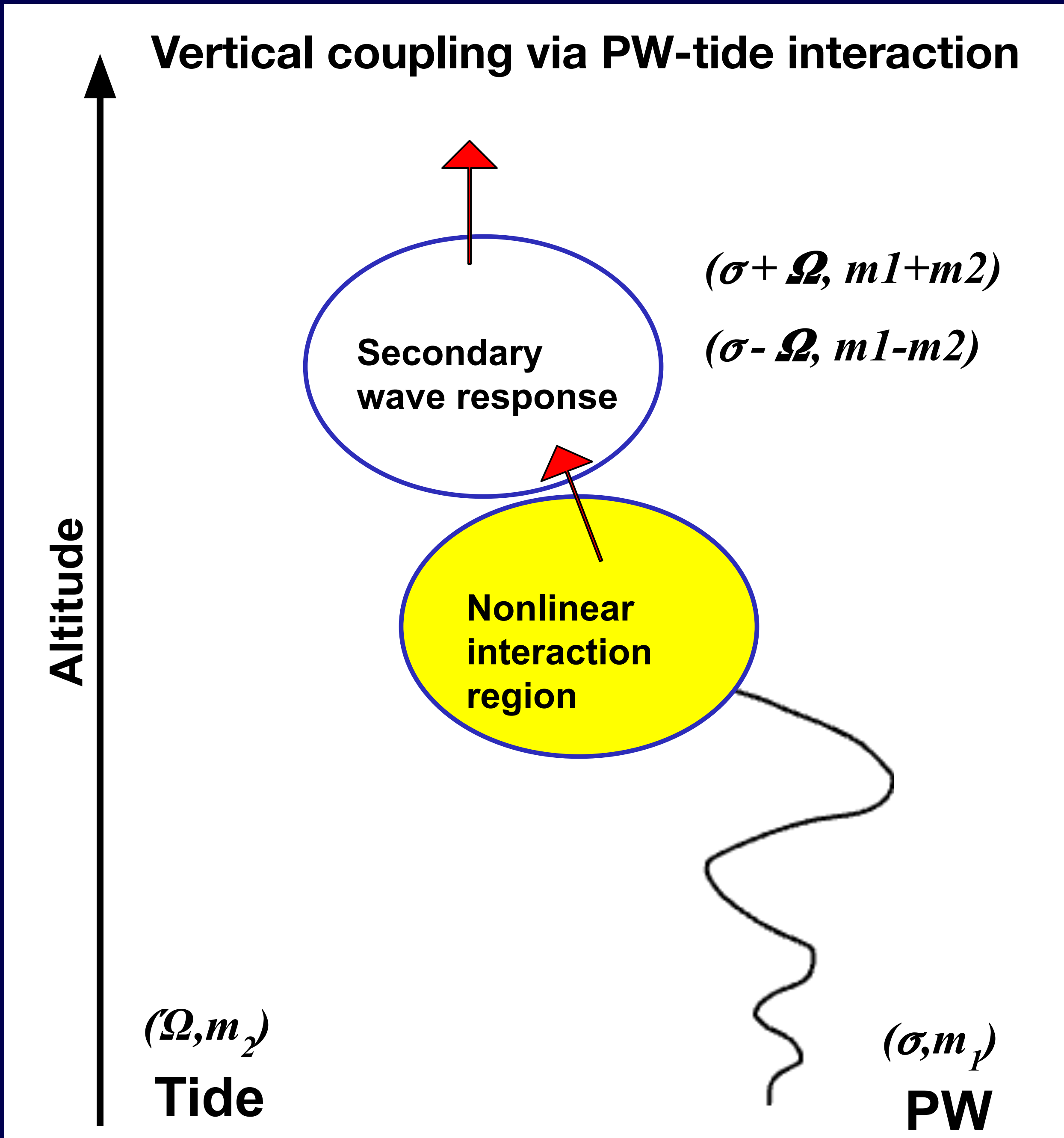
DW1*PW1 → DW2, DS0

SW2*PW1 → SW3, SW1

QTDW3*DW1 → Q2DW2, 16hr4

QTDW3*SW2 → 16hrE1, 9.6hr5

DE3 * UFKW → 18 hrs E4, 1.4 days, E2



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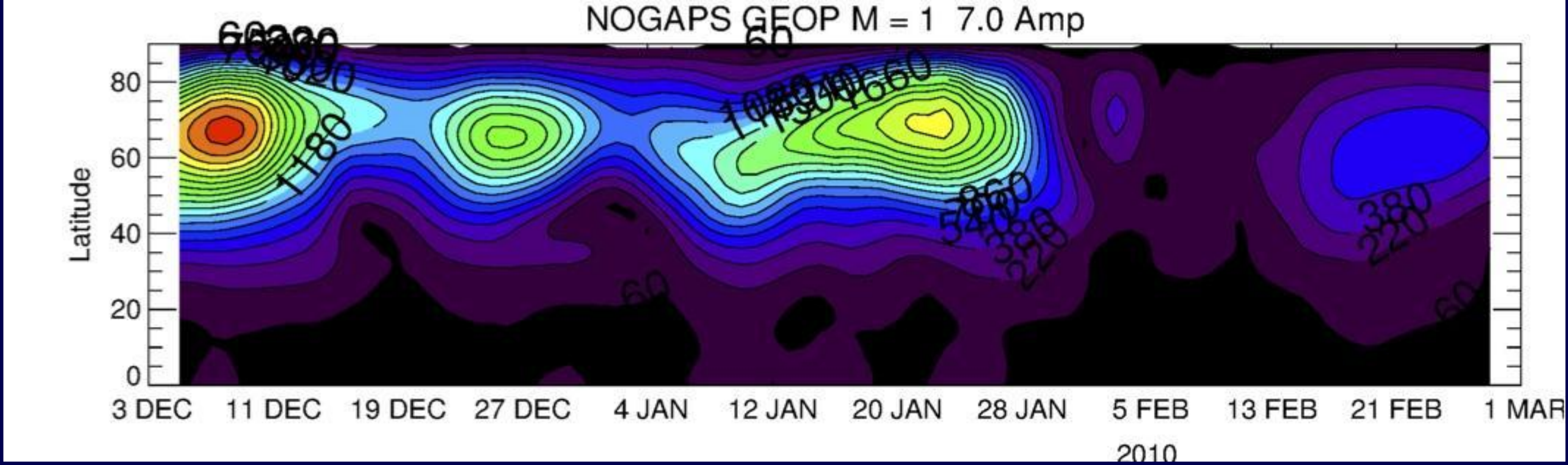
Parent wave, disturbed stratospheric polar vortex ~ 45 km



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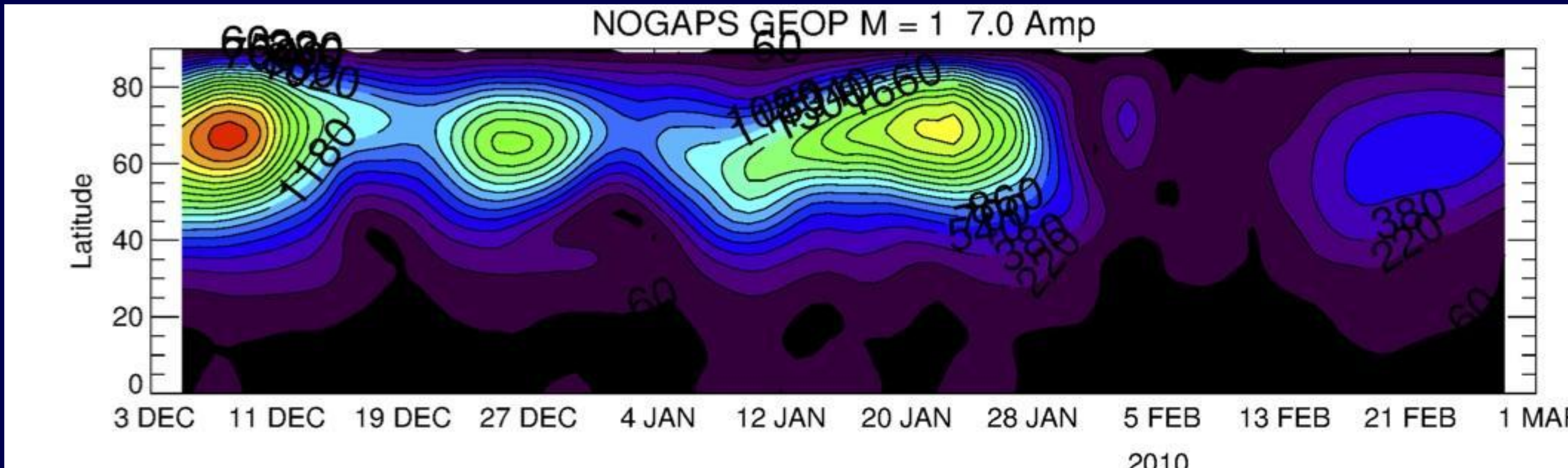
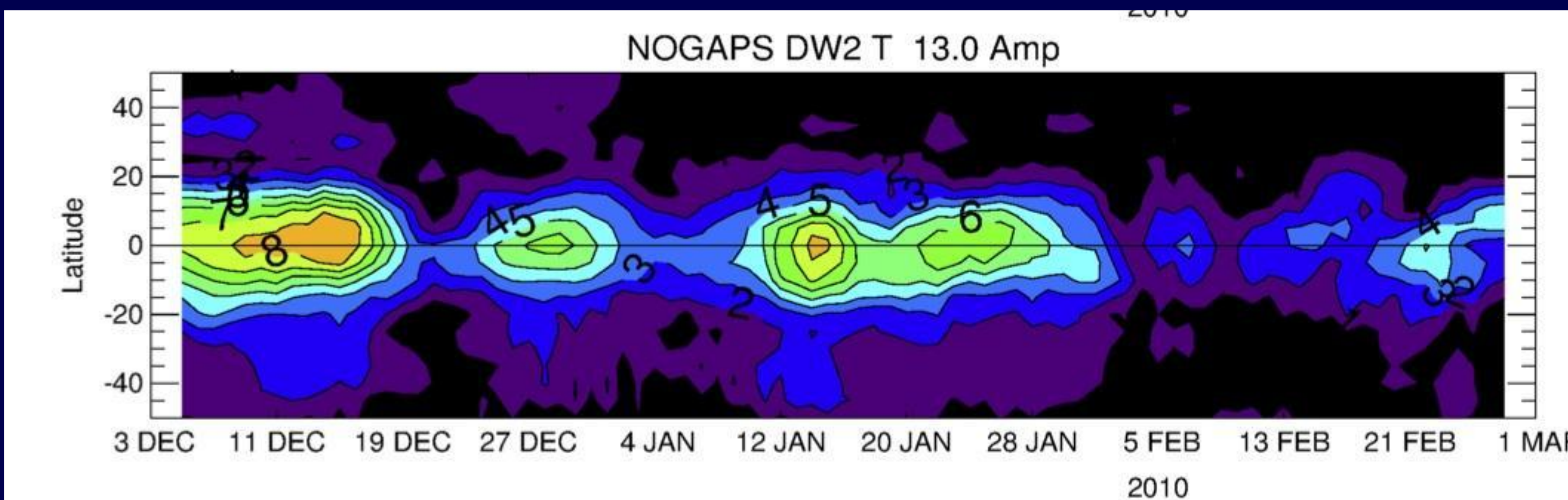


Child wave, ~80 km



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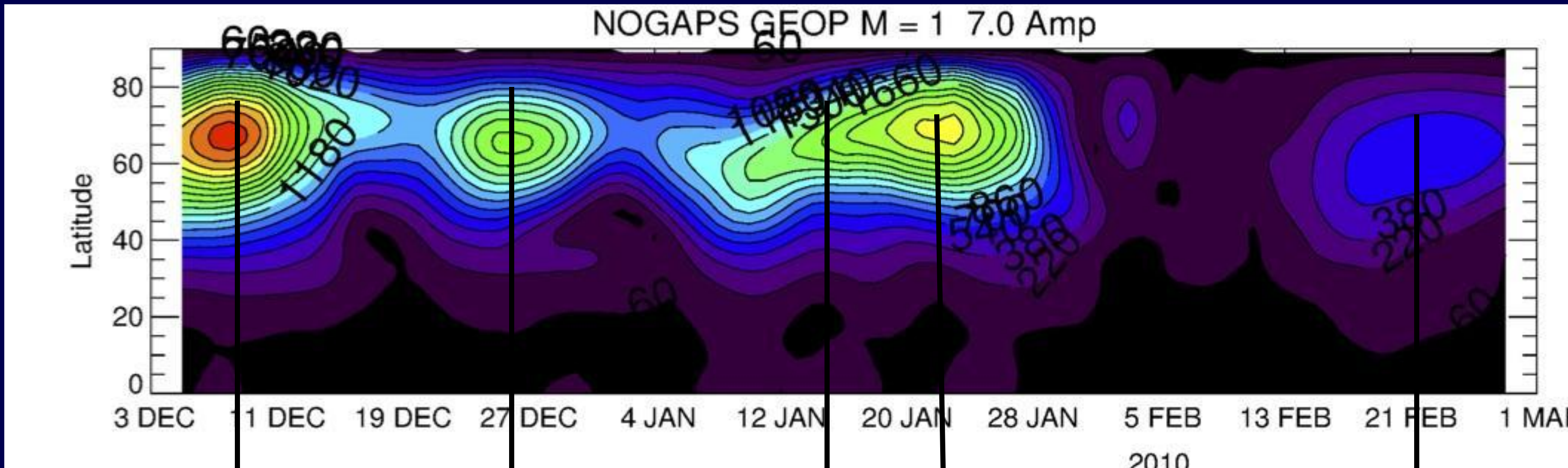

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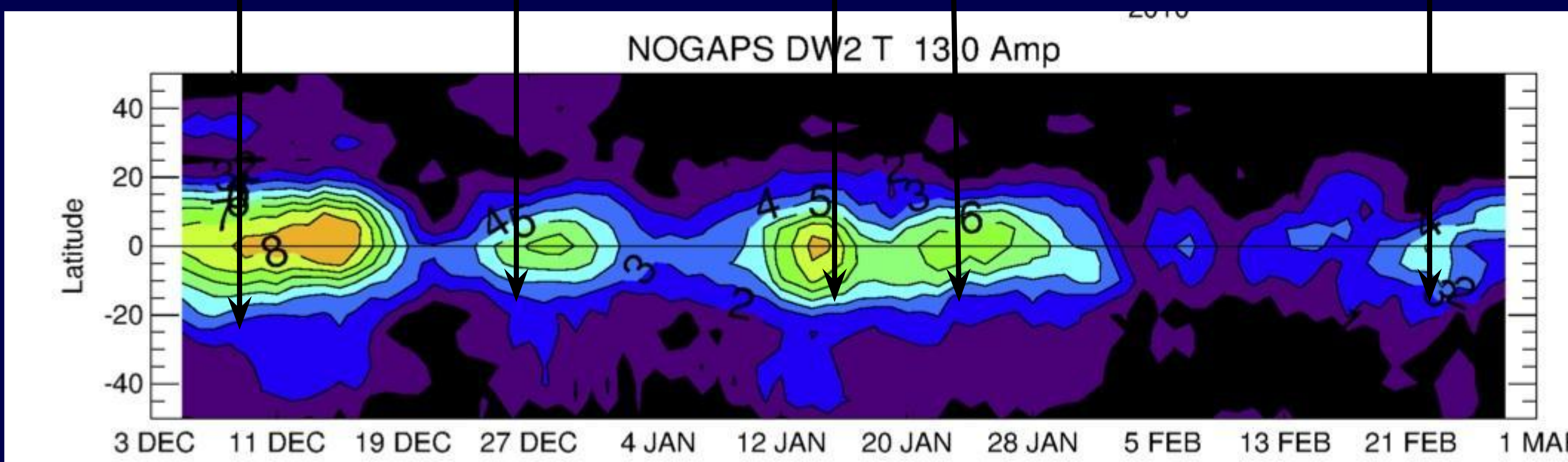
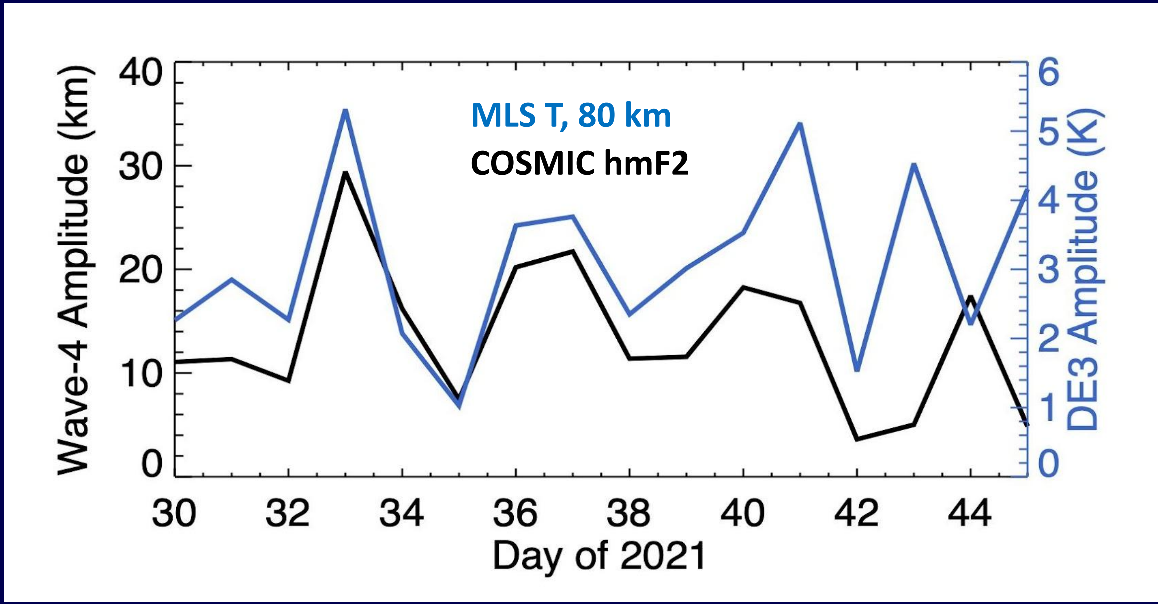


Lieberman et al., 2015

Liu et al. ,2021



3.5-day amplitude modulation of DE3 in both T and F-layer height.

These are signatures of DE3-UFKW interaction…

…and plasma-neutral coupling!

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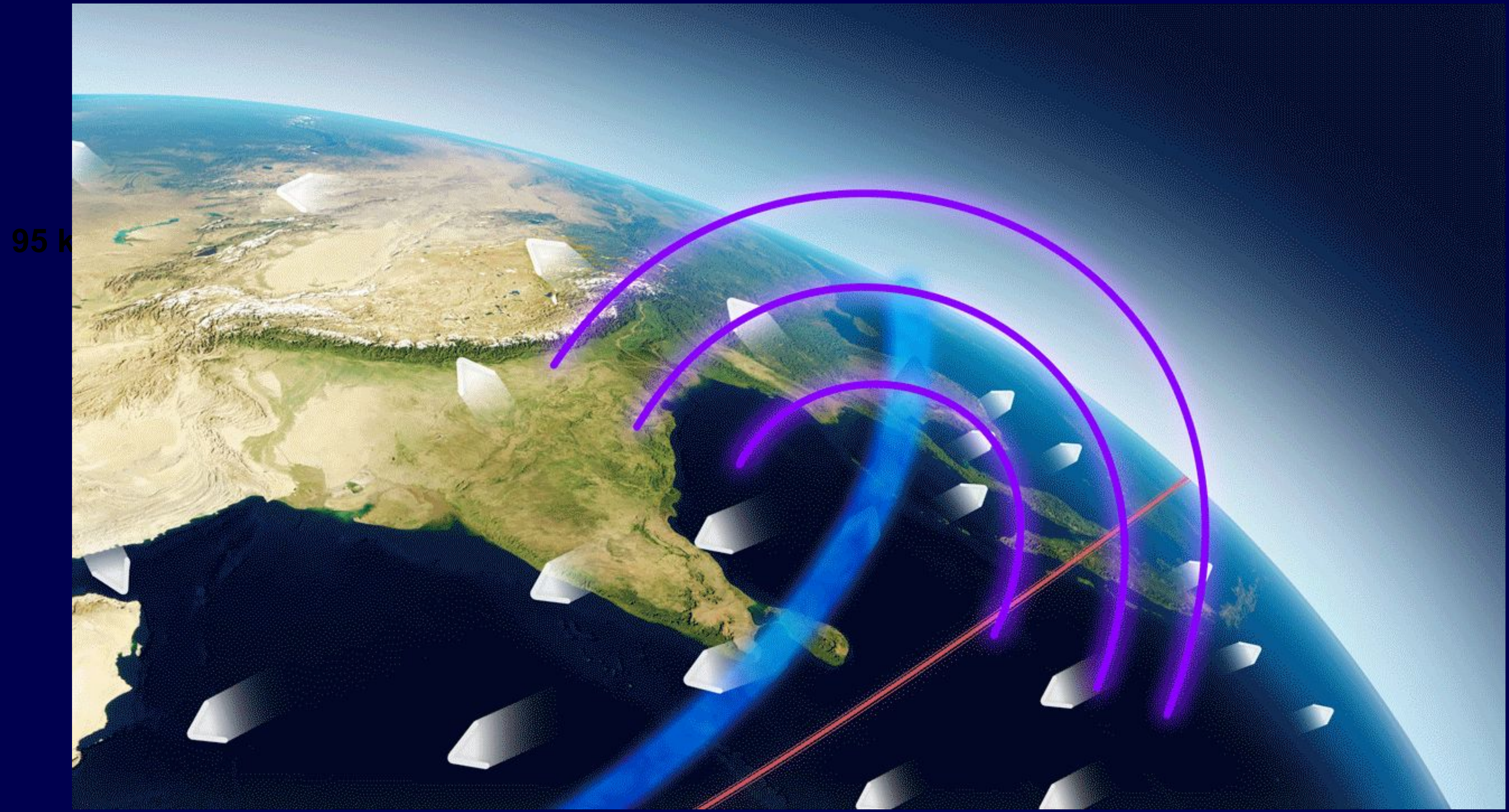
How does the neutral atmosphere imprint upon the F-region?

- E x B and field aligned drift.
- Changes to composition and photochemical rates.

How are recent missions helping us to meet the challenges articulated in DS?

Future missions, observing and analysis strategies.



Tidal or PW winds (white arrows) in the E-region move ions, and separate them from electrons, forming a dynamo electric field (blue line).

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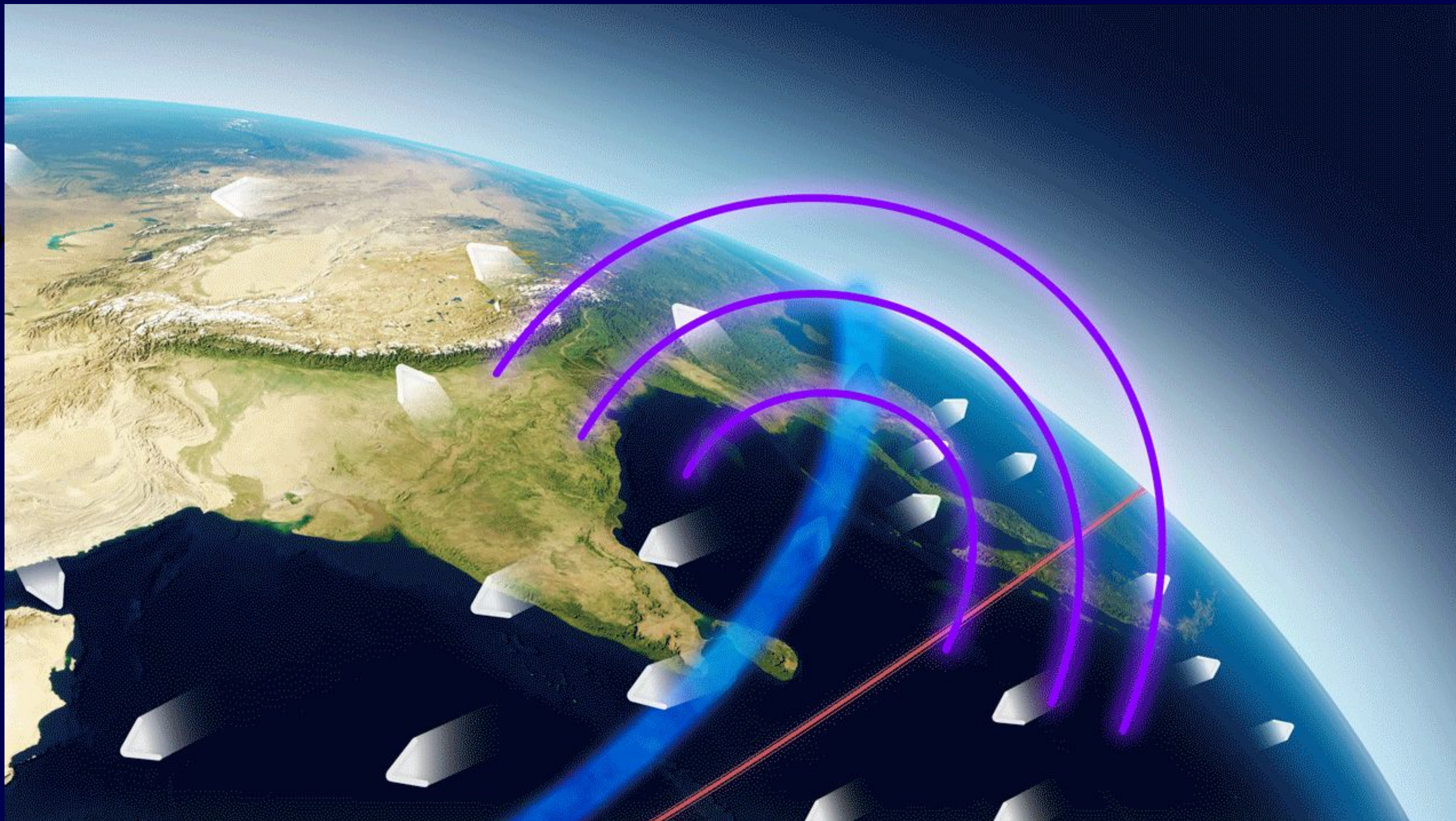

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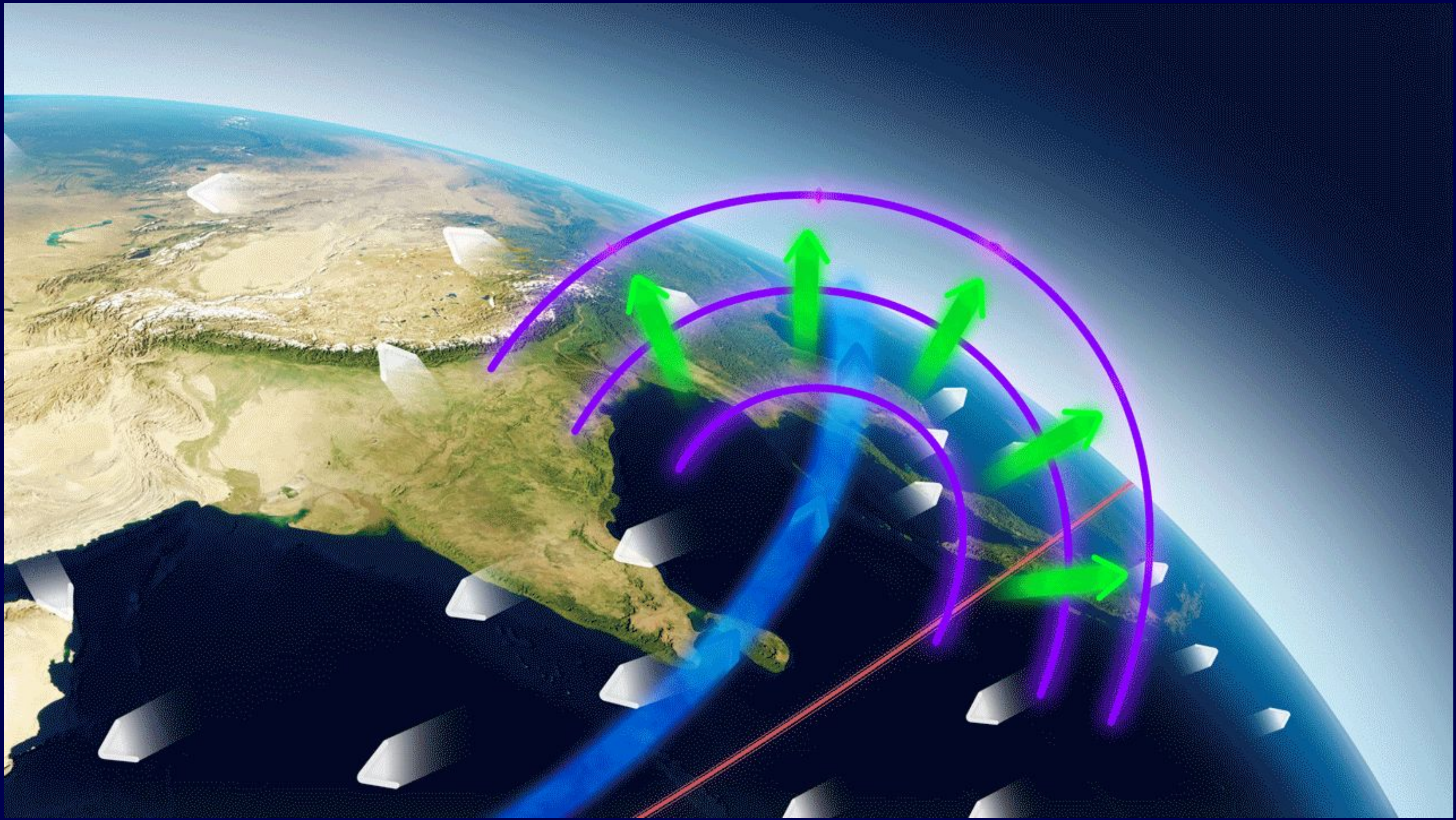
E x B lofts plasma upwards (green) and downwards like a fountain at 370 miles above Earth's surface.



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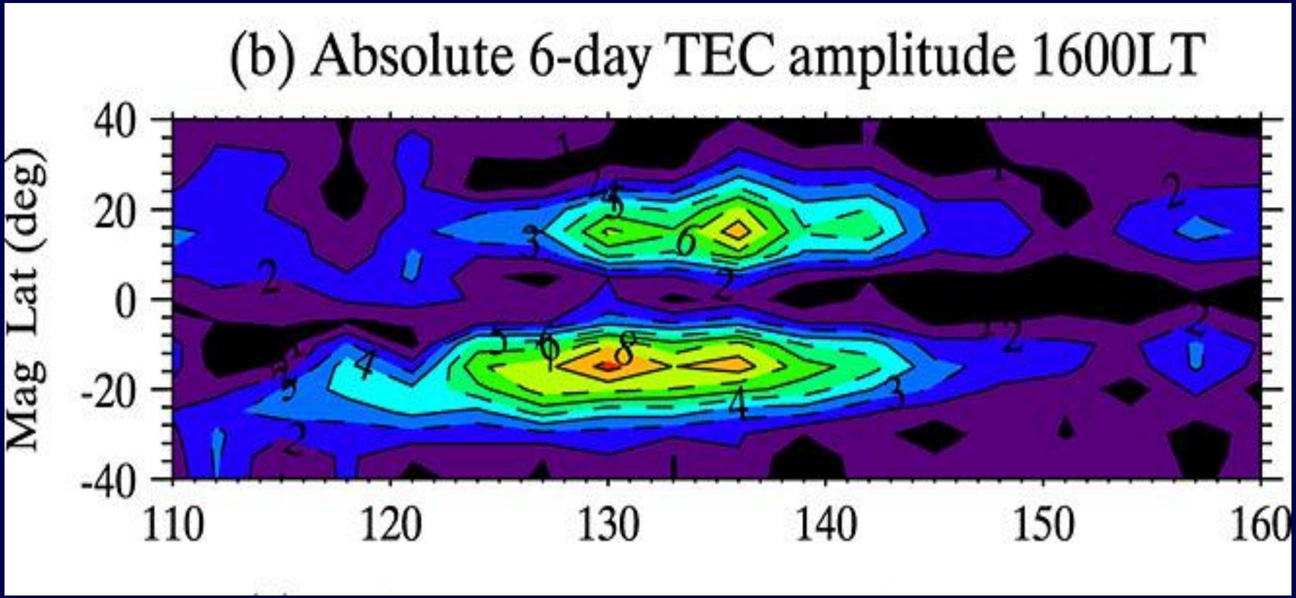
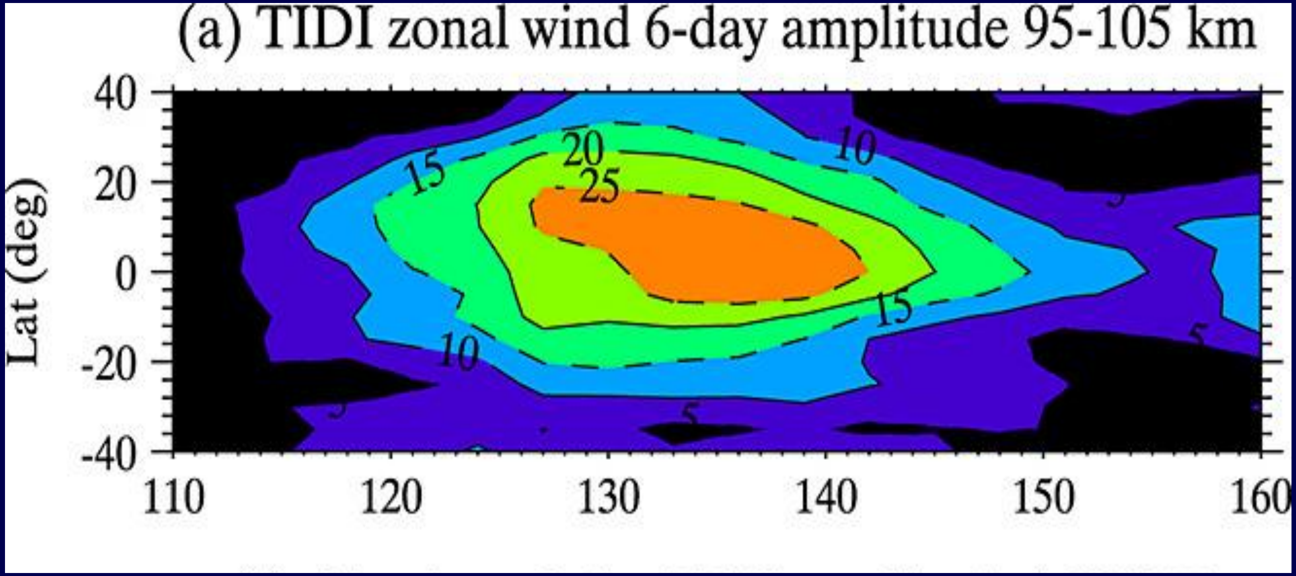
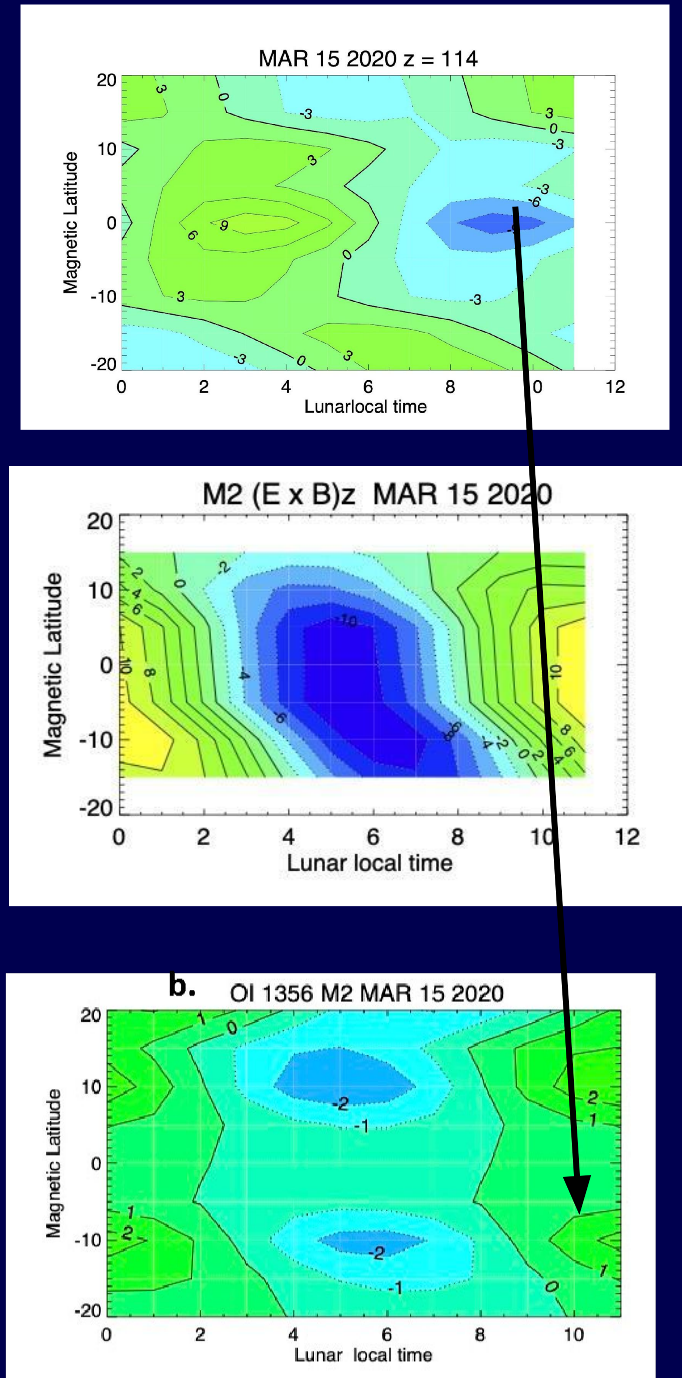
Credit: NASA's Conceptual Animation Lab.

Gu et al., 2014



Amplitude peaks: 7 TEC units, about 15% of background TEC.





Lieberman et al., 2022

East-west wind (ICON/MIGHTI)

E x B drift (ICON/IVM)

OI 135.6 nm brightness (GOLD)

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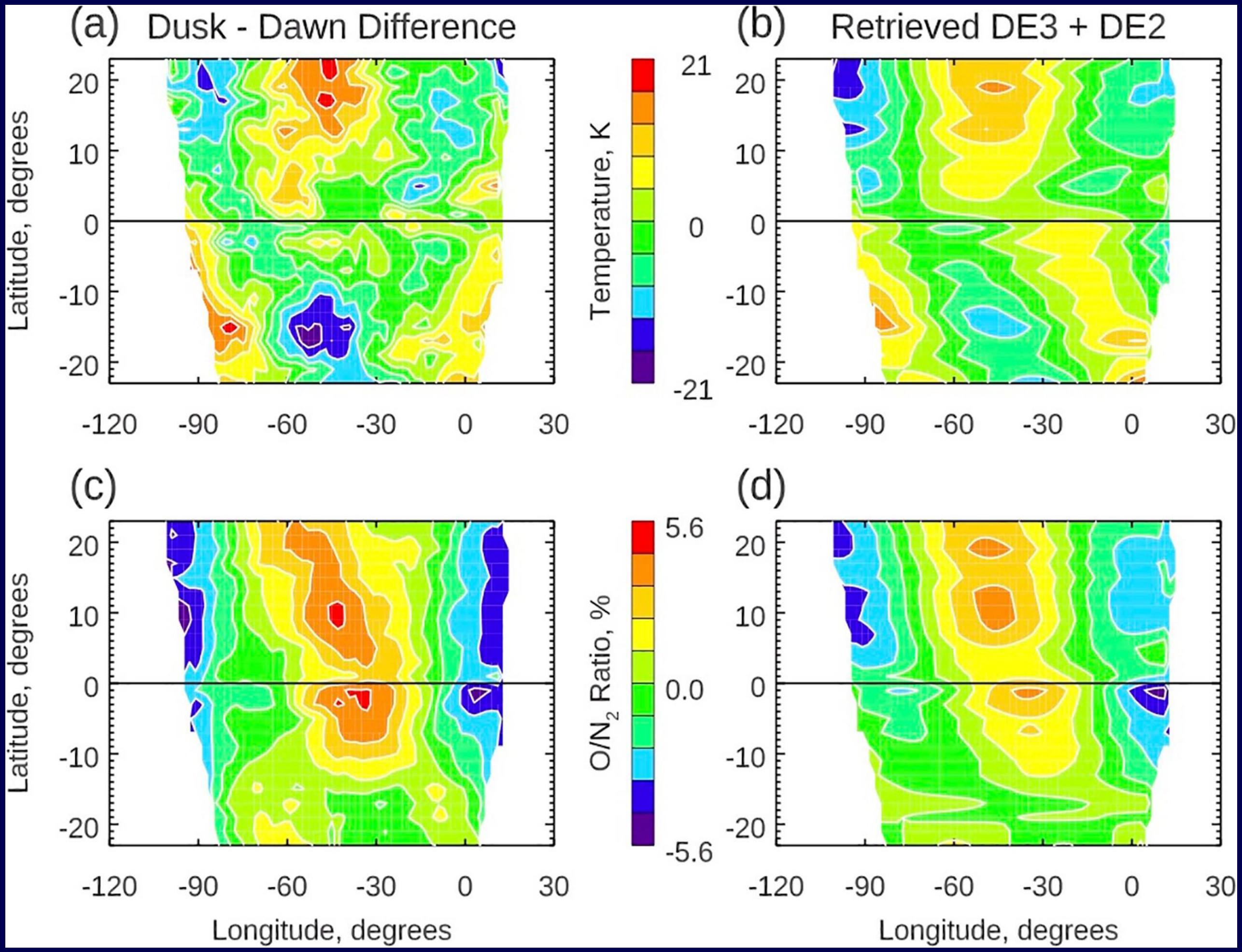
Krier et al., 2022



DE2 and DE3 T waves (forced by tropical convection) propagate into the thermosphere.

The tides also perturb the O/N_2 .

2014 Forbes CEDAR Prize Lecture: Progress, Outstanding Issues, Challenges

- To what extent do PWs penetrate above 100 km?

- Do the PW modulate the tides, which then carry the PW periodicities into the IT?

- How does dynamo-driven wave spectrum between 130-200 differ from < 130 km?

- Do PWs modulate GW momentum deposition?

- How do PWs and GWs affect the zonal mean in the IT?

- How can we measure the system to enable us to understand how wave variability drives ionospheric variability?

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- Do the PW modulate the tides, which then carry the PW periodicities into the IT? **Yes: UFKW, QTDW-tide interactions.**

- How does dynamo-driven wave spectrum between 130-200 differ from < 130 km? **Long vertical waves common to both regions; shorter vertical waves couple nonlinearly; need more aggressive sampling of F-region.**

- Do PWs modulate GW momentum deposition?

- How do PWs and GWs affect the zonal mean in the IT?

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- How does dynamo-driven wave spectrum between 130-200 differ from < 130 km? Long vertical waves common to both regions; shorter vertical waves couple nonlinearly; need more aggressive sampling of F-region.

- Do PWs modulate GW momentum deposition? Yes, not shown.

- How do PWs and GWs affect the zonal mean in the IT?

- How can we measure the system to enable us to understand how wave variability drives ionospheric variability?

2014 Forbes CEDAR Prize Lecture: Progress, Outstanding Issues, Challenges

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- **How can we measure the system to enable us to understand how wave variability drives ionospheric variability?** Measure neutrals and plasma globally, simultaneously over 24 hours.

Atmospheric Waves Explorer (AWE), launching December 2023): OH nightglow emission near ~87 km.

AWE will deduce GWs with 30< λ_H < 300 km, and their energy and momentum fluxes.

Geospace Dynamics Constellation (GDC) + DYNAMIC (~2029):

GDC: Six (6) observatories, measuring plasma and magnetic fields in-situ (~400 km).

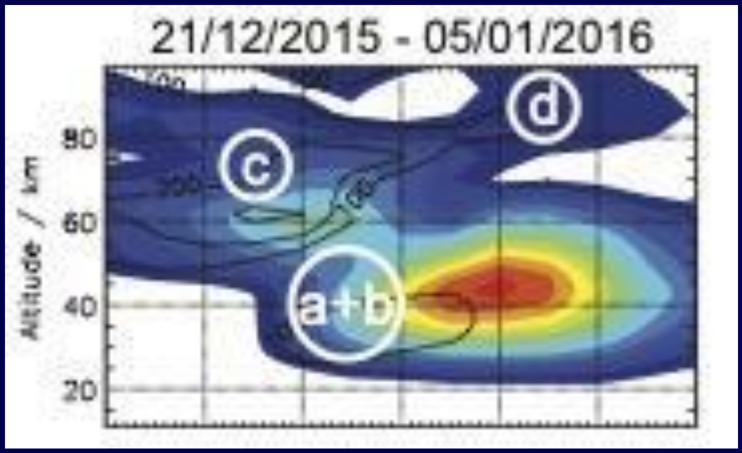
DYNAMIC: Two (2) observatories, measuring neutral winds, temperature and composition between ~90 -300 km

Between 4-8 LT daily in final stages of orbital separation.

Thank you for your attention

Quasi-geostrophic wave facts

Mathias and Ern et al., 2018



20N Latitude 80N

Generally divergent, conserve "potential vorticity"

Pure gravity waves at the equator.

But inertial (Coriolis) effects kick in by 10°; Note that $f = \Omega$ at 30°

Vertical propagation when U < 25 m s^{-1}

Equatorward propagation with altitude (along the U = 0 line); saturates in upper stratopause.

Waves transfer *westward* momentum to the mean flow.

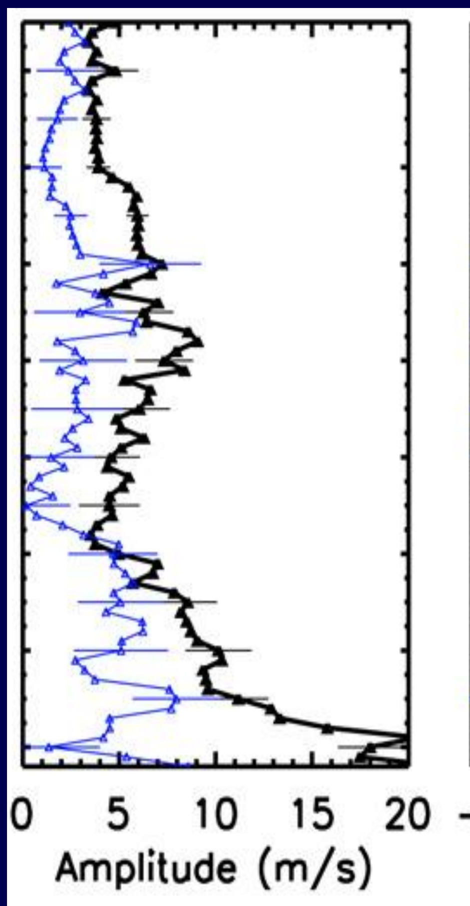
Traveling (non-stationary) PWs: 2-day, 5-day, etc. have MLT sources (instability); propagate into MLT.

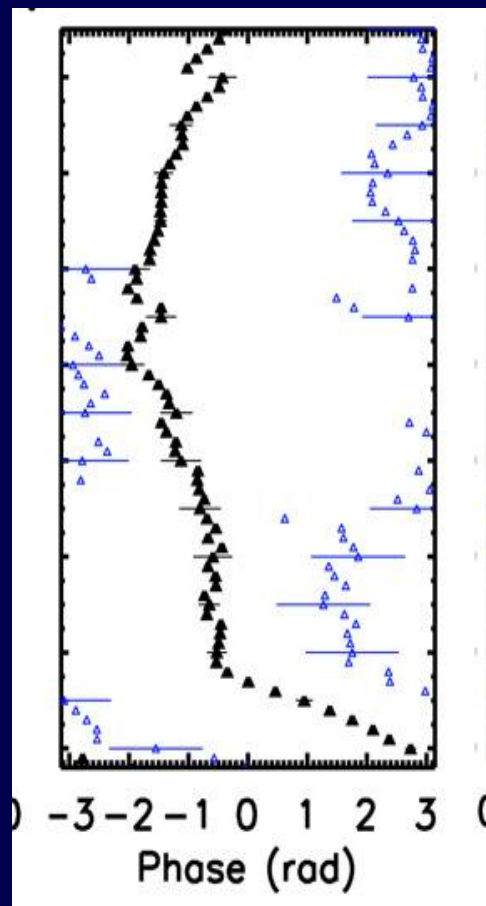
Traveling waves

Two-day wave: Forbes et al., 2021

240 km

100 km





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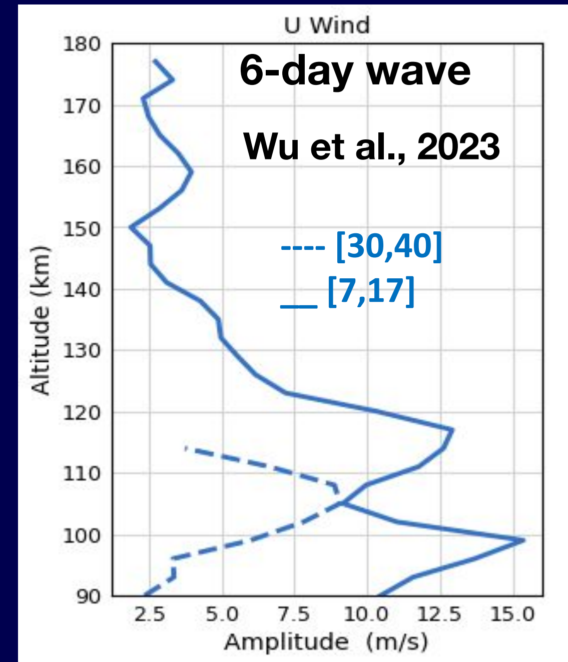
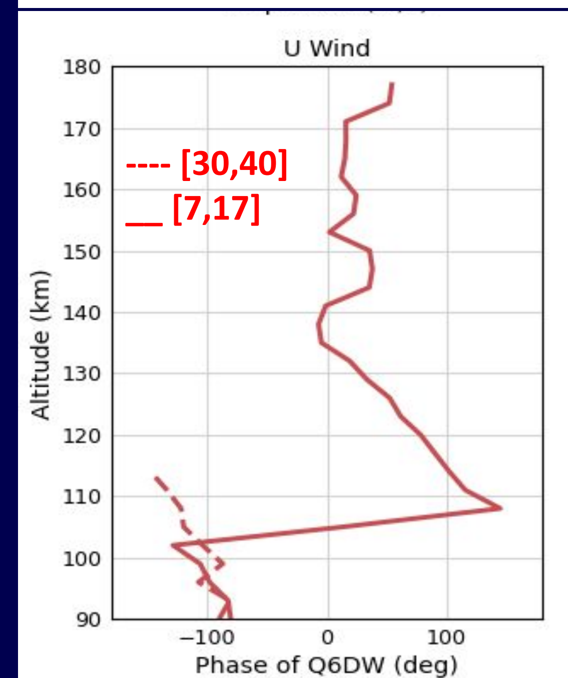
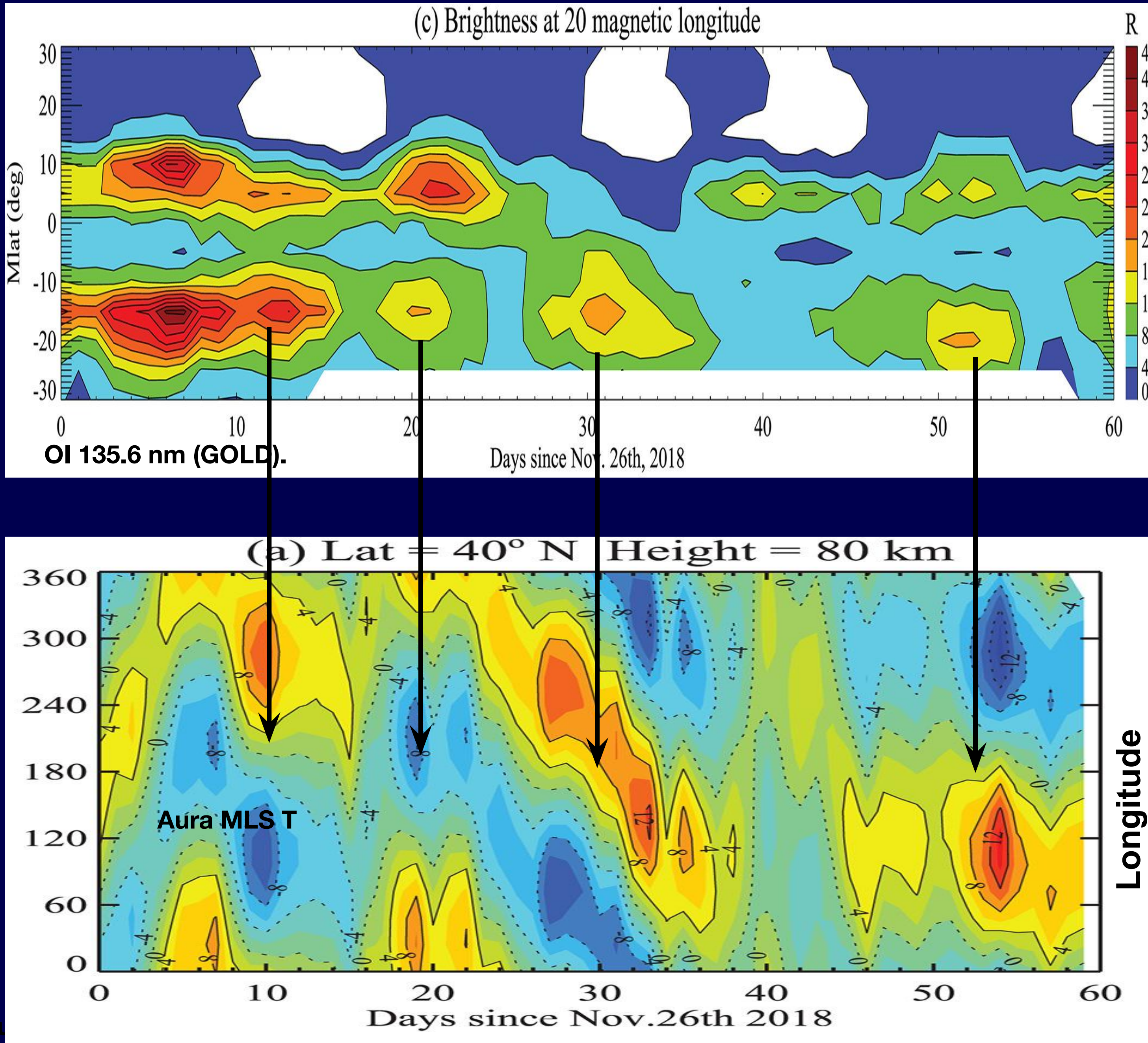





(c) Brightness at 20 magnetic longitude
R
Mlat (deg)
Days since Nov. 26th, 2018
OI 135.6 nm (GOLD).
(a) Lat = 40° N Height = 80 km
Aura MLS T
Longitude
Days since Nov.26th 2018

Lit

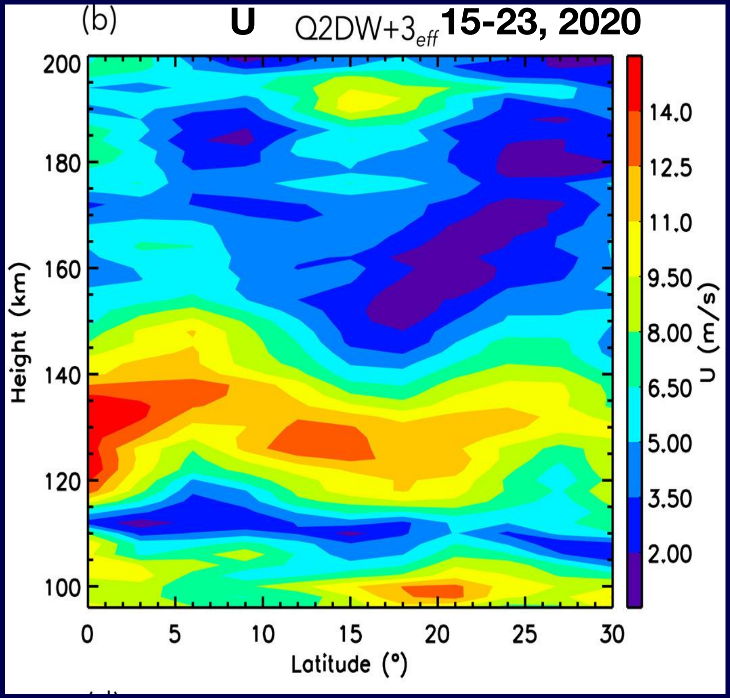
"Apparent" Q2DWs: **Q2DW+2 and Q2DW+3 characteristics derived from traditional longitude-UT fits that potentially contain (unknown) aliasing contributions from SWs. Refers to analysis of either SB data that are undersampled in time, or GB data undersampled in longitude. This includes longitudinal subdivision method (Forbes and Moudden).**

"True": Q2DW resolved from sufficient space-time network.

"*Effective*" Q2DWs: k_s fits give Q2DW+2 or Q2DW+3, and SWs combined. "eff" implies that the signal includes all contributions (Q2DW+SWs) to the S-B wavenumber

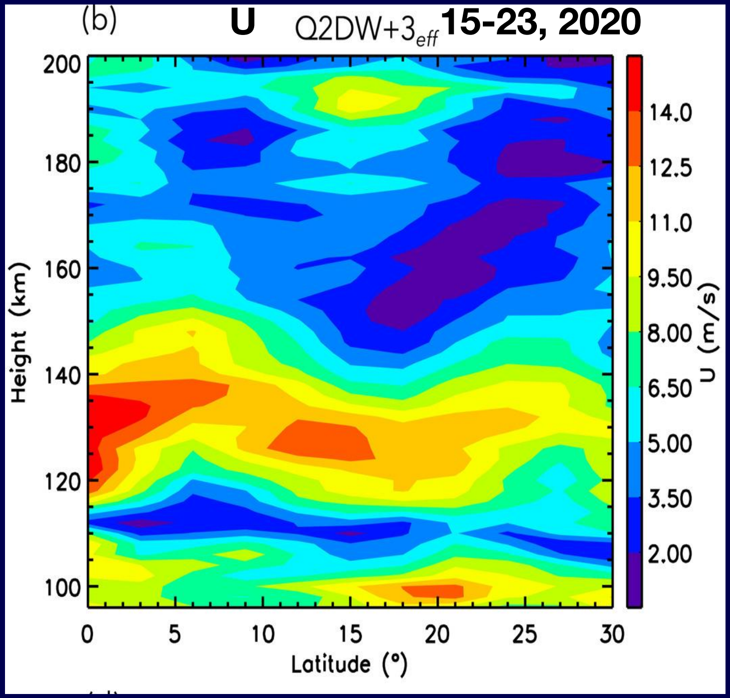
Q2DW+3_{eff} and Q2DW+2_{eff} will thus consist of the true Q2DW+3 and Q2DW+2 plus the contributions of SWs due to interactions between these Q2DWs and all migrating tides.

Forbes et al. ,2021



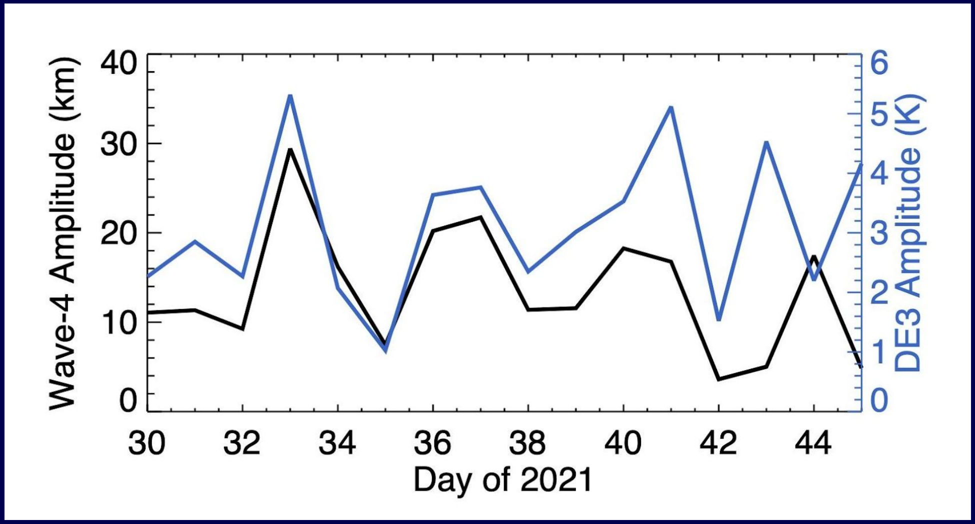
Amplitude of wave products generated by tide-2-day wave coupling.

Forbes et al. ,2021



Amplitude of wave products generated by tide-2-day wave coupling.

Liu et al. ,2021



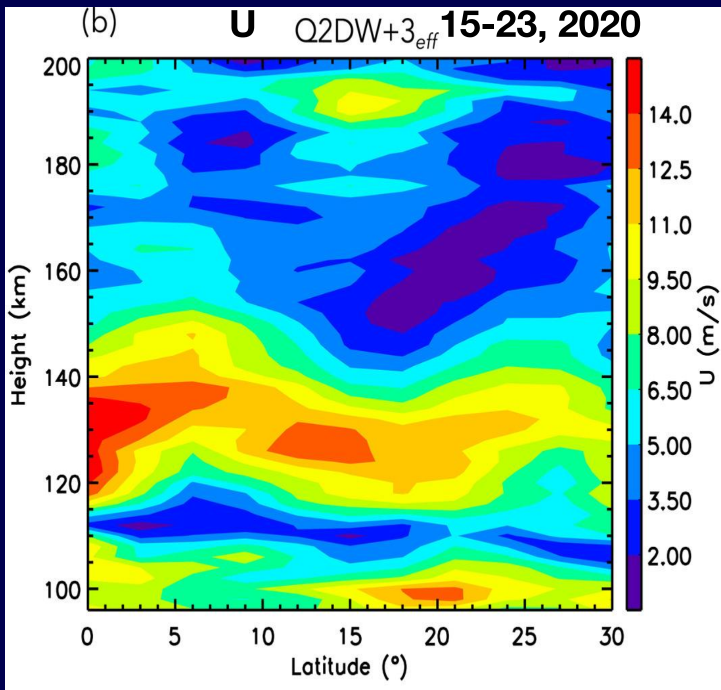
3.5-day amplitude modulation of DE3 in both T and F-region height.

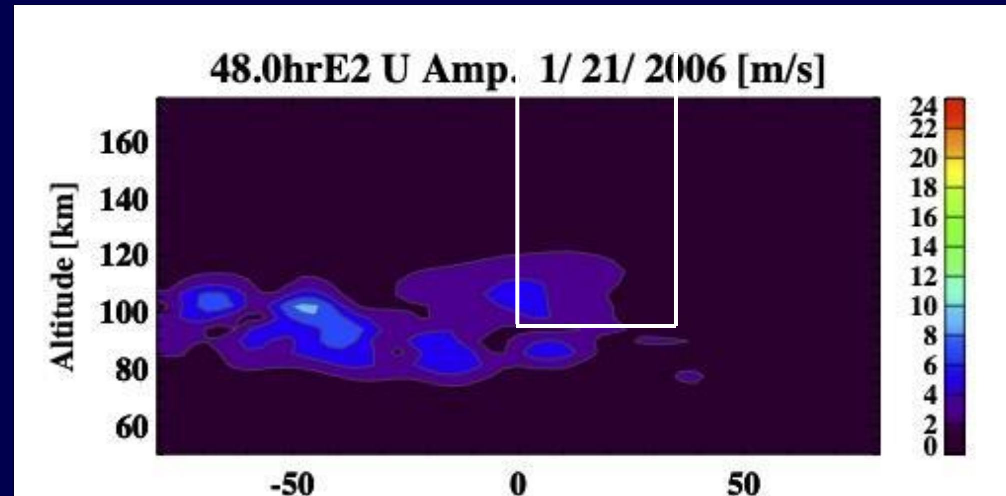
These are signatures of DE3-UFKW interaction…

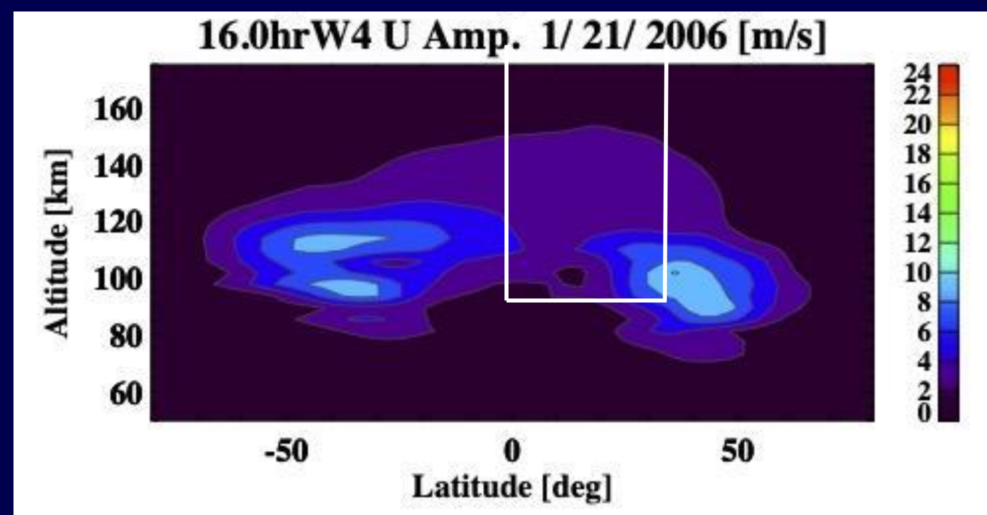
…and plasma-neutral coupling!

Nguyen, 2016

Forbes et al. ,2021



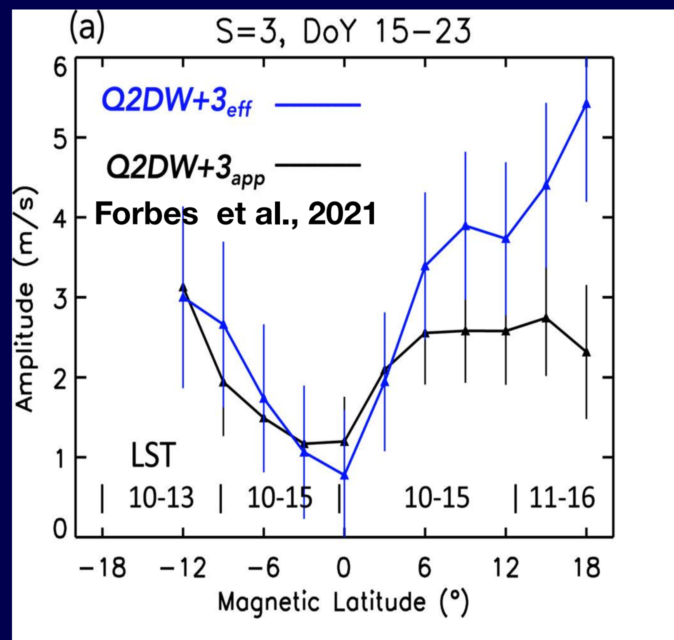




Amplitude of wave products generated by tide-2-day wave coupling.

QTDW2 (top), 16hr4 (bottom) amplitudes.

ICON Semidiurnal lunar U



Lieberman et al., 2022