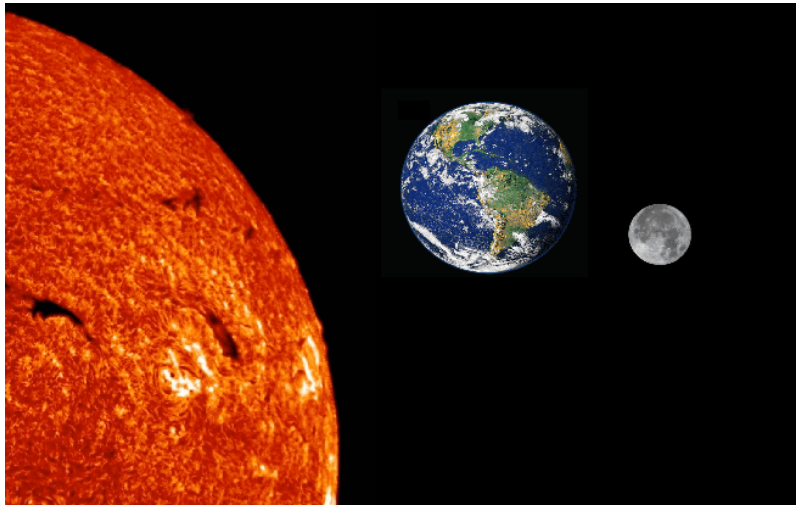
Atmosphere-Ionosphere Coupling by Tides and Planetary Waves

Jeff Forbes

How do interactions between the Sun, Moon, and Earth introduce complexity into the ionosphere-thermosphere system?



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Mack Jones
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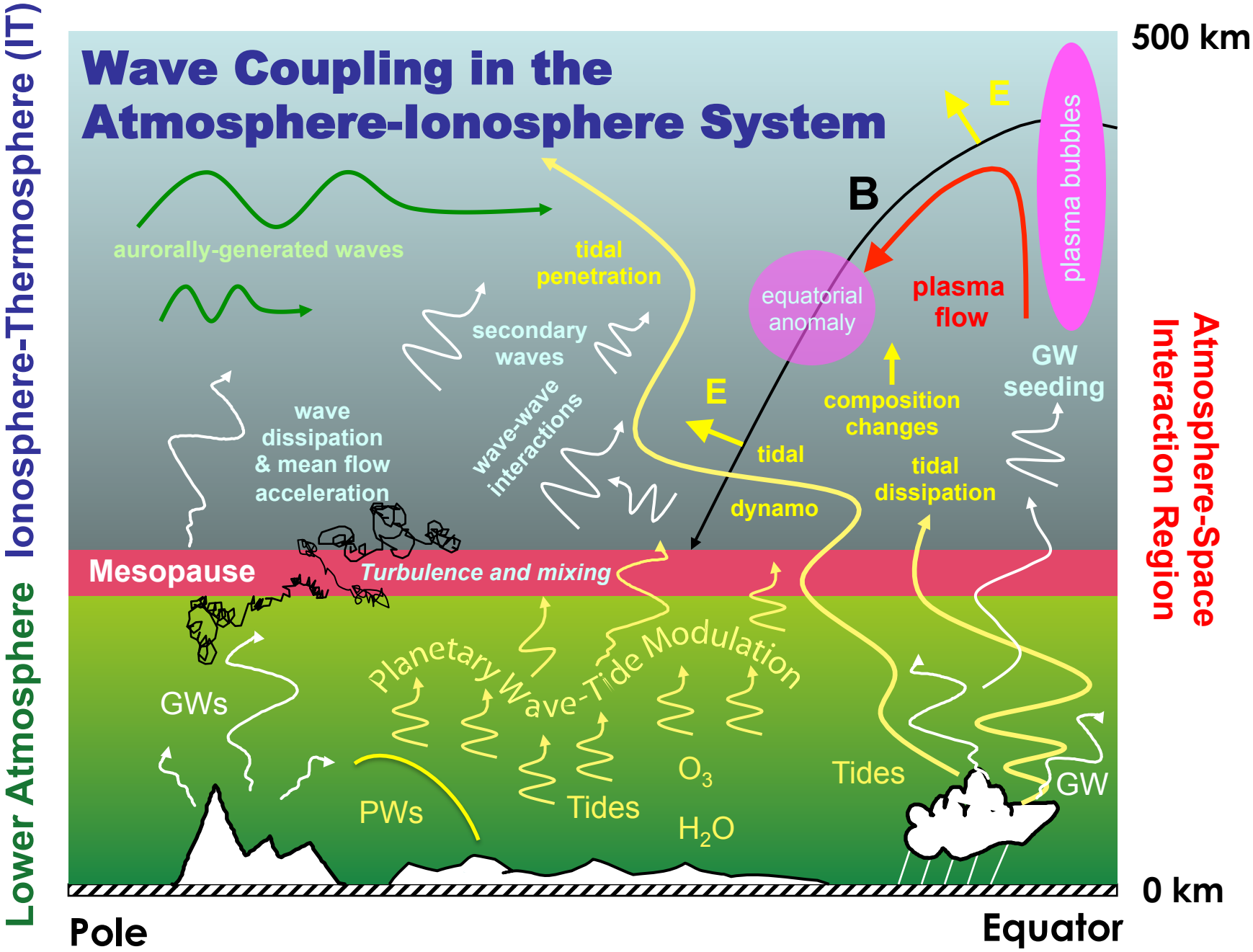
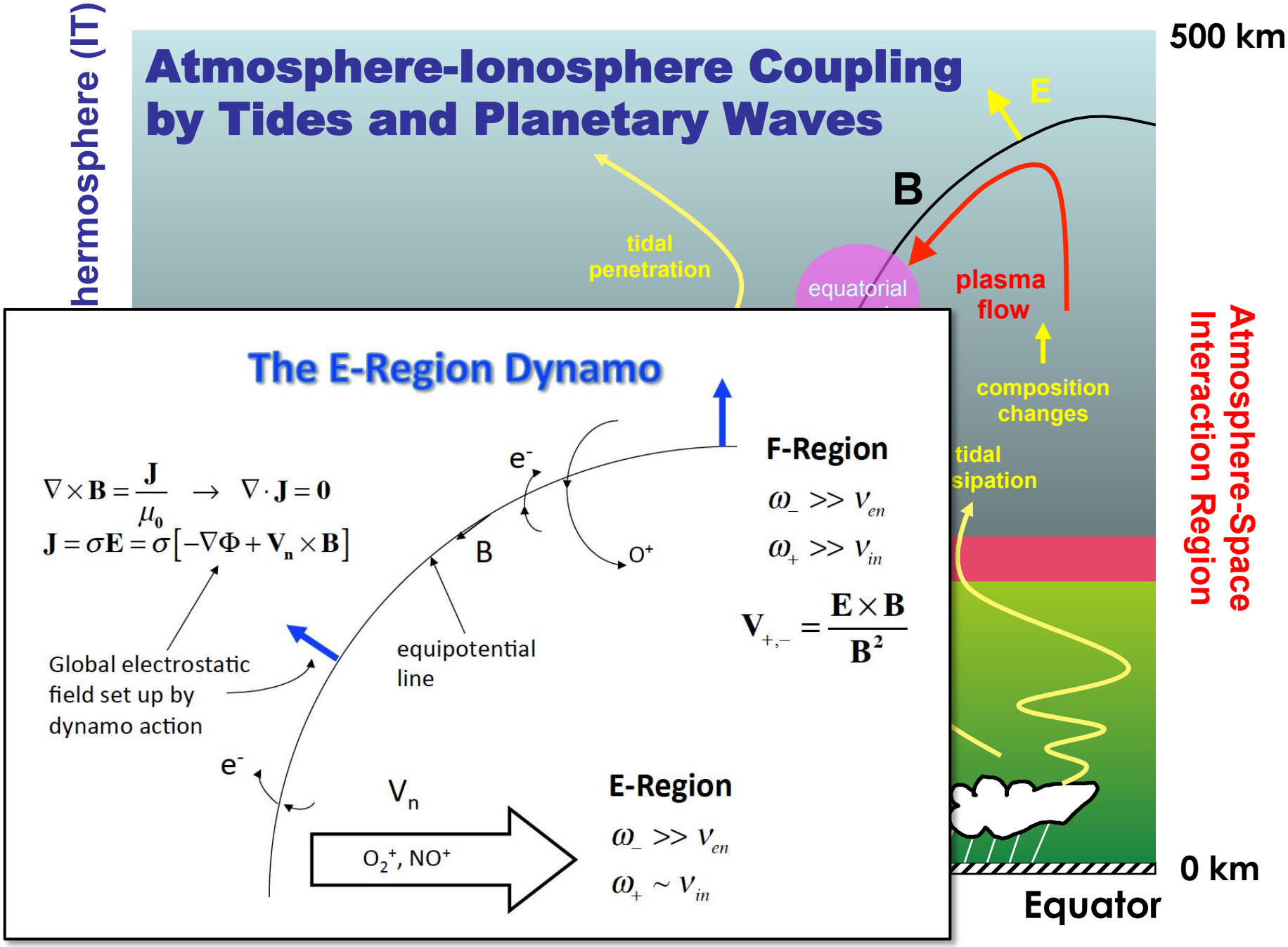

Wave Coupling in the Atmosphere-Ionosphere System
500 km
0 km
Lower Atmosphere Ionosphere-Thermosphere (IT)
Atmosphere-Space Interaction Region
aurorally-generated waves
tidal penetration
secondary waves
wave dissipation & mean flow acceleration
wave-wave interactions
E
B
equatorial anomaly
plasma flow
plasma bubbles
GW seeding
composition changes
tidal
dynamo
tidal dissipation
Mesopause
Turbulence and mixing
Planetary Wave-Tide Modulation
GWs
PWs
Tides
O_3
H_2O
Tides
GW
Pole
Equator

Atmosphere-Ionosphere Coupling by Tides and Planetary Waves



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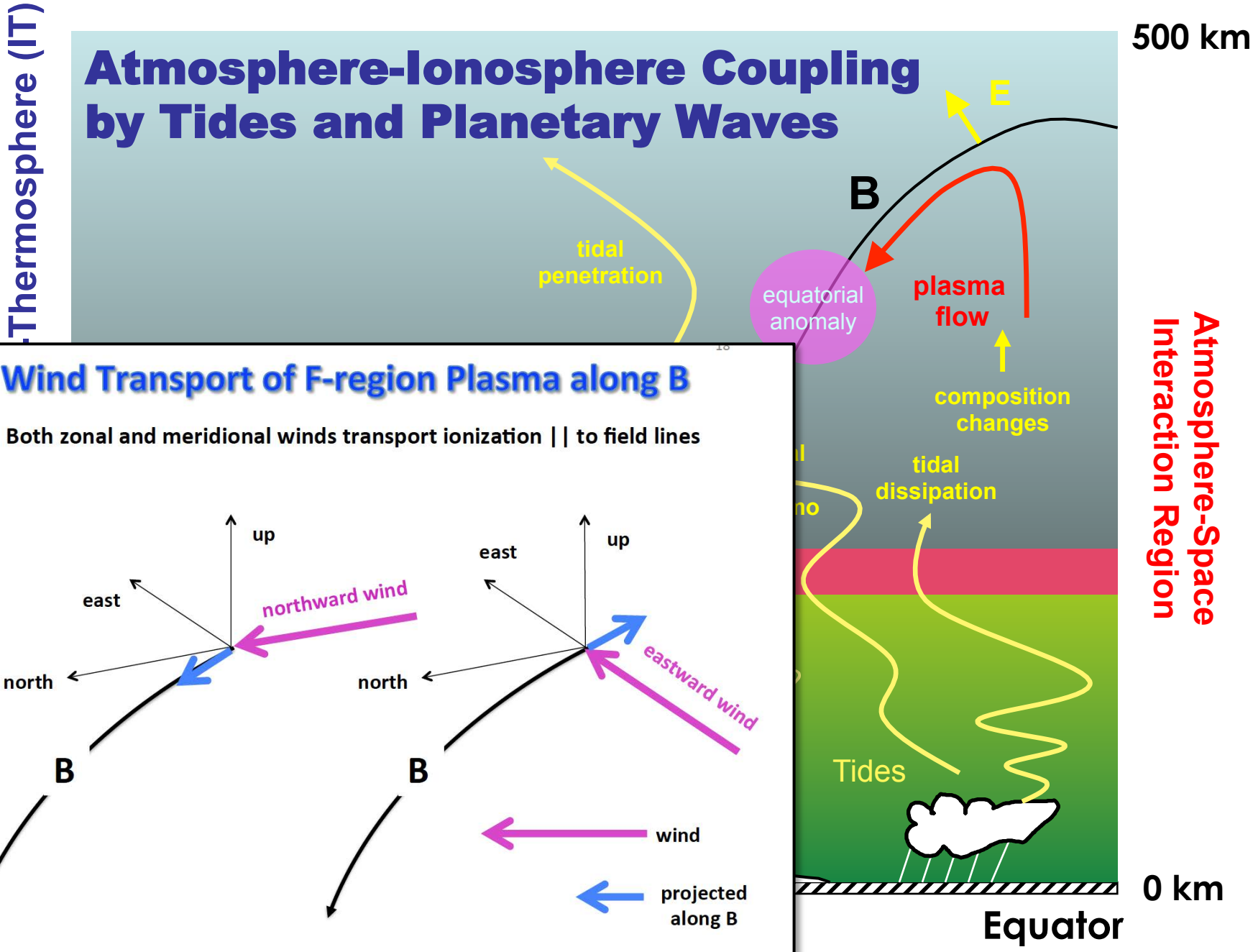


Wind Transport of F-region Plasma along B

Both zonal and meridional winds transport ionization || to field lines

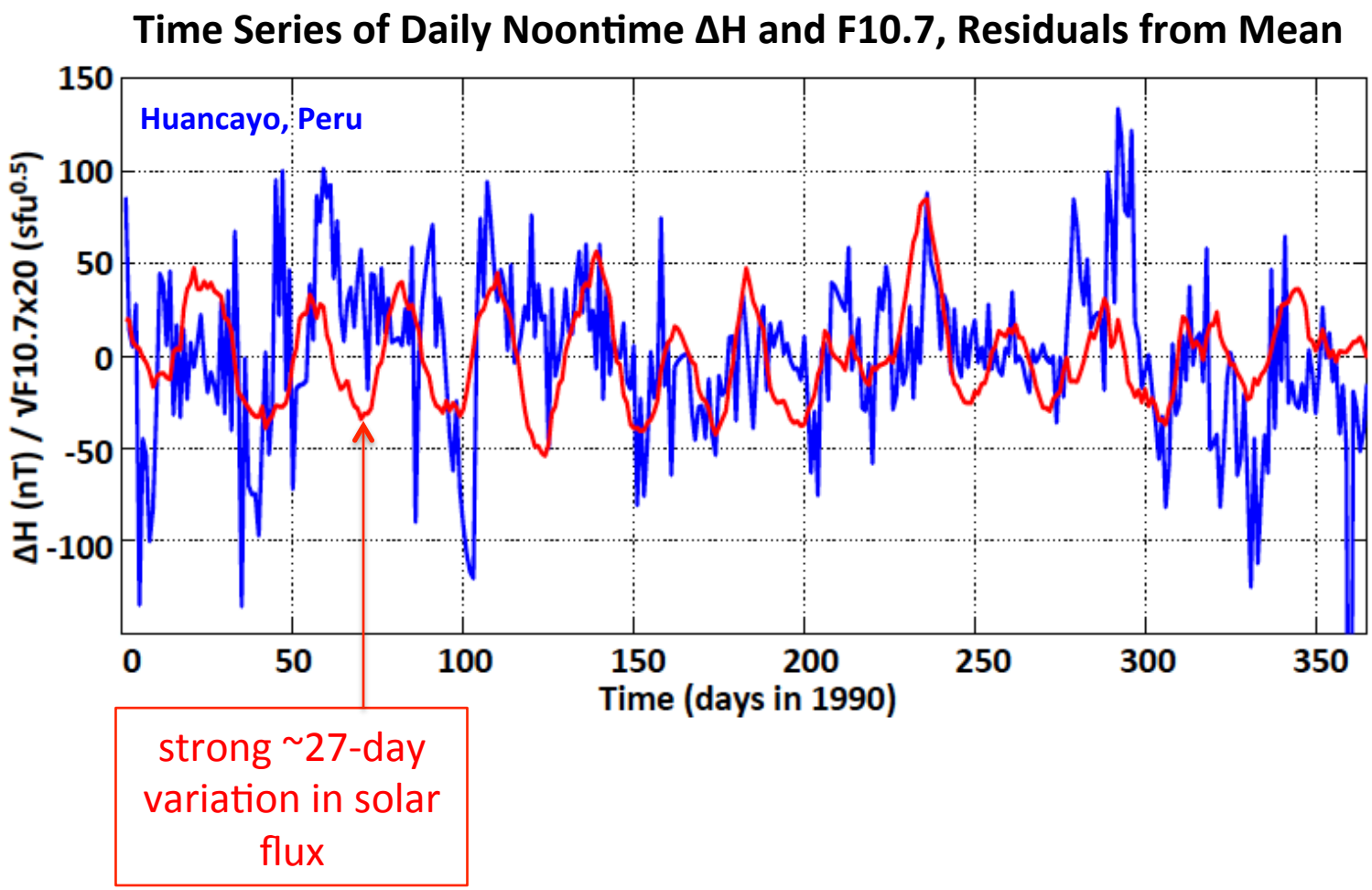
CEDAR Strategic Vision

"Complexity" used 45 times
"Complex" used 66 times

Complexity Associated with Atmosphere-Ionosphere Coupling by Tides and Planetary Waves (PW)

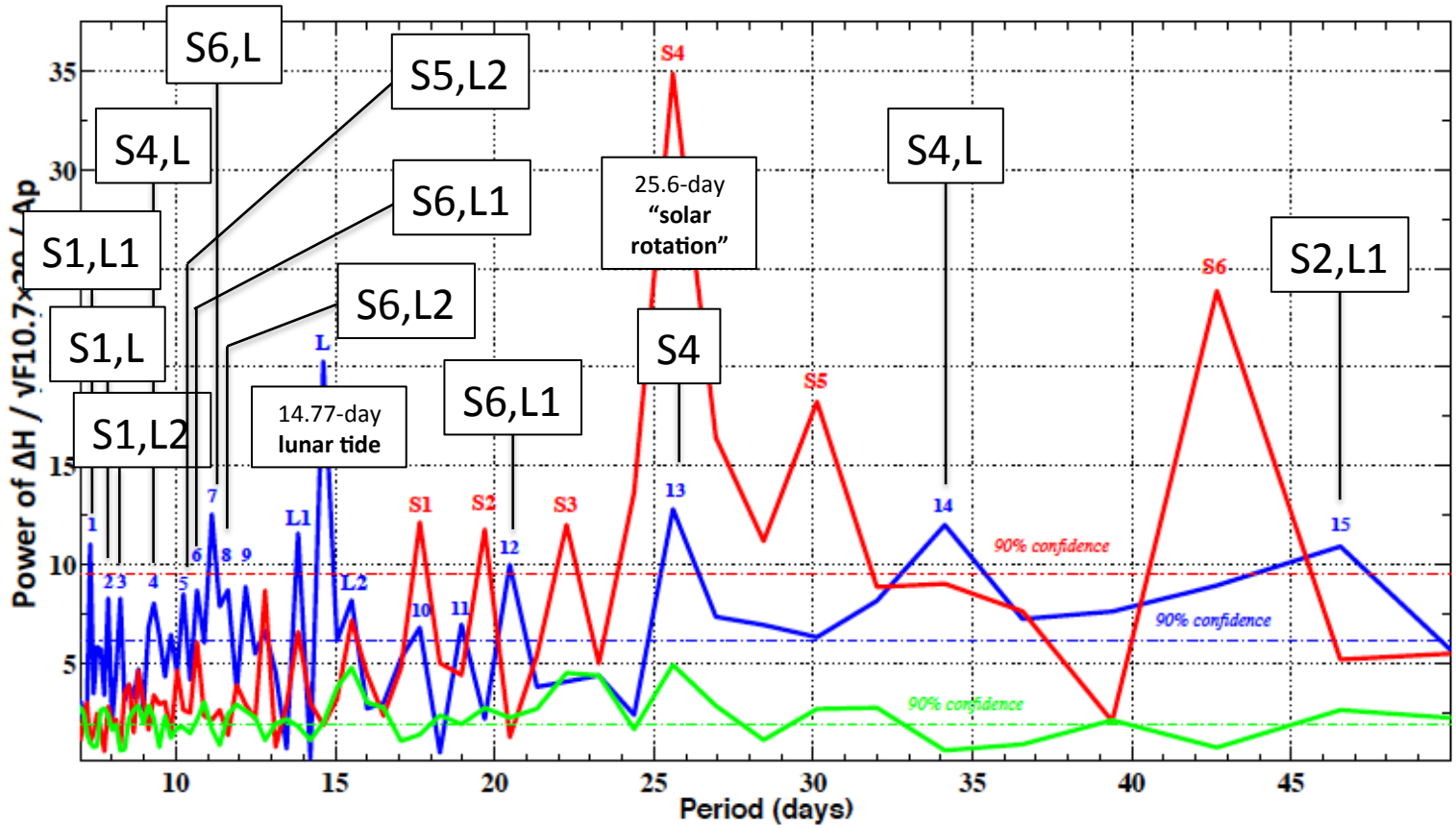
- Temporal variability of the tide-PW spectrum (days, weeks, seasonal, inter-annual)
- Longitude variability of the tide-PW spectrum
- Wave-wave interactions within the tide-PW spectrum
- Solar modulation of ionospheric conductivity in the dynamo region
- Global magnetic field configuration (longitude-latitude variations in inclination, declination; displacement from geographic coordinate system)

Example of complexity:
Lunar-solar interactions in the equatorial electrojet (EEJ)*



Gasperini, F., and J. M. Forbes (2014), Lunar-solar interactions in the equatorial electrojet, Geophys. Res. Lett., 41, doi:10.1002/2014GL059294.

Spectra of ΔH, F10.7, Ap - 1990



Cowling conductivity

Electrostatic E-W electric field due to global dynamo action by lunar tidal winds

$$\Delta H \propto \int \sigma_C E_L dz$$

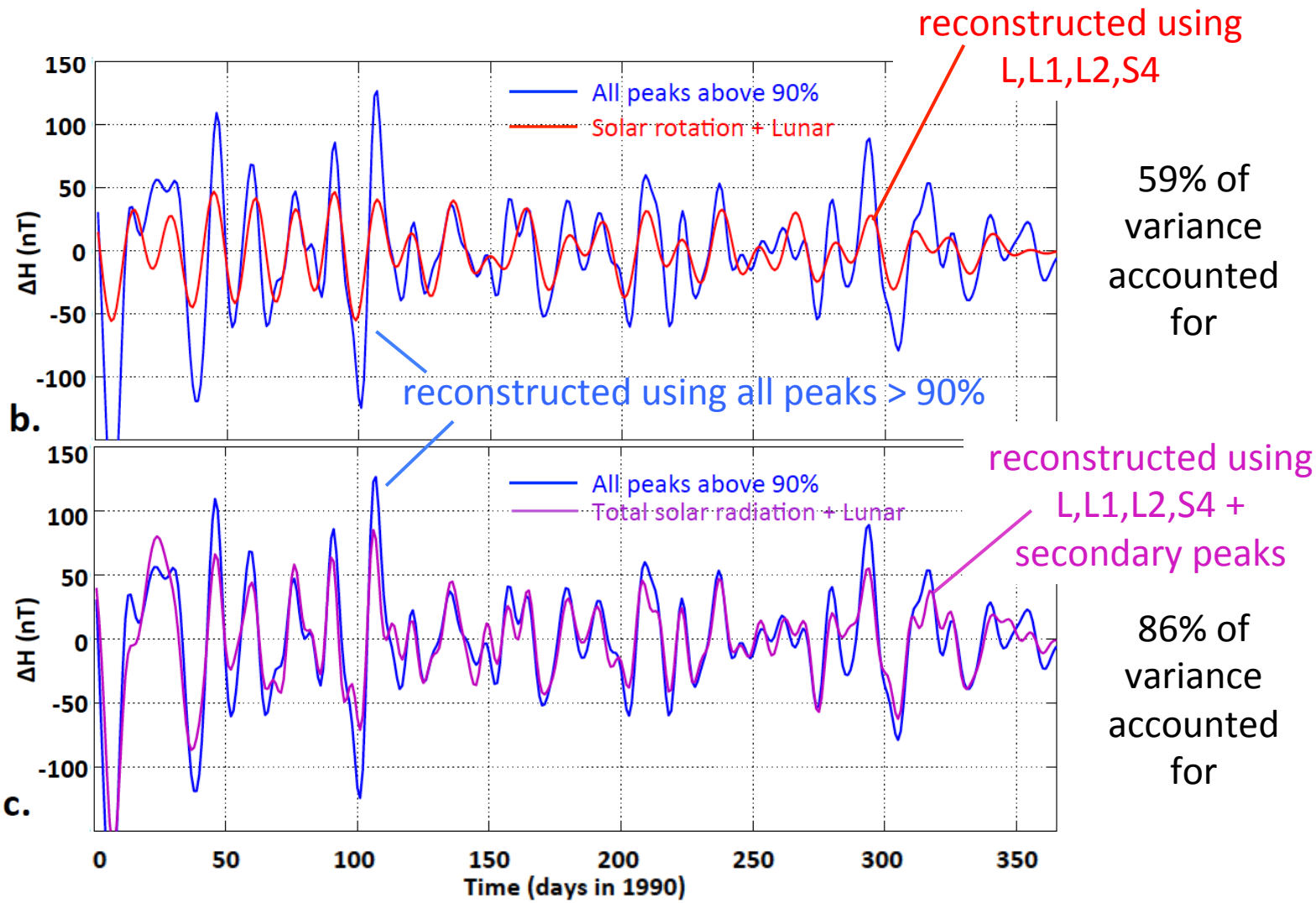
Modulation of E_L by σ_C leads to sum and difference sidebands in the spectrum

$$\cos\omega_s \cos\omega_L \;\rightarrow\; \cos(\omega_s+\omega_L)+\cos(\omega_s-\omega_L) \;=\; \cos\omega^+ + \cos\omega^-$$

$$\omega_s = \frac{1}{25.6d},\; \omega_L = \frac{1}{14.77d} \;\rightarrow\; \omega^+ = \frac{1}{9.3d},\; \omega^- = \frac{1}{34.1d}$$

S4 L

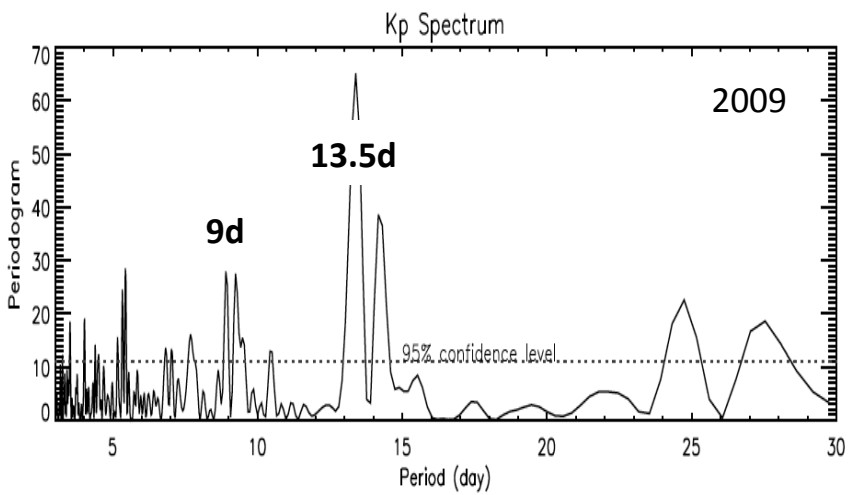
Secondary Peaks Play Important Role in Explaining Variability

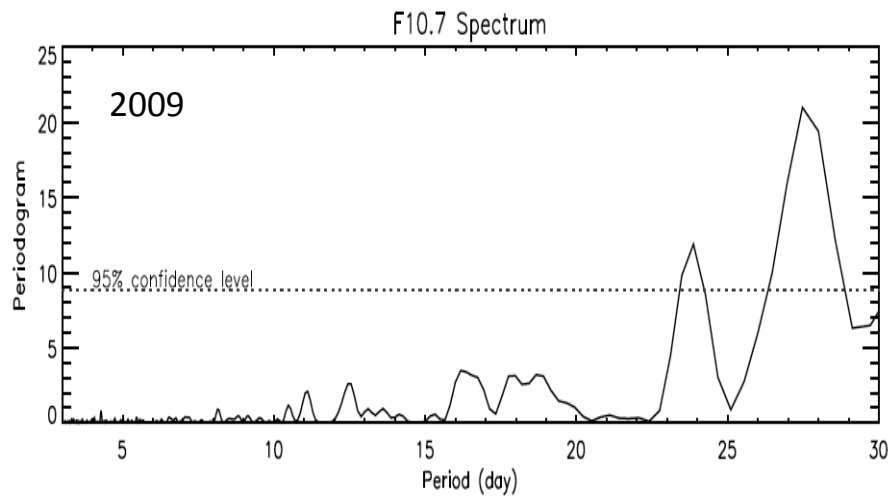


The Sun, Moon and Earth have interacted to produce complexity into the ionosphere !

Now imagine the previous example of complexity:

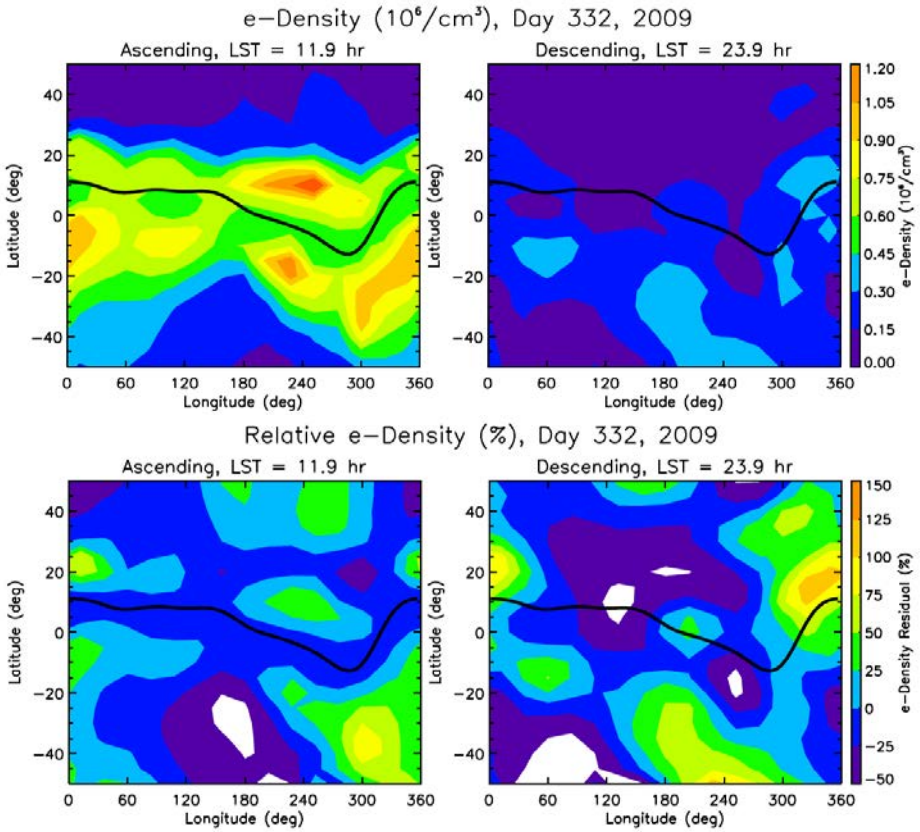
- expanded globally
- including the full spectrum of diurnal and semidiurnal tides and PW
- modulated by the complexity of the magnetic field
- modulated by solar flux influences on the conductivity
- compounded by periodicities associated with recurrent magnetic activity (e.g., 9d, 13.5d)





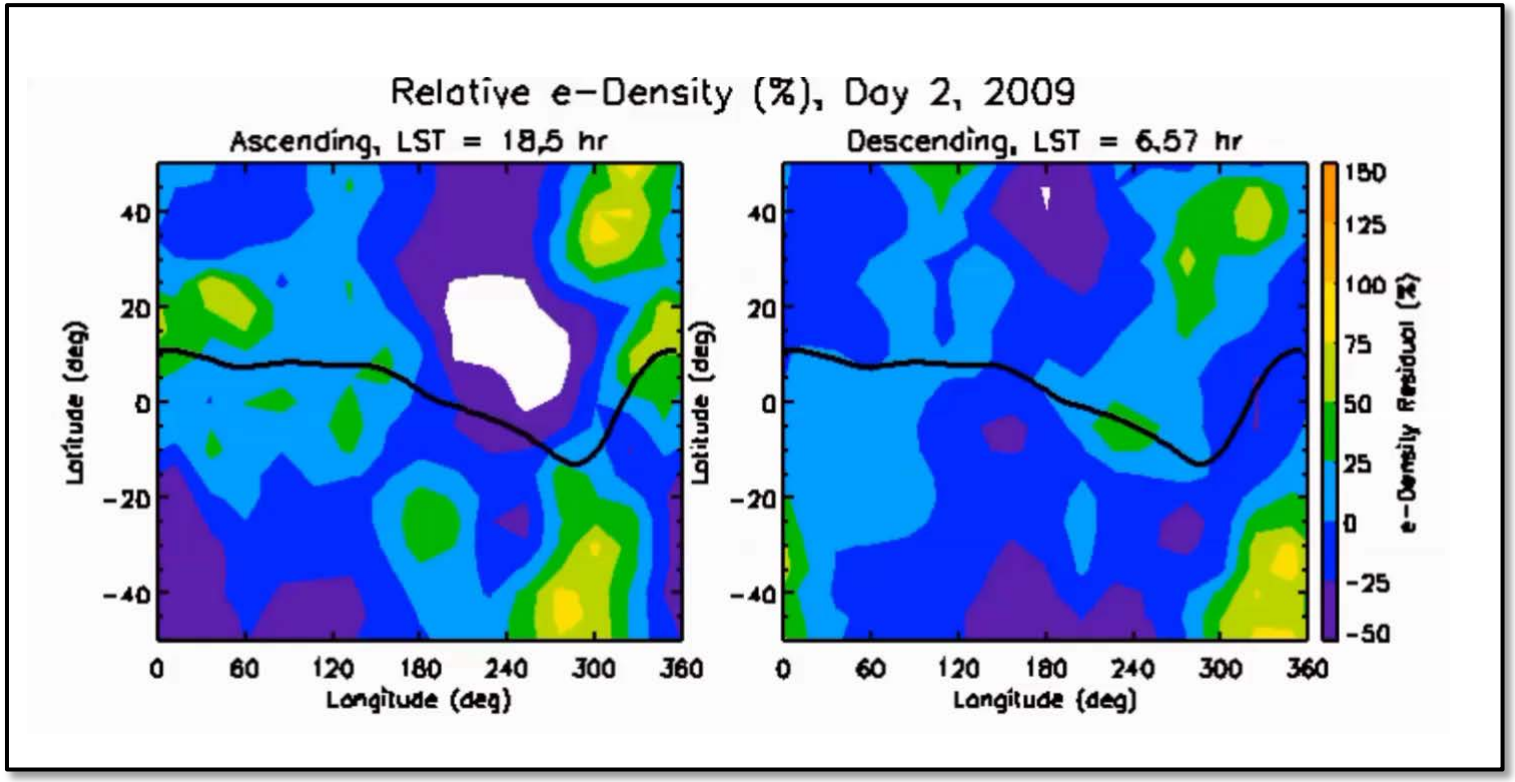
Manifestation of Complexity in CHAMP Electron Densities

- CHAMP launched July 15, 2000 into an almost circular, near polar (i = 87°) orbit with an initial altitude of 454 km
- Carried accelerometers which measured neutral densities and cross-track winds, and a Langmuir probe that measured electron densities.



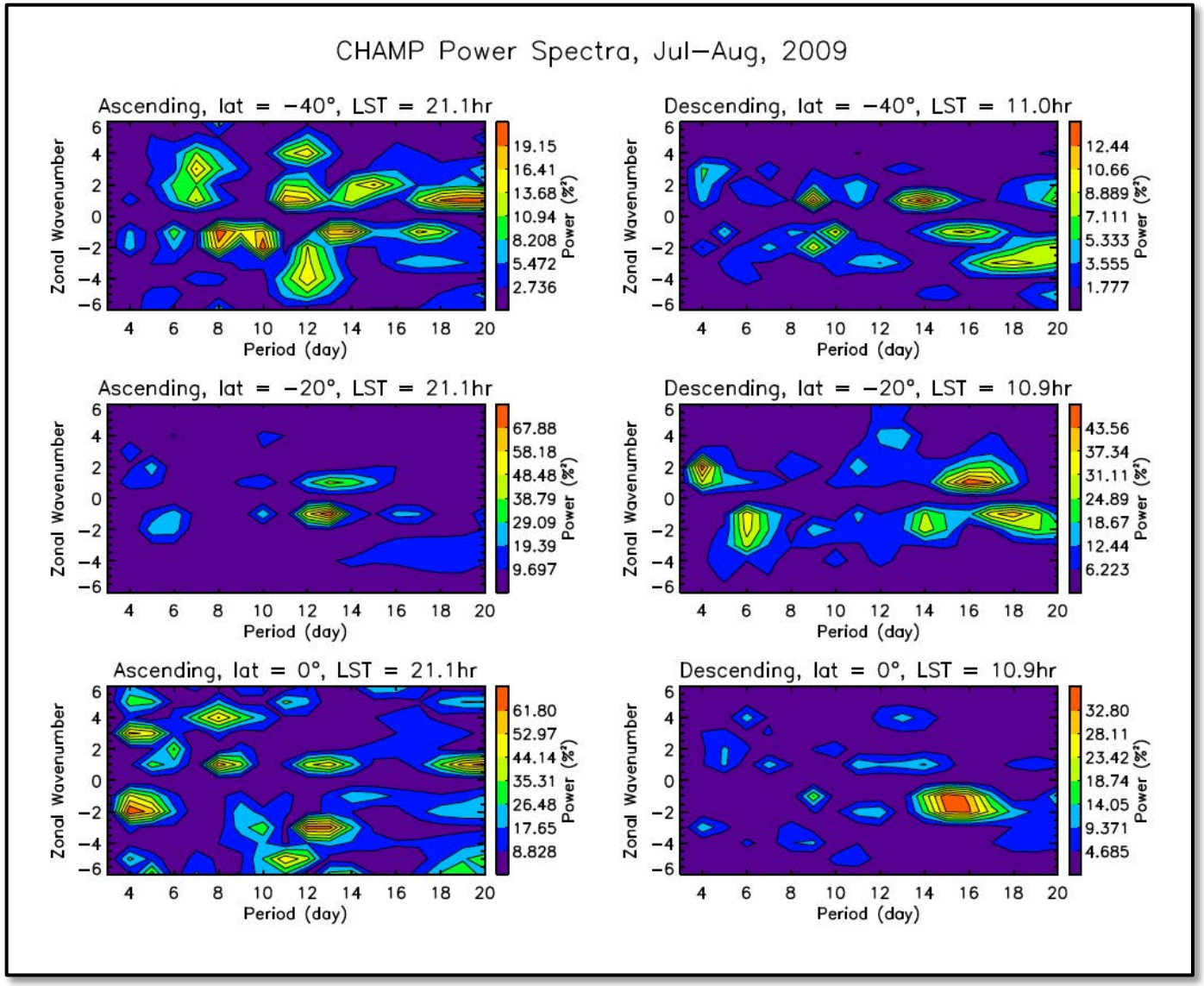
- Daily electron densities during 2009
- 300-350 km
- Geographic coordinates
- Slowly precessing in local time (ascending part of orbit, 24 h LST in 130 days)

Day-to-Day Variability of CHAMP Electron Density Residuals – Ionospheric "Weather" during 2009



Quantifying the Variability: Periodicities in Time and Longitude

- distinct peaks
- eastward- and westward-propagating waves
- significant differences in latitude and local time



Observational Strategies

- Without measuring several local times simultaneously, we cannot extract the tides on a day by day basis, and moreover cannot determine to what degree the PW periodicities in the data arise from PW modulation of the tides vs. the PW themselves.
- Need to sample multiple local times and longitudes each day, at a given latitude.

3 satellites, polar orbits

- 24° longitude resolution - zonal wavenumbers ±7
- continuous latitude coverage
- 6 local times: mean, diurnal, semidiurnal

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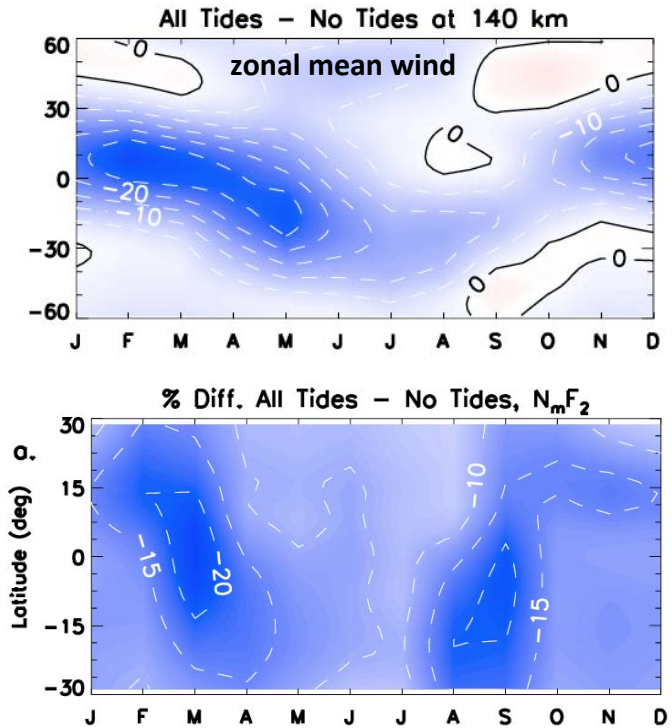
30 ground-based sites

- 60° longitude resolution - zonal wavenumbers ±2; OK for PW except Q2DW, not tides
- 30° latitude resolution
- continuous local time coverage
- need ~7 (longitude) x 10 (latitude) = 84 sites, ±60°

Another Example of Complexity: Effects of Dissipating Tides on the Mean Thermal, Dynamical, and Compositional State of the IT System*

- Force lower boundary of TIE-GCM with monthly-mean tidal spectra based on TIMED measurements.
- Examine differences between "all tides" and "no tides" lower boundary forcing (CTMT) on diurnal- and zonal-mean winds, temperatures, neutral and plasma densities.
- Differences mainly due to DW1, SW2, DE3.
- Dissipating tides give rise to net fluxes of momentum, heat, and constituents:

$$\overline{u'v'},\ \overline{w'u'},\ \overline{w'T'},\ \overline{w'[O]'},\ \text{etc.}$$



Jones, M., Jr., J.M. Forbes, M. E. Hagan, and A. Maute (2014), Impacts of vertically propagating tides on the mean state of the ionosphere-thermosphere system, J. Geophys. Res. Space Physics, 119, 2197–2213, doi: 10.1002/2013JA019744.

Jones, M., Jr., J.M. Forbes, M. E. Hagan (2014), Tidal-induced net transport effects on the oxygen distribution in the thermosphere, Geophys. Res. Lett., in press. Also, see poster

Net Tidal Transport and Advective Transport

Continuity equation for atomic oxygen:

$$\frac{\partial[O]}{\partial t} = P - L - \frac{\partial w[O]}{\partial z} + \ldots$$

assume:

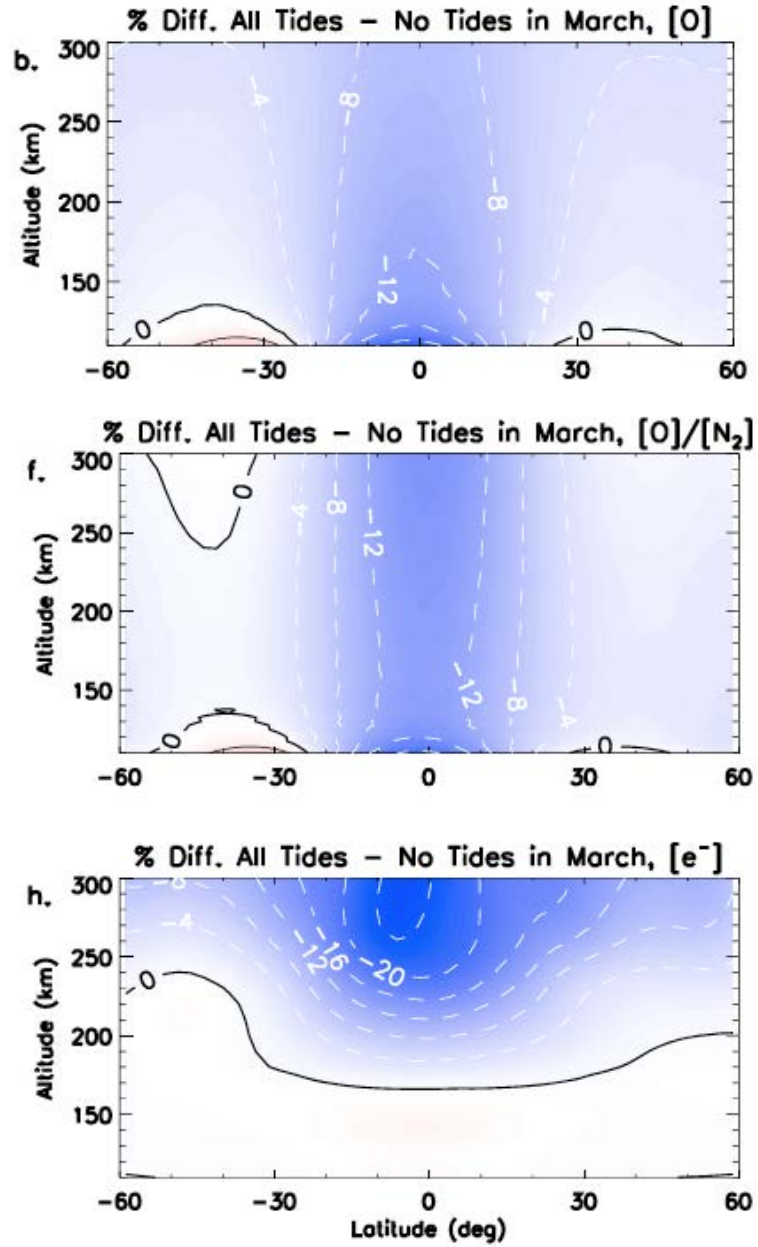
$$w = \overline{w} + \mathrm{w}', \quad [\mathrm{O}] = \overline{[O]} + [\mathrm{O}]'$$

Insert above in continuity equation, expand, and integrate over time and longitude:

$$\frac{\partial\overline{[O]}}{\partial t} = -\frac{\partial\overline{w}\,\overline{[O]}}{\partial z} - \frac{\partial\overline{w'[O]'}}{\partial z} + \ldots\ldots$$

$\overline{w}\,\overline{[O]}$ = net advection of O due to mean circulation produced by dissipating tides [Yamazaki and Richmond, 2014]

$\overline{w'[O]'}$ = net flux of O due to dissipating tides, w' and [O]' out of quadrature



Outstanding Issues, Questions and Challenges

- To what extent do PW penetrate above 100 km? Are they assisted by GW filtering, i.e., PW modulation of GW momentum deposition? Or do the PW modulate the tides, which then carry the PW periodicities into the IT?

- A significant part of the daytime dynamo originates from winds between 130-200 km [Maute et al., 2012]; how does the wave spectrum there differ from that below 130 km?

- How do the PW and GW parts of the wave spectrum affect the zonal mean state of the IT?

- How do we measure the GW, PW and tidal spectra to understand the fundamental wave-wave and wave-mean state interactions?

- How do we measure the system in a way that enables use to understand how wave variability drives ionospheric variability?