Dynamics of the Thermosphere

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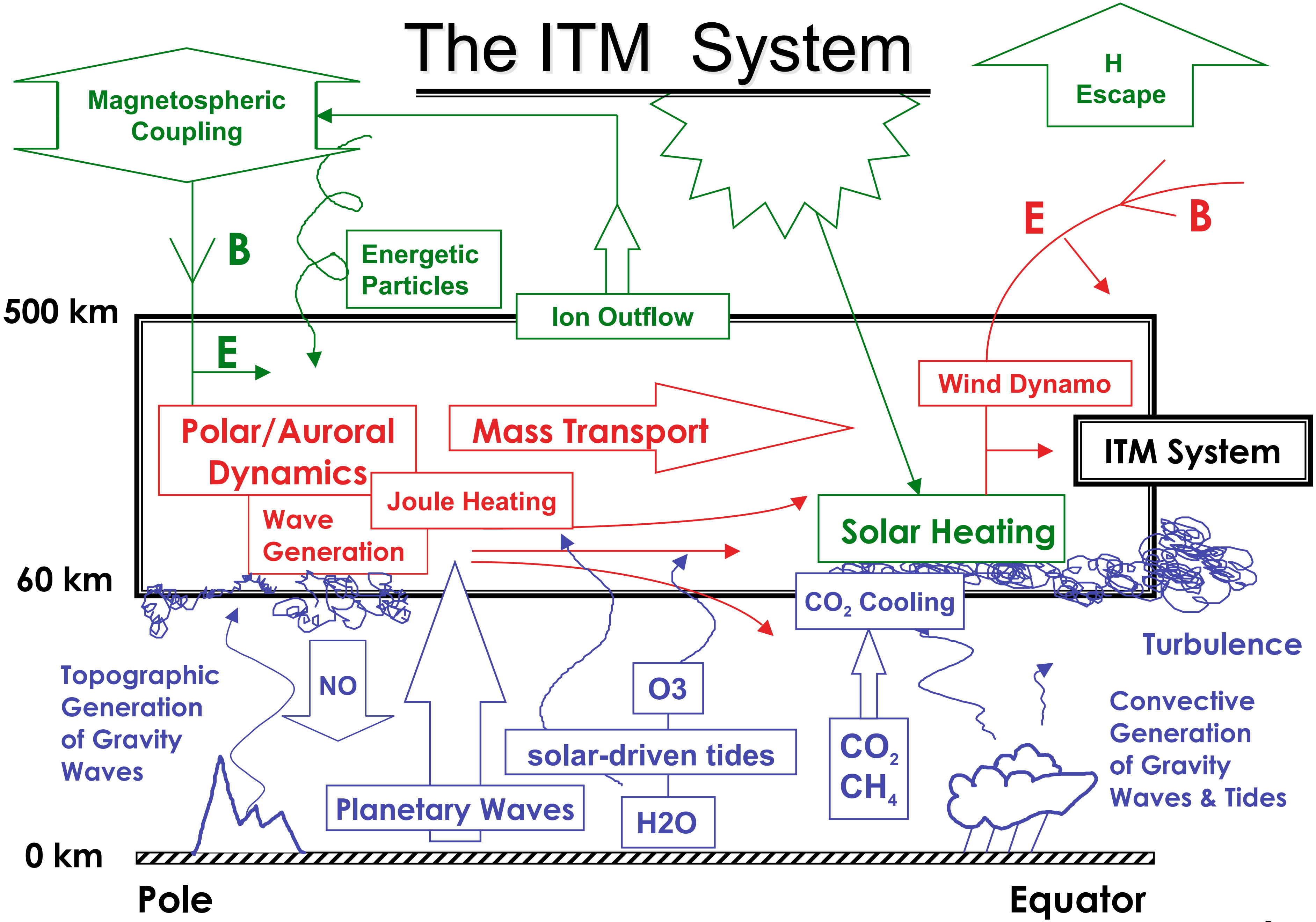
http://spot.colorado.edu/~forbes/Home.html

http://sisko.Colorado.EDU/FORBES/asen5335/
ASEN5335 Aerospace Environment:
Space Weather of Solar-Planetary Interactions and Effects on Systems

Lecture Topics

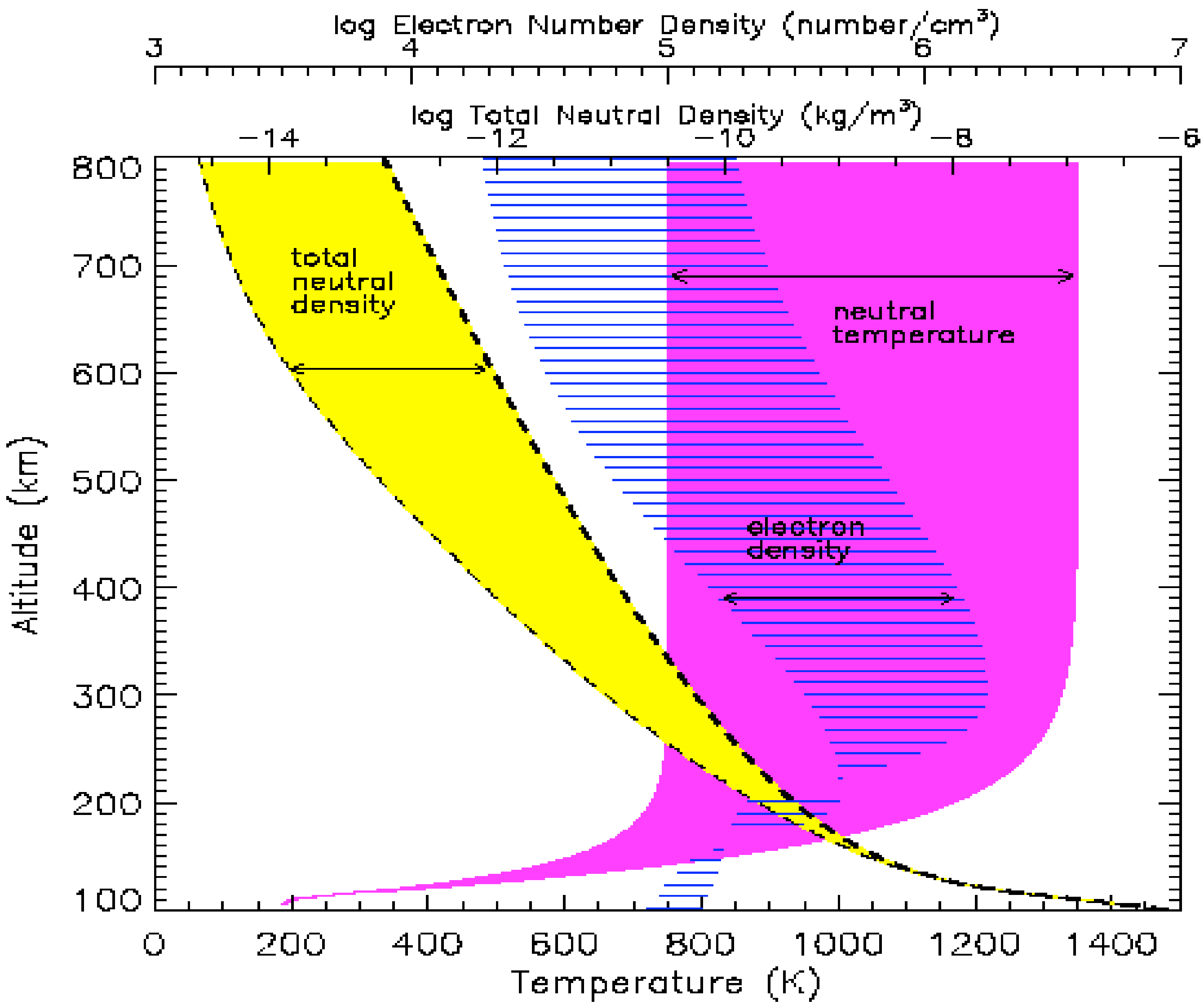
- The Ionosphere-Thermosphere-Mesosphere (ITM) System
- Thermosphere Temperature and Composition
- Momentum Balance
- Winds and Composition: Seasonal Variations
- Thermosphere Weather: Magnetic Storm Response
- Thermosphere Weather: Coupling with the Lower Atmosphere

The ITM System



Thermosphere
Temperature & Composition

Temperature and Density Distributions and Ranges
Diurnal and Solar Cycle



Atmospheric Composition

$$H_i = \frac{kT}{m_i g}$$

$$n \sim n_{io} e^{-h/H_i}$$

$$\overline{m} = \frac{\sum m_i n_i}{\sum n_i}$$

$$= 28.97 \text{ g mole}^{-1}$$

$$\overline{H} = \frac{kT}{\overline{m} g}$$

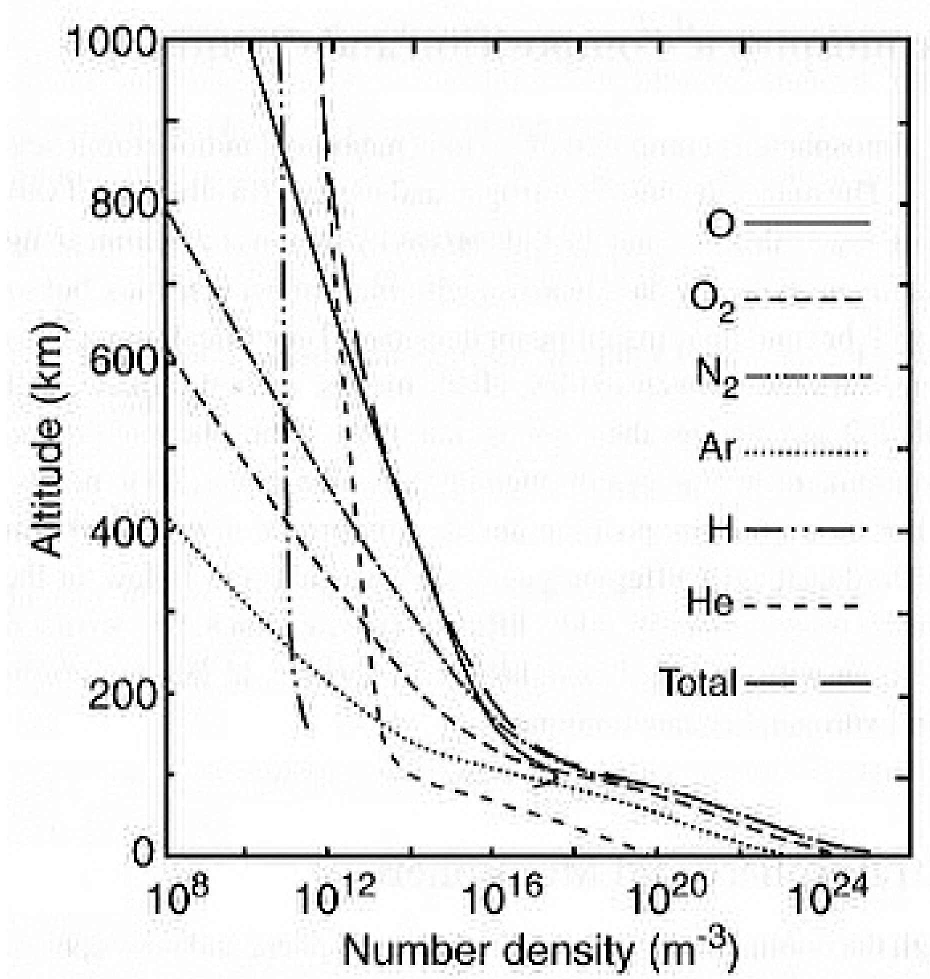


Figure 8.4 Atmospheric density and composition profile. (From *Richmond*.[4])

Momentum Balance

Governing Equations

These equations are written in terms of total density & pressure; in practice, must actually consider multi-component equations, and self-consistent coupling between neutral species, and coupling with ionospheric and electrodynamic equations

Substantial or convective derivative

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + \vec{U} \cdot \nabla$$

pressure gradient

Coriolis

molecular viscosity (diffusion of momentum)

ion drag

Continuity Equation

$$\frac{D\rho}{Dt} + \rho \nabla \cdot \vec{U} = 0 \ \text{ or } \ \frac{\partial \rho}{\partial t} + \nabla \cdot \rho \vec{U} = 0$$

Hydrostatic Law

$$\frac{dp}{dz} = -\rho g$$

Thermodynamic Equation

$$c_p \frac{DT}{Dt} - \frac{1}{\rho}\frac{Dp}{Dt} = J$$

Equation of State

$$p = \rho R T$$

Closed System for the Unknowns

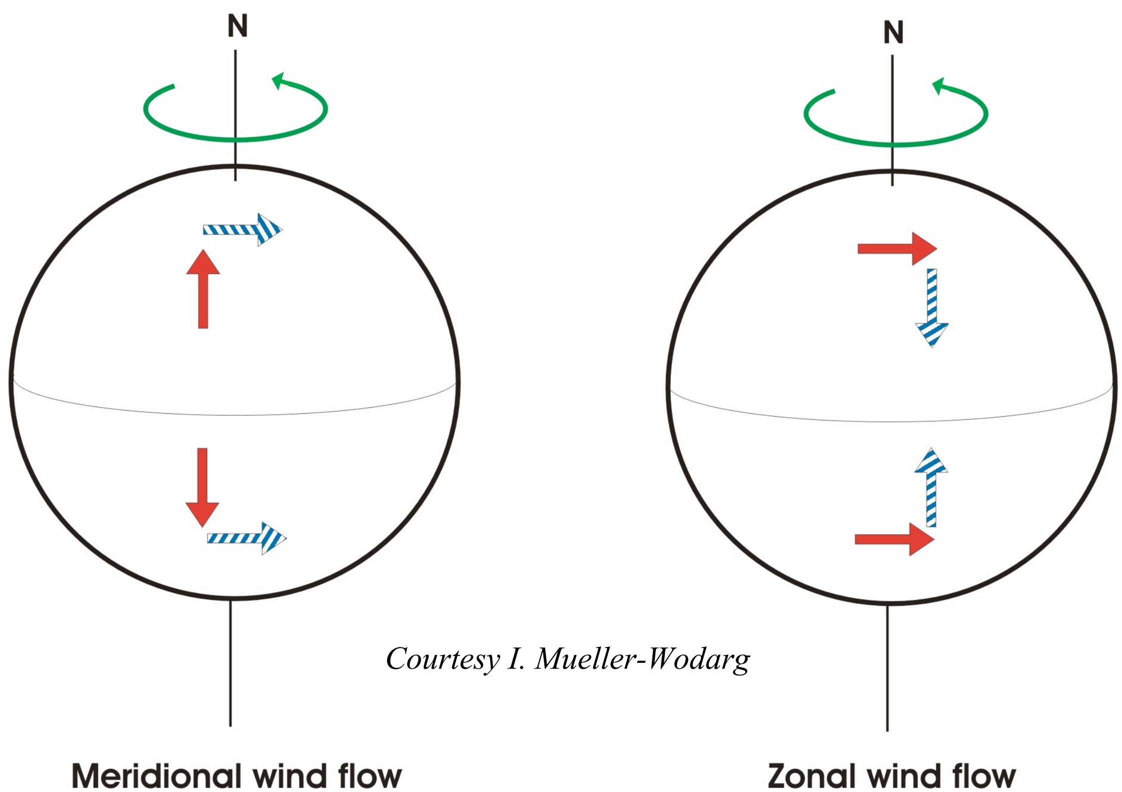
$$u, v, w, p, T, \rho$$

Horizontal Momentum Equation

$$\frac{D\vec{U}_H}{Dt} = -\frac{1}{\rho}\vec{\nabla}_H p - 2\vec{\Omega} \times \vec{U}_H + \frac{1}{\rho}\vec{\nabla}\left(\mu \vec{\nabla} \vec{U}_H\right) - \nu_{ni}\left(\vec{U}_H - \vec{V}_i\right)$$

$$\frac{D\vec{U}_H}{Dt} = -\frac{1}{\rho}\vec{\nabla}_H p - 2\vec{\Omega}\times\vec{U}_H + \frac{1}{\rho}\vec{\nabla}\left(\mu\vec{\nabla}\vec{U}_H\right) - \nu_{ni}\left(\vec{U}_H - \vec{V}_i\right)$$

Coriolis force acts ***perpendicular*** to the ***wind vector***. It deflects poleward winds towards the east and eastward winds equatorward. So, winds are driven clockwise (anticlockwise) in the northern (southern) hemisphere around pressure maxima.



Near steady-state flow below about 150 km is usually involves approximate balance between the pressure gradient and Coriolis forces, leading to the ***geostrophic approximation***, where the flow is ***parallel to the isobars*** (clockwise flow around a ***High*** in the Northern Hemisphere)

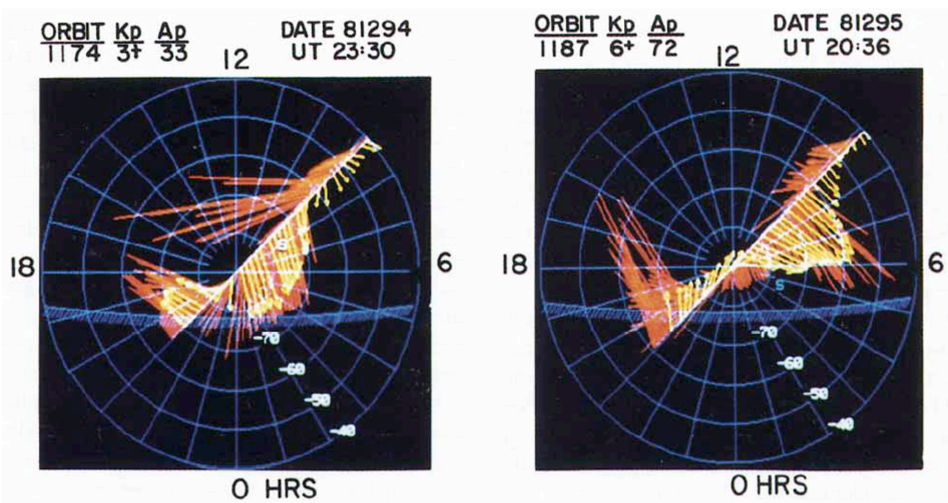
$$\frac{D\vec{U}_H}{Dt} = -\frac{1}{\rho}\vec{\nabla}_H p - 2\vec{\Omega}\times\vec{U}_H + \frac{1}{\rho}\vec{\nabla}\left(\mu\vec{\nabla}\vec{U}_H\right) - \nu_{ni}\left(\vec{U}_H - \vec{V}_i\right)$$

$$\approx \frac{1}{\rho}\frac{\partial}{\partial z}\mu\frac{\partial \vec{U}_H}{\partial z}$$

The absence of any momentum sources at high levels implies

$$\frac{\partial \vec{U}_H}{\partial z} \to 0 \quad \text{as} \quad z \to \infty$$

In the absence of any ion drifts *(V_i = 0)*, the presence of ions that are bound to magnetic field lines act to decelerate the neutral wind, due to neutral-ion collisions.



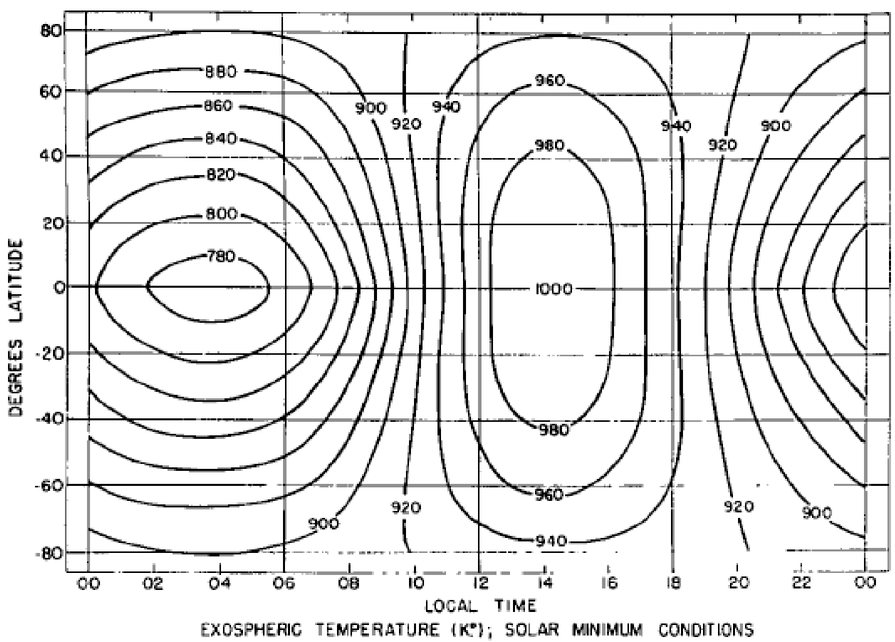
Dynamics Explorer (DE)-2 neutral wind (yellow) and plasma drift (orange) measurements in the polar thermosphere (Killeen)

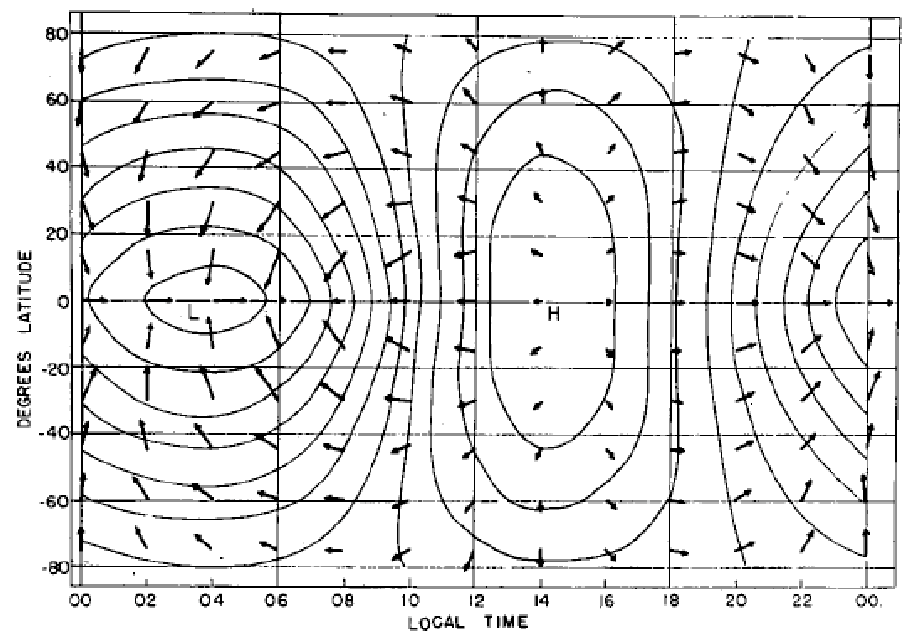
If the ion-neutral collision frequency is sufficiently large, and if the ion drift is sufficiently large and acts over a sufficient length of time, then the neutral gas circulation will begin to mirror that of the plasma.

$$\frac{D\vec{U}_H}{Dt} = -\frac{1}{\rho}\vec{\nabla}_H p - 2\vec{\Omega}\times\vec{U}_H + \frac{1}{\rho}\vec{\nabla}\left(\mu\vec{\nabla}\vec{U}_H\right) - \nu_{ni}\left(\vec{U}_H - \vec{V}_i\right)$$

In the upper thermosphere, balance between pressure gradient, ion drag, and viscous diffusion tends to prevail, such that the flow is ***across the isobars***.

September 1968 R. E. Dickinson and J. E. Geisler 607

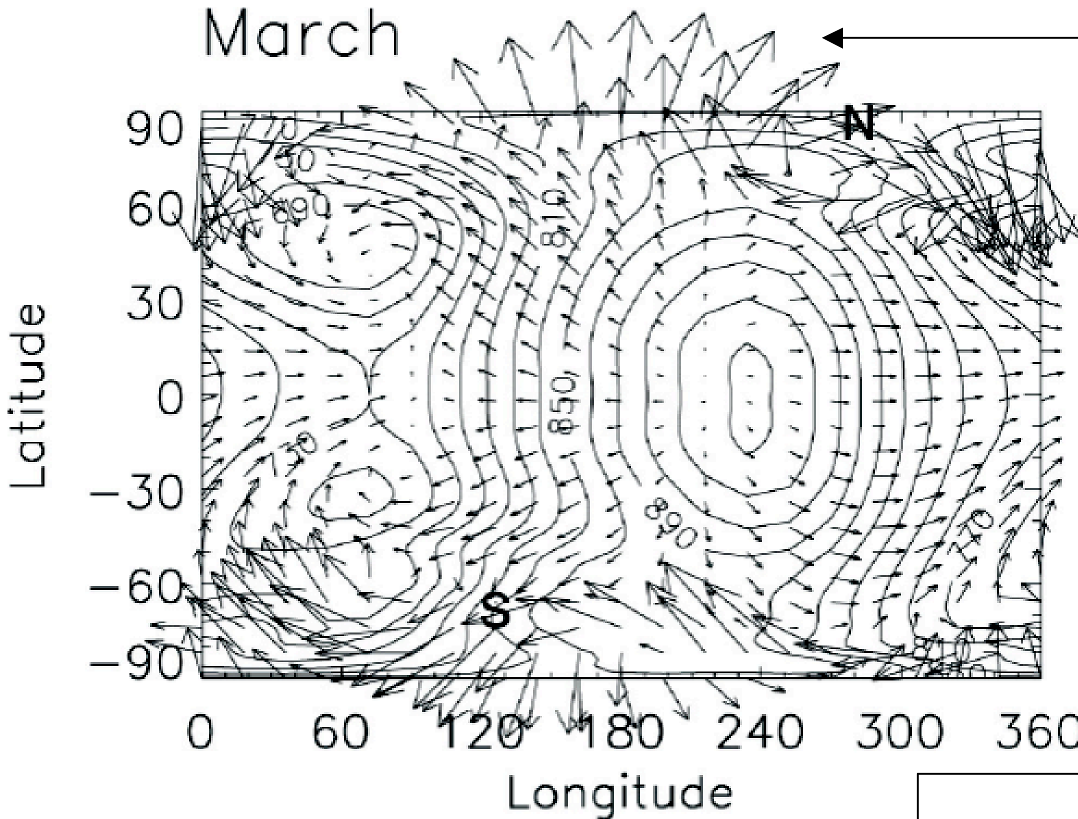




Exospheric Temperatures from Jacchia 1965 model, used with model densities to derive pressures and pressure gradients

Wind vectors calculated from momentum equation with Jacchia 1965 pressure gradient forcing. Isobars are shown by solid lines

The gross features of this early work are consistent with those embodied in the more recent CTIP modeling (Rishbeth et al., 2000)



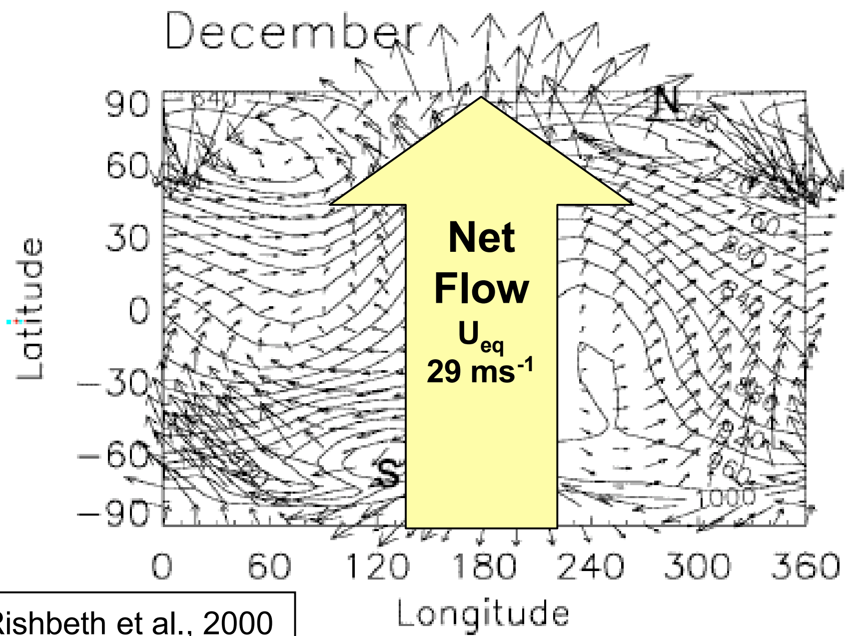
"quiet convection" (Kp = 2)

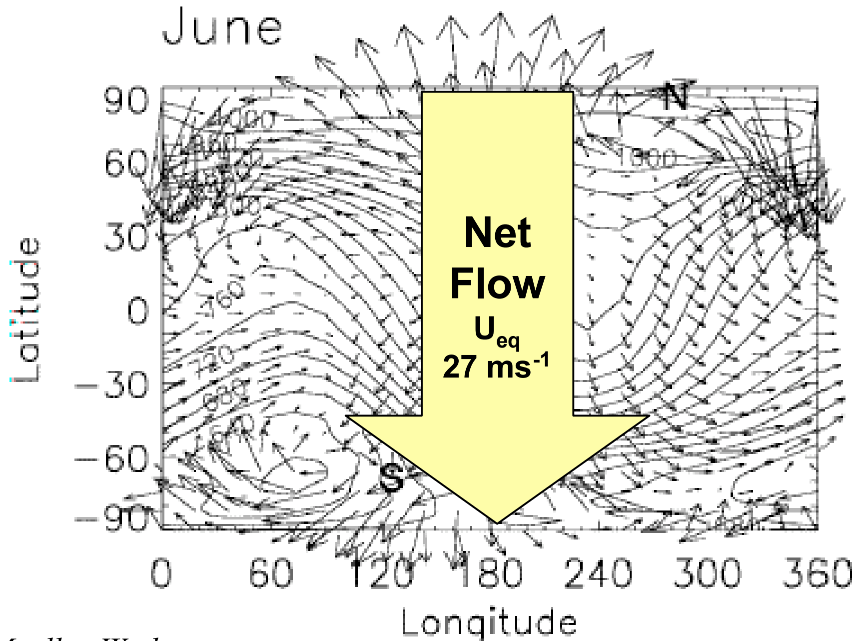
Shift from noon maximum due to "secondary heat source" associated with vertical motions

Exospheric temperatures peak near **15:30 h** local time.

Day-night temperature differences at low latitudes reach around **200 K**.

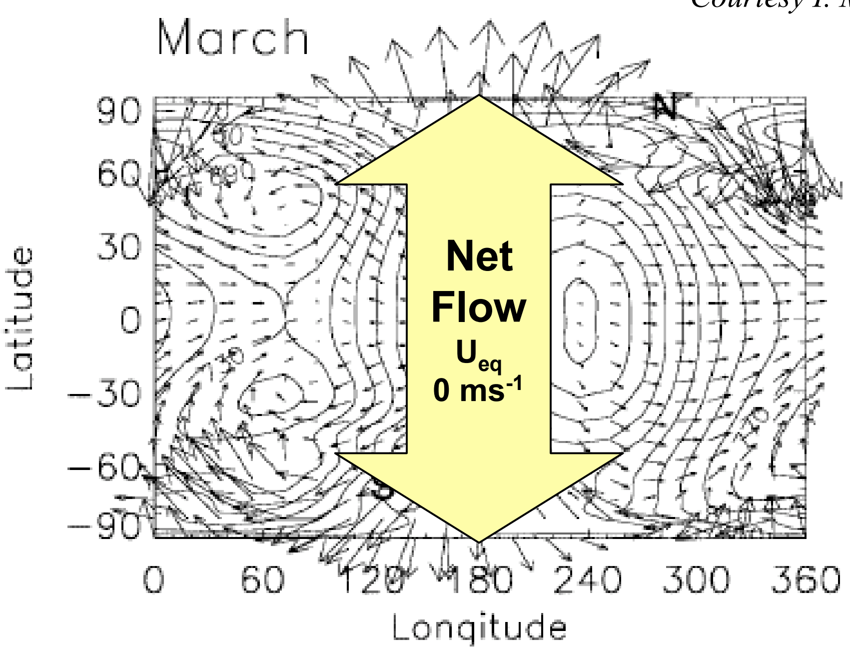
Predominantly EUV-Driven Circulation





Rishbeth et al., 2000

Courtesy I. Mueller-Wodarg



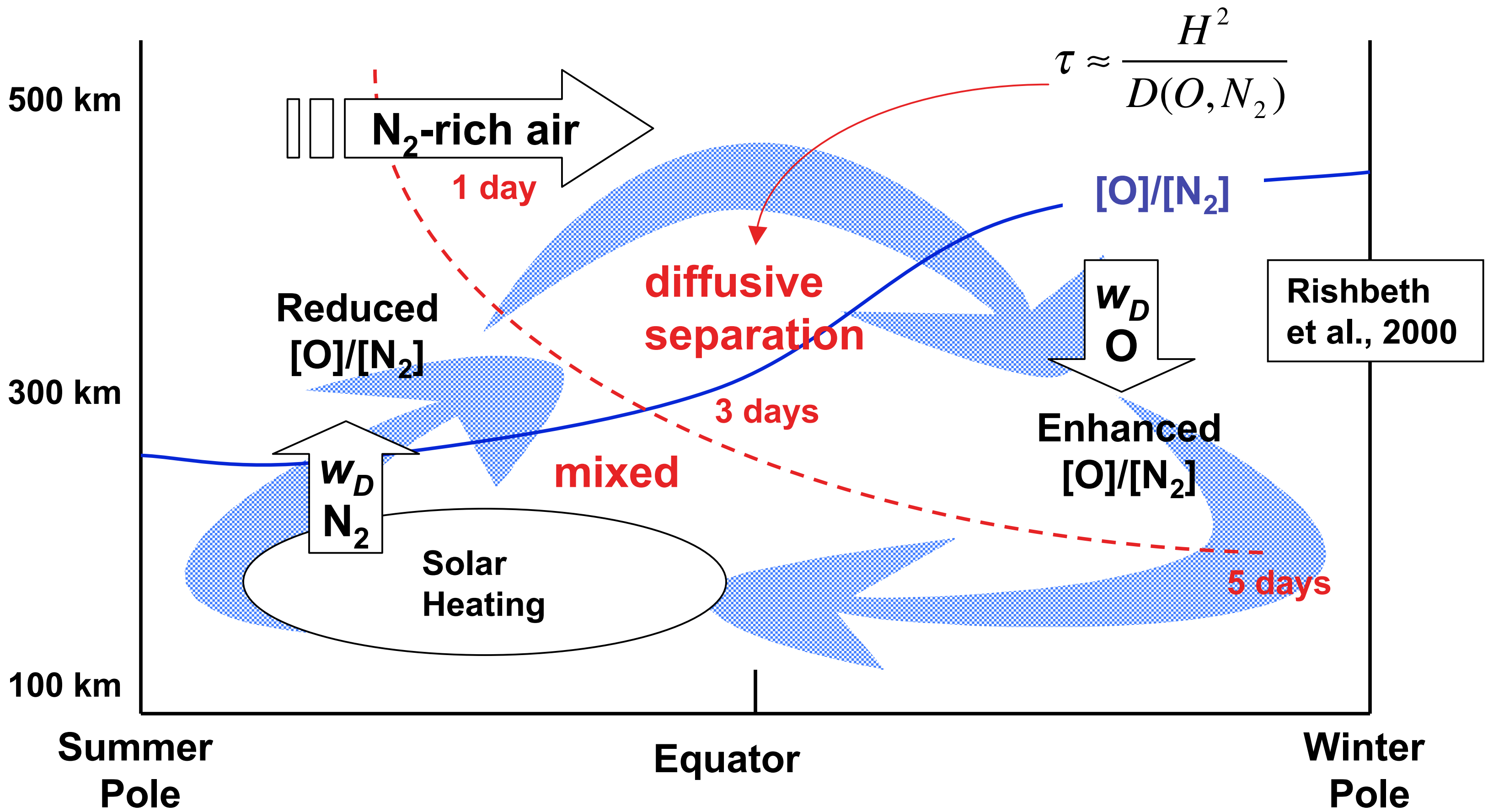
Winds flow essentially from the summer to the winter hemisphere.

At equinox winds are quasi-symmetric, from the equator towards the poles.

Polar winds are strongly controlled by ion drag

Winds and Composition: Seasonal Variations

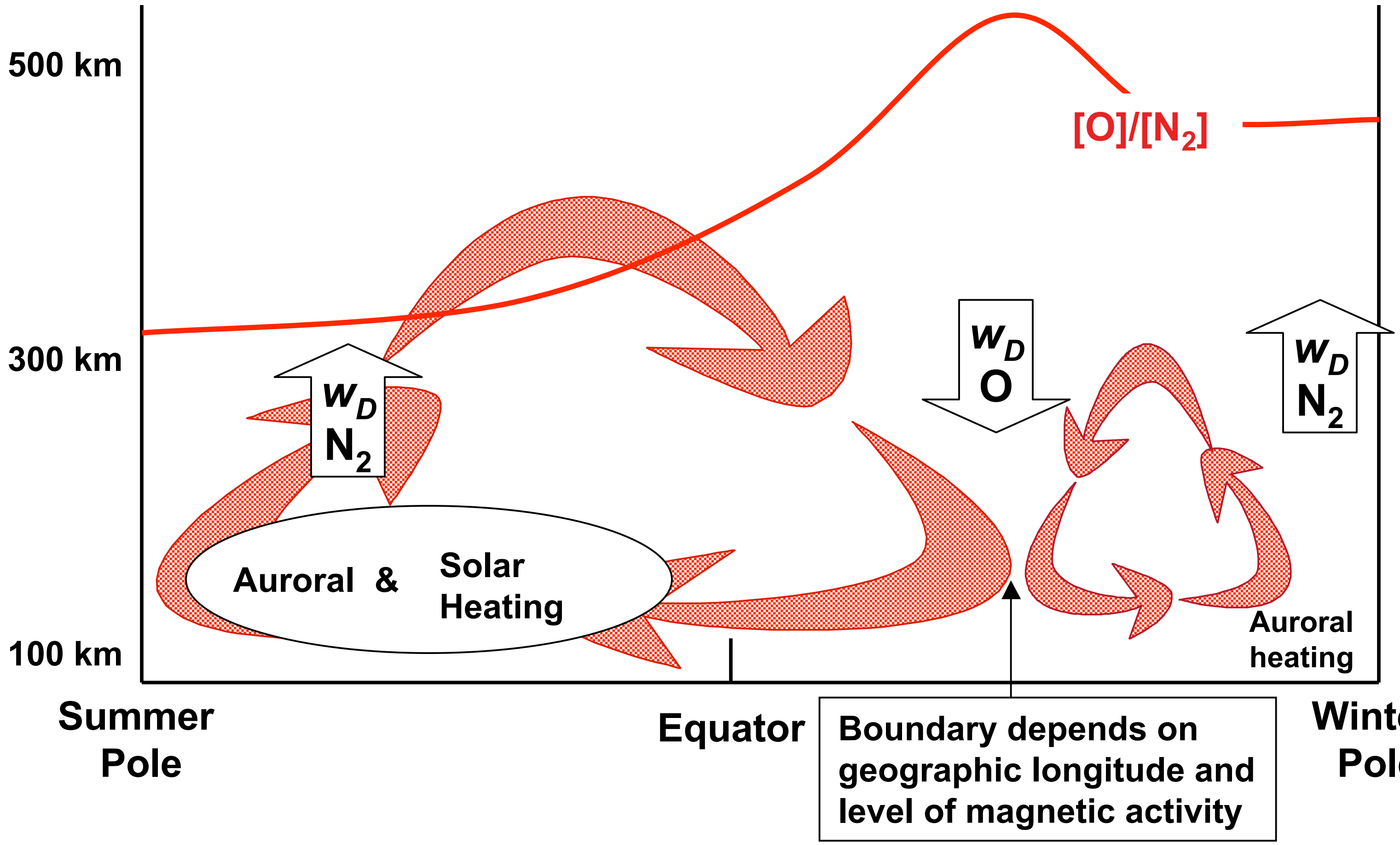
Solar EUV-Driven (Magnetically-Quiet) Circulation and O-N_2 Composition



Upwelling occurs in the summer hemisphere, which upsets diffusive equilibrium.

Molecular-rich gases are transported by horizontal winds towards the winter hemisphere, where diffusive balance is progressively restored, from top (where diffusion is faster) to bottom

Solar EUV & Aurorally-Driven Circulation and O-N_2 Composition



A secondary circulation cell exists in the winter hemisphere due to upwelling driven by aurora heating. The related O/N_2 variations play an important role in determining annual/semiannual variations of the thermosphere & ionosphere.

Ionospheric Effects

- *The O/N_2 ratio influences the plasma density of the F-region; hence regions of enhanced O/N_2 tend to have higher plasma densities, and vice-versa*
- *Therefore, seasonal-latitudinal and longitudinal variations in O/N_2 ratio also tend to be reflected in F-layer plasma densities.*

Semiannual Variation in Thermosphere Density

- *The "mixing" of the thermosphere near solstice has been likened to the effects of a large thermospheric "spoon" by Fuller-Rowell (1998)*
- *Around solstice, mixing of the atomic and molecular species leads to an increase in the mean mass, and hence a reduction in pressure scale height.*
- *This "compression" of the atmosphere leads to a reduction in the mass density at a given height at solstice.*
- *During the equinoxes, the circulation (and mixing) is weaker, leading to a relative increase in mass density.*
- *This mechanism may explain, in part, the observed semi-annual variation in density.*

Thermosphere Weather: Magnetic Storm Response

Solar-Terrestrial Coupling Effects in the Thermosphere: New Perspectives from CHAMP And GRACE Accelerometer Measurements of Winds And Densities

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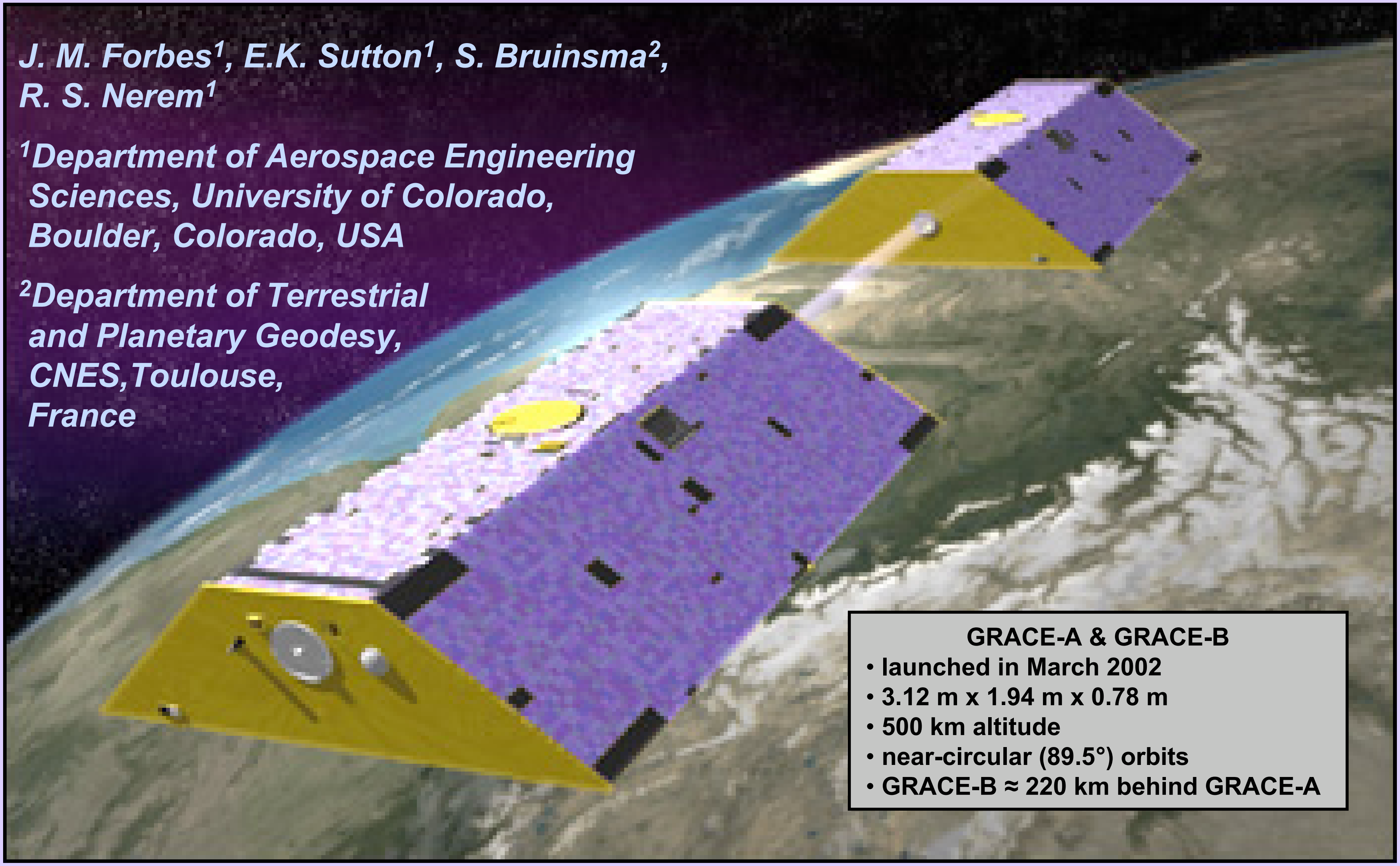
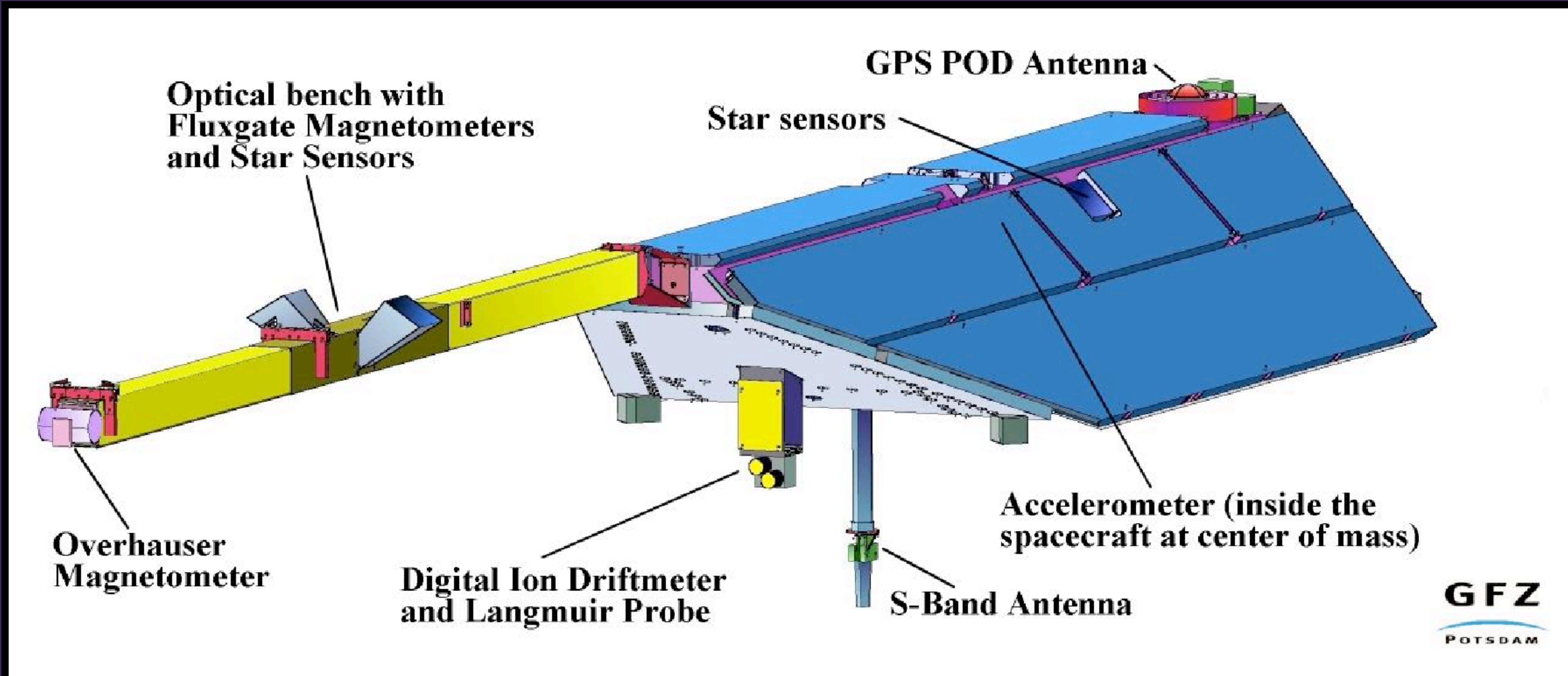
[1]Department of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado, USA

[2]Department of Terrestrial and Planetary Geodesy, CNES,Toulouse, France



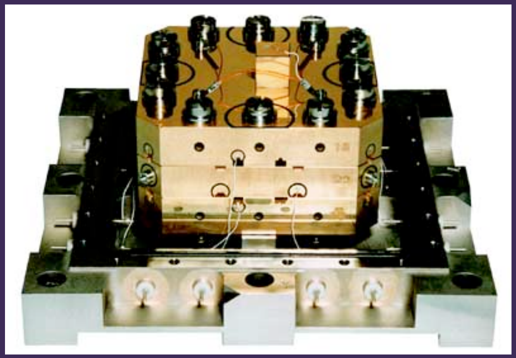
The CHAMP satellite was launched in July 2000 at 450 km altitude in a near-circular orbit with an inclination of 87.3°



The physical parameters of the CHAMP satellite are:

- Total Mass 522 kg
- Length (with 4.044 m Boom) 8.333 m
- Area to Mass Ratio 0.00138 m^2kg^{-1}
- Height 0.750 m
- Width 1.621 m

- ***Non-gravitational forces acting on the CHAMP and GRACE satellites are measured in the in-track, cross-track and radial directions by the STAR accelerometer***



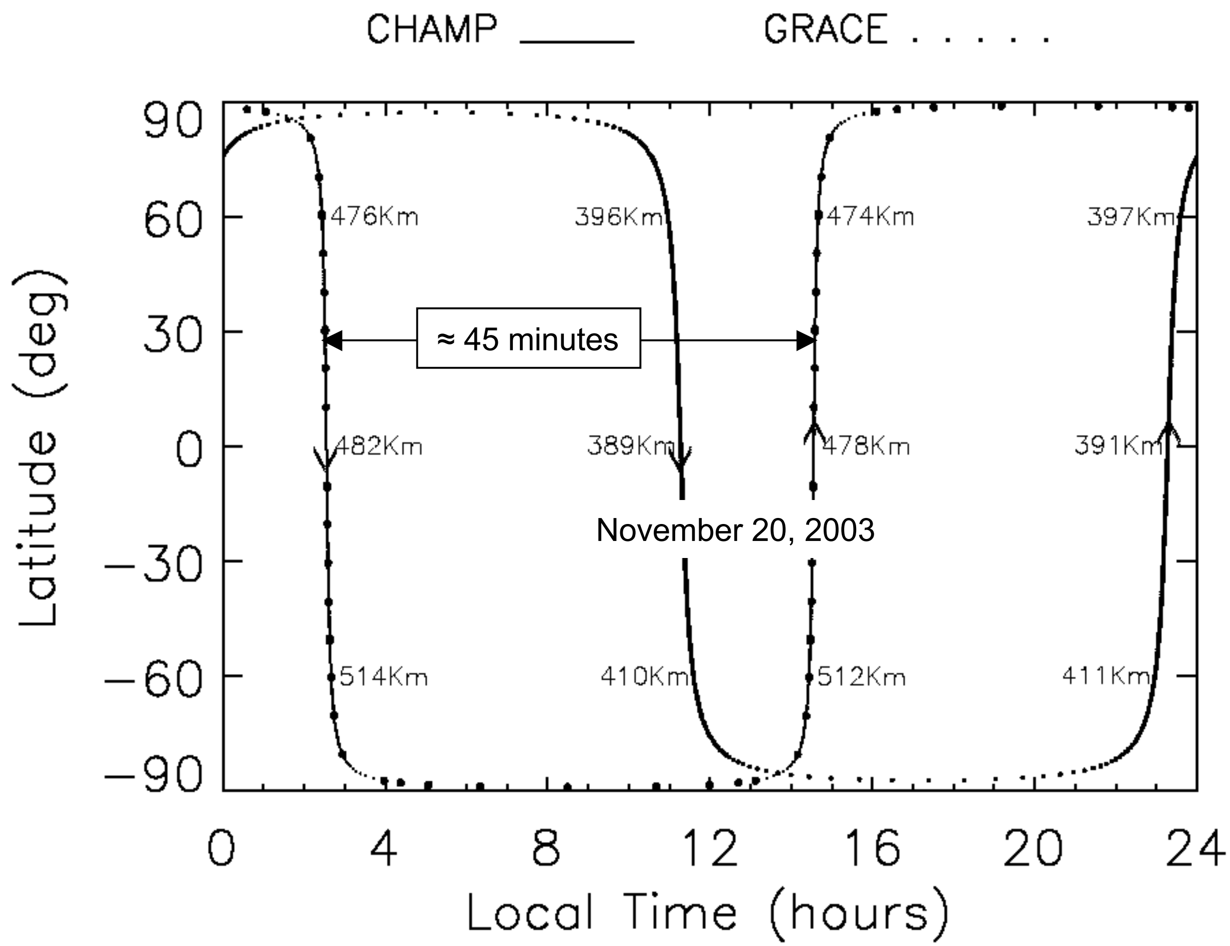
STAR accelerometer by Onera

- ***Separation of accelerations due to mass density (in-track) or winds (cross-track and radial) require accurate knowledge of***

  - ***spacecraft attitude***
  - ***3-dimensional modeling of the spacecraft surface (shape, drag coefficient, reflectivity, etc.)***
  - ***accelerations due to thrusting***
  - ***solar radiation pressure***
  - ***Earth albedo radiation pressure***

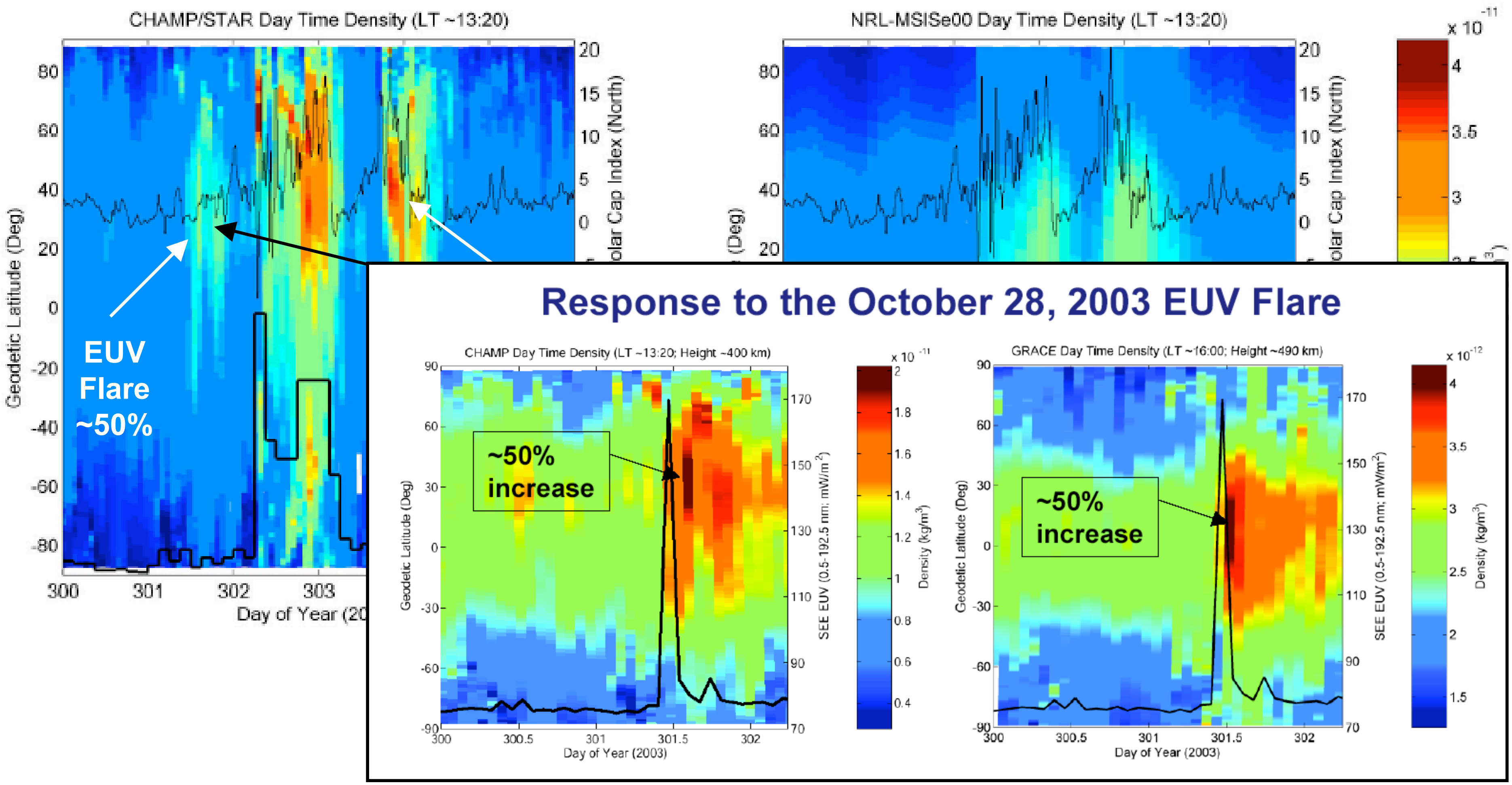
CHAMP and GRACE offer new perspectives on thermosphere density response characterization:

latitude, longitude, temporal and local time sampling

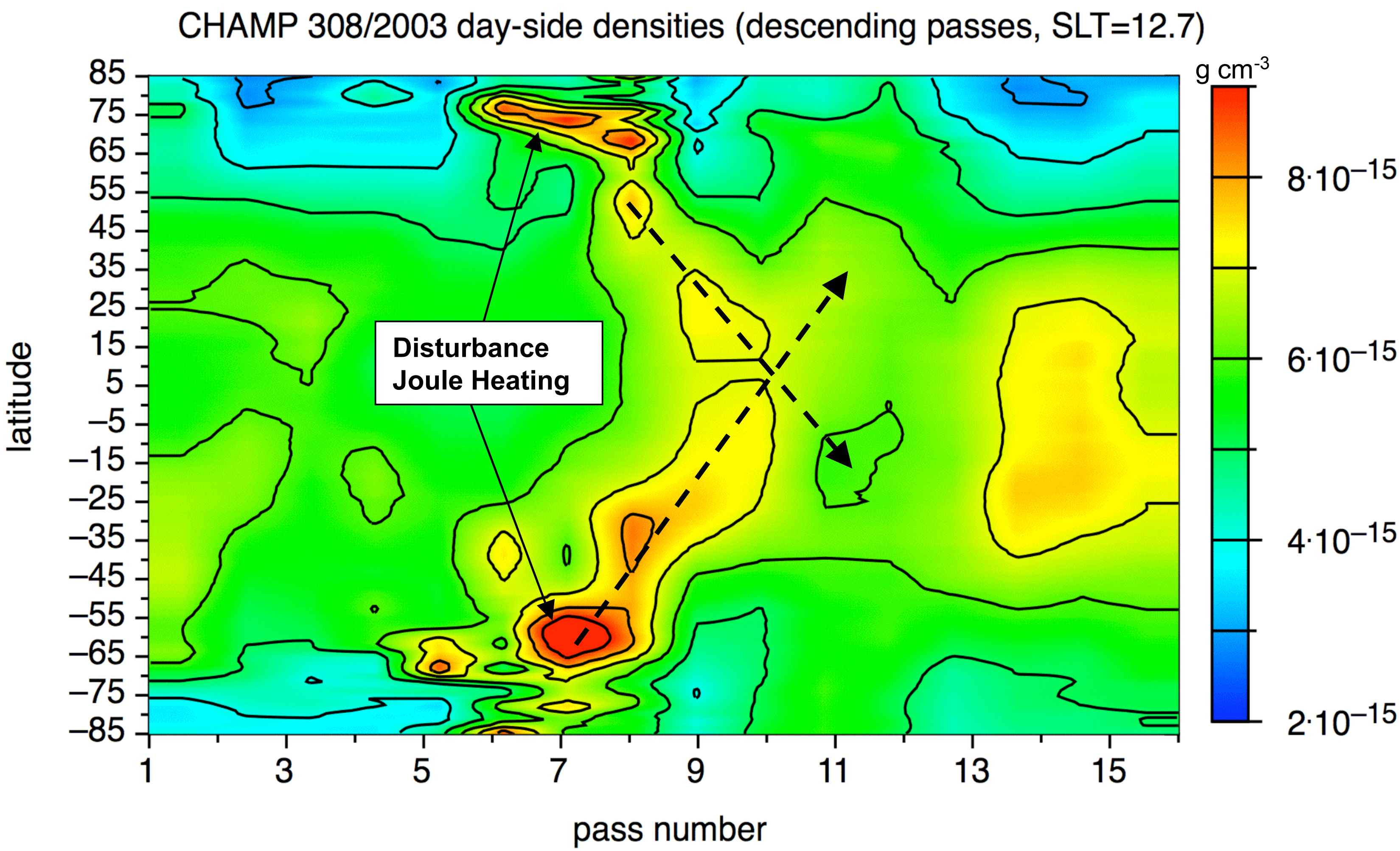


Thermosphere Density Response to the October 29-31 2003 Storms from CHAMP Accelerometer Measurements

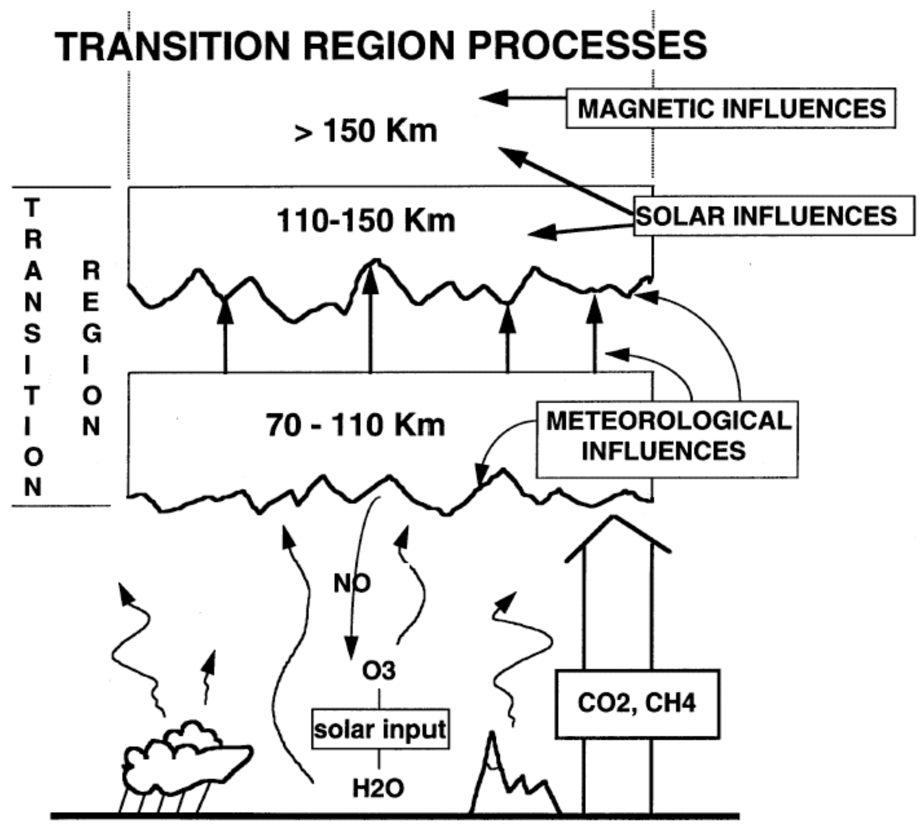
(Sutton et al., JGR, 2005)



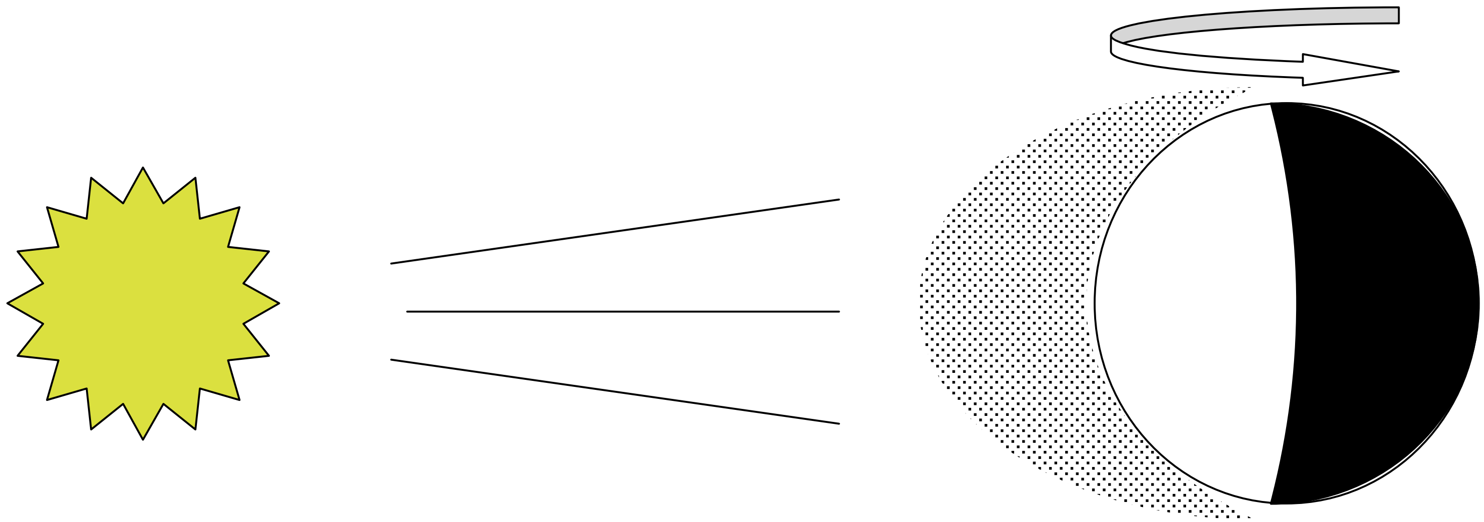
Traveling Atmospheric Disturbances

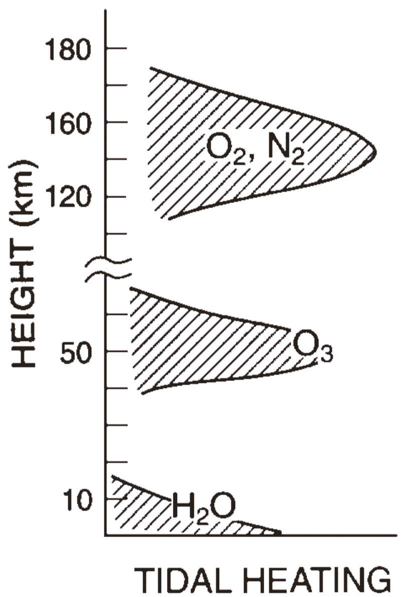


Thermosphere Weather: Coupling with the Lower Atmosphere



Solar Thermal Tides





Solar thermal tides are excited in a planetary atmosphere through the periodic (local time, longitude) absorption of solar radiation.

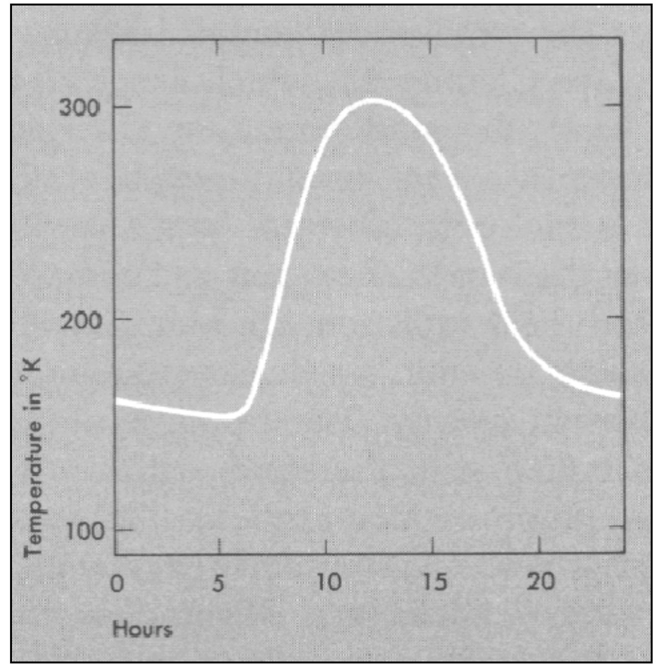
In general, tides are capable of propagating vertically to higher, less dense, regions of the atmosphere; the oscillations grow exponentially with height.

The tides are dissipated by molecular diffusion above 100 km, their exponential growth with height ceases, and they deposit mean momentum and energy into the thermosphere.

In the local (solar) time frame, the heating, or changes in atmospheric fields due to the heating, may be represented as

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

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



Local time (t_{LT})

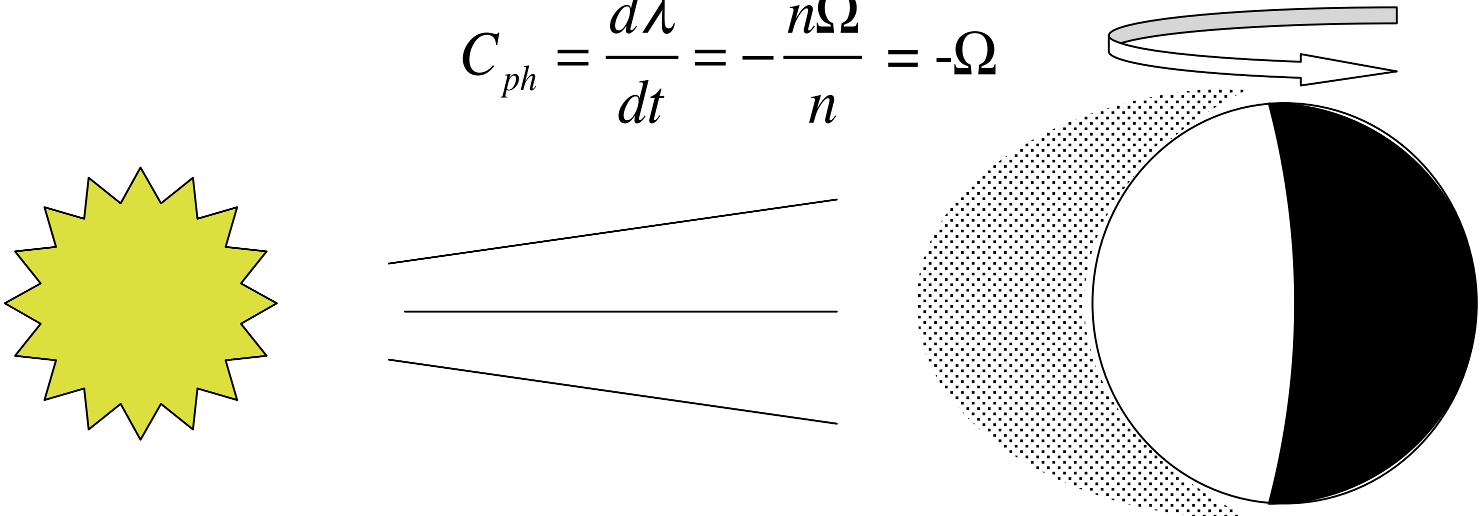
Converting to universal time $t_{LT} = t + \lambda/\Omega$, we have

n = 1 "diurnal
n = 2 "semidiurnal"
n = 3 "terdiurnal"

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

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

$$C_{ph} = \frac{d\lambda}{dt} = -\frac{n\Omega}{n} = -\Omega$$



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

To an observer on the ground, the bulge is moving westward at the apparent motion of the Sun, i.e., 2π day^{-1}. It is sometimes said that the bulge is 'migrating' with the apparent motion of the Sun with respect to an observer fixed on the planet.

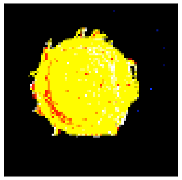
This is what things look like if the solar heating is the same at all longitudes.

The Global Scale Wave Model (GSWM)

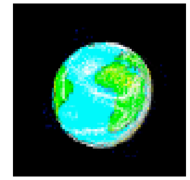
- ***The GSWM solves the coupled momentum, thermal energy, continuity and constitutive equations for linearized steady-state atmospheric perturbations on a sphere from near the surface to the thermosphere (ca. 400 km).***

- ***Given the frequency, zonal wavenumber and excitation of a particular oscillation, the height vs. latitude distribution of the atmospheric response is calculated.***

- ***The model includes such processes as surface friction; prescribed zonal mean winds, densities and temperatures; parameterized radiative cooling, eddy and molecular diffusion and ion drag.***

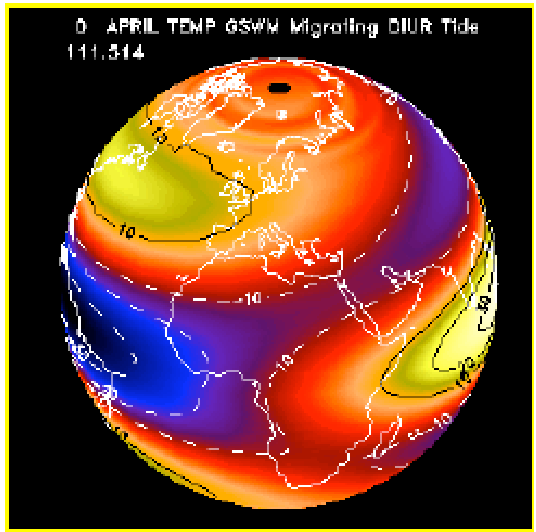


GSWM: Global Scale Wave Model



A Numerical Model of Planetary Waves and Solar Tides in the Earth's Atmosphere

High Altitude Observatory (HAO)
National Center for Atmospheric Research (NCAR)



GSWM-98 24-hr Tidal Temperature Perturbation (K) for April, 111km.
Click for animation with alternating "Earth" vs. "Space" frame of reference (1.5M).
(Animation runs 4 loops; [ESC] stops it!)

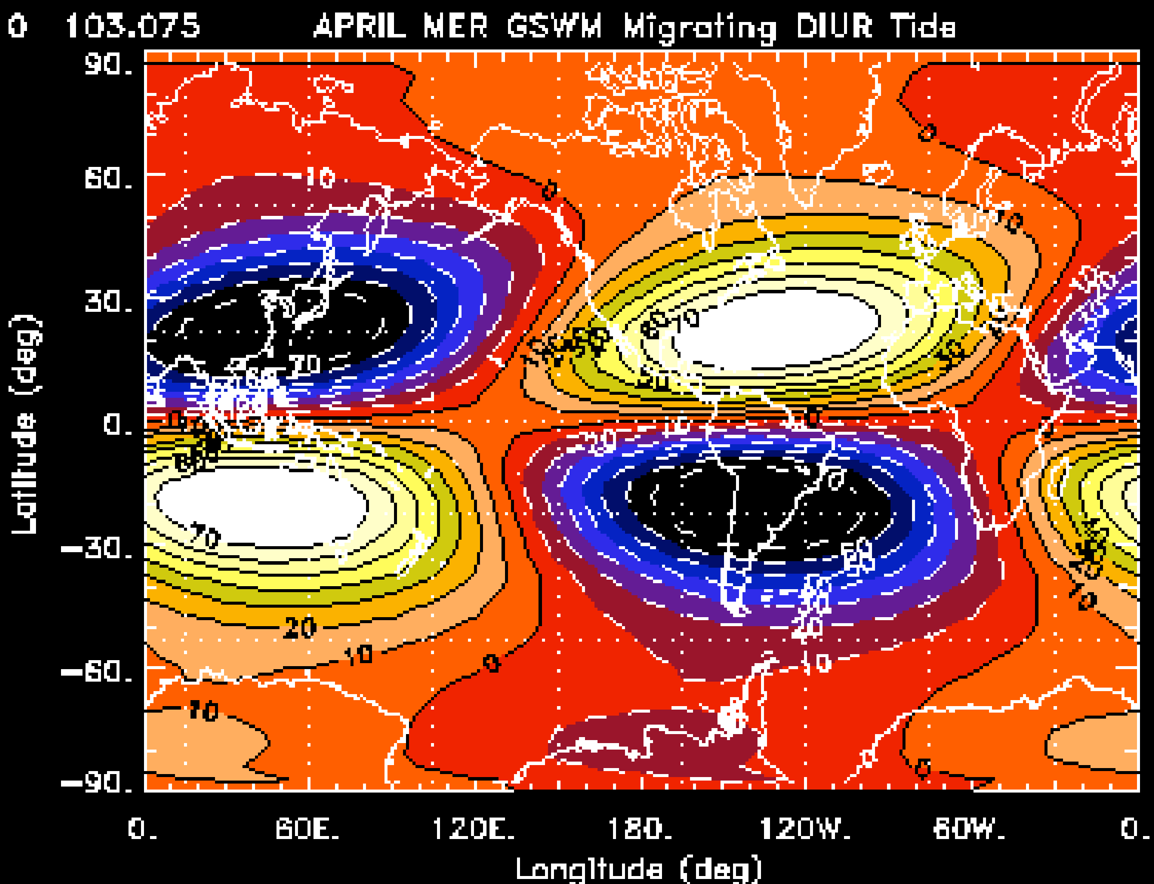
Download tables of monthly GSWM-00 migrating diurnal and semidiurnal results.

Download monthly GSWM-02 migrating and nonmigrating diurnal and semidiurnal results at user specified locations.

Download netcdf files of GSWM-02 results that mimic TIMED/CEDAR observations

http://web.hao.ucar.edu/public/research/tiso/gswm/gswm.html

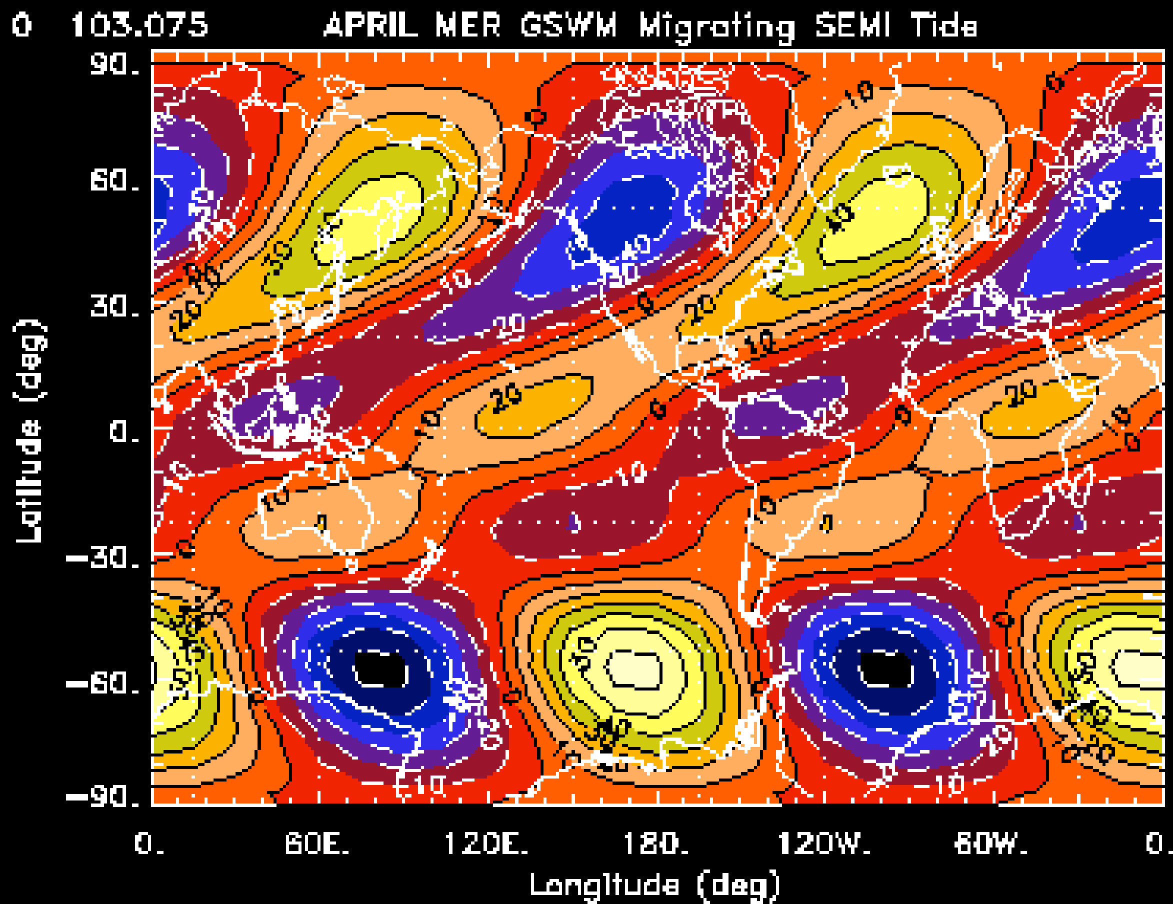
Meridional wind field at 103 km (April) associated with the diurnal tide propagating upward from the lower atmosphere, mainly excited by near-IR absorption by H_2O in the troposphere



Courtesy M. Hagan

The tide propagates westward with respect to the surface once per day, and is locally seen as the same diurnal tide at all longitudes.

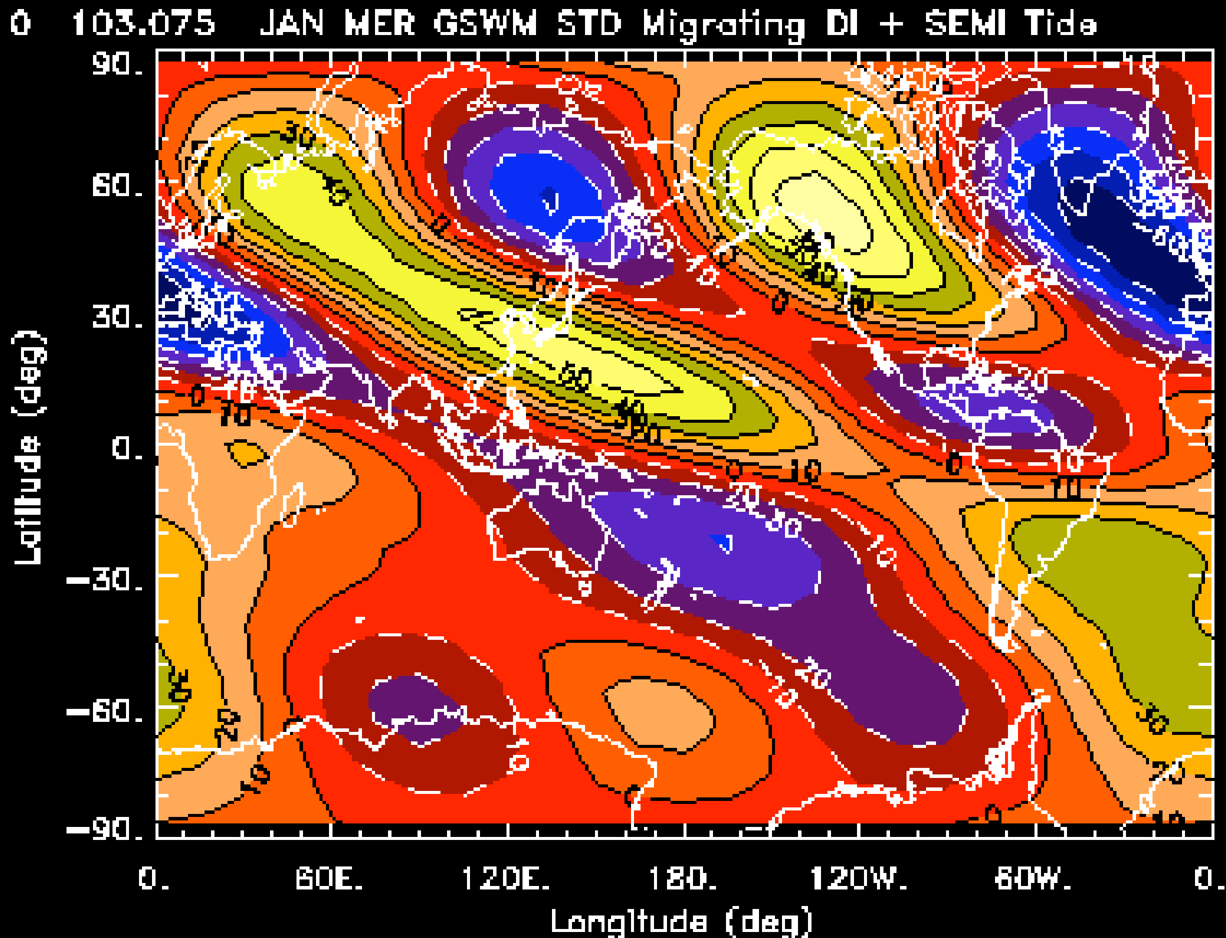
Meridional wind field at 103 km (April) associated with the semidiurnal tide propagating upward from the lower atmosphere, mainly excited by UV absorption by O_3 in the stratosphere-mesosphere



Courtesy M. Hagan

The tide propagates westward with respect to the surface once per day, and is locally seen as the same semidiurnal tide at all longitudes.

Meridional wind field at 103 km (January) associated with the combined diurnal and semidiurnal tides propagating upward from the lower atmosphere



Courtesy M. Hagan

Both tides propagate westward with respect to the surface once per day, and is locally seen as the same local time structure at all longitudes.

However, if the excitation depends on longitude, the spectrum of tides that is produced is more generally expressed as a linear superposition of waves of various frequencies (n) and zonal wavenumbers (s):

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

implying zonal phase speeds

$$C_{ph} = \frac{d\lambda}{dt} = -\frac{n\Omega}{s} \qquad \therefore \qquad \mathrm{s} > 0 \quad \Rightarrow \quad \text{westward propagation}$$

The waves with s ≠ n are referred to as non-migrating tides because they do not migrate with respect to the Sun to a planetary-fixed observer.

Non-Migrating Tides are Not Sun-Synchronous

Thus, they can propagate westward around the planet both faster than the Sun, i.e., $\frac{\sigma}{s} < -\Omega$

or slower than the Sun, i.e., $-\Omega < \frac{\sigma}{s} < 0$ **,**

and opposite in direction to the Sun, i.e., $\frac{\sigma}{s} > 0$ **,**

or just be standing: s = 0 (i.e., the whole atmosphere breathes in and out at the frequency σ **.**

The total atmospheric response to solar forcing is some superposition of migrating and nonmigrating tidal components, giving rise to a different tidal response at each longitude.

“Weather” due to Tidal Variability

Eastward Winds over Saskatoon, Canada, 65-100 km

Note the predominance of the semidiurnal tide at upper levels, with downward phase progression.

Note the transition from easterlies (westerlies) below ~80-85 km to westerlies (easterlies) above during summer (winter), due to GW filtering and momentum deposition.

Courtesy of C. Meek and A. Manson

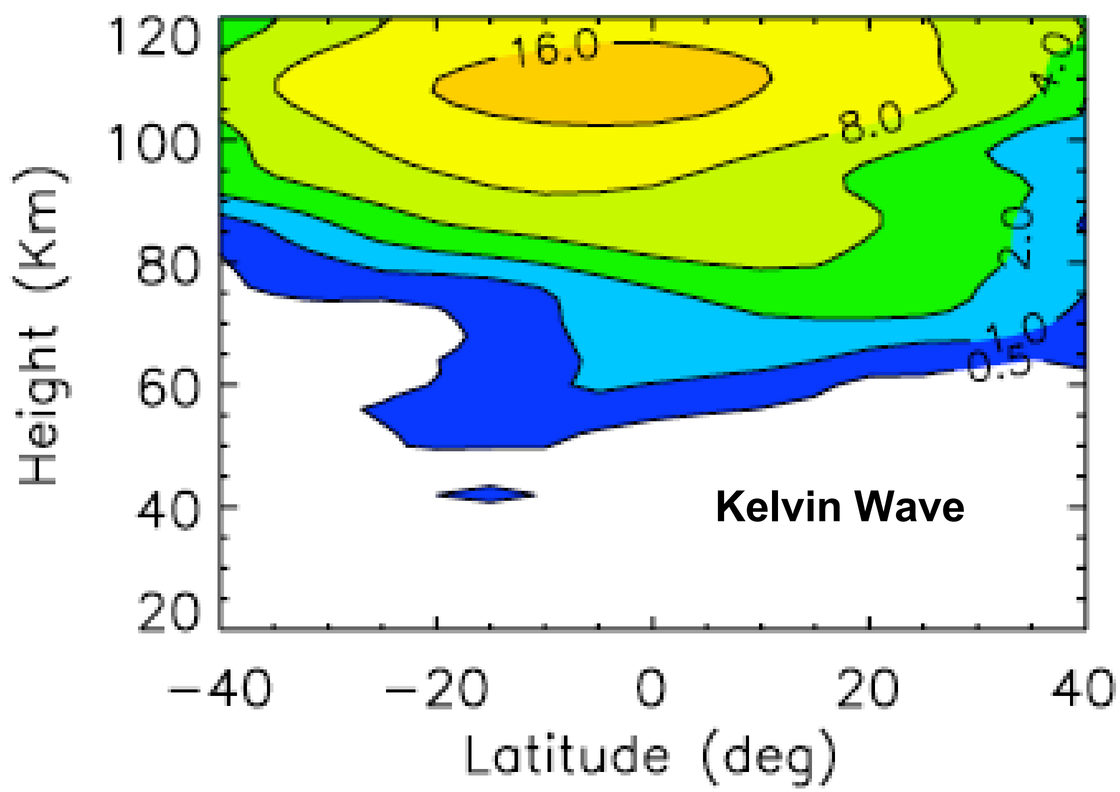
Example: Temperatures from TIMED/SABER
15 Jul - 20 Sep 2002 yaw cycle
good longitude & local time coverage

Space-Time Decomposition

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

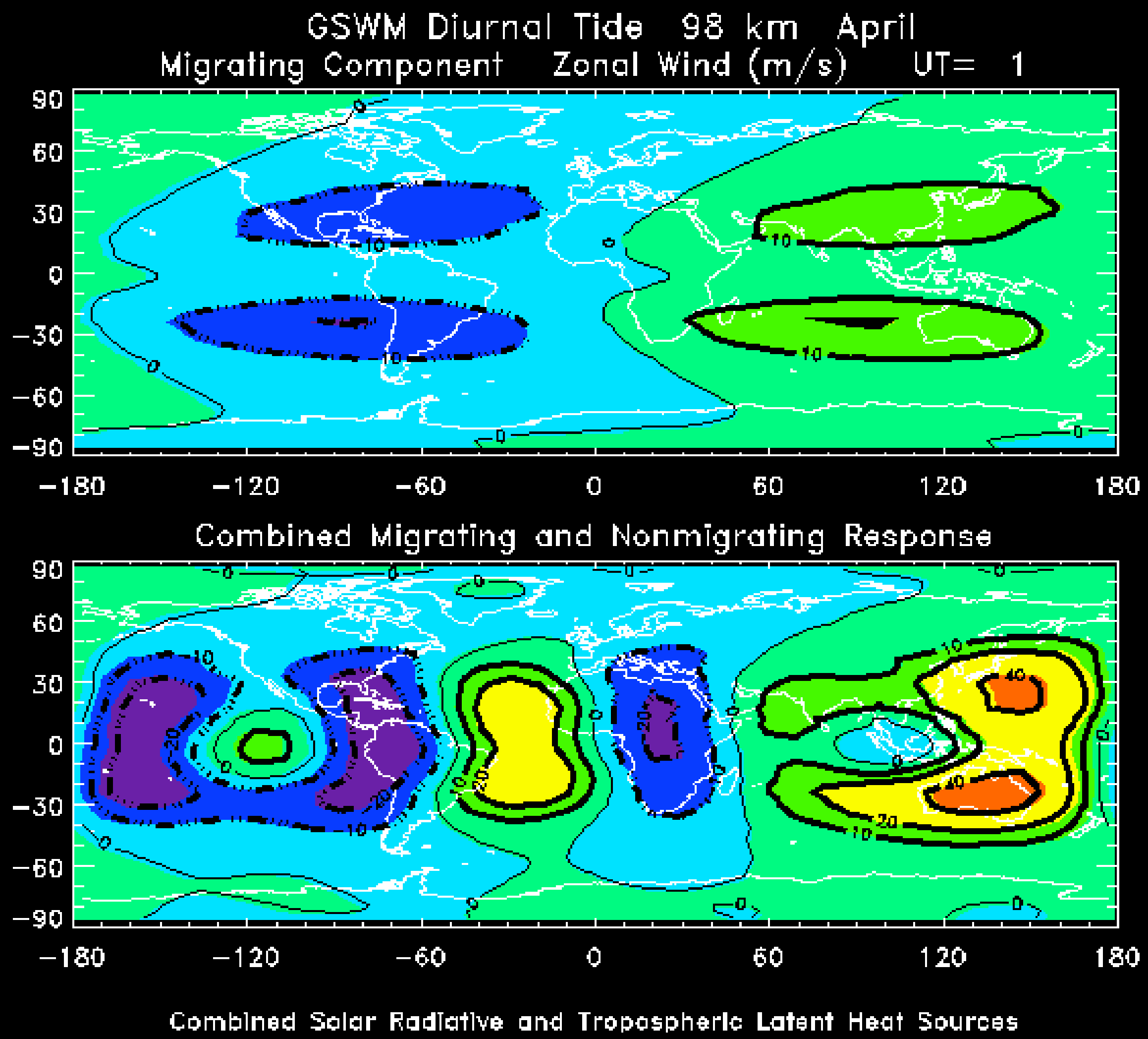
Predominant waves
n = 1, s = 1
n = 1, s = -3

Diurnal (n = 1), s = -3



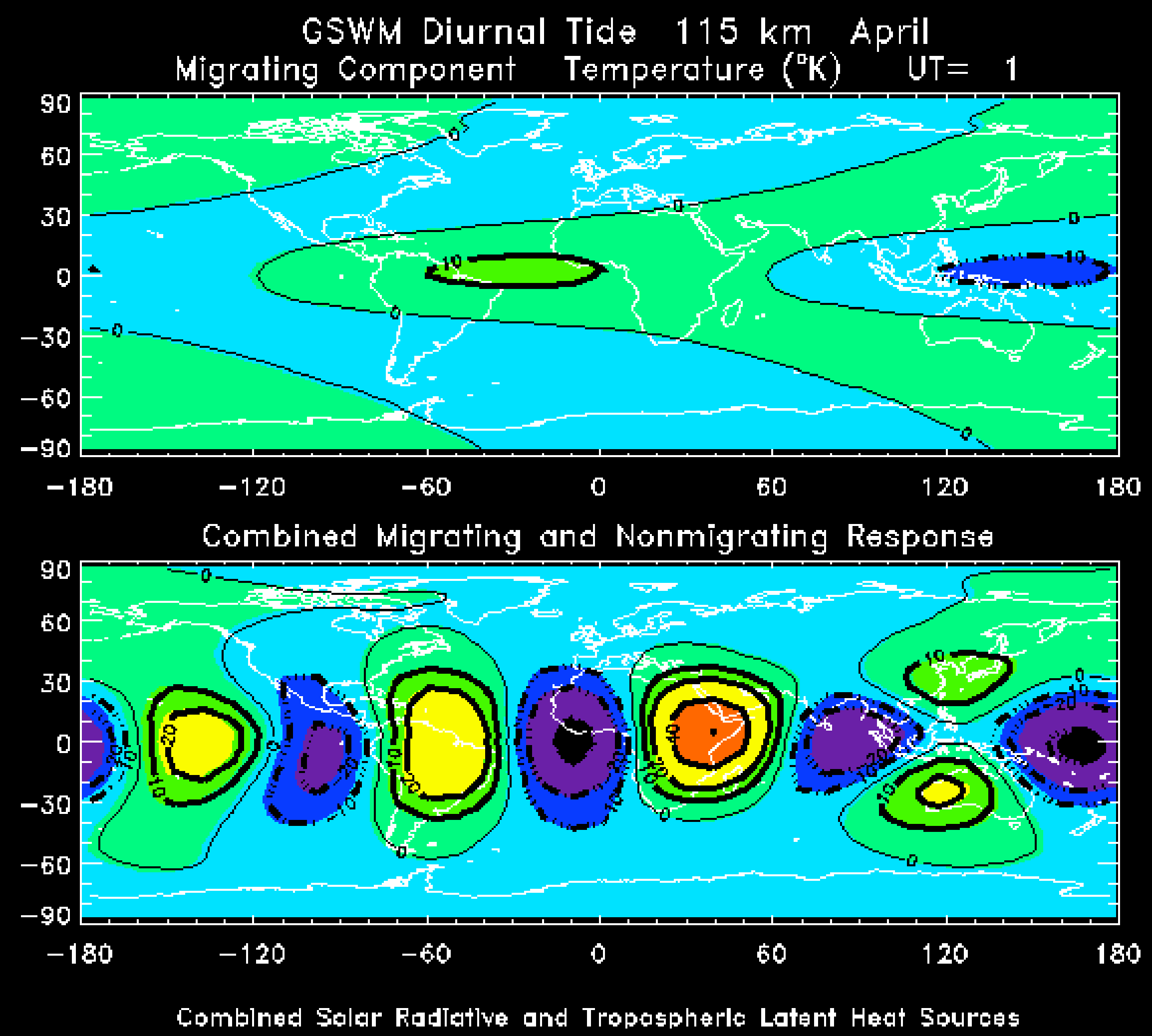
Note:
|s - n| = 4

DW1 & DE3 as viewed in the GSWM: U at 98 km



Courtesy M. Hagan

DW1 & DE3 as viewed in the GSWM: T at 115 km



Courtesy M. Hagan

How Does the Wave Appear at Constant Local Time (e.g., Sun-Synchronous Orbit)?

In terms of local time

$t_{LT} = t + \lambda/\Omega$

$$T_{n,s} \cos\left[n\Omega t + s\lambda - \phi_{n,s} \right]$$

becomes

$$T_{n,s} \cos\left[n\Omega t_{LT} + (s-n)\lambda - \phi_{n,s} \right]$$

Diurnal (n = 1), s = -3

=> |s - n| = 4

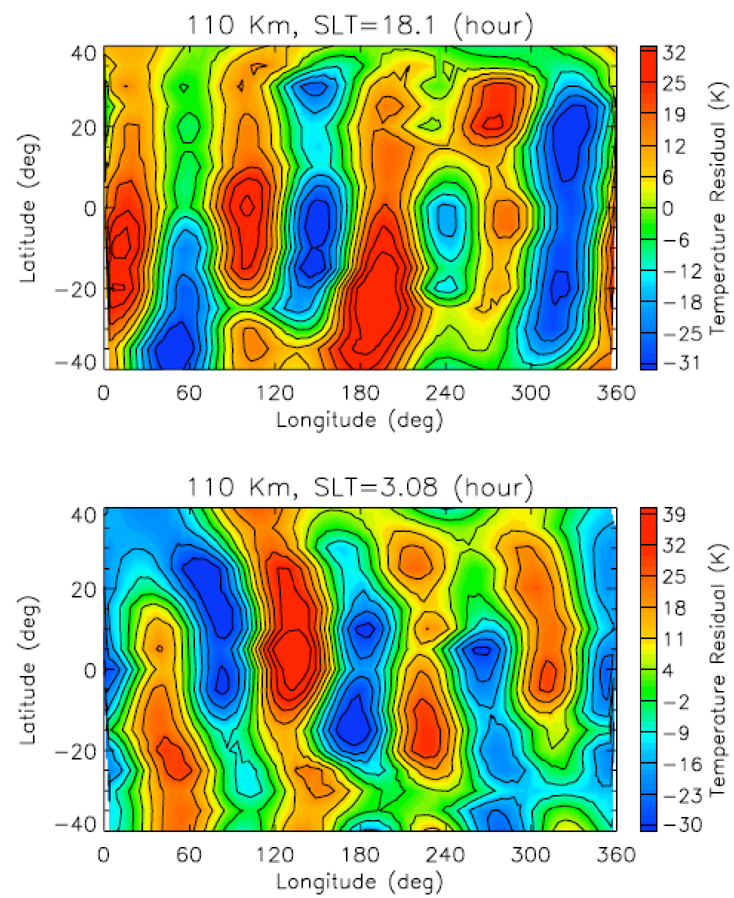
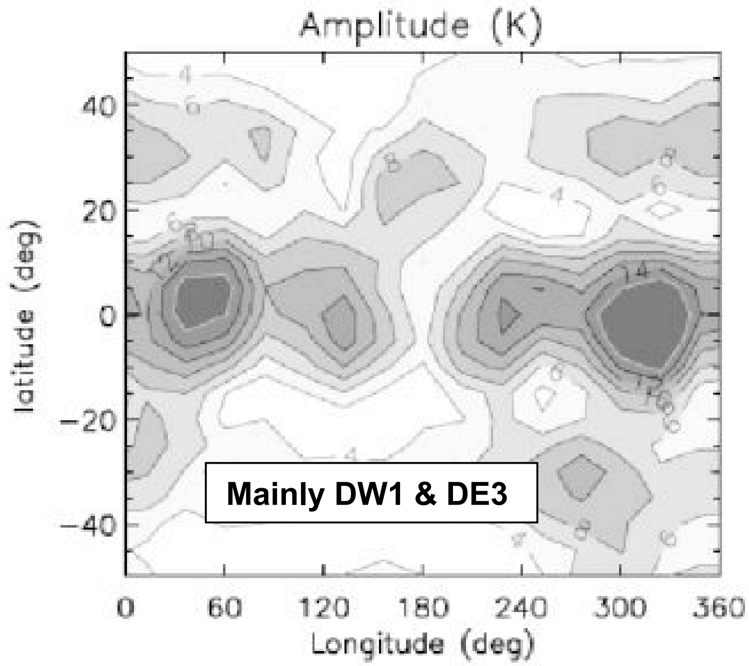
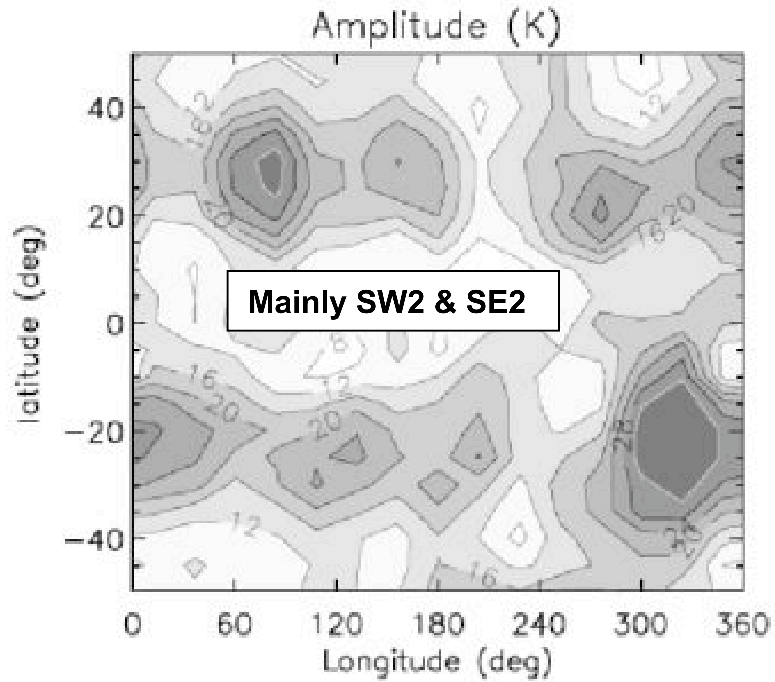


Figure 6. Mean residuals from the 5-day mean of temperatures at 110 km centered on day 238 of 2002. Top: ascending portion of the orbit (mean local solar time = 18.1 hours). Bottom: descending portion of the orbit (mean local solar time = 3.08 hours).

SABER Temperature Tides (Zhang et al., 2006)

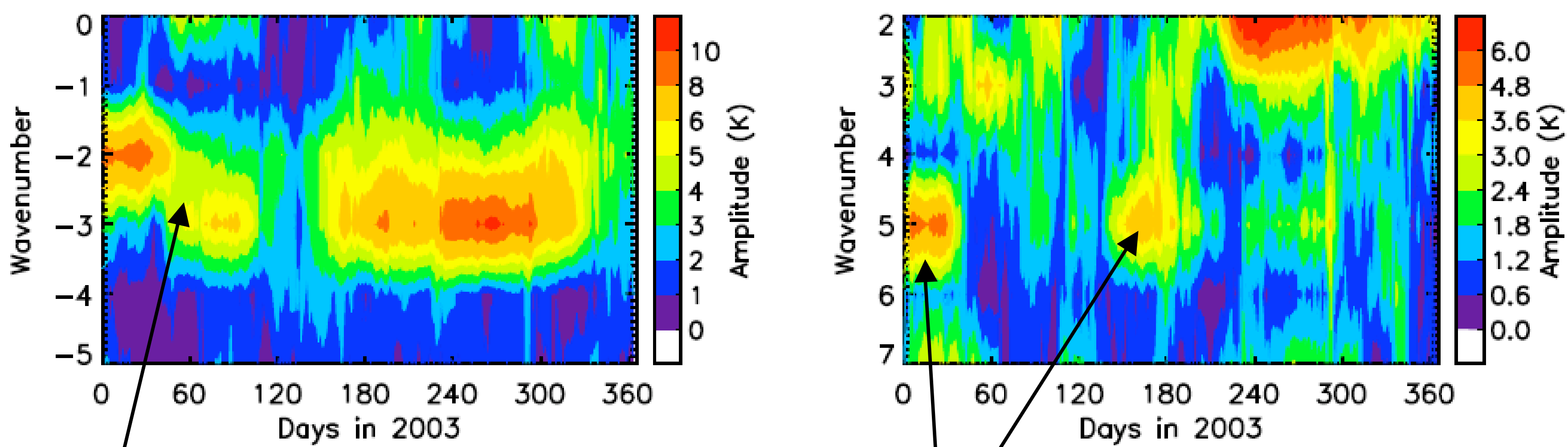


Diurnal tide at 88 km, 120-day mean centered on day 267 of 2004



Semidiurnal tide at 110 km, 120-day mean centered on day 115 of 2004

SABER Diurnal Amplitude (K), Latitude = 0°, Height = 116Km

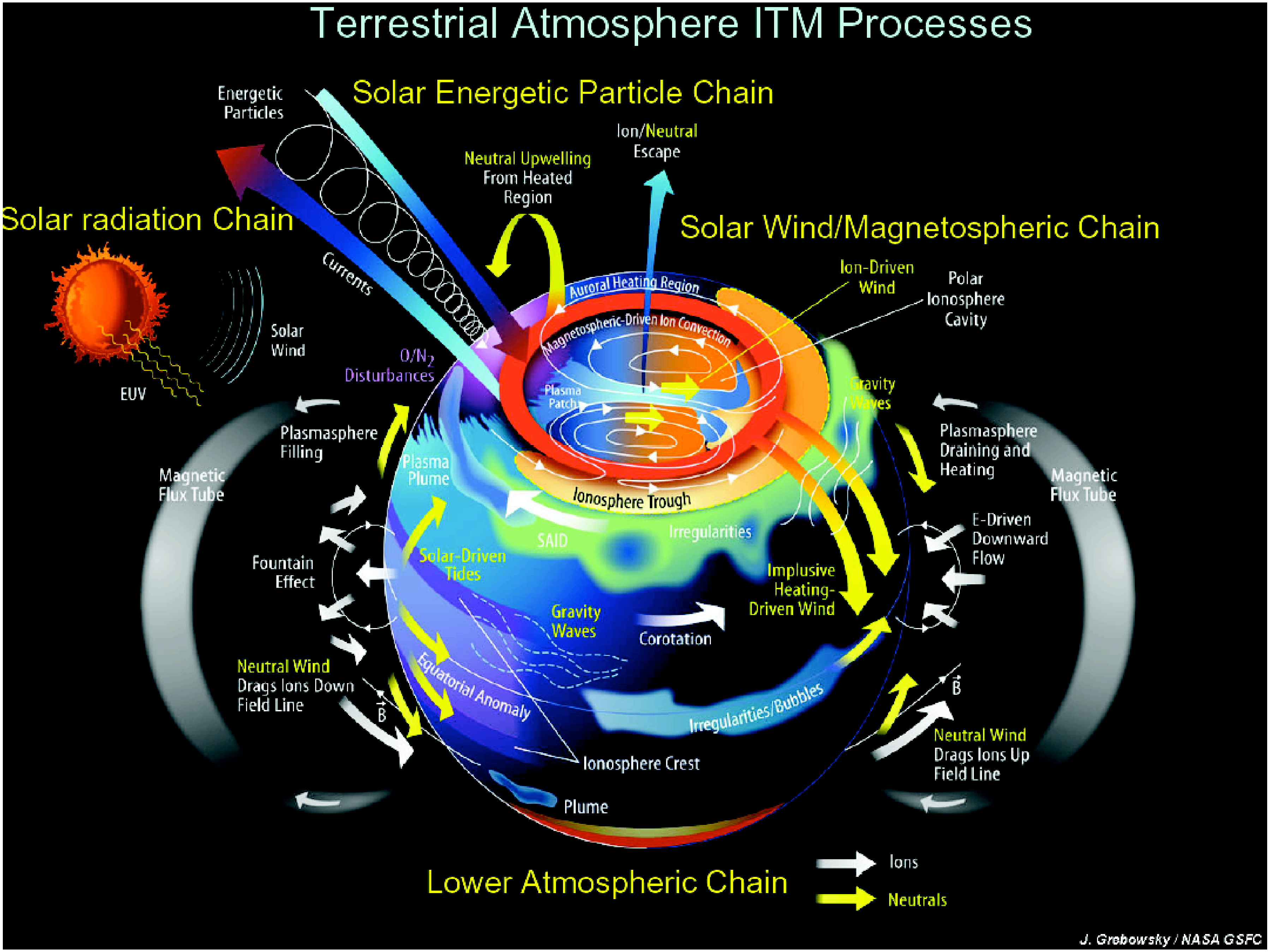


Transition from DE2 to DE3 (wave-3 to wave-4)

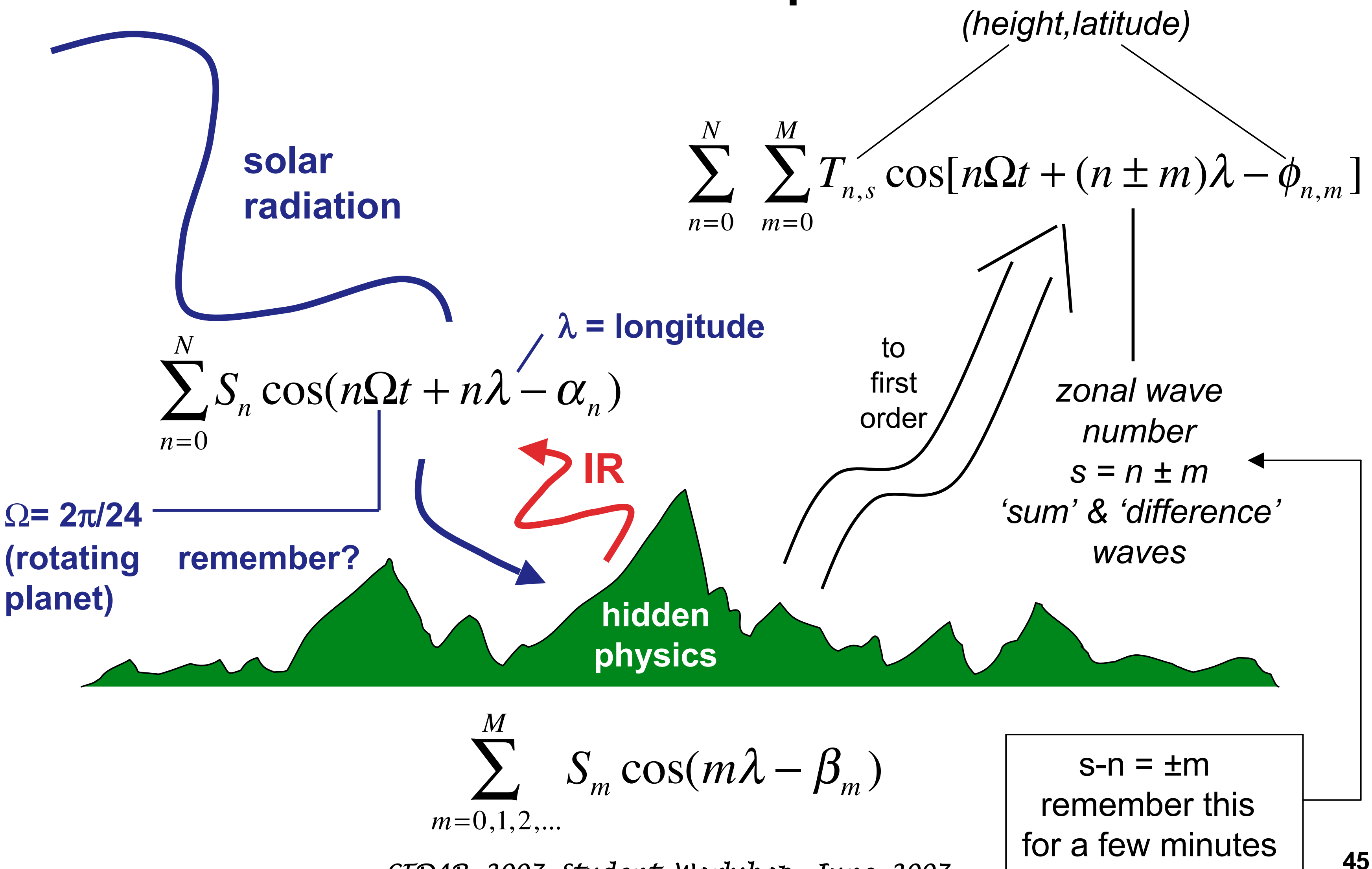
DW5 also gives rise to wave-4 in longitude

Thank you
for your attention!

Additional Slides


Terrestrial Atmosphere ITM Processes
Solar Energetic Particle Chain
Energetic Particles
Ion/Neutral Escape
Neutral Upwelling From Heated Region
Solar radiation Chain
Solar Wind/Magnetospheric Chain
Currents
Solar Wind
EUV
O/N2 Disturbances
Auroral Heating Region
Magnetospheric-Driven Ion Convection
Ion-Driven Wind
Polar Ionosphere Cavity
Plasma Patch
Gravity Waves
Plasmasphere Filling
Plasmasphere Draining and Heating
Magnetic Flux Tube
Plasma Plume
Ionosphere Trough
SAID
Irregularities
E-Driven Downward Flow
Fountain Effect
Solar-Driven Tides
Implusive Heating-Driven Wind
Gravity Waves
Corotation
Neutral Wind Drags Ions Down Field Line
Equatorial Anomaly
Irregularities/Bubbles
Neutral Wind Drags Ions Up Field Line
Ionosphere Crest
Plume
Lower Atmospheric Chain
Ions
Neutrals
J. Grebowsky / NASA GSFC

A spectrum of thermal tides is generated via topographic/land-sea modulation of periodic solar radiation absorption:



$$\sum_{n=0}^{N} \sum_{m=0}^{M} T_{n,s} \cos[n\Omega t + (n \pm m)\lambda - \phi_{n,m}]$$

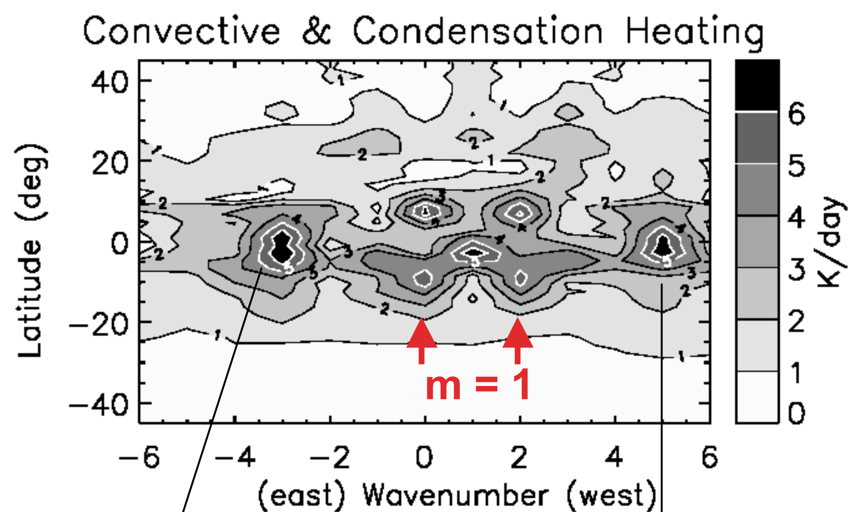
$$\sum_{n=0}^{N} S_n \cos(n\Omega t + n\lambda - \alpha_n)$$

$$\sum_{m=0,1,2,\ldots}^{M} S_m \cos(m\lambda - \beta_m)$$

Example: Diurnal (24-hour or n = 1) tides excited by latent heating due to tropical convection (Earth)

Dominant zonal wavenumber representing low-latitude topography & land-sea contrast on Earth is s = 4

Annual-mean height-Integrated (0-15 km) diurnal heating rates (K day^{-1}) from NCEP/NCAR Reanalysis Project



diurnal harmonic of solar radiation n = 1

hidden physics

dominant topographic wavenumber m = 4

s = -3

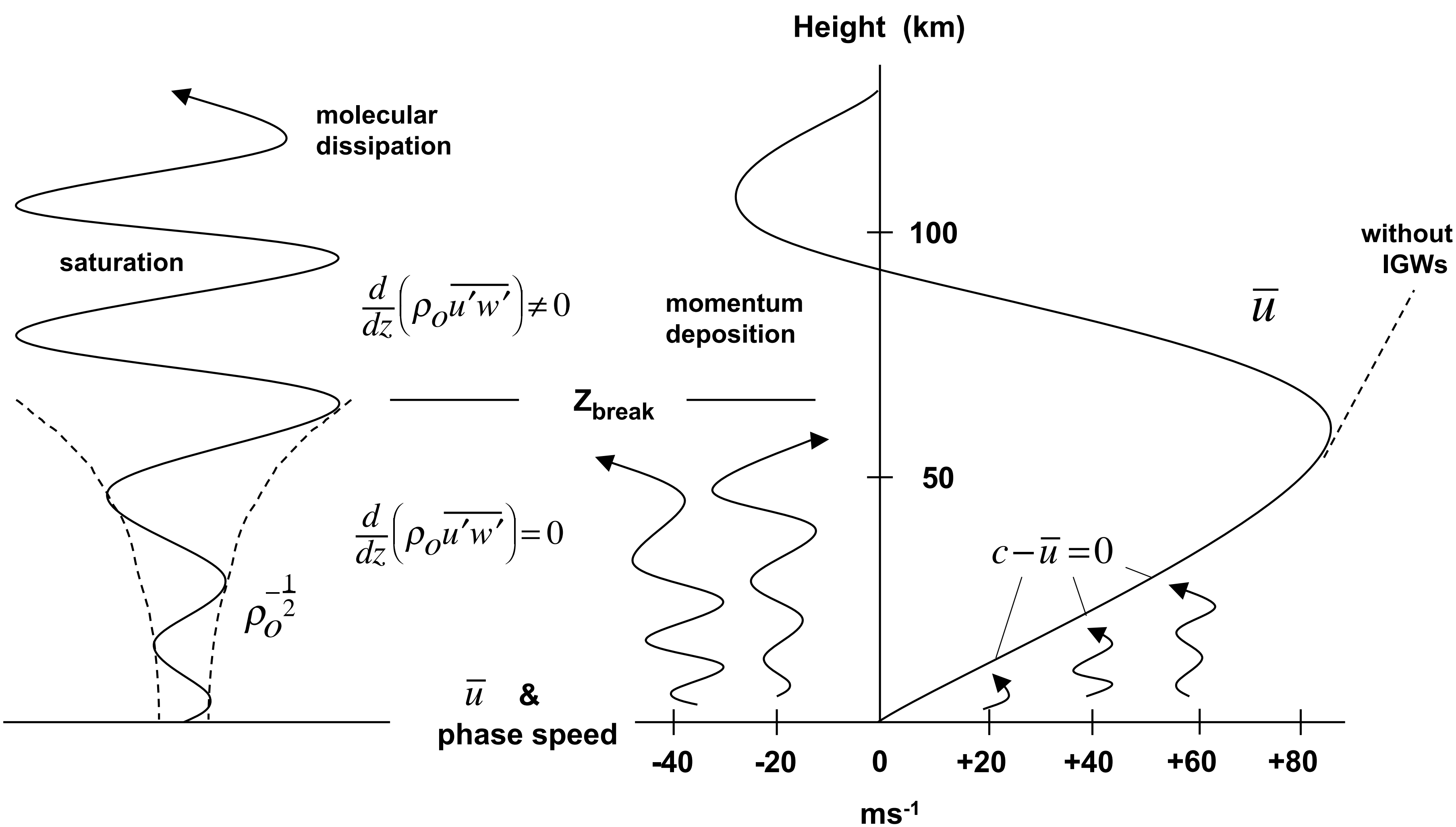
(short vertical wavelength)

s = +5

$$\cos(\Omega t + \lambda) \;\times\; \cos 4\lambda \quad = \quad \cos(\Omega t - 3\lambda) + \cos(\Omega t + 5\lambda)$$

eastward propagating **westward propagating**

Gravity Wave Coupling in Earth's Atmosphere



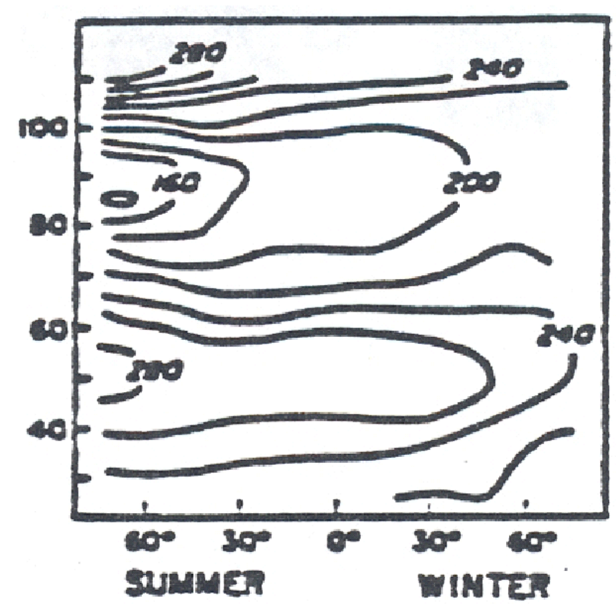
Gravity Waves and Effects on the Mean Thermal Structure

Due to the exponential decrease of density, amplitudes of gravity waves grow exponentially with height --- in the "reentry" regime they become so large that they go unstable, generate turbulence, and deposit heat and momentum into the atmosphere.

The generated turbulence accounts for the "turbulent mixing" and the turbopause (homopause) that we talked about before.

The deposited momentum produces a net meridional circulation, and associated rising motions (cooling) at high latitudes during summer, and sinking motions (heating) during winter, causing the so-called "mesopause anomaly" in temperature.

$$\frac{\partial \overline{u}}{\partial t} + \ldots\ldots\ldots - fv = -\frac{1}{\rho}\frac{\partial}{\partial z}\left(\rho\overline{u'w'}\right)$$



WAVE/MEAN-FLOW/THERMAL INTERACTIONS