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Ionosphere-Thermosphere Basics - II
Dynamics of the Thermosphere

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Ionosphere-Thermosphere Basics - II
Dynamics of the Thermosphere

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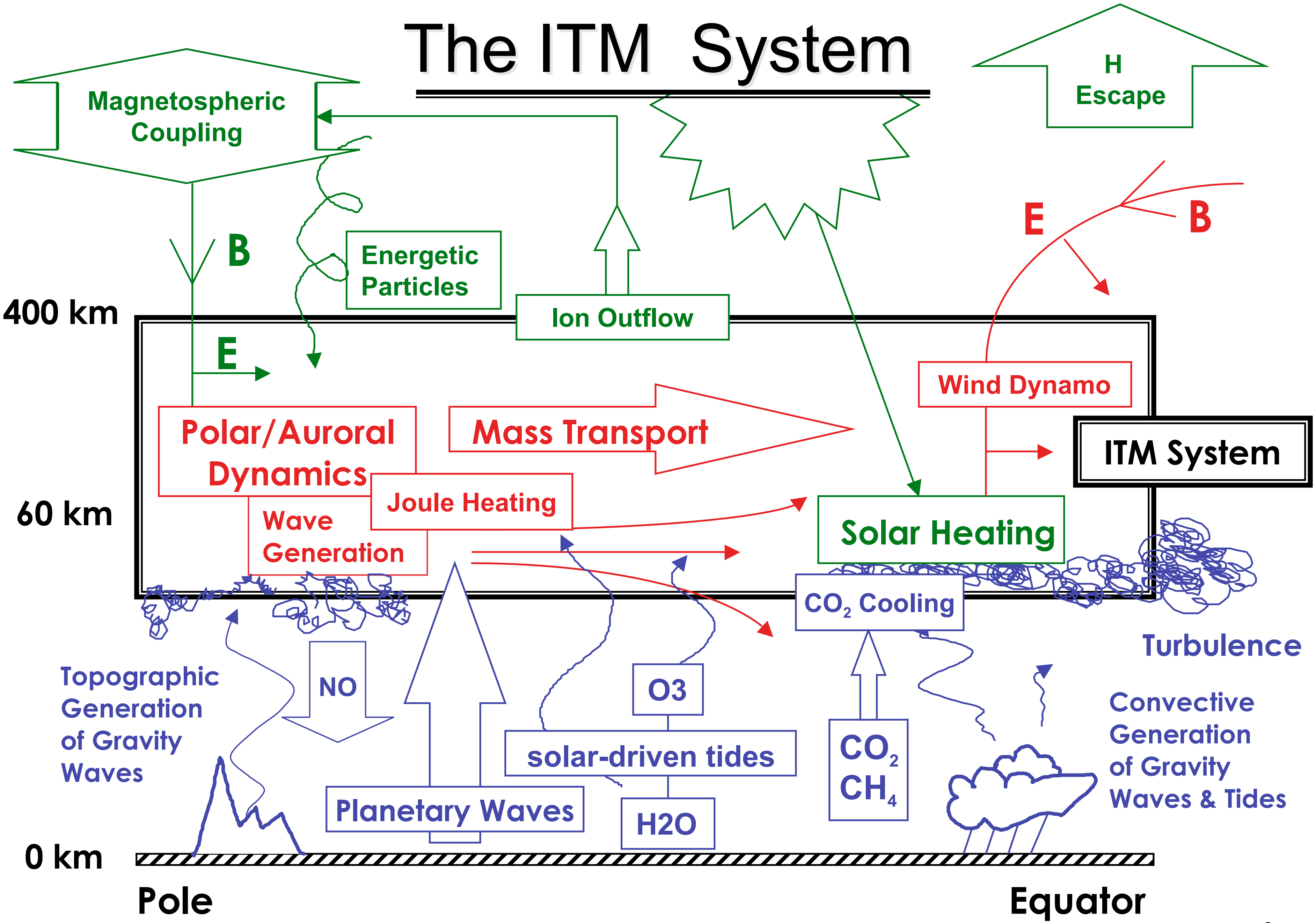
http://spot.colorado.edu/~forbes/Home.html

Lecture Topics

- Momentum Balance
- Winds and Composition: Diurnal Variations
- Winds and Composition: Seasonal Variations
- Thermosphere Weather: Magnetic Storm Response
- Thermosphere Weather: Coupling with the Lower Atmosphere

The ITM System



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

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

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

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

By considering conservation of mass above a constant pressure surface, p_o (Dickinson & Geisler, 1968), it can be shown that the total vertical wind may be expressed in terms of two components, the **barometric** wind and the **divergence** wind. The former is due to thermal expansion/contraction of the atmosphere, the latter is caused by diverging horizontal winds and the conservation of mass:

$$w = w_B + w_D = \left(\frac{\partial h}{\partial t}\right)_p + \frac{1}{\rho}\nabla\cdot\int_{h(p_0)}^{\infty}\rho\vec{U}_H dz$$

They furthermore show that $w_D = -\frac{1}{\rho g}\frac{Dp}{Dt}$ (Vertical motion of air with respect to a fixed pressure surface)

so that the thermodynamic equation $c_p\frac{DT}{Dt} - \frac{1}{\rho}\frac{Dp}{Dt} = J$ (*J* is NET heating from all sources, including conduction)

becomes $c_p\frac{DT}{Dt} + g w_D = J$

$$c_p \frac{DT}{Dt} + g w_D = J$$

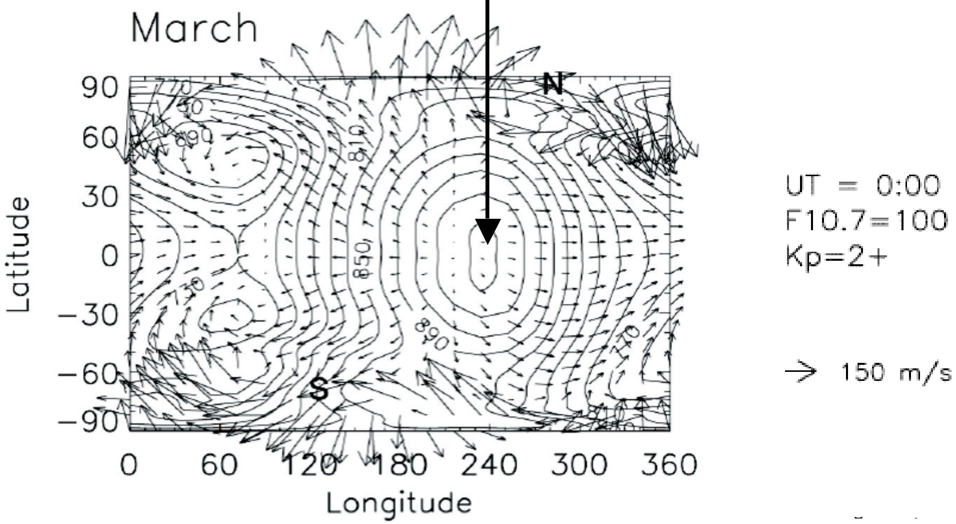
To a first approximation, to explain vertical structure, one can linearize about a mean basic state dependent only on height (overbar); w-bar = 0

$$\frac{DT}{Dt} \approx \frac{\partial T}{\partial t} + w_D \frac{\partial \bar{T}}{\partial z} \longrightarrow \frac{\partial T}{\partial t} = \frac{J}{c_p} - w_D \Gamma$$

An additional "heat source" as important as direct EUV heating.

$$\Gamma = \frac{\partial \bar{T}}{\partial z} + \frac{g}{c_p}$$ is the mean atmospheric stability

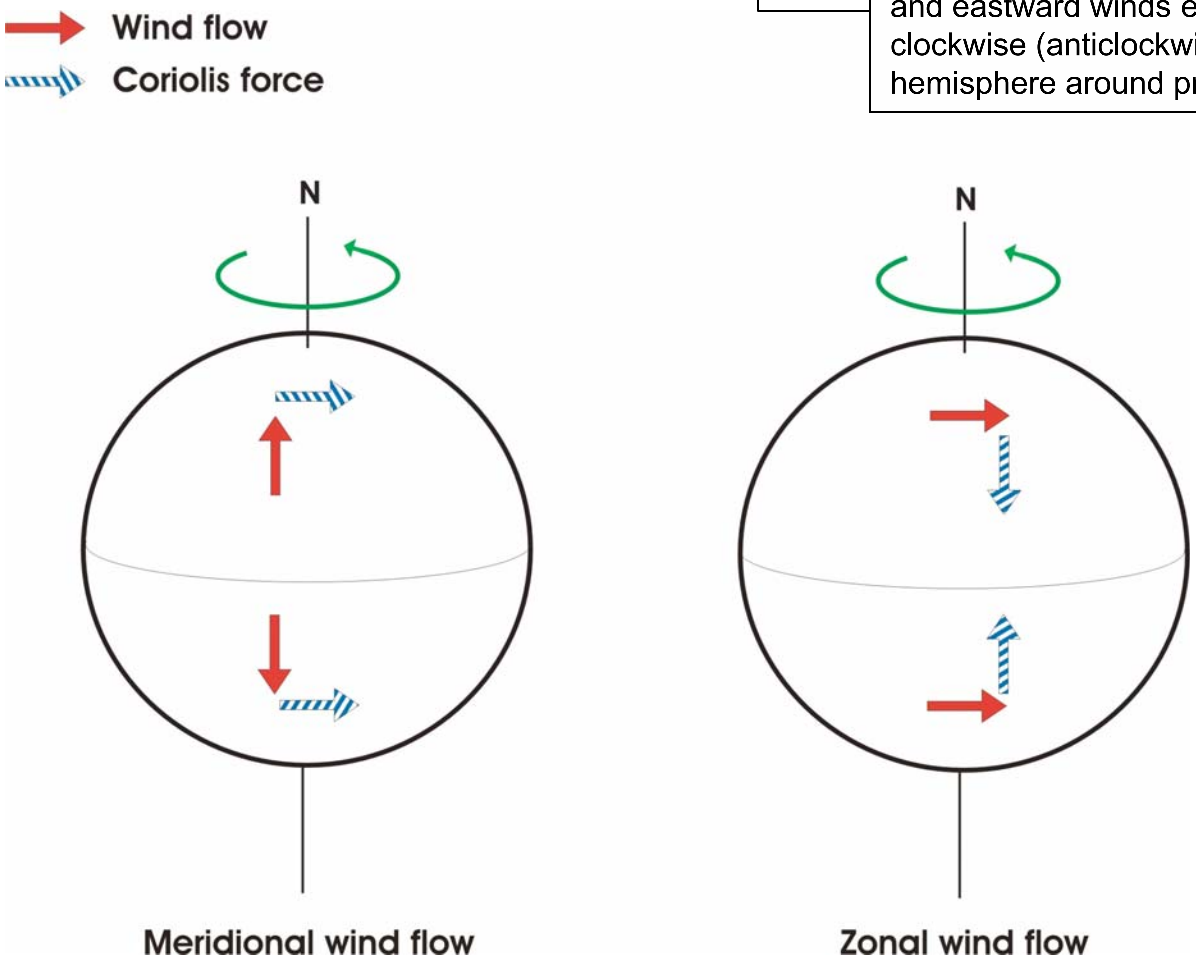
Accounts for much of the observed shift in the time of temperature maximum to late afternoon.



CTIP (Coupled Thermosphere - Ionosphere - Plasmasphere) model results (University College London Model; Fuller-Rowell et al., 1996; Millward et al., 1996; Zhou et al., 2000; Rishbeth et al., 2000)

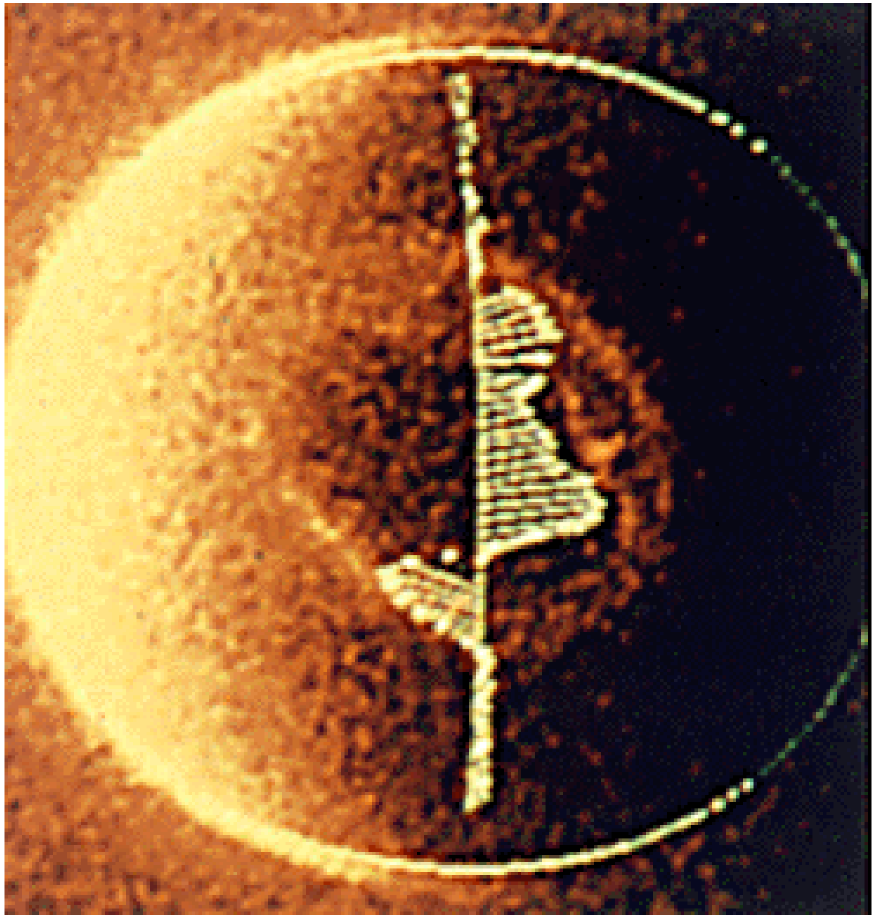
$$\frac{D\vec{U}_H}{Dt} = -\frac{1}{\rho}\vec{\nabla}_H p - 2\vec{\Omega}\times\vec{U}_H + \frac{1}{\rho}\vec{\nabla}\left(\mu\vec{\nabla}\vec{U}_H\right) - \nu_{in}\left(\vec{U}_H - \vec{V}_i\right)$$

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 minima.



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)

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


Neutral winds and auroral oval from Dynamics Explorer measurements (Killeen et al., 1988)

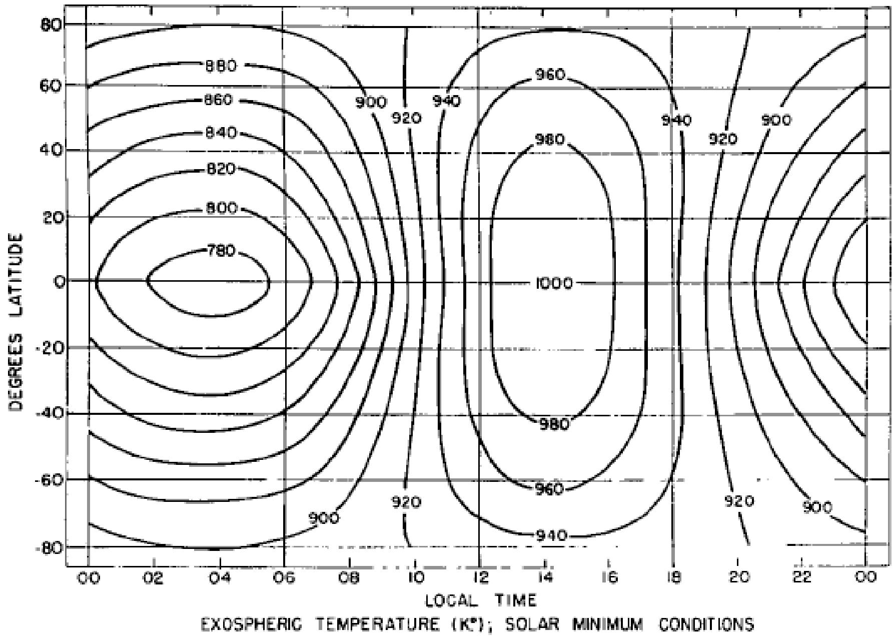
...ence of any ion drifts *(V_i = 0)*, the ...of ions that are bound to ...ield lines act to decelerate the ...nd, due to neutral-ion collisions.

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.

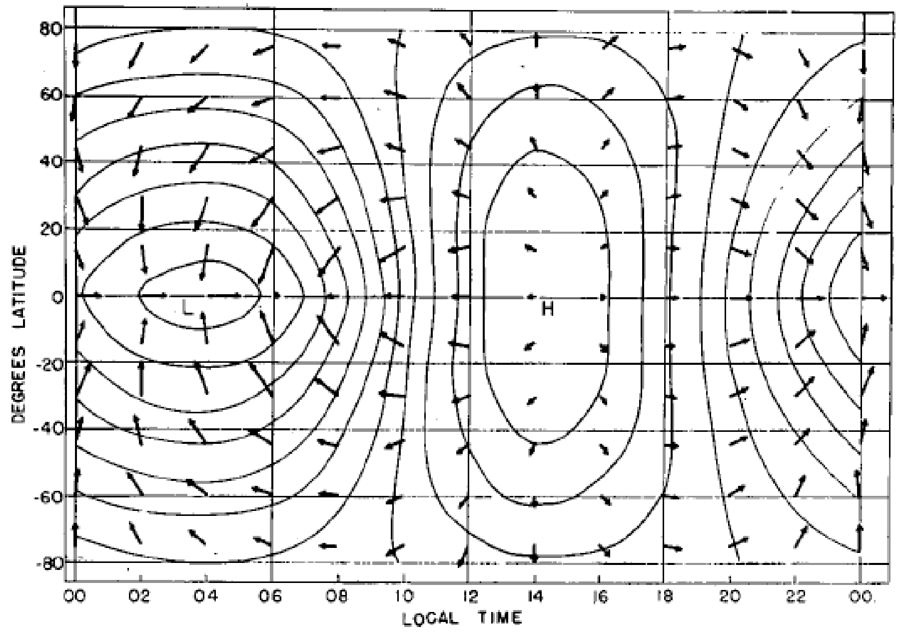
$$\frac{D\vec{U}_H}{Dt} = -\frac{1}{\rho}\vec{\nabla}_H p - 2\vec{\Omega}\times\vec{U}_H + \frac{1}{\rho}\vec{\nabla}\left(\mu\vec{\nabla}\vec{U}_H\right) - \nu_{in}\left(\vec{U}_H - \vec{V}_i\right)$$

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

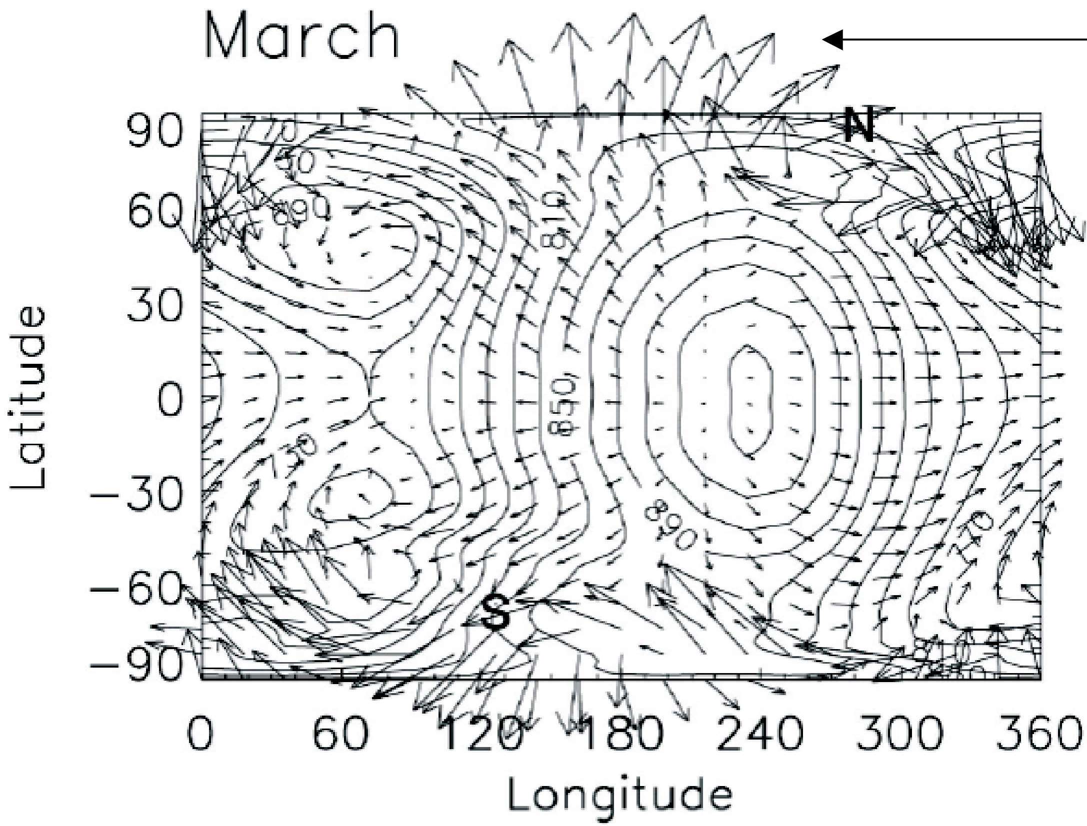


Exospheric Temperatures from Jacchia 1965 model, used with model densities to derive pressures and pressure gradients



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

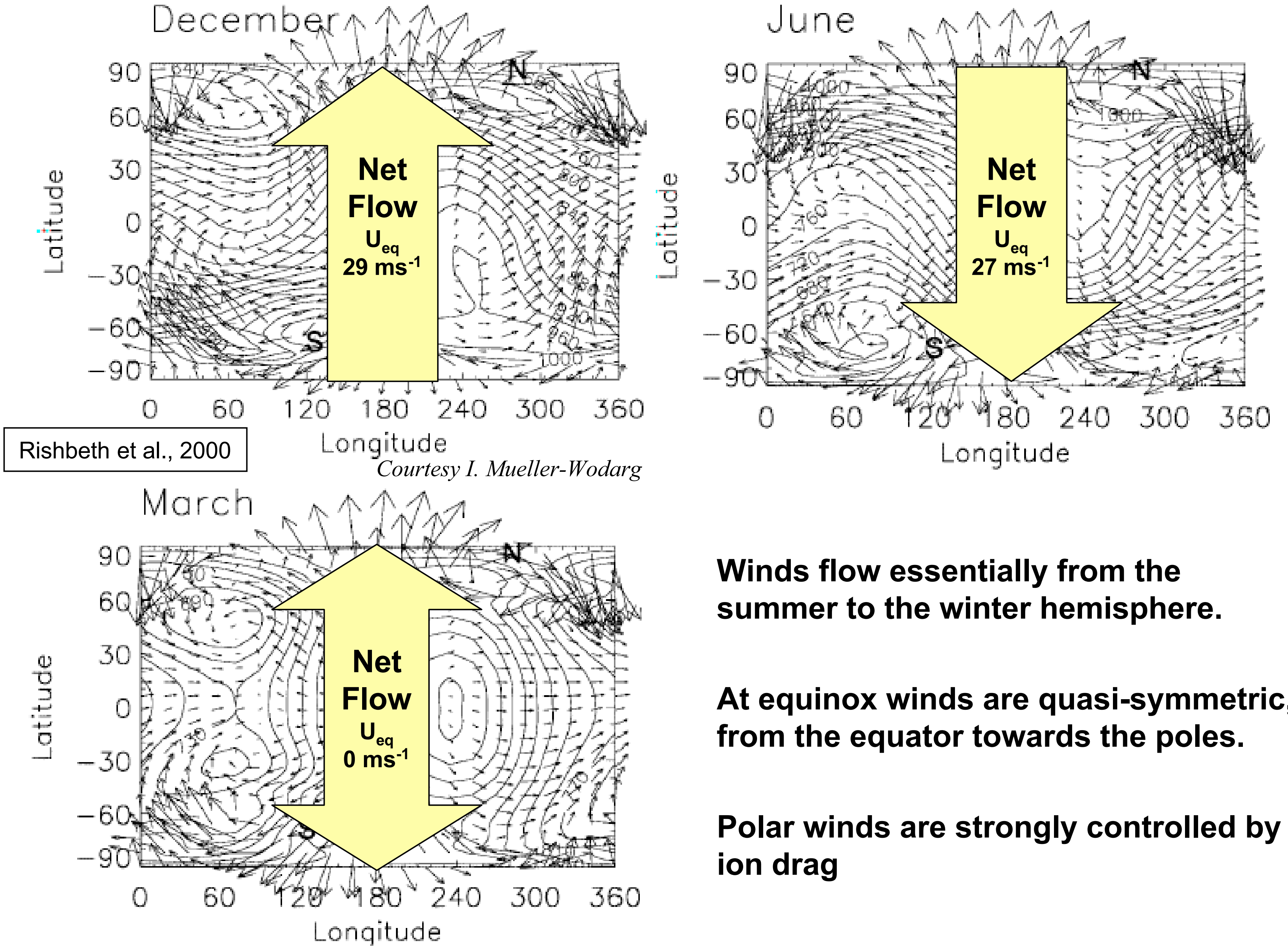


"quiet convection" (Kp = 2)

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

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

Predominantly EUV-Driven Circulation



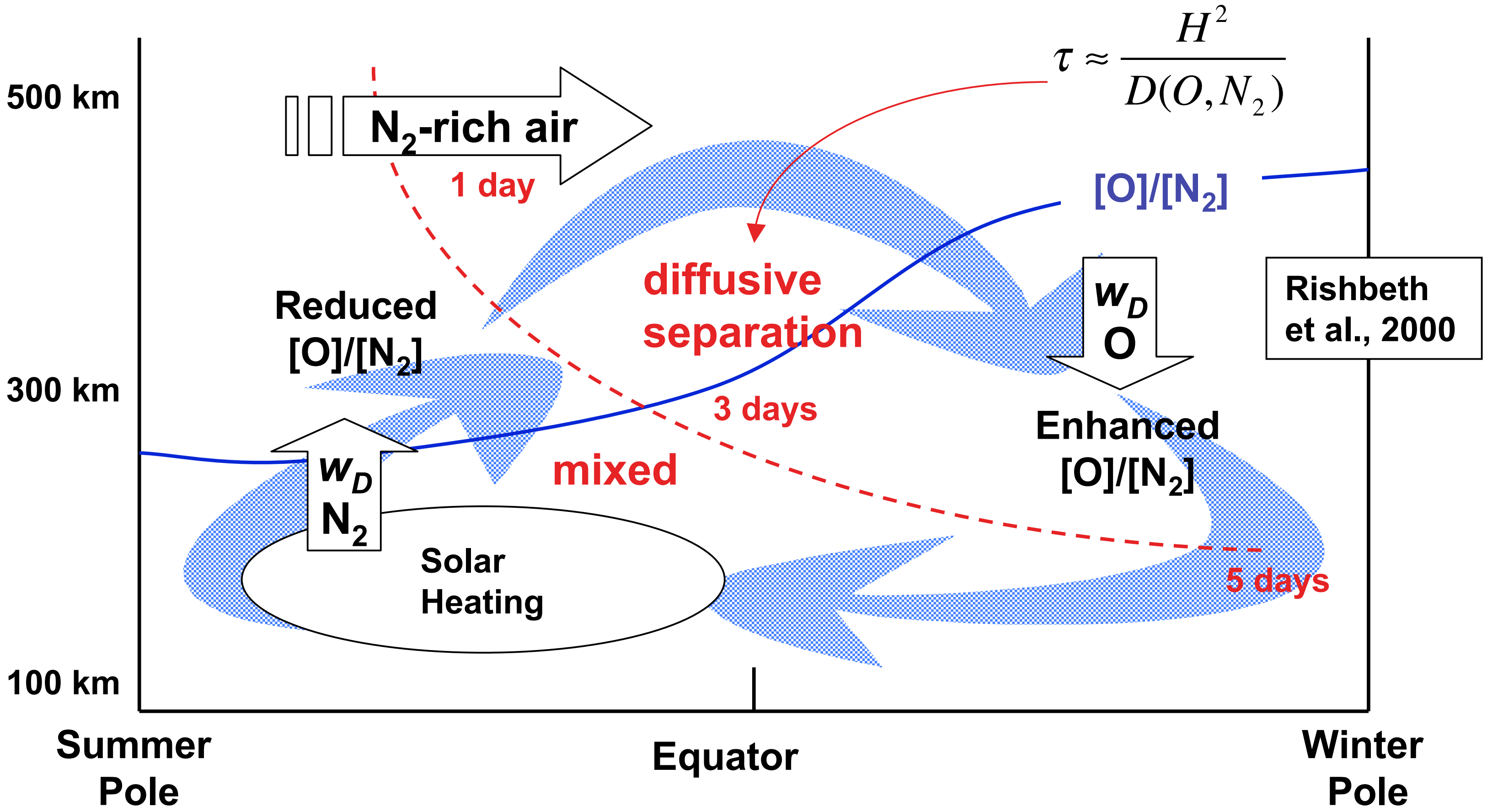
Winds flow essentially from the summer to the winter hemisphere.

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

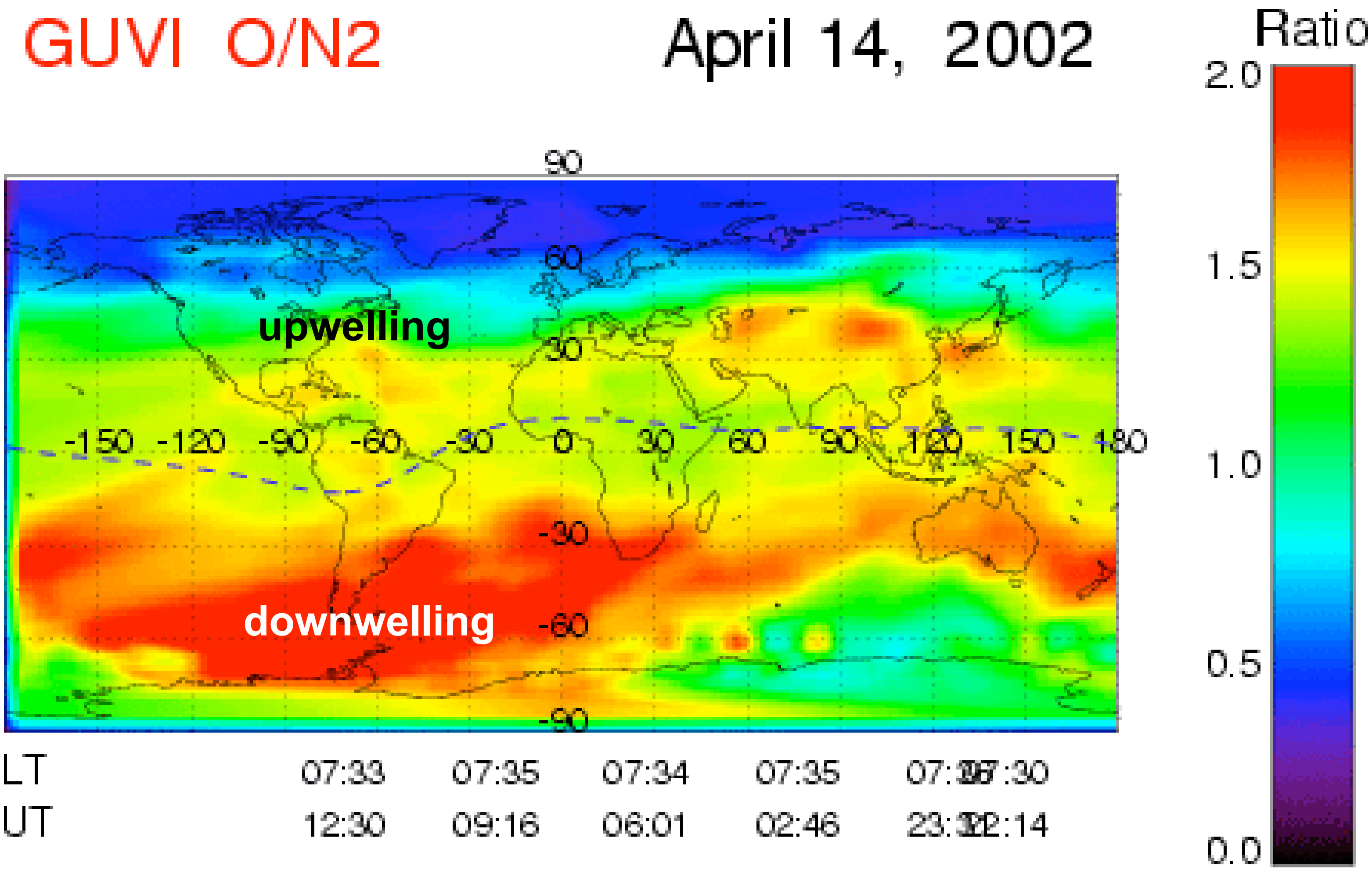
Solar EUV-Driven (Magnetically-Quiet) Circulation and O-N_2 Composition



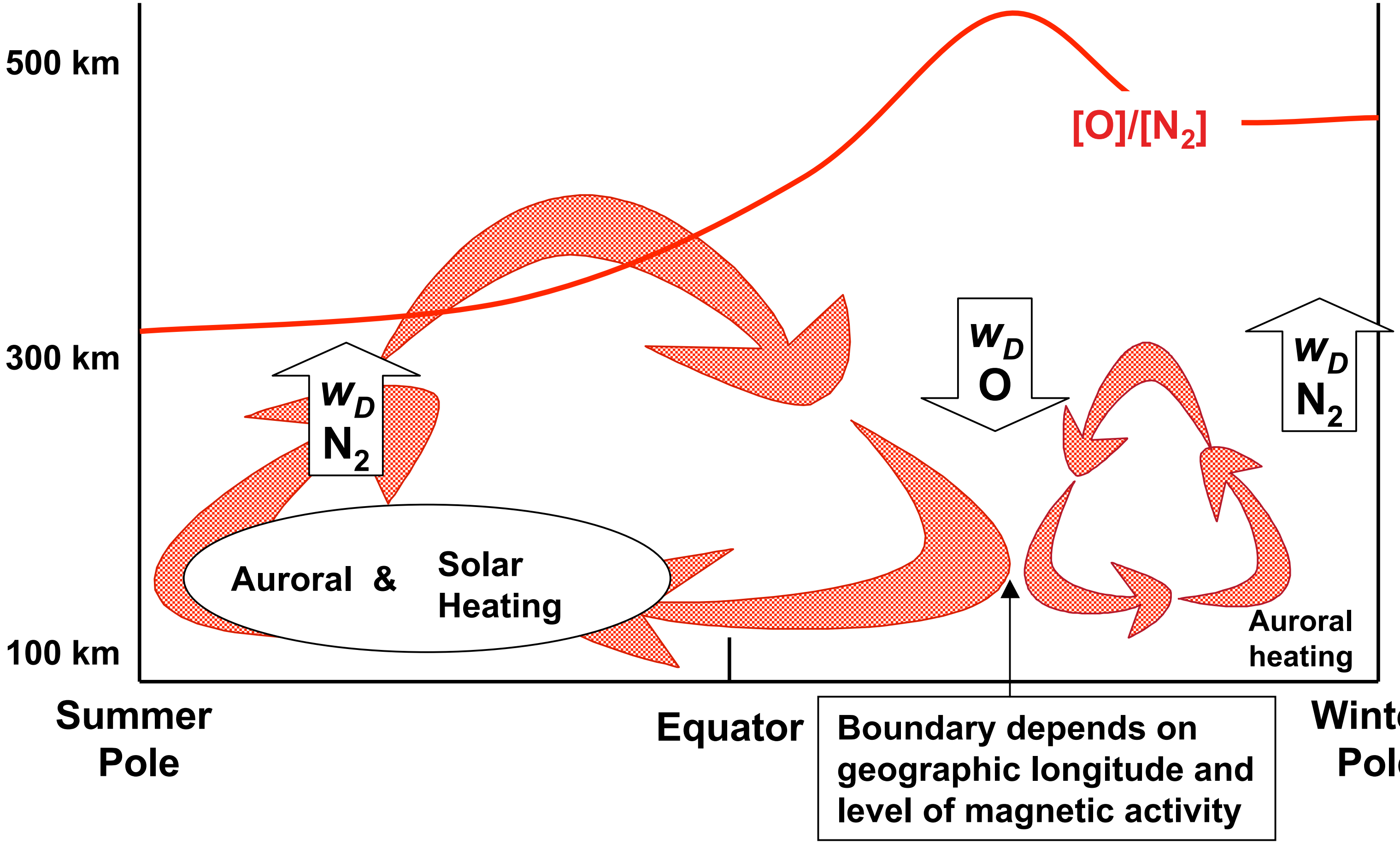
Upwelling occurs in the summer hemisphere, which upsets diffusive equilibrium.

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

Shift Between "Summer" and "Winter" Occurs in a Short Period Around Equinox



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.

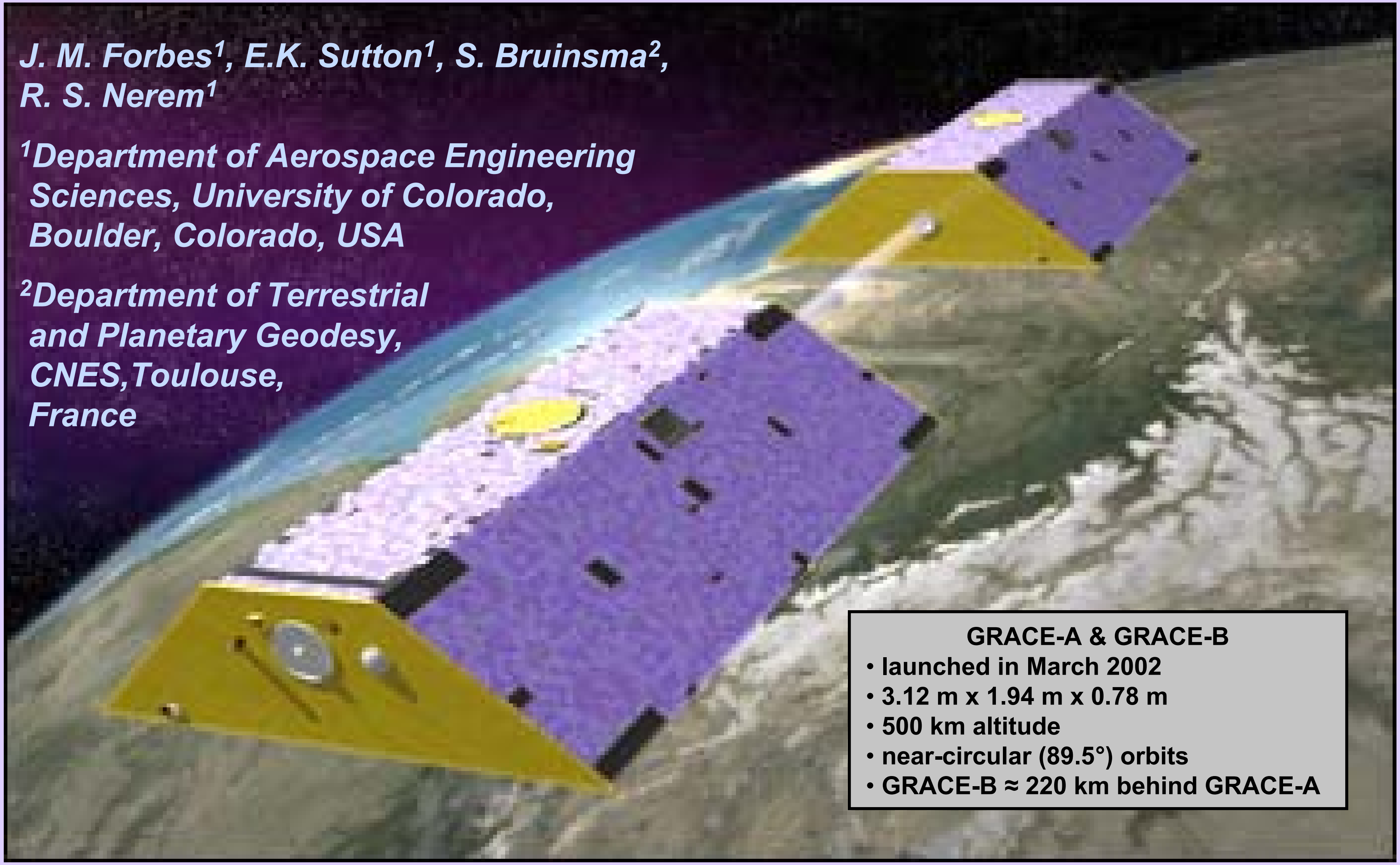
Thermosphere Weather: Magnetic Storm Response

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

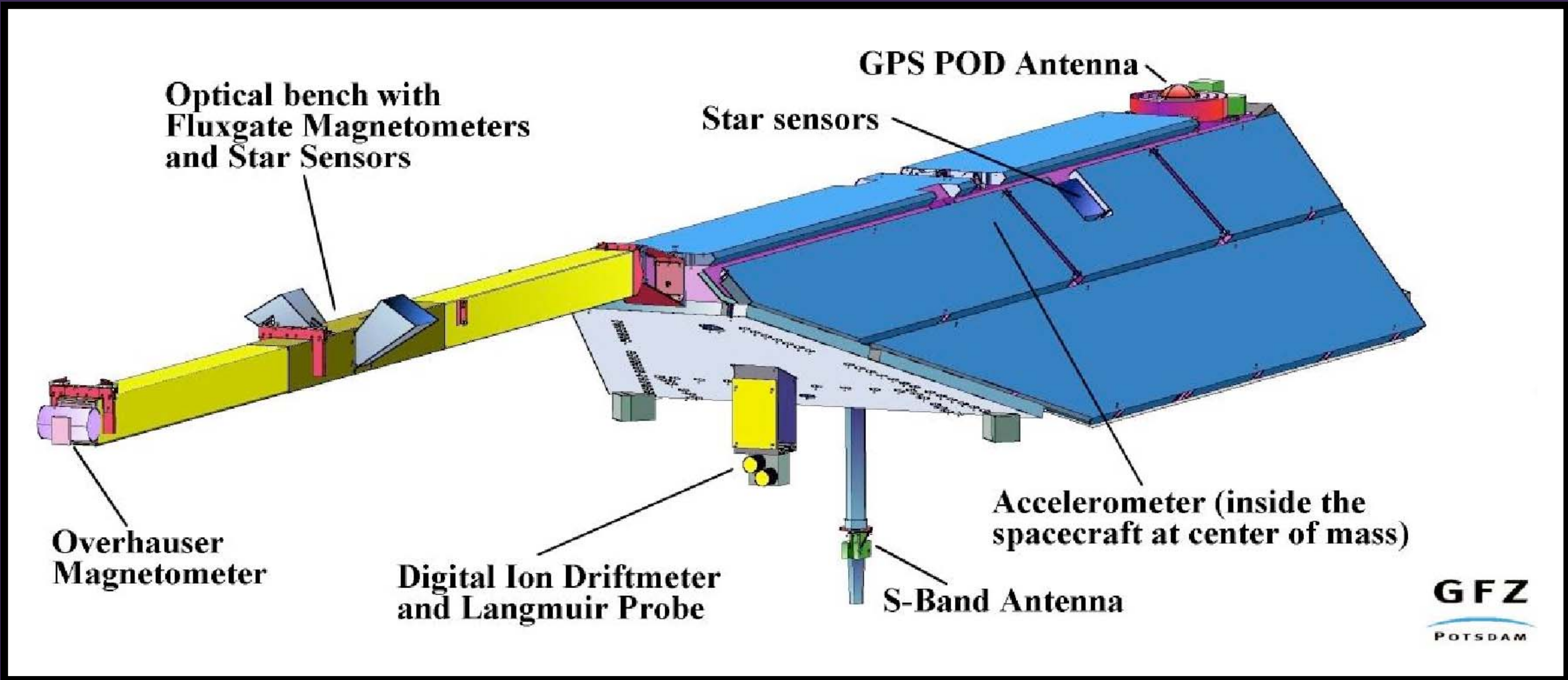
J. M. Forbes[1], E.K. Sutton[1], S. Bruinsma[2], R. S. Nerem[1]

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

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



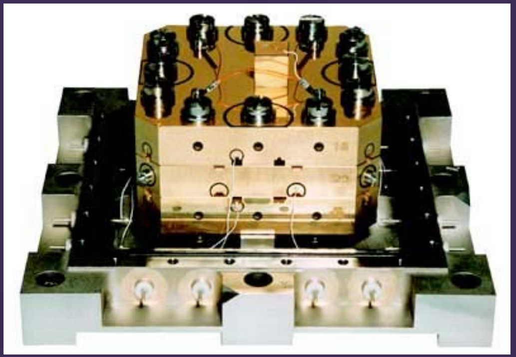
The CHAMP satellite was launched in July 2000 at 450 km altitude in a near-circular orbit with an inclination of 87.3°



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 $m^2 kg^{-1}$
- 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***

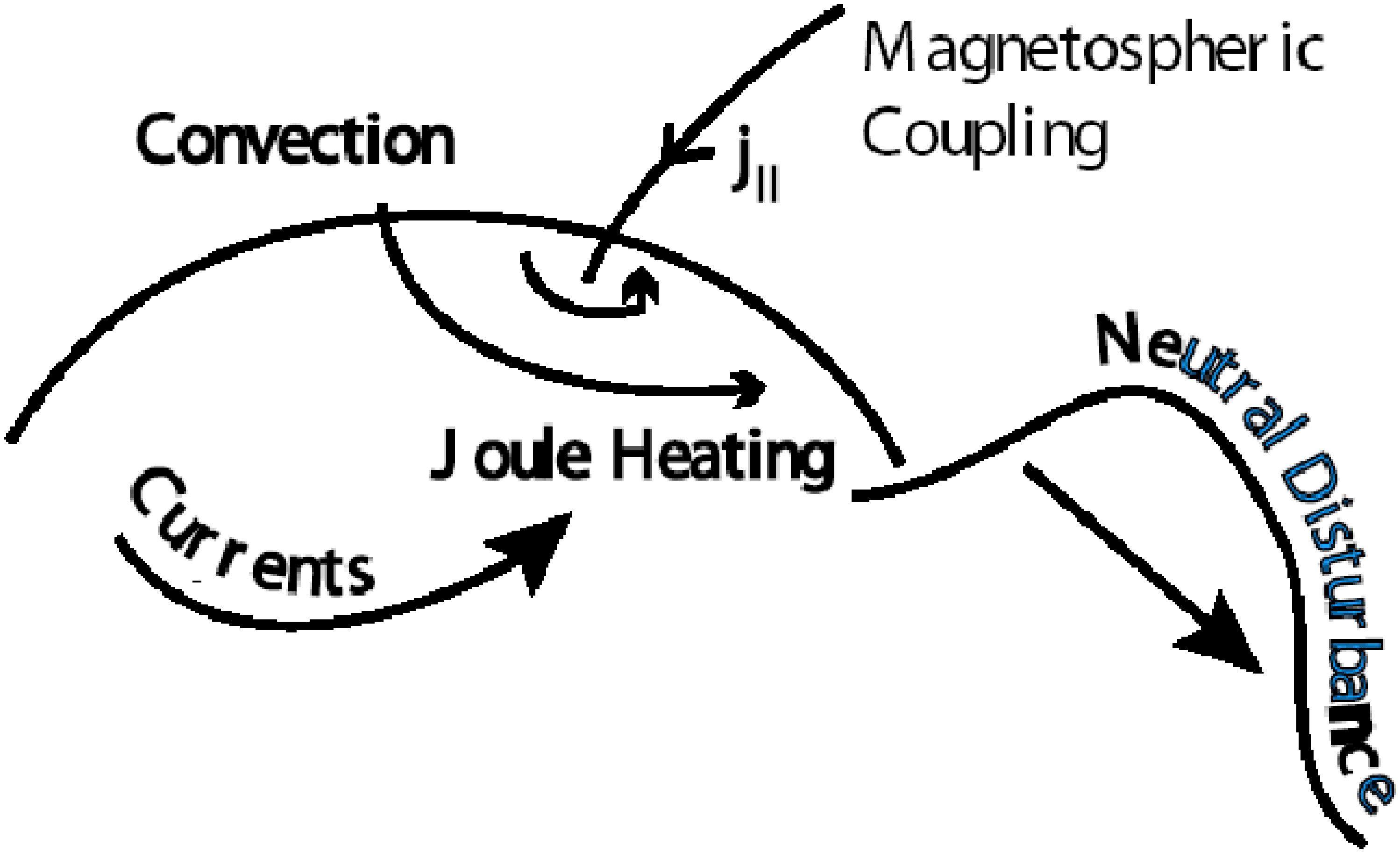


STAR accelerometer by Onera

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

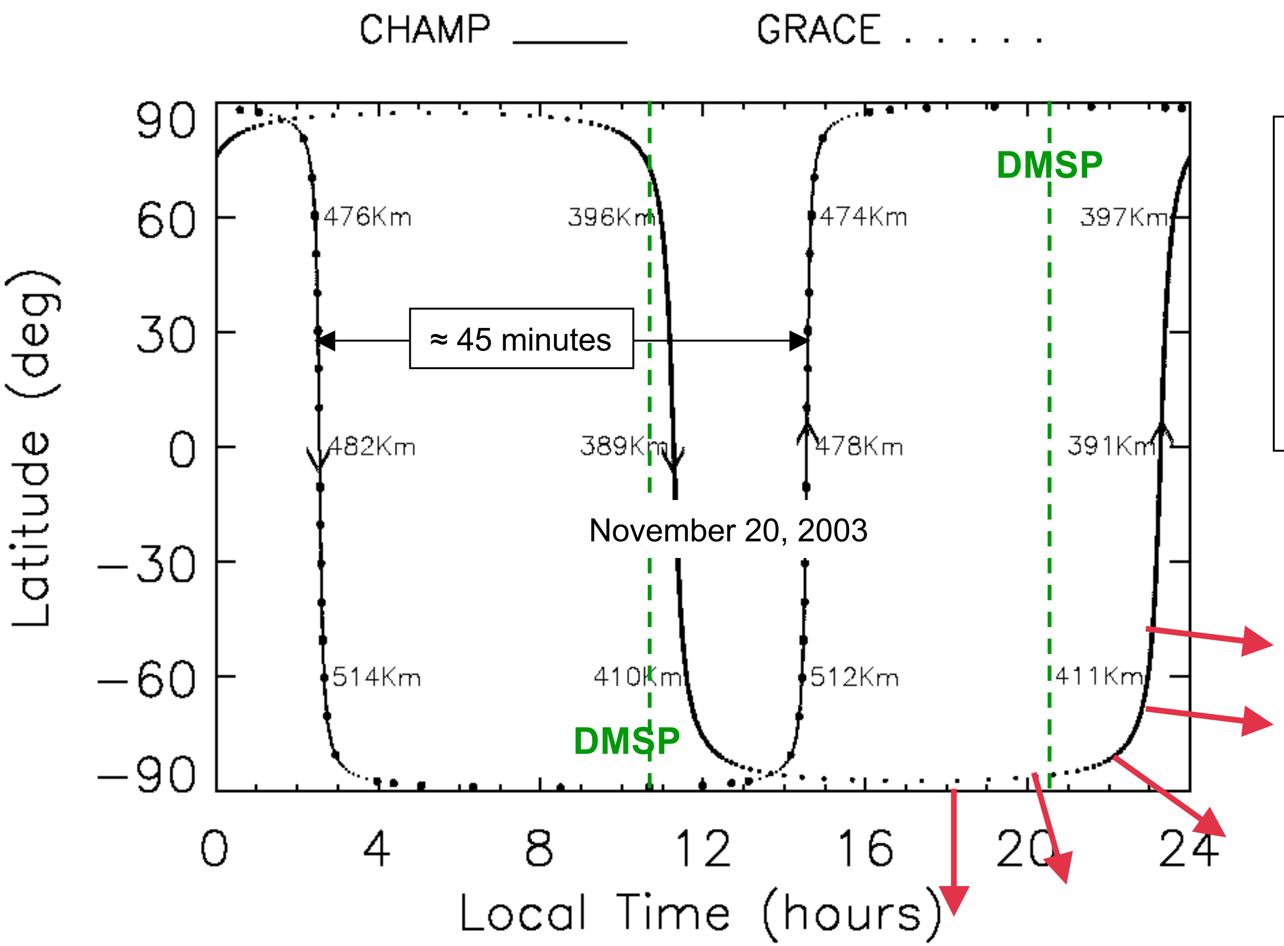
- *spacecraft attitude*
- *3-dimensional modeling of the spacecraft surface (shape, drag coefficient, reflectivity, etc.)*
- *accelerations due to thrusting*
- *solar radiation pressure*
- *Earth albedo radiation pressure*

CHAMP & GRACE in the Context of Magnetosphere-Ionosphere-Thermosphere Coupling



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

latitude, longitude, temporal and local time sampling

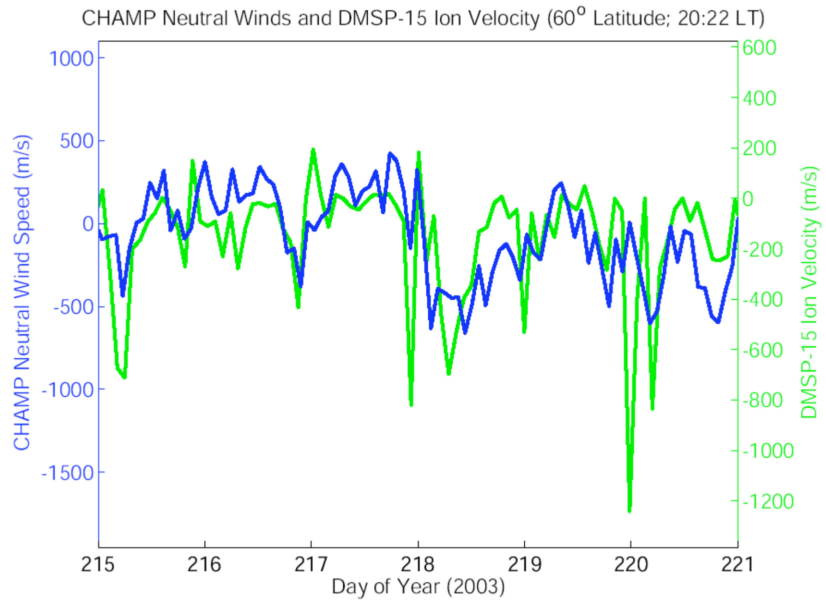


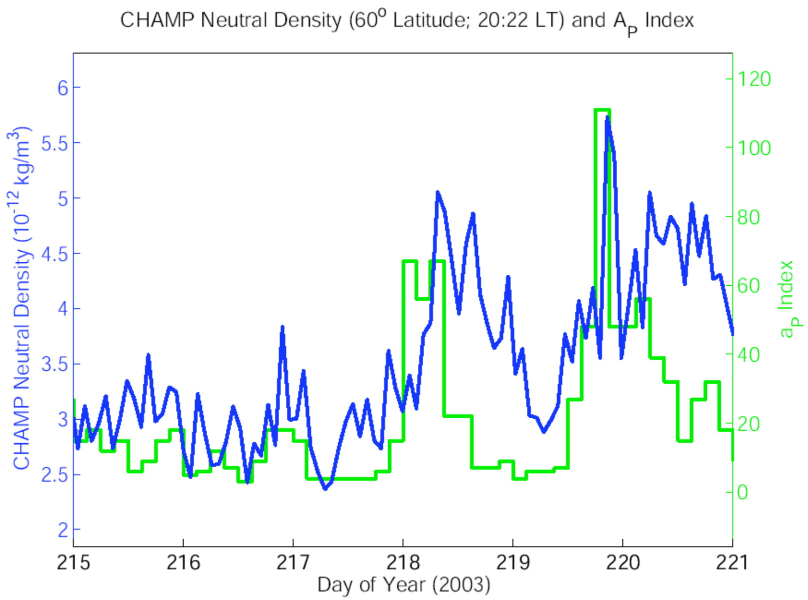
Local time precession rate of CHAMP is about 24 hours/133 days

Only cross -track winds can be inferred

$$\frac{\partial \vec{U}_n}{\partial t} \sim -\nu_{in}\left(\vec{U}_n - \vec{V}_i\right) + \ldots$$

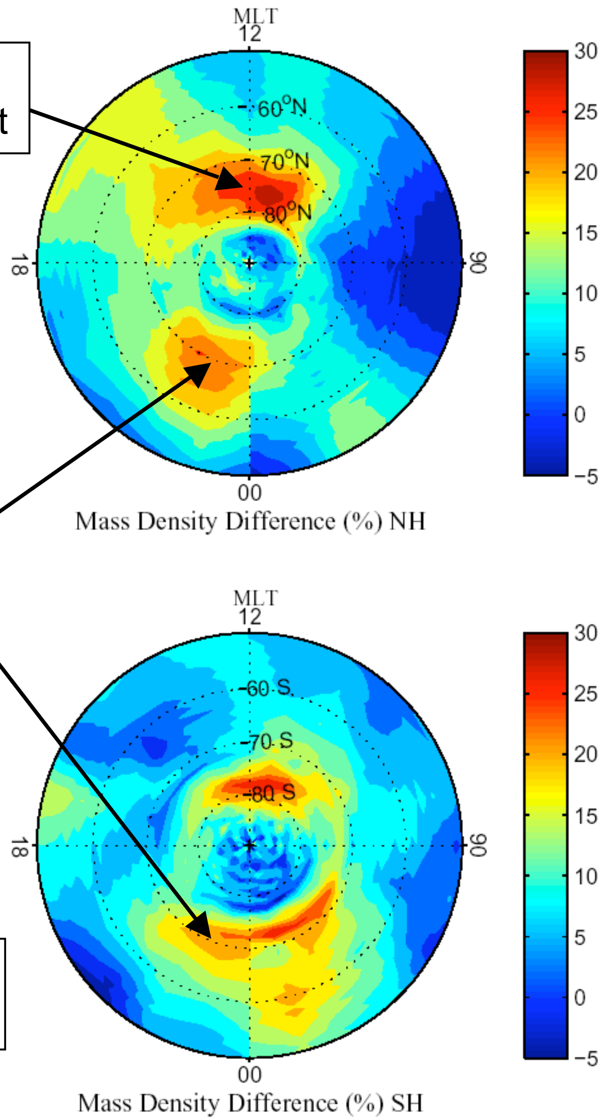
CHAMP and GRACE orbits periodically intersect with those of the DMSP satellites, offering the opportunity to study ion-neutral coupling processes.





Liu et al., JGR, 2005: “Global Distribution of the Thermospheric Mass Density Derived from CHAMP”

Percent Differences from MSIS90 for K_p = 0-2 during 2002 > 50° Latitude



Cusp region enhancement

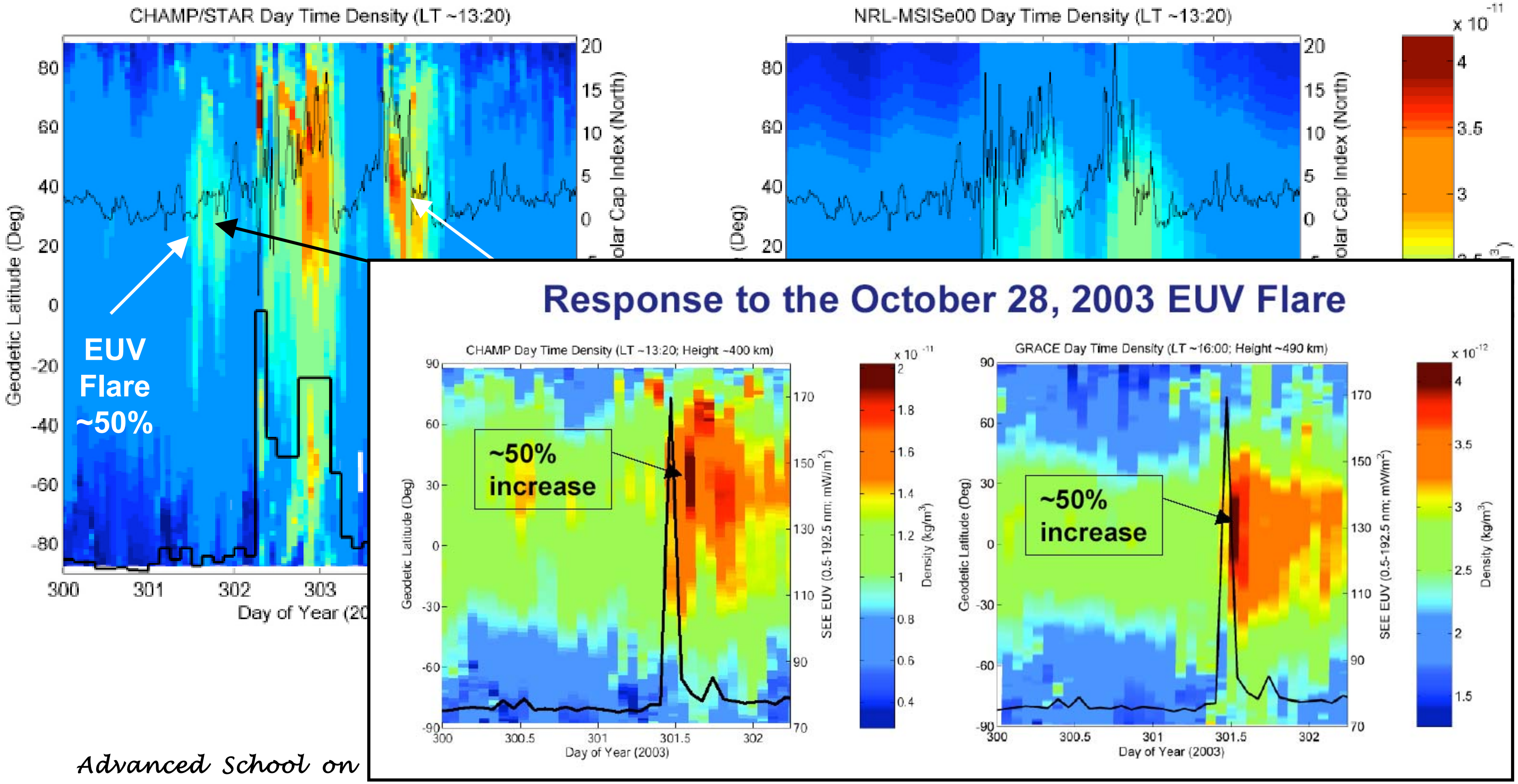
Pre-midnight/ midnight enhancement

North-South asymmetry

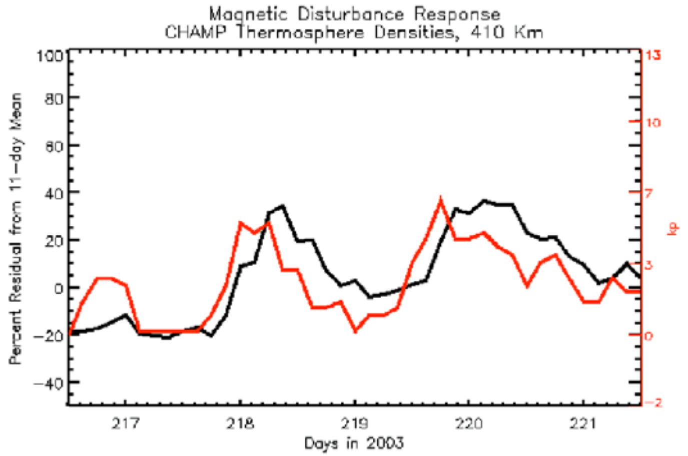
Co-location with field-aligned currents

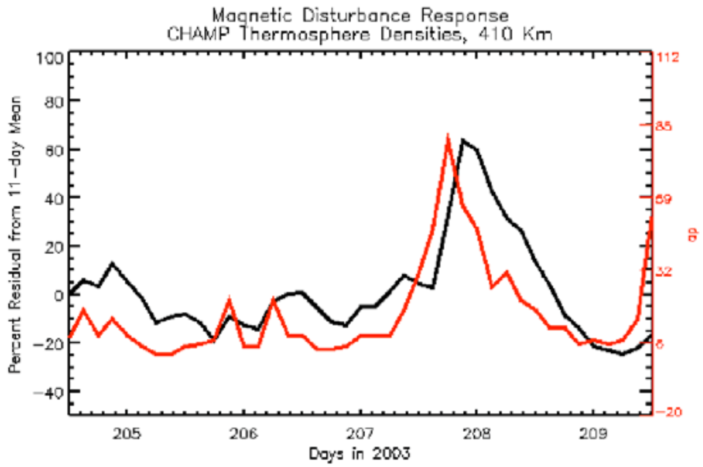
Thermosphere Density Response to the October 29-31 2003 Storms from CHAMP Accelerometer Measurements

(Sutton et al., JGR, 2005)

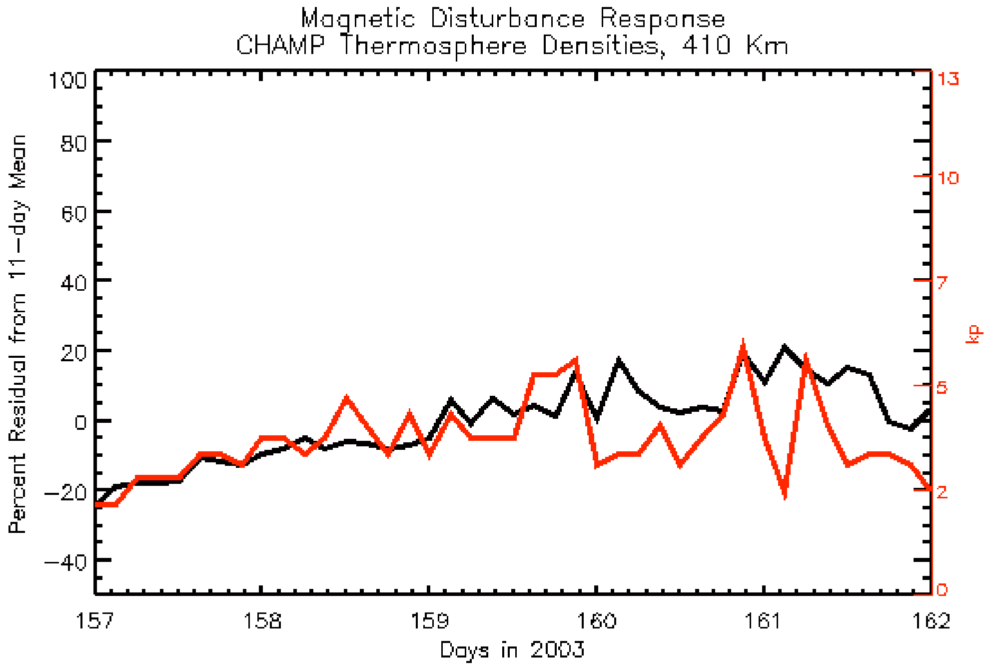


“Integrated (Orbit-Average) Response”

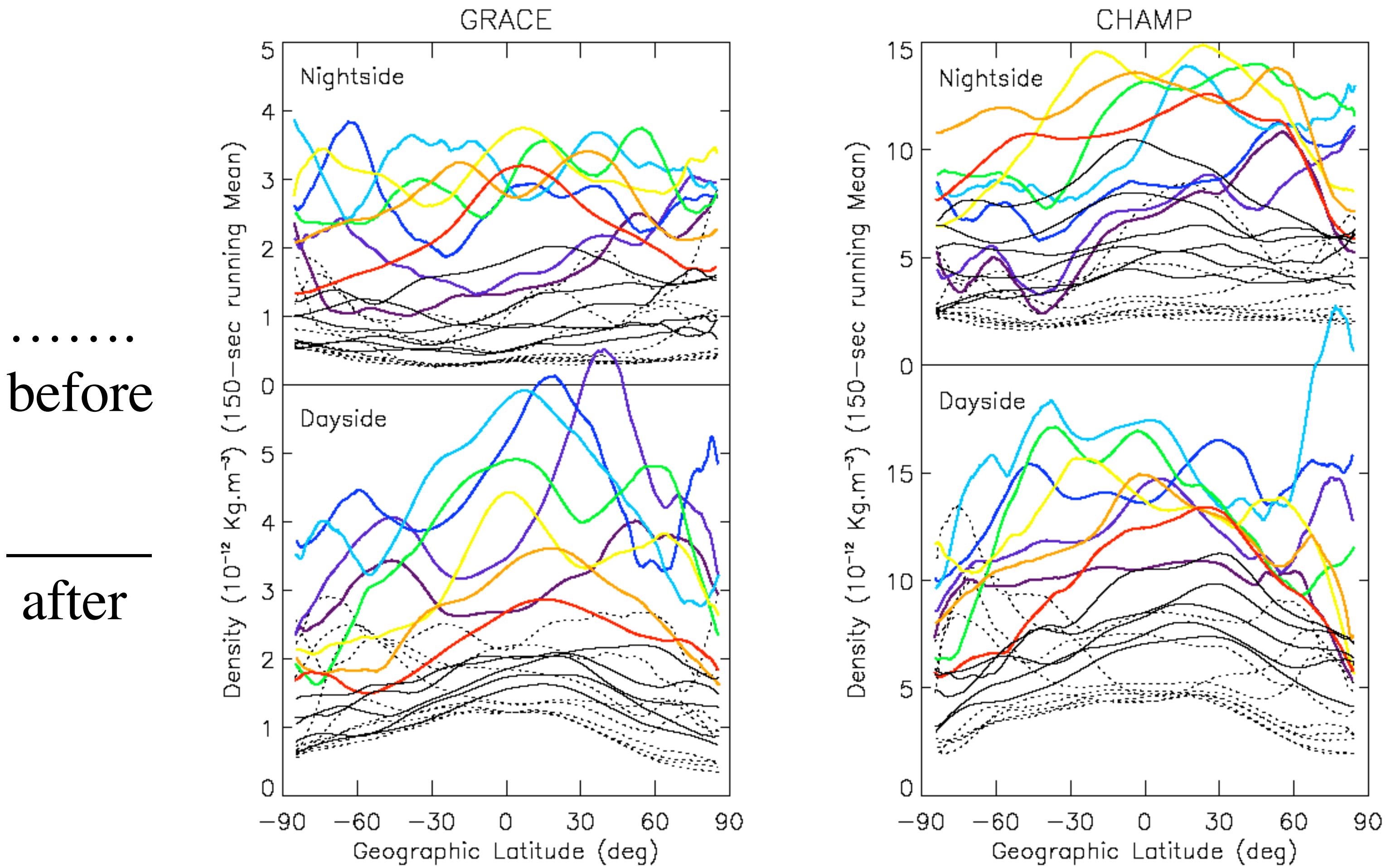




90-minute avg densities last half of 2003

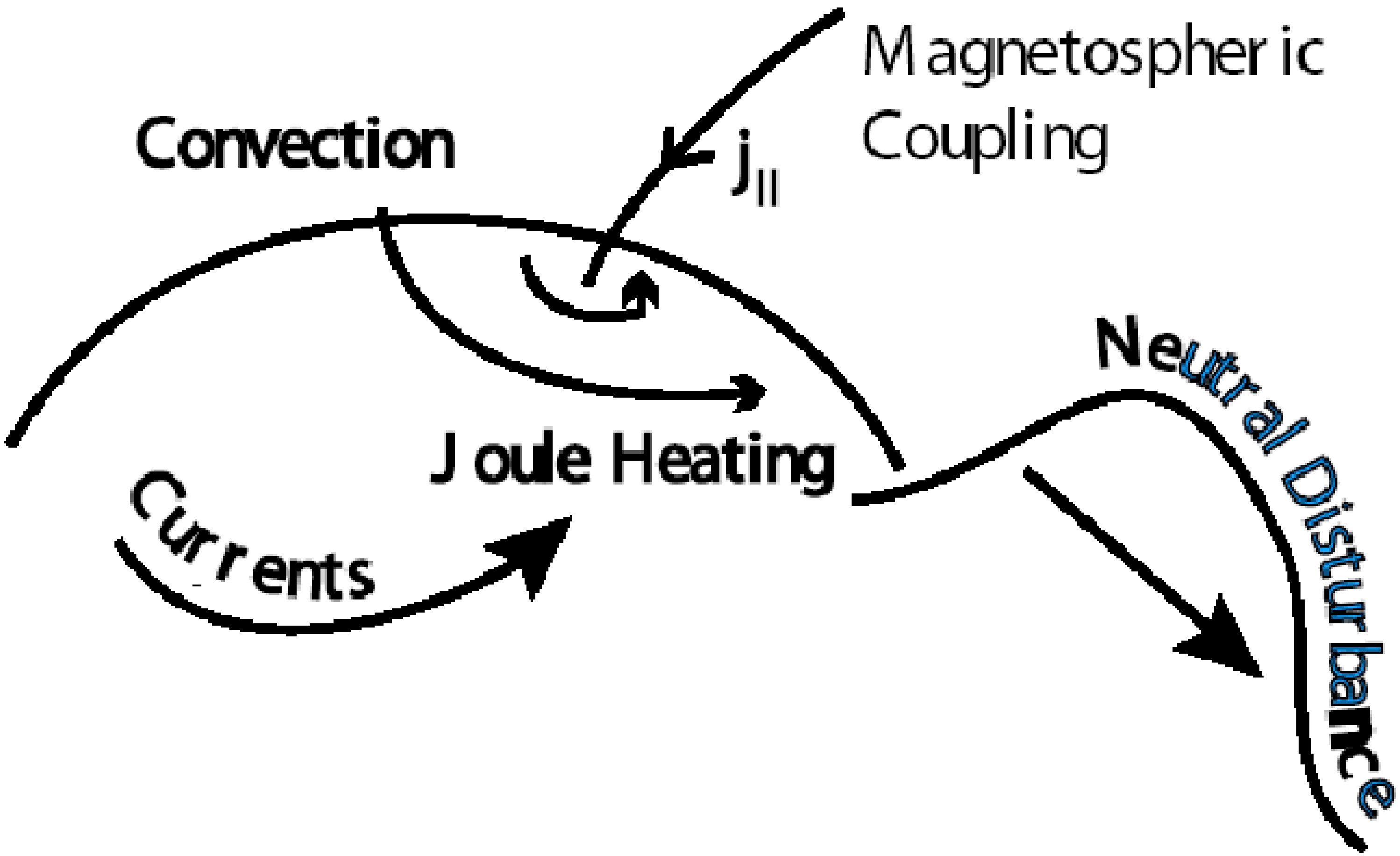


November 19-21 2003 Storm
Density Structures at Scales > 1200 km: "Large-Scale" Waves

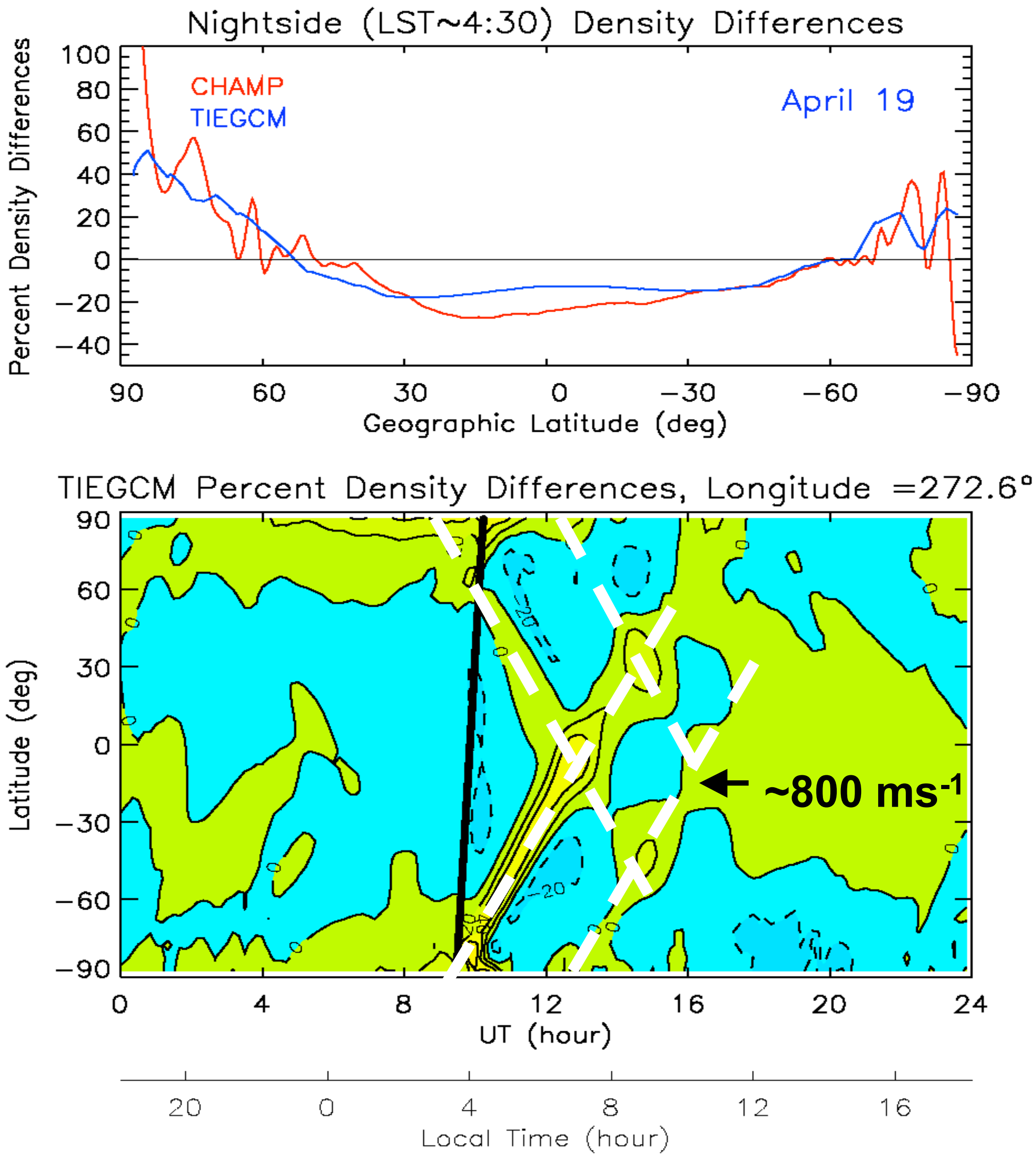


(150-sec (~1200 km) running means applied to raw data)

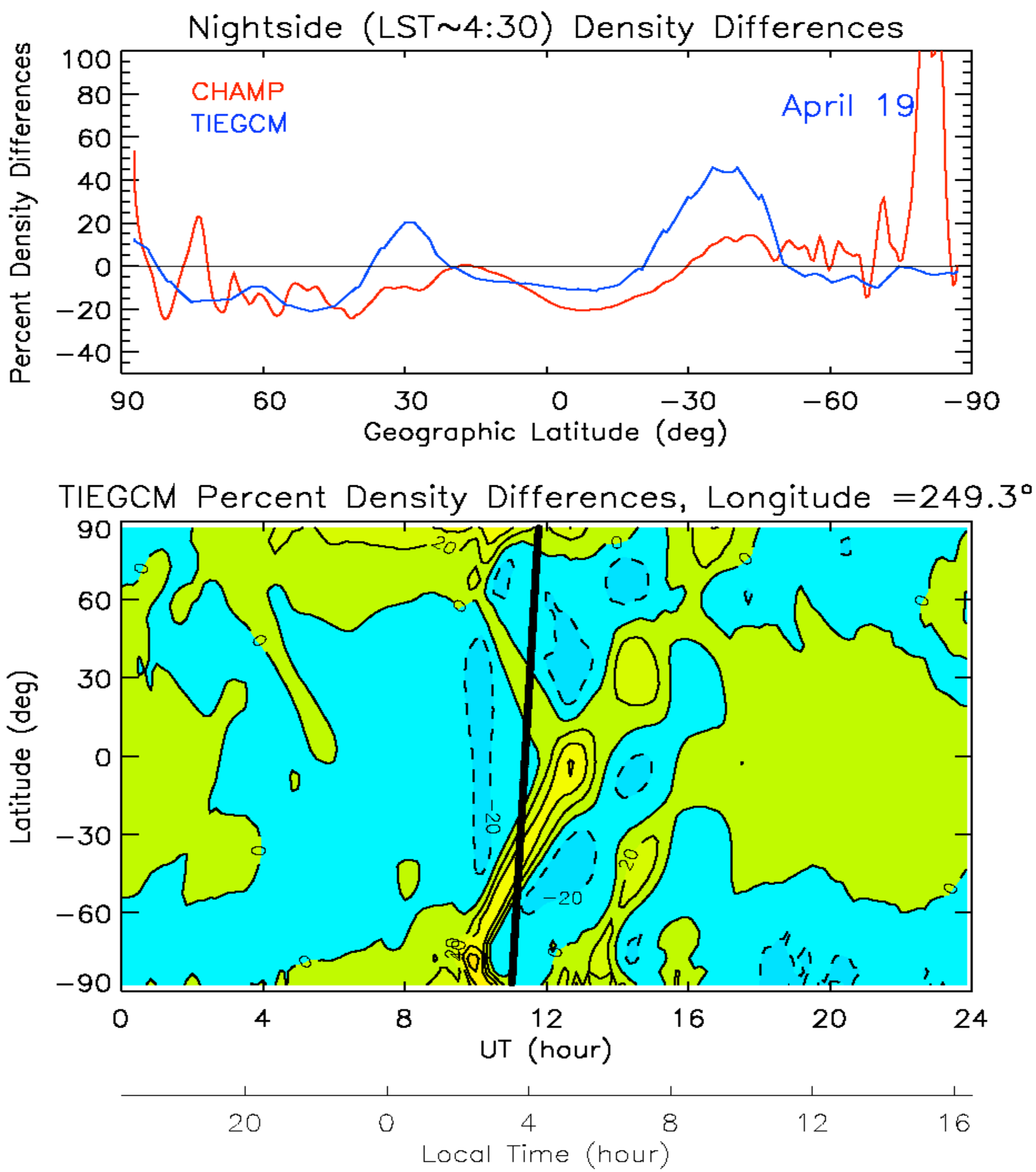
Time Delay and Traveling Atmospheric Disturbances



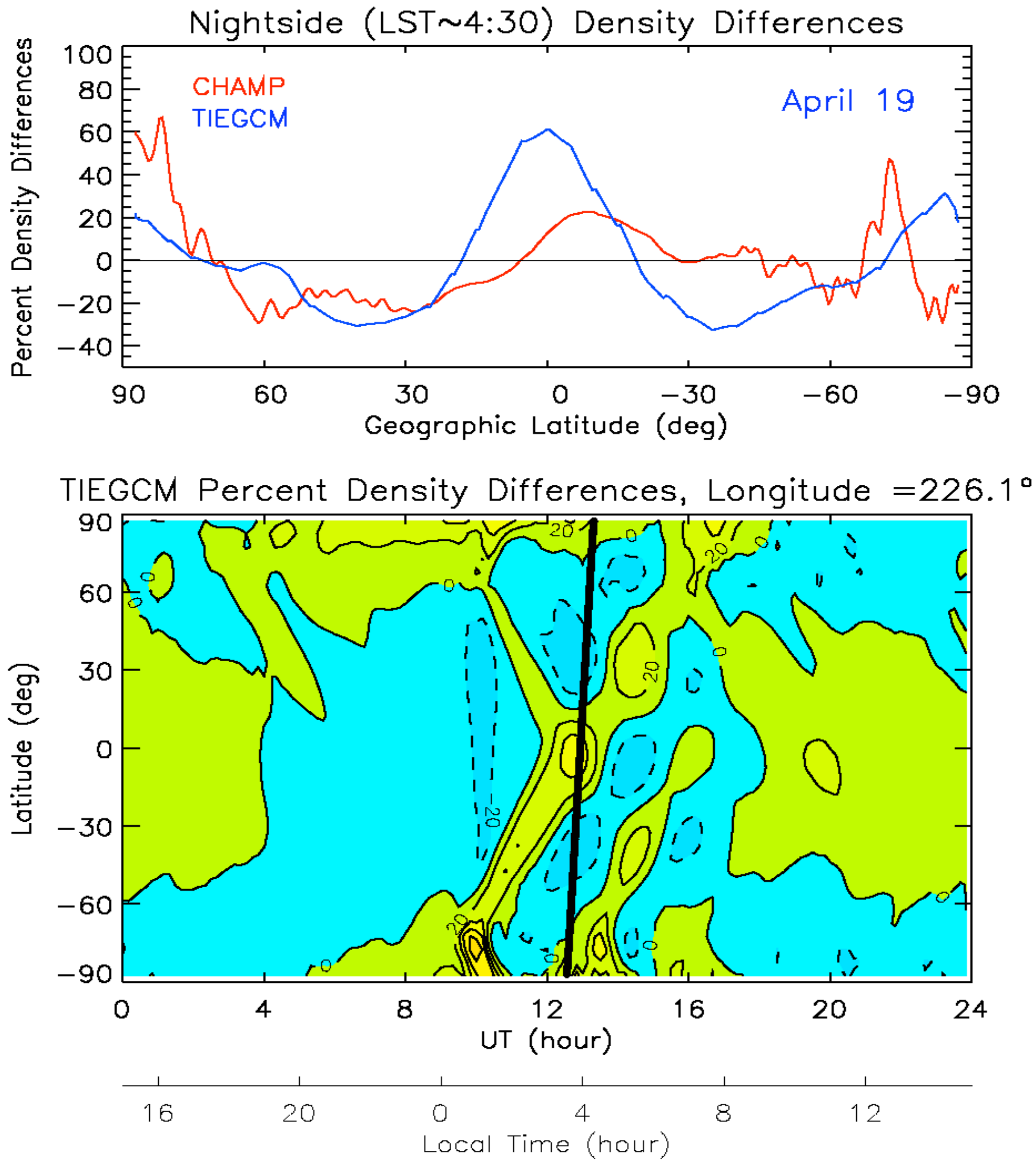
% density difference from orbit average



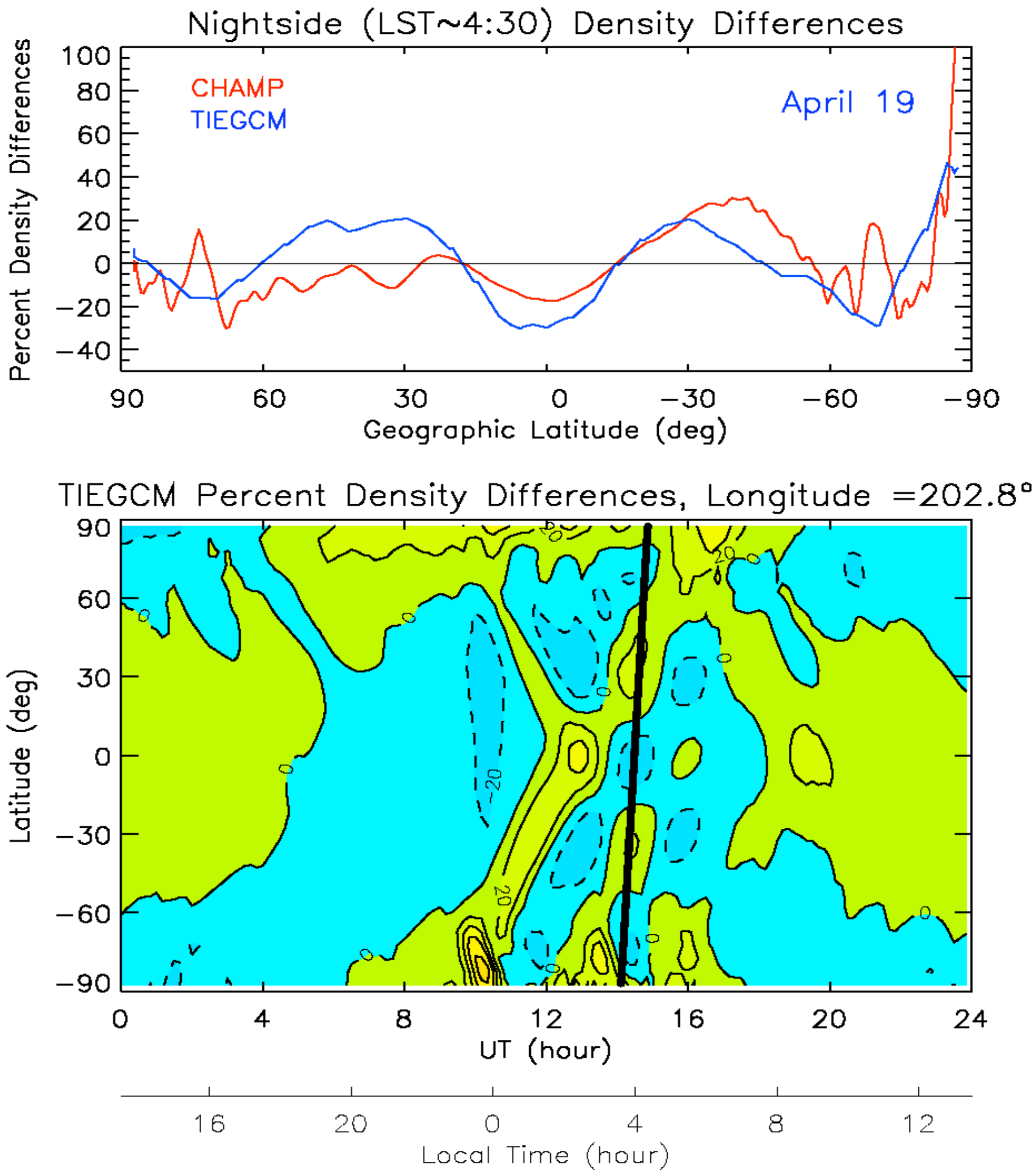
April 2002 storm period



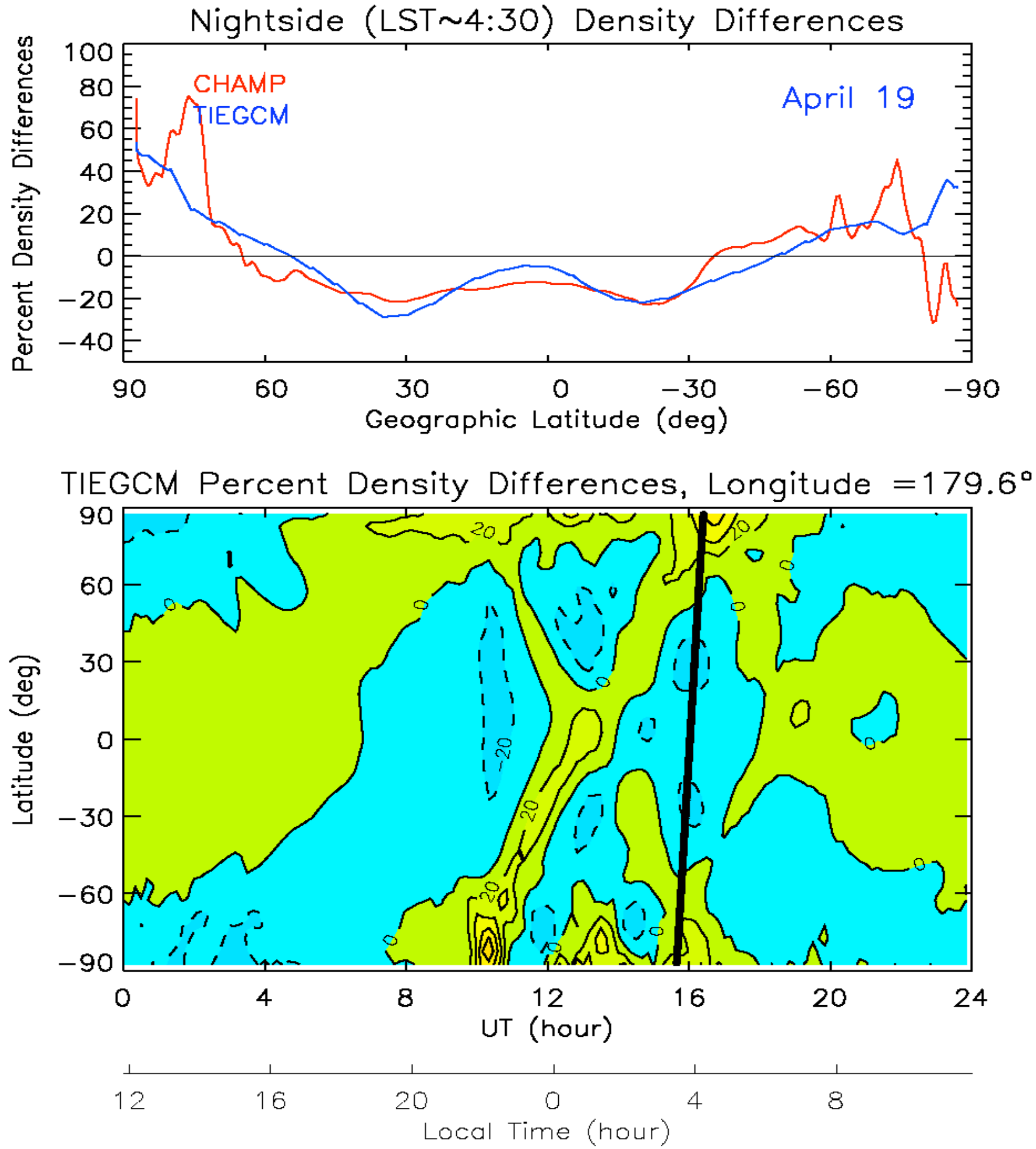
Nightside (LST~4:30) Density Differences
CHAMP
TIEGCM
April 19
Percent Density Differences
Geographic Latitude (deg)
TIEGCM Percent Density Differences, Longitude =249.3°
Latitude (deg)
UT (hour)
Local Time (hour)



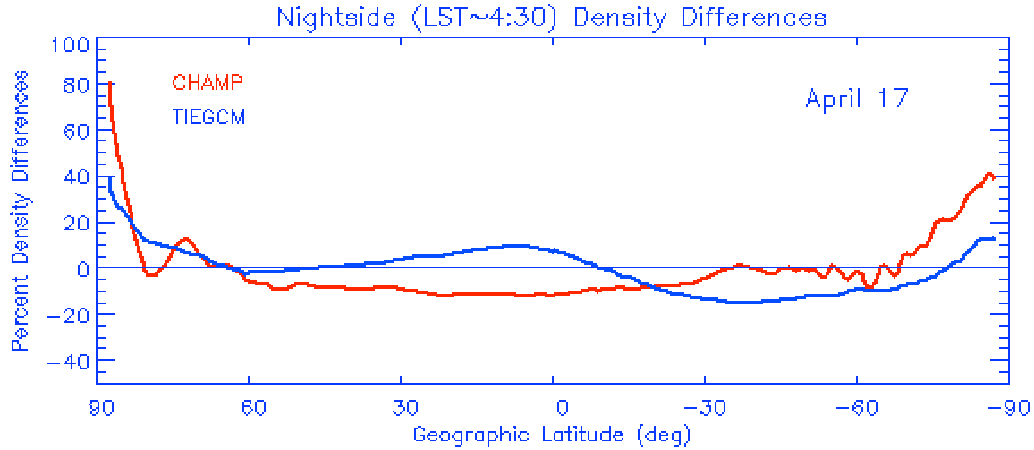
Nightside (LST~4:30) Density Differences
Percent Density Differences
CHAMP
TIEGCM
April 19
100
80
60
40
20
0
−20
−40
90
60
30
0
−30
−60
−90
Geographic Latitude (deg)
TIEGCM Percent Density Differences, Longitude =226.1°
Latitude (deg)
90
60
30
0
−30
−60
−90
0
4
8
12
16
20
24
UT (hour)
16
20
0
4
8
12
Local Time (hour)

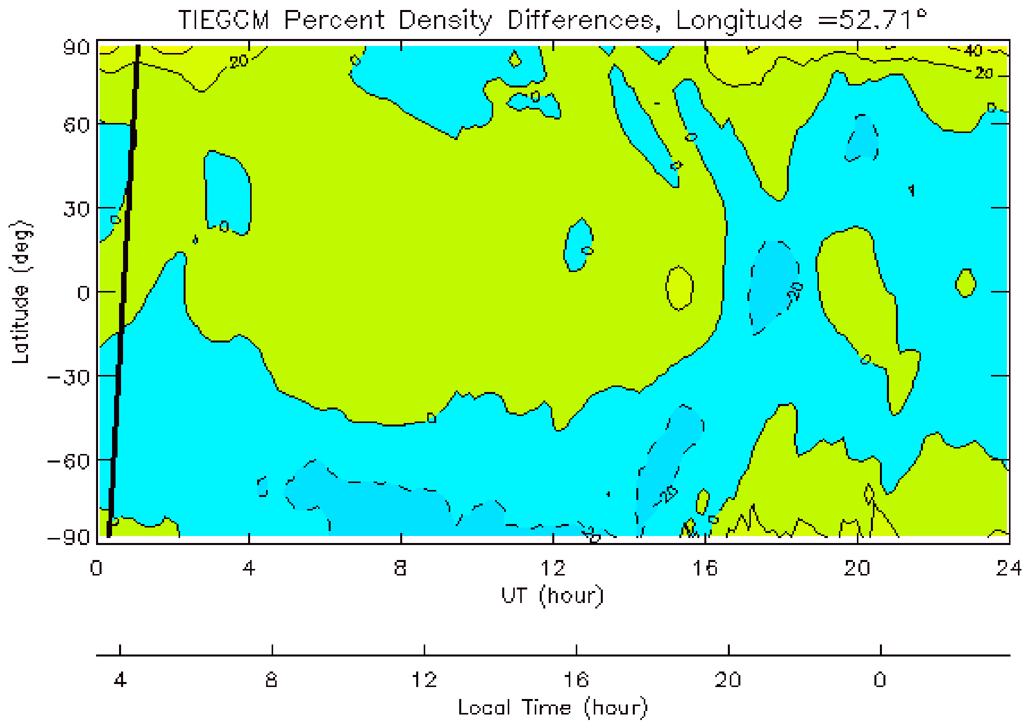


Nightside (LST~4:30) Density Differences
CHAMP
TIEGCM
April 19
Percent Density Differences
100
80
60
40
20
0
−20
−40
90
60
30
0
−30
−60
−90
Geographic Latitude (deg)
TIEGCM Percent Density Differences, Longitude =202.8°
Latitude (deg)
UT (hour)
0
4
8
12
16
20
24
Local Time (hour)
16
20
0
4
8
12

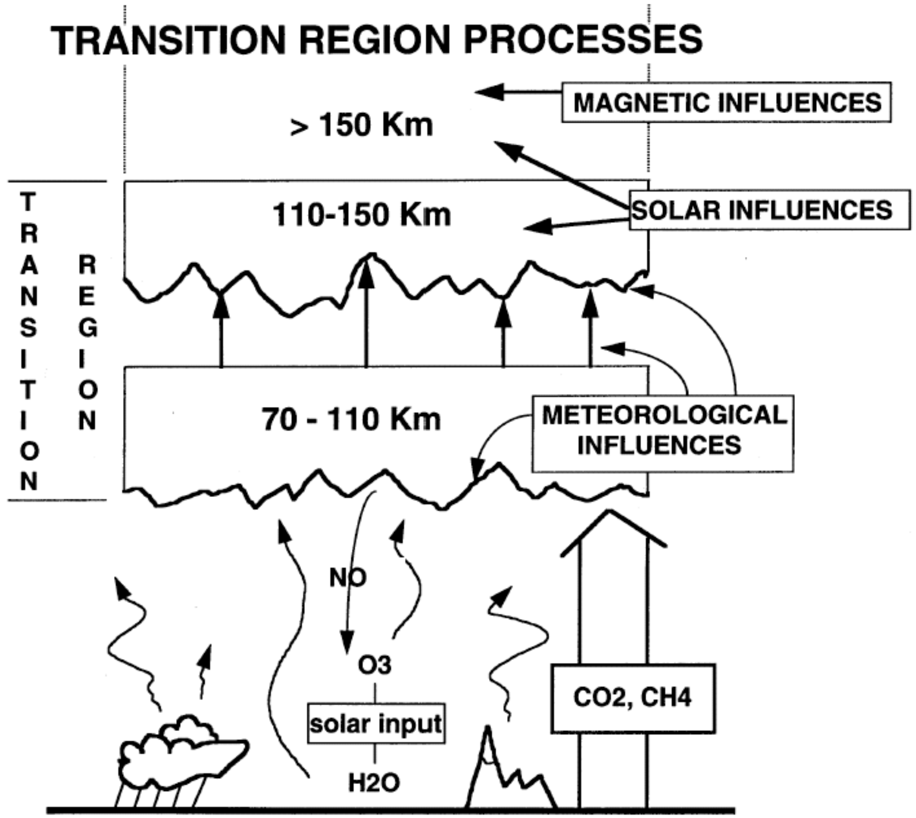


Nightside (LST~4:30) Density Differences
Percent Density Differences
100
80
60
40
20
0
−20
−40
CHAMP
TIEGCM
April 19
90
60
30
0
−30
−60
−90
Geographic Latitude (deg)
TIEGCM Percent Density Differences, Longitude =179.6°
Latitude (deg)
0
4
8
12
16
20
24
UT (hour)
12
16
20
0
4
8
Local Time (hour)

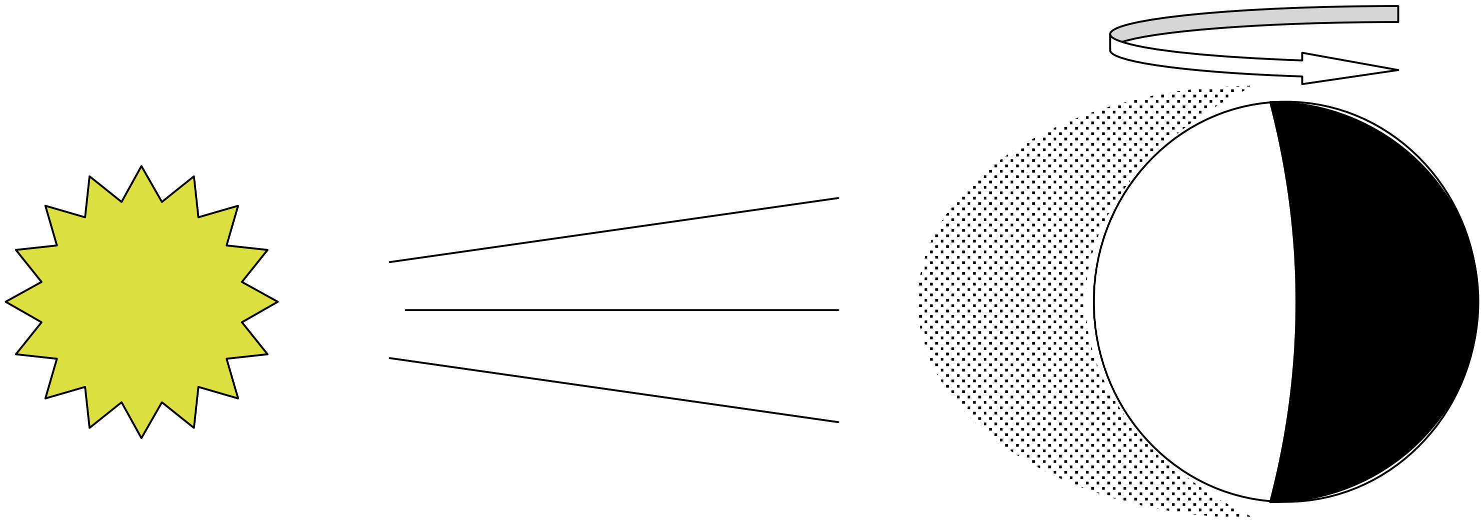

Nightside (LST~4:30) Density Differences
CHAMP
TIEGCM
April 17
Percent Density Differences
Geographic Latitude (deg)
100
80
60
40
20
0
-20
-40
90
60
30
0
-30
-60
-90

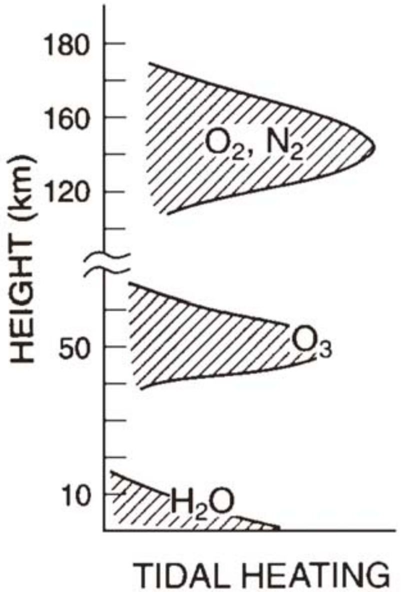

TIEGCM Percent Density Differences, Longitude =52.71°
Latitude (deg)
UT (hour)
Local Time (hour)
90
60
30
0
-30
-60
-90
0
4
8
12
16
20
24
4
8
12
16
20
0

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.

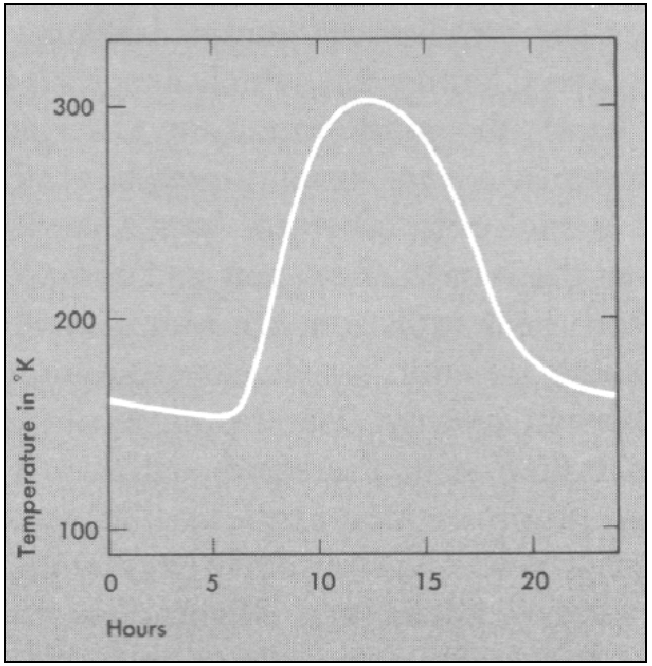
In general, tides are capable of propagating vertically to higher, less dense, regions of the atmosphere; the oscillations grow exponentially with height.

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

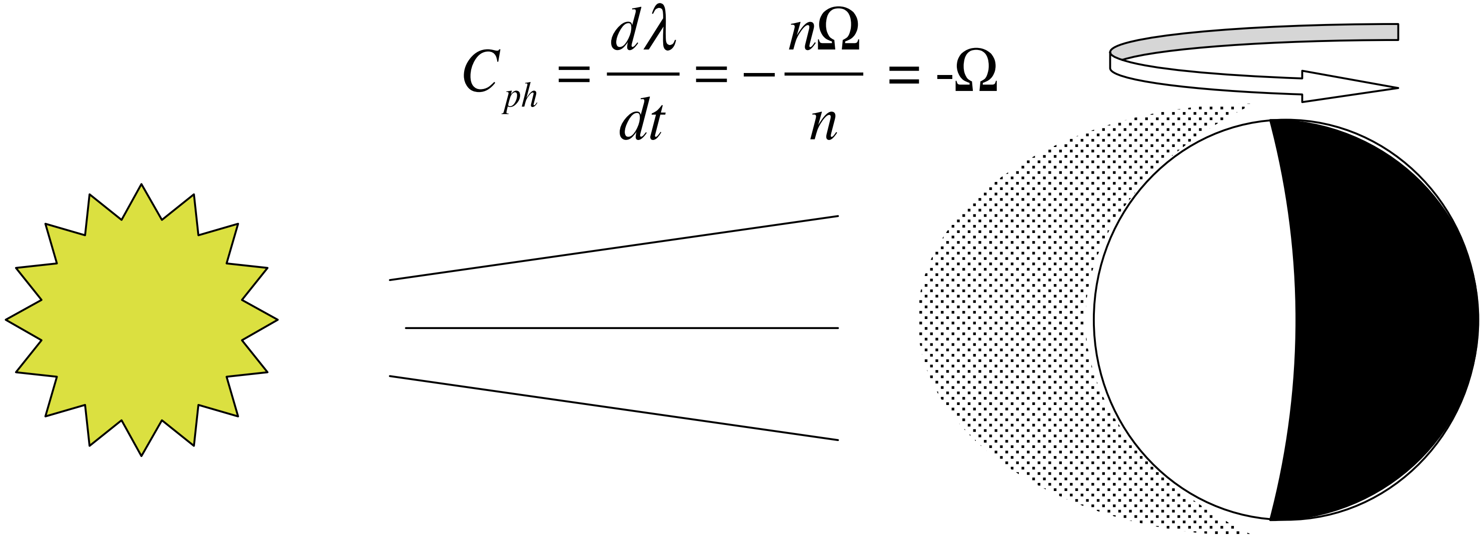
Converting to universal time $t_{LT} = t + \lambda/\Omega$, we have

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.

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.

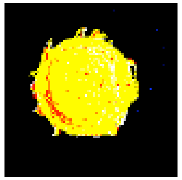
“Weather” due to Tidal Variability

Eastward Winds over Saskatoon, Canada, 65-100 km

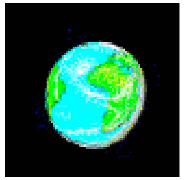
Note the predominance of the semidiurnal tide at upper levels, with downward phase progression.

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

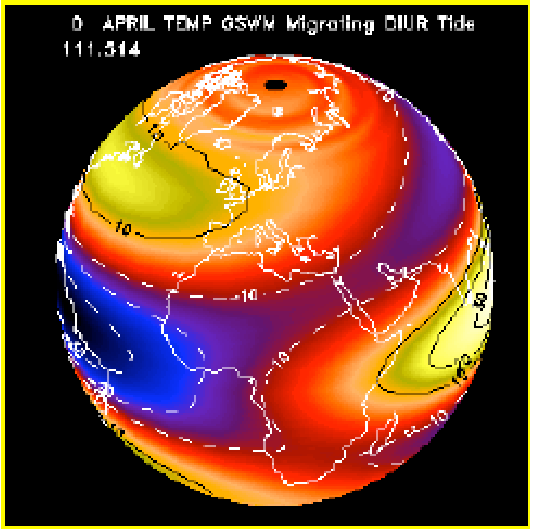


GSWM: Global Scale Wave Model



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!)

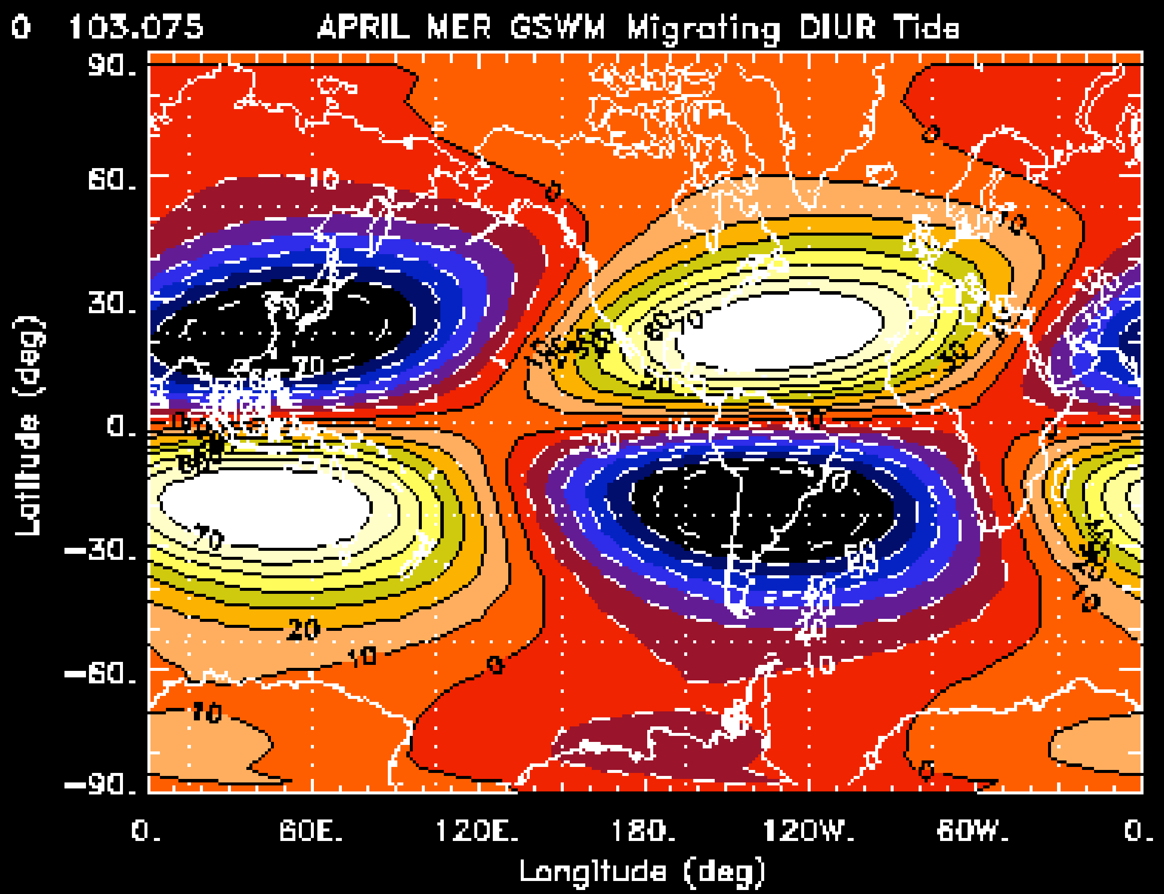
Download tables of monthly GSWM-00 migrating **diurnal** and **semidiurnal** results.

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

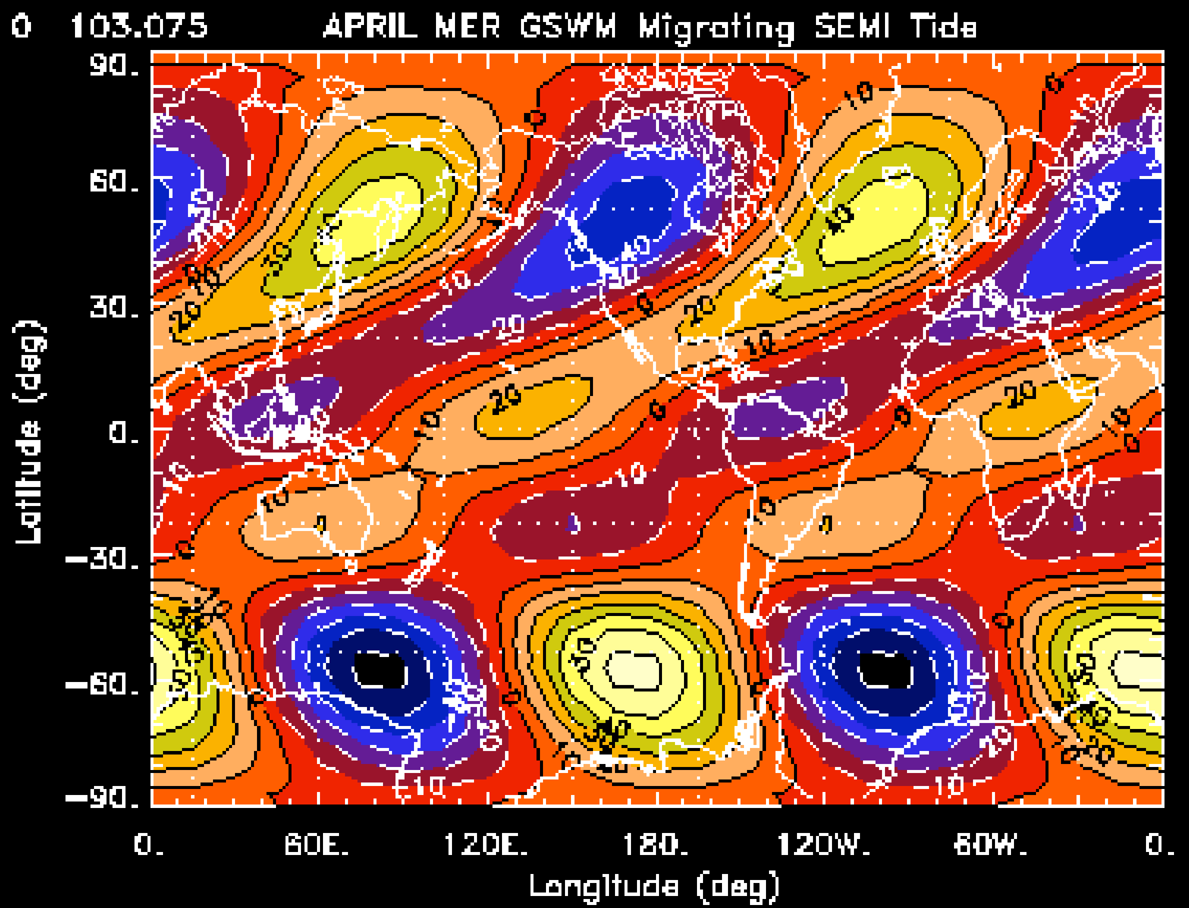
Meridional wind field at 103 km (April) associated with the diurnal tide propagating upward from the lower atmosphere, mainly excited by near-IR absorption by H_2O in the troposphere



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.

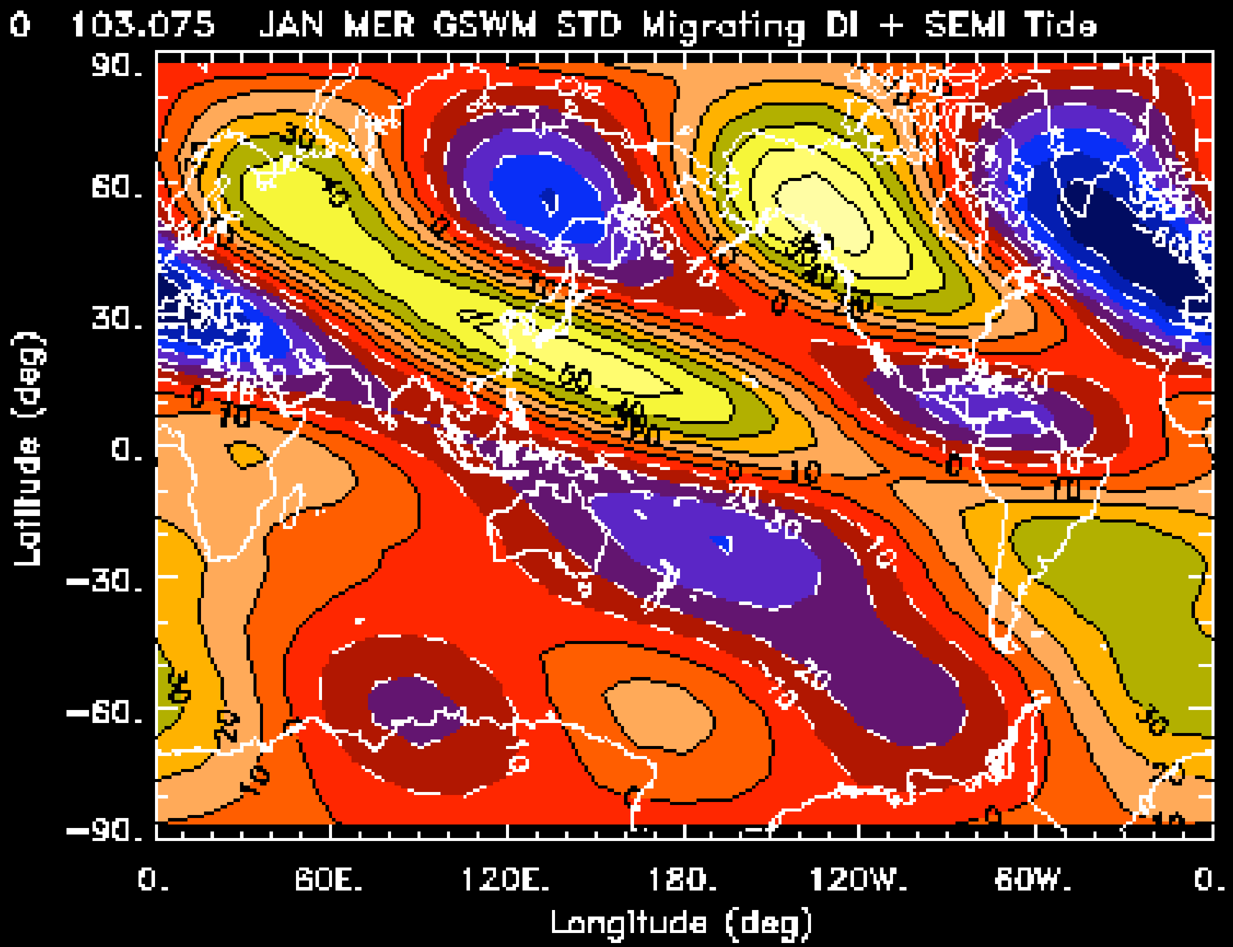
Meridional wind field at 103 km (April) associated with the semidiurnal tide propagating upward from the lower atmosphere, mainly excited by near-IR absorption by O_3 in the troposphere



Courtesy M. Hagan

The tide propagates westward with respect to the surface once per day, and is locally seen as the same 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



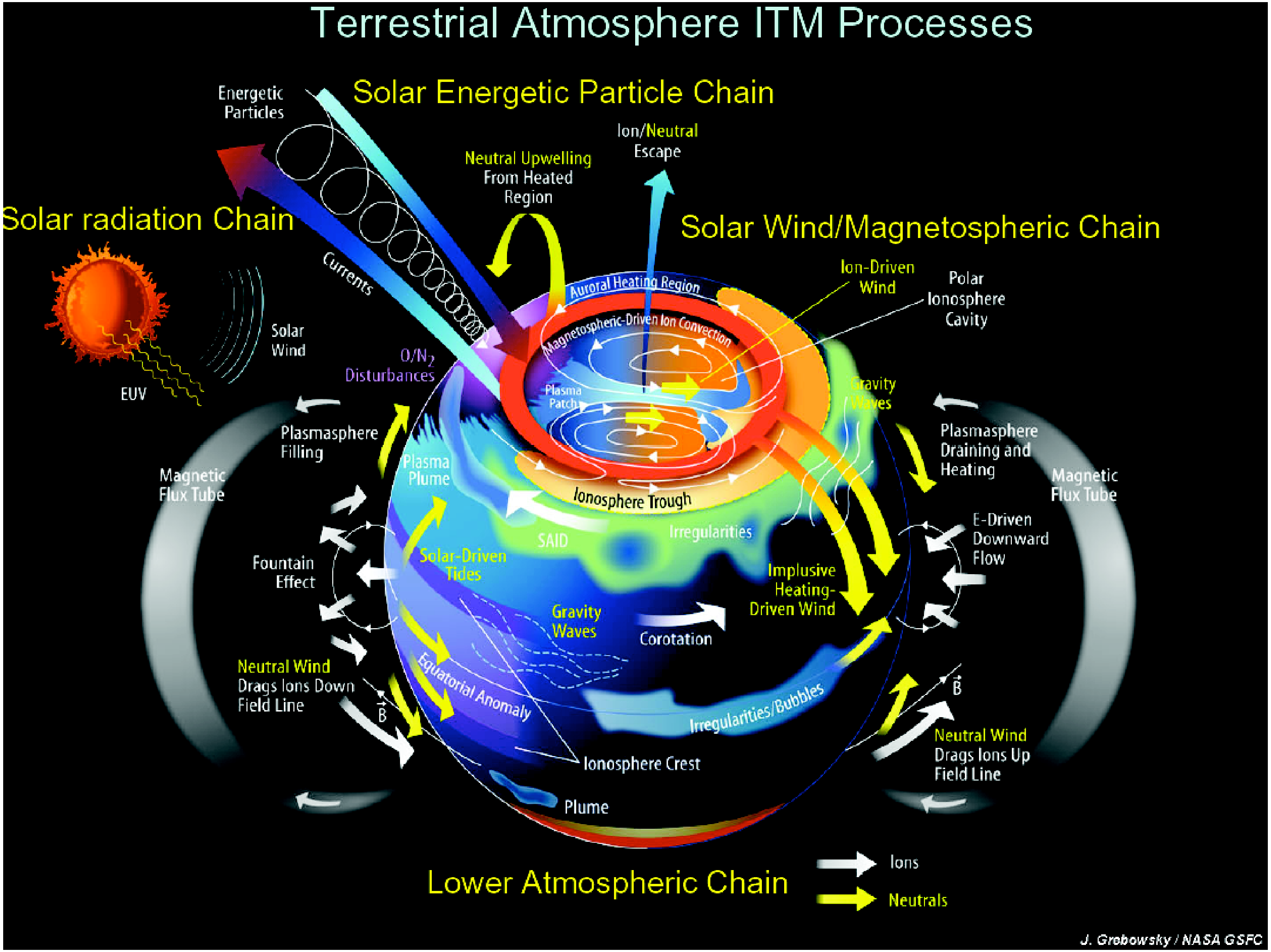
Courtesy M. Hagan

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.

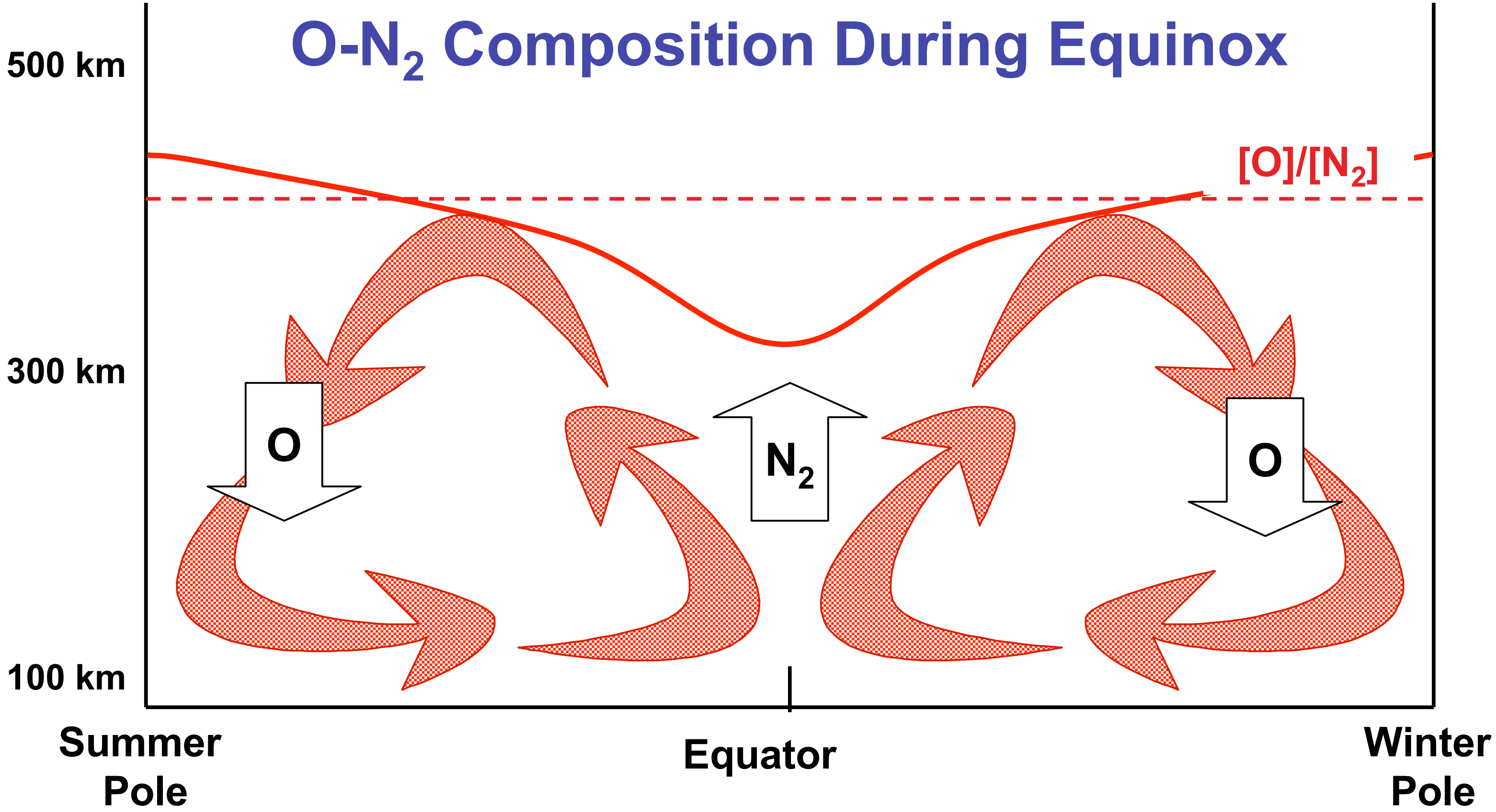
Summary of Basic Thermosphere Characteristics

- Solar heating is main energy source
- Main cooling is through molecular conduction; secondary, radiative cooling by O, CO_2, NO
- Main gases: O, O_2, N_2, He (high altitudes only)
- Strong variability of temperature, winds and composition with solar cycle, season, local time, geomagnetic activity
- The seasonal composition changes are controlled primarily by global winds, the diurnal ones by photochemistry
- At low latitudes effects of upward propagating tides, planetary waves and gravity waves are important
- At high latitudes, heating from the magnetosphere occurs in the form of Joule heating and precipitating particles

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/N_2 Disturbances
Auroral Heating Region
Magnetospheric-Driven Ion Convection
Ion-Driven Wind
Polar Ionosphere Cavity
Plasma Patch
Gravity Waves
Plasmasphere Filling
Plasma Plume
Magnetic Flux Tube
Plasmasphere Draining and Heating
Magnetic Flux Tube
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

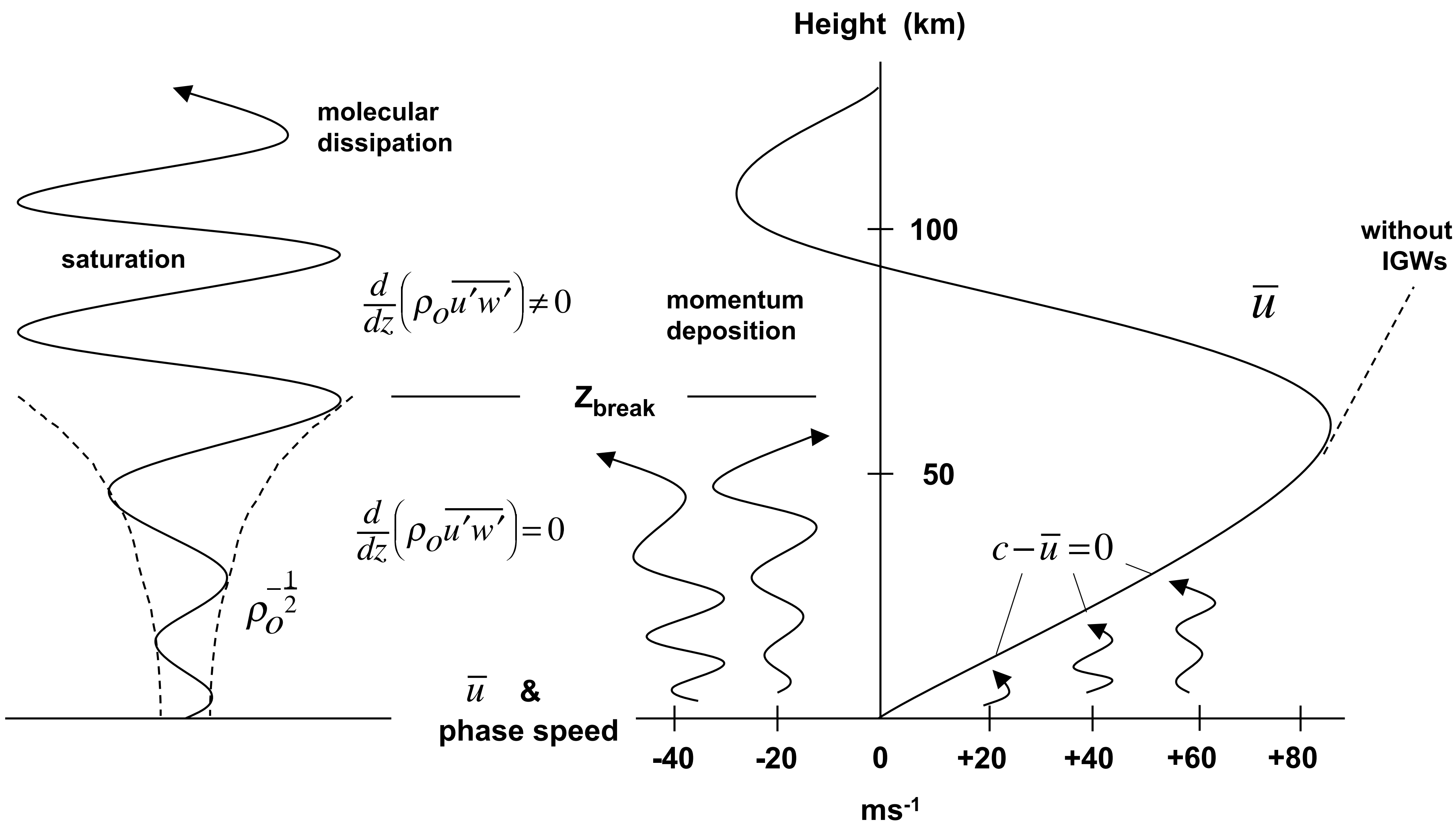
Solar EUV-Driven Circulation and O-N_2 Composition During Equinox



The increased mean mass (M) over regions of upwelling (and beyond) reduces the total density scale height H = R*T/Mg at a given altitude, essentially "mixing" and "compressing" the atmosphere.

However, from model simulations (Fuller-Rowell, 1998), this effect is more important during solstice, even at low latitudes, such that a semiannual variation in total density results, with maxima at the equinoxes.

Gravity Wave Coupling in Earth's Atmosphere



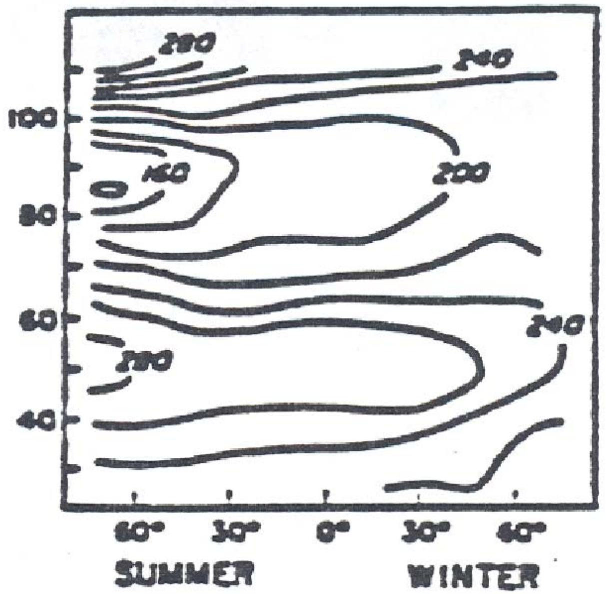
Gravity Waves and Effects on the Mean Thermal Structure

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