Atmospheric Dynamics in the Equatorial Region: Long-period motions and their variabilities

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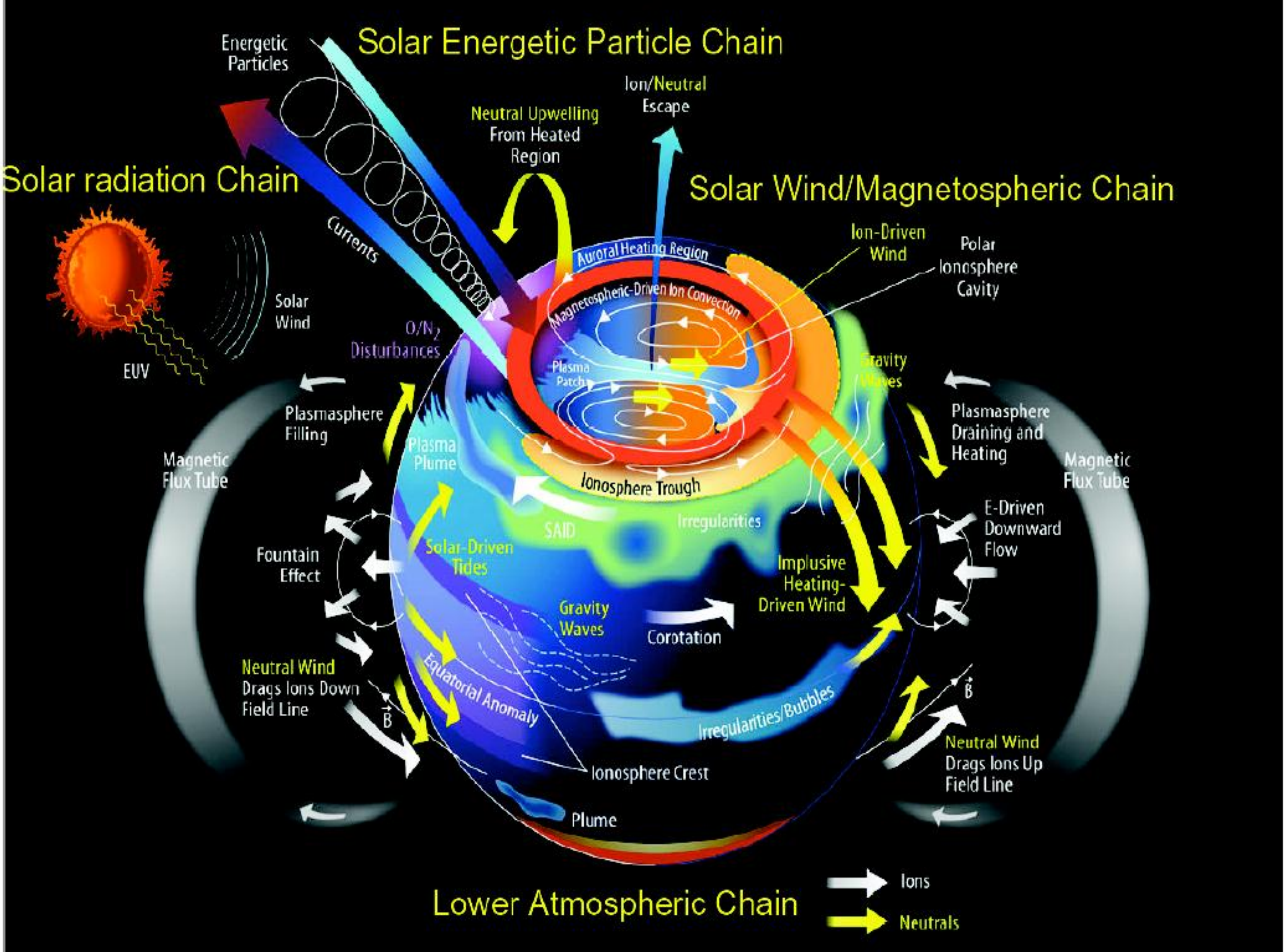
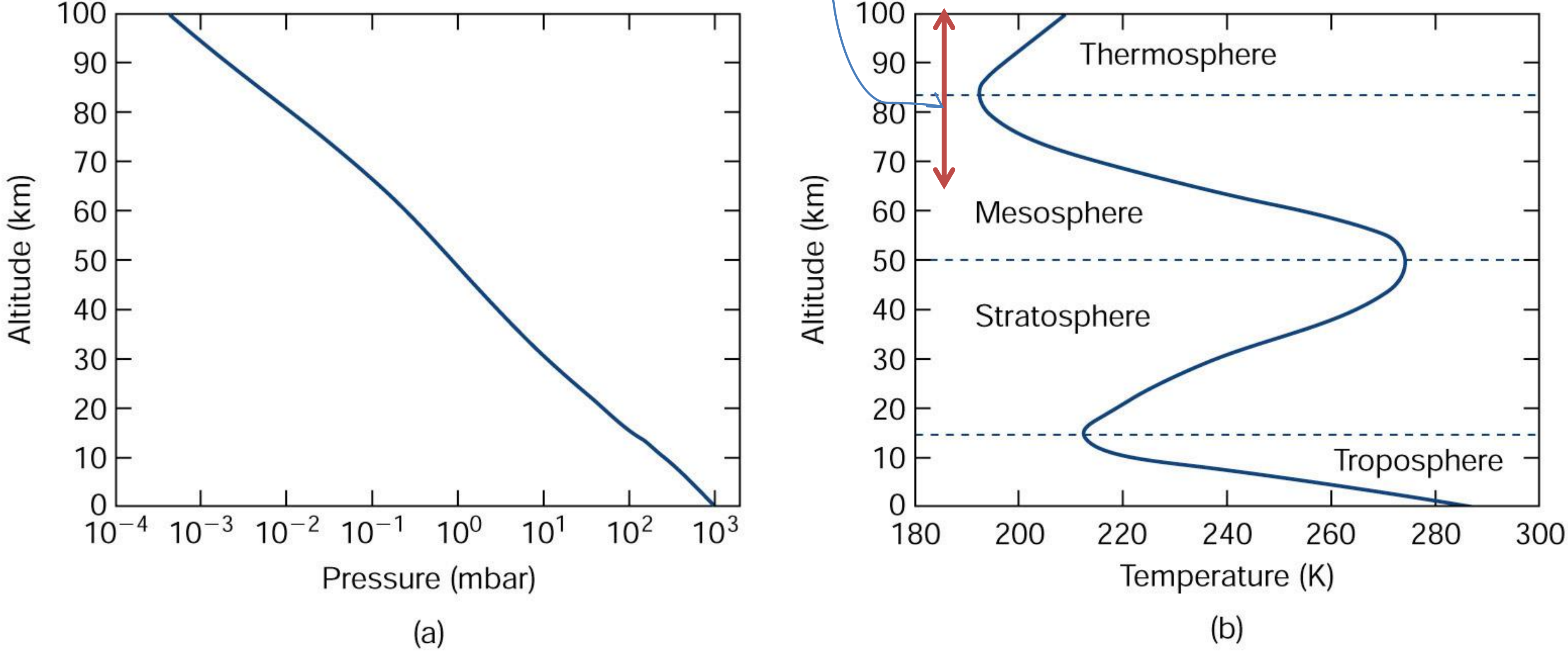
Atmospheric Coupling Processes I, ISWI-MAGDAS Space Science School, Ciloto, 21 September 2012

Terrestrial Atmosphere ITM Processes

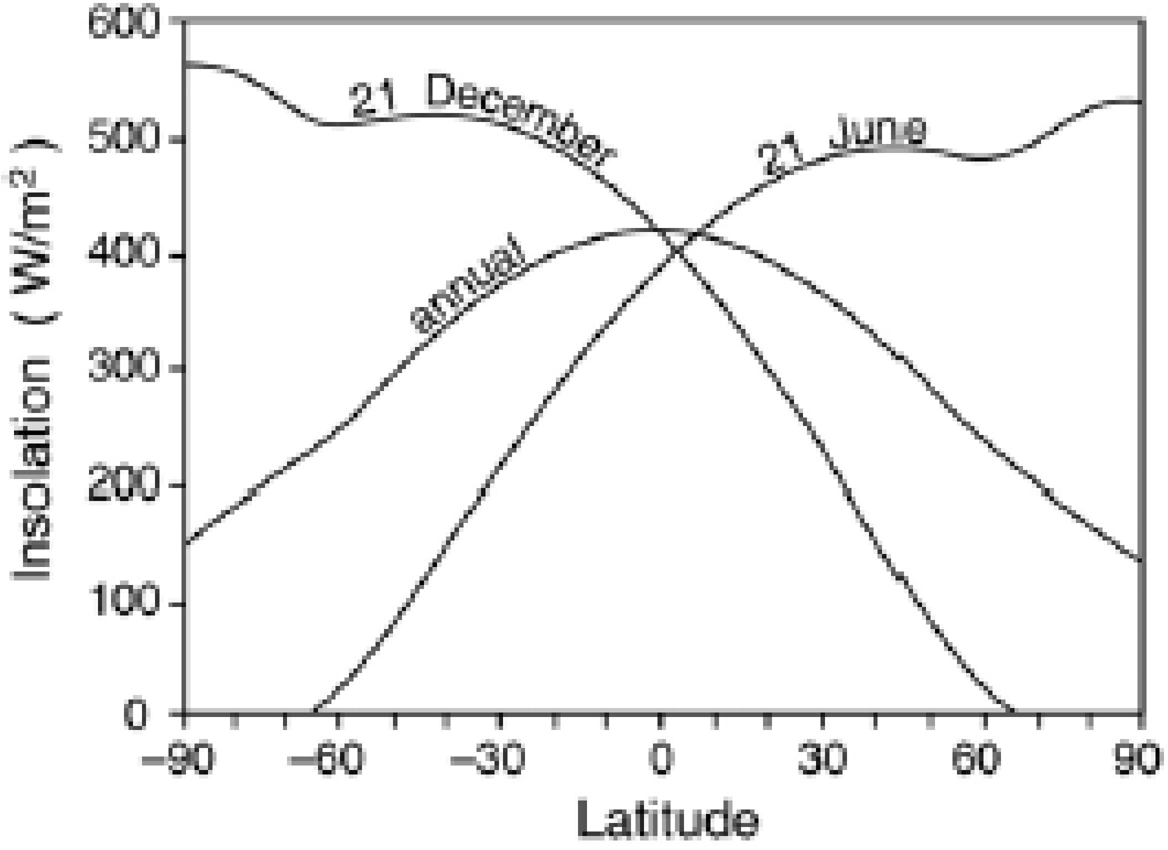


J. Grobowsky / NASA GSFC

Critical Transition Region (60-120 km)

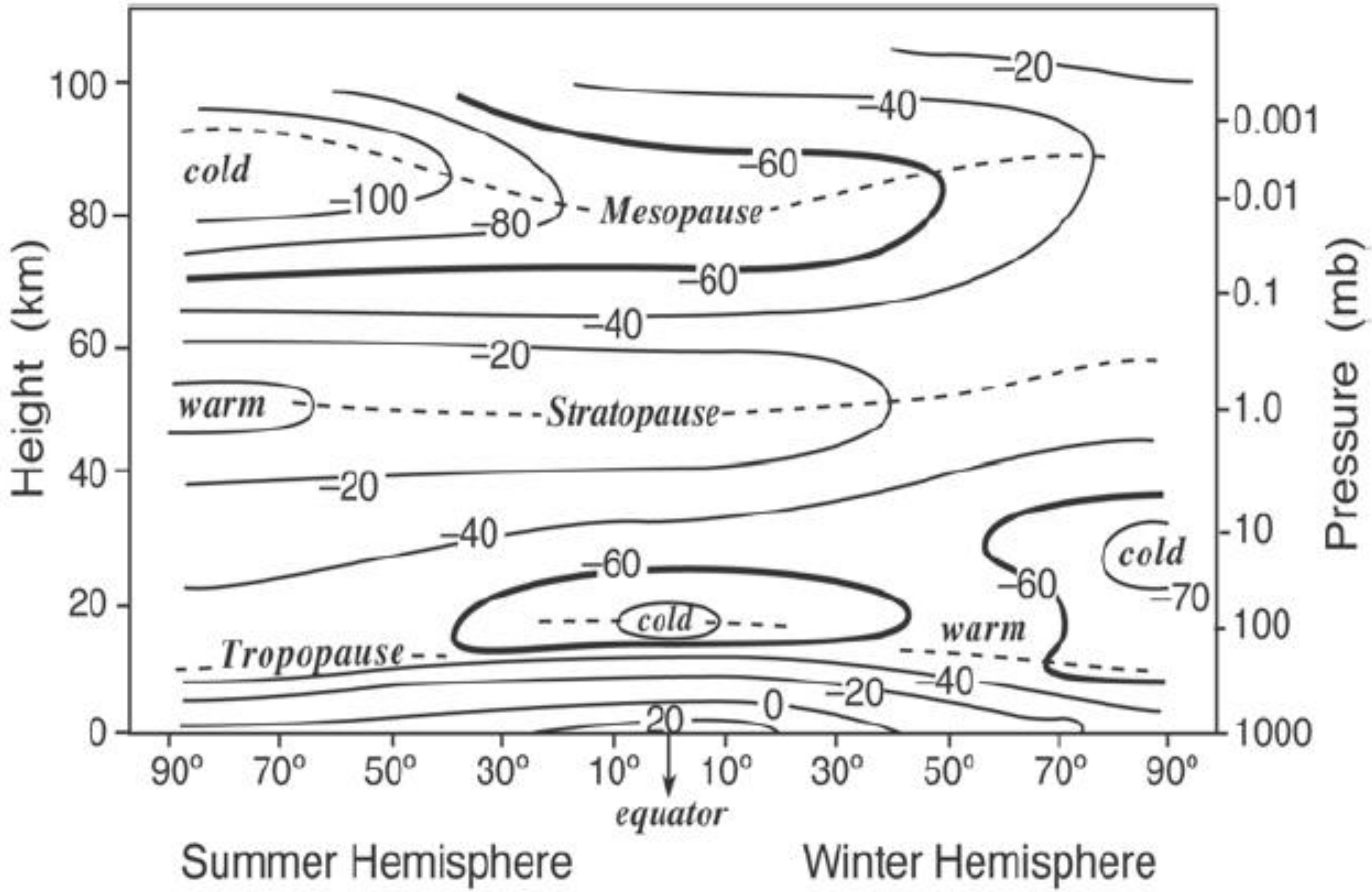


Atmospheric Structure – Pressure and temperature variation with altitude (up to 100 km)



Distribution of annual mean and solstice incoming solar radiation

Radiative forcing provided by solar UV absorption by ozone is a major contributor to the meridional temperature gradient and the resultant zonal (symmetric) wind circulation at stratospheric heights.

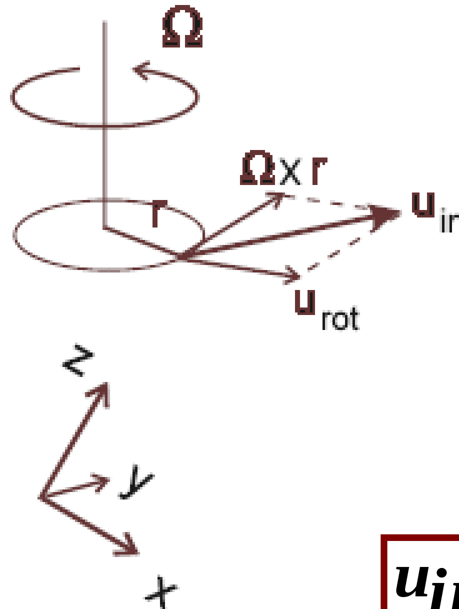


The observed, longitudinally averaged temperature, T, distribution at northern summer solstice from the surface to a height of 100km (after Houghton, 1977).

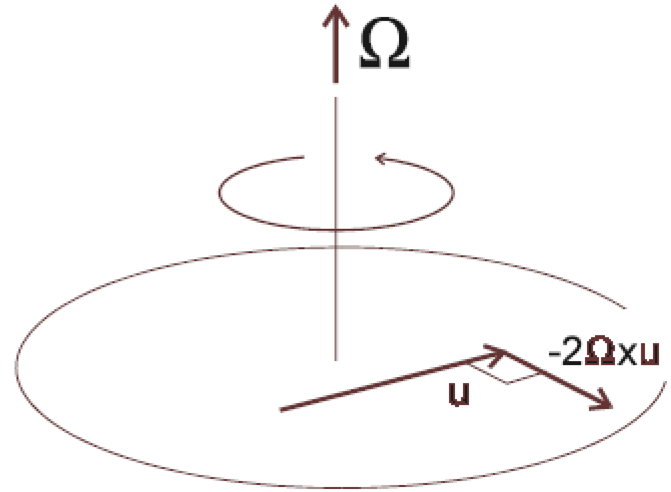
Significant deviations from structures derived from radiative equilibrium conditions occur – role of dynamical processes is emphasized here…

Equation of motion needs to be modified for incorporation in a non-inertial frame

INERTIAL



ROTATING



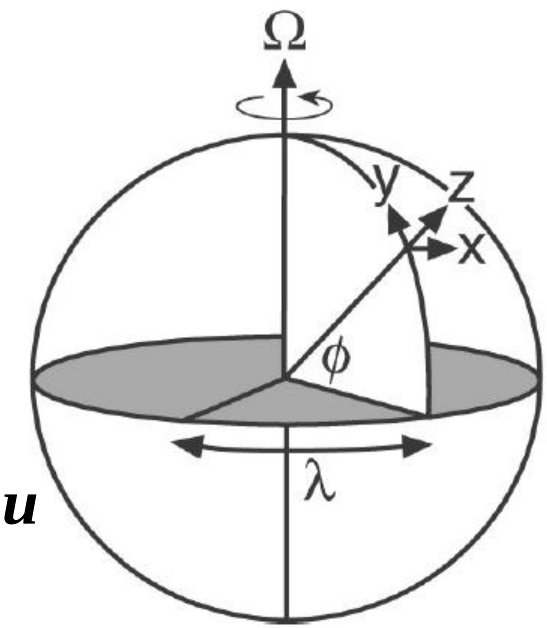
$$\boxed{u_{in} = u_{rot} + \Omega \times r}$$

$$\boxed{\frac{Du}{Dt} = -2\Omega \times u}$$

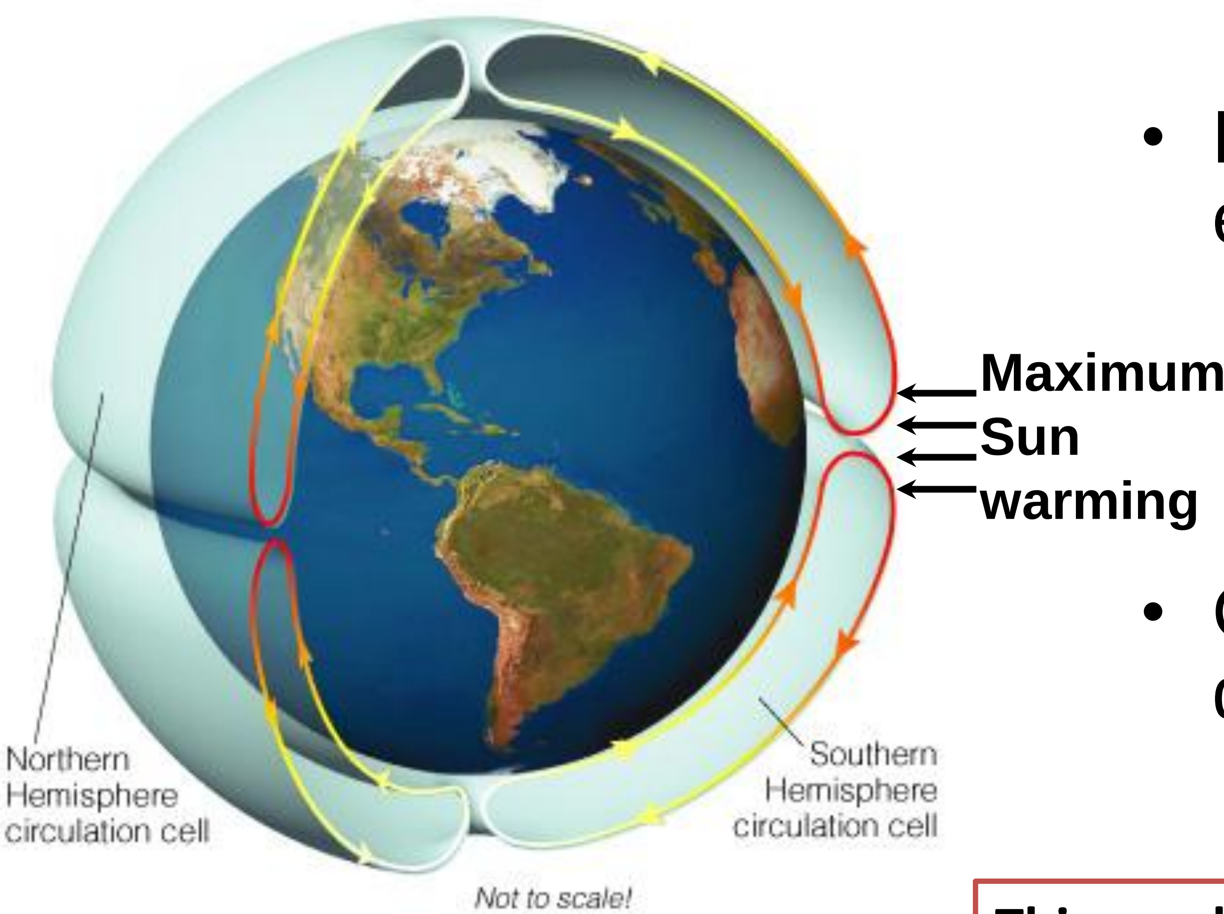
(in the absence of other forces)

Coriolis term

$$-2\Omega \times u \approx (-2\Omega v \sin\varphi, 2\Omega u \sin\varphi, 0) = -f\hat{z} \times u$$



Atmospheric Circulation (convection)

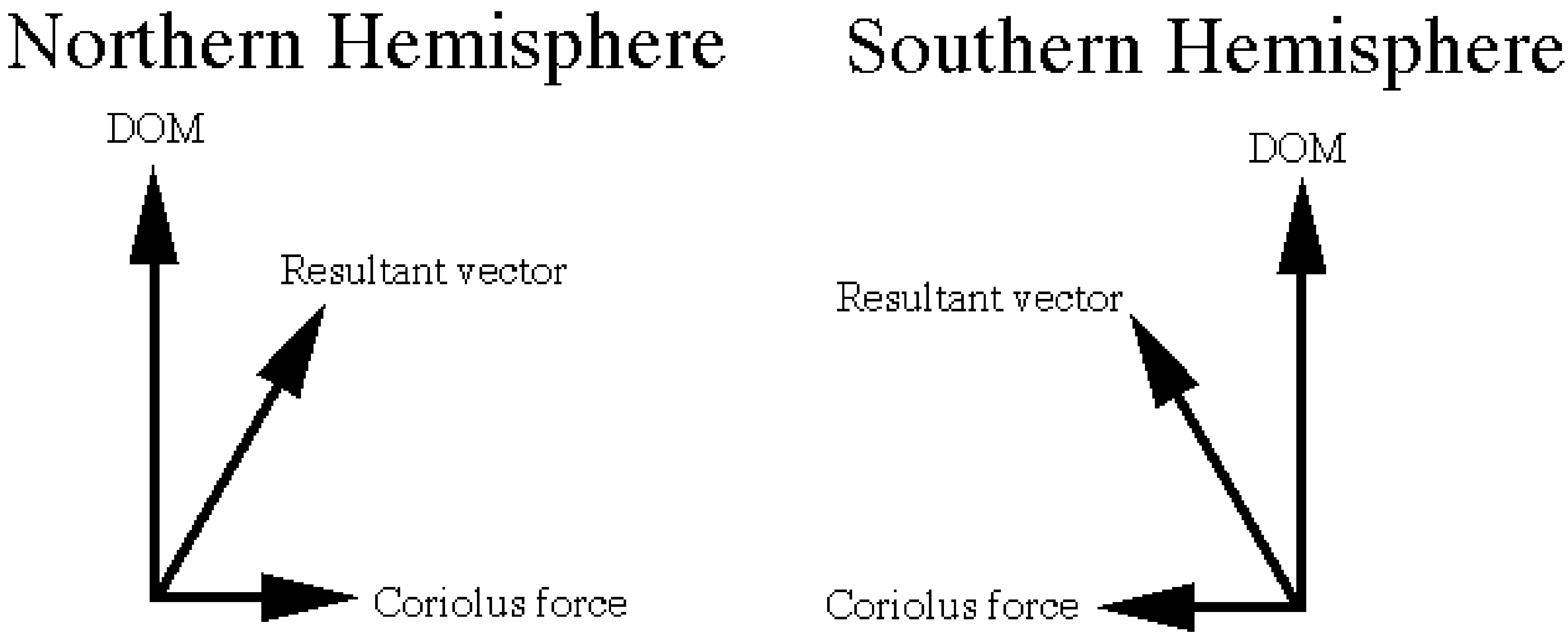


- Heated air rises at equator
- Cooler air descends at poles

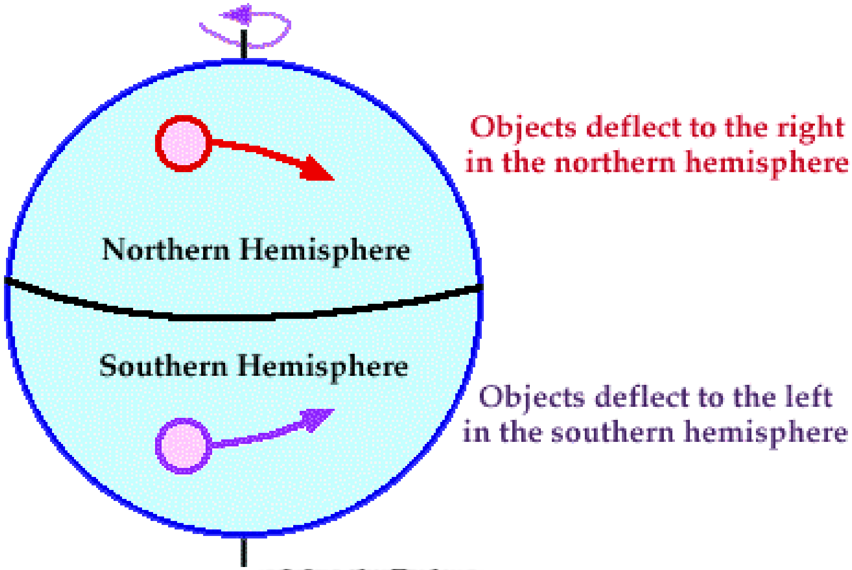
This would have been the situation in the absence of Coriolis force

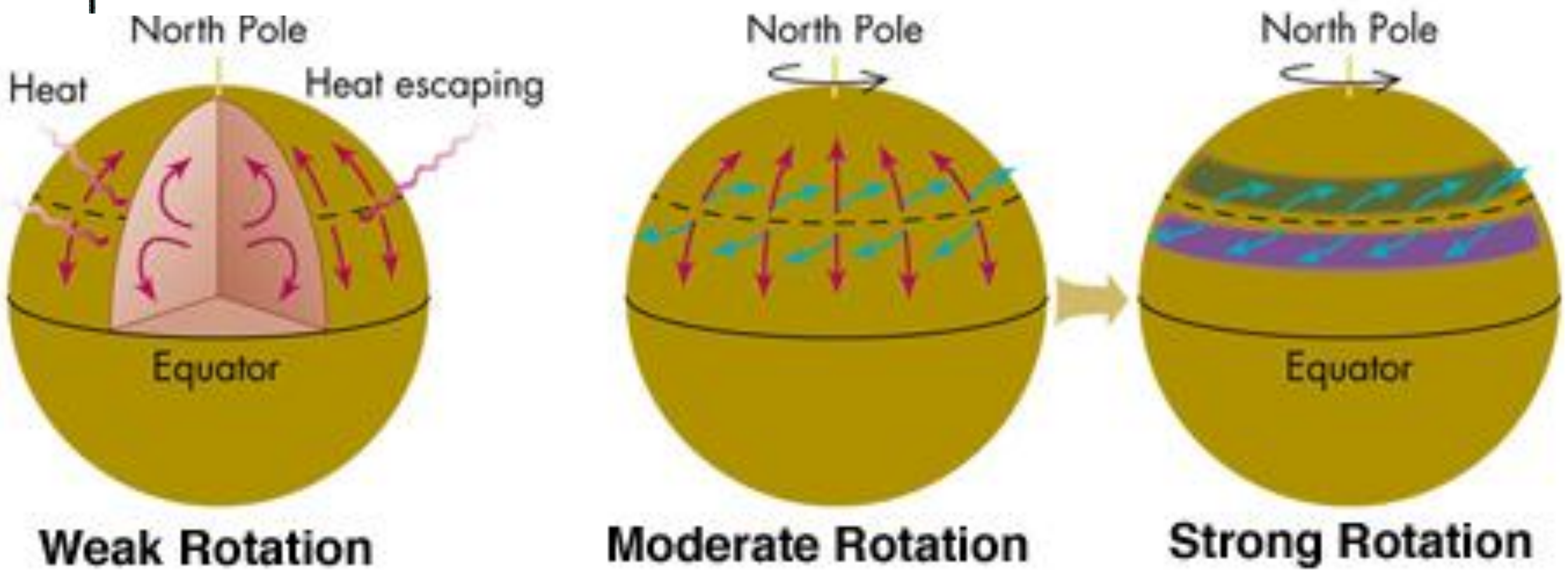
Coriolis Effect

Coriolis effect deflects north-south winds into east-west winds

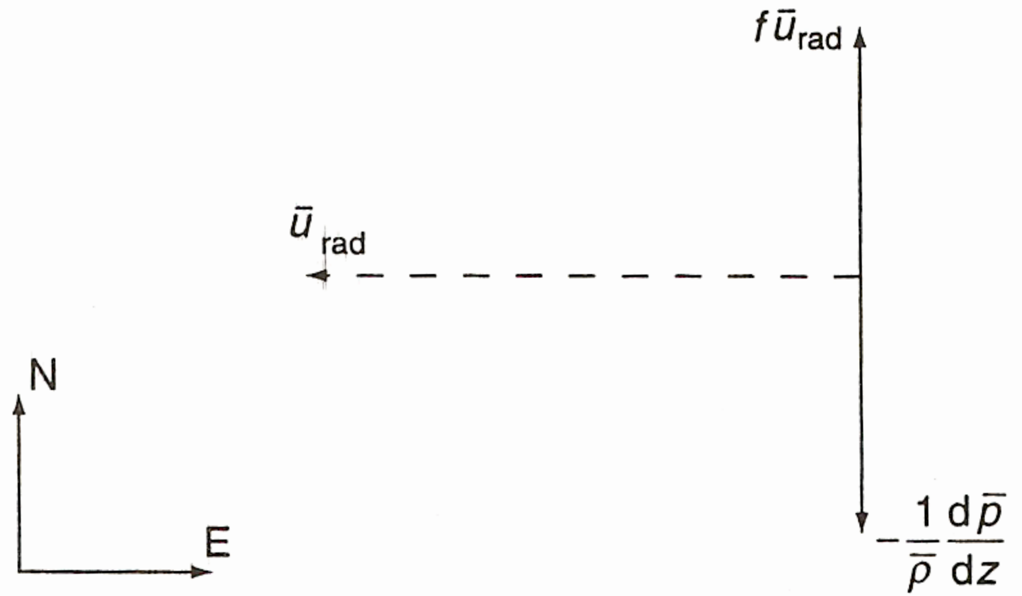


Coriolis Effect





Winds blow N or S	**Winds are diagonal**	**Winds blow W or E**
Venus	**Earth** **Mars**	**Jupiter, Saturn** **Neptune, Uranus(?)**



Geostrophic balance

Horizontal momentum equations:

$$\frac{d\hat{v}_h}{dt} + f\hat{k}\times\hat{v}_h = -\nabla_p\Phi - \hat{D}$$

Geostrophic equilibrium:

$$f\hat{k}\times\hat{v}_g = -\nabla_p\Phi$$

(Horizontal pressure gradients balance the Coriolis force;
Flow is along the isobars)

Primitive equations with linearized perturbation terms representing spherical atmosphere

$$\frac{du}{dt} - \left(f + \frac{u\tan\varphi}{a}\right)v = -\frac{1}{\rho a\cos\varphi}\frac{\partial p}{\partial\lambda} - D_\lambda$$

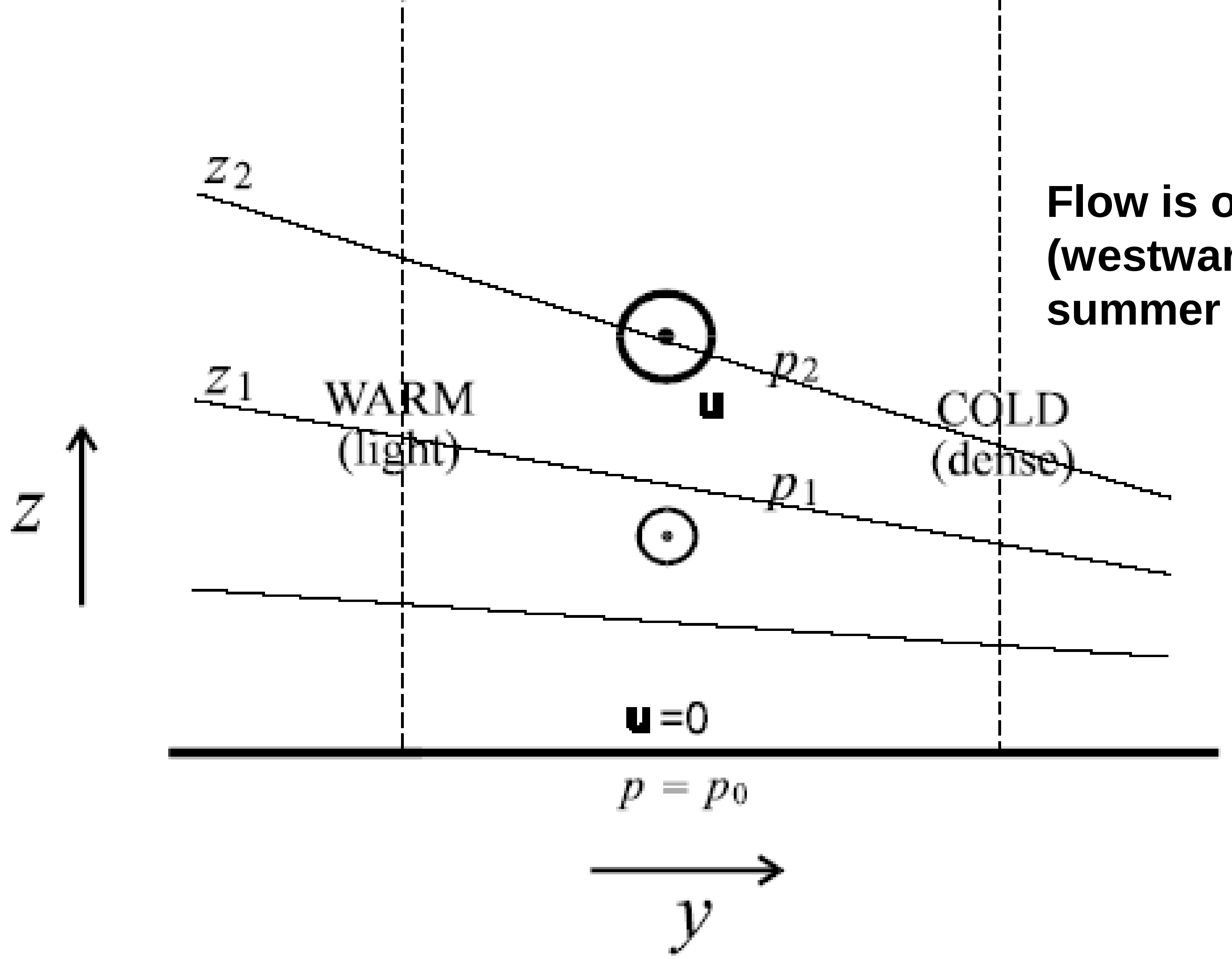
$$\frac{dv}{dt} + \left(f + \frac{u\tan\varphi}{a}\right)u = -\frac{1}{\rho a}\frac{\partial p}{\partial\varphi} - D_\varphi$$

$$\frac{1}{\rho}\frac{\partial p}{\partial z} = -g$$ **(hydrostatic balance in the vertical with zeroth order terms)**

$$\frac{d\rho}{dt} + \rho\nabla.v = 0$$ **(mass conservation equation)**

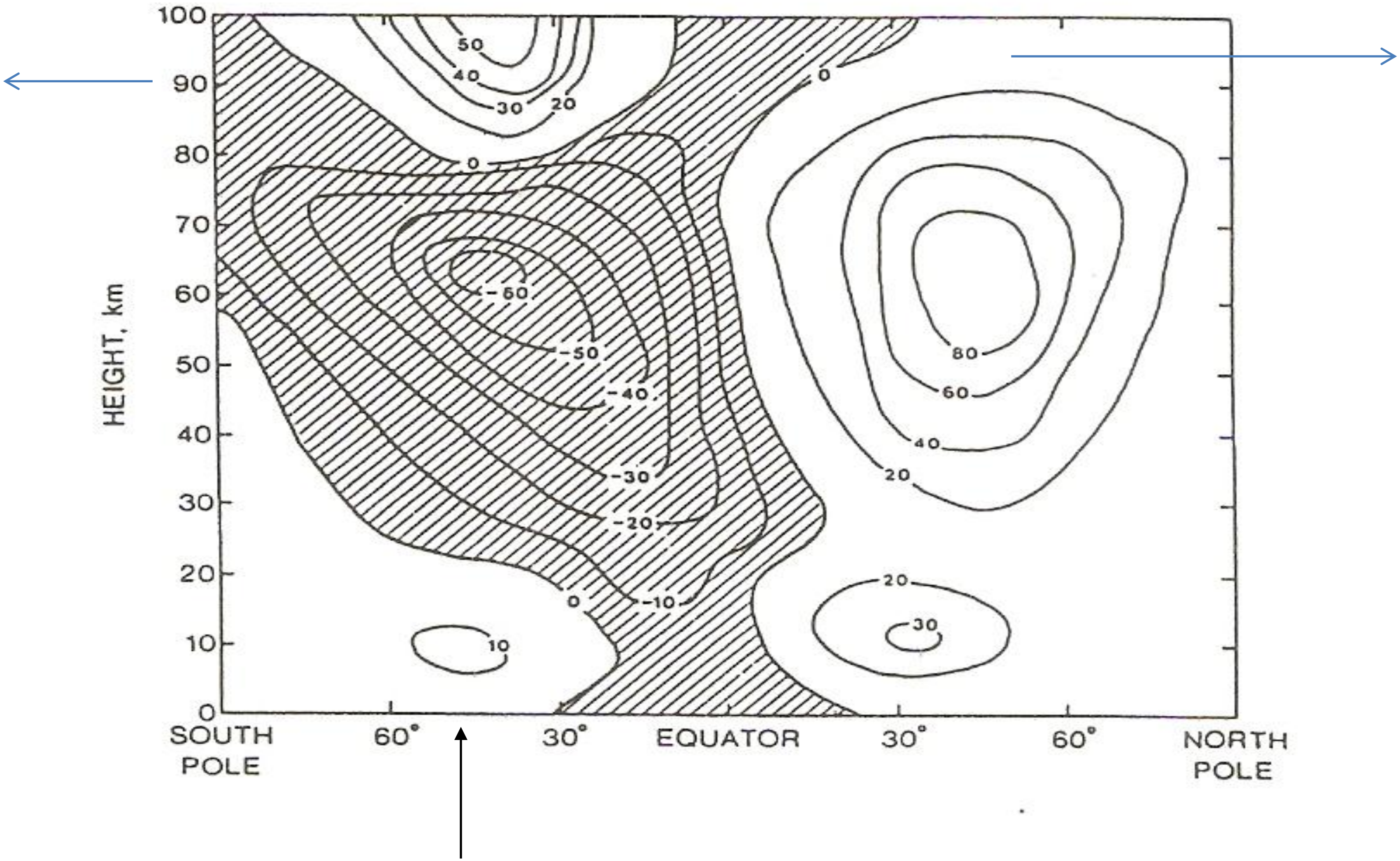
$$\rho c_v\frac{dT}{dt} + p\nabla.v = \dot{q}_{net}$$ **(first law of thermodynamics)**

f **is the coriolis parameter:** $2\Omega\sin\varphi$ **;** (λ, φ)**: (long, lat)**



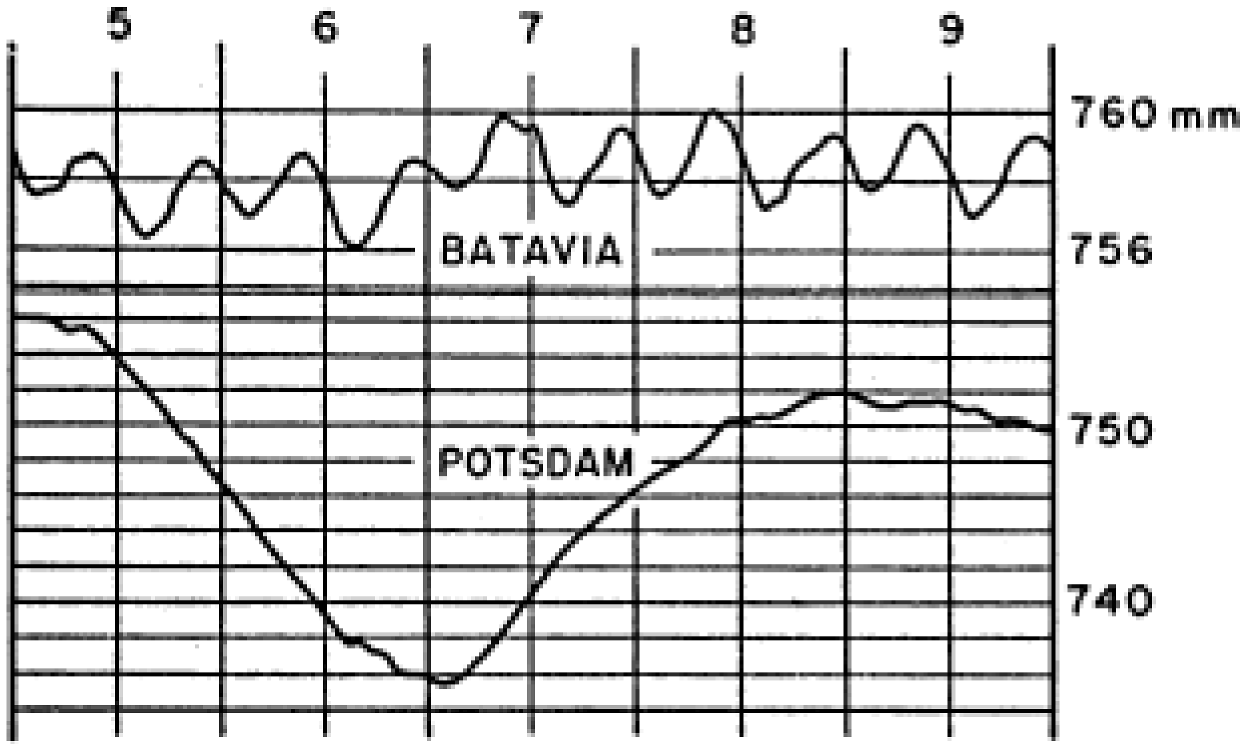
Flow is outwards (westwards) in the NH summer scenario

Warm columns of air expand, cold columns contract, leading to a tilt of pressure surfaces which typically increases with height in the troposphere & stratosphere. The geostrophic wind in balance with the tilting pressure surfaces increases with height. (Thermal wind equation indicates that the geostrophic flow is proportional to the meridional temperature gradient)



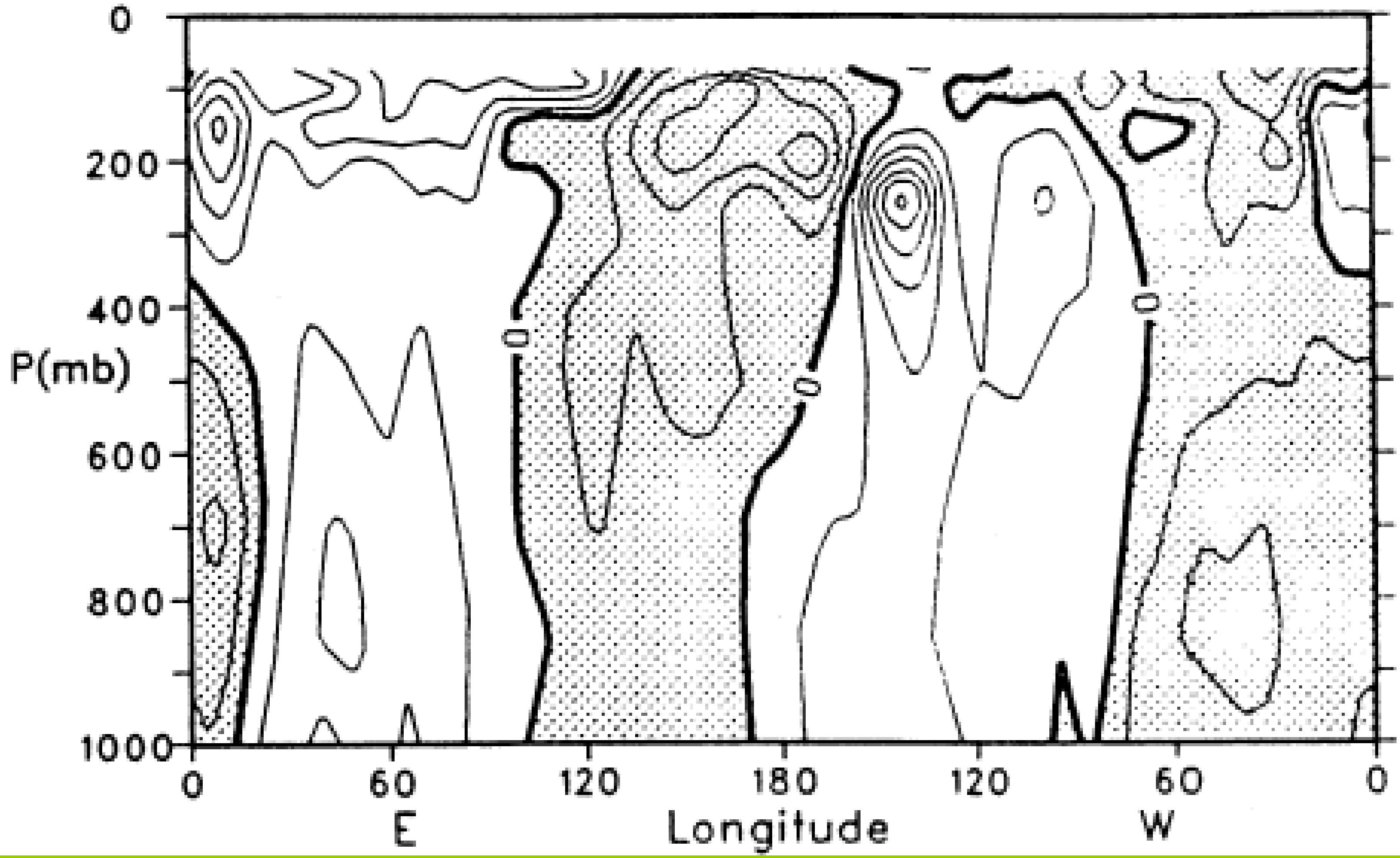
Mean circulation is primarily radiatively driven, but significant departures occur due to wave influence. **What are these due to? Waves…?**

Notice the semi-diurnal variation at Batavia and a long-period variation (~ 5 days) at Potsdam



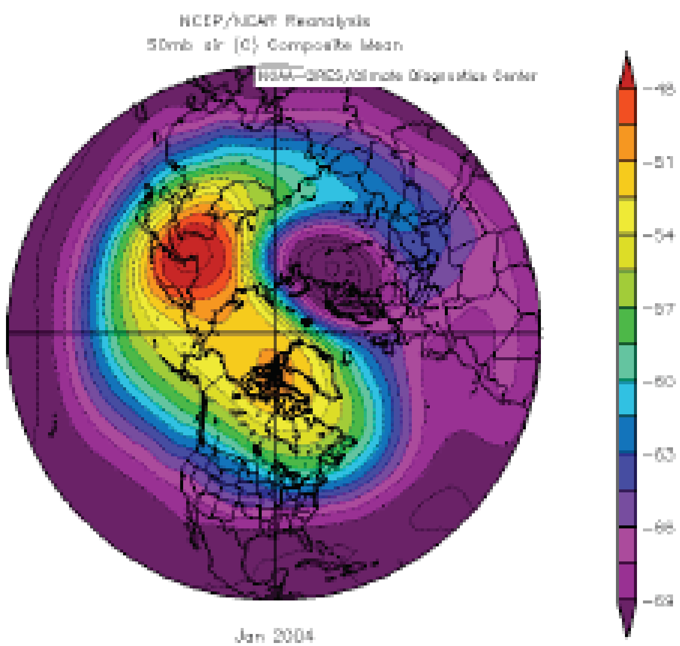
Barometric variations (on twofold different scales) at Batavia (6ºS) and Potsdam (52ºN) during November, 1919. After Bartels (1928).

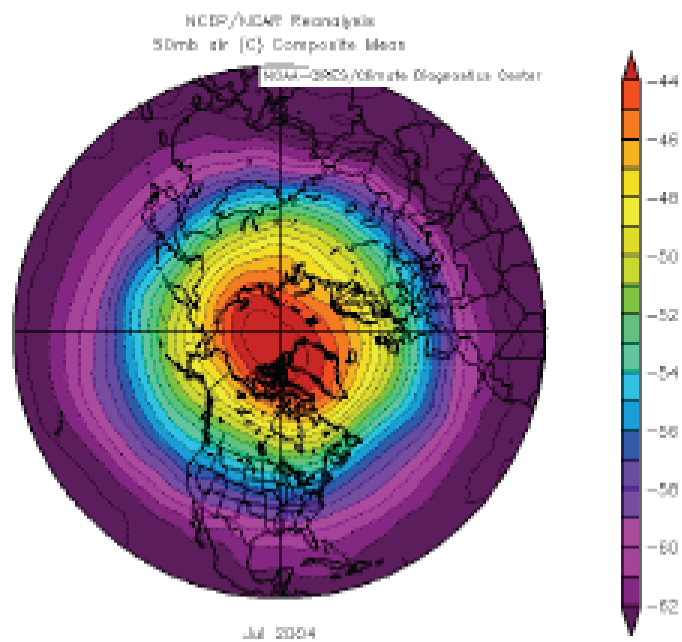
Zonal wavenumber 2 pattern (semi-diurnal) seen here with little phase change with height (troposphere and lower stratosphere)



Semidiurnal zonal wind field for DJF 1986/87 along the equator; contour interval 0.2 m/sec. Regions of negative values are shaded. *ECMWF calculations after Hsu and Hoskins (1989)*.

50 hPa Temperatures from NCEP/NCAR Reanalysis



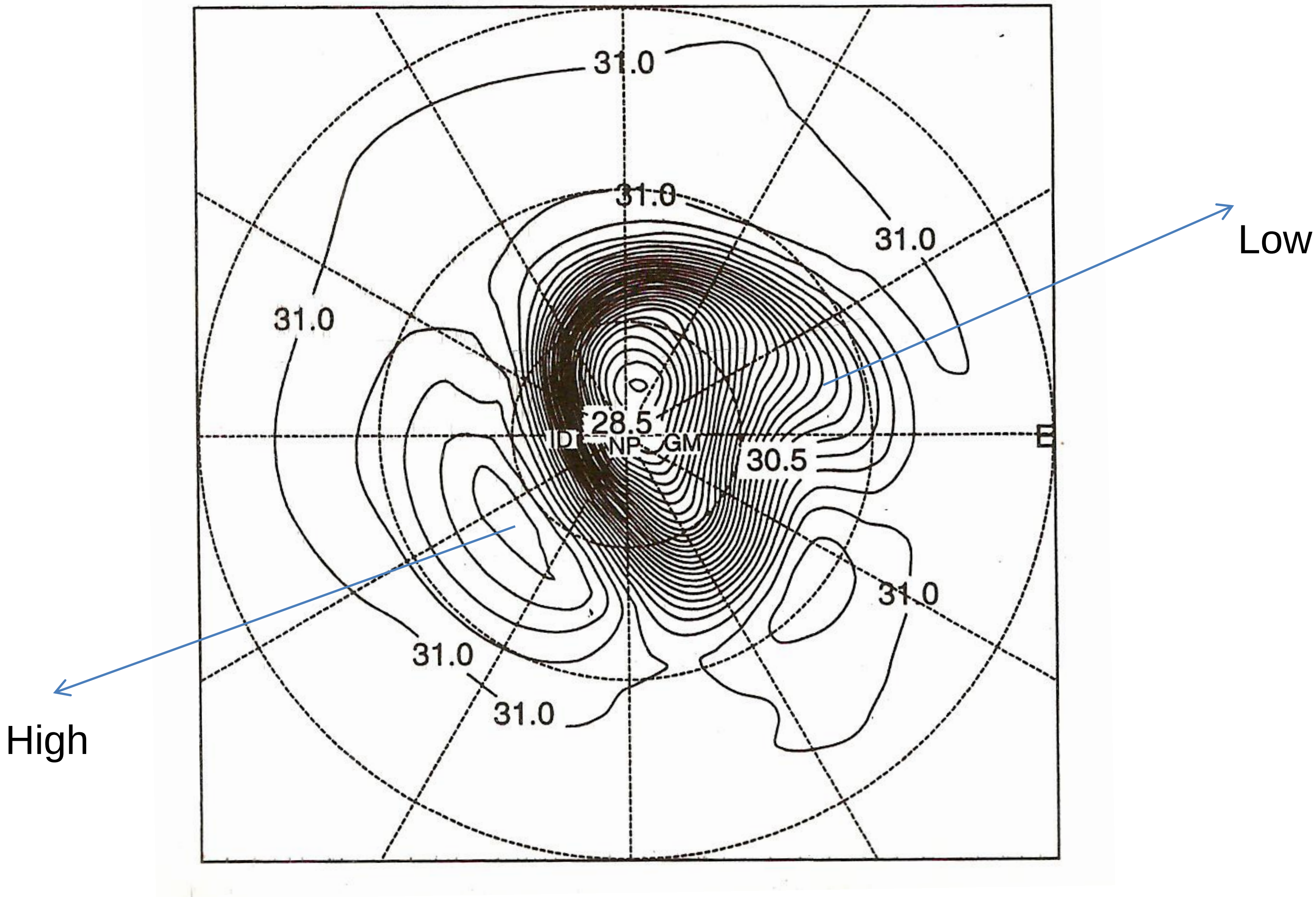


Northern Hemisphere winter →strong longitudinal variation

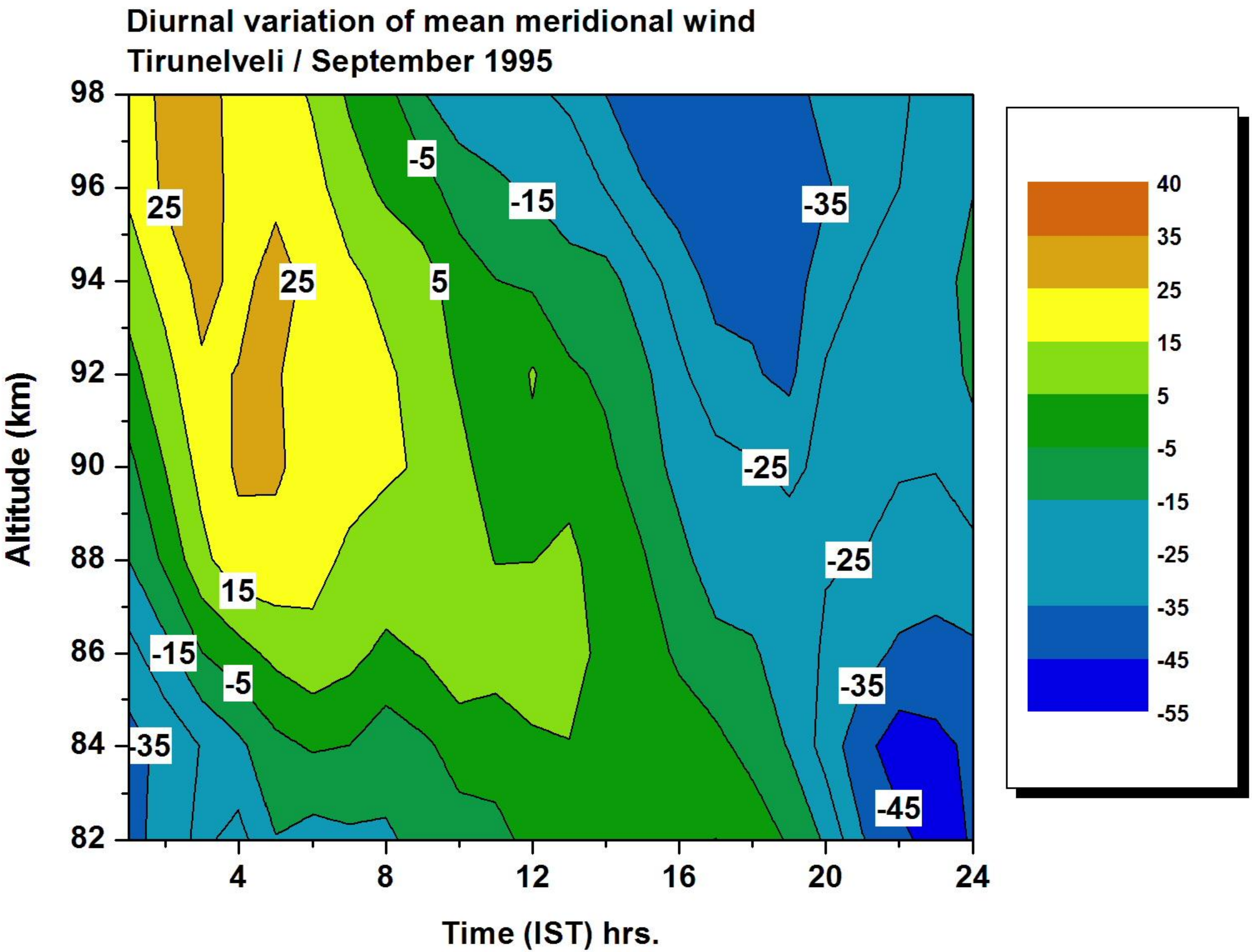
Northern Hemisphere summer →weak longitudinal variation

(McLandress)

Geopotential height at 10hPa on 20 January 1979 (derived from satellite data)



Planetary wave: Deviation from zonal symmetry (wavenumber 1 evident above)



Diurnal variation of mean meridional wind
Tirunelveli / September 1995
Altitude (km)
Time (IST) hrs.
98
96
94
92
90
88
86
84
82
4
8
12
16
20
24
25
25
15
-15
-5
-35
-5
5
-15
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-45
40
35
25
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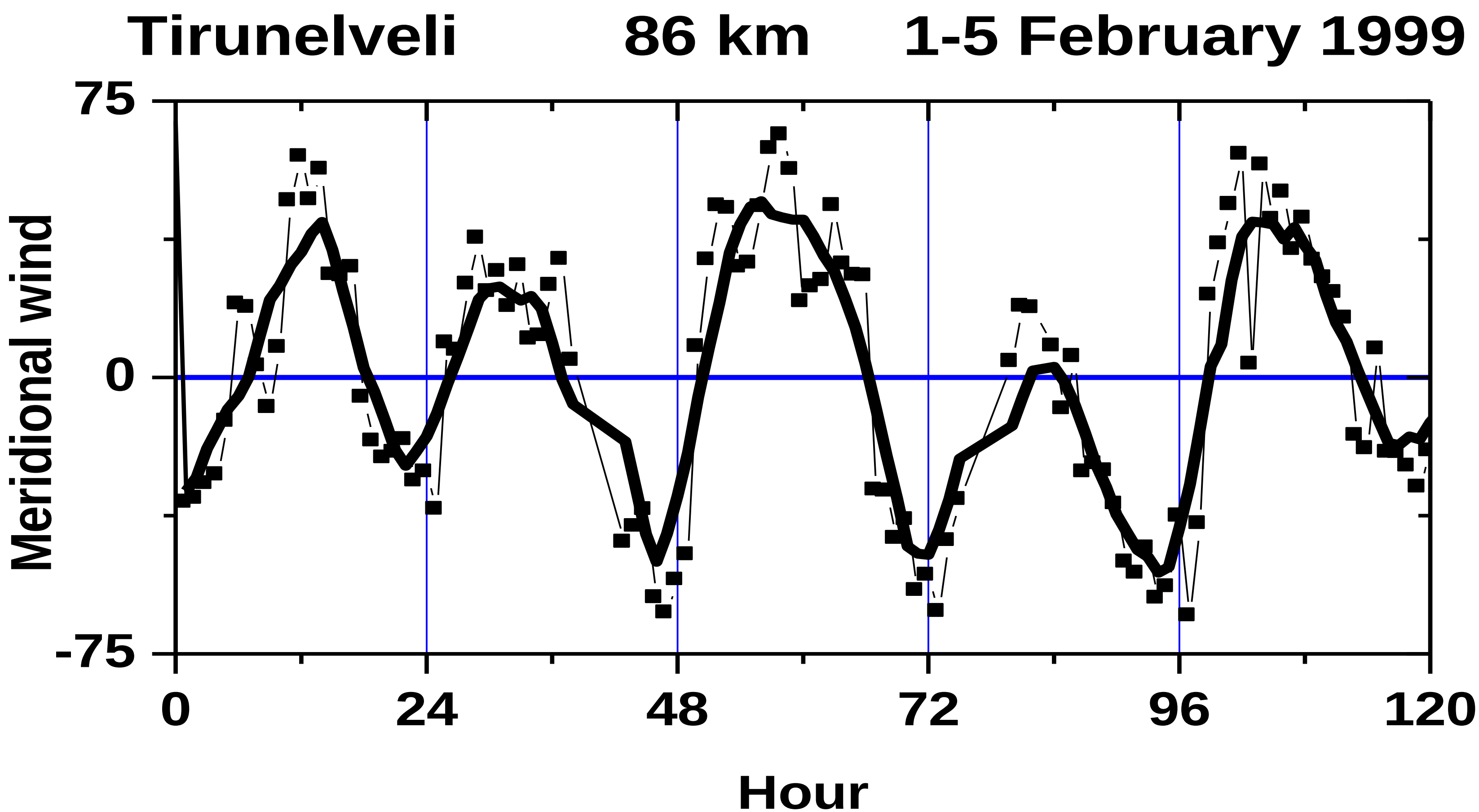
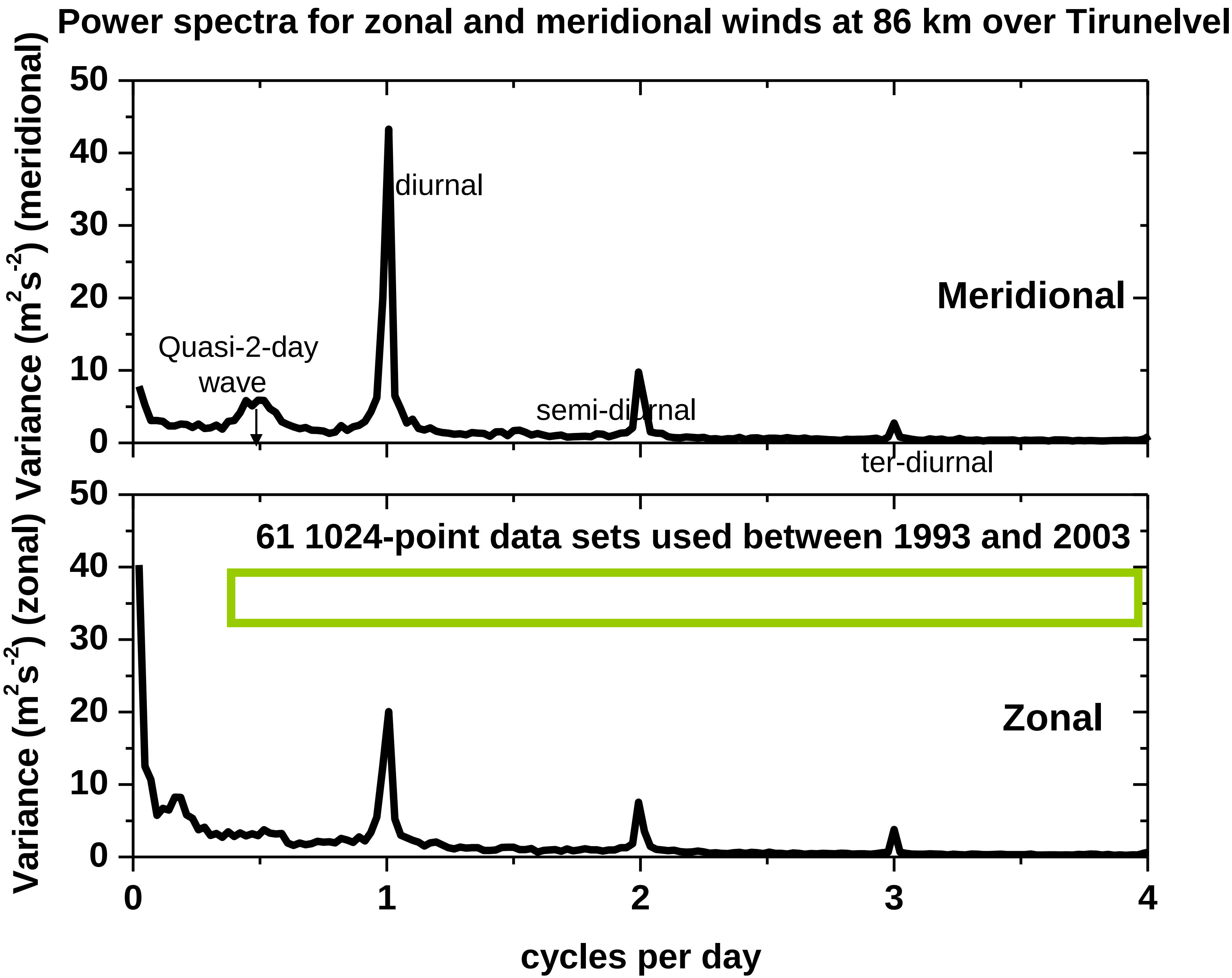
-25
-35
-45
-55

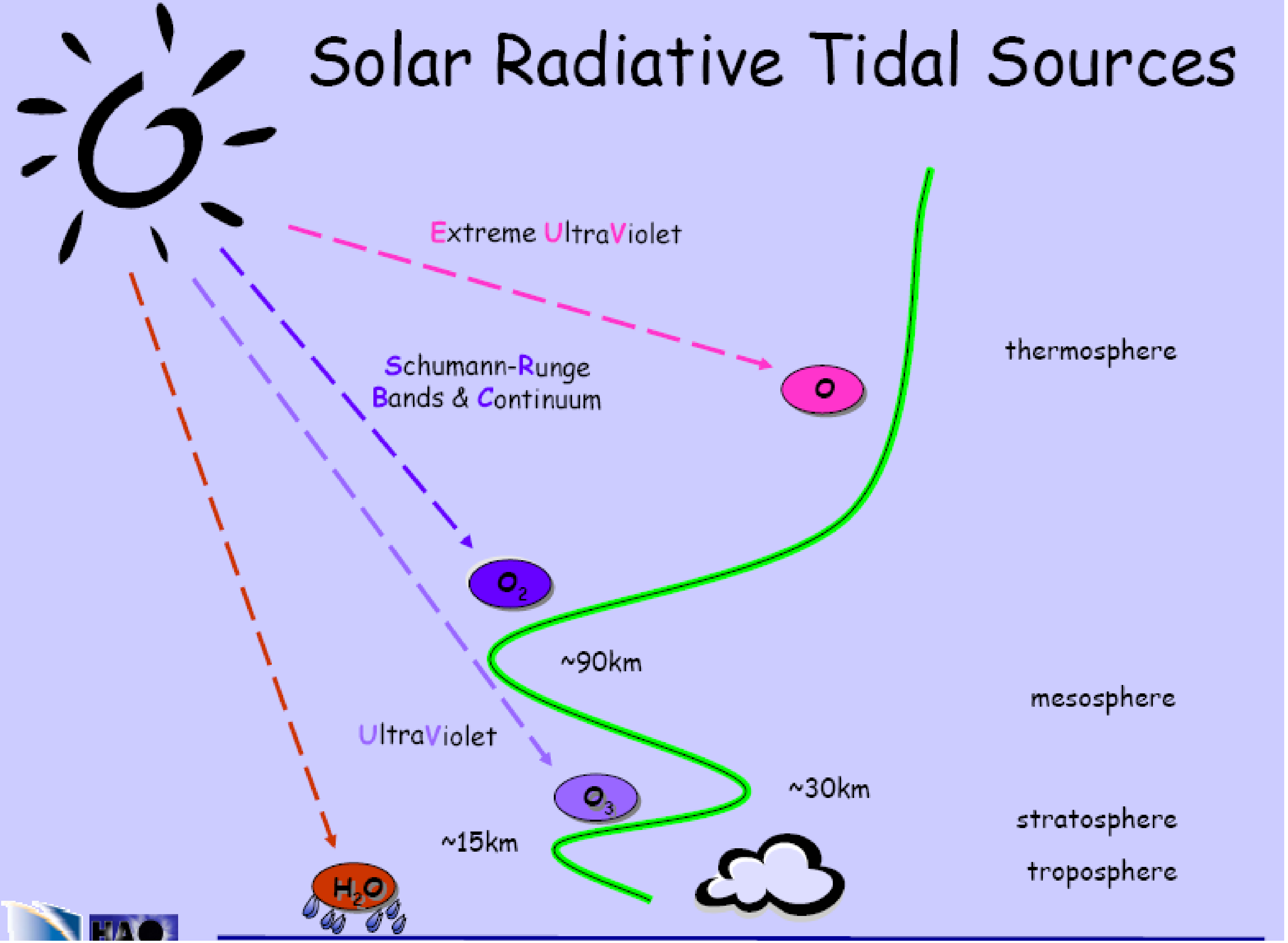


Radar observations at Tirunelveli (8.7ºN, 77.8ºE) often reveal diurnal oscillations in winds in the height region 80-100 km



How are these tides and planetary waves generated and where are their sources?

Solar Radiative Tidal Sources



Solar Atmospheric Tides

(Ubiquitous – Persistent – Measurable)

periods – harmonics of a solar day

migrating – propagate westward with the Sun

nonmigrating – propagate eastward / westward / stands

- produce variations with longitude

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

Heating rate = $$Q_o + \sum_{n=1}^{N} a_n \cos n\Omega t_{LT} + a_n \sin n\Omega t_{LT}$$

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

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

Conversion to UT yields $t_{LT} = t + \lambda / \Omega$

We then have for the heating rate

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

The zonal phase speed is given by $c_{ph} = \dfrac{d\lambda}{dt} = -\dfrac{n\Omega}{n} = -\Omega$

Migrating tides: the pattern is 'fixed' with respect to the Sun and the Earth rotates beneath

Nonmigrating tides: the pattern does not 'migrate' with the apparent position of the Sun

In the latter case, the result is the superposition of several components:

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

for which the zonal phase speeds are given by

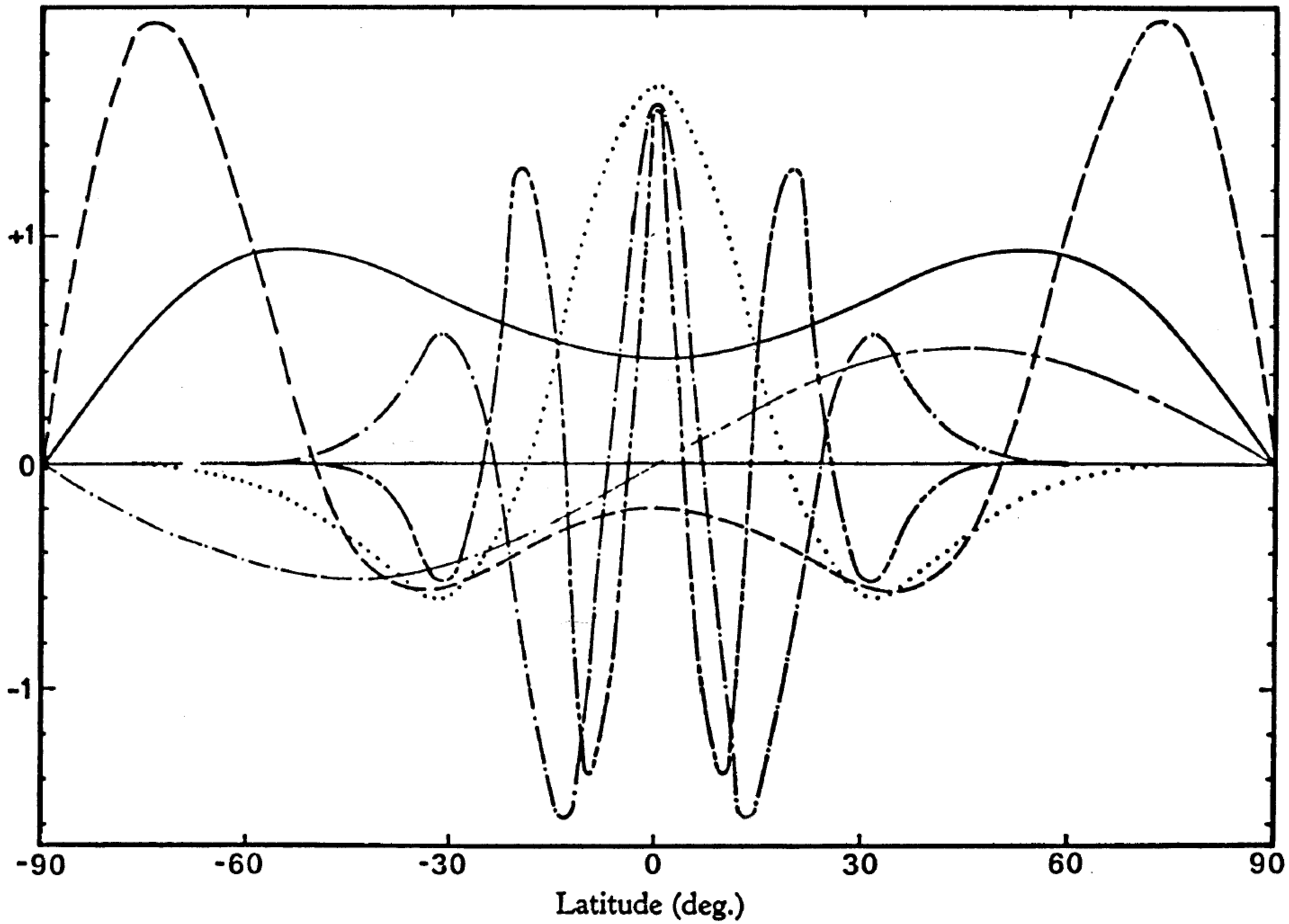
$$c_{ph} = \frac{d\lambda}{dt} = -\frac{n\Omega}{s}$$

indicating the presence of nonmigrating components with + *S* representing westward moving pattern

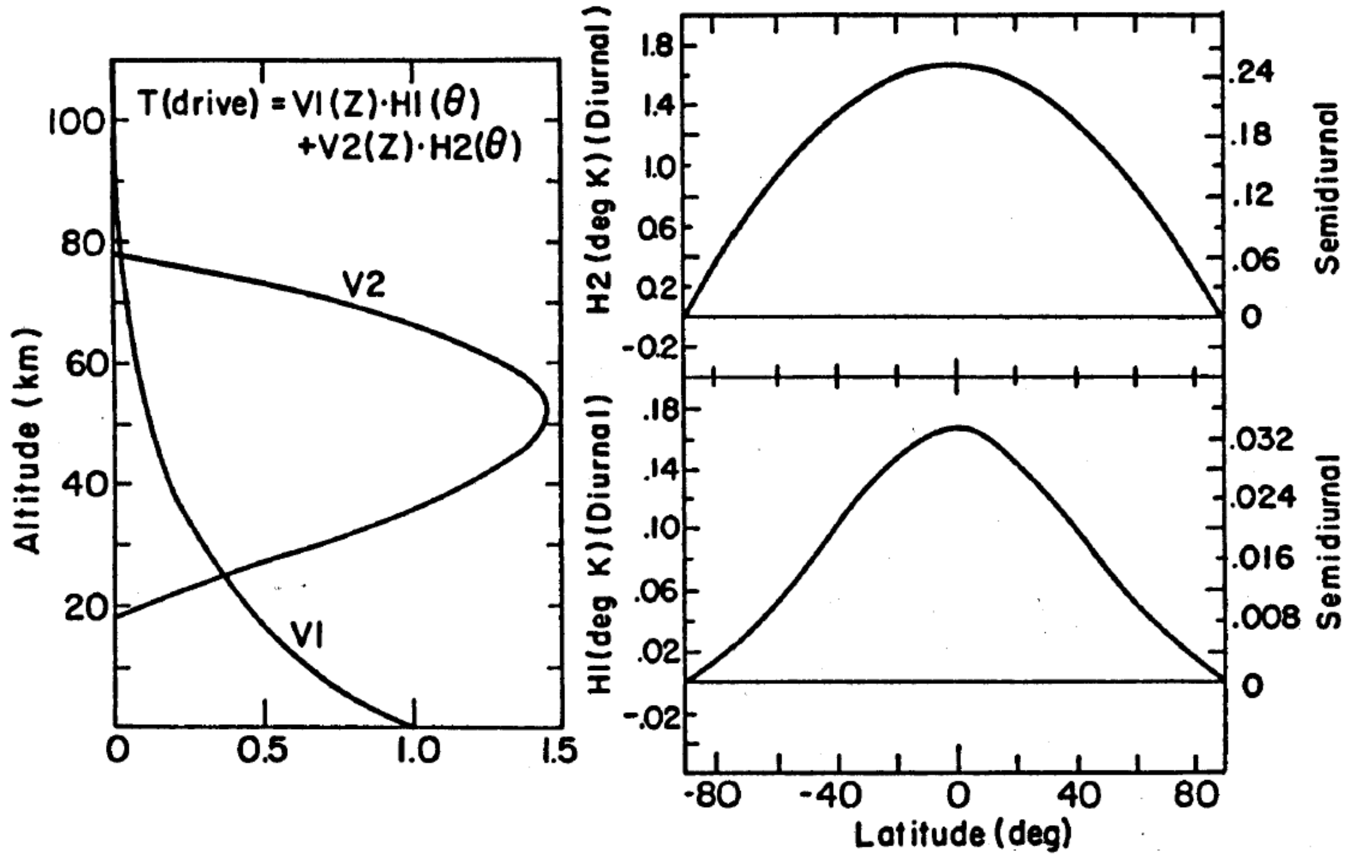
Discrete modes $\xrightarrow[(s,n)]{\sim \exp i(s\lambda-\sigma t)}$ **have distinct height-latitude structure**

(s is an integer (=1 for diurnal and =2 for semidiurnal), n labels the latitudinal structure of the mode)

Hough functions



Thermal excitation due to water vapour and ozone: vertical and latitudinal distributions



The role of excitation source is governed by how well its vertical and spatial distributions match the mode's vertical and spatial structure

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

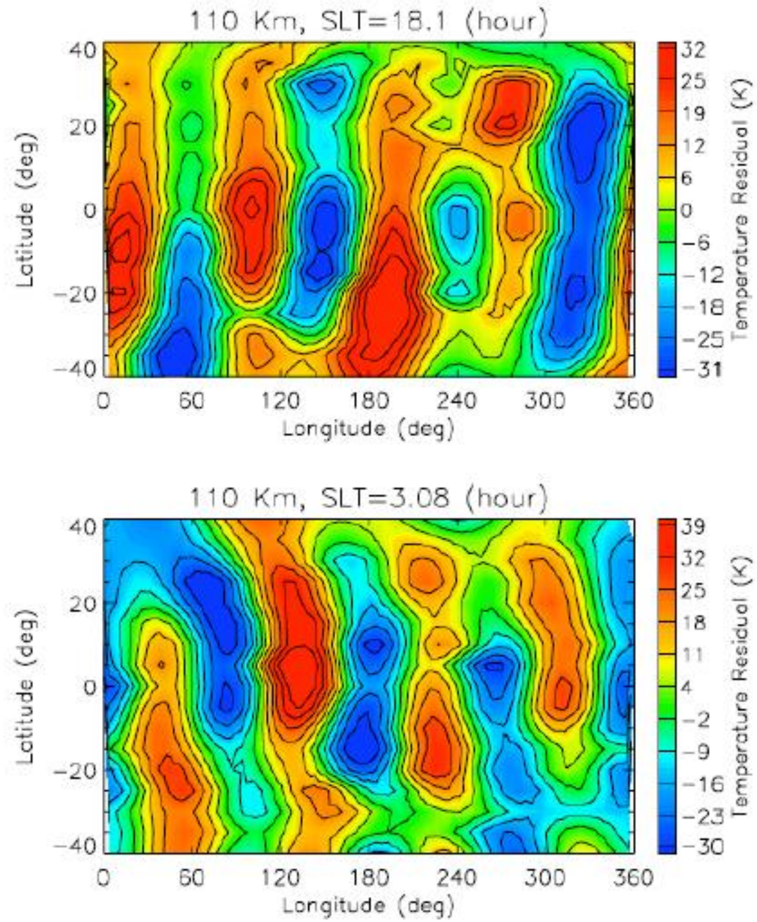
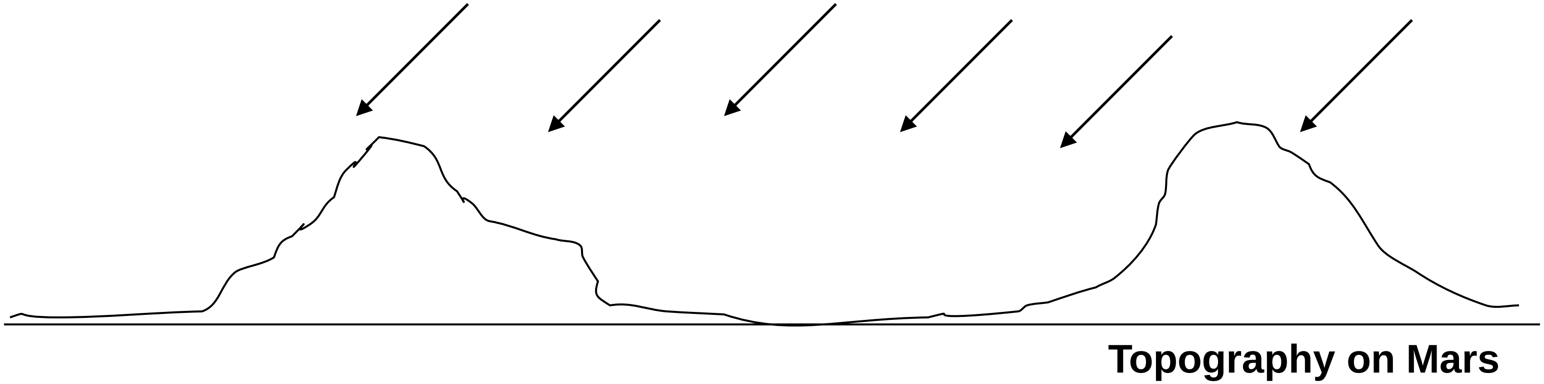


Figure 6. Mean residuals from the 5-day mean of temperatures at 110 km centered on day 238 of 2002. Top: ascending portion of the orbit (mean local solar time = 18.1 hours). Bottom: descending portion of the orbit (mean local solar time = 3.08 hours).

Courtesy: *Jeffrey Forbes*

Westward migrating solar radiation interacting with a *s*=2 topography



$$\cos(\sigma t+\lambda)\cos 2\lambda \rightarrow \cos(\sigma t+3\lambda)+\cos(\sigma t-\lambda)$$

westward propagating
***s* = +3**

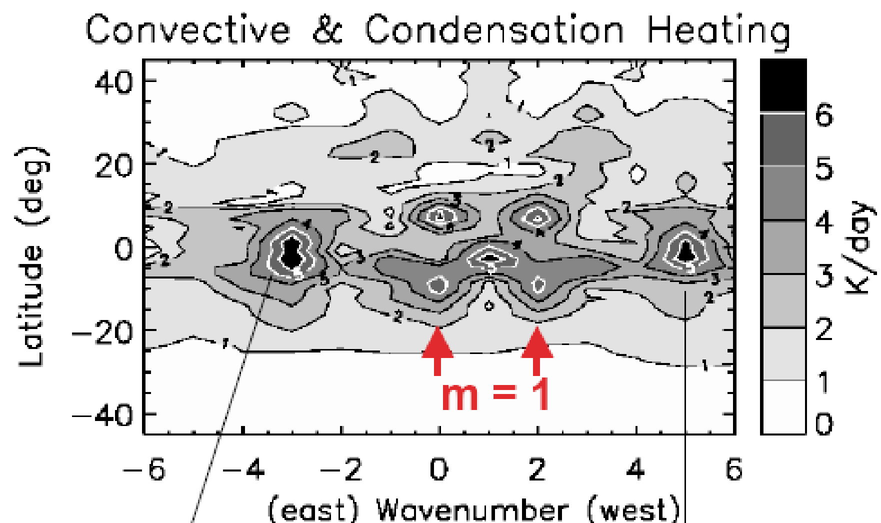
eastward propagating
***s* = -1**

Generation of non-migrating tides through interaction of solar radiation with topography

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

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

eastward propagating

westward propagating

Courtesy: ***Jeffrey Forbes***

Migrating and nonmigrating tides – classification

Classical tidal theory

Absorption of solar radiation by water vapor in the troposphere and ozone in the stratosphere (*radiative heating*)

Topography/land-sea contrast (*sensible heat flux*)

Water vapor distribution in the troposphere (*radiative heating*)

Latent heat release in tropical deep convective clouds (*latent heating*)

Migrating tides

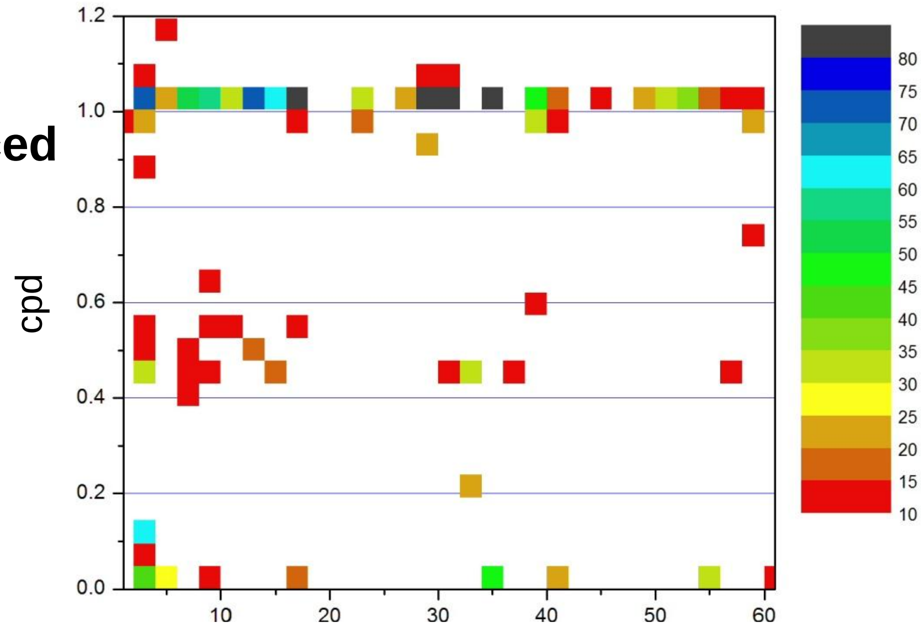
Nonmigrating tides

Planetary waves

MF radar wind observations at Tirunelveli (Period considered: 1993-2003)

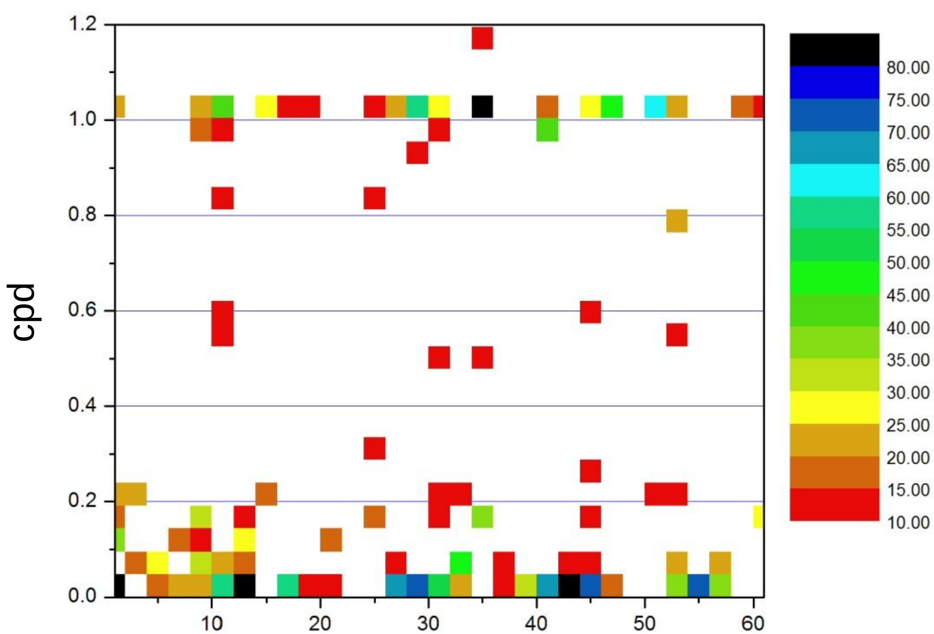
Bursts of wave occurrence noticed in moving power spectra

Meridional wind



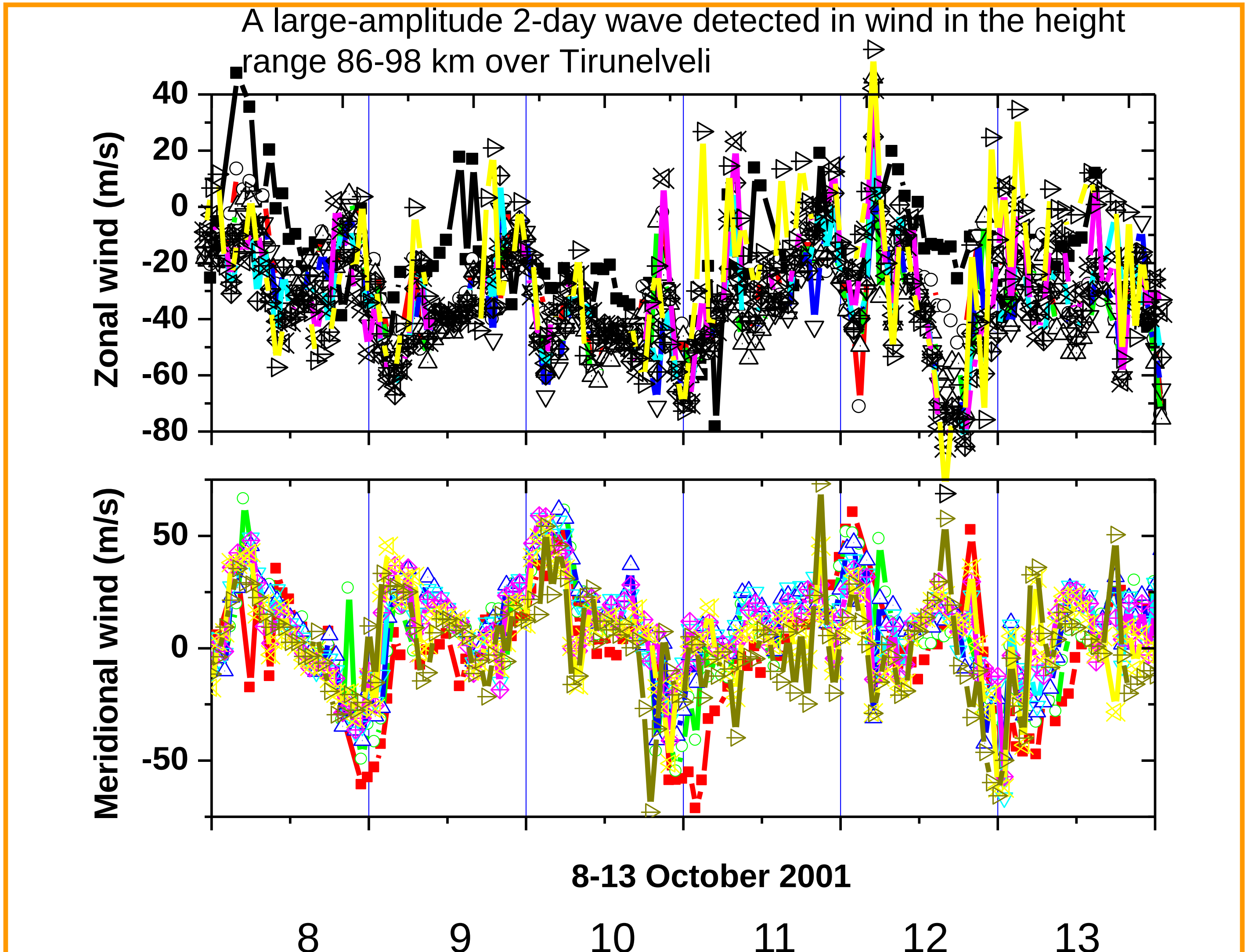
Quasi-2-day wave component stronger in meridional component

Zonal wind



Longer periods (>2 days) stronger and more variable in zonal wind

A large amplitude 2-day wave detected in the height region 86-98 km over Tirunelveli (period: 8-13 October 2001)



Planetary wave – a large-scale perturbation of the atmospheric dynamical structure that extends coherently around a full longitude circle

Planetary waves →
- Quasi-stationary Rossby waves
- Normal modes
- Equatorial waves

Earth's rotation plays an important role –

(i) Latitudinal gradient of the background planetary vorticity provides a restoring force for the mid-latitude quasi-stationary Rossby waves.

(ii) Long-period oscillations can propagate as gravity waves close to the equator where f is small and they are trapped there.

Characteristics of planetary Rossby waves

- **planetary waves are disturbances having zonal wavelengths of the scale of the Earth's radius**

- **in the extratropics the planetary waves are in approximate geostrophic balance**

- **forcing occurs in the troposphere and is provided by land-sea temperature contrasts and synoptic disturbances**

- **restoring force is latitudinal gradient of planetary vorticity**

- **horizontal propagation is westward with respect to the background zonal wind**

- **vertical propagation into the stratosphere occurs for the largest spatial scales**

Normal modes in the atmosphere

- **unforced disturbances**

- **analytical solutions are obtained by solving the linear primitive equations on the sphere for a windless background atmosphere without dissipation**

- **for each zonal wavenumber there is a discrete set of normal modes each with a different frequency and meridional structure**

- **if a disturbance is forced at this frequency the response is *resonant* – it is the normal mode that grows most rapidly in time and dominates the overall response**

Gravity waves

- Gravity waves are buoyancy waves – restoring force comes from Archimedes' principle.
- They involve vertical displacement of air parcels but along slanted paths in most cases.
- The waves are transverse.
- They can propagate vertically and horizontally, transporting momentum from their source to their sink.

Atmospheric Gravity Wave Scales:

Horizontal wavelengths ~ 10-1000s km

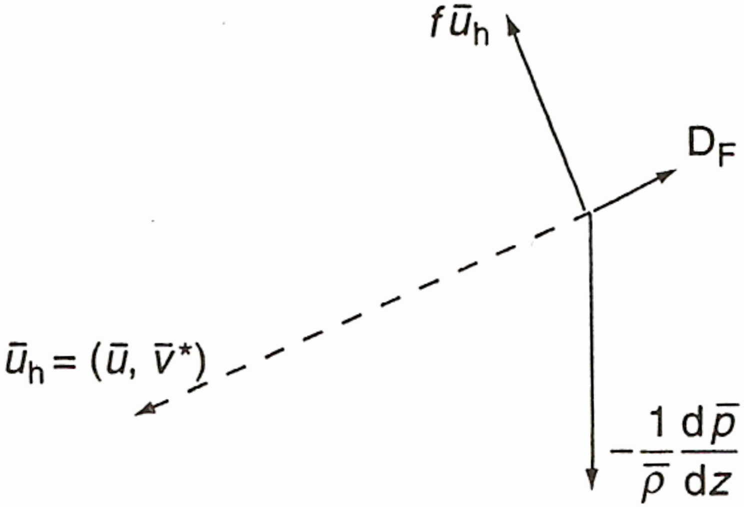
Vertical wavelengths ~ 1-30 km, and possibly longer

Periods:

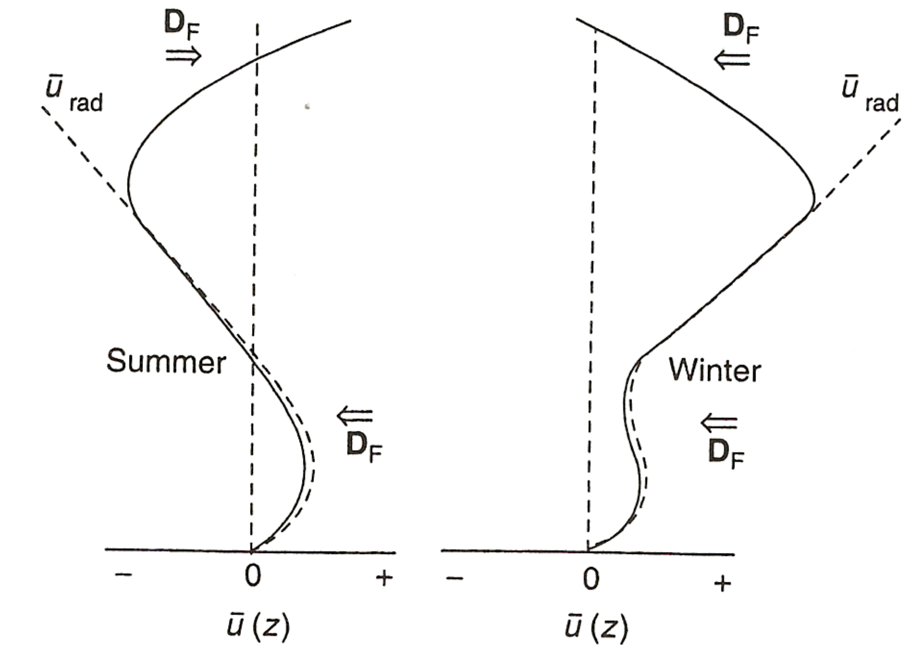
Intrinsic frequency $f < \hat{\omega} < N$ (5 min. – several days)

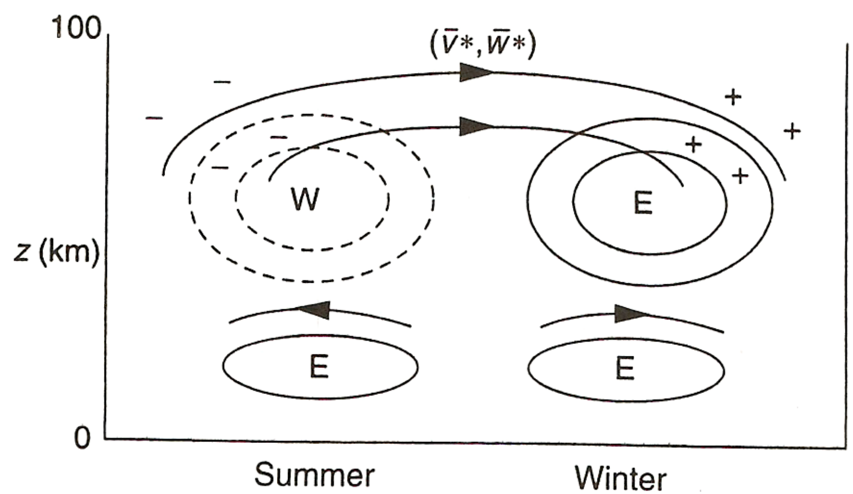
Observed from ground $\omega = \hat{\omega} + \langle u \rangle k$ can extend outside this range

Phase speeds ~ 0-100 m/s, and possibly higher



Balanced flow with wave drag





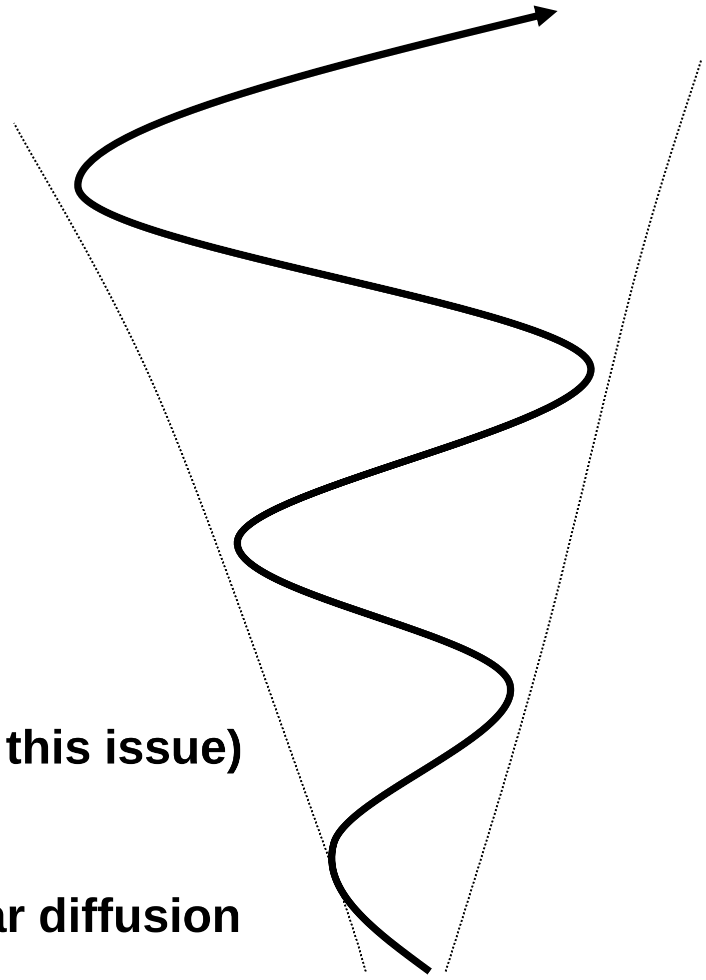
Wave drag on the zonal motion is responsible for the reversed meridional temperature gradient observed at mesopause heights

Wave drag counteracts the Coriolis torque on zonal flow driven by radiative heating

Wave processes away from source regions

Waves grow with height (in order to conserve kinetic energy density $\frac{1}{2}\rho u'^2$) as:

$$\boxed{u' \sim e^{z/2H}}$$



Without damping or dissipation, wave amplitudes would be too large at higher altitudes!

(Classical tidal theory does not address this issue)

Dissipative processes: eddy and molecular diffusion and radiative/thermal damping

Wave breaking results from convective and shear instabilities and 'eats' away energy and momentum quickly

Wave-mean flow interactions

Wave-induced change in the mean state is

$\bar{u} \rightarrow c$

$$\frac{\partial \bar{u}}{\partial t} = -\frac{1}{\bar{\rho}}\frac{\partial}{\partial z}(\bar{\rho}\overline{w'u'})$$

Vertical change in wave stress (zonal momentum flux) is related to the mean flow change.

Wave dissipation
Transience
Nonlinearity
Critical level interactions

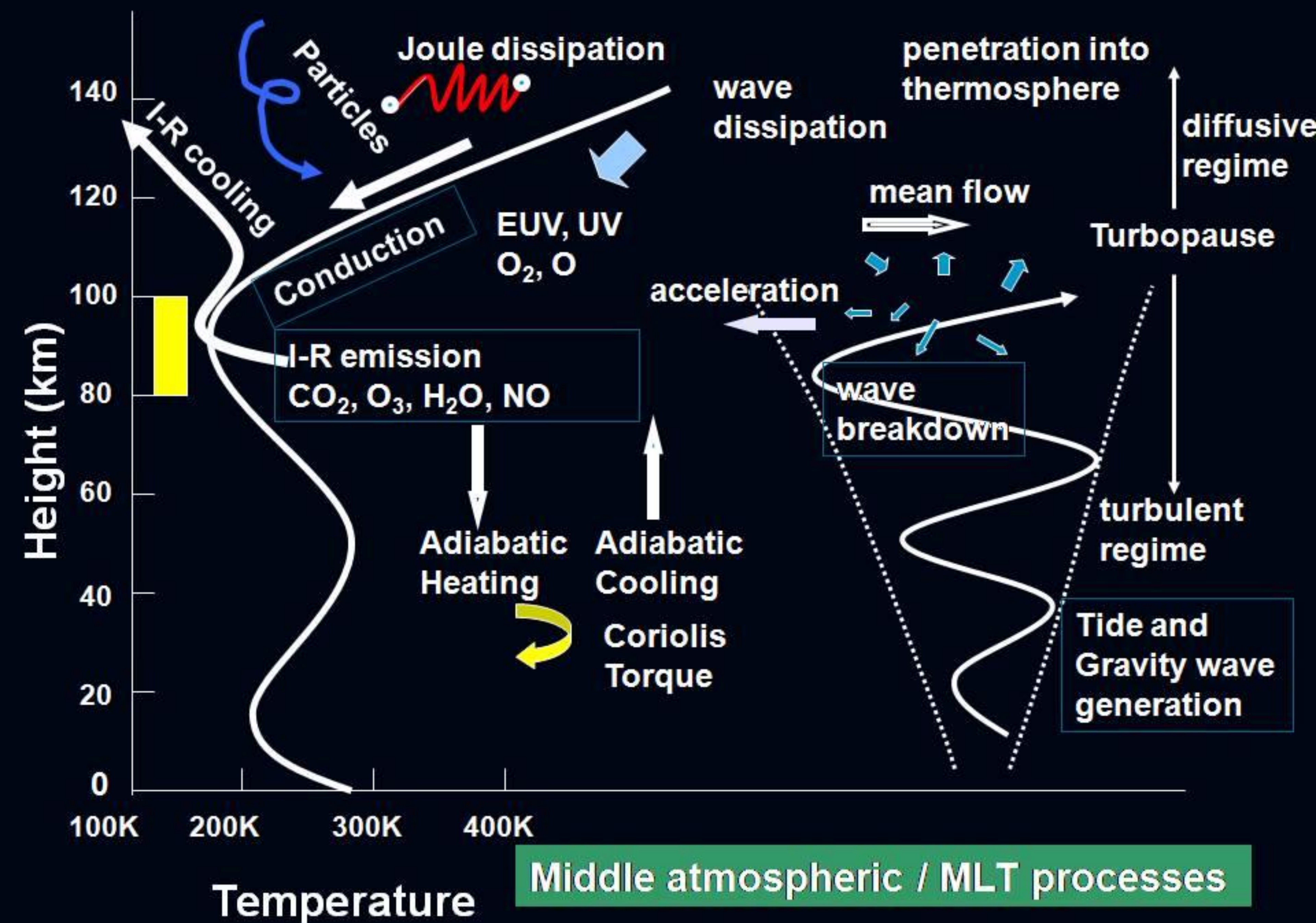
Processes that violate the non-acceleration condition

Pseudotides

Tides do not directly interact with mean flow due to their high zonal phase speeds but do modulate background flow by modulating gravity waves

Tides $\xrightarrow{\text{modulate}}$ gravity wave-mean flow interactions

Mean flow acceleration is modulated at tidal period (secondary response owing to local non-linear interactions modulated by tides)



Joule dissipation
Particles
I-R cooling
wave dissipation
penetration into thermosphere
diffusive regime
mean flow
Turbopause
Conduction
EUV, UV
O_2, O
acceleration
I-R emission
CO_2, O_3, H_2O, NO
wave breakdown
Adiabatic Heating
Adiabatic Cooling
turbulent regime
Coriolis Torque
Tide and Gravity wave generation
Height (km)
140
120
100
80
60
40
20
0
100K
200K
300K
400K
Temperature
Middle atmospheric / MLT processes

Characteristics of Mesosphere-Lower Thermosphere-Ionosphere (60-150 km) region

- Turbulent mixing gives way to molecular diffusive separation and transport.

- Radiative processes dominate the thermal balance below and thermal conduction dominates above.

- Composition changes from that of molecular to atomic.

- Heating rates due to solar EUV/UV absorption, Joule heating and particle heating all maximize. Loss rates due to radiative cooling become important.

- Gravity wave breaking and plasma instabilities play significant roles in the energy and momentum budgets.

- Ionospheric conductivities maximize–significant currents flow. Charged particle dynamics is increasingly controlled by electric and magnetic fields.

- Equatorial atmosphere: (a) small Coriolis frequency leads to trapping of certain wave modes; (b) deep tropical convection generates a variety of short and long-period gravity waves at different zonal wavenumbers

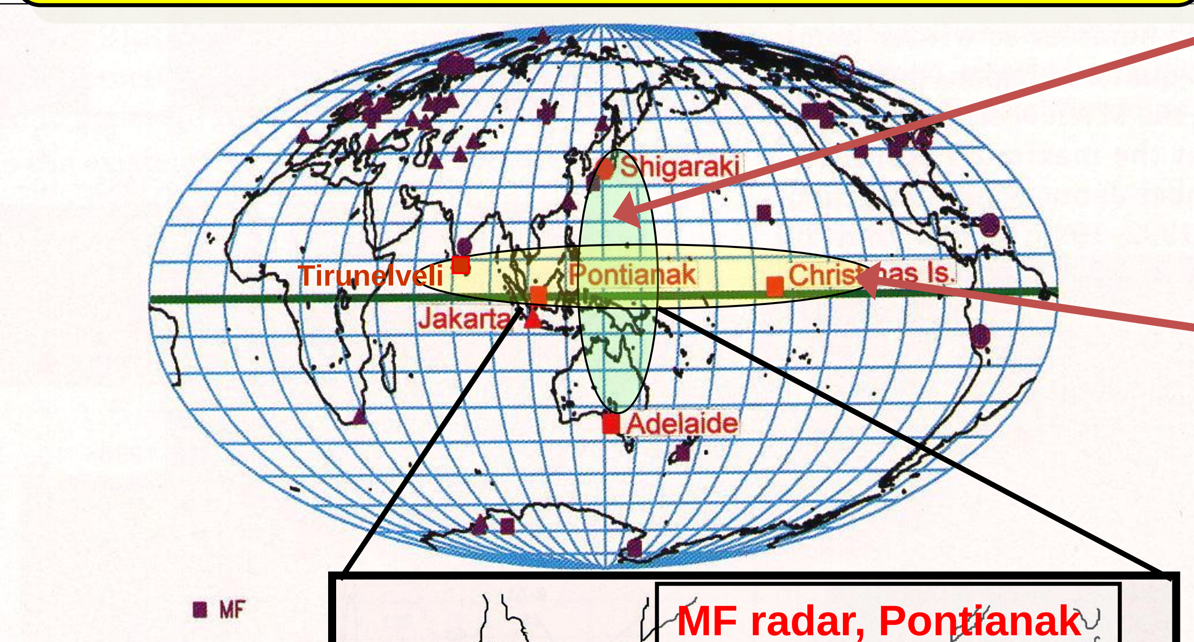
- Equatorial ionosphere: low geomagnetic inclination leads to phenomena like EEJ, EIA, ETWA, ESF

- Dynamical coupling arises through vertical propagation of planetary-scale waves, tides and gravity waves

- Electrodynamical coupling occurs primarily through dynamo process – electric fields so generated can be mapped to other regions along geomagnetic field lines

- Chemistry of MLTI region is closely linked to dynamics

Coordinated Radar Observation Network of the MLT region in the Equatorial Region



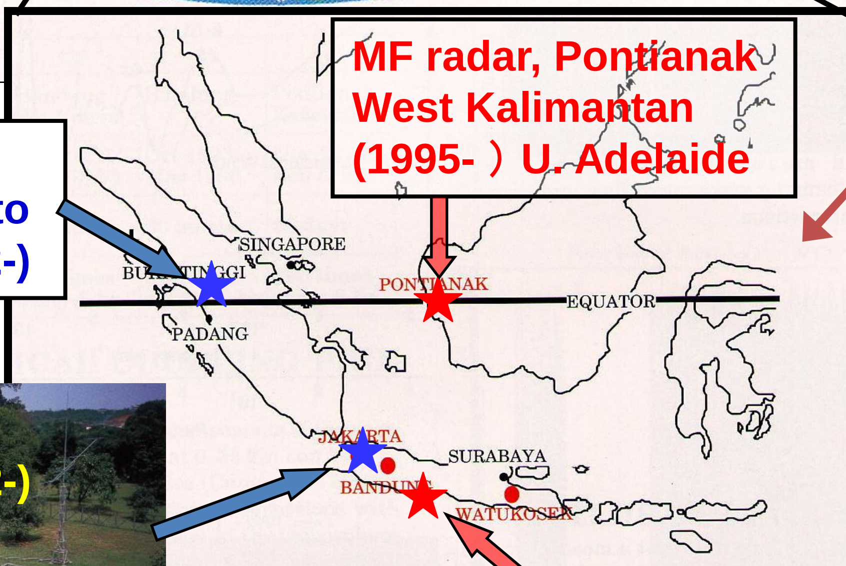
Hemispheric Comparison (1977-)
Shigaraki: Meteor radar, MU radar, lidar, CCD
Adelaide; MF radar

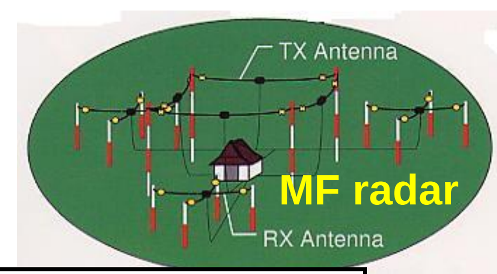
Equatorial Network
Christmas Island
Indonesia, India

Regional network in Indonesia (1992-)
Meteor radar; Jakarta, Koto Tabang
MF radar; Pontianak, Pameungpeuk

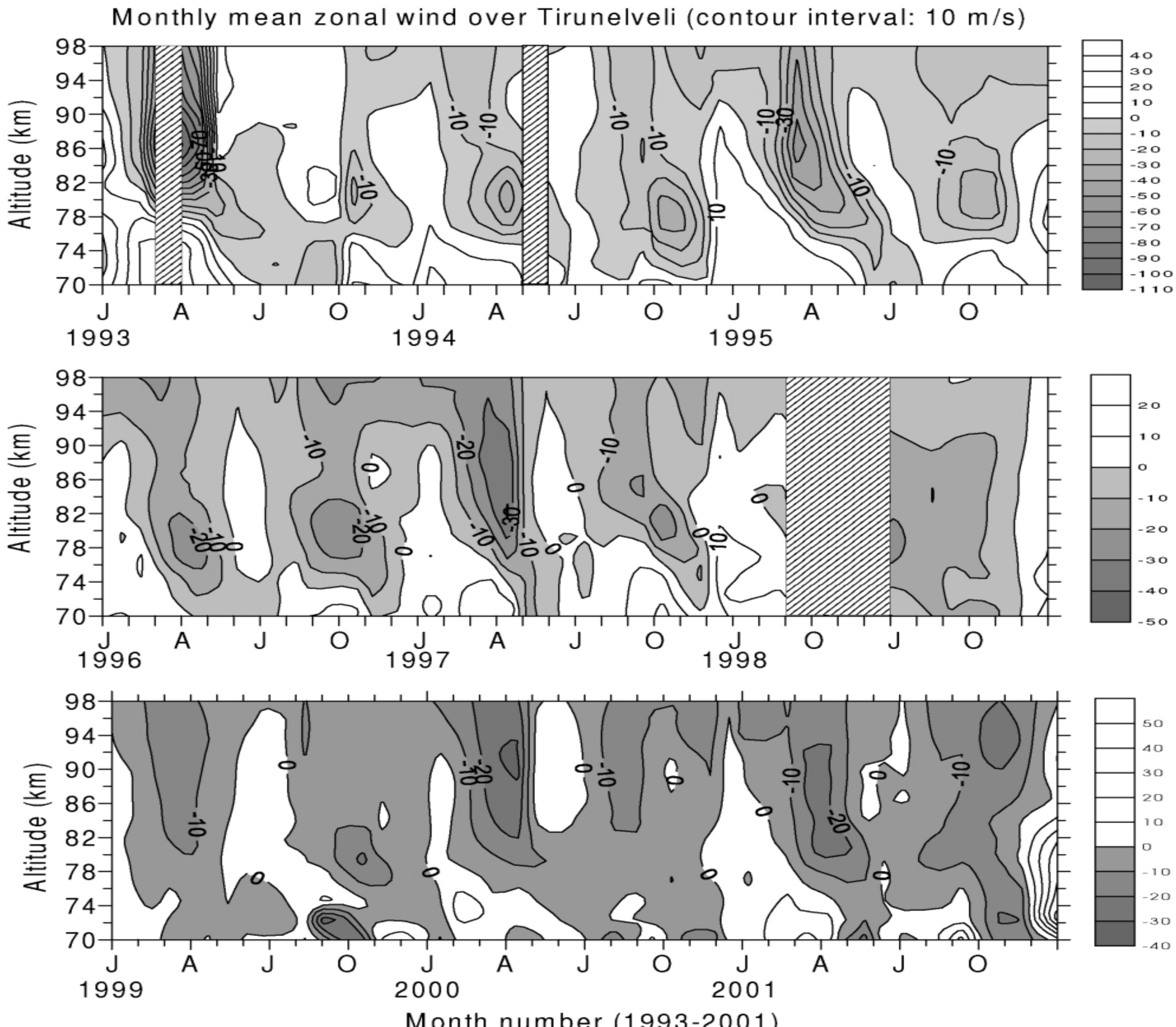
MF radar, Pontianak West Kalimantan (1995-）U. Adelaide

Meteor radar EAR site, Koto Tabang (2002-)

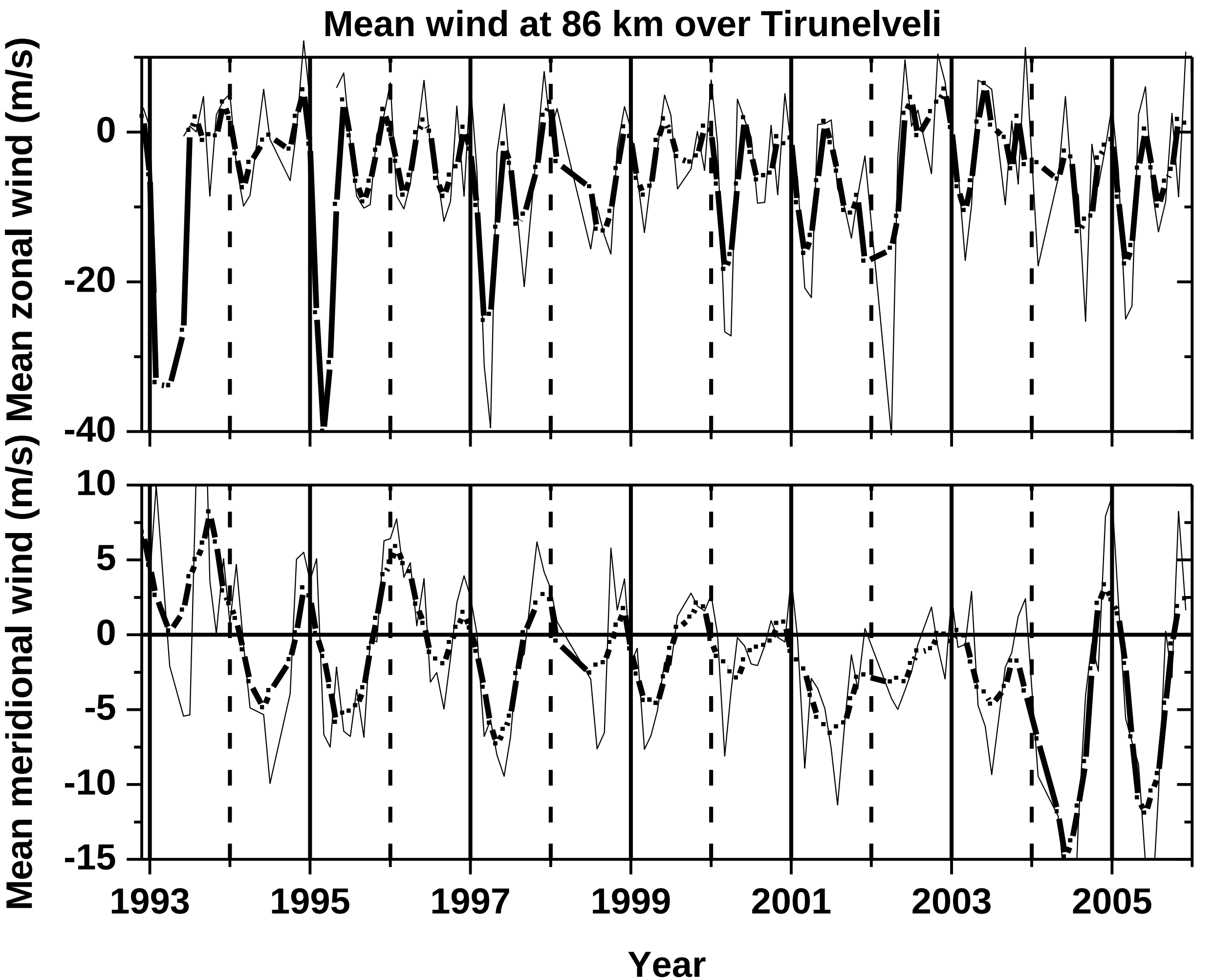




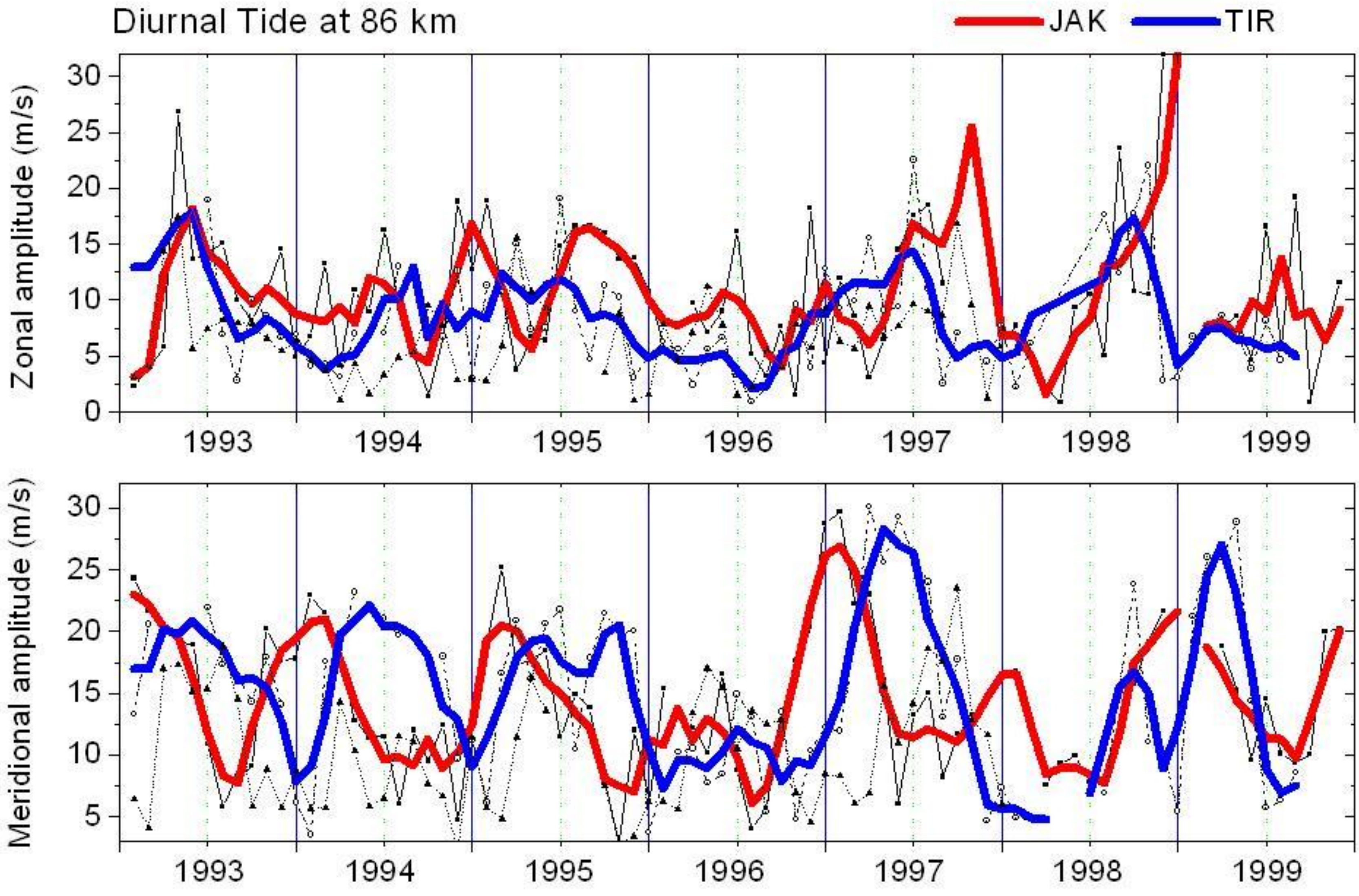
MF radar, Pameungpeuk (2003-)



SAO and its interannual variability is evident in this plot

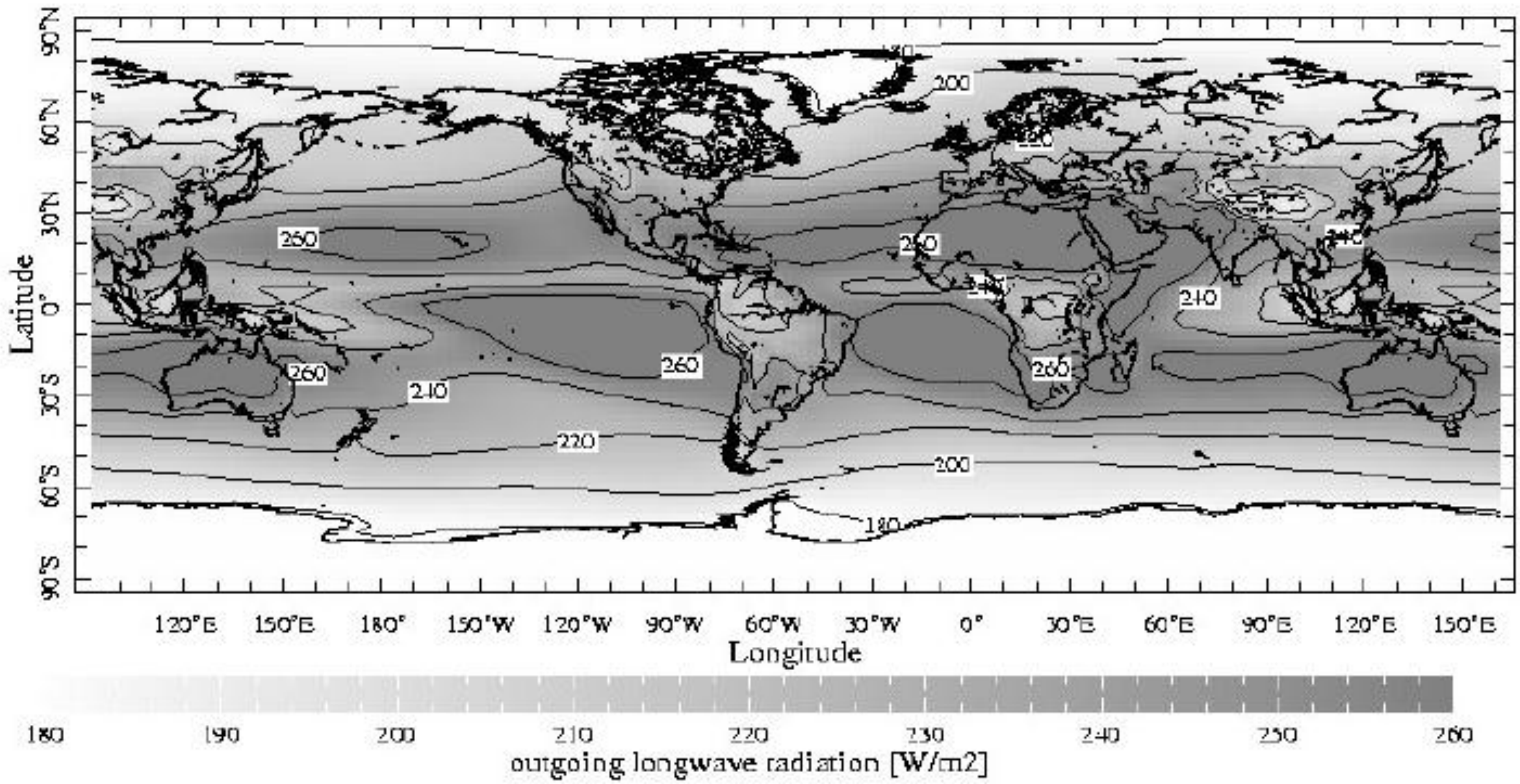


Annual cycle in meridional wind and SAO/QBO signatures in zonal wind are the prominent features.



Stronger seasonal variation
Seasonal maxima peak in different months

(Gurubaran et al., 2005)



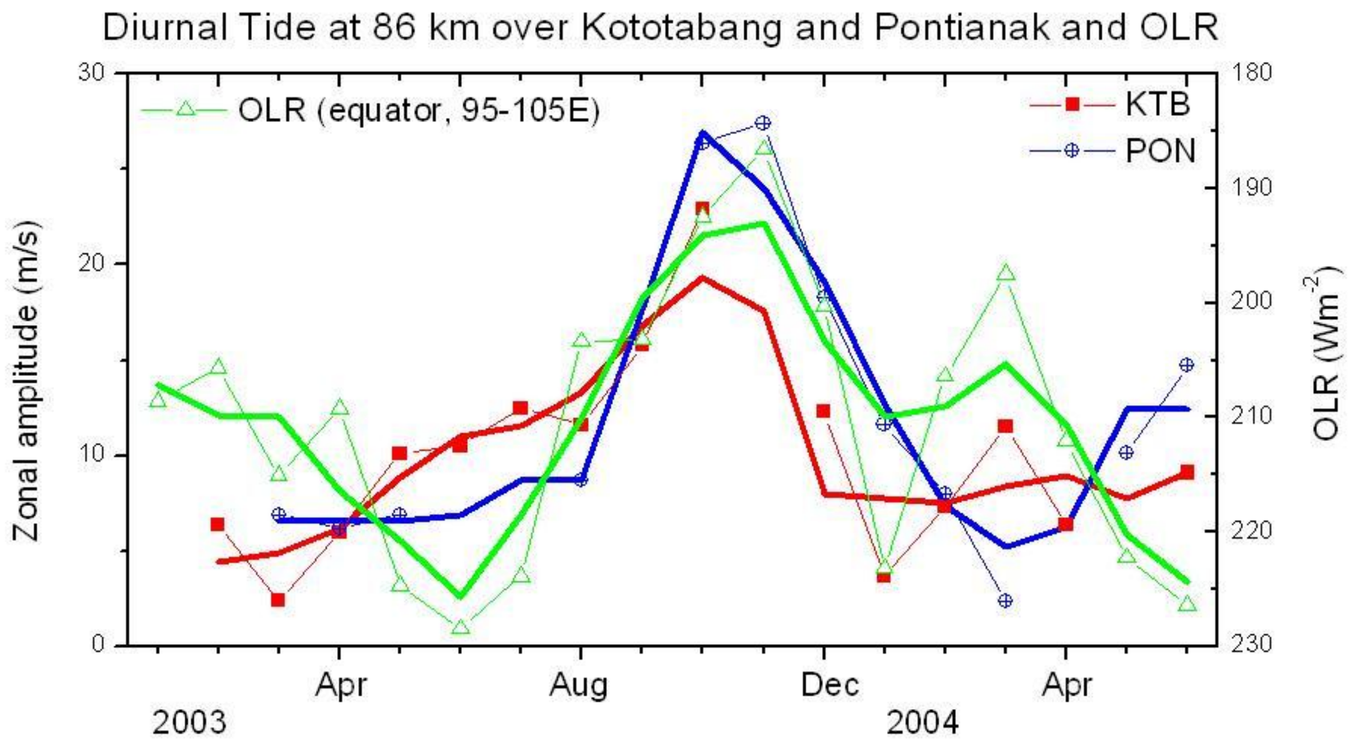
Outgoing longwave radiation (OLR: contour interval 20 Wm^{-2}) averaged over the year. Note the high values over the subtropics and low values over the three wet regions on the equator: Indonesia, Amazon and equatorial Africa.

Diurnal tide at 86 km over Indonesian stations

<u>Equatorial stations</u>

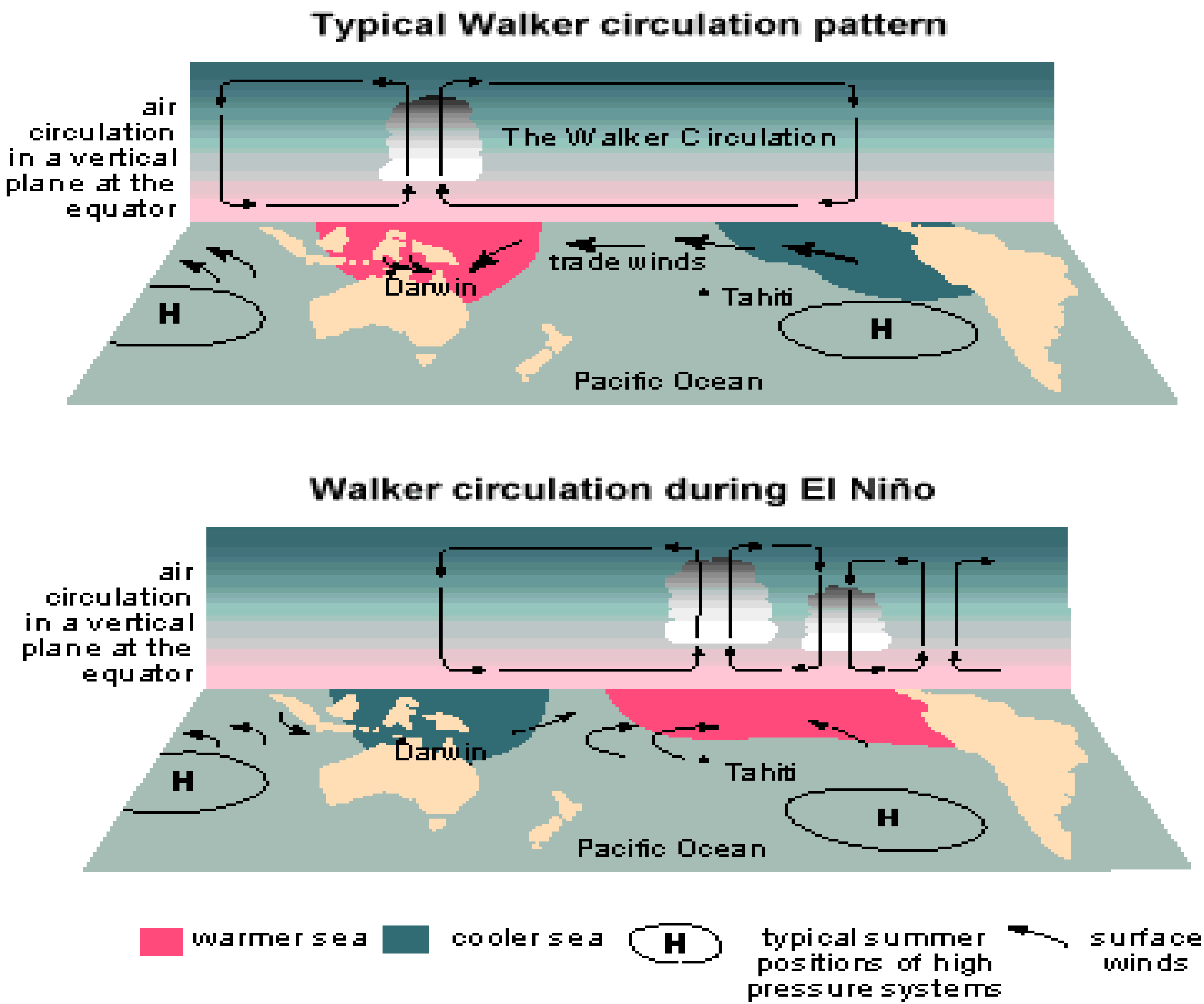
Kototabang
(0.2^{o}S, 100.3^o E)

Pontianak
(0.03^{o}N, 109.3^{o}E)

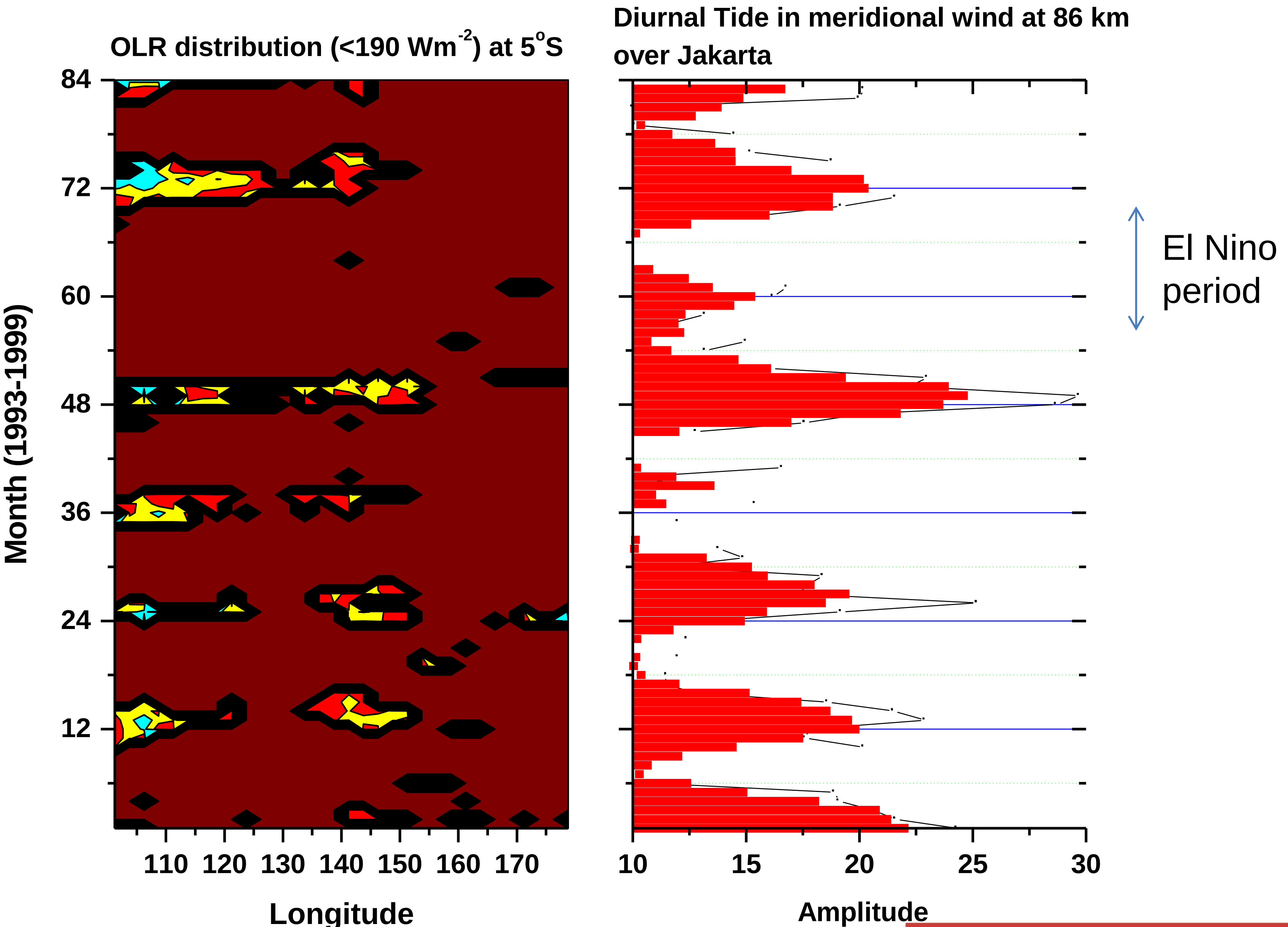


Enhanced tidal activity during October-November 2003 occurred around the same time when deep tropical convection was active over Indonesia

Latent heat release in convective clouds – source for such observed tides?

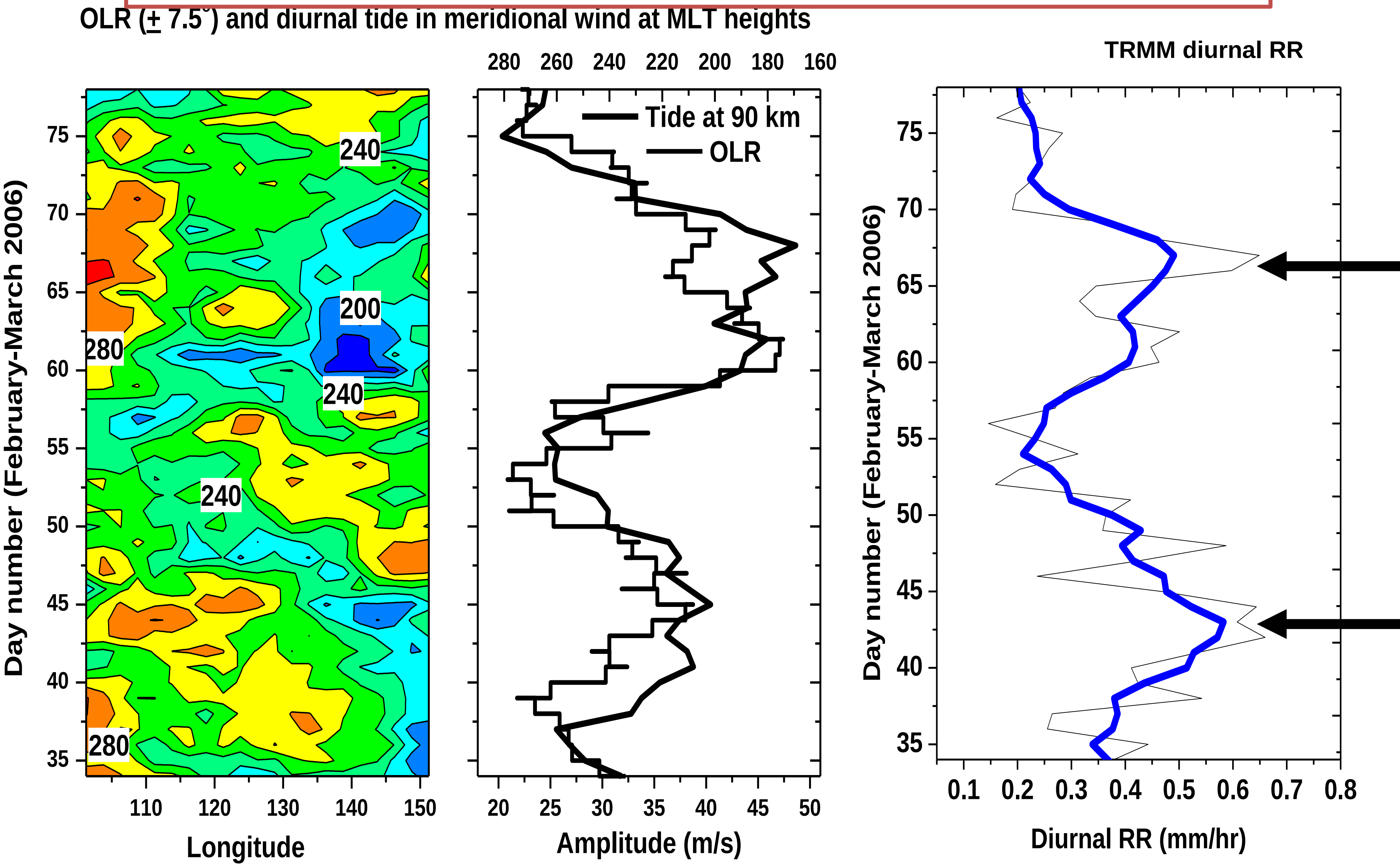

Typical Walker circulation pattern
air circulation in a vertical plane at the equator
The Walker Circulation
trade winds
Darwin
Tahiti
H
H
Pacific Ocean
Walker circulation during El Niño
air circulation in a vertical plane at the equator
Darwin
Tahiti
H
H
Pacific Ocean
warmer sea
cooler sea
H
typical summer positions of high pressure systems
surface winds

Tidal winds over Jakarta: Links to deep tropical convection and El Nino



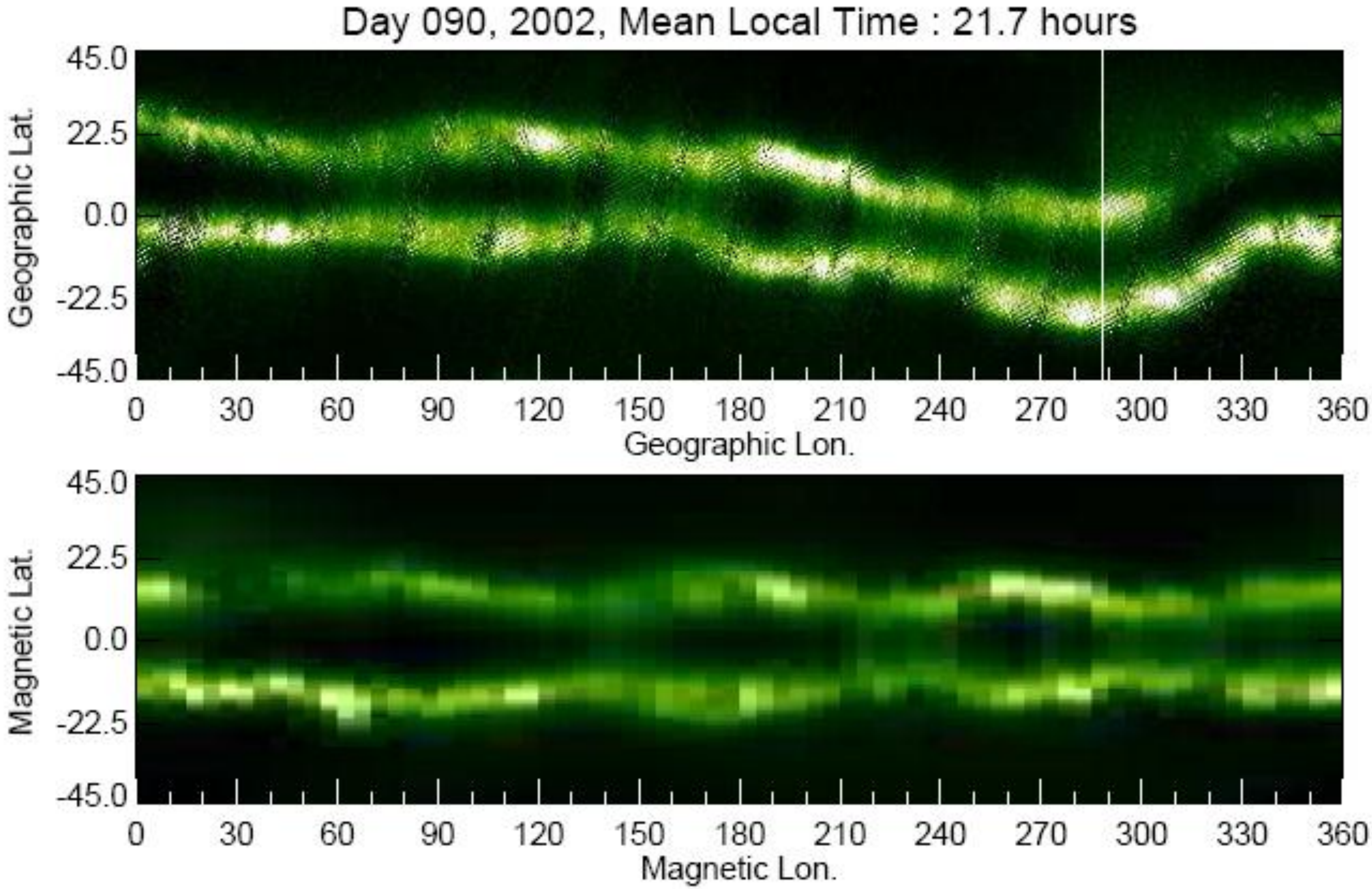
(Gurubaran et al., 2005)

Deep tropical convection and diurnal tide variability at 90 km



Were the time-varying convective sources driving tidal variabilities over Tirunelveli? (Gurubaran et al., 2008)

GUVI images of EIA – longitudinal variabilities

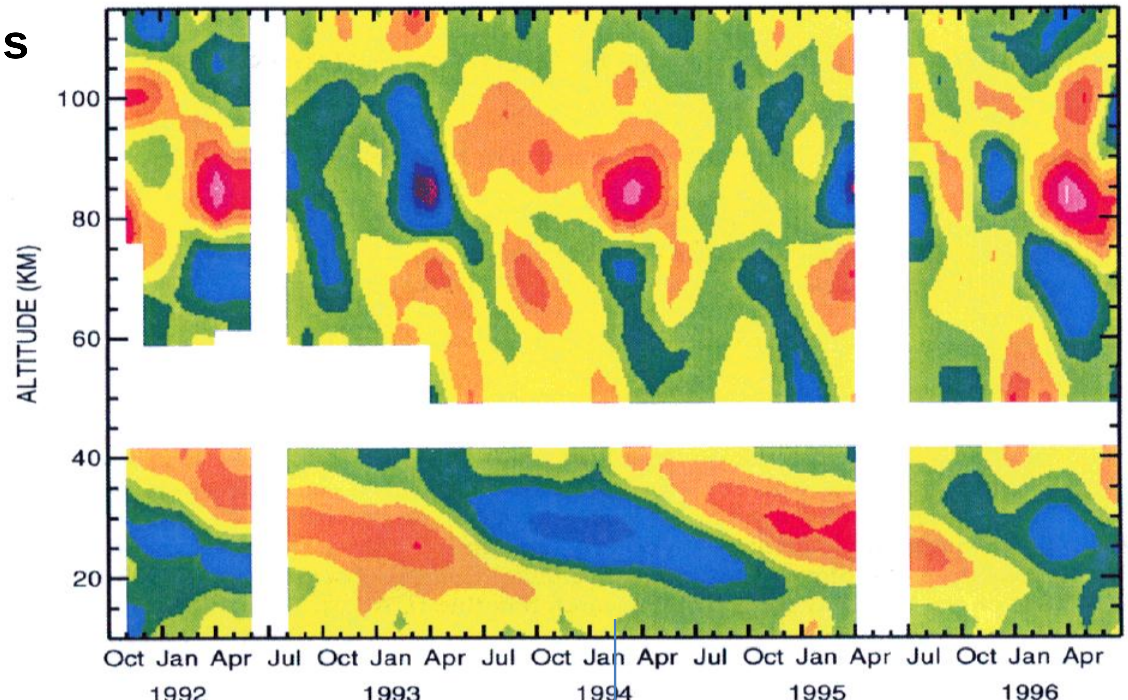


4 maxima/minima due to tidal drive?
(Tides of lower atmospheric origin are considered important)

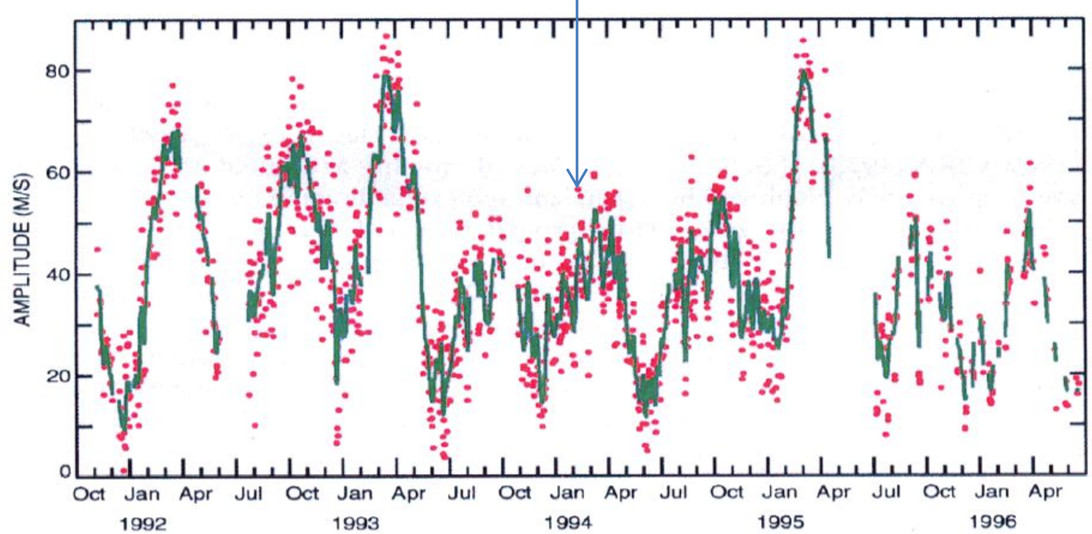
(Immel et al., 2007)

Zonal mean zonal winds and tidal amplitudes derived from UARS satellite data sets

HRDI zonal winds at the equator (AO and SAO removed)

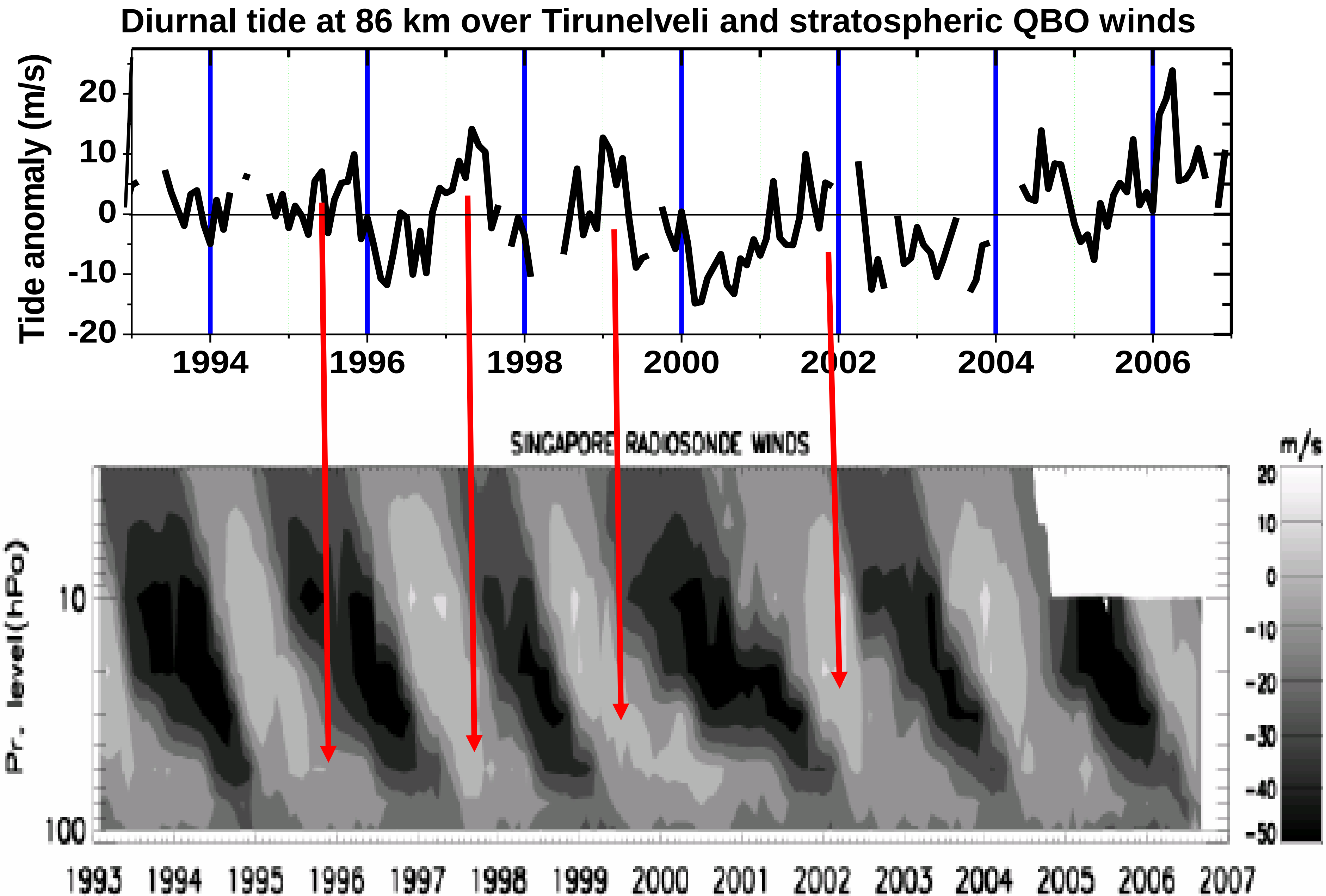


HRDI diurnal (1,1) meridional wind at 95 km and 20° N

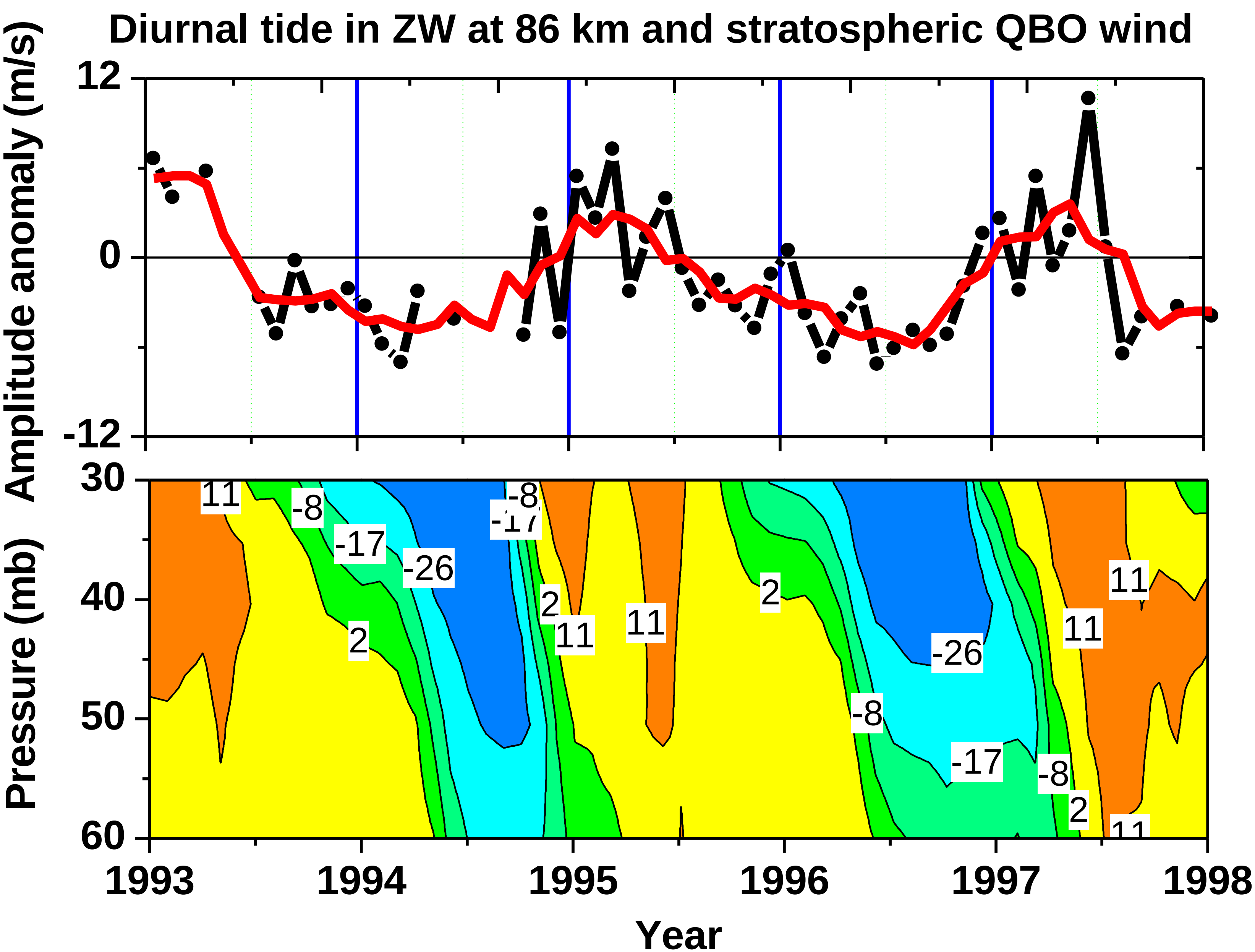


Links to QBO?

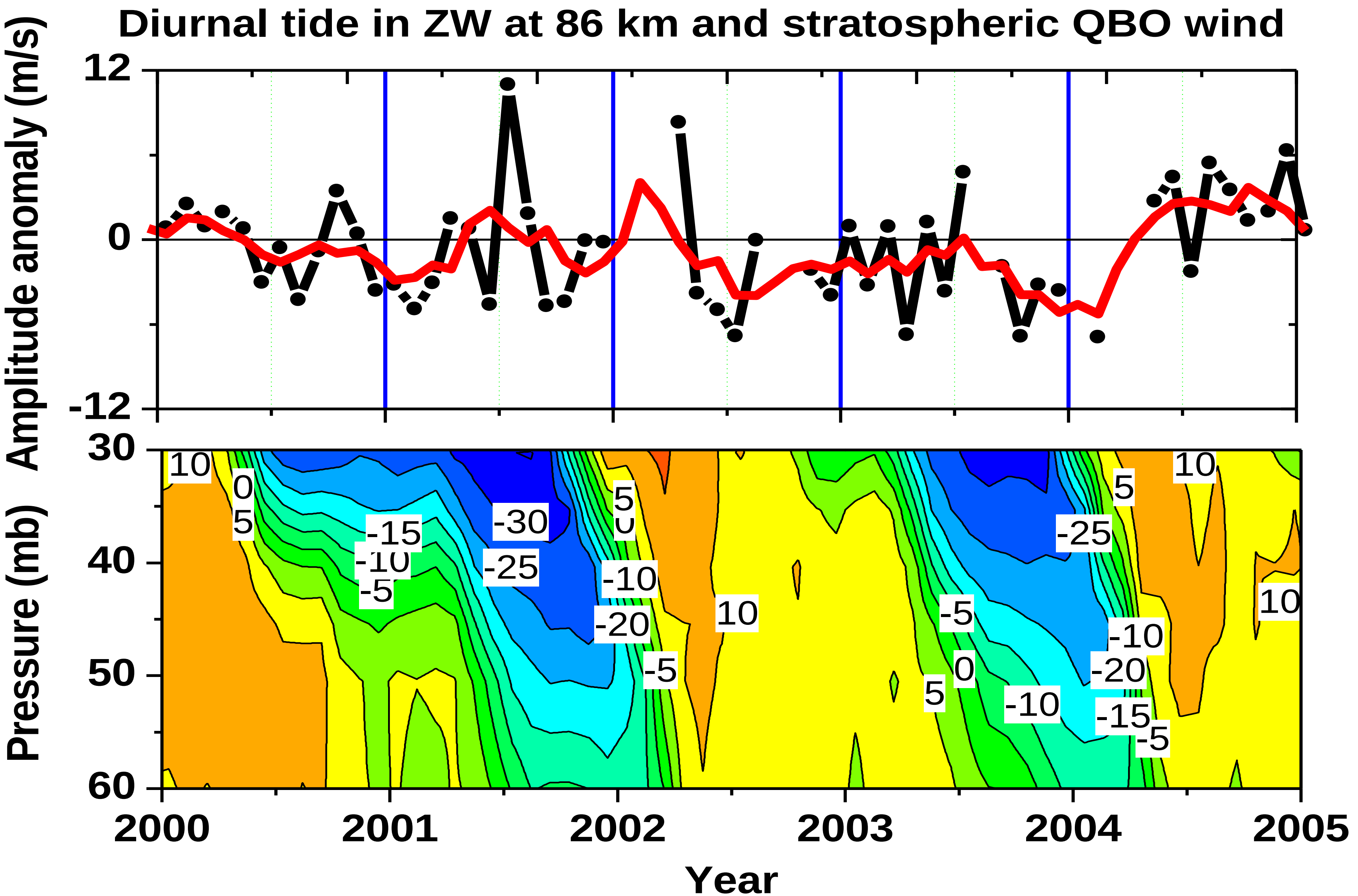
Smaller tidal amplitudes during the easterly phase of QBO



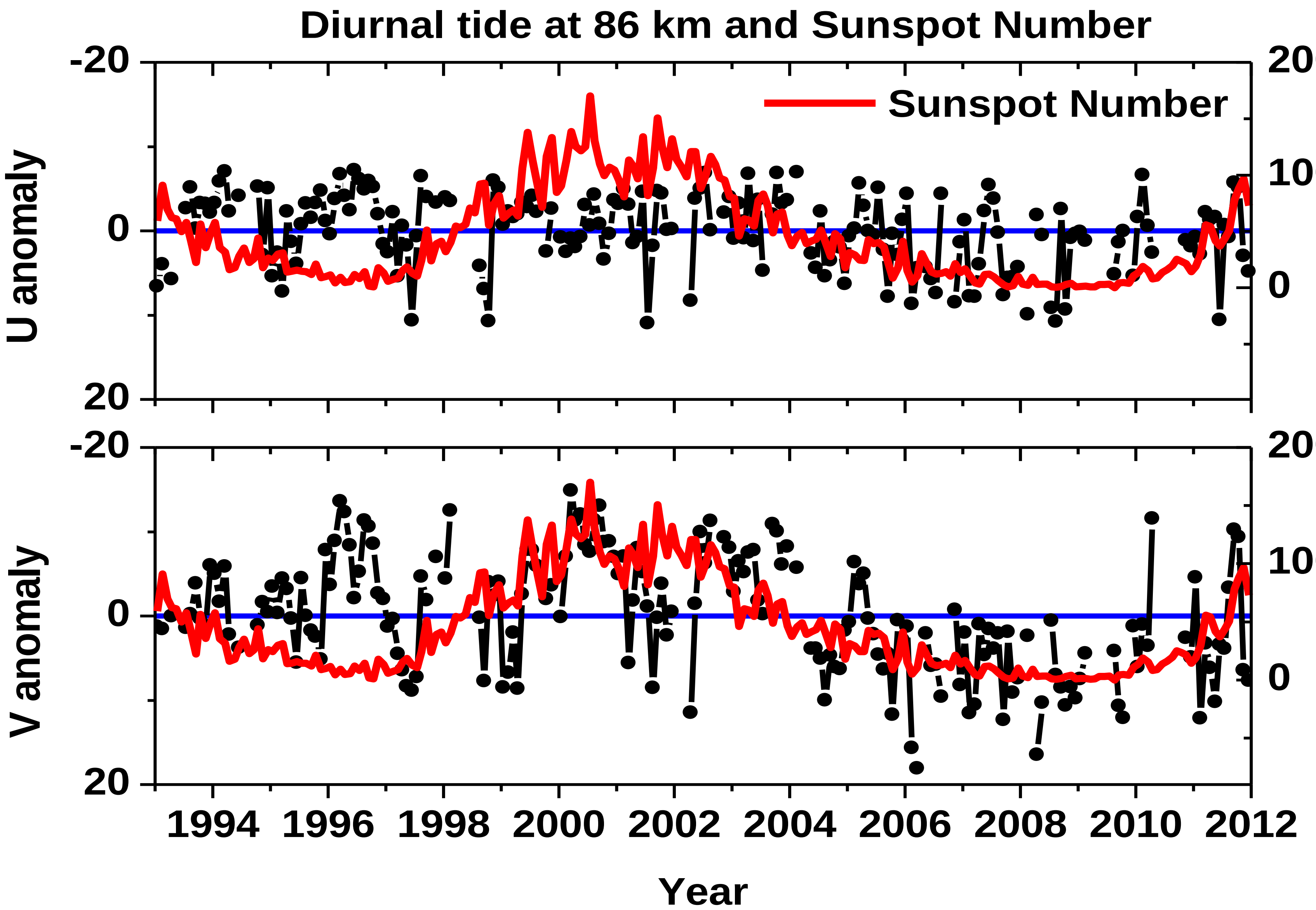
Diurnal tide at 86 km over Tirunelveli and stratospheric QBO winds
Tide anomaly (m/s)
20
10
0
-10
-20
1994
1996
1998
2000
2002
2004
2006
SINGAPORE RADIOSONDE WINDS
Pr. level(hPa)
10
100
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
m/s
20
10
0
-10
-20
-30
-40
-50



Clear QBO signature seen during this period

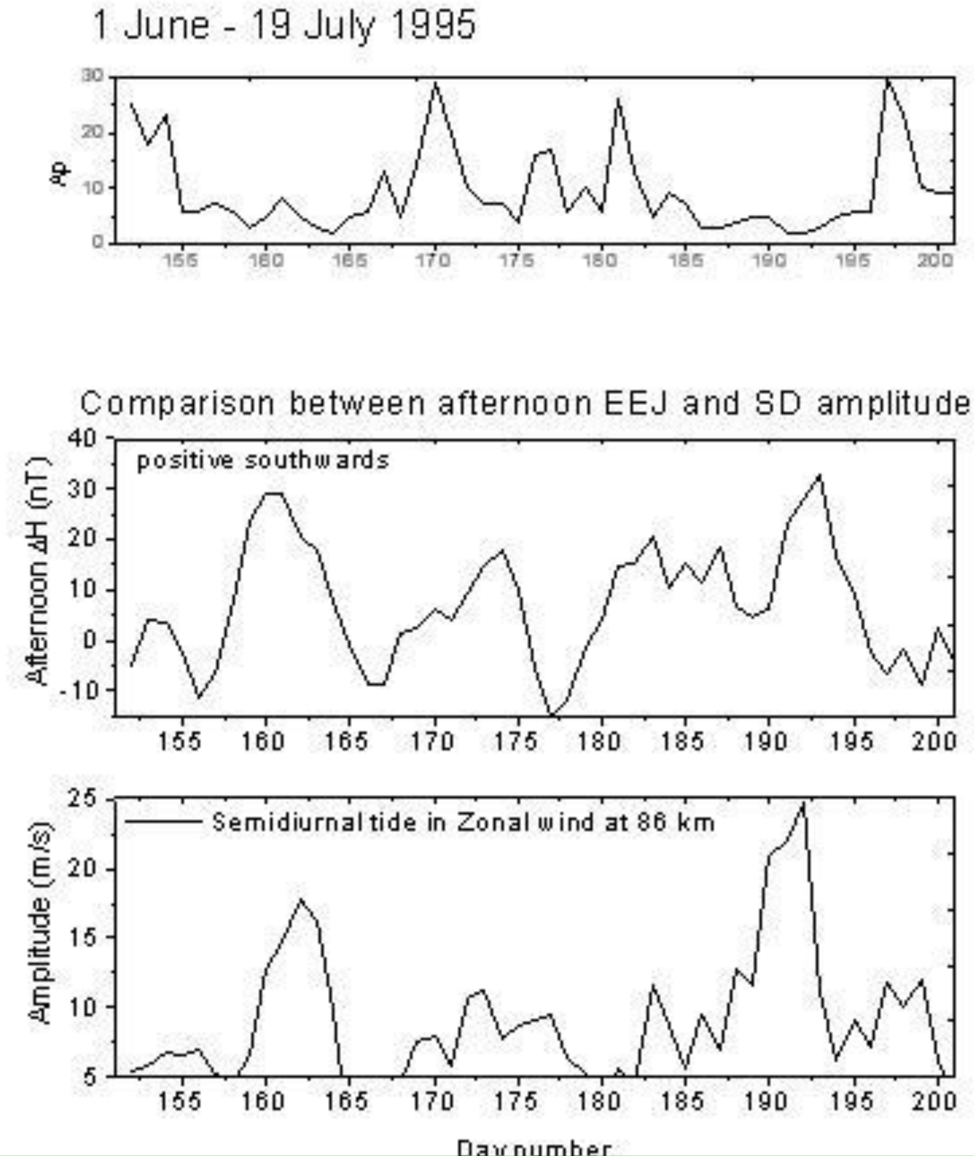


QBO modulation not so evident



Greater than climatological means during low sunspot years (2006-2010), especially in the meridional component of the tide

Semi-diurnal tide in wind at 86 km and afternoon counter-electrojet

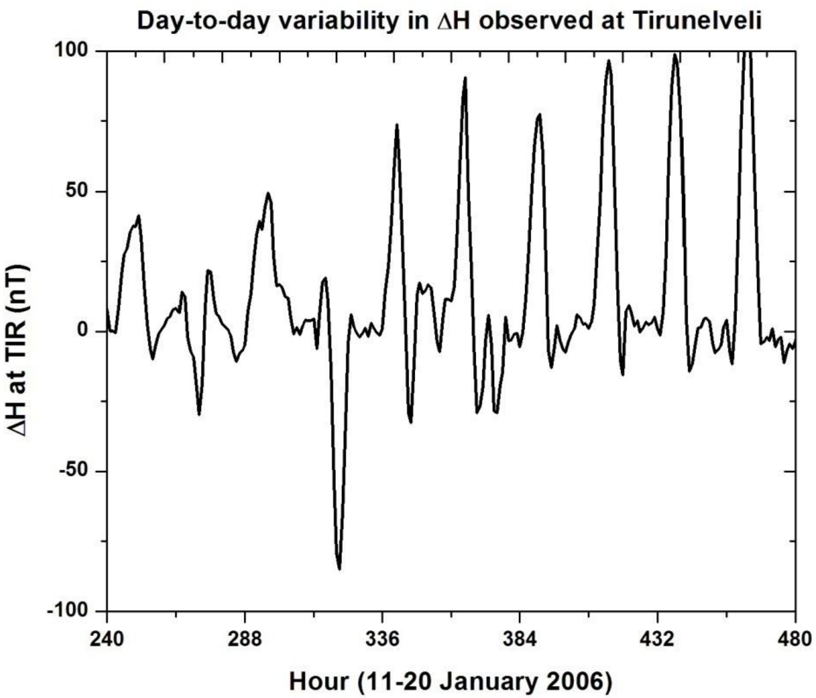


What is the role of non-migrating tides in short-term variabilities of EEJ?

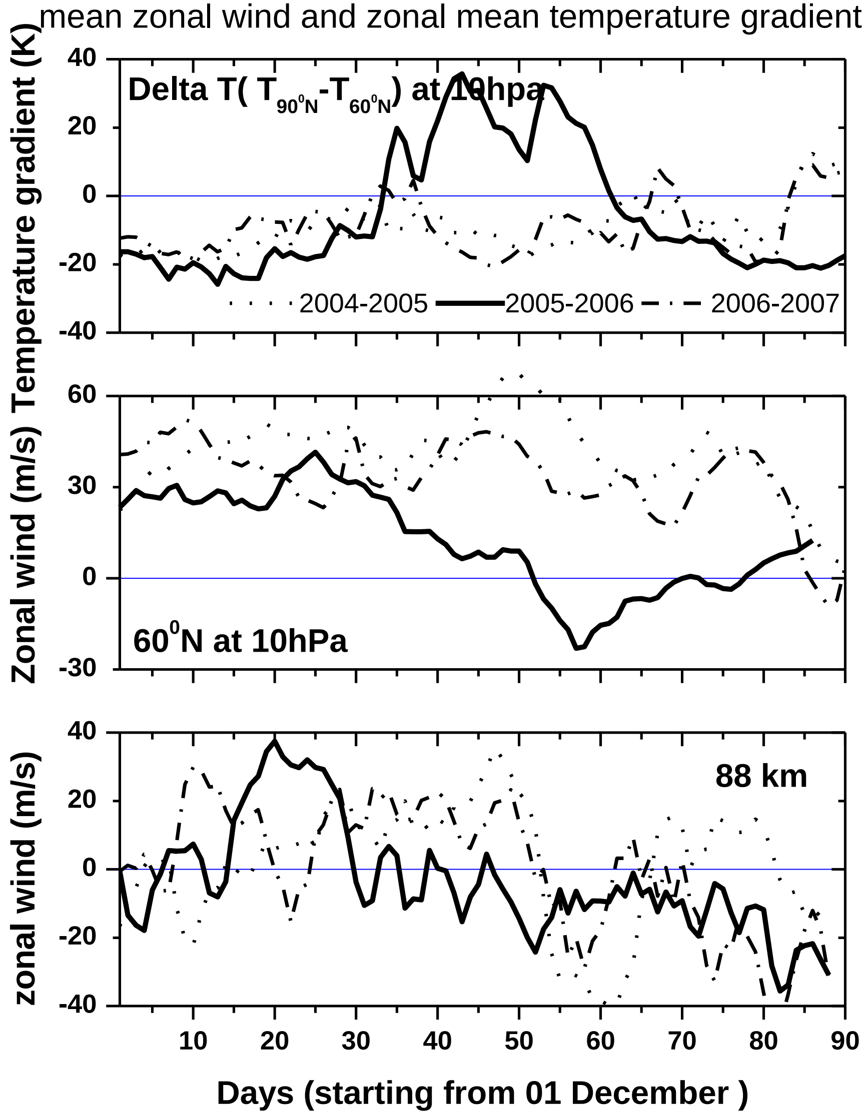
(Sridharan et al., 2002)

Enhancement in semi-diurnal tide amplitude in zonal wind at 86 km was noticed on days of afternoon reversal in ΔH during these months

Very unusual CEJ on 14 Jan 2006

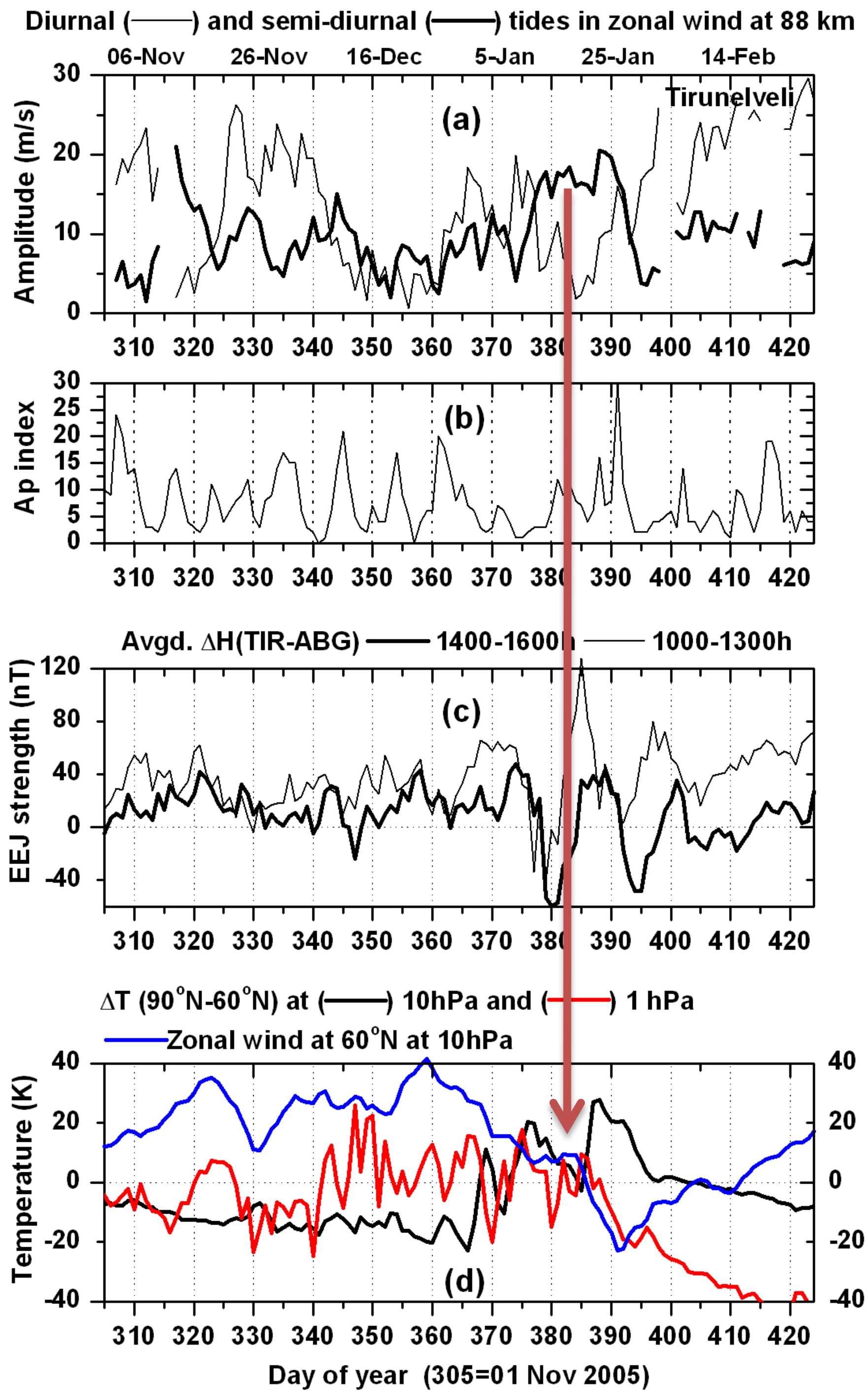


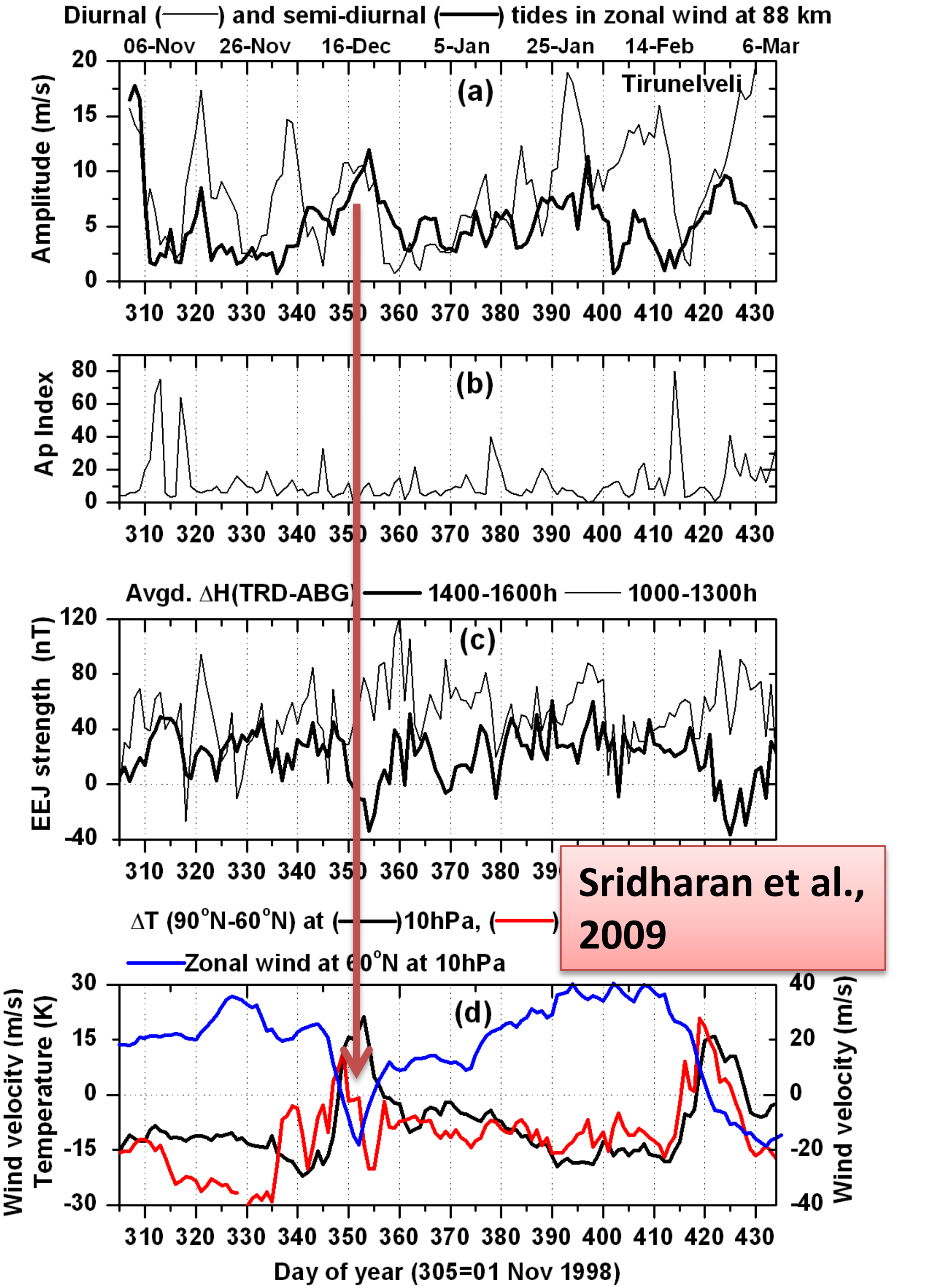
3d mean mesopaue zonal wind and lower stratospheric mean zonal wind and zonal mean temperature gradient



Stratospheric warming:

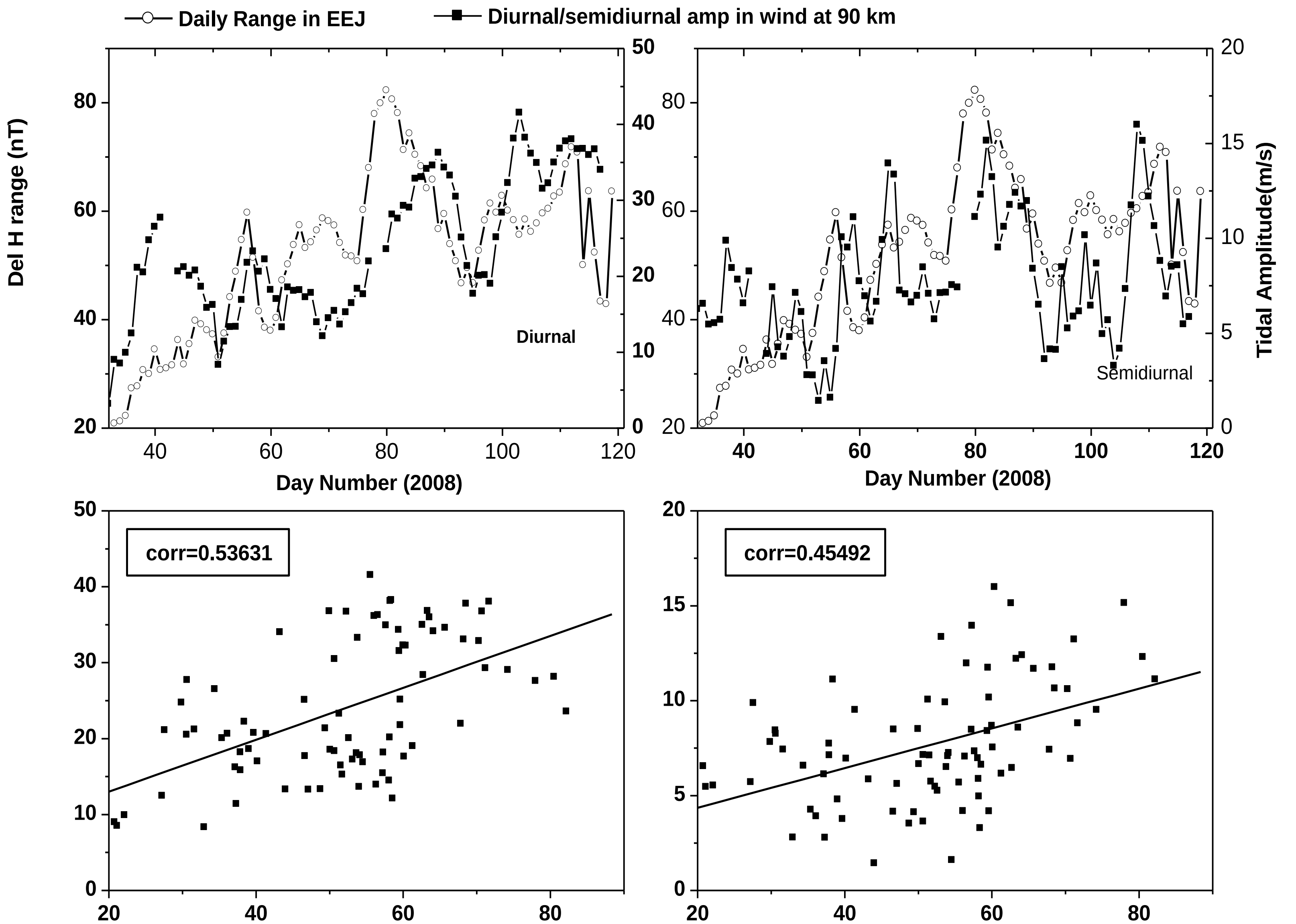
change in global scale winds resulting in CEJ? (ref. *Stening et al.*, 1995)



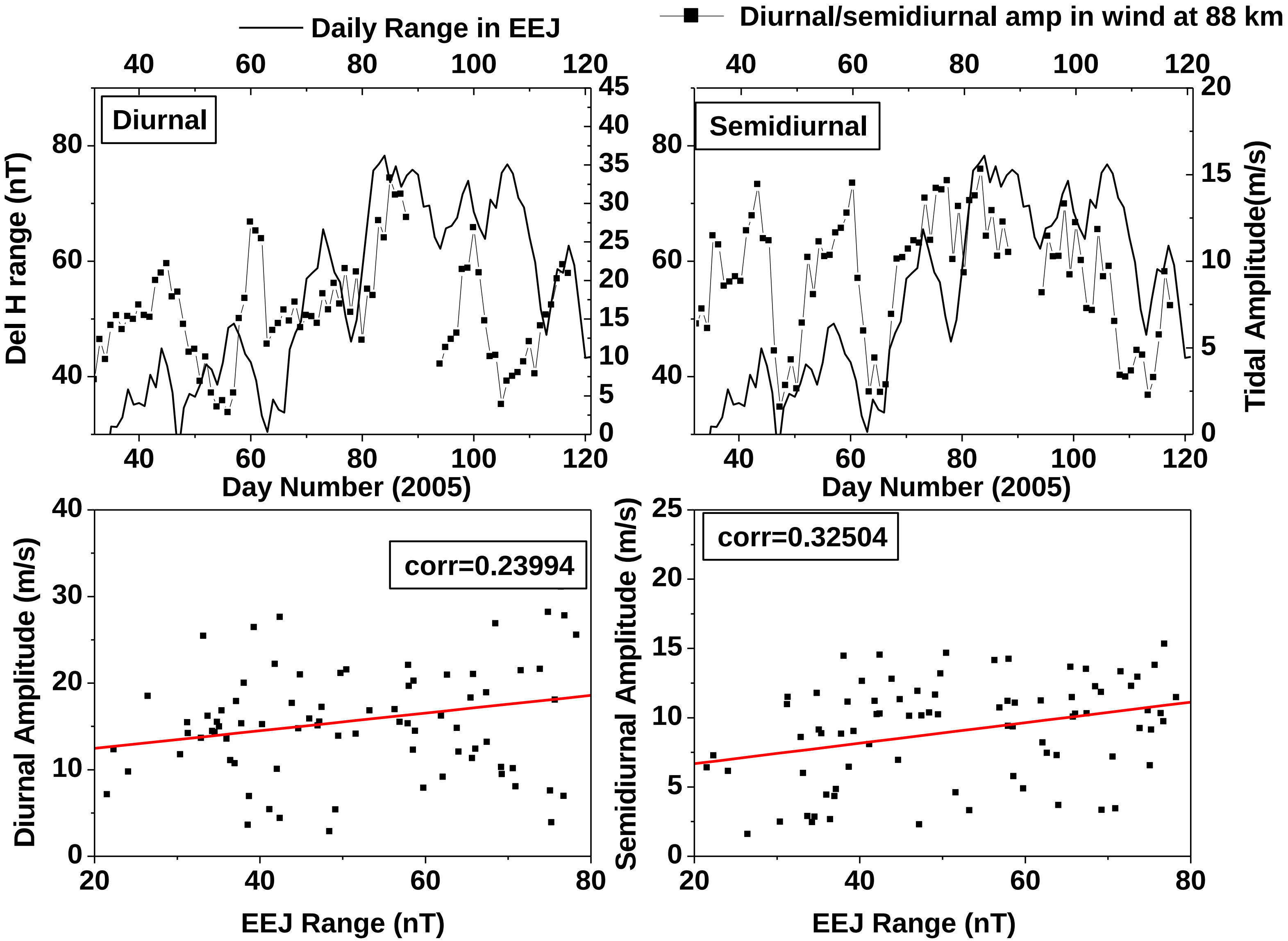


Sridharan et al., 2009

Daily Range in EEJ & Tidal Amplitudes during February-April 2008



Daily Range in EEJ & Tidal Amplitudes during February-April 2005

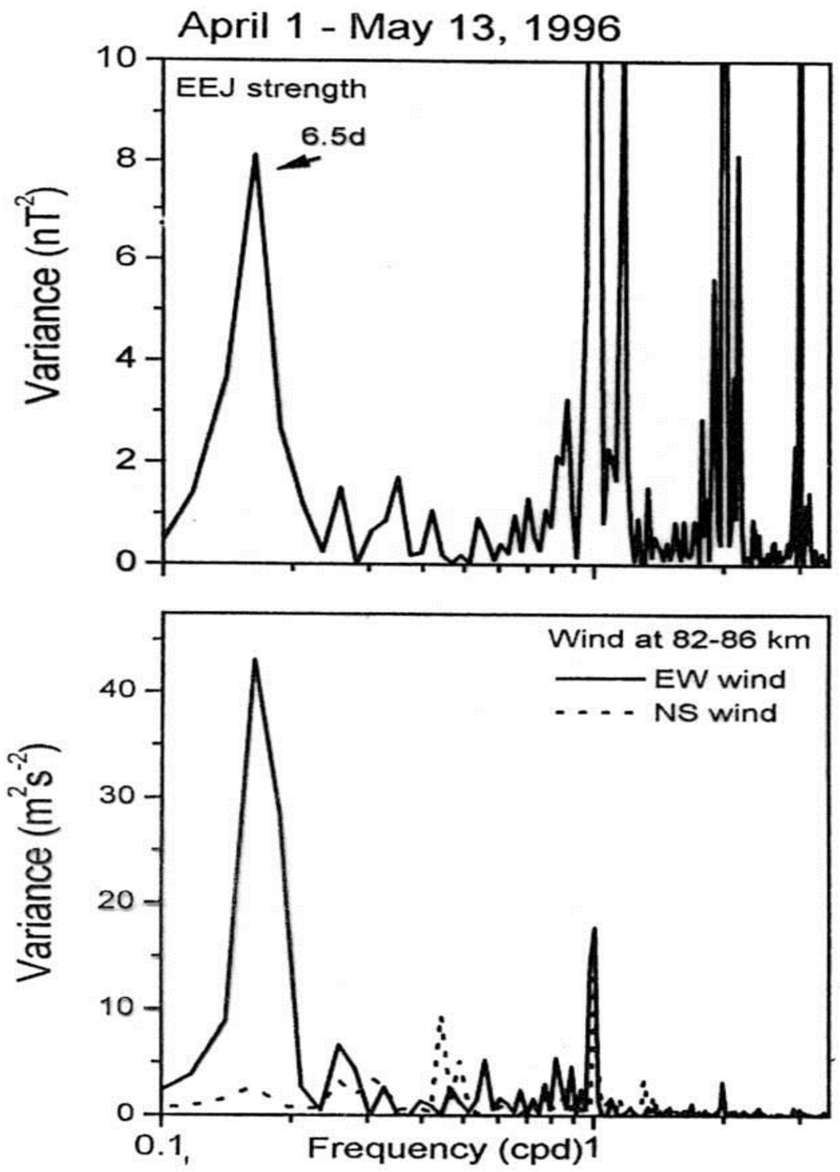


Weaker correlation noticed during 2005!

MLT winds and EEJ strength (ΔH) over low latitudes

Two mechanisms have been suggested:

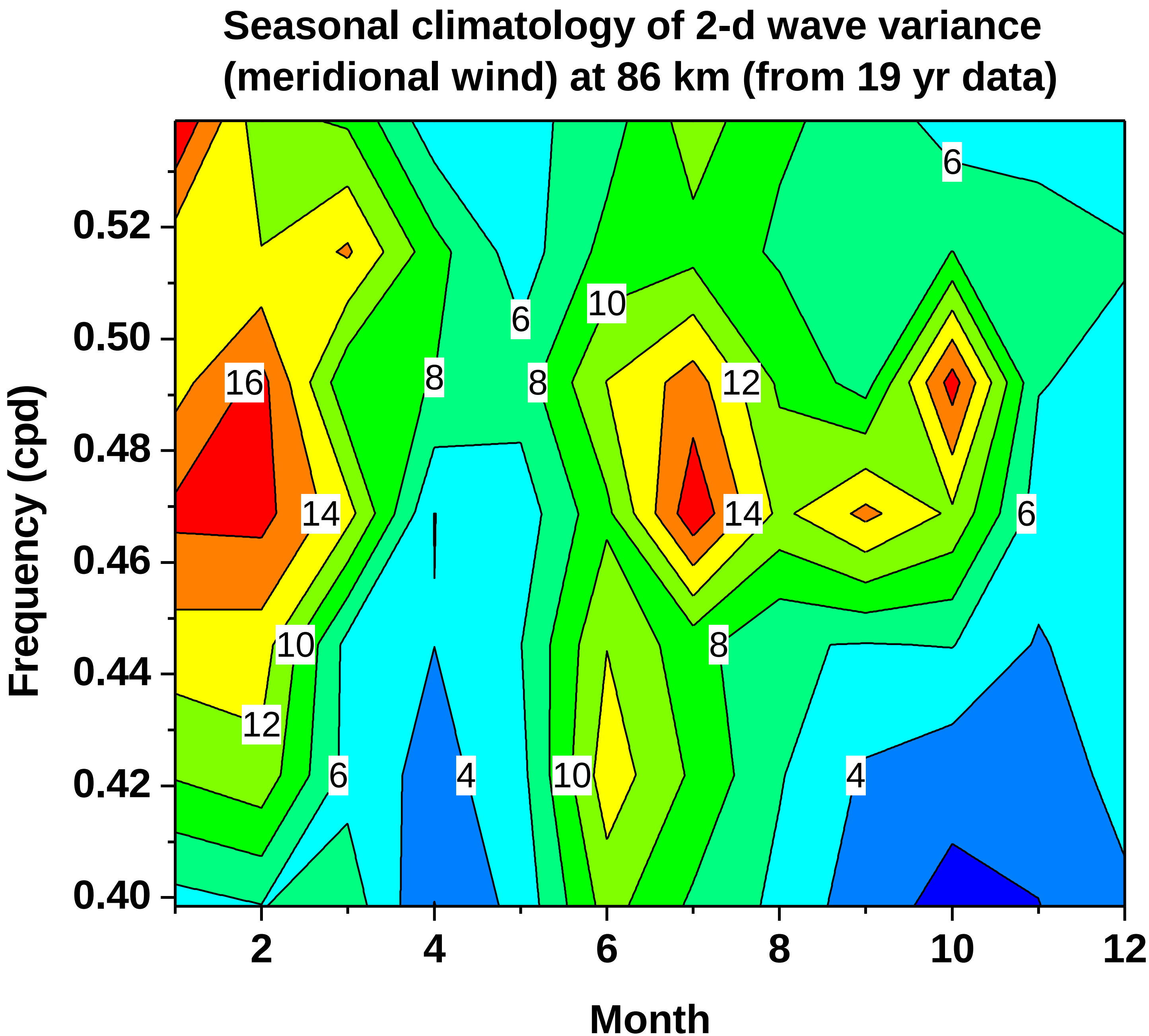
(1) Vertical motions induce changes in composition; (2) Wind dynamo

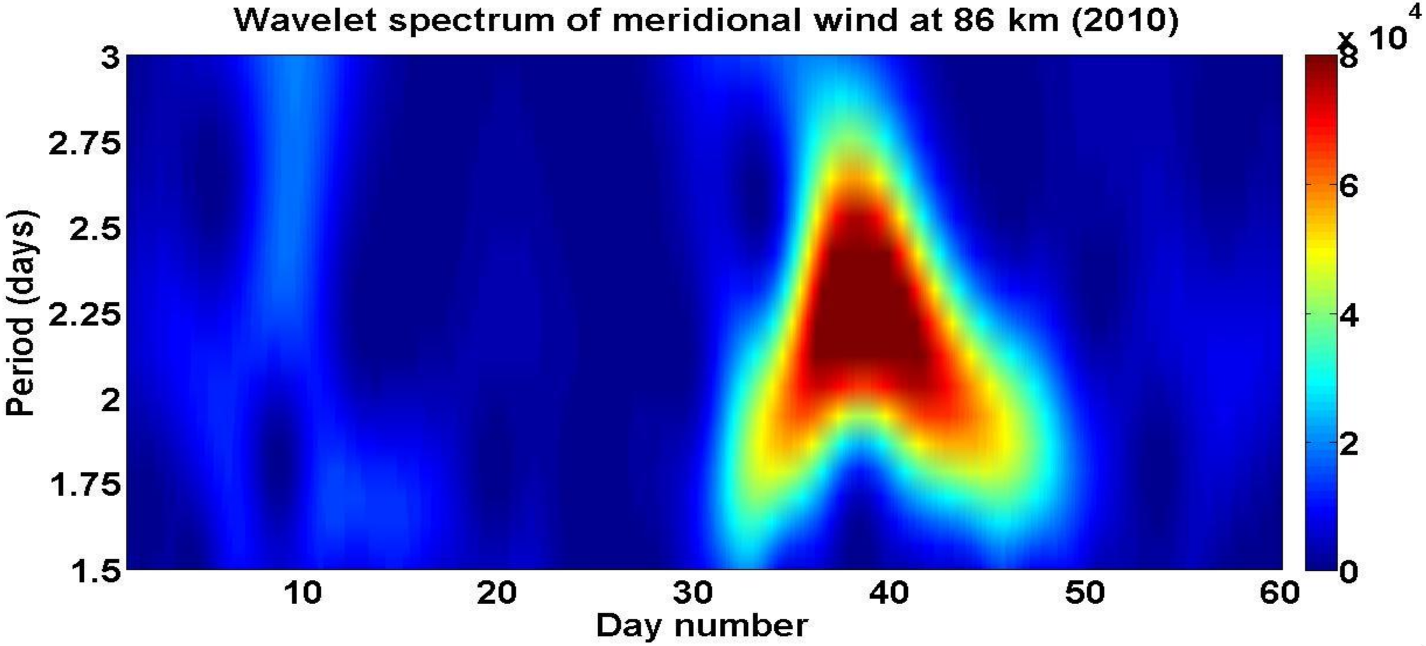


Magnetometer data

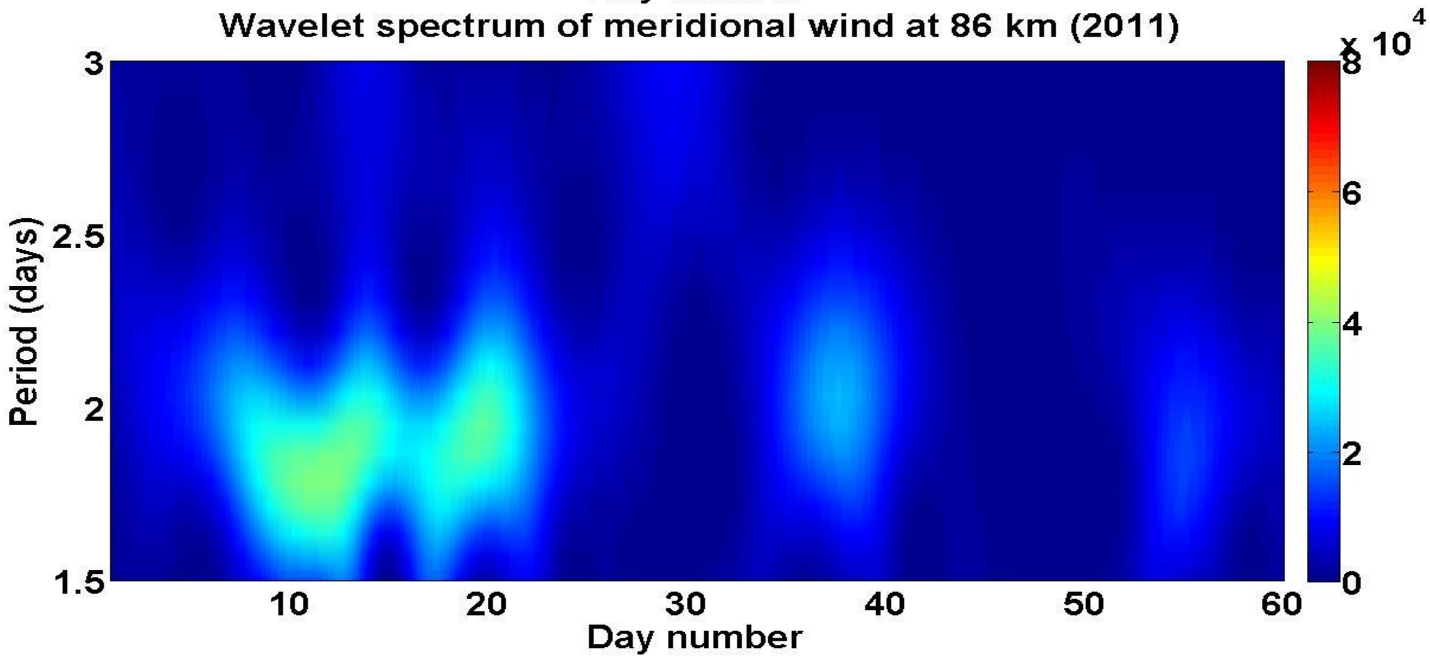
6.5-d wave modulation of EEJ is seen

MF radar winds


Seasonal climatology of 2-d wave variance
(meridional wind) at 86 km (from 19 yr data)
Frequency (cpd)
Month
0.40
0.42
0.44
0.46
0.48
0.50
0.52
2
4
6
8
10
12
16
14
10
12
6
4
8
6
8
10
12
14
8
10
4
6
6



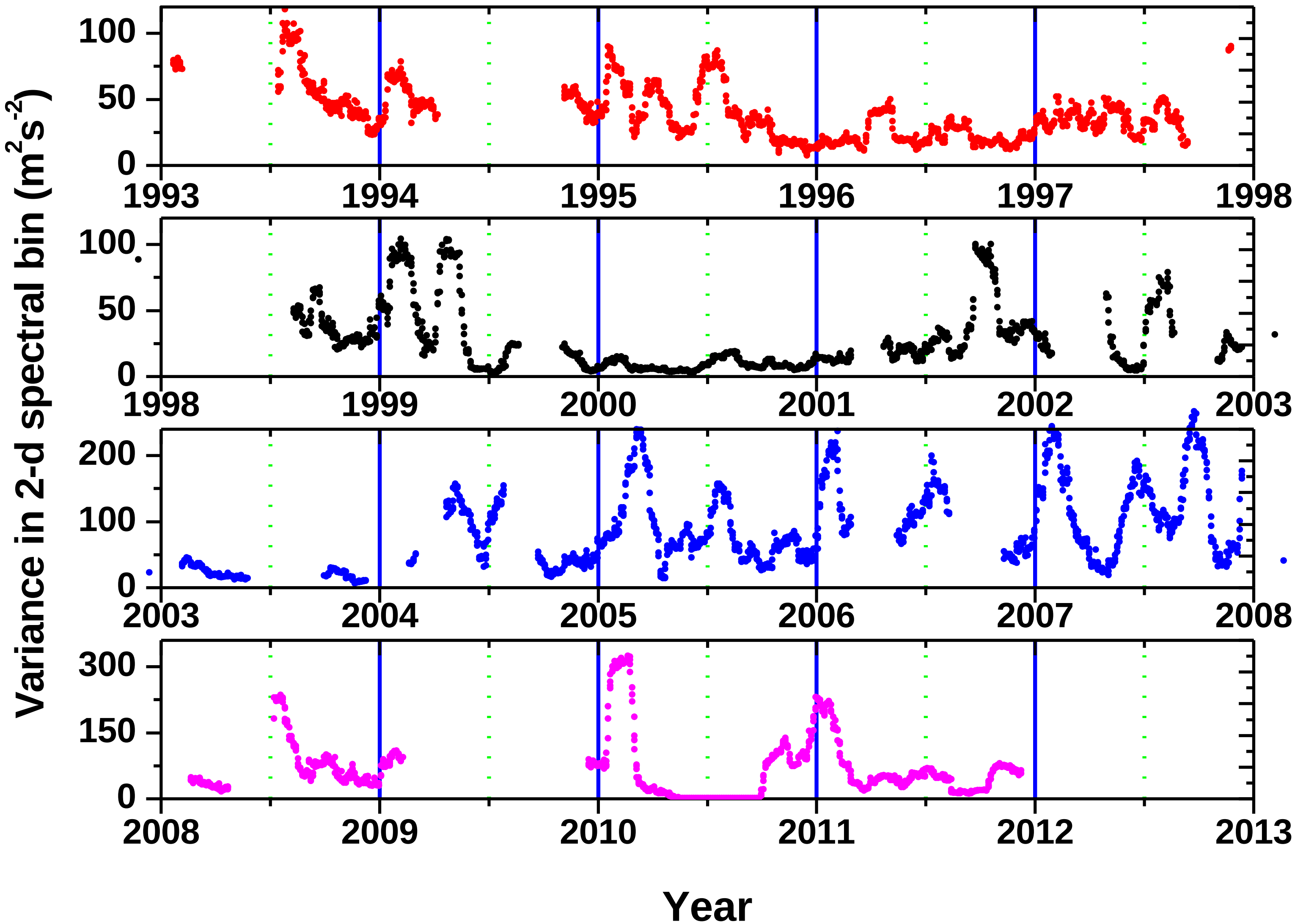
2010



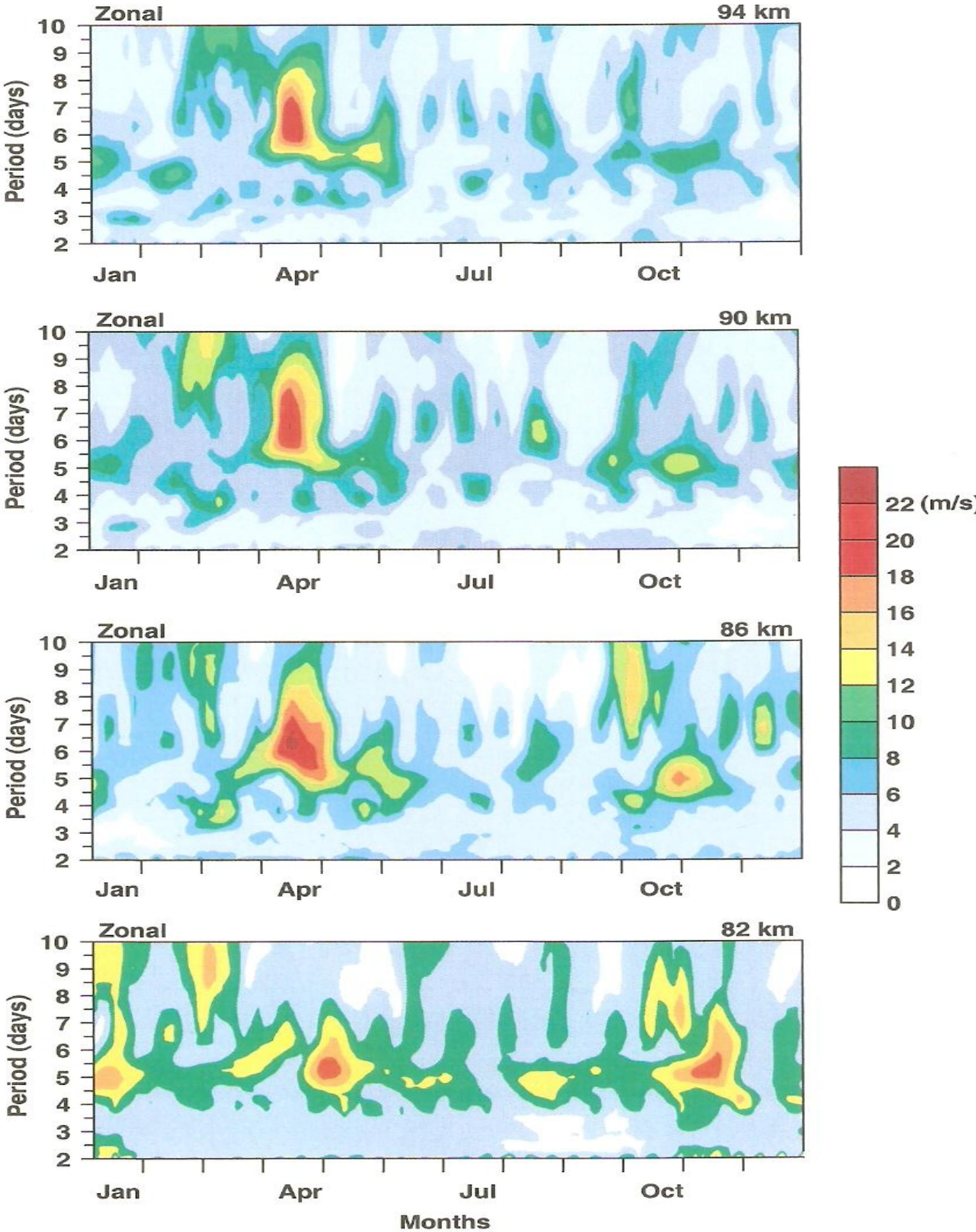
2011

Significant interannual variability in the quasi-2-day wave

Quasi-2-day wave in meridional wind at 86 km over Tirunelveli

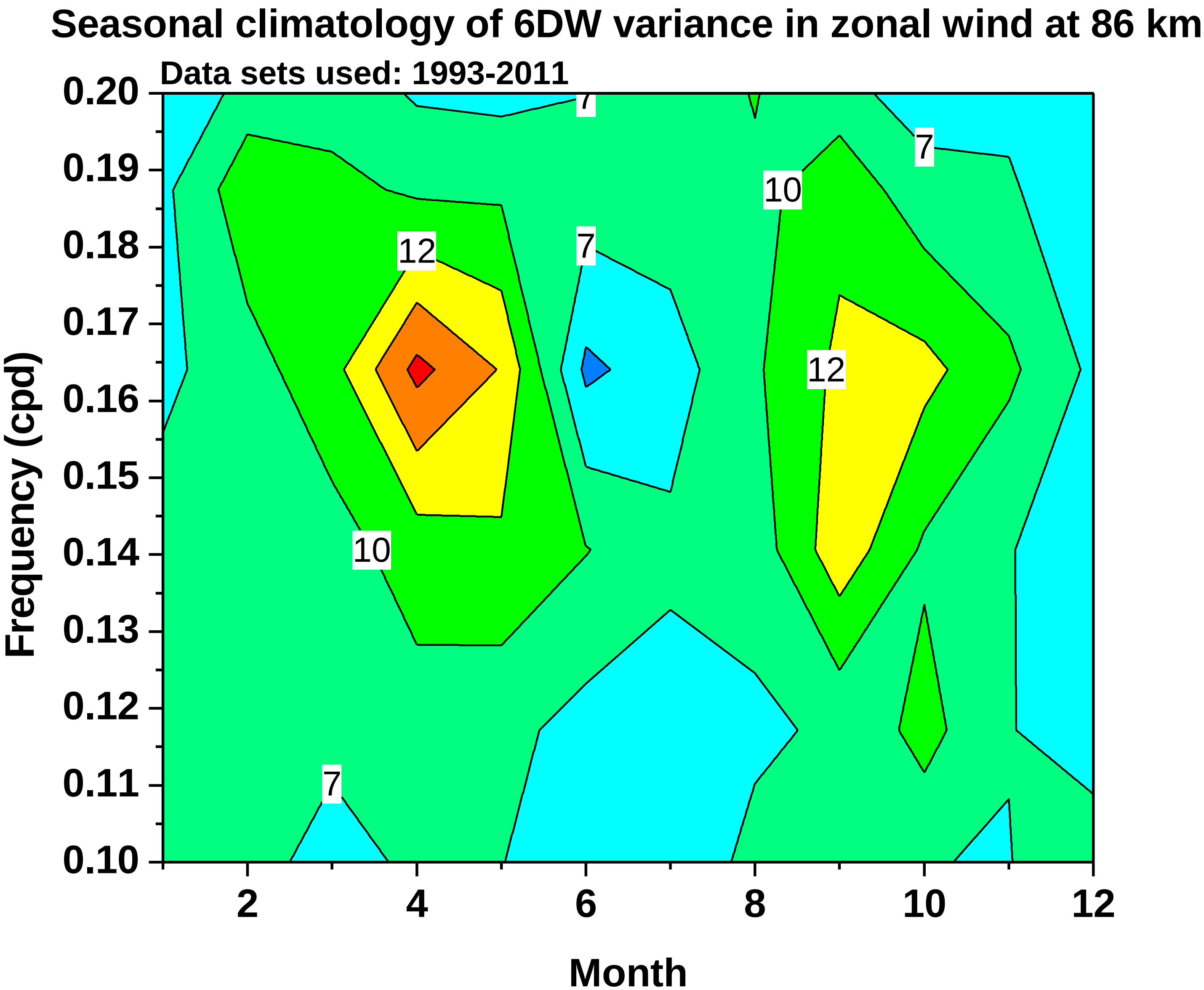


Observed features: (1) Strong seasonal variability (post solstice period)
(2) Stronger 2-d wave activity since 2004 peaking during early 2010; (3) weak activity during 2000 & 2001

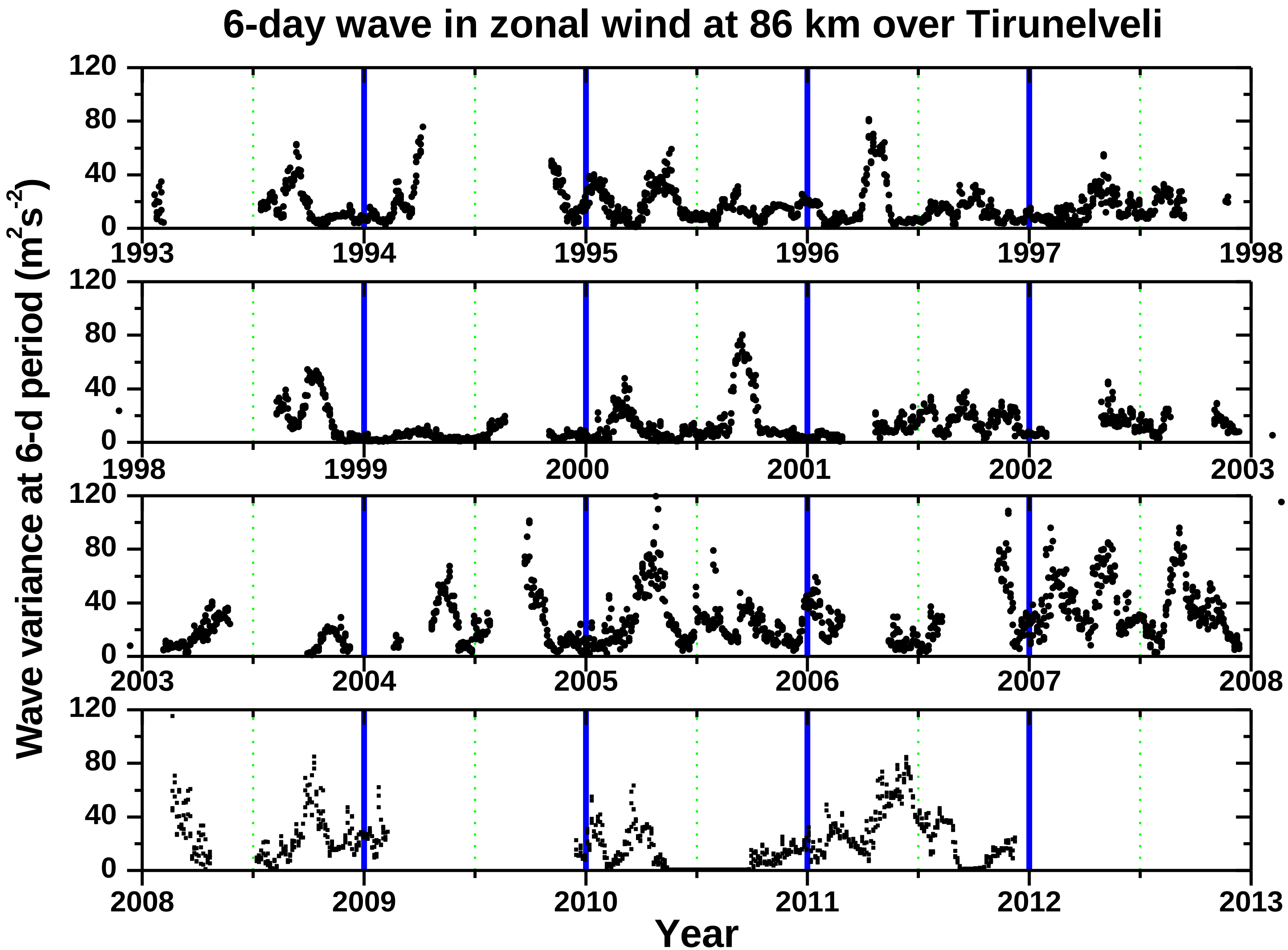


An intense 6.5-day wave observed during April 1996

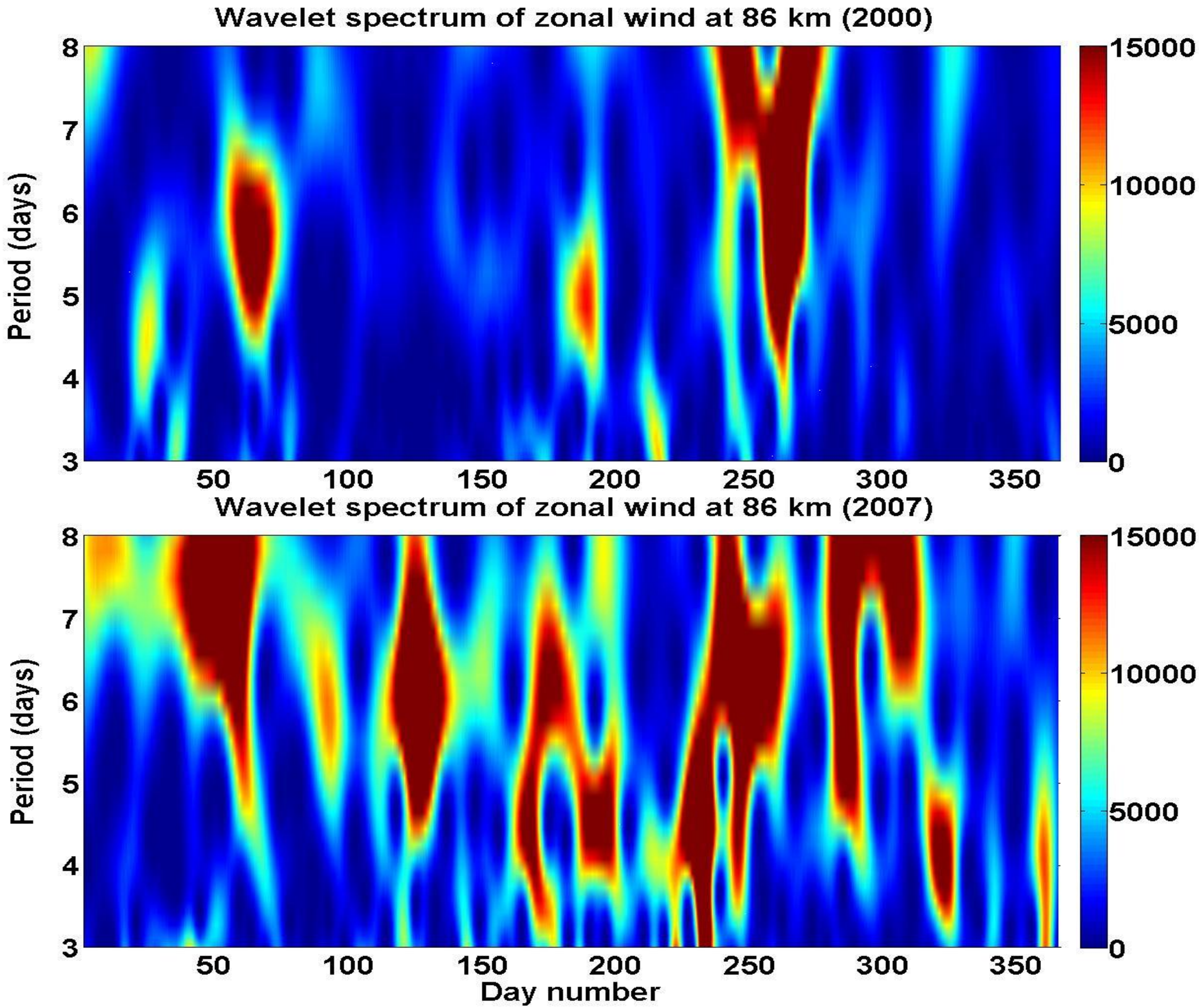
Similar observations from other sites reveal that this is a global planetary-scale wave – recent studies indicate that this wave originating at lower levels amplifies through unstable regions (*Liu et al.*, 2004).



Equinoctial maxima in 6-d wave activity noticed



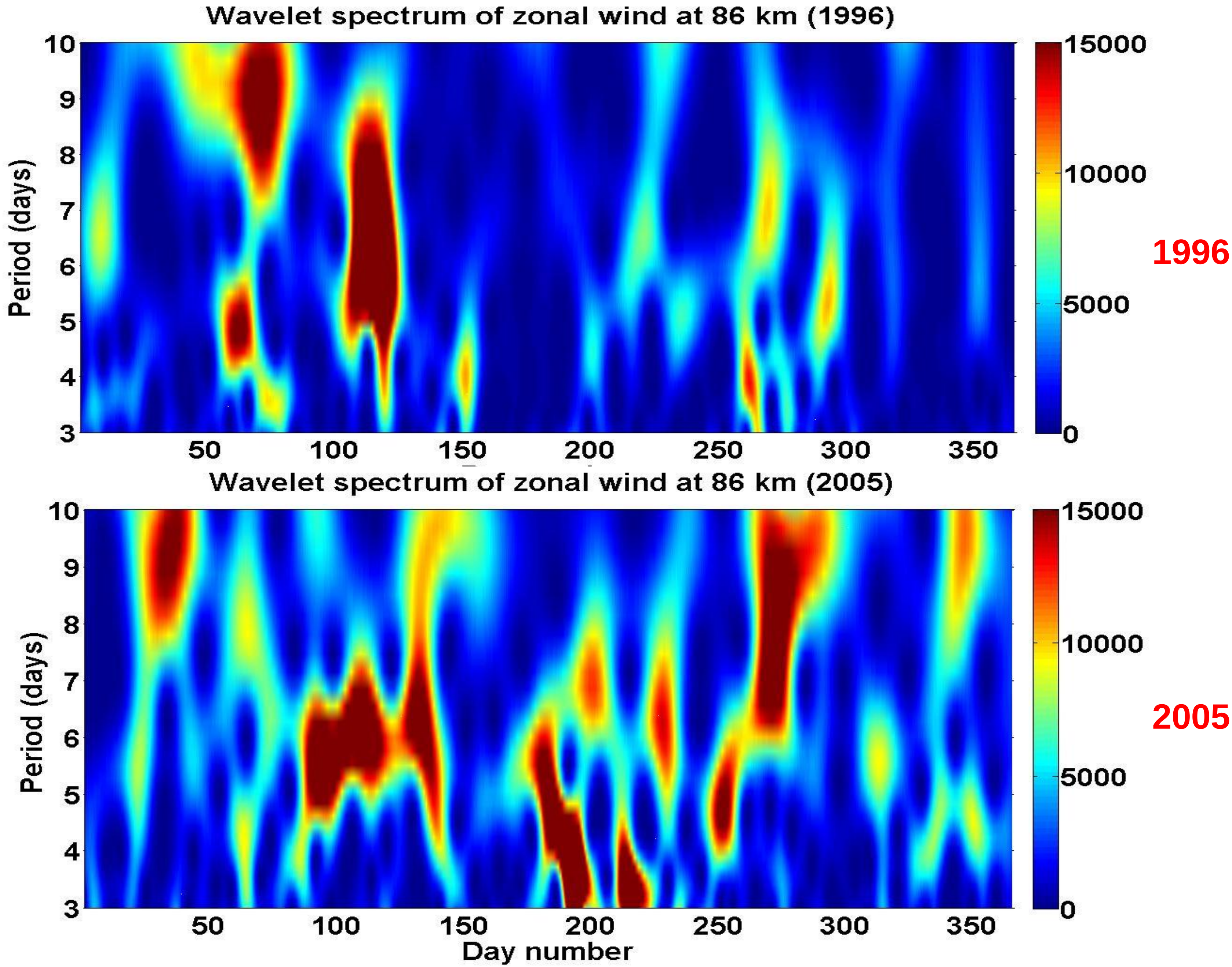
Semi-annual variation during 2000, 2004 and 2008 and tri-annual variation during 2005 and 2007 noticed



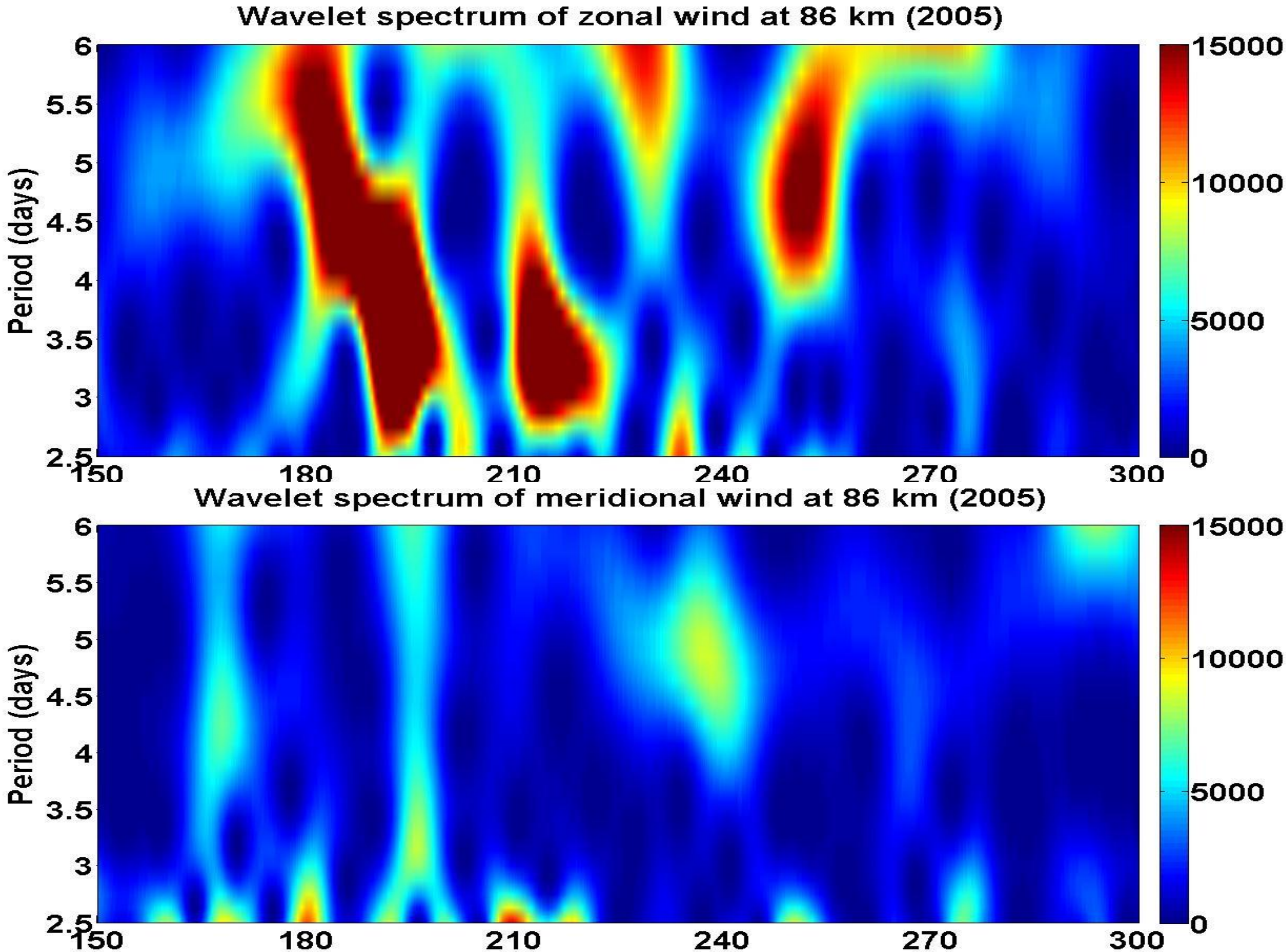
2000

2007

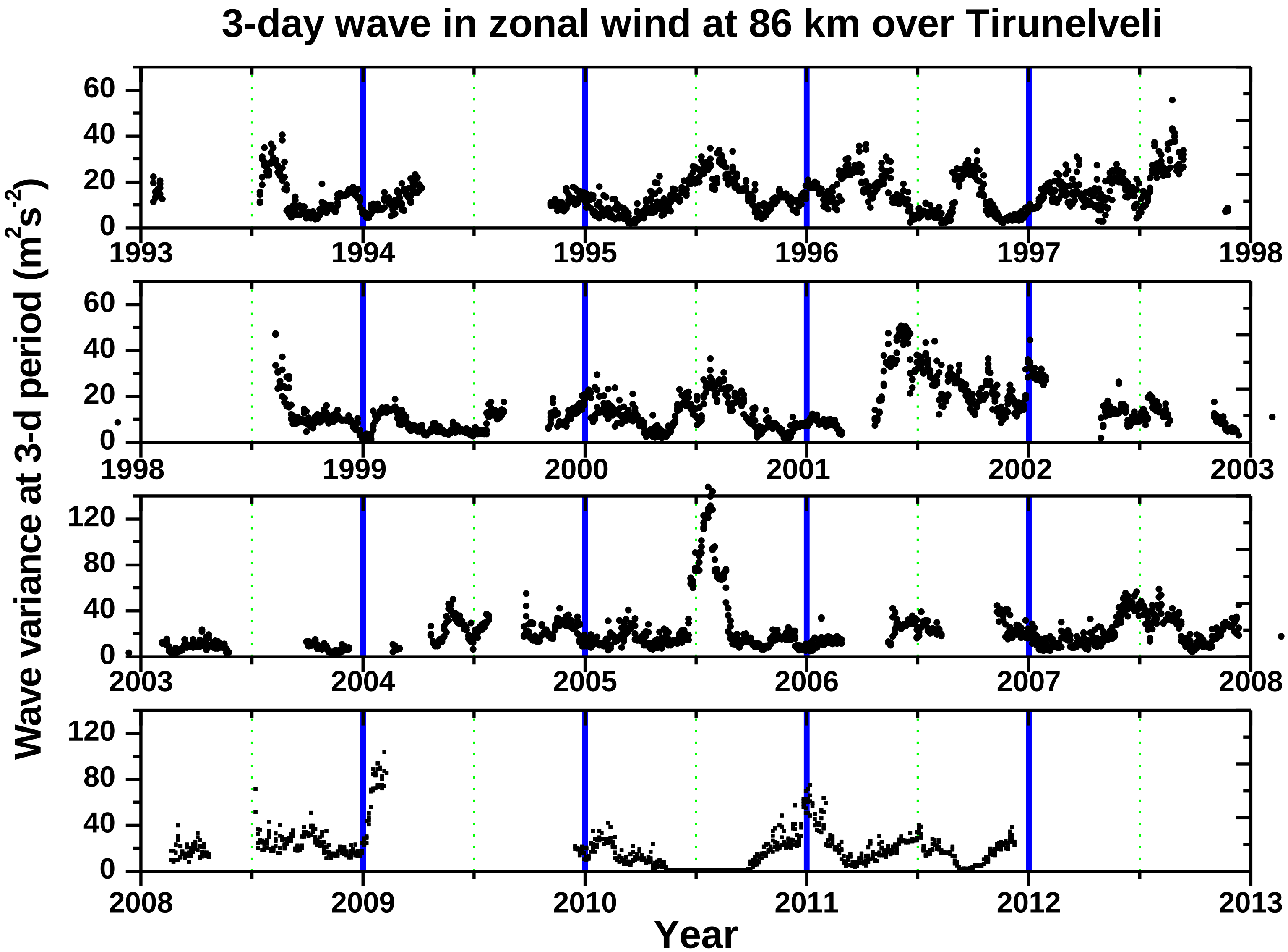
Bursts of 6 day wave seen at several times during 2007



6-day wave stronger and more frequent during 2005-2008 than during other years

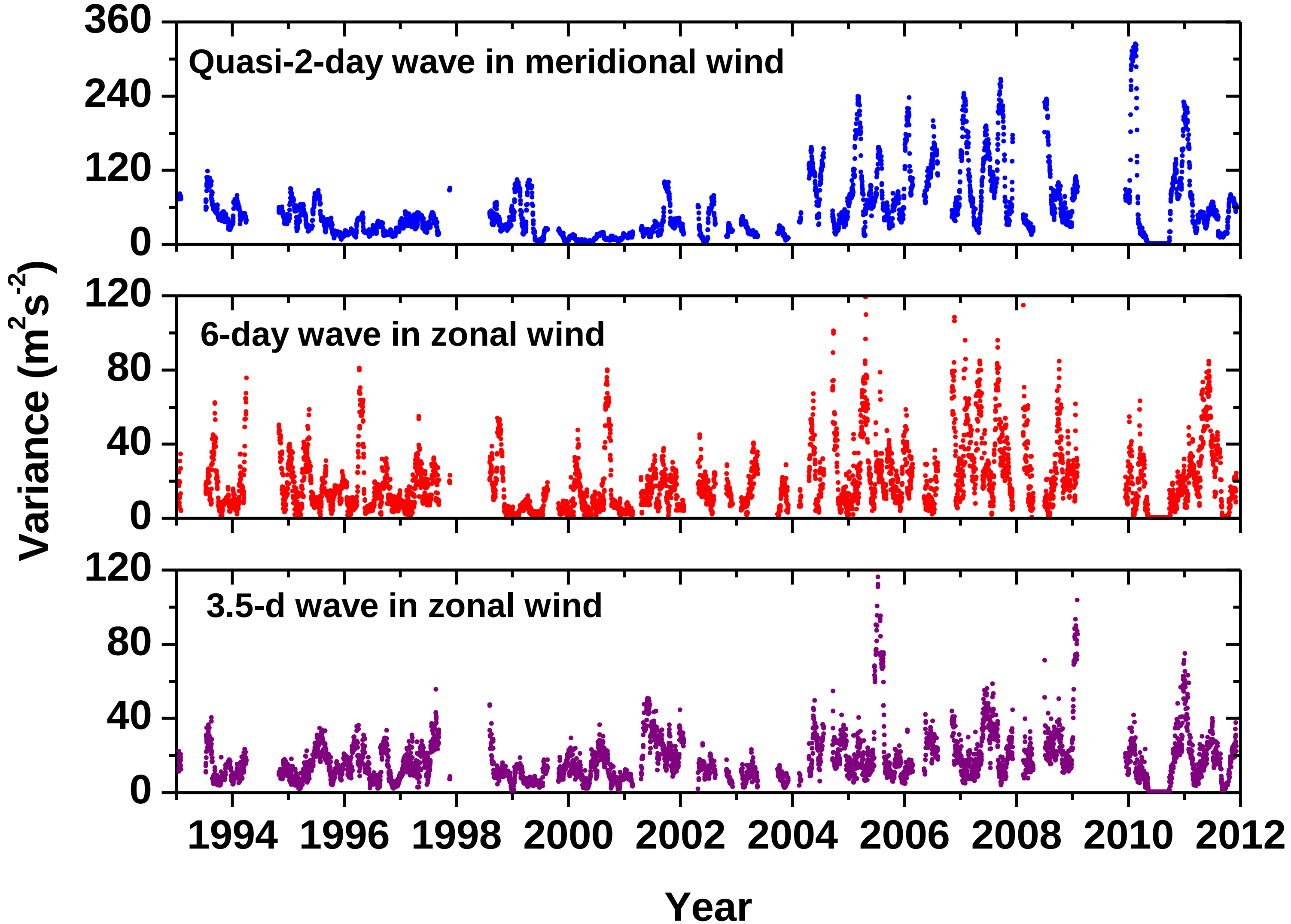


Stronger 3-day wave activity in zonal wind than in meridional wind indicating the presence of 3.5-d ultra-fast Kelvin wave during this period



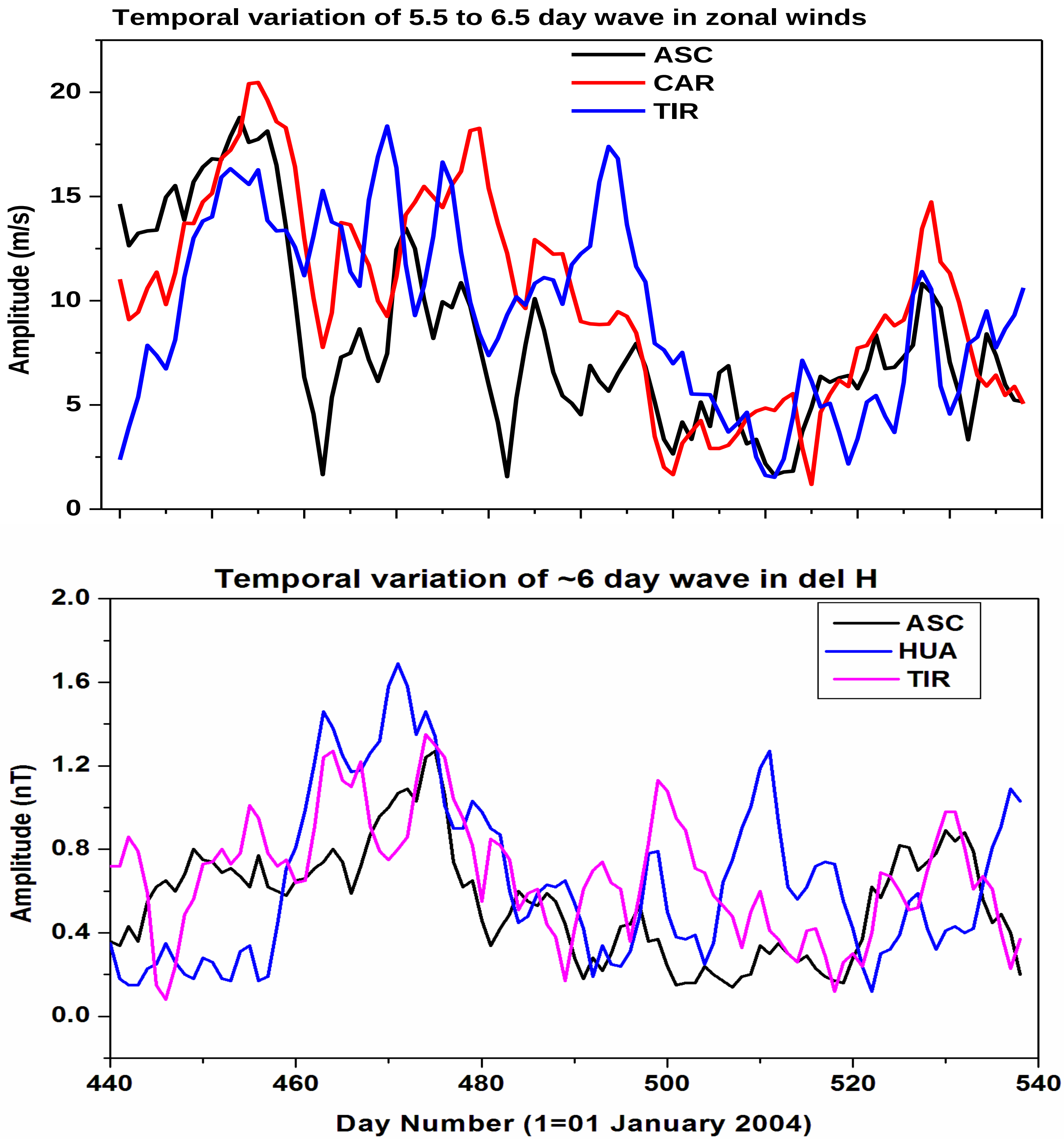
Unusually large 3-day wave activity during 2005 (note the doubling of scale)

Long-period (2-10 day range) variability in winds at 86 km over Tirunelveli



6-d wave and 2-day wave reveal large enhancements during 2004-2009

Could the 6-day planetary wave observed in winds have been responsible for low latitude geomagnetic field variations?



Potential scientific questions

• What planetary-scale waves propagate up to the equatorial MLT region? What are their sources? What are their variabilities and what is the relationship to their sources? What is their contribution to the SAO and QBO momentum budgets?

• What are the temporal and spatial variabilities of gravity wave activity in the middle atmosphere in the tropical regions? What is their relation to potential sources, such as convection, in the lower atmosphere?

• What gravity wave spectrum penetrates the low latitude MLTI region at any instant to have an impact on the equatorial ionospheric phenomena?

• What mechanisms contribute to the observed variabilities of MLT tides?

Potential science issues (contd…)

• What is the role of MLT tides in the electrojet variability, including the counter-electrojet?

• What are the driving mechanisms for ionospheric variabilities? Up to what heights in the ionosphere planetary-scale waves propagate?

• What composition changes occur at the turbopause and what is the role of wave processes in this process?

• What dynamical processes participate in airglow chemistry?

• What circulation changes occur in the equatorial MLTI region during magnetic storms? What are the associated electric field and current patterns?