Wave Dynamics in the Stratosphere Revealed by Using GPS Radio Occultation (RO) Data

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OUTLINE

1. Introduction on atmospheric gravity wave and its role in maintaining the general circulation.
2. Characteristics of temperature profiles from GPS RO measurements, esp, its accuracy and height resolution.
3. Data analysis procedure of temperature perturbations (due to atmospheric waves) in the stratosphere using GPS RO data
4. Various generation sources of gravity waves
5. Global and regional behavior of gravity wave activities
   - ✓ Mid-latitude: jet stream, orographic generation (mountain waves), etc
   - ✓ Polar regions: polar vortex decay, orography and SSW (sudden stratospheric warming)
   - ✓ Equatorial region: tropical convection and effects of wave-mean flow interaction

Classification of atmospheric waves

(Middle atmosphere dynamics by D.G. Andrews, J.R. Holton and C.B. Leovy)

(1) Restoring mechanism

Planetary (Rossby) waves: Coriolis Effects (meridional potential vorticity gradient)

Gravity (buoyancy) waves: Gravity (stratification) (*)

(Inertio-gravity waves; combination of stratification and Coriolis effects)

(2) Forced waves

Forced waves are continually maintained by an excitation mechanism of given phase speed and wave number.

Thermal tides excited by diurnal solar heating

Free waves: gravity waves, normal modes

(3) Propagation

Some waves can propagate in all directions. But, horizontally propagating planetary waves can be trapped in the vertical under some circumstances

Equatorial waves can propagate vertically and zonally, but are trapped around the equator. Kelvin wave, mixed-Rossby-grabity (MRG) wave

(*) Typical scales of gravity waves

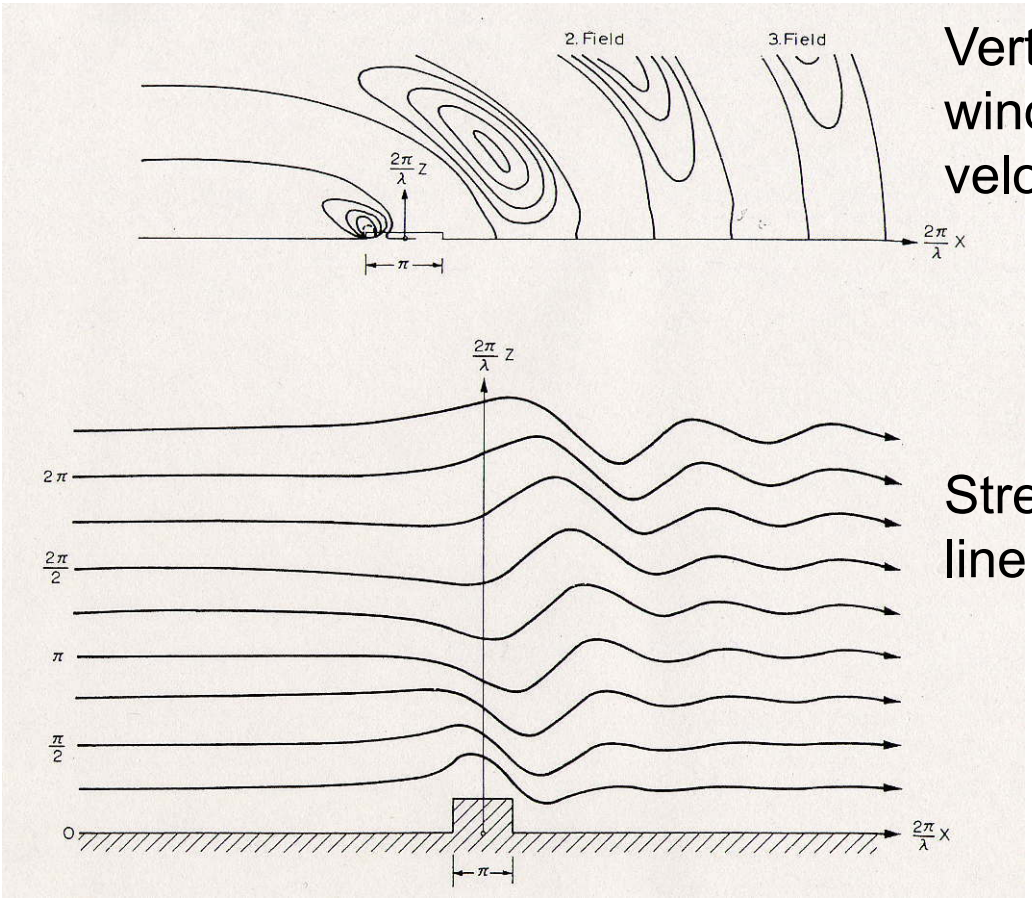
Wave periods: buoyancy (5-10 min.) to inertial (12hrs - several days) periods

Vertical wave length: shorter than 3-5 km

Horizontal scale: a few tens to thousands km

Excitation of atmospheric gravity waves

- Interaction of surface winds with topography (orographic, or mountain wave)
- Meteorological disturbances
- Jet stream
- Cloud convections in the tropics



(Gossard and Hooke, 1975)

Gravity wave generation by cloud convection in the tropics

Numerical model of gravity wave generation by tropical convection

T. Lane and M. Reeder (2001)

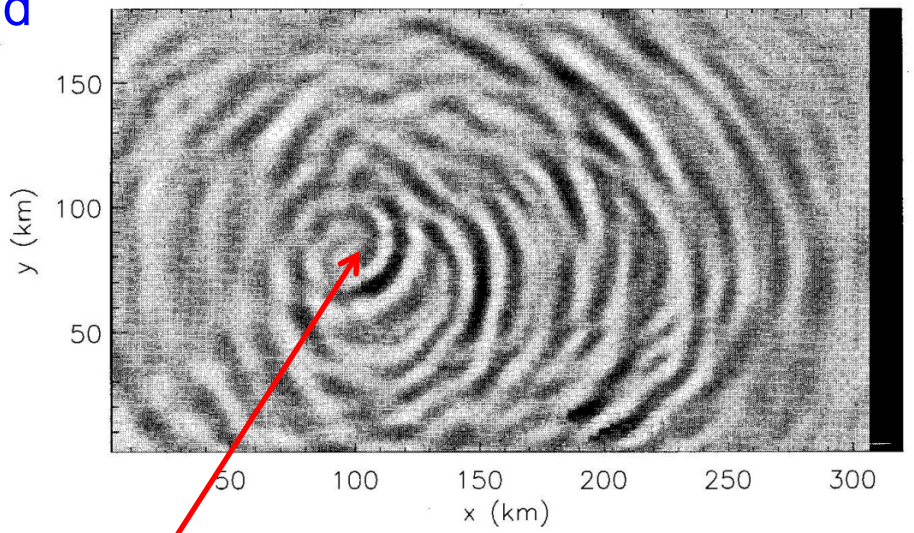
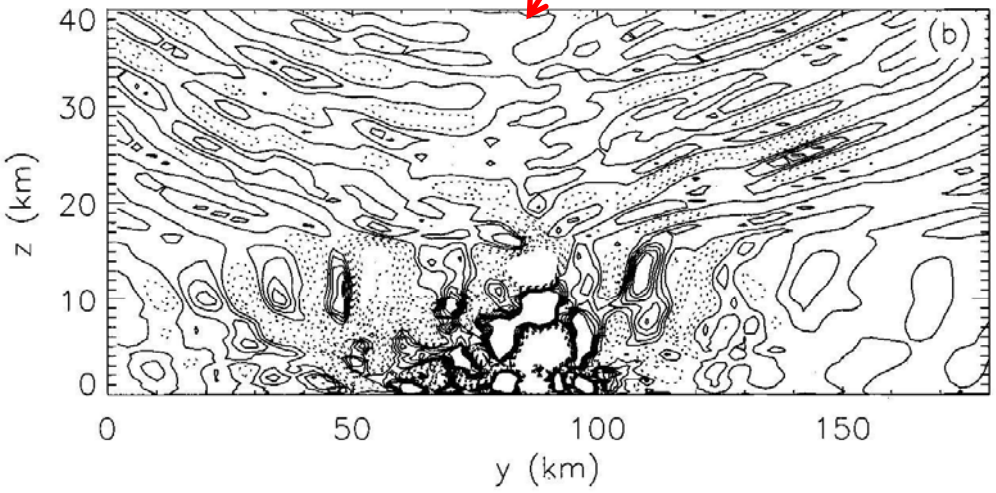


Figure 5. Horizontal cross-section of vertical velocity at $z = 40$ km in Domain 1 at 1330 LST.



Convect
the Nort

Figure 4. (a) Zonal cross-section of vertical velocity through $y = 100$ km for Domain 1. (b) Meridional cross-section of vertical velocity through $x = 100$ km for Domain 1. Vertical velocity is contoured at 0.1 m s^{-1} intervals, with the negative values dashed. Both plots are valid at 1300 LST. Note that (b) has a different horizontal scale from (a).

Horizontal (top) and Height-meridional (left) cross section of vertical velocity

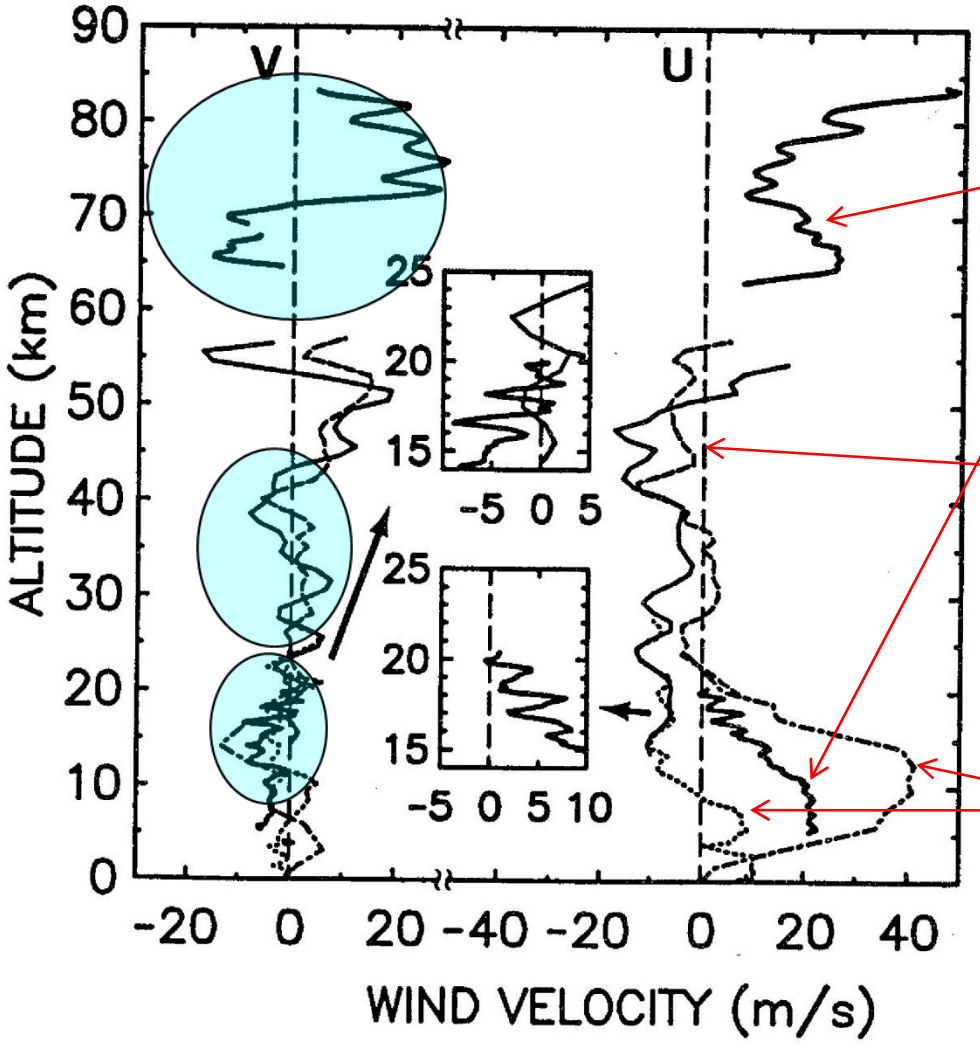
Typical wave parameters

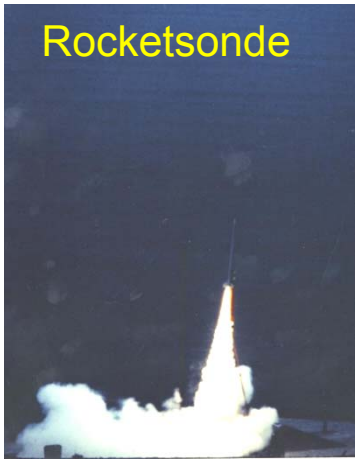
λx ~ 15-20 km

λz ~ 4-6 km

No preferential direction

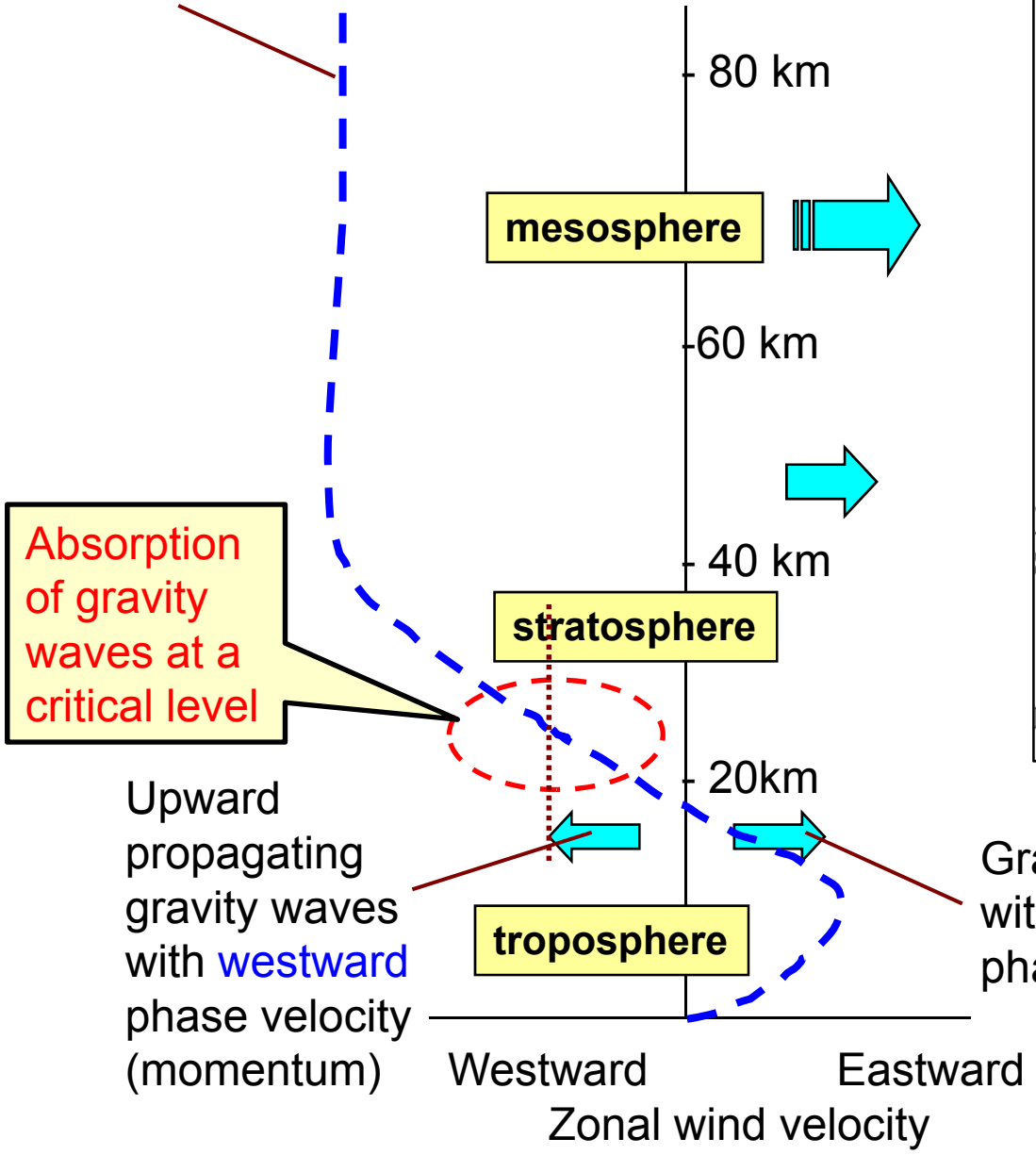
Wind velocity profiles observed with the MU radar, radiosondes and rocketsondes





Both wave amplitudes and wave lengths (λ_z) increase along height.
λ_z =2 – 3 km in the lower stratosphere; λ_z =5km in the middle stratosphere;
λ_z =10km in the mesosphere

Mean zonal (eastward positive) wind velocity at mid-latitudes in the northern hemisphere Summer (assuming radiative equilibrium only)

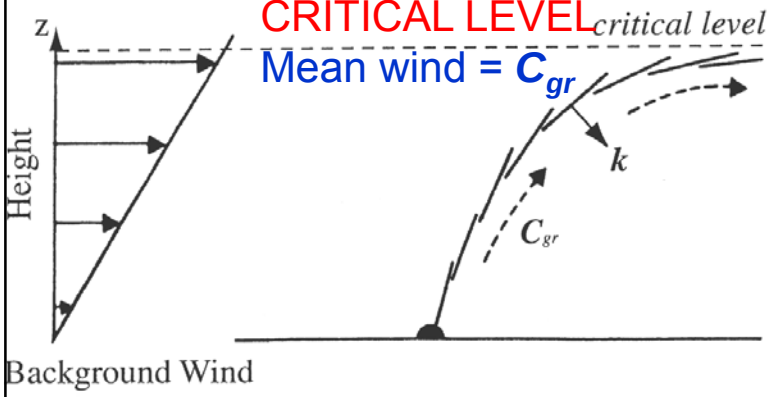


CRITICAL LEVEL

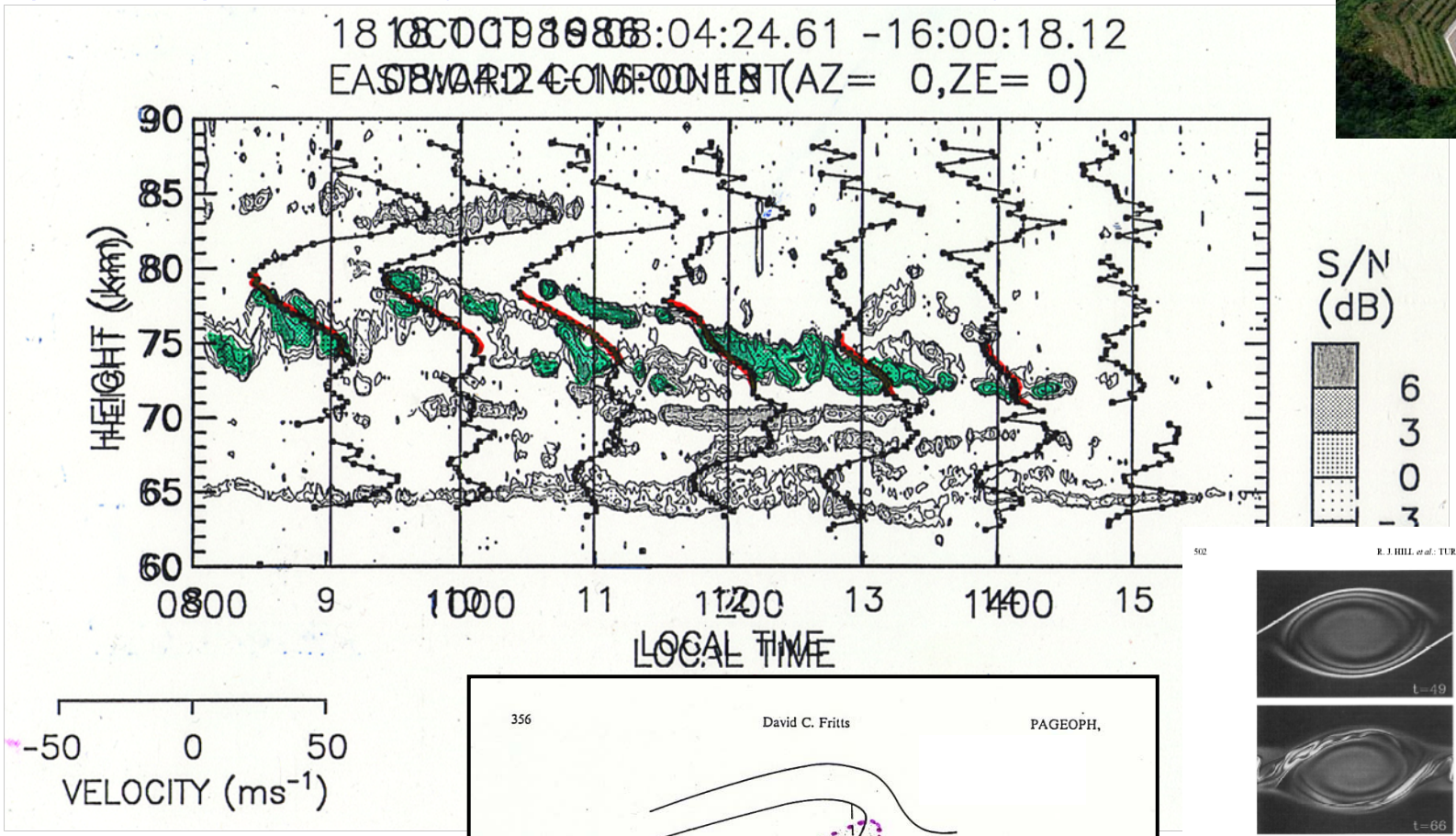
Vertical propagation of a gravity wave in the vertical wind shear (LEFT). Short solid lines (RIGHT) show phase surface of the gravity wave [adapted from Matsuno and Shimazaki, 1981].

C_{gr} is the phase velocity of the wave.

k is the vector perpendicular to the wave propagating direction.



Radar Observations of Turbulence Echo Power (contour) and Hourly Meridional Wind Velocity



Generation of turbulence due to breaking of gravity waves

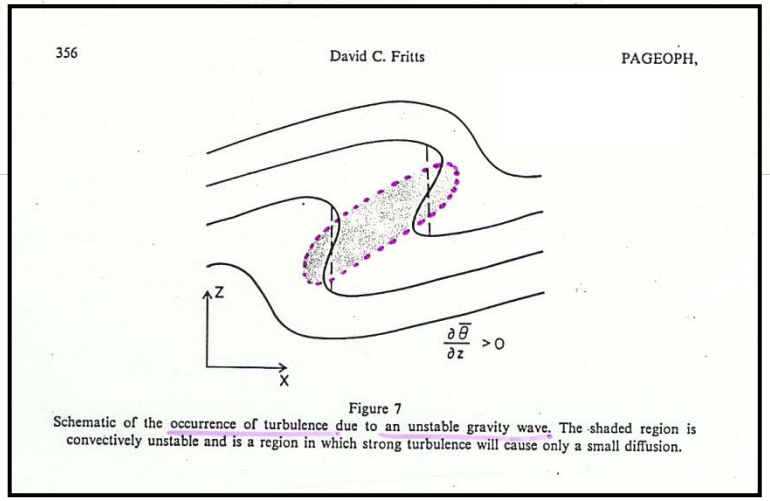


Figure 7
Schematic of the occurrence of turbulence due to an unstable gravity wave. The shaded region is convectively unstable and is a region in which strong turbulence will cause only a small diffusion.

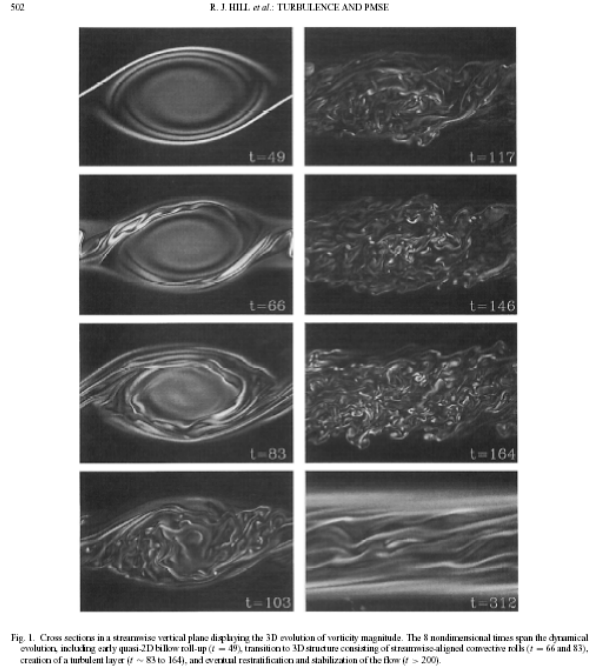
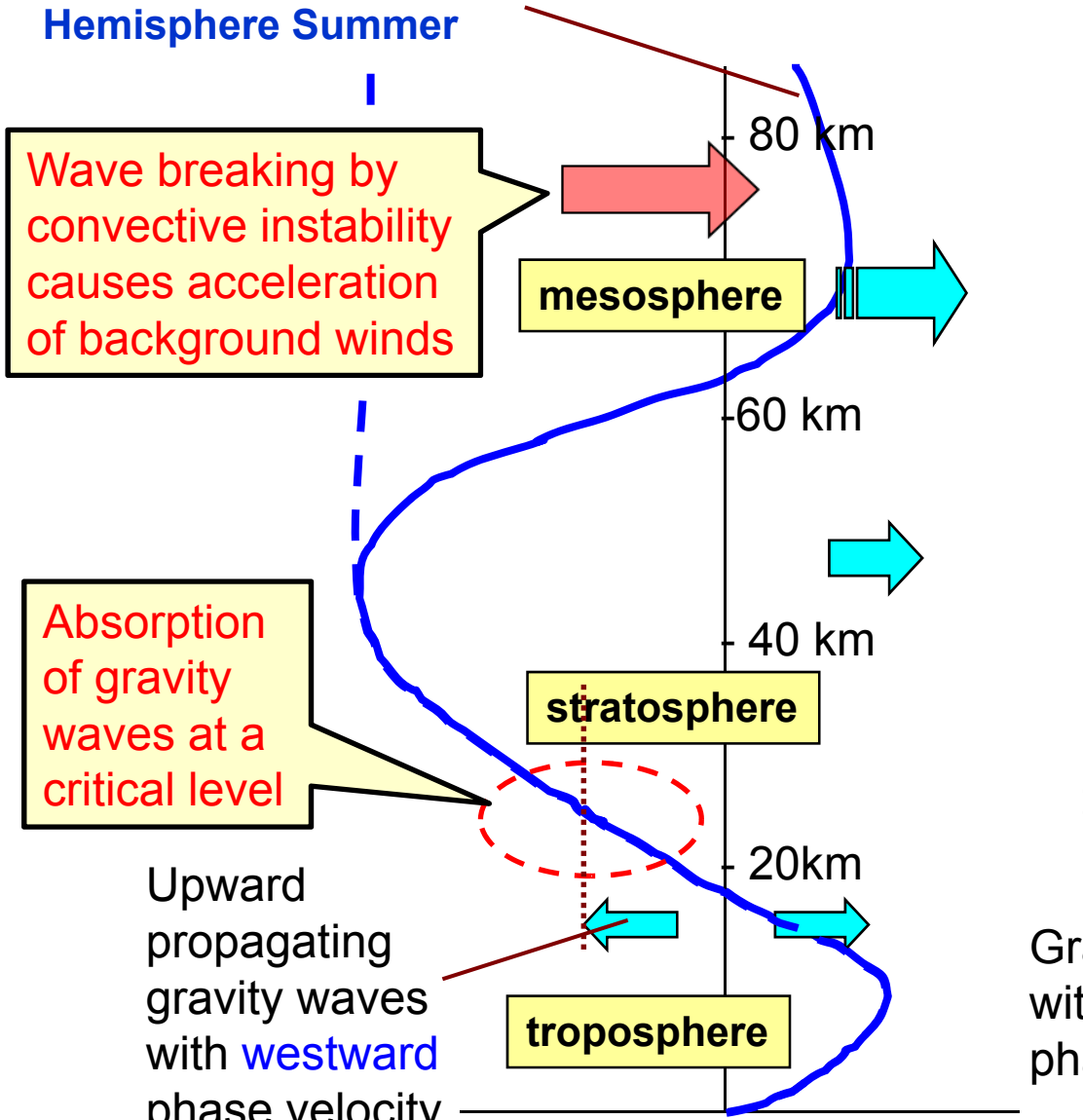


Fig. 1. Cross sections in a streamwise vertical plane displaying the 3D evolution of vorticity magnitude. The 8 nondimensional times span the dynamical evolution, including early quasi-2D billow roll-up ($t = 49$), transition to 3D structure consisting of streamwise-aligned convective rolls ($t = 66$ and 83), creation of a turbulent layer ($t \sim 83$ to 164), and eventual restratification and stabilization of the flow ($t > 200$).

Height Profile of Mean Zonal (eastward positive) Wind Velocity at mid-latitudes in the Northern Hemisphere Summer



CRITICAL LEVEL

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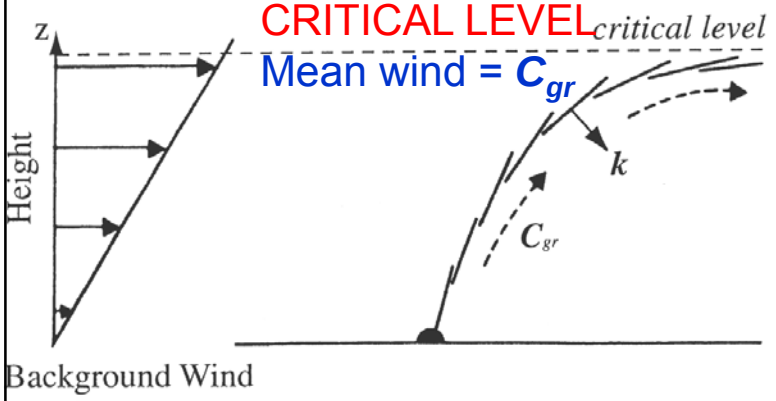
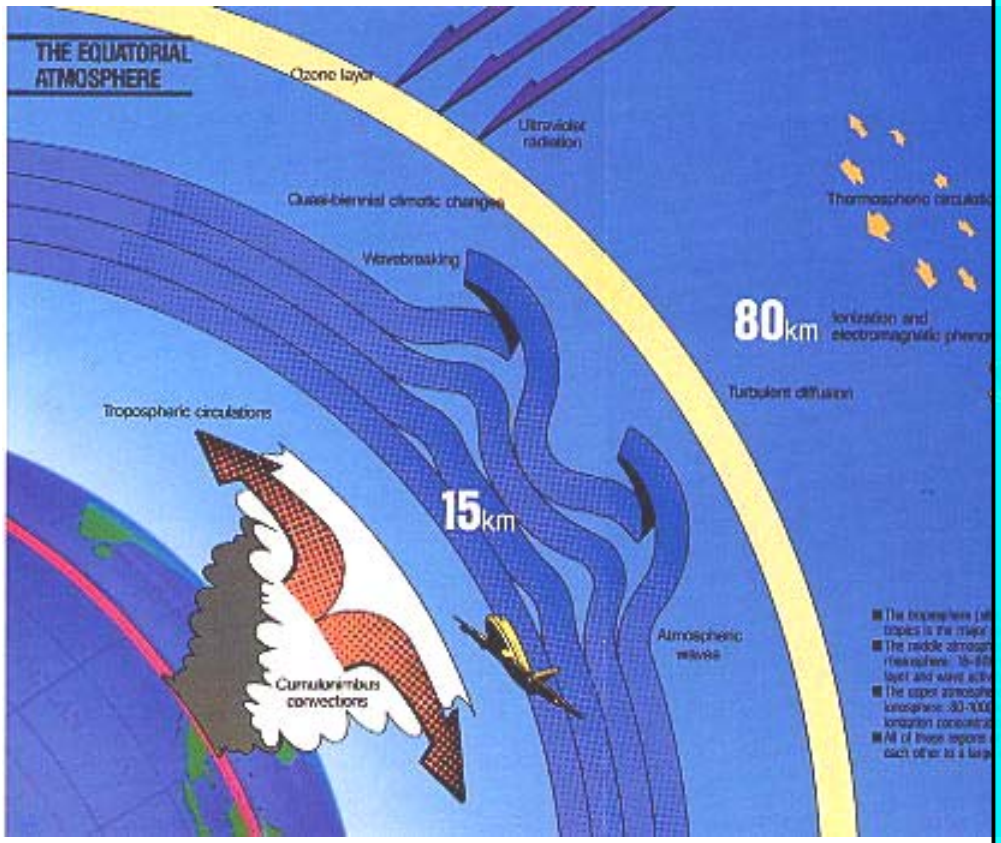


Generation, Propagation and Dissipation of Atmospheric Gravity Waves (in the Equatorial Region)



(Dissipation)

The waves dissipate through various instability processes, and deposit the momentum to the background winds (accerelation), which plays a key role to maintain the general circluation of the atmosphere.

(Propagation)

These waves propagate upward, growing their amplitudes. The waves transport vertically the kinetic energy and momentum.

(Generation)

Active convection in the troposphere generates various atmospheric waves, such as gravity waves, equatorial Kelvin wave, etc.

AGU Chapman Conference on Atmospheric Gravity Waves and Their Effects on General Circulation and Climate (Hawaii, 28/2-4/3 2011)

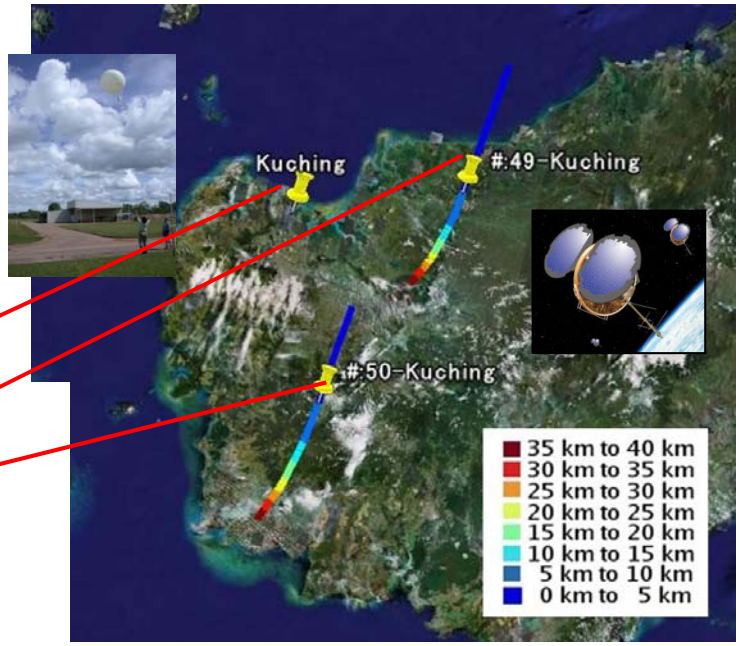
- Gravity waves are a dominant mode of variability in the atmosphere at scales near the resolution of current climate model simulations.
- They are generated by a variety of processes including the interaction of surface winds with topography, deep convective storms, and unbalanced flow in the jet stream.
- Circulation changes associated with gravity wave dissipation are now known to have wide-ranging effects on NWP, climate change response patterns, forecasts of stratospheric ozone recovery, and space weather.
- The global scale of these issues requires global knowledge of gravity wave properties despite the fact that the scales of the waves themselves are too small to be fully simulated in a global model or fully sampled in global observations.
- The problem of gravity waves and their effects on the general circulation thus requires a broad range of studies, those using local high-resolution observations, limited-area wave-resolving models, global models, and global observational data sets such as those acquired from satellite.

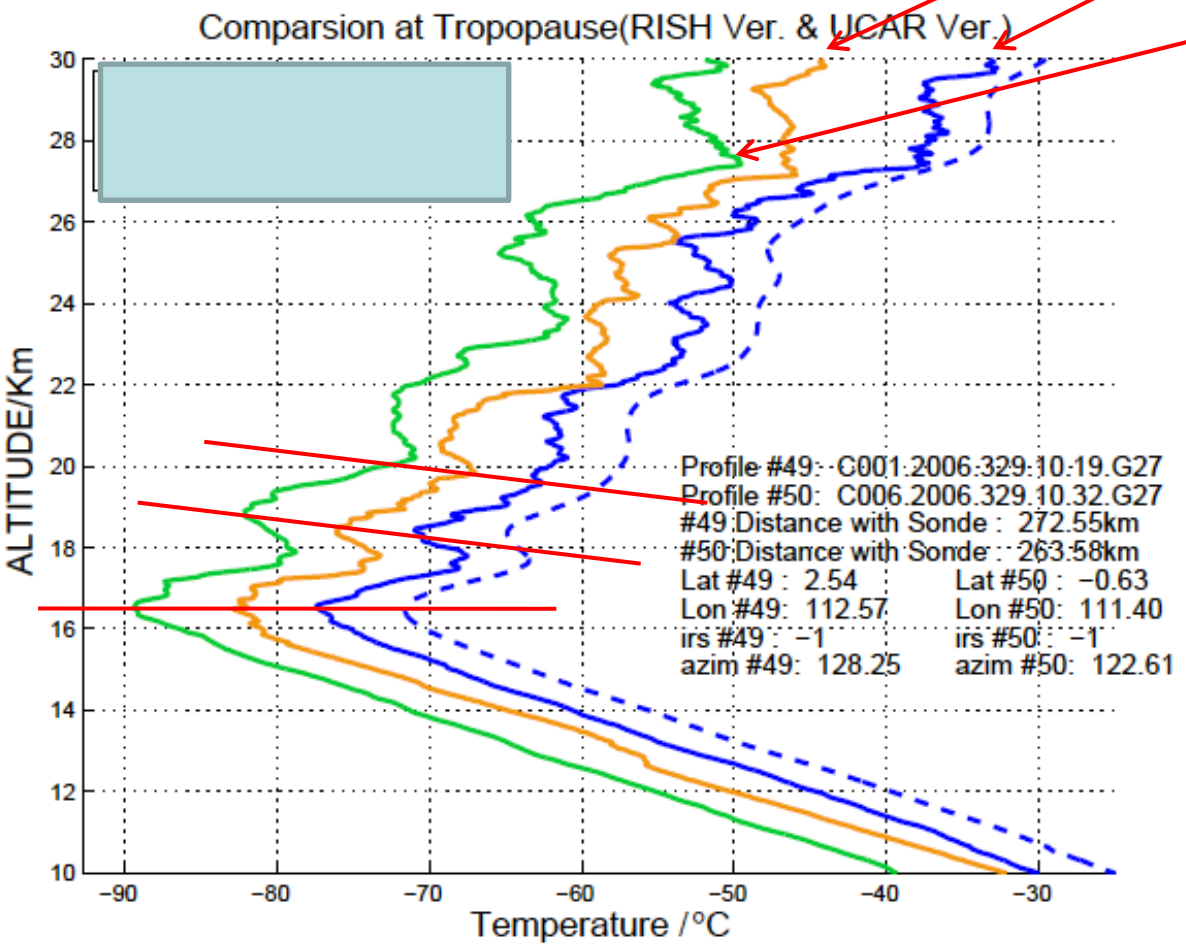
The GPS RO data having a very good height resolution provides a unique opportunity to study a global morphology of stratospheric gravity waves.

2. Characteristics of Temperature profiles from GPS RO measurements. esp, height resolution.

Q: Is the small vertical scale temperature perturbation physically meaningful, i.e. manifestation of gravity waves, or just a measurement noise?

Comparison of temperature profiles between the two COSMIC GPS RO results (#49 and #50) and radiosonde at Kuching, Malaysia.
Profiles are shifted by 5K each.

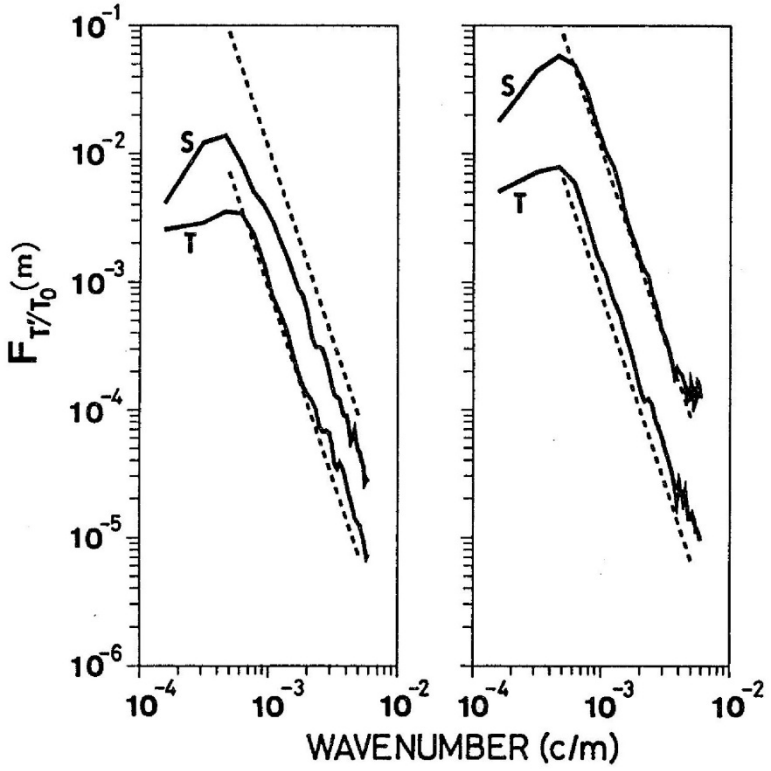




Temperature profiles with GPS RO have a height resolution comparable to a radiosonde.

- detailed structure of the tropopause
- perturbations due to atmospheric waves

Vertical wave number spectra of temperature fluctuations (T'/T_0)

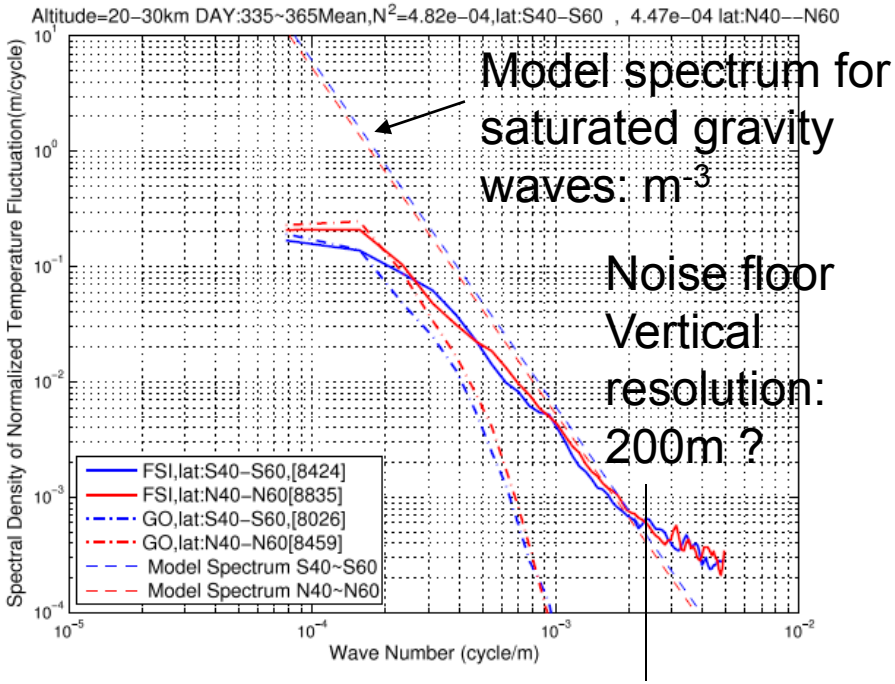


Radiosonde results at 18.5-25km (S) and 2-8.5km (T) at the MU radar site, Japan, in summer (Left: Jun.-Sep. 1987) and winter (Right: Dec-Feb 1986/7) (Tsuda et al., 1991)

Gravity wave spectra from GPS/MET occultation observations, A.K. Steiner and G. Kirchengast, J. Tech, 2000

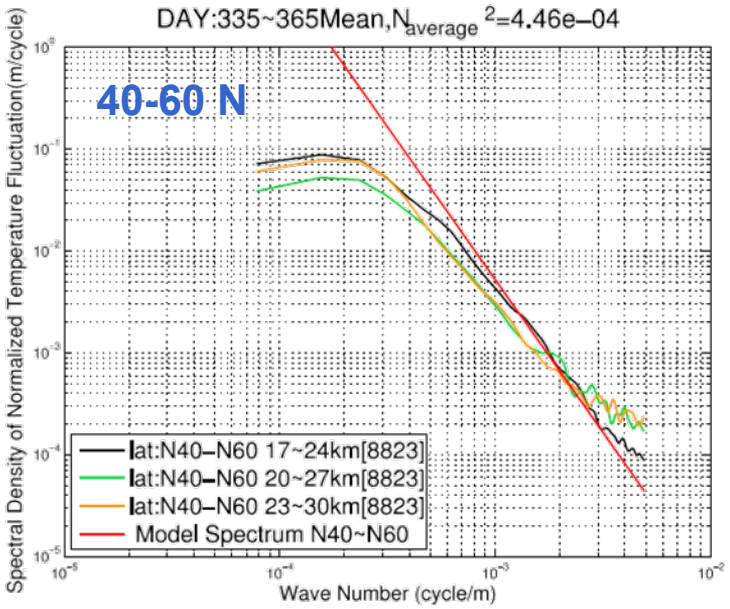
Vertical wave number spectrum of temperature fluctuations in the stratosphere using GPS occultation data, T. Tsuda and K. Hocke, J. Met. Soc. Japan, 2002

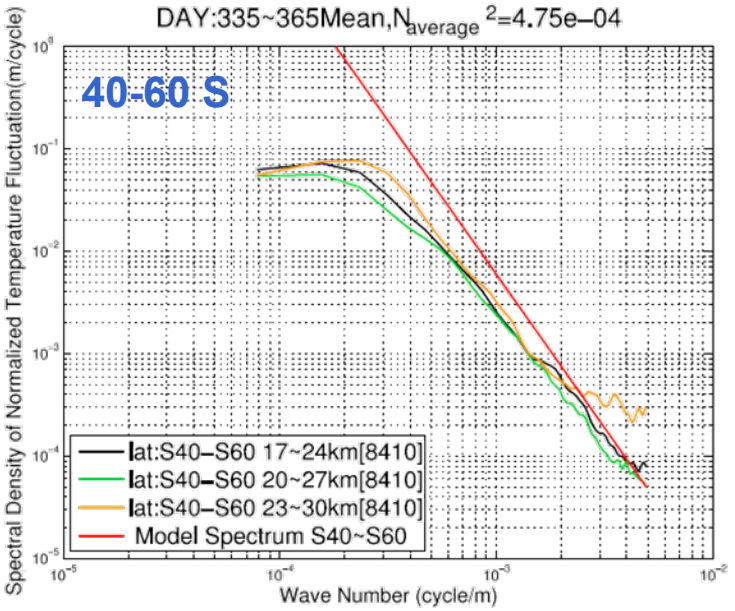
Spectra using GO (dotted line) and FSI (solid line) retrievals from COSMIC GPS RO data (40-60N and 40-60S)

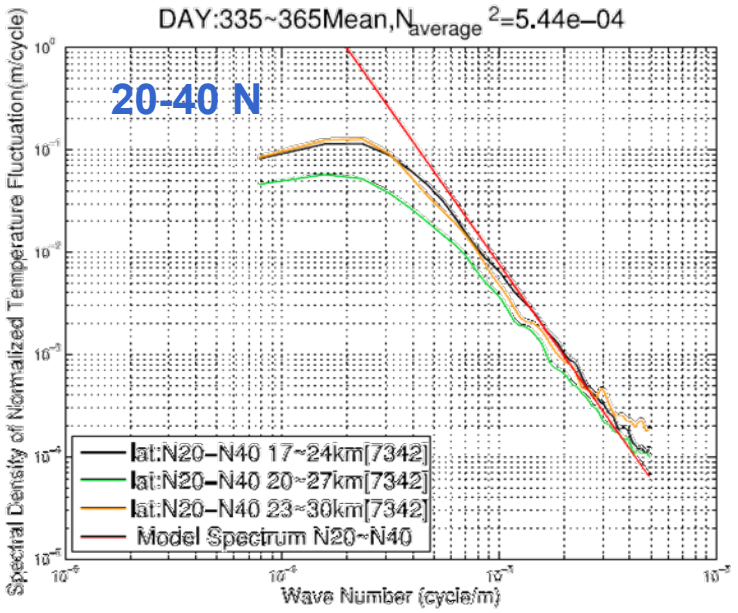


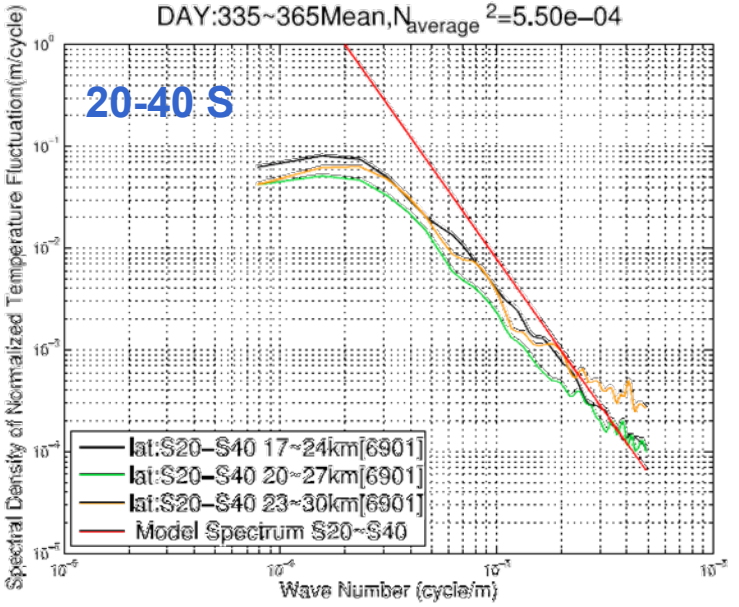
Vertical wave number spectra at 17-24 km (Blue), 20-27 km (Green) and 23-30 km (Red) in December 2006

COSMIC









3. Data analysis procedure of meso-scale temperature perturbations in the stratosphere using randomly distributed GPS RO profiles

Q: How can we separate T_0 and T' from GPS RO T profiles?

T_0: mean profile in a longitude-latitude cell

T'_1: sinusoidal fitting with zonal wave numbers

- Zonal propagation characteristics of equatorial waves, like Kelvin waves, MRG waves, planetary waves
- Mean profile for GW analysis (Wang and Alexander 2009)

T'_2: residual (Gravity waves)

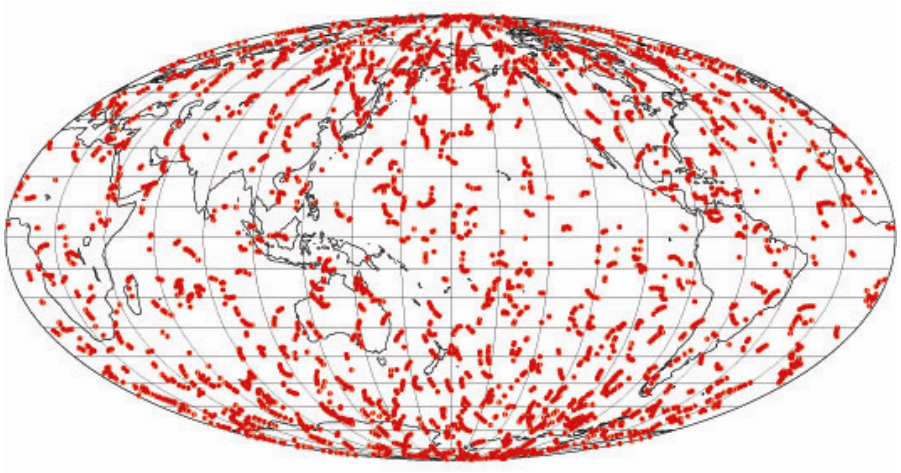
- Gravity wave energy: temperature variance
- Spatial structure of gravity waves

Global Distribution of Gravity Waves with GPS RO Data

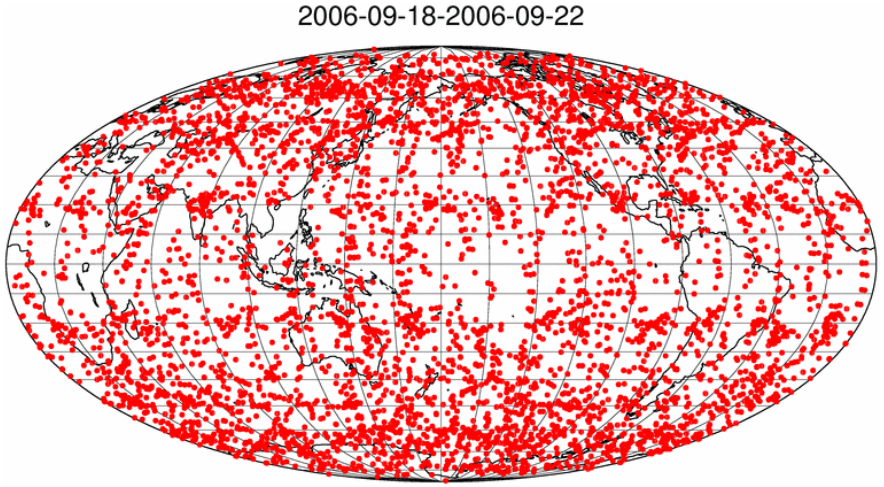
Climatological study (every 1-3 months) with CHAMP GPS RO data from May 2001- Dec 2005

Analysis with COSMIC data after September 2006, with a time resolution of 5-10 days

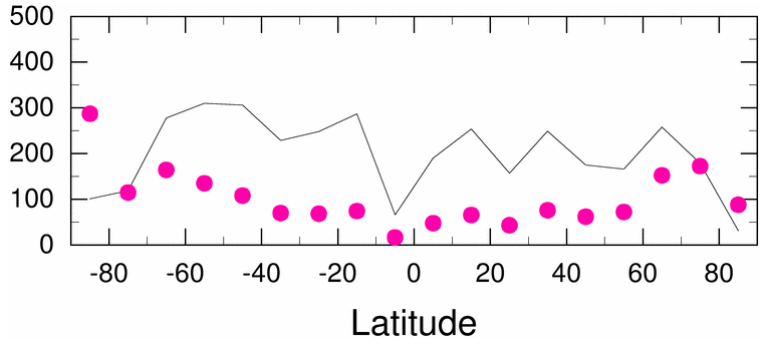
Distribution of the CHAMP GPS RO data in one month (October 2002)

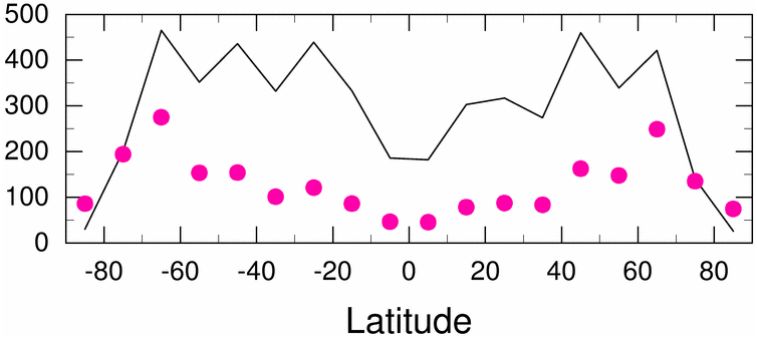


COSMIC GPS RO data in 5 days on 18–22 September 2006



line: number of GPS data in each 10 deg, red dot: data rate normalized by the area



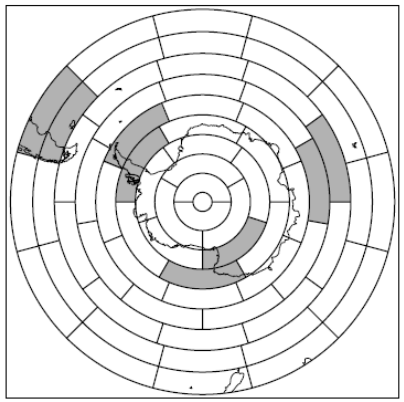


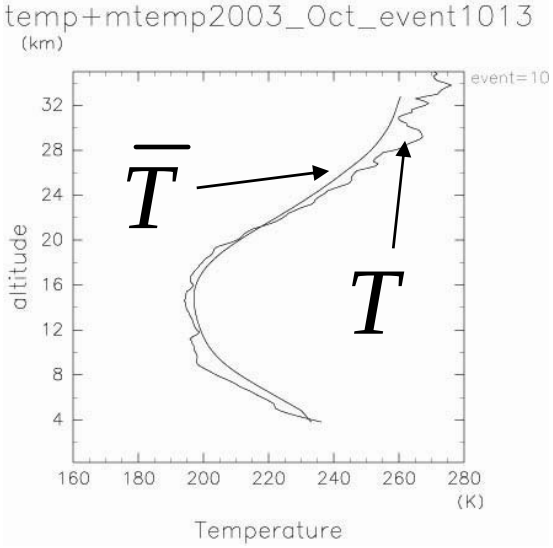
Atmospheric Gravity Wave Energy (*PE or Ep*) in the Stratosphere by Using GPS RO Temperature (*T*) Data

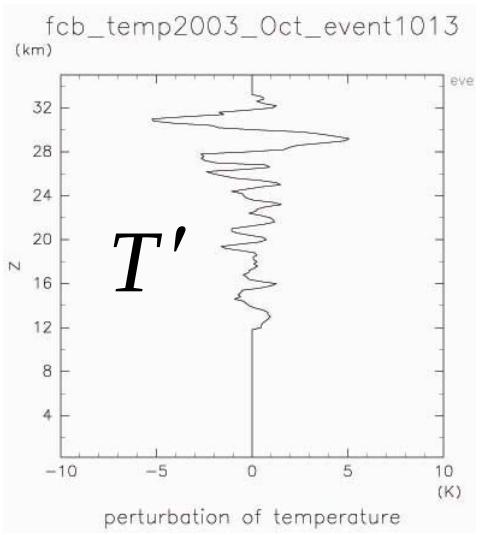
Wave potential energy, $PE=1/2(g/N)^2(T'/T_0)^2$

g; acceleration of gravity, *N*; Brunt-Vaisala frequency,

T'; temperature perturbation, T_0; background temperature





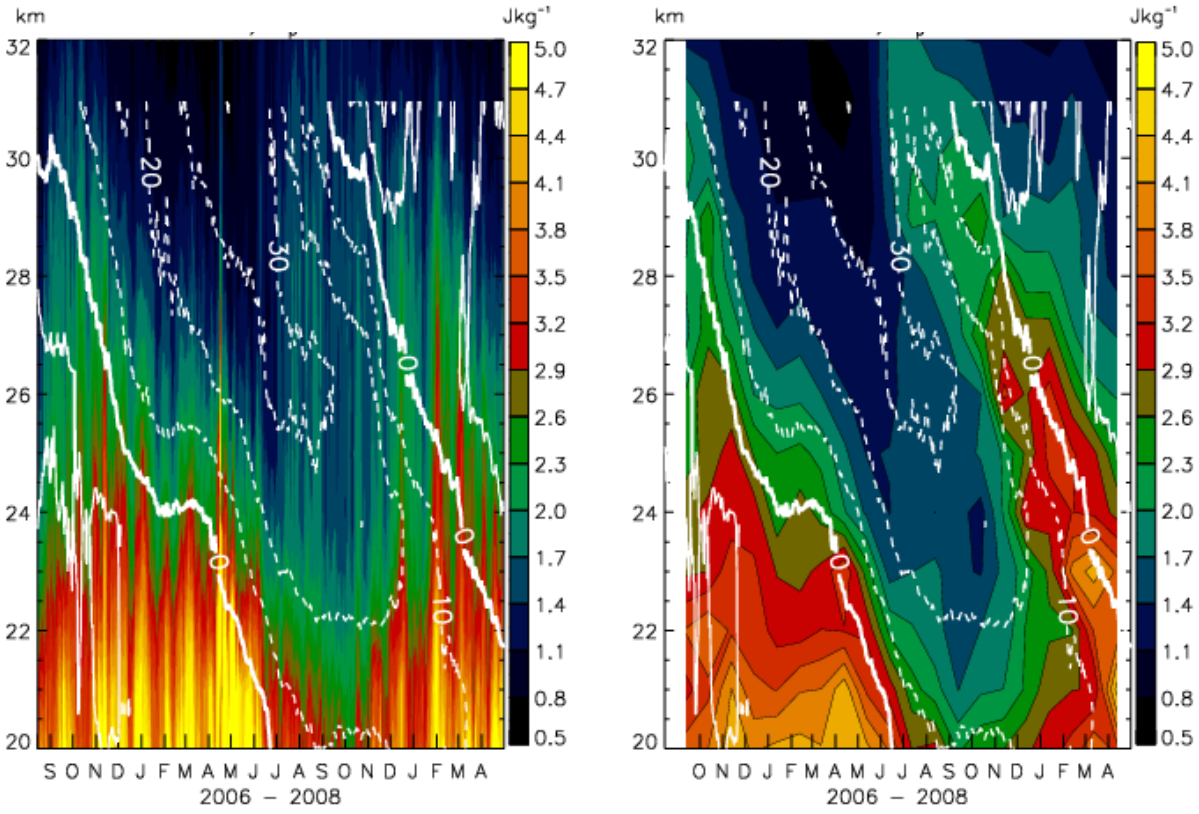


Analysis procedure

- Select a time resolution: 5-7 days for COSMIC, one month for CHAMP
- Select longitude and latitude resolution of a cell : 20^ox10^o, 10^ox5^o
- Obtain mean T_0:
  - Simple average of T in each cell and smoothing along height.
  - Decomposition into sinusoidal harmonics with zonal wave numbers.
- Extraction of T': Calculate $T'=T-T_0$, then apply a high-pass filter with a cut-off at 5-10 km along altitude.

Season-height section of zonal mean PE at 25.S-2.5N from Sep 2006 to Apr 2008

COSMIC



- QBO westward shear initially, then eastward shear after mid-2007.
- QBO removes gravity waves, especially close to the 0 m/s phase line.

LEFT:

- **Grid size: 20°x5°x7 days,**
- **7km high-passed perturbations from individual profiles, and get PE by integrating vertically over 7km, stepping up by 1km and forward by 1 day.**
- **Mainly meso-scale GWs with minor MRGW and higher speed KW contributions.**

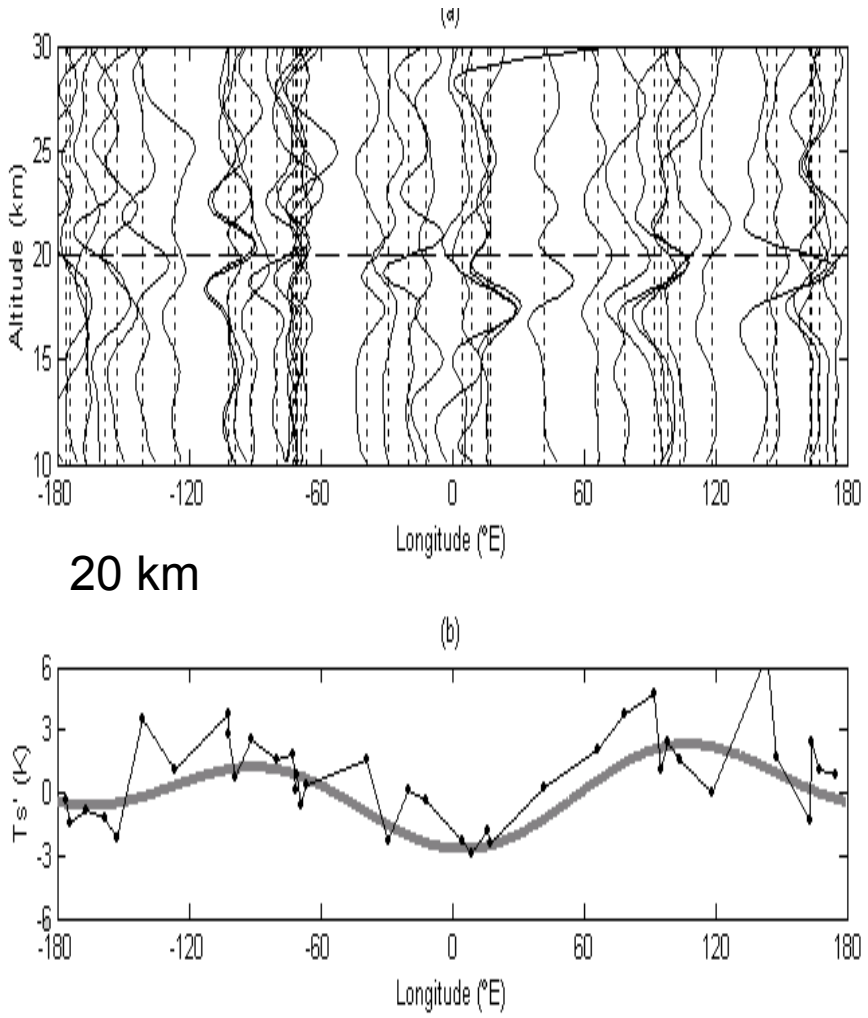
RIGHT

- **Grid size: 20°x5°x one month**
- **Height independent (1km) data by assuming that all wave phases are represented at that particular height**
- **Slower speed KWs but still mainly consists of GWs**

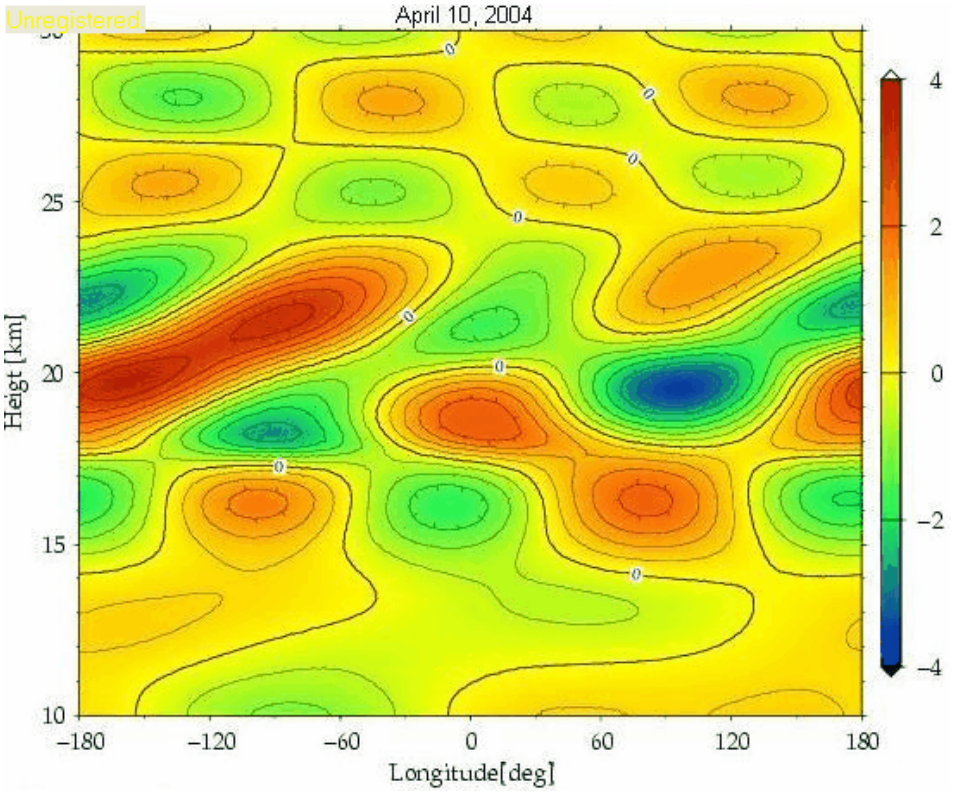
White contours: NCEP zonal mean zonal wind, units m/s, east/westward; solid dashed

Residual temperature fluctuations (T') at 10°N-10°S, and longitude variations of T' at 20 km altitude during 3-5 May 2004.

CHAMP

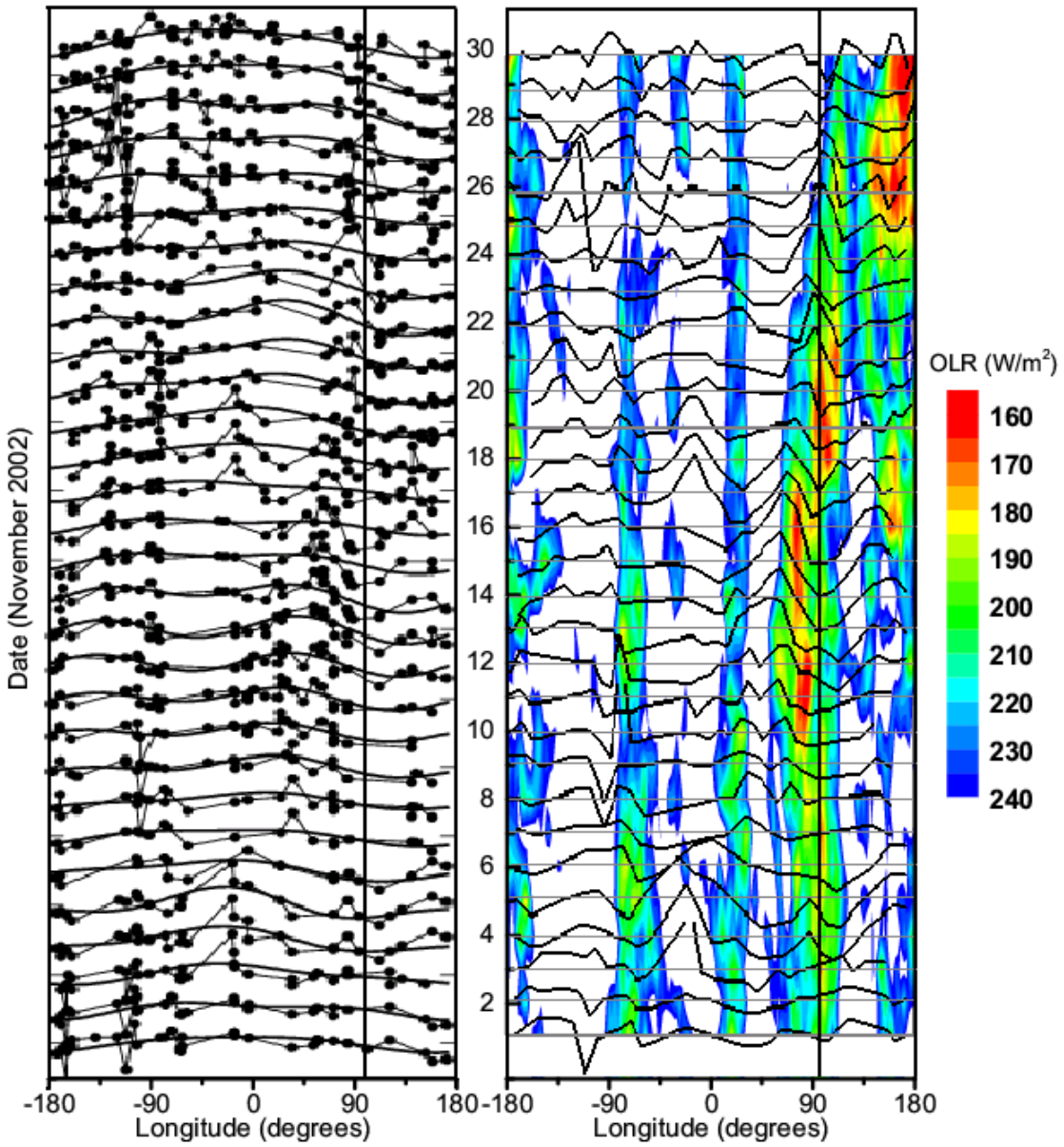


Longitude-Height variation of Kelvin waves in April-May 2004 (CHAMP)



Kelvin wave-like perturbations with zonal wave numbers 3-4 during enhanced cloud convection in the tropics (Ratnam et al., 2006)

CHAMP



(left panel)

Time-longitude variations of *T'* (dotted thin line) and *TF'* (smoothed curve) at 16 km in November 2002.

T' and *TF'* are constructed every three adjacent days and are vertically shifted to the middle date daily.

Each curve is shifted 4 K vertically. The vertical line at 100E.

(right panel)

Time-longitude section of OLR over 10N-10S (contour)

Time-longitude variations of the deviation from the *TF'* (*TF'* – *T'* = *TR'*) at 16 km.

Horizontal structure of gravity waves from series of GPS RO profiles

Spatial structures and statistics of atmospheric gravity waves derived using a heuristic vertical cross-section extraction from COSMIC GPS radio occultation data

Takeshi Horinouchi and Toshitaka Tsuda

(JGR, doi:10.1029/2008JD011068, 2009)

- During early stage of COSMIC, multiple LEO satellites successively passed over the same orbit, resulting in quasi-linearly aligned GPS RO profiles with separation of 1,500-5,000 km. Then, almost instantaneous (within 1 hr) snapshots of vertical-horizontal cross sections of atmospheric temperature could be obtained.
- Horizontal wavelengths of GWs in the winter (here northern) hemisphere were generally smaller than those in the equatorial region or in the other hemisphere.
- For GWs in the northern mid-latitudes, both eastward and westward propagations relative to background winds were identified. The GW amplitude had a negative correlation with zonal wind shear. In the meridional direction, northward propagation was dominant, indicating that the dominant source region of meridionally propagating GWs was in the subtropics.

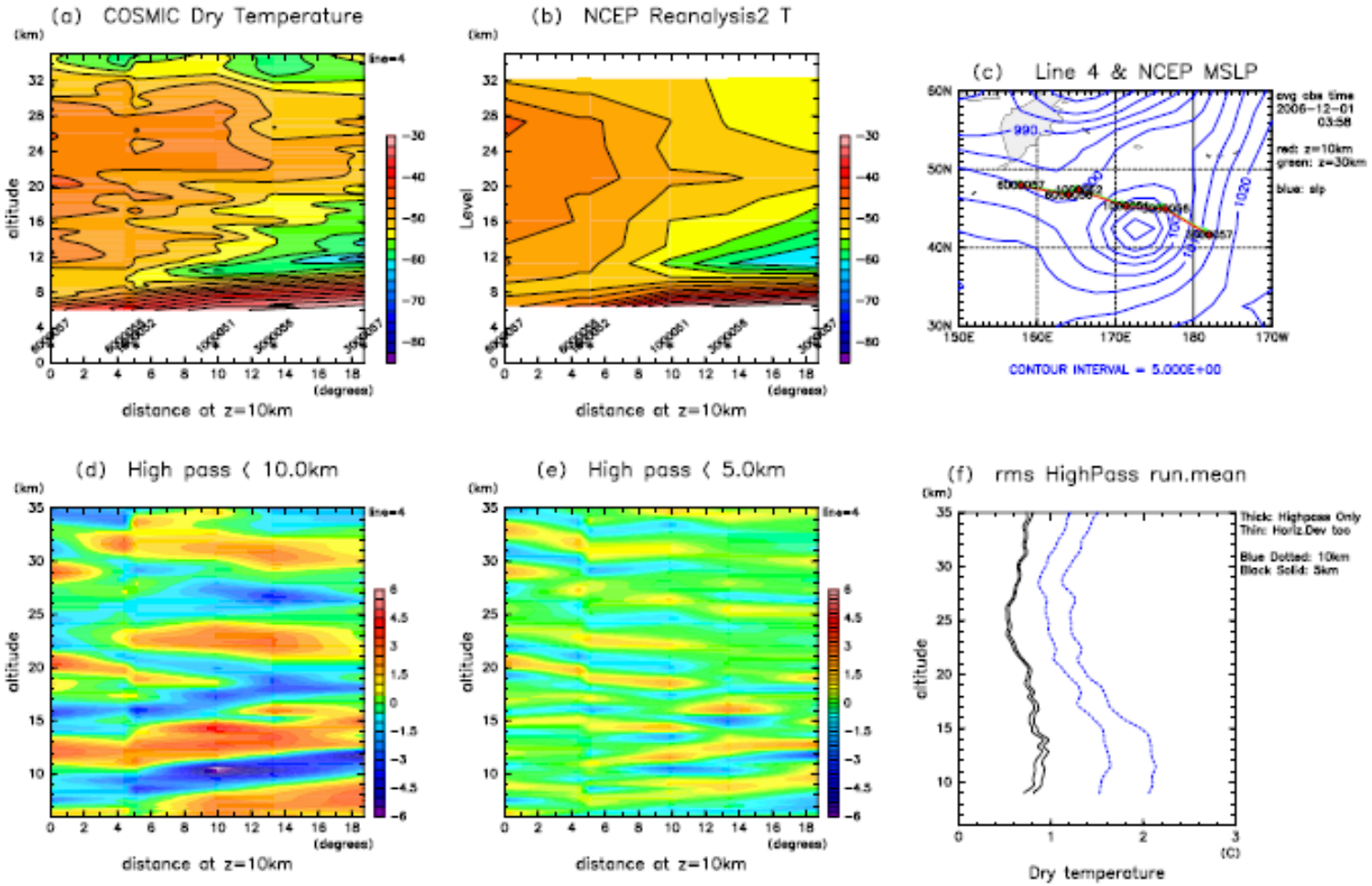
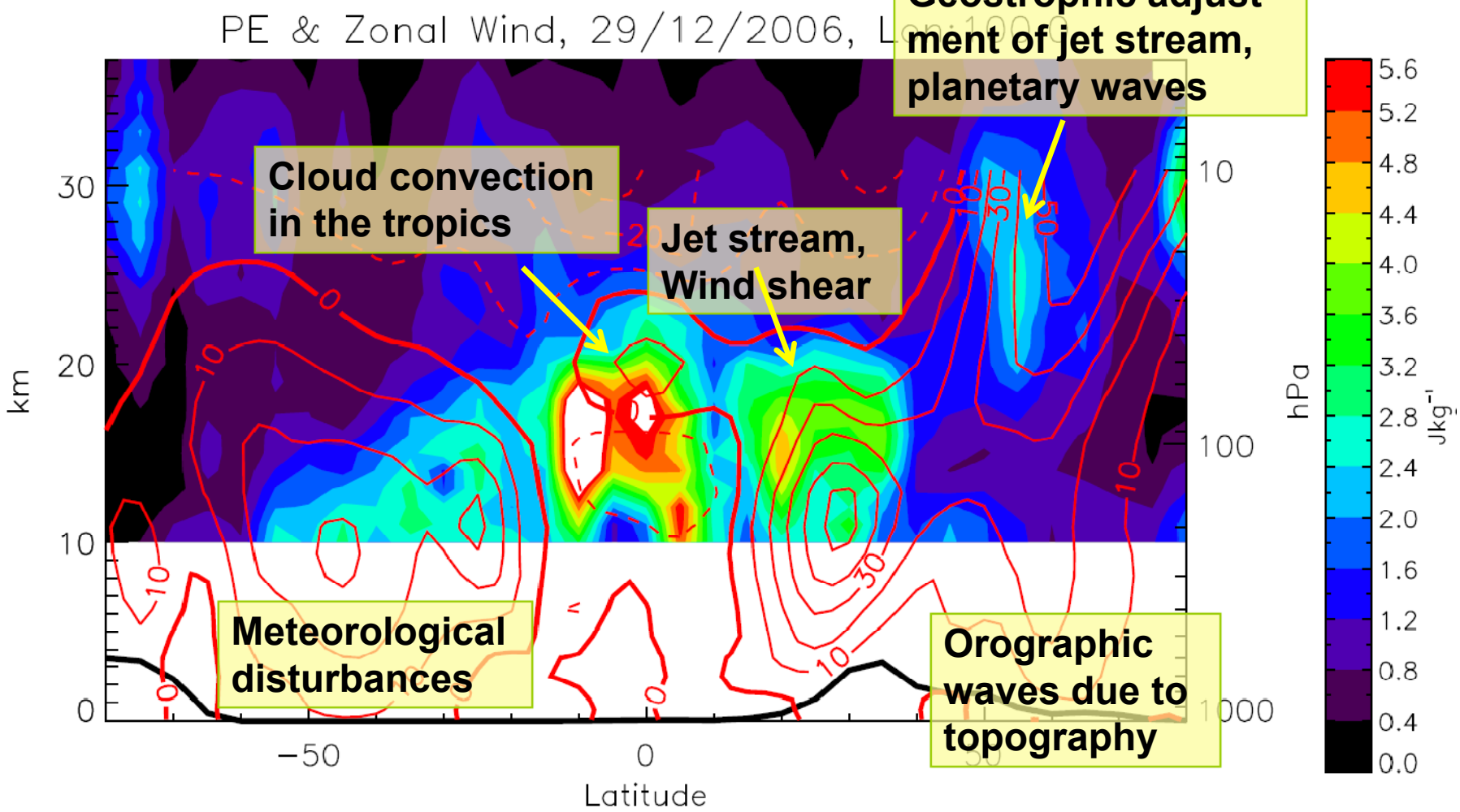


Figure 6. (a) Vertical cross section of the dry temperature along a line obtained on 1 December 2006. (b) The temperature from the NCEP reanalysis 2 data sampled at the same data points after linear interpolation. (c) The locations of the data points, where the tangent points at the altitude of 10 km are shown in red and those on top of the tangent points at 30 km, which are almost hidden, are shown in green. The times of occultations are shown in the right margin of Figure 6c. The blue contours show the sea level pressure from the NCEP data. Horizontal axes of Figures 6a, 6b, 6d, and 6e are the locations of the tangent points at 10 km projected onto the line segment between the two ends of the line with the westernmost point on the left-hand side. Figure 6c shows the temperature from the NCEP reanalysis 2 data interpolated horizontally to the data points. COSMIC dry temperature disturbances obtained by the high-pass filtering with (d) $\lambda_{zc} = 10$ and (e) $\lambda_{zc} = 5$ km. (f) The root-mean-square amplitudes with running means for $\lambda_{zc} = 10$ and 5 km in blue and black, respectively, and without and with the subtraction of horizontal averages (see section 4.1) with thick and thin lines, respectively.

4. Various Generation Sources of Gravity Waves

COSMIC

A height-latitude section of the wave potential energy (Ep) (T' with vertical wave lengths < 7 km) from the COSMIC GPS RO data in 7 days centered on December 29, 2006 at the longitude of 140°E (130°-150°E).
Zonal winds from NCEP and topography (elevation) at 140°E are also plotted in red and black curves, respectively.

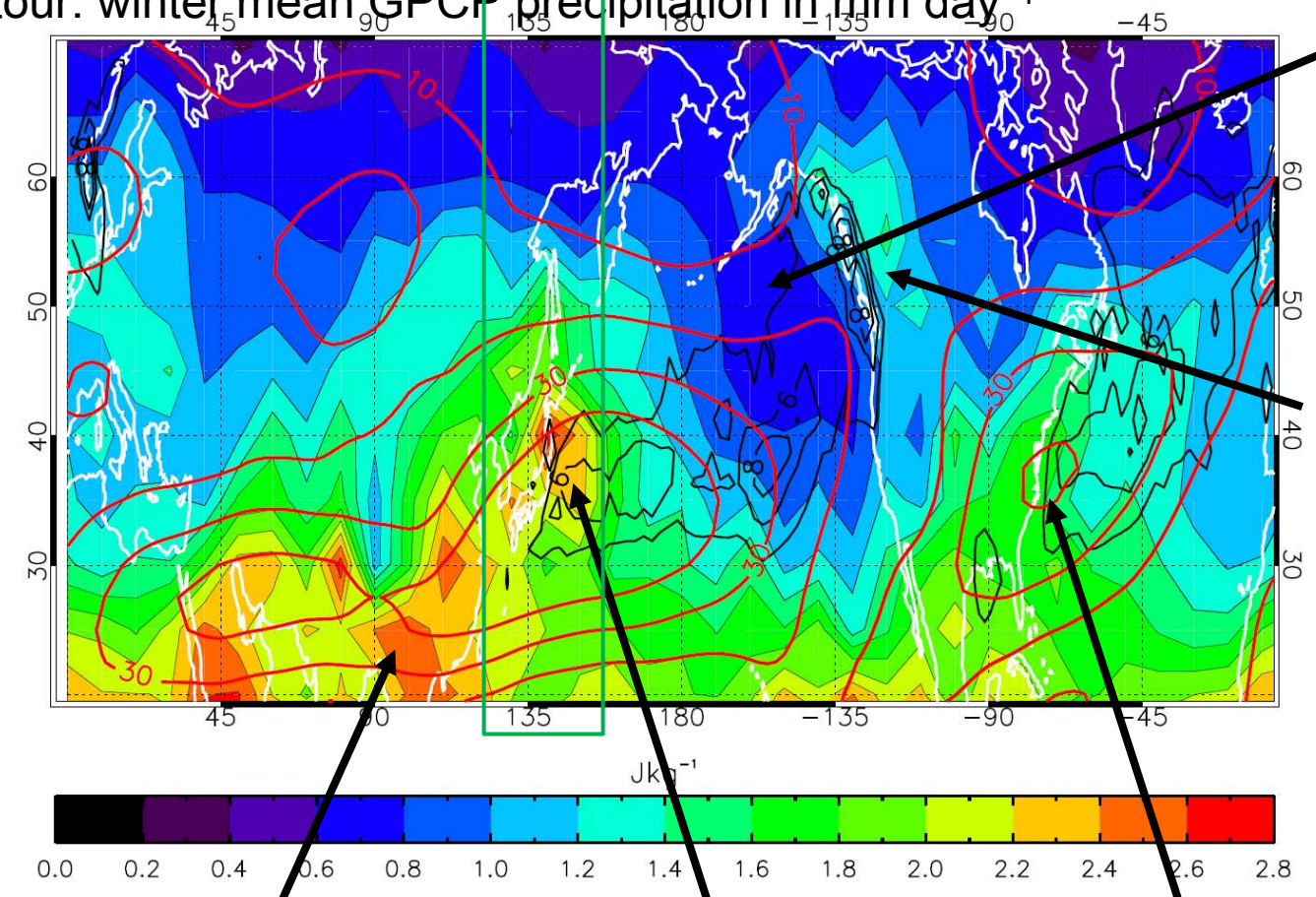


COSMIC

Gravity wave potential energy (Ep) at 17–23 km altitude in winter 2006/07 (Dec-Feb) by using the COSMIC GPS RO temperature data.

Red contour: the winter mean NCEP u at 500–100 hPa in units of ms^{-1}.

Black contour: winter mean GPCP precipitation in mm day^{-1}



Ep is low over Pacific

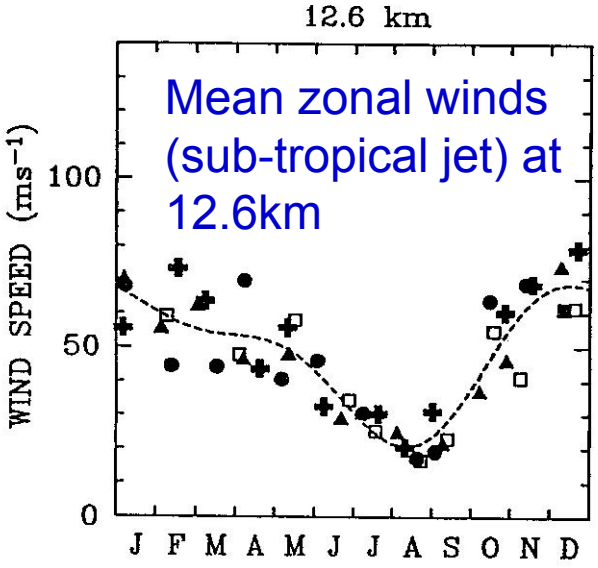
Canadian Rockies have large Ep

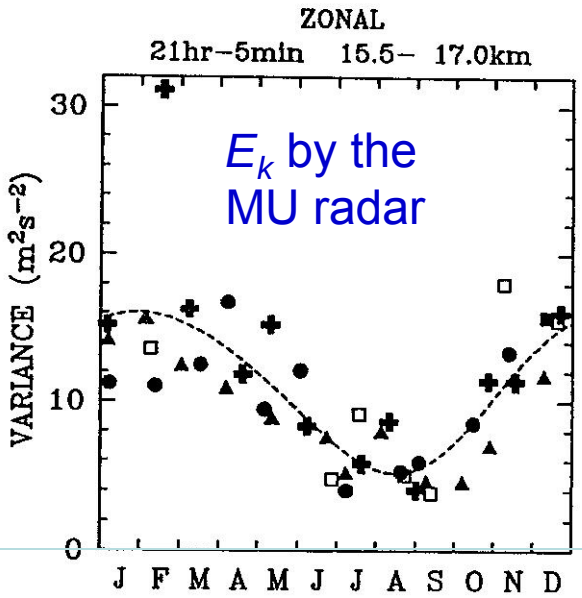
Himalayas & Tibet have large Ep – some orographic effects but also jet stream

Japan – separate large Ep: strong jet & orography

Large Eastern USA Ep associated with strong winter jet

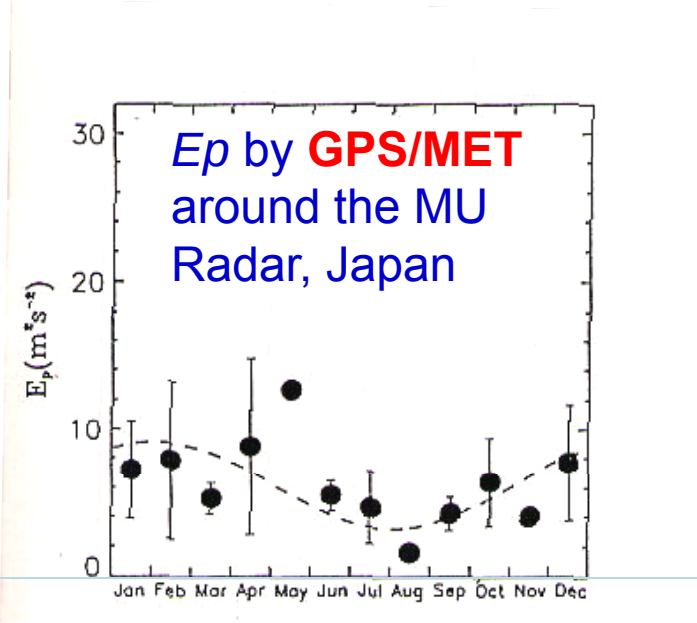
Comparison of GW energy between ground-based radar (MU radar) and GPS RO data (GPS/MET)



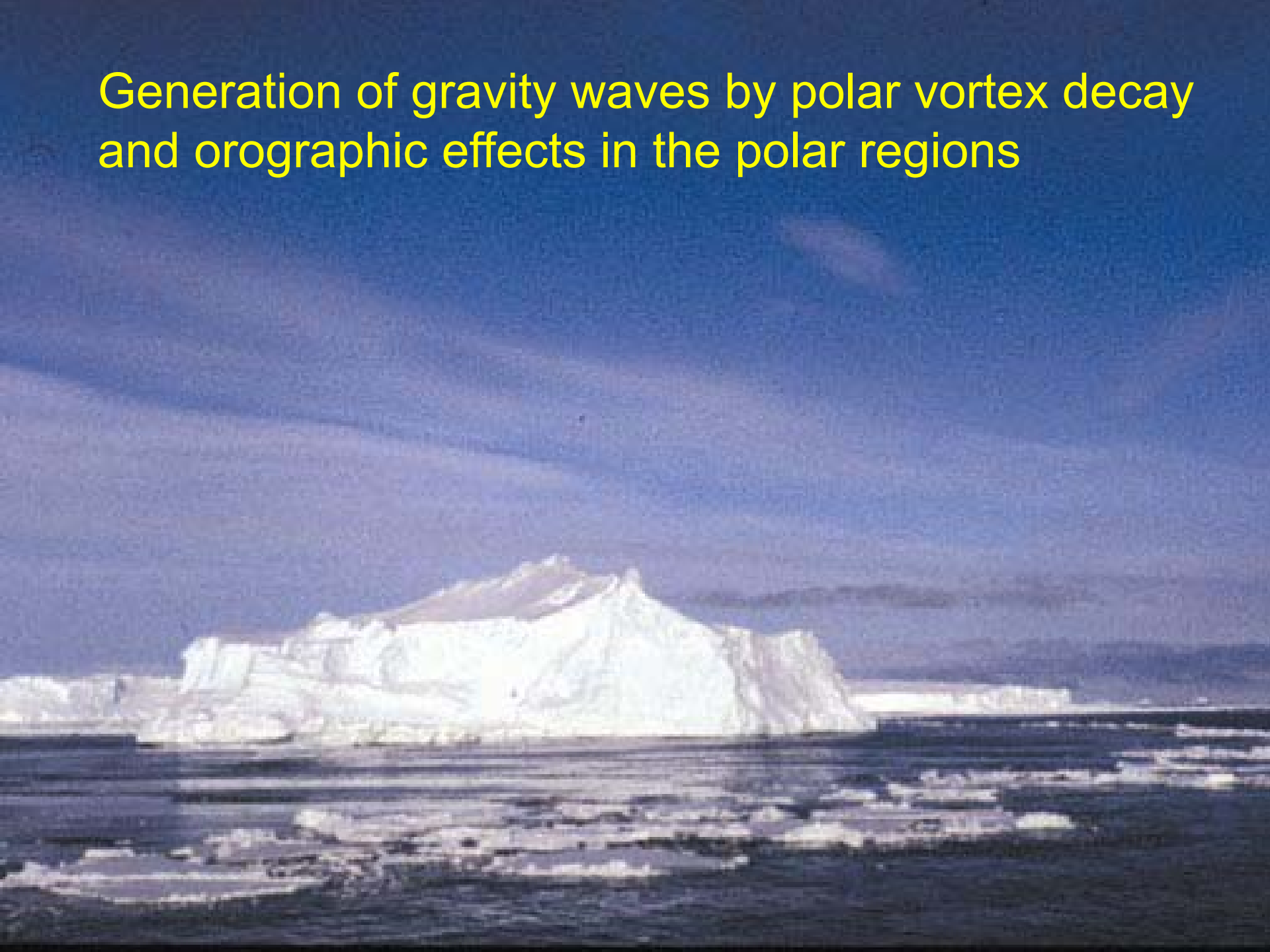


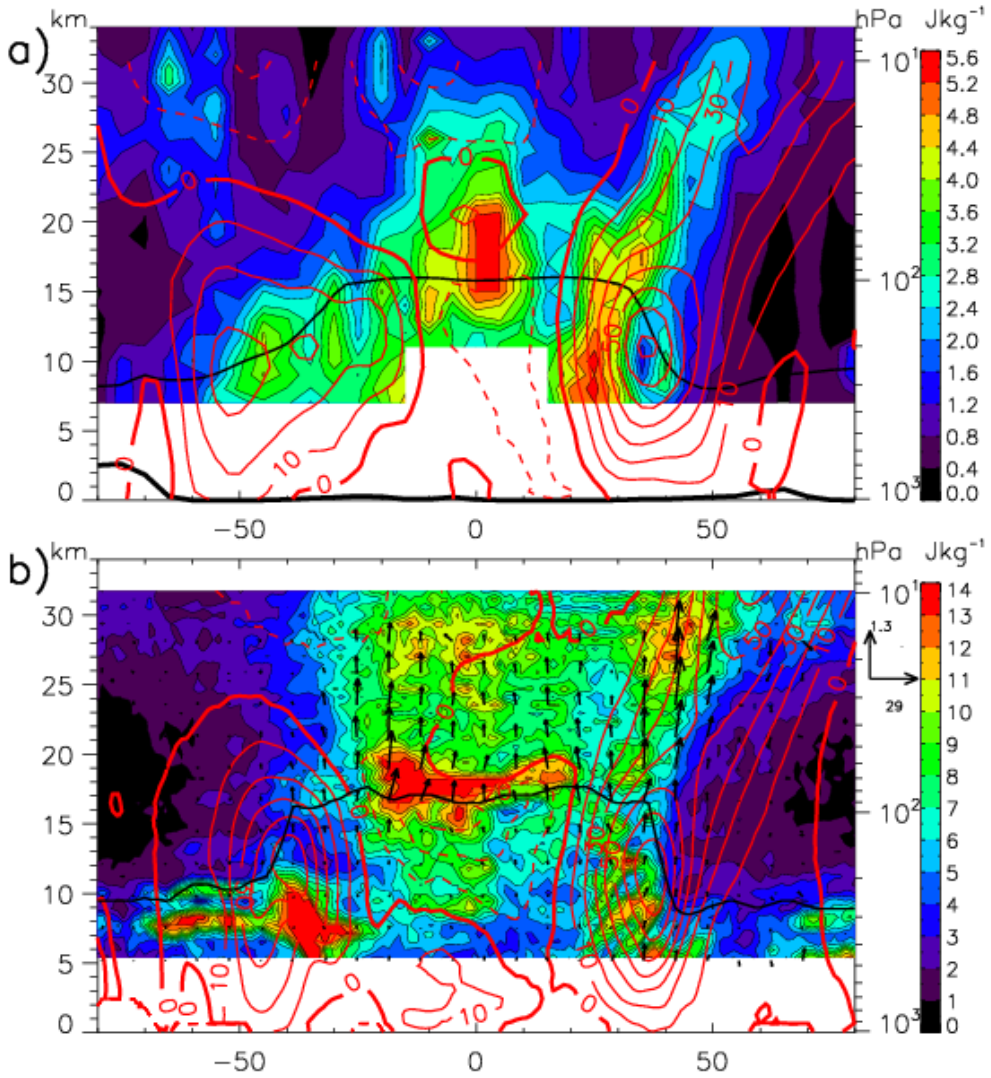
1. Monthly mean *Ep* =½(g/N)2(T'/T)2 at 15-20 km around the MU radar, Japan (35°N, 136°E) in 1985-1989.
2. Seasonal variations of *Ep* from GPS/MET agree well with the climatological behavior of E_k (wind velocity variance) due to gravity waves observed with the MU.
3. E_k /*Ep* = 1.67-2.0

   Theoretical prediction= 1.7.



Generation of gravity waves by polar vortex decay and orographic effects in the polar regions





COSMIC PE at 140E during 12 – 18 Dec 2006

- Strong winter time sub-tropical jet
- Large PE from mid-troposphere up to polar night jet

AGCM PE 140E, 1 – 7 Jan (similar wind conditions to COSMIC)

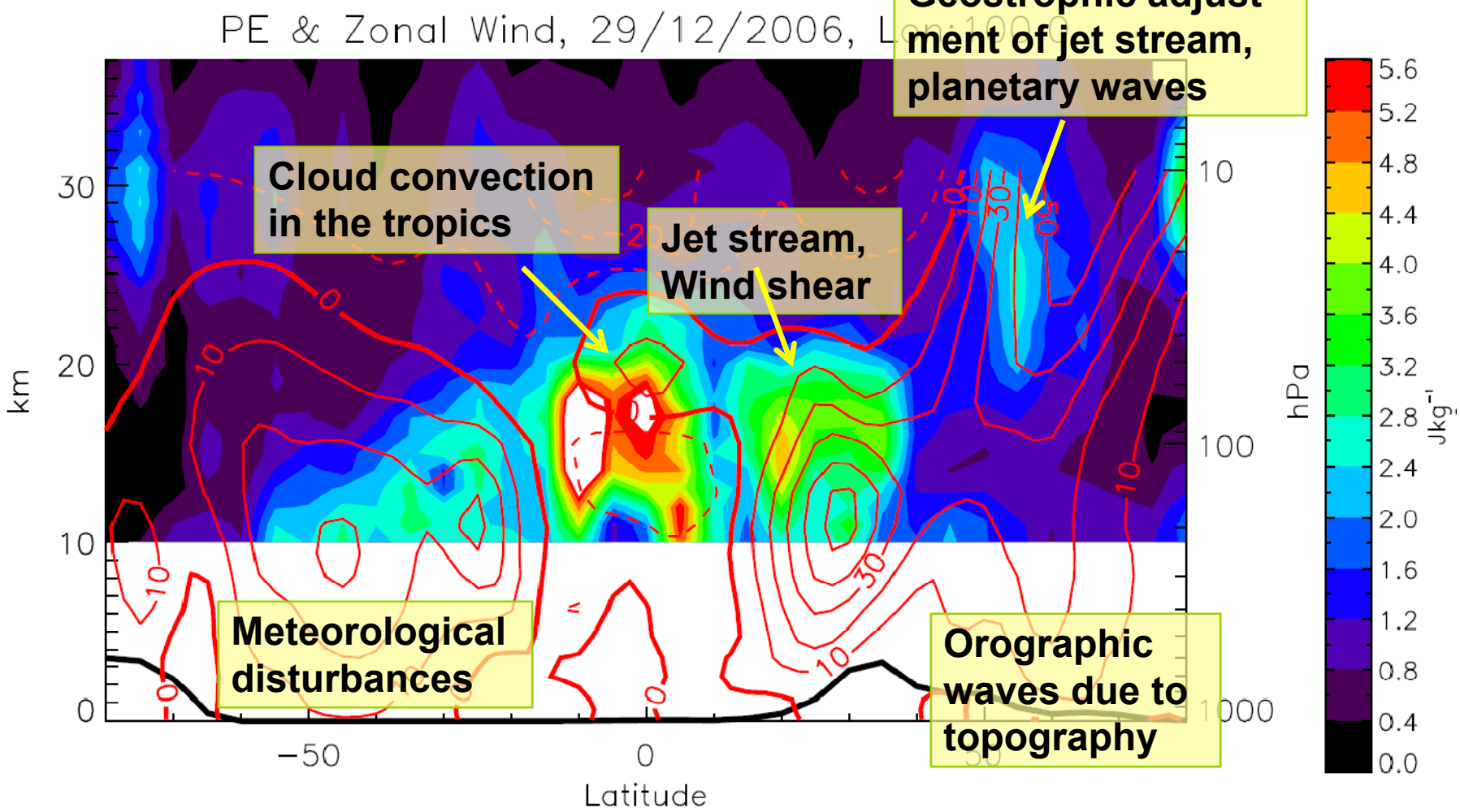
- PE from waves with periods 6hr – 1 month, $\lambda_z < 7$km, $380 < \lambda_x < 40{,}000$km
- Note different colour scale
- Vectors show meridional and vertical energy fluxes due to $\lambda_z < 7$km

- Comparison between the COSMIC and AGCM data indicates the relatively low PE values at 20N, which is a region that also corresponds to weaker energy flux.
- Larger PE at 40N is mostly due to subtropical jet (located equatorward of the jet), and is also distributed upward and poleward along the zonal wind contour lines.
- The polar night jet itself generates gravity waves which propagate upward and downward, as evident in (b) by the downward flux vectors on the polar side of the jet above 20 hPa.

4. Various Generation Sources of Gravity Waves

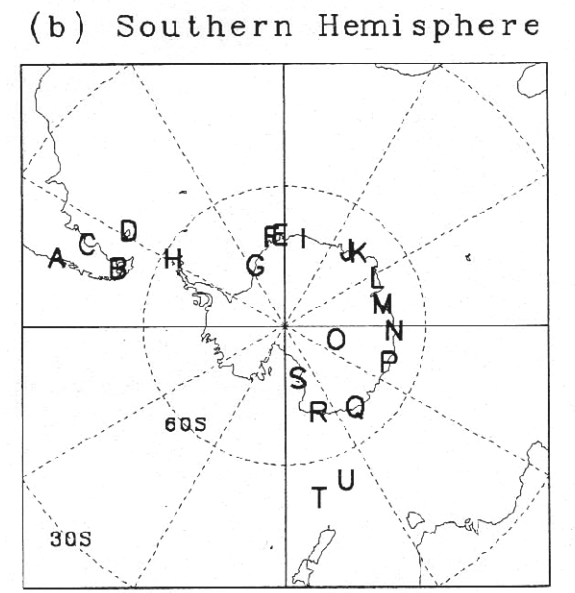
COSMIC

A height-latitude section of the wave potential energy (Ep) (T' with vertical wave lengths < 7 km) from the COSMIC GPS RO data in 7 days centered on December 29, 2006 at the longitude of 140°E (130°-150°E).
Zonal winds from NCEP and topography (elevation) at 140°E are also plotted in red and black curves, respectively.

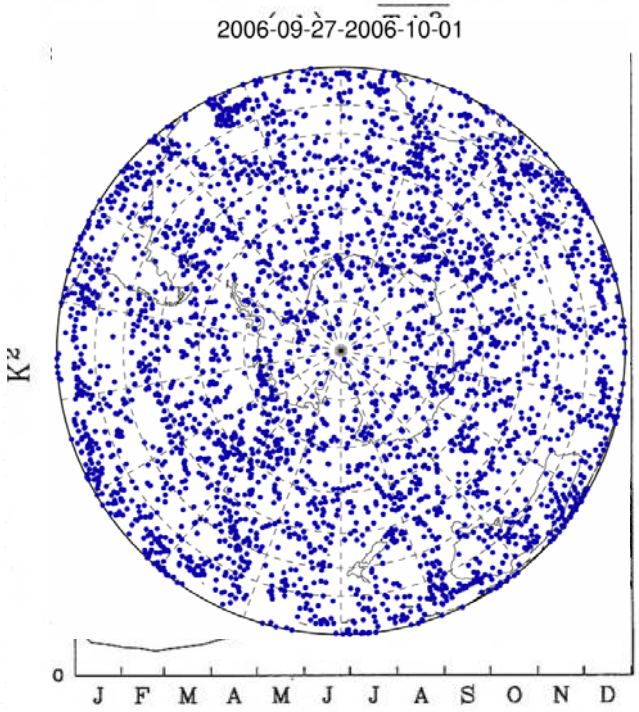


Earlier studies of gravity waves (GW) in Antarctic region

- By using routine radiosonde data at Antarctic bases, GW energy is found to be large in October-November. [Yoshiki and Sato., 2000]
- The intensity of background mean winds (polar night jet) seem to be related to a generation mechanism of GW.
- GW energy was enhanced when the polar night jet approached over the station during its dissipating phase in spring. [Yoshiki et al., 2004]
- Rantnam et al. [2004] reported enhancement of GW at around the polar vortex during the major stratospheric sudden warming in 2002 by using CHAMP GPS RO data.



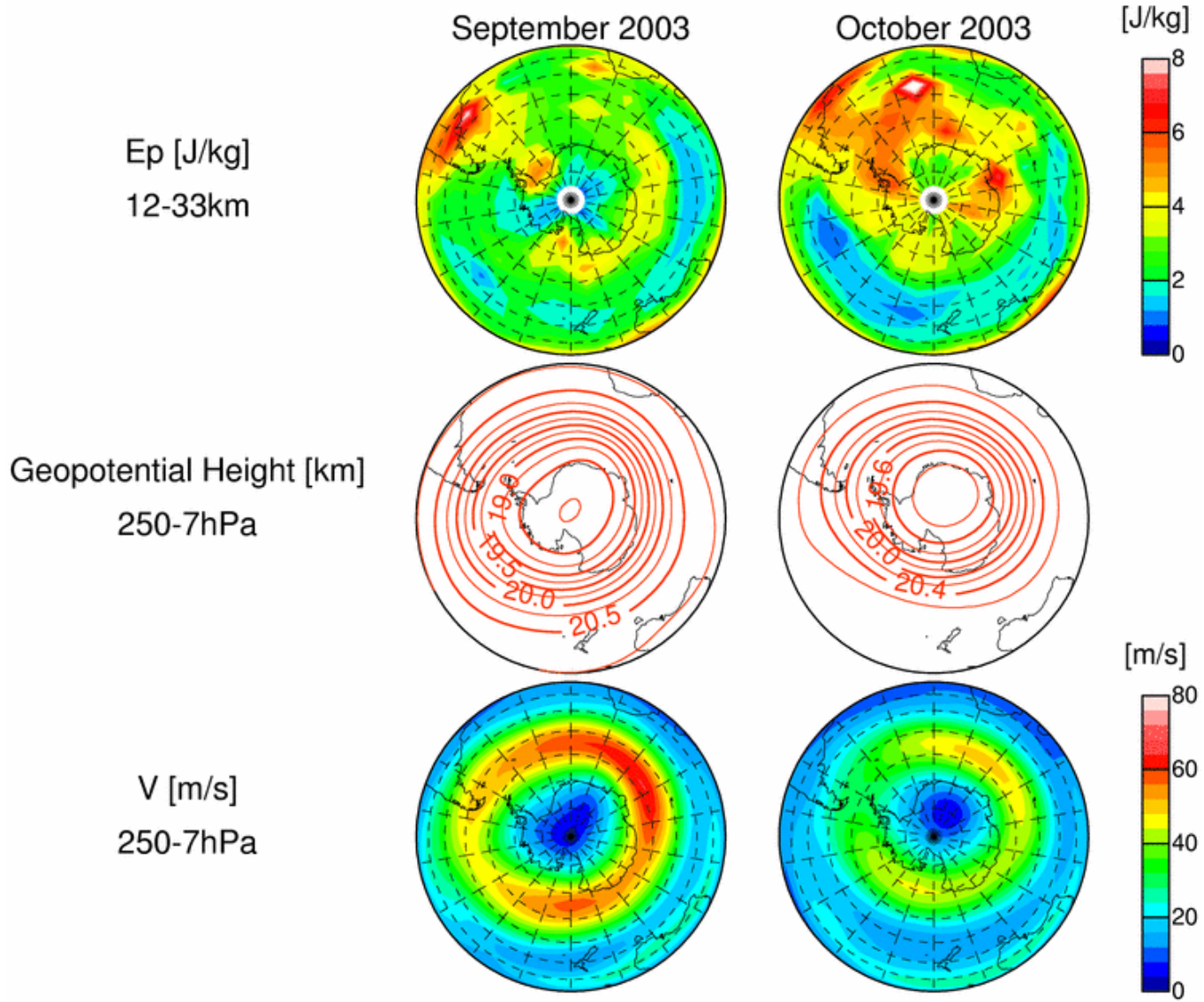
r the analysis in this study. The stations denoted by



Distribution of COSMIC GPS RO data around Antarctica in 5 days from 27 September to 1 October 2006

Horizontal distribution of Ep (12-33km), Geopotential height (250-7HPa) and Horizontal winds (250-7HPa)in September and October 2003

CHAMP

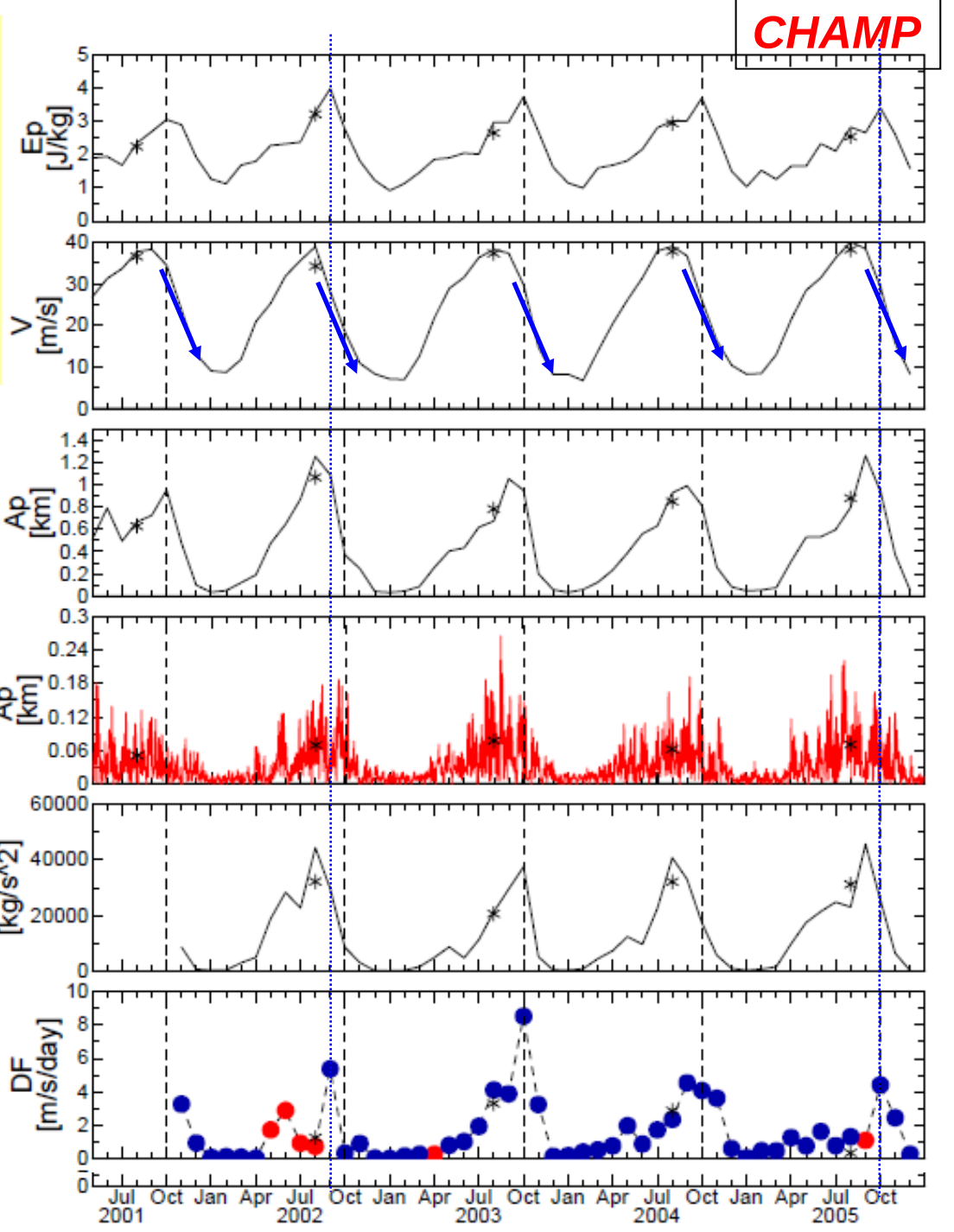


Monthly mean values of Ep (top) in the Antarctic region and Mean winds V, Planetary wave amplitude Ap, and its fluctuations Ap'. Vertical component of E-P flux (Fz), and E-P flux divergence (DF).

Ep gradually increases in winter (Sep-Oct), and it is largely enhanced in spring (Sep-Oct), then, it rapidly decreases.

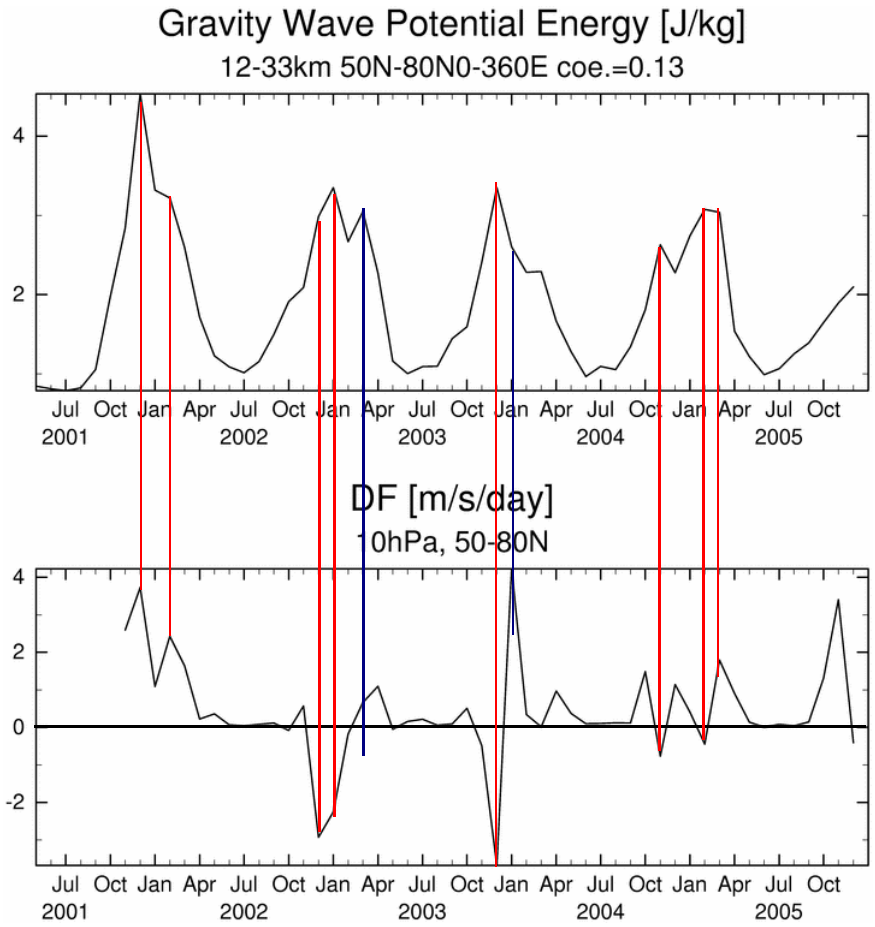
Maximum of V occurs one month earlier than Ep peak. dV/dt coincides with Ep peak, i.e., GW are enhanced during a decay phase of polar vortex.

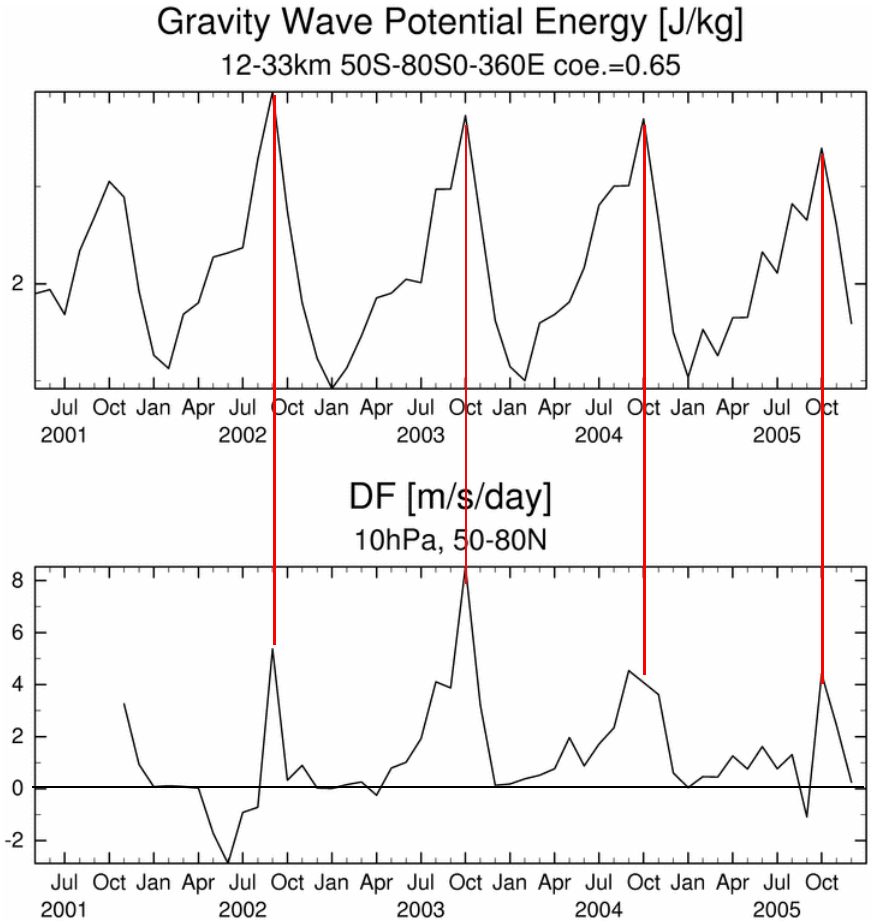
Annual cycle of Fz correlates well with Ep (and Ap as well). However, DF coincides better.



CHAMP

Comparison between the monthly mean Ep and E-P flux divergence in the Arctic (Left) and Antarctic (Right) regions



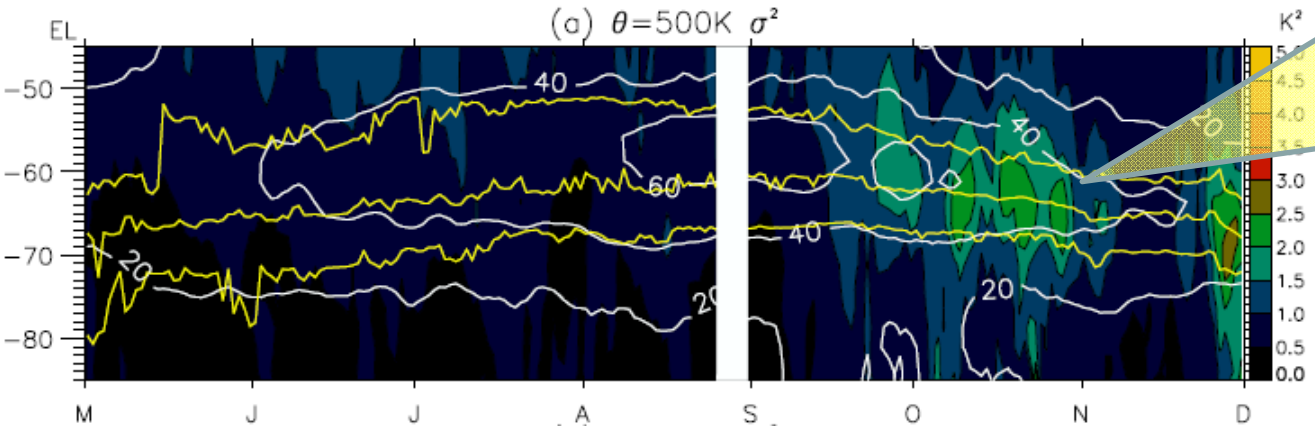


A good correlation between *Ep* and the divergence of the E-P flux, DF, suggests that the active planetary wave generates gravity waves through planetary wave transience and/or breaking.

Structure of the polar vortex and wave variance (Ep) distribution

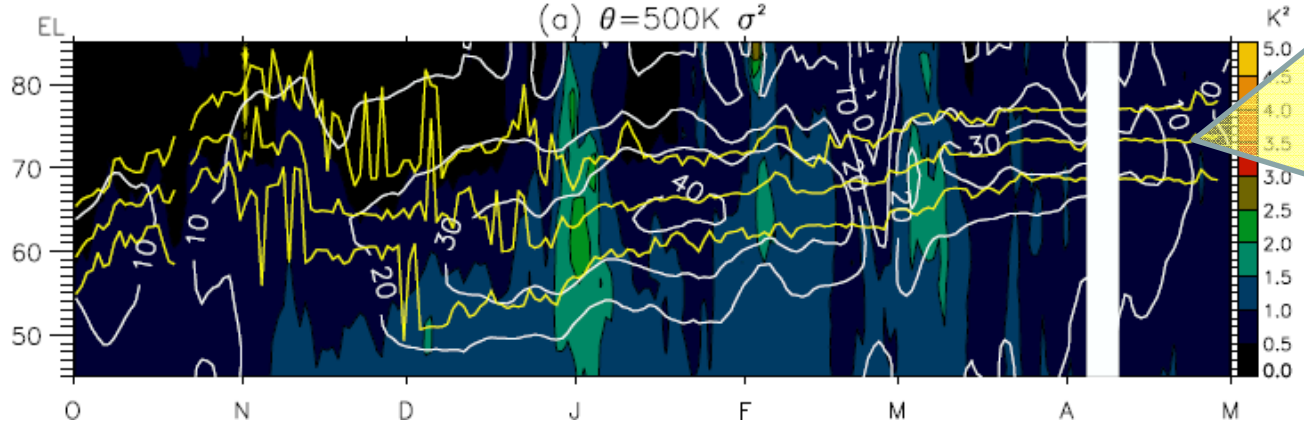
COSMIC

May-December 2007 in Antarctica at 500 K (about 19-20 km)



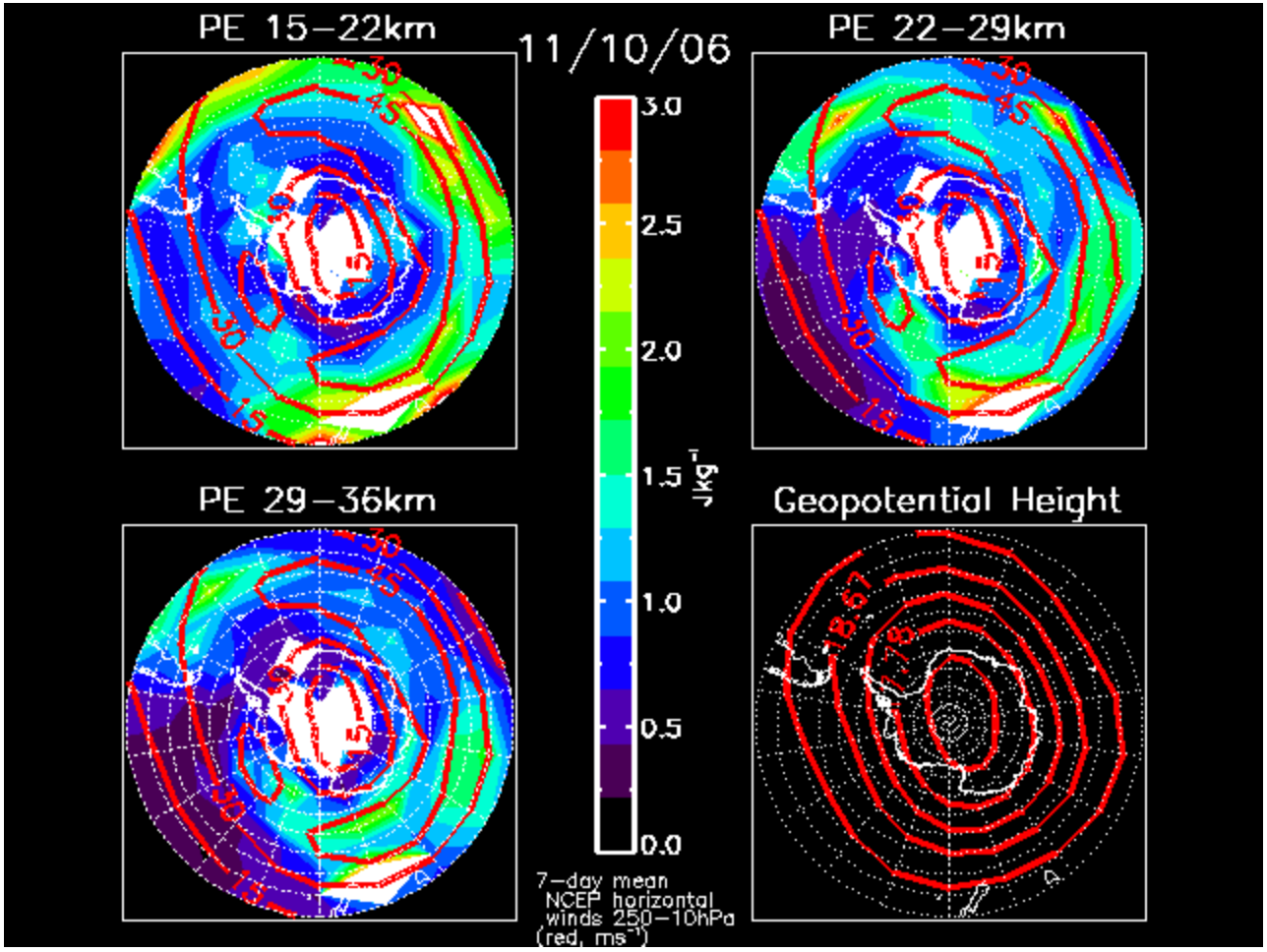
During winds decreased from 60m/s to 40 m/s in late-Sep to Oct (spring), large wave variance is observed inside the vortex boundary with symmetric distribution

October-May 2006/7 for the Arctic vortex at 500 K

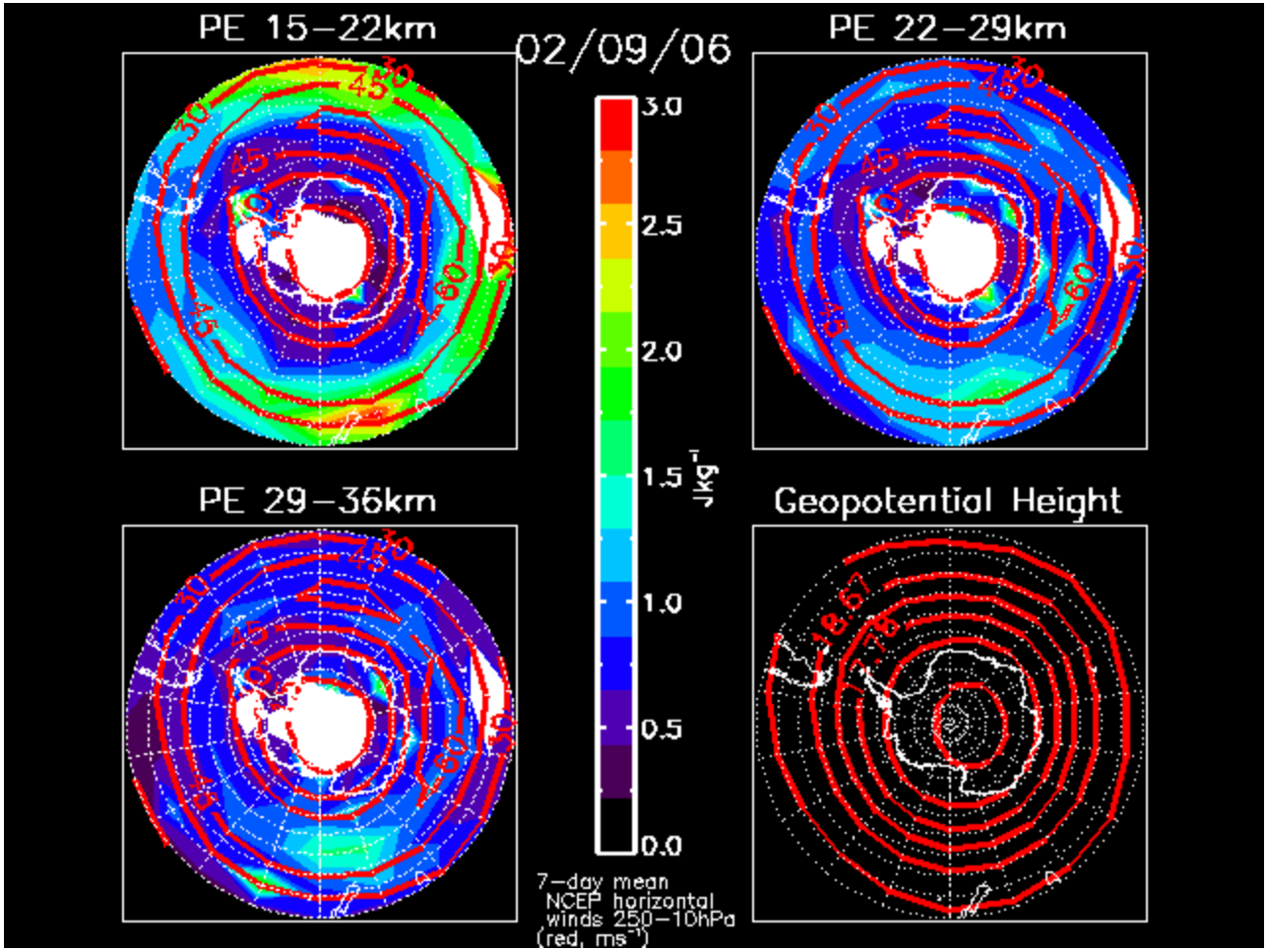


Enhancement of Ep does not occur during the vortex decay phase. But, large Ep in early Jan, Feb and March coincides with SSW (sudden stratospheric warming)

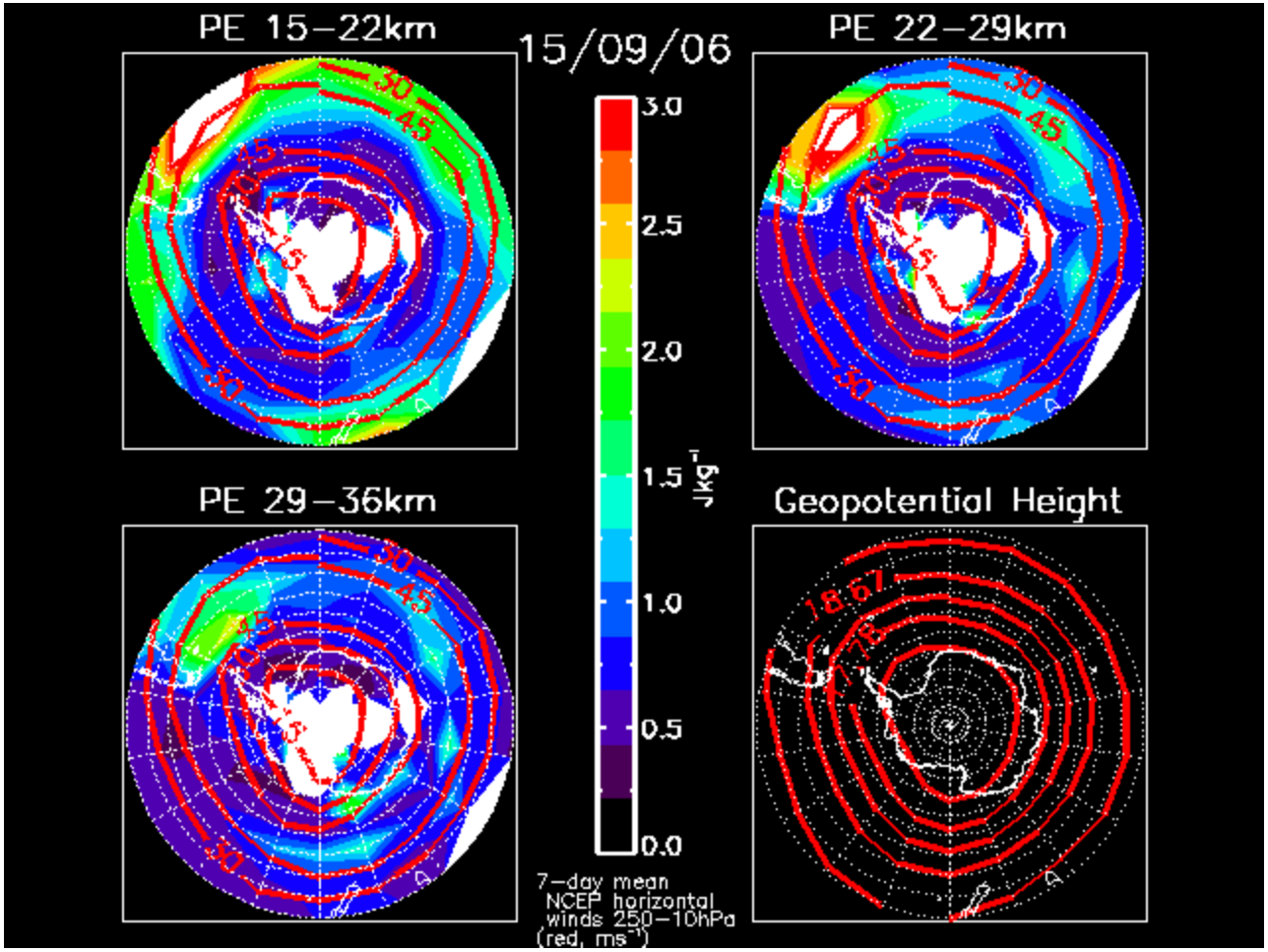
Contour: Ep, White line: 5-day smoothed UKMO zonal mean zonal winds (m/s, eastward solid),
Yellow line: vortex edge (thick) and vortex boundary region (between the thin yellow lines).


PE 15–22km
11/10/06
PE 22–29km
PE 29–36km
Geopotential Height
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Jkg^{-1}
7–day mean
NCEP horizontal
winds 250–10hPa
(red, ms^{-1})

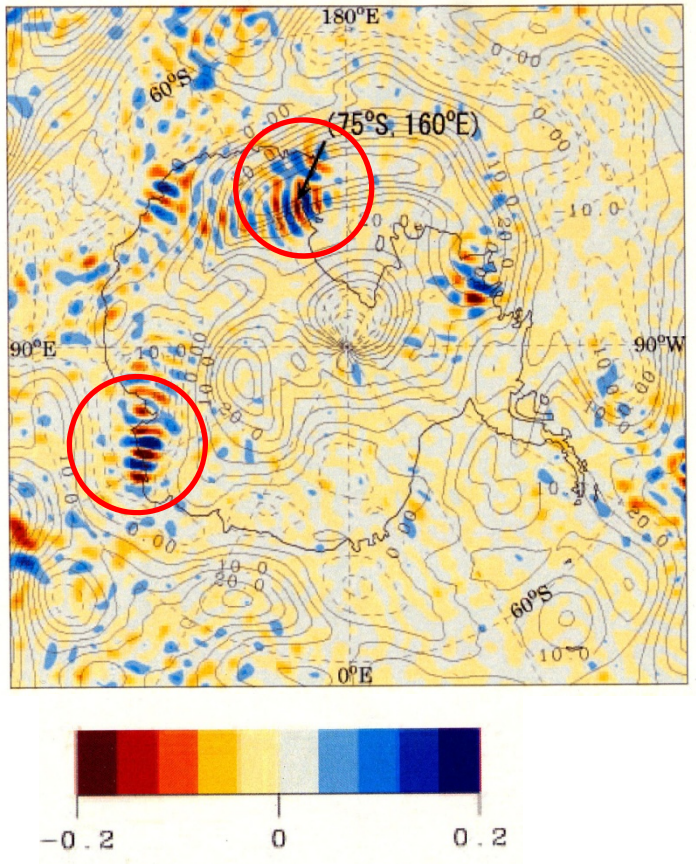
COSMIC

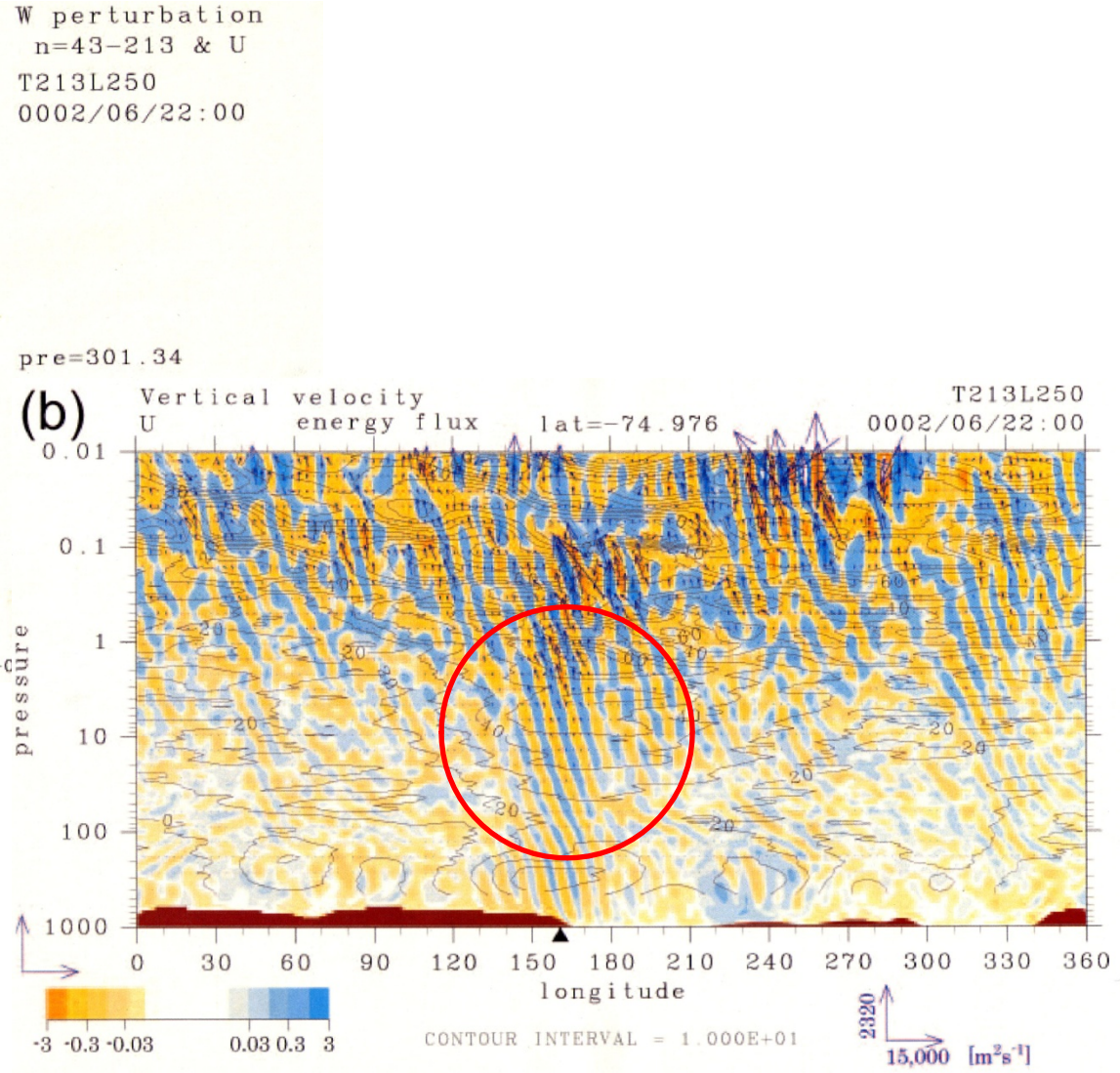


Movie


PE 15–22km
15/09/06
PE 22–29km
PE 29–36km
Geopotential Height
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Jkg⁻¹
7–day mean
NCEP horizontal
winds 250–10hPa
(red, ms⁻¹)

Numerical model results for orographic generation of gravity waves





S. Watanabe et al., SOLA, 2005

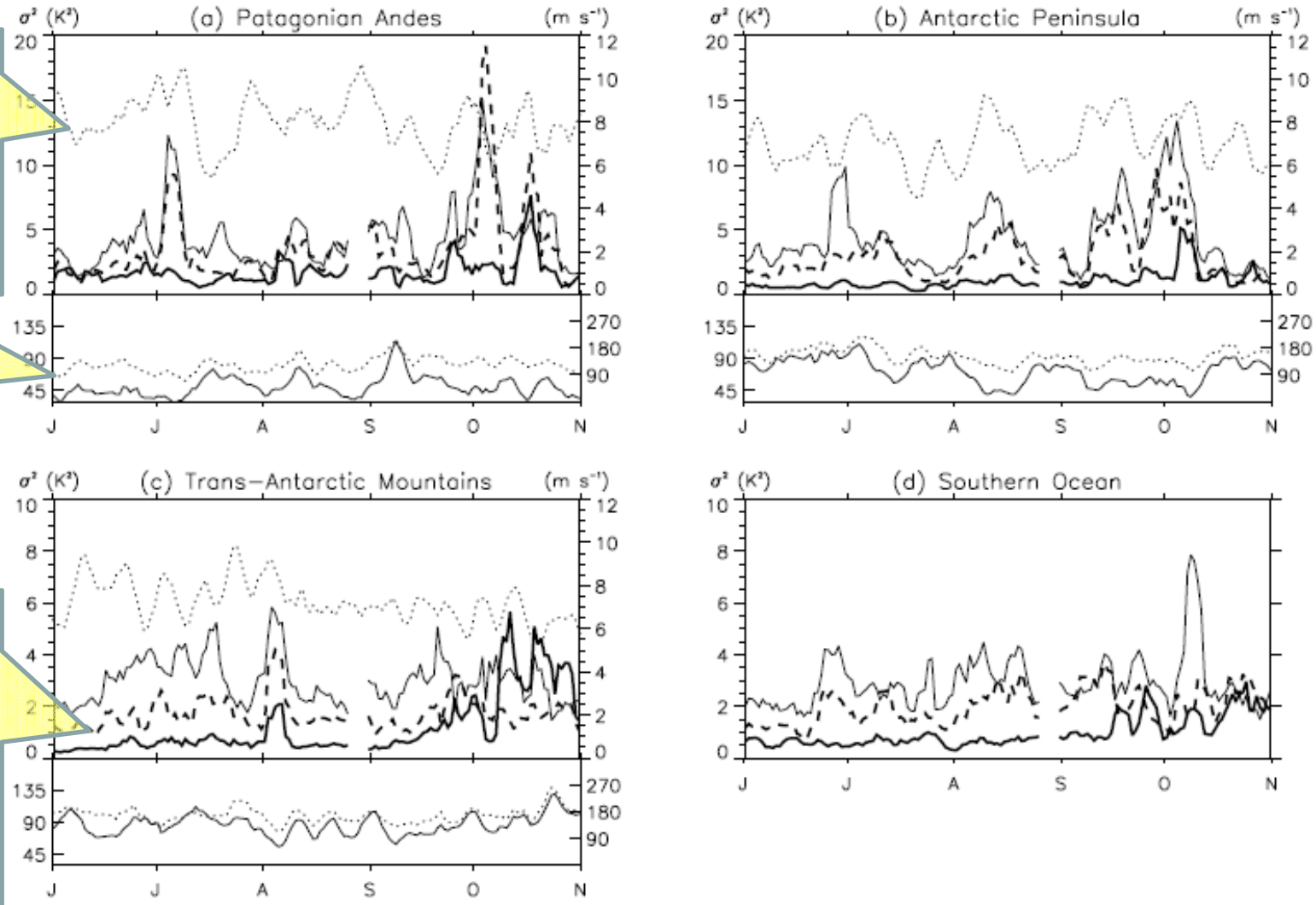
Short-term wave variability in Antarctica

COSMIC

Near-surface wind speed (dotted line, scale to the right)

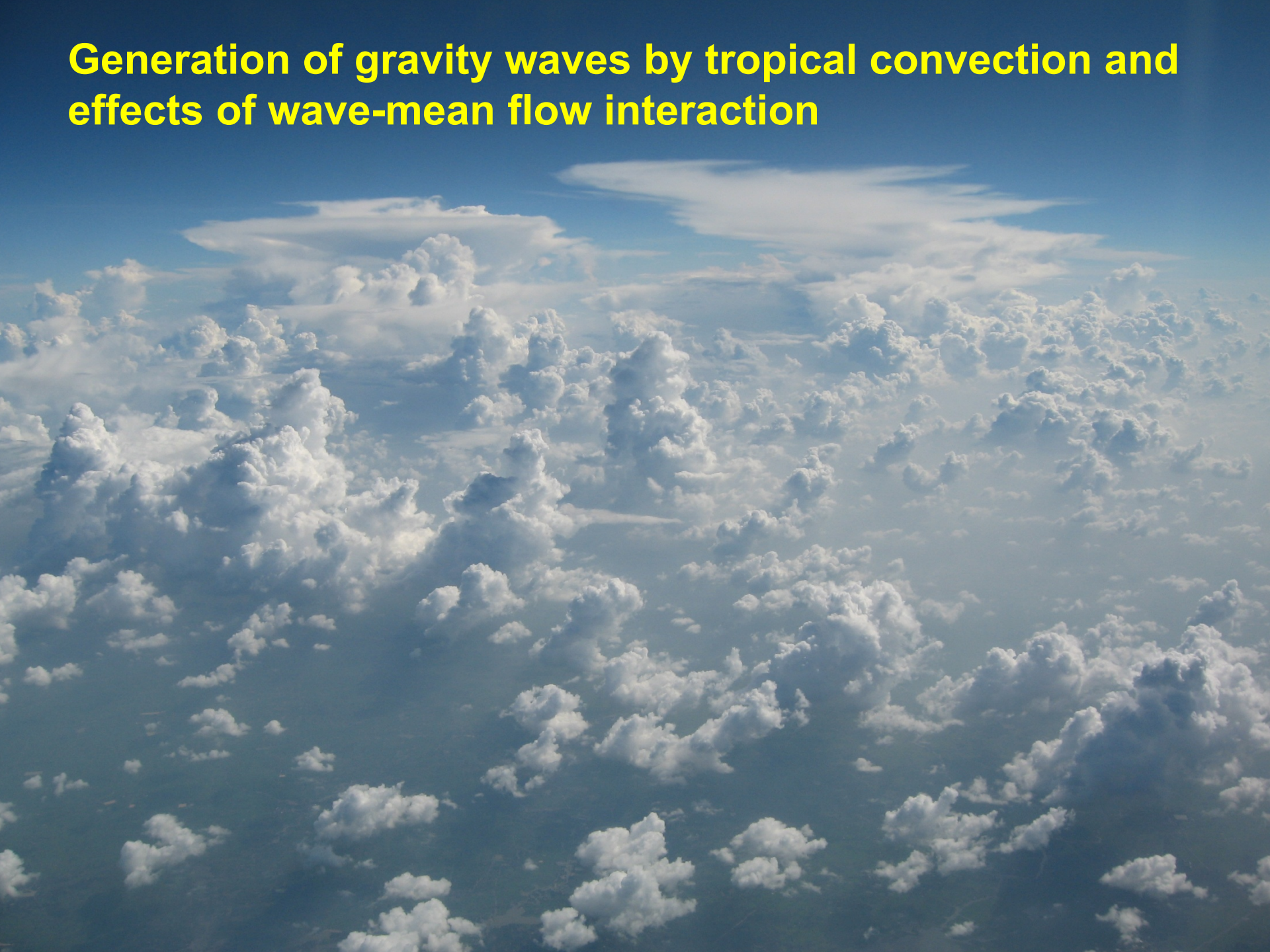
Rotation angle of mean winds

Ep at
500 K: thick solid
800 K: dashed
1000 K: thin solid)



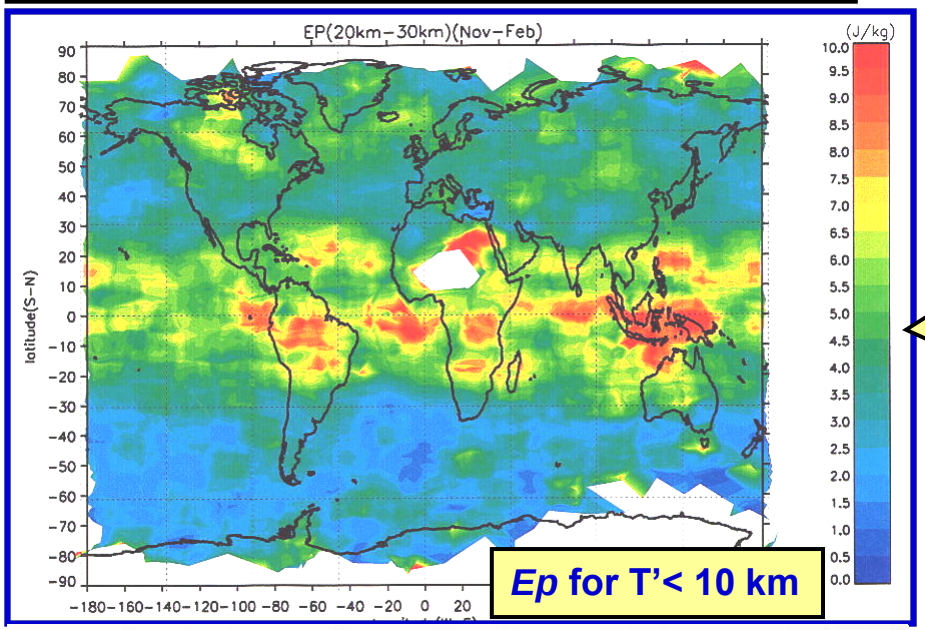
Intermittent peaks of Ep occur with 5-10 day duration, with larger values over Andes and Antarctic Peninsula than the Trans-Antarctic mountains. Orographic waves are not continuously generated, but they depend on the mean wind conditions.

Generation of gravity waves by tropical convection and effects of wave-mean flow interaction

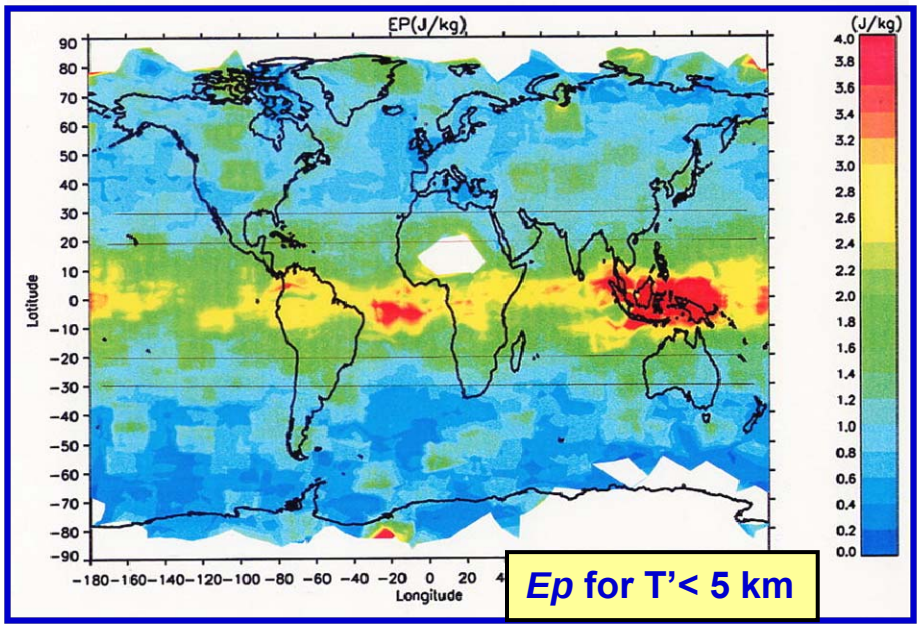


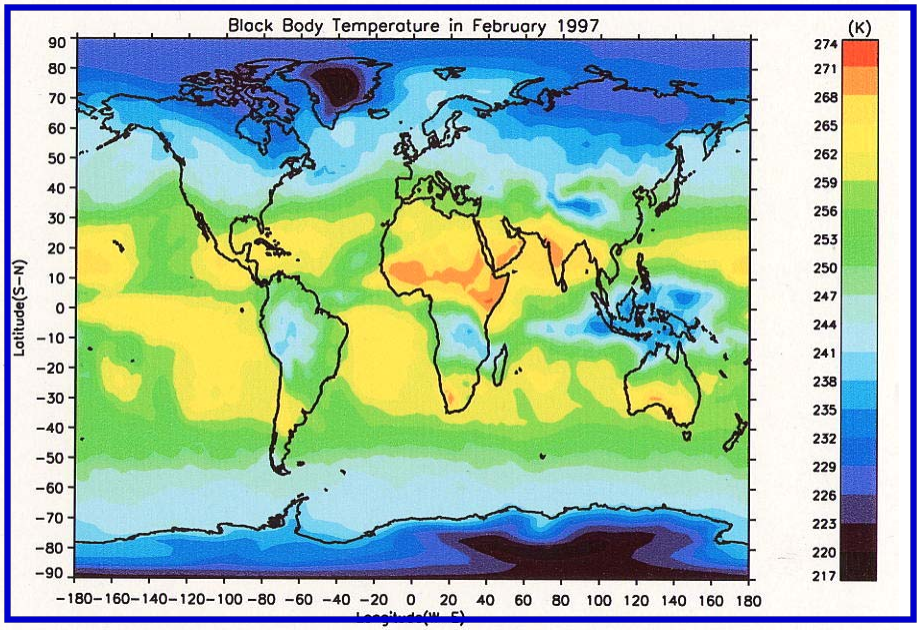
Correlation between Gravity Wave Energy (Ep) and Cloud Convection

(Left) Latitude-longitude distribution of the wave potential energy $Ep=1/2(g/N)^2(T'/T)^2$ at 20-30 km in Nov-Feb from GPS/MET in 1995-1997
(Bottom) Black body temperature (OLR) in Feb, 1997



Large Ep values are detected at low latitudes (25N - 25S), and they are particularly enhanced over the regions of active convection , i.e, Indonesia, Indian ocean, Africa and South America.





CHAMP

Jun-Jul-Aug, 2001

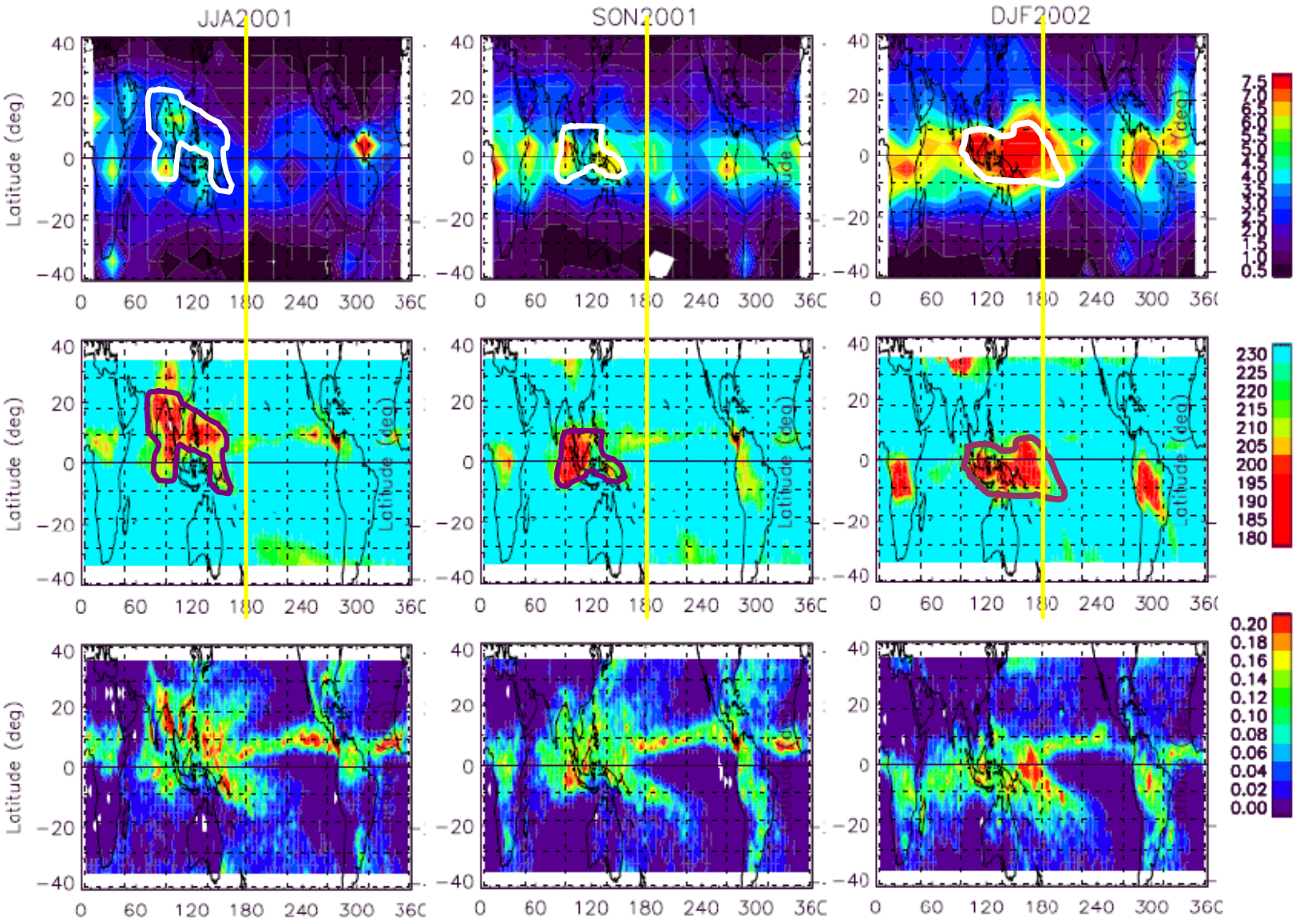
Sep-Oct-Nov, 2001

Dec, 2001 – Jan-Feb, 2002

Ep
Strato-spheric gravity wave energy

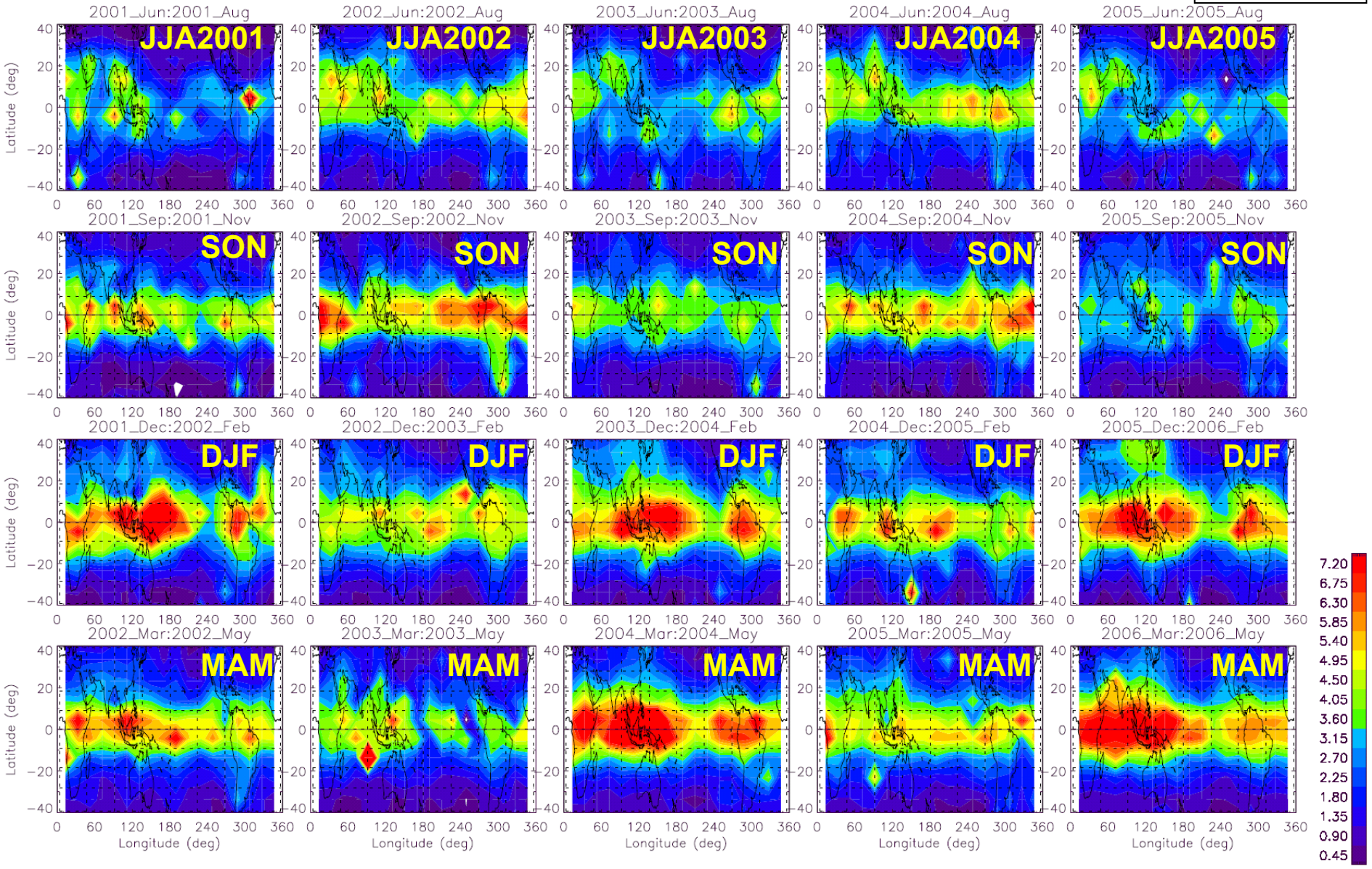
OLR
Cloud top height

TRMM-PR
Convecti ve rain rate

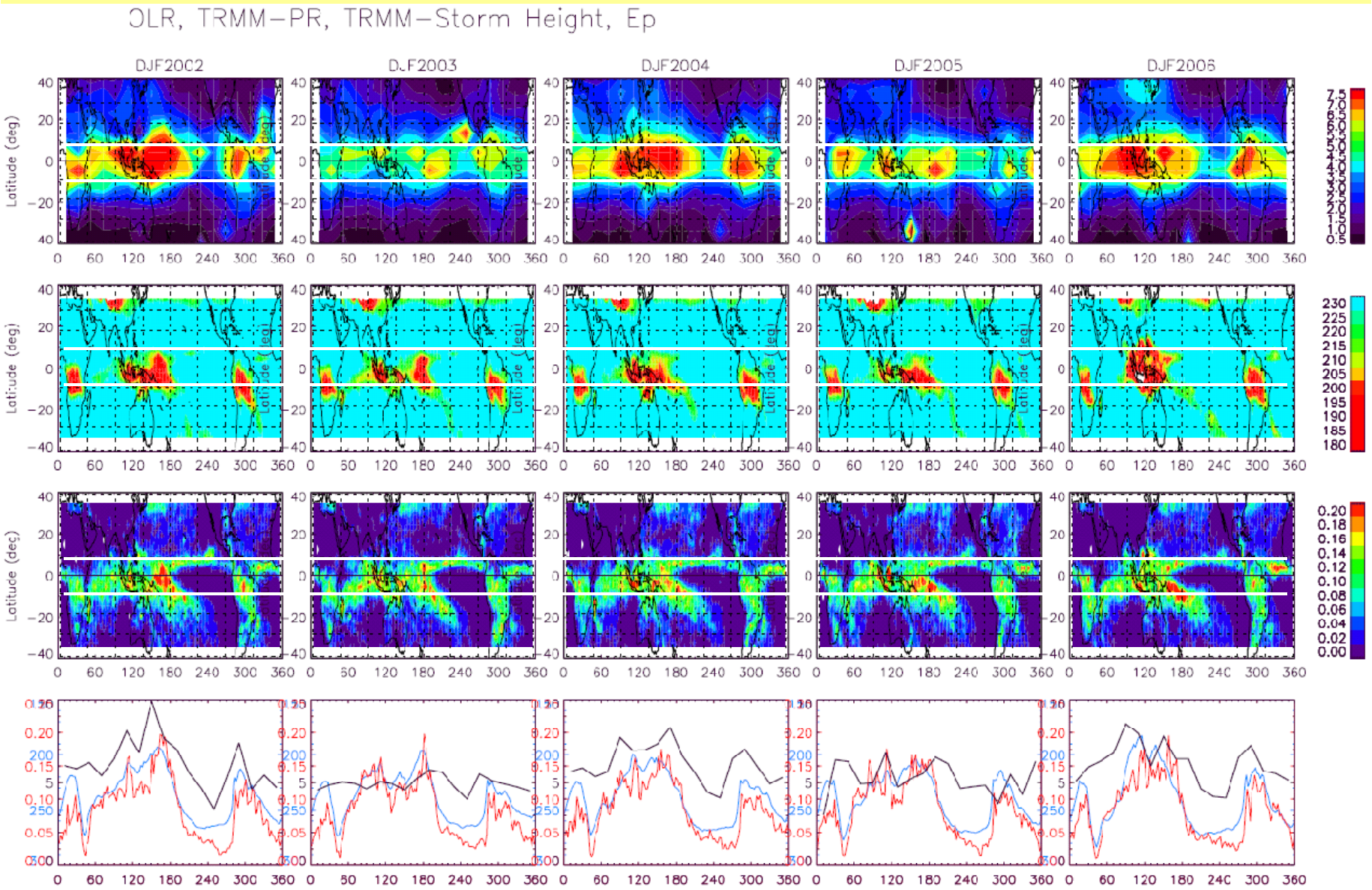


Ep with CHAMP/GPS RO in 2001–2005 19–26 km

CHAMP



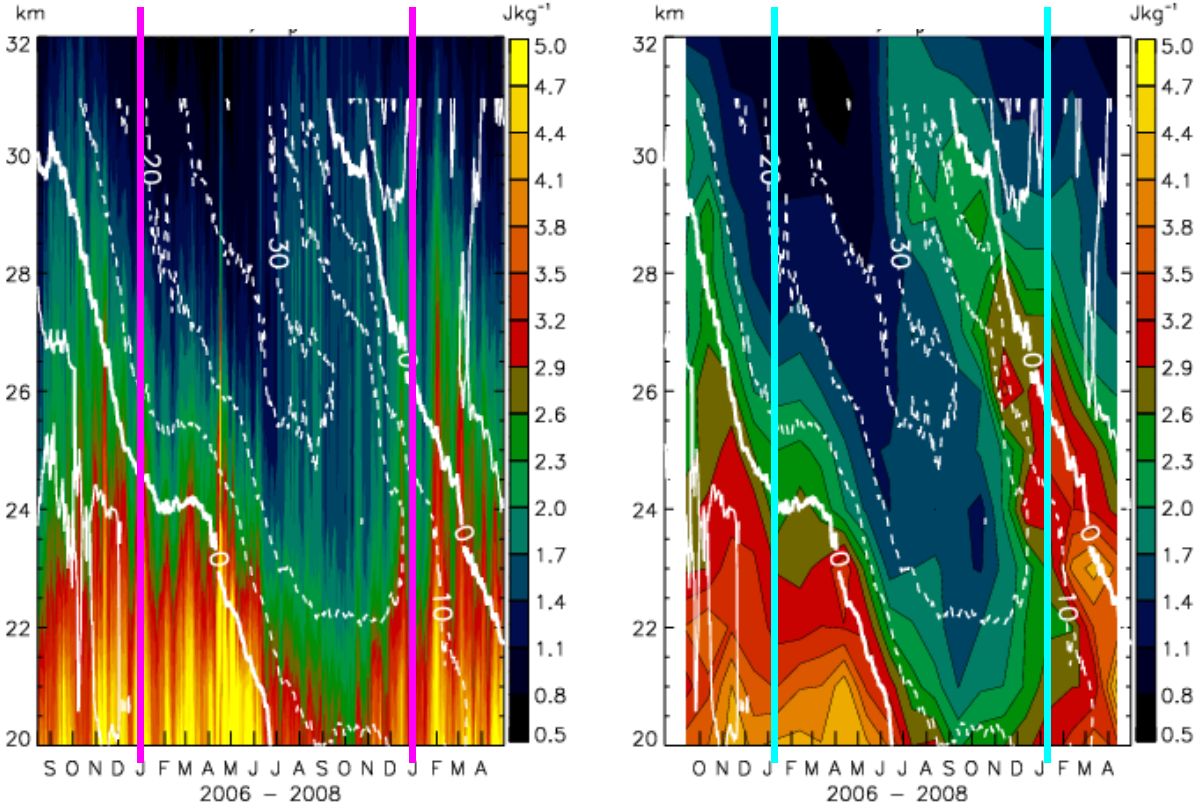
Year-to-year variations of wave energy (Ep), OLR and convective rain rate in Dec/Jan/Feb in 2001-2005



Black: Ep (0-10 J/kg), Blue: OLR (300-150K), Blue: Rain rate (0-0.25 mm)

Season-height section of zonal mean PE at 25.S-2.5N from Sep 2006 to Apr 2008

COSMIC



- QBO westward shear initially, then eastward shear after mid-2007.
- QBO removes gravity waves, especially close to the 0 m/s phase line.

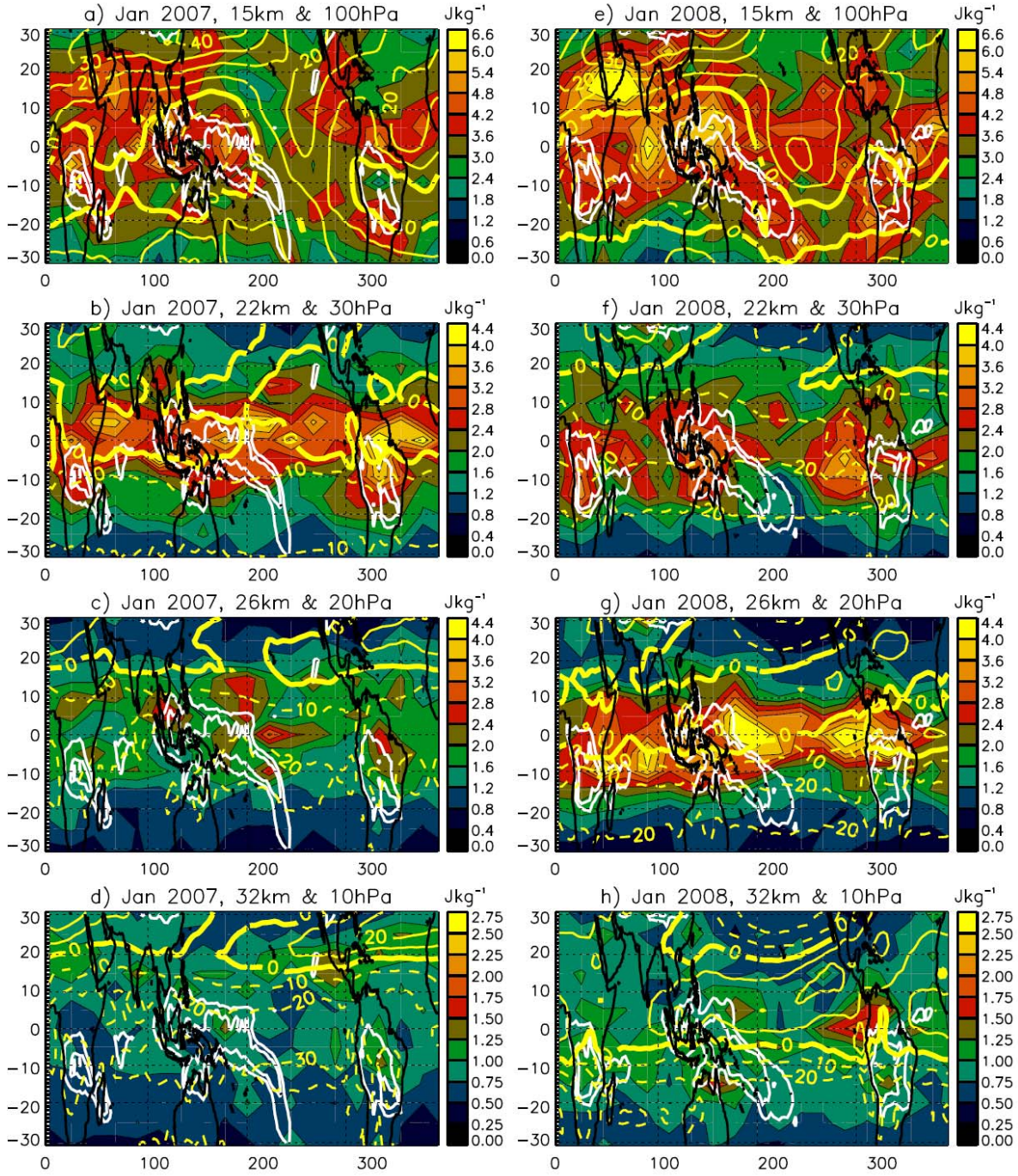
LEFT:

- **Grid size: 20°x5°x7 days,**
- **7km high-passed perturbations from individual profiles, and get PE by integrating vertically over 7km, stepping up by 1km and forward by 1 day.**
- **Mainly meso-scale GWs with minor MRGW and higher speed KW contributions.**

RIGHT

- **Grid size: 20°x5°x one month**
- **Height independent (1km) data by assuming that all wave phases are represented at that particular height**
- **Slower speed KWs but still mainly consists of GWs**

White contours: NCEP zonal mean zonal wind, units m/s, east/westward; solid dashed



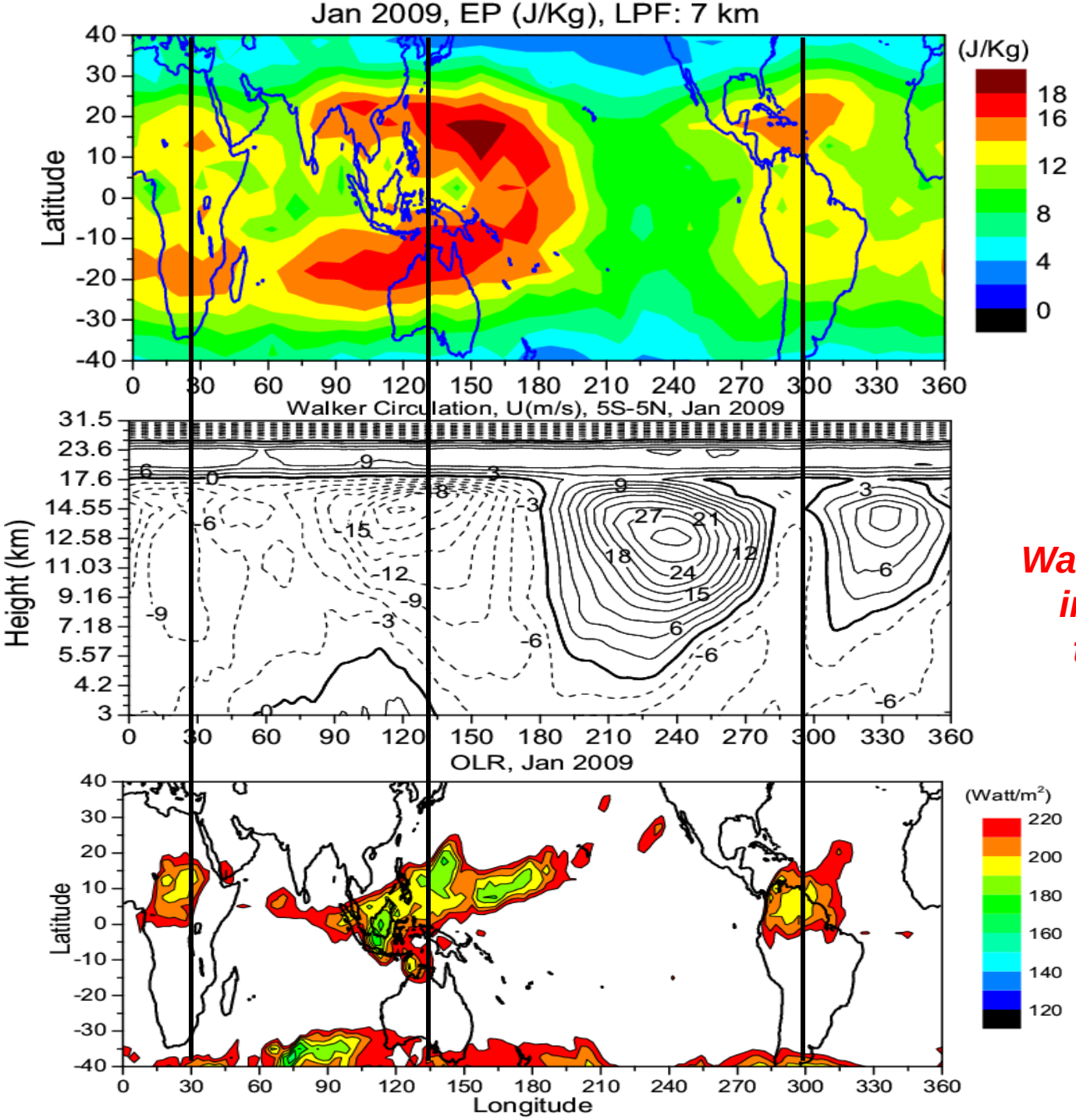
PE (1 km) in Jan 2007/8

PE in January 2007 and 2008 are shown.

Although the convective source distribution is similar for both months, the stratospheric PE is different due to the changes in the QBO structure.

In January 2007, the QBO is in its westward shear phase with the 0 m/s line at 24 km, while one year later, the QBO is in its eastward shear phase with the 0 m/s line at 25 km.

COSMIC

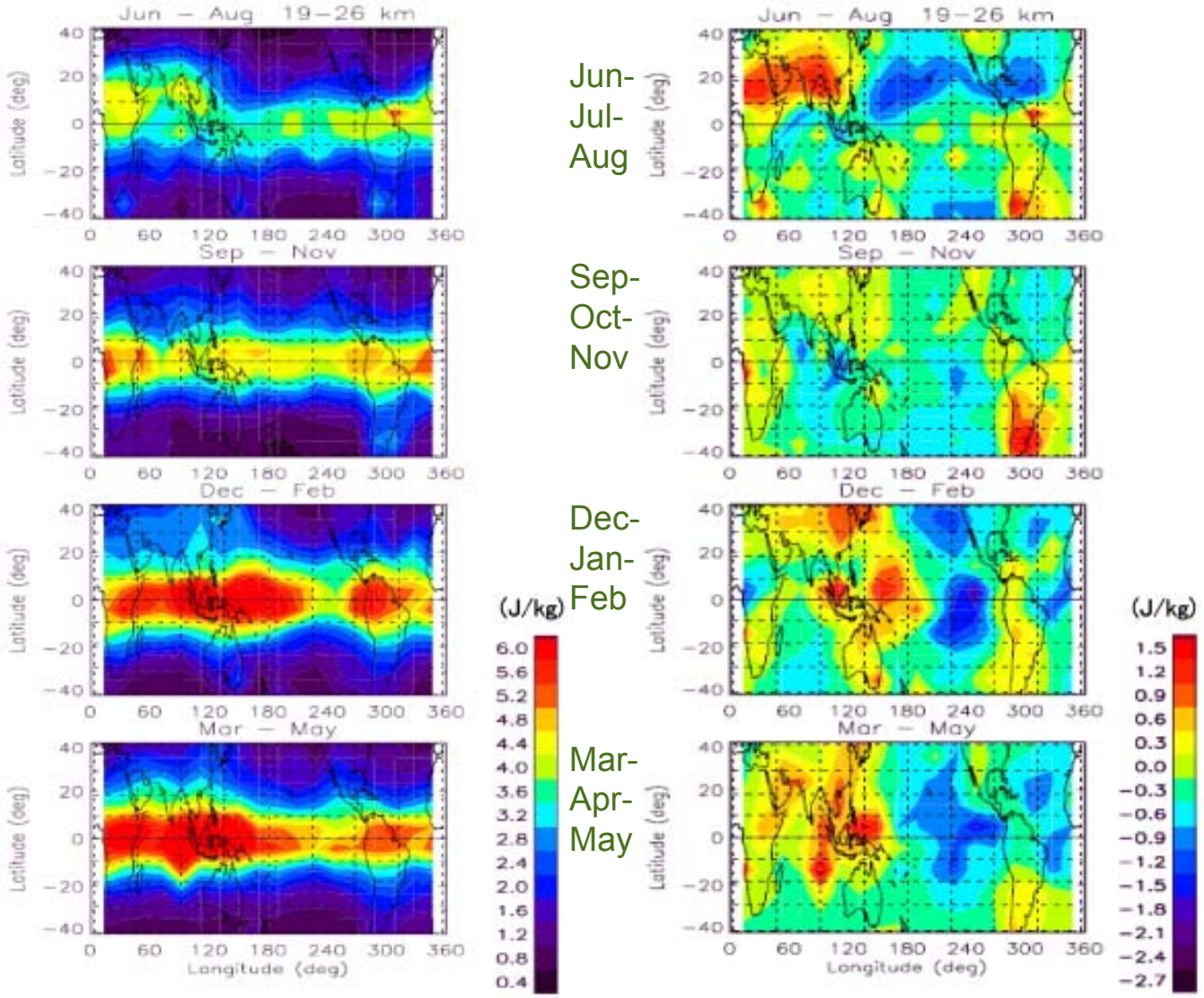


Walker circulation in the tropical troposphere

CHAMP

(a) Longitude-latitude distribution of *Ep at 19–26 km by averaging Ep in 2001–2006.*

(b) *In each year residual of Ep from global average in (a) is calculated, then, they are averaged for 5 years*



Results in (a) indicate a climatological pattern of the temperature disturbances in the sratosphere, including Kelvin waves, GW, etc.

While, (b) shows regional wave activity, esp. GW is dominant

GW energy seems to be larger over the Asian monsoon region, Indonesia-western Pacific by convection, and Sotuth America (Andes) due to orographic waves

SUMMARY

- GPS RO temperature profiles with a superior height resolution enabled us to analyse the global distribution of meso-scale temperature perturbations due to atmospheric gravity waves (GW) in the stratosphere. COSMIC data with high density have resulted in a more detailed understanding of the GW activity on shorter time intervals (5-d) than previously possible.

- Global and regional characteristics of gravity waves are studied.
  - ✓ Mid-latitudes in northern winter; GW energy in the Asian region is mostly due to the sub-tropical jet, and some additional effects by mountain waves above Canadian Rockies, Japan, and Scandinavia.
  - ✓ In the polar regions, the GW energy related to the behaviour of stratospheric polar vortex, esp. Antarctic springtime decay and SSW. Large GW energy above various mountainous regions in the polar and sub-polar regions due to orographically generated waves.
  - ✓ Tropics; Convectively generated GW is evident, showing regional and hemispheric scale changes which are related to the convective source as well as background wind conditions (QBO, Walker circulation) .


Thank you