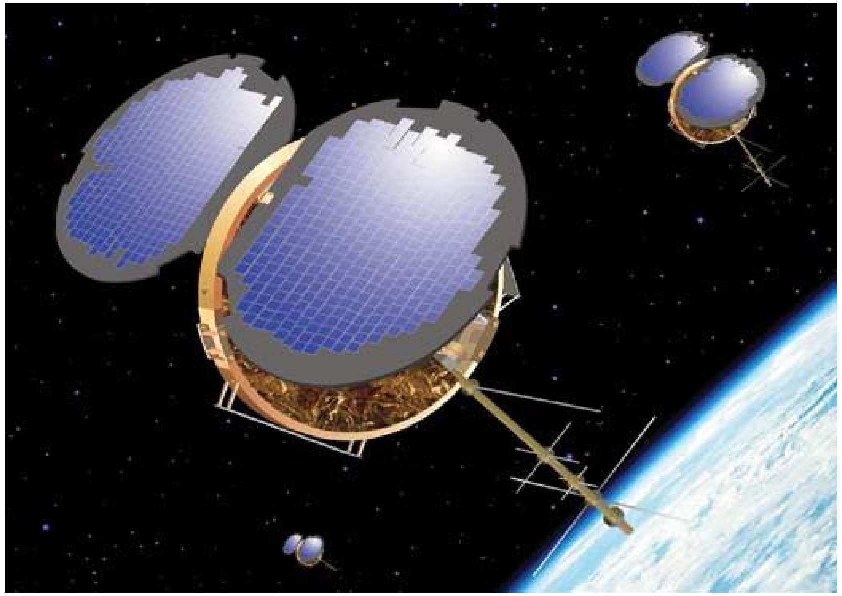
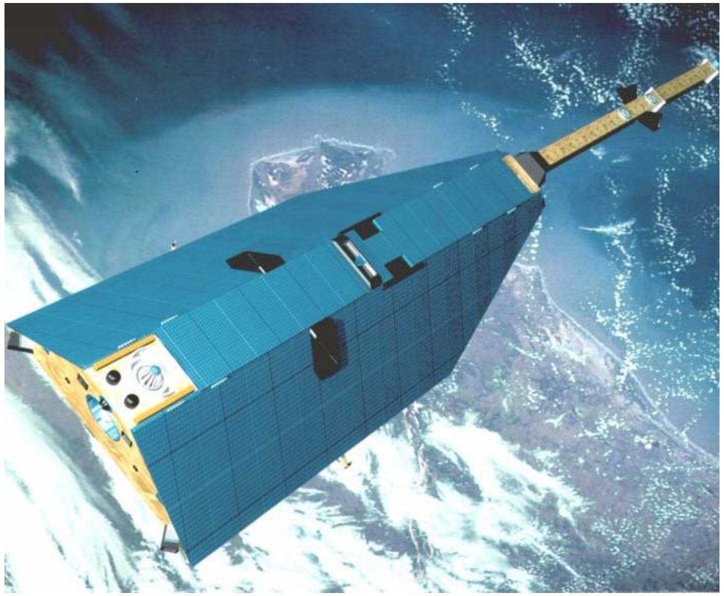
Global and Regional Scale Studies of Stratospheric Gravity Wave Energy using COSMIC and CHAMP





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RISH, Kyoto University, Japan

Presentation Outline

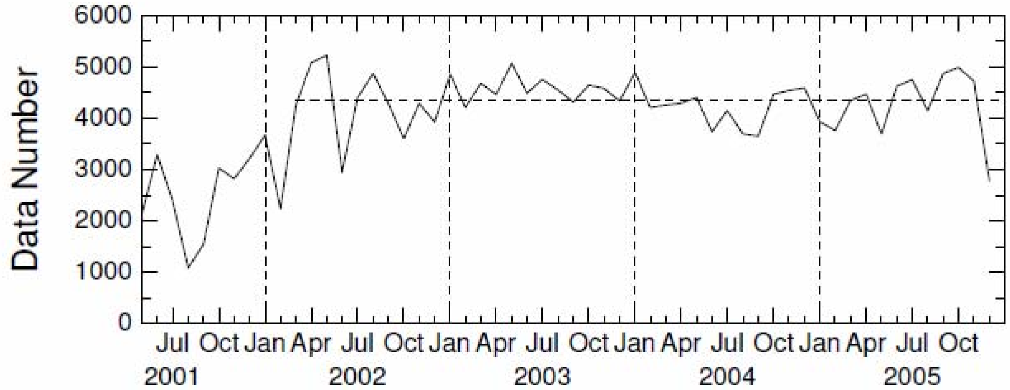
- Background: scientific reasons for using GPS-RO to study atmosphere
- COSMIC Northern Hemisphere mountain / jet-stream wave activity
- COSMIC Antarctic 2006/07 observations
- CHAMP five year polar climatology of wave generation, propagation and intermittency
- COSMIC tropical analysis
- Conclusions

Background

- GPS-RO provides a valuable tool for studying atmospheric physics: the coupling between troposphere and stratosphere, wave generation and propagation and variability in space and time. Also able to study the ionosphere
- GPS-RO satellites provide global coverage which are not possible with ground-based observations due to oceans, inhospitable terrain etc.
- Gravity (buoyancy) waves with horizontal scales greater than several hundred km and vertical scales approximately between 2 – 10km, periods longer than ~ few days can be studied (note this observational filter effect is different for other satellites and some ground-based instruments)
- Studying the derived waves and their energy is important to determine atmospheric coupling and energy transport and distribution

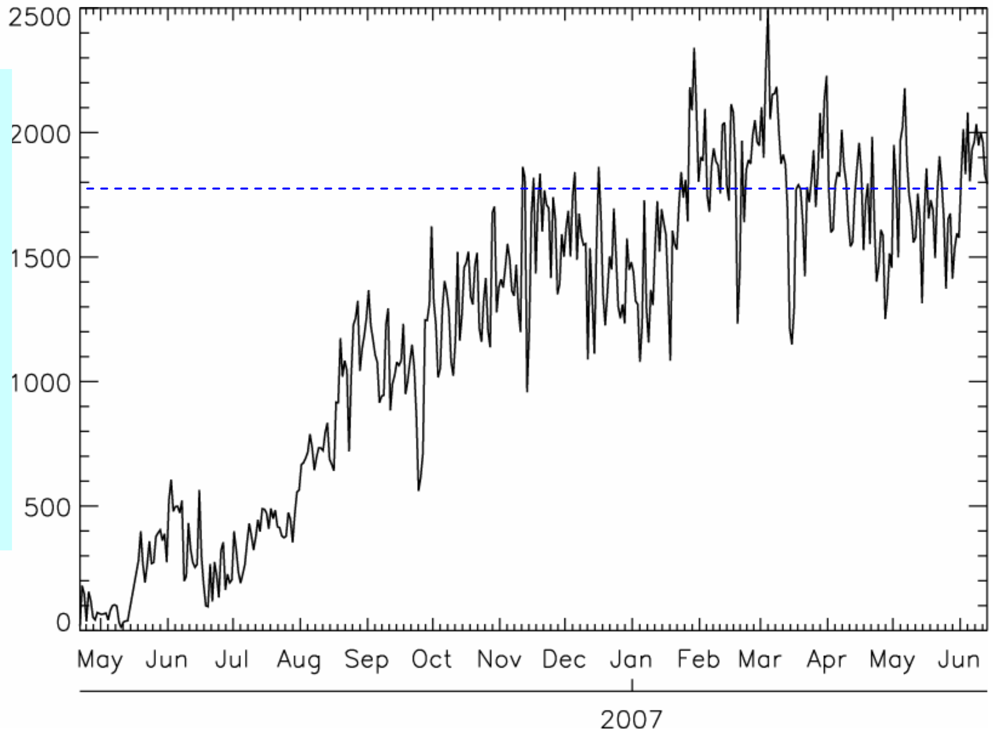
Number of GPS RO data with CHAMP (top) and FORMOSAT-3/COSMIC (bottom)

CHAMP
One GPS RO antenna



4,500/month =150/day

COSMIC :
6 LEO satellites
2 GPS RO antennas
(It is expected to obtain 12 times larger data than CHAMP)



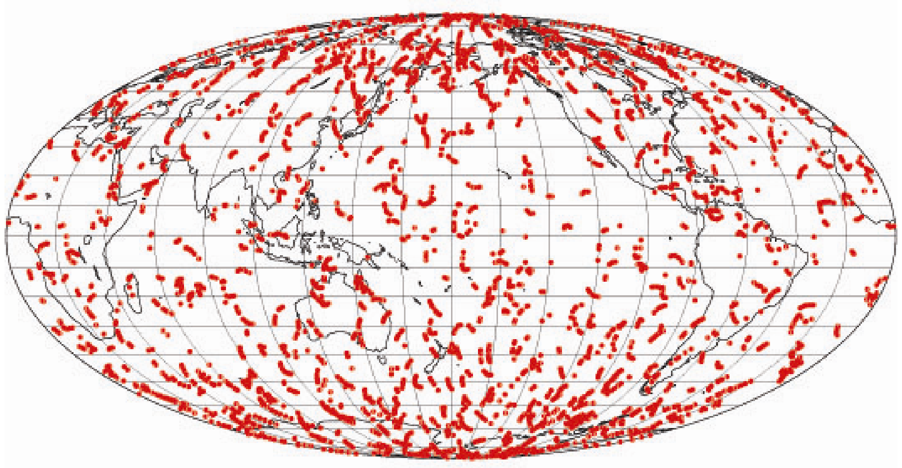
2,000/day

CHAMP / COSMIC Occultations

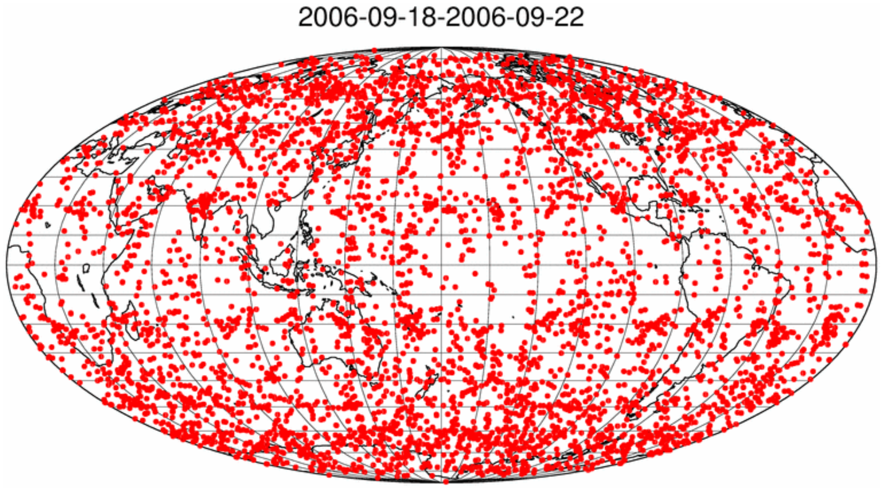
Climatological study (monthly mean) with CHAMP GPS RO data from May 2001- Dec 2005

Preliminary case studies with COSMIC data after September 2007, with a better time and spatial resolution

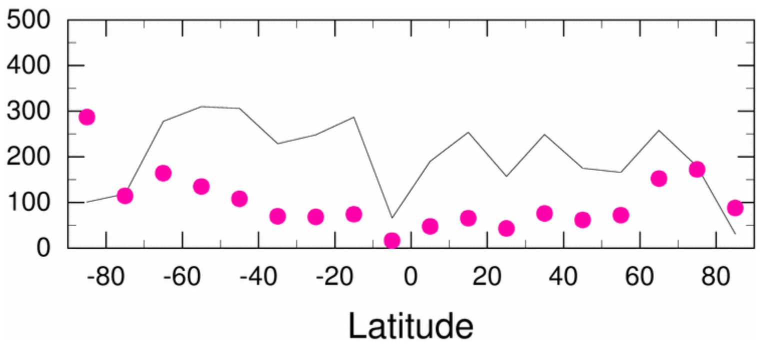
Distribution of the CHAMP GPS RO data in October 2002

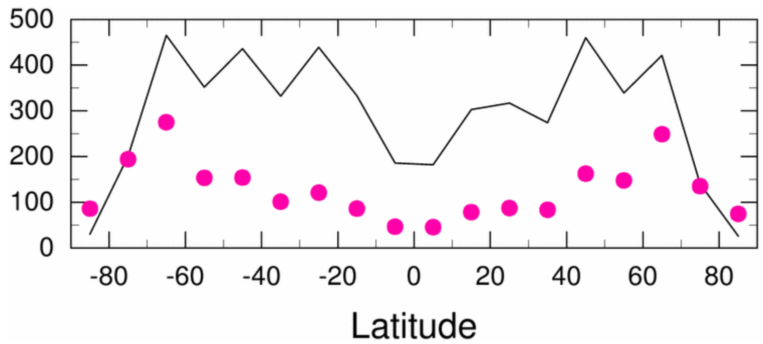


COSMIC GPS RO data in 5 days on 18–22 September 2006

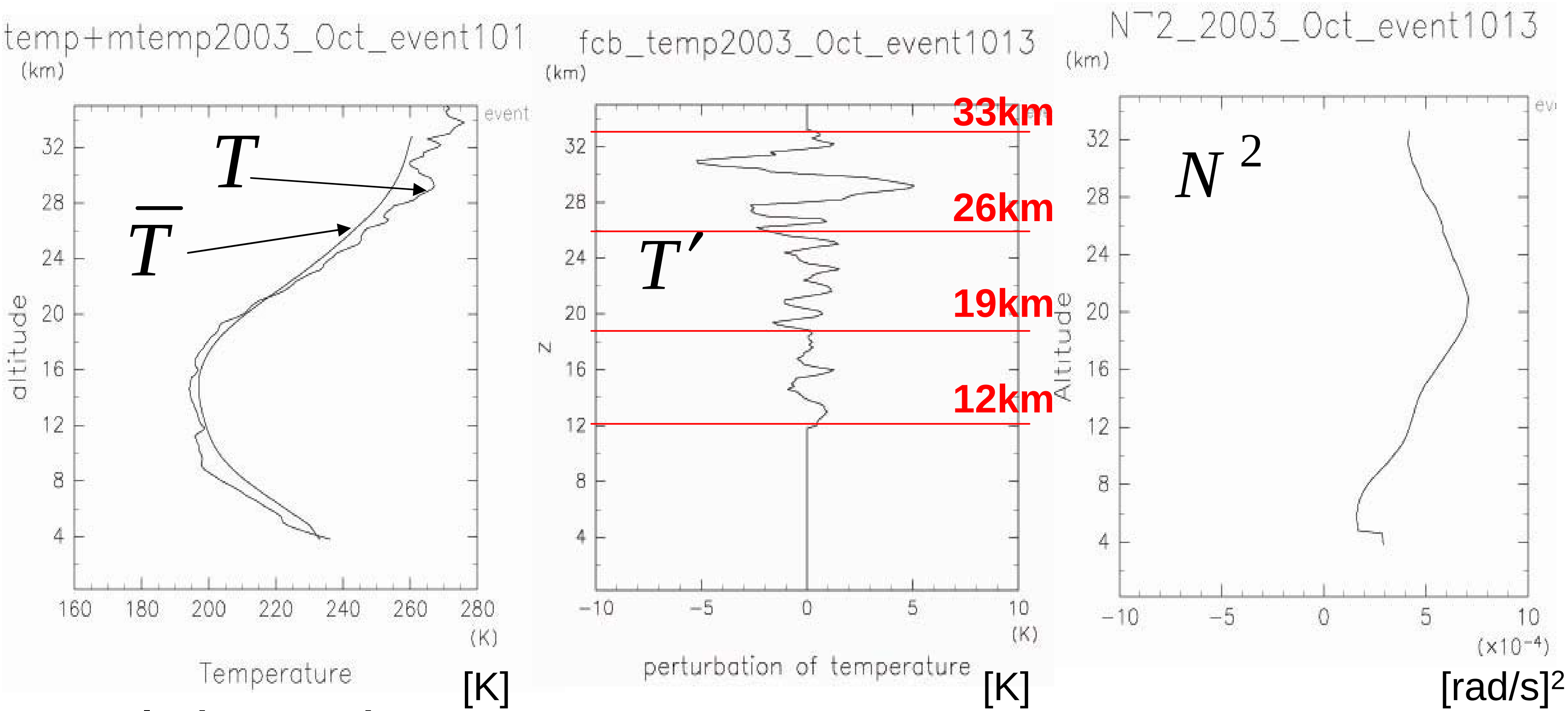


line: number of GPS data in each 10 deg, red dot: data rate normalized by the area





Temperature profile with CHAMP GPS RO at 76.9S, 92.9E on Oct 11, 2003



Analysis procedure:

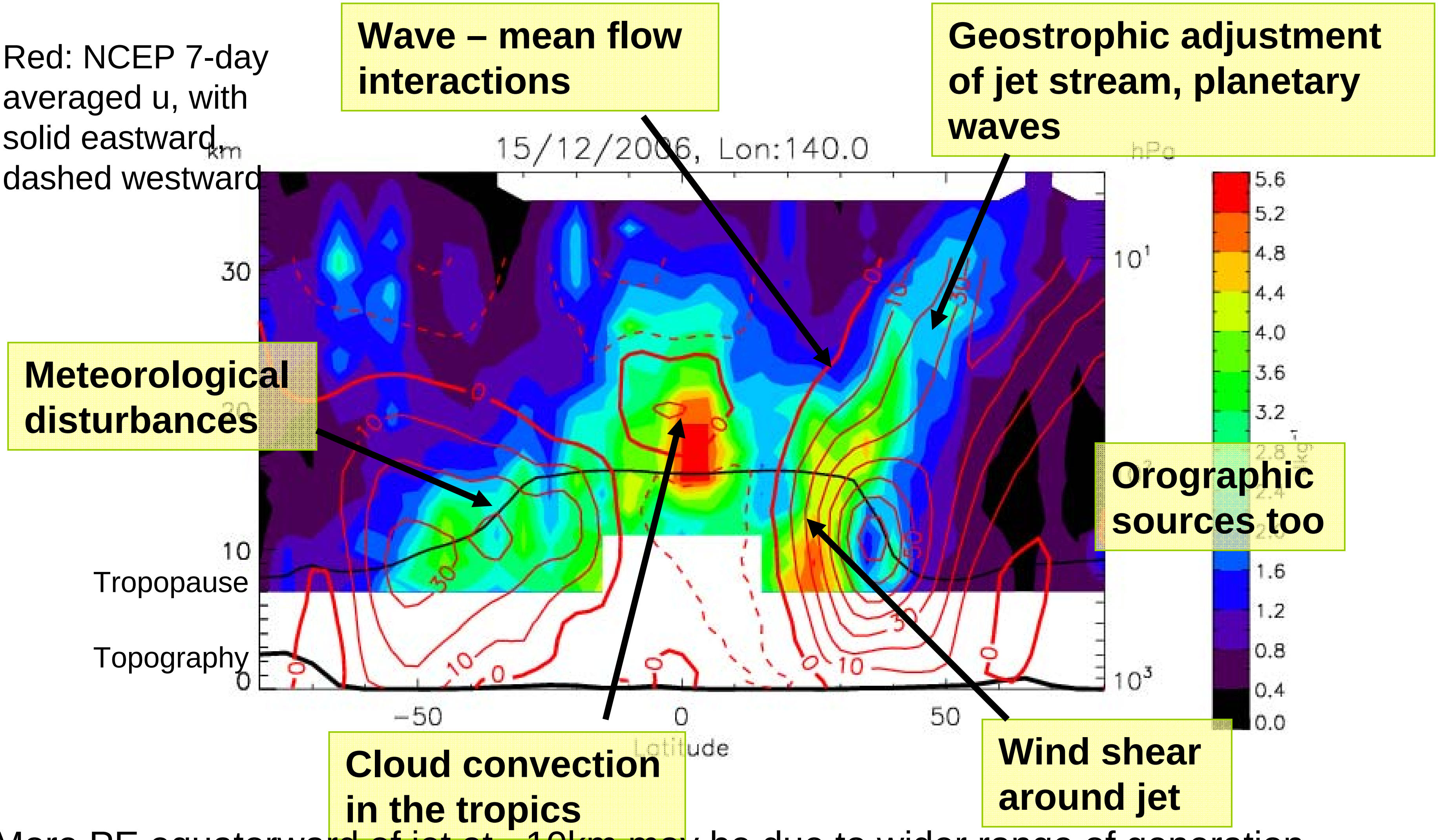
(1) Obtain all available GPS RO data in individual cell in one month (7 days for COSMIC), and calculate the mean *T* profile, then apply a low-pass filter with a cutoff at 7km. Then, the mean *T* profile (T_0) is determined.

(2) Calculate $T' = T - T_0$ for individual GPS RO profiles, and apply FFT at 12-33 km along altitude, then, extract the fluctuating components (T') with vertical wave lengths shorter than 7km. Finally, Ep is determined at 12-19km, 19-26km and 26-33km by integrating the spectral density.

COSMIC Northern Hemisphere Mid-Latitude Winter 06/07 Wave Sources and Propagation

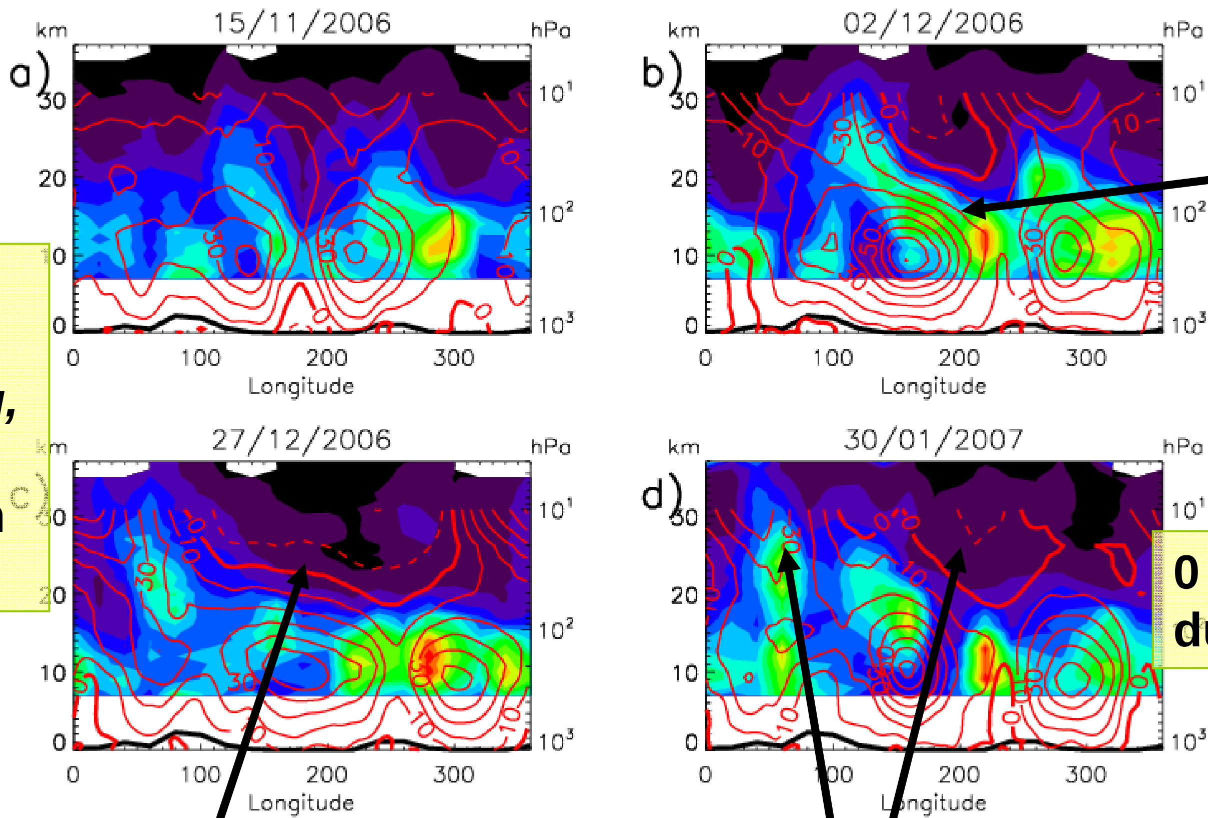
- COSMIC data grid size: 20˚ x 5˚ x 7 days, stepped forward by one day
- Allows study of much shorter duration events than CHAMP
- PE uncertainties: ~20% per grid, but ~5% per seasonal average
- Observe wave activity related to geostrophic adjustment of tropospheric sub-tropical jet
- See the stratospheric interaction between gravity waves and planetary waves
- Find that while some PE is probably due to mountain waves, most is related to geostrophic adjustment, with very large PE over Japan

COSMIC: Sub-tropical jet, 140E, 12 – 18 Dec 2006



More PE equatorward of jet at ~10km may be due to wider range of generation frequencies. Note low PE at jet core. Interaction between waves and background mean flow (NH). Large PE extends upward and poleward toward the polar night jet.

Stratospheric Gravity Wave – Planetary Wave Interaction, 40N



PWs: large scale waves which affect *u*, *v*, *T* & are most active in winter

Jet-stream generation

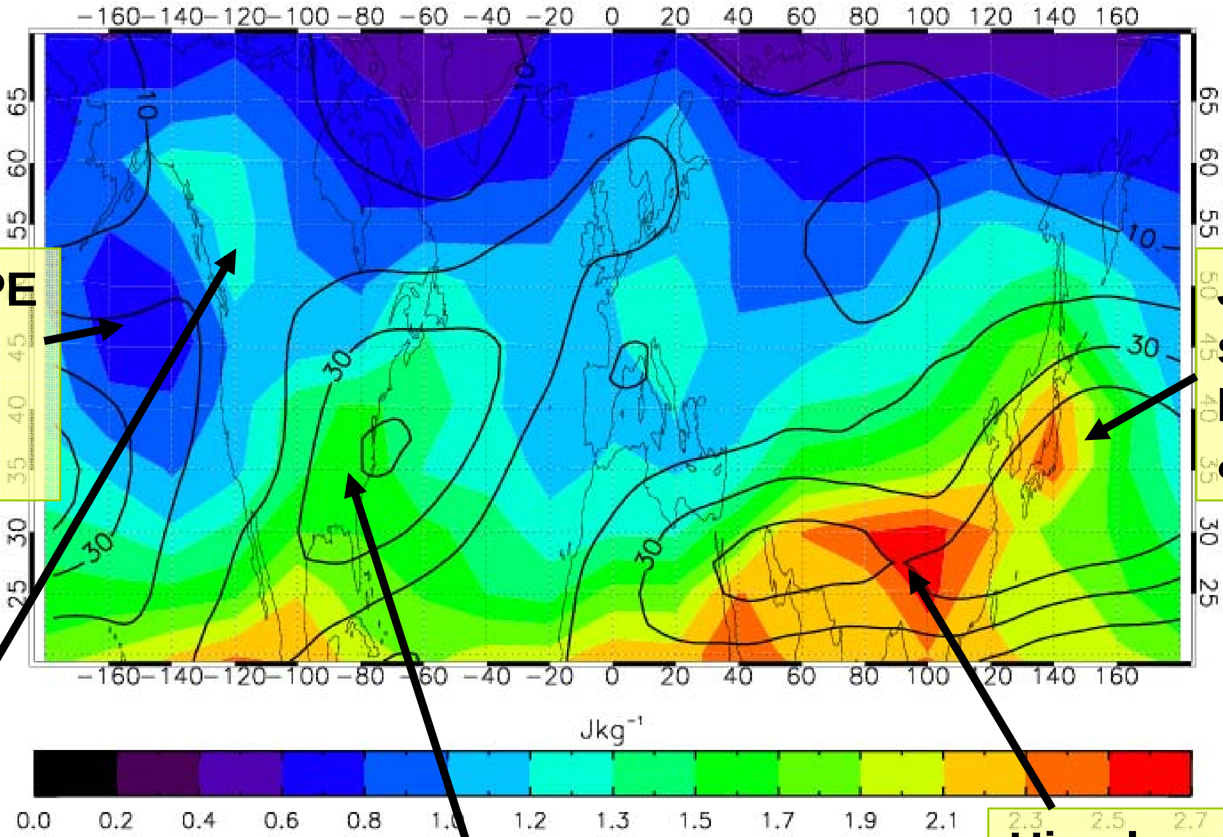
0 ms^{-1} changes during winter

Consistent westward winds above the Pacific – low PE

Stratospheric PE affected by background – critical level filtering

DJF 06/07 Winter Mean PE at 17 – 23km

Black contours:
500 – 100hPa
DJF NCEP *u*



Low Pacific PE due to lower-level critical wave filtering

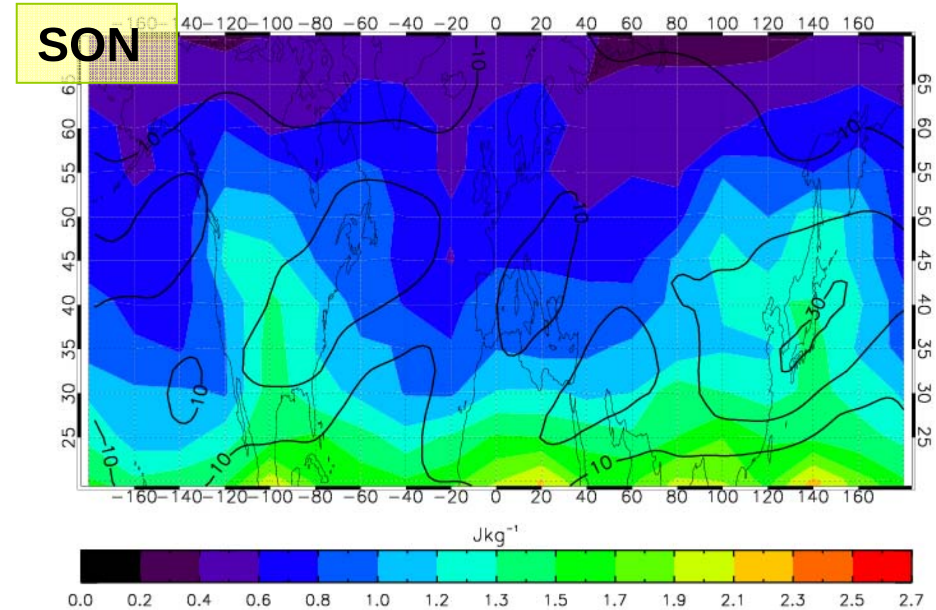
Japan – separate large PE: strong jet & orography

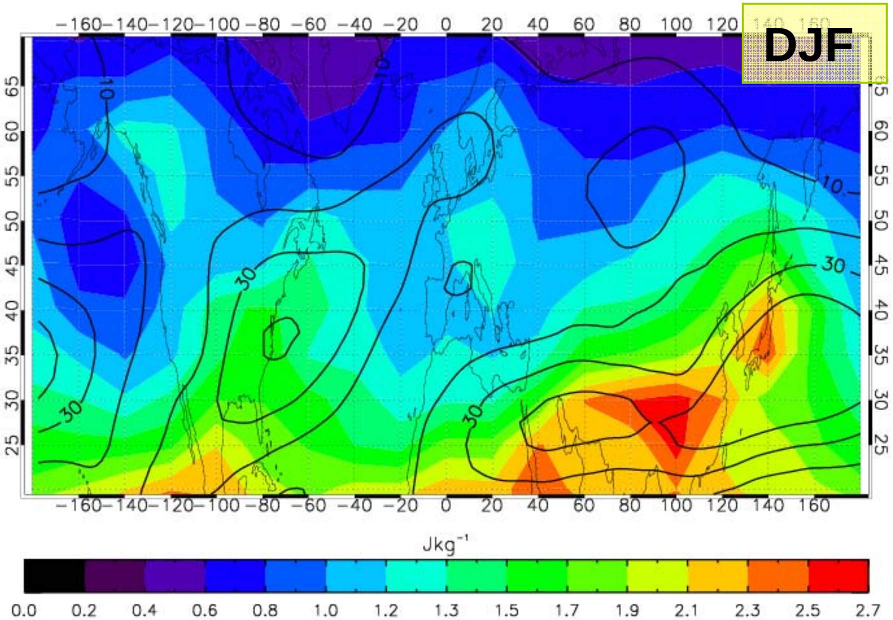
Canadian Rockies and European Alps have large PE

Large Eastern USA PE associated with jet

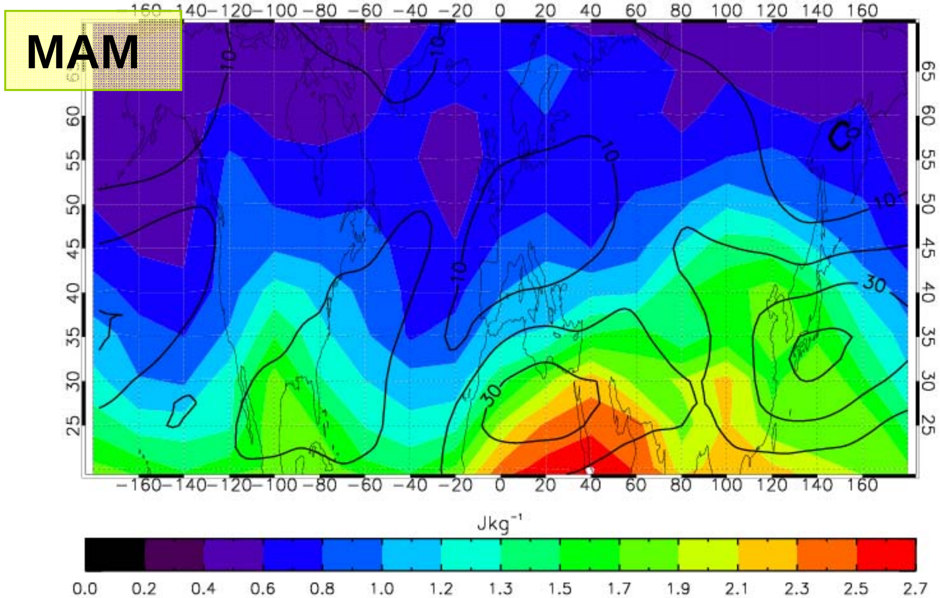
Himalayas & Tibet have large PE – some orographic effects but also jet stream

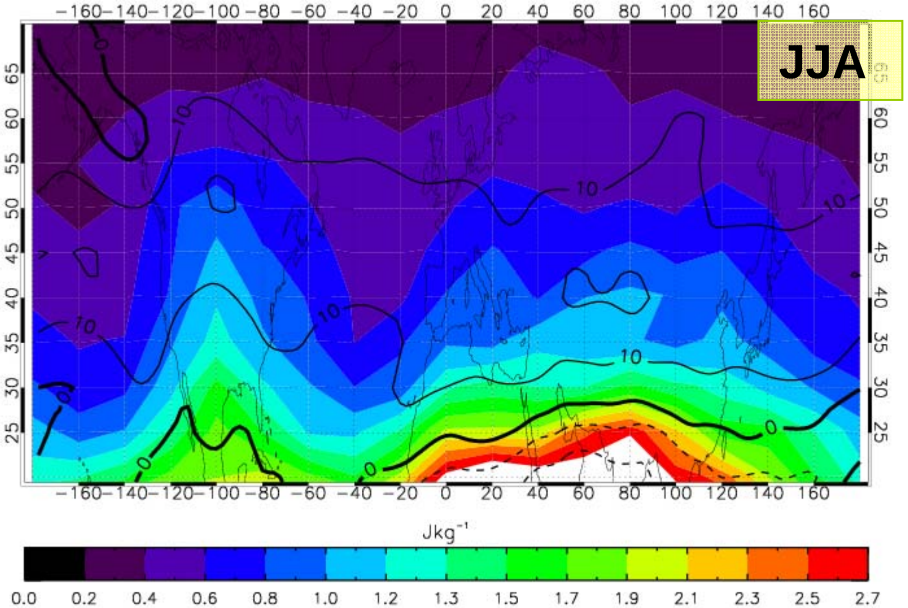
Note that the large Japanese PE was not reported by Tsuda et al (2000) or Ratnam et al (2004) because the previous data were temporally too coarse, but radiosondes have observed anomalously large Japanese PE (e.g. Ogino et al 1999).





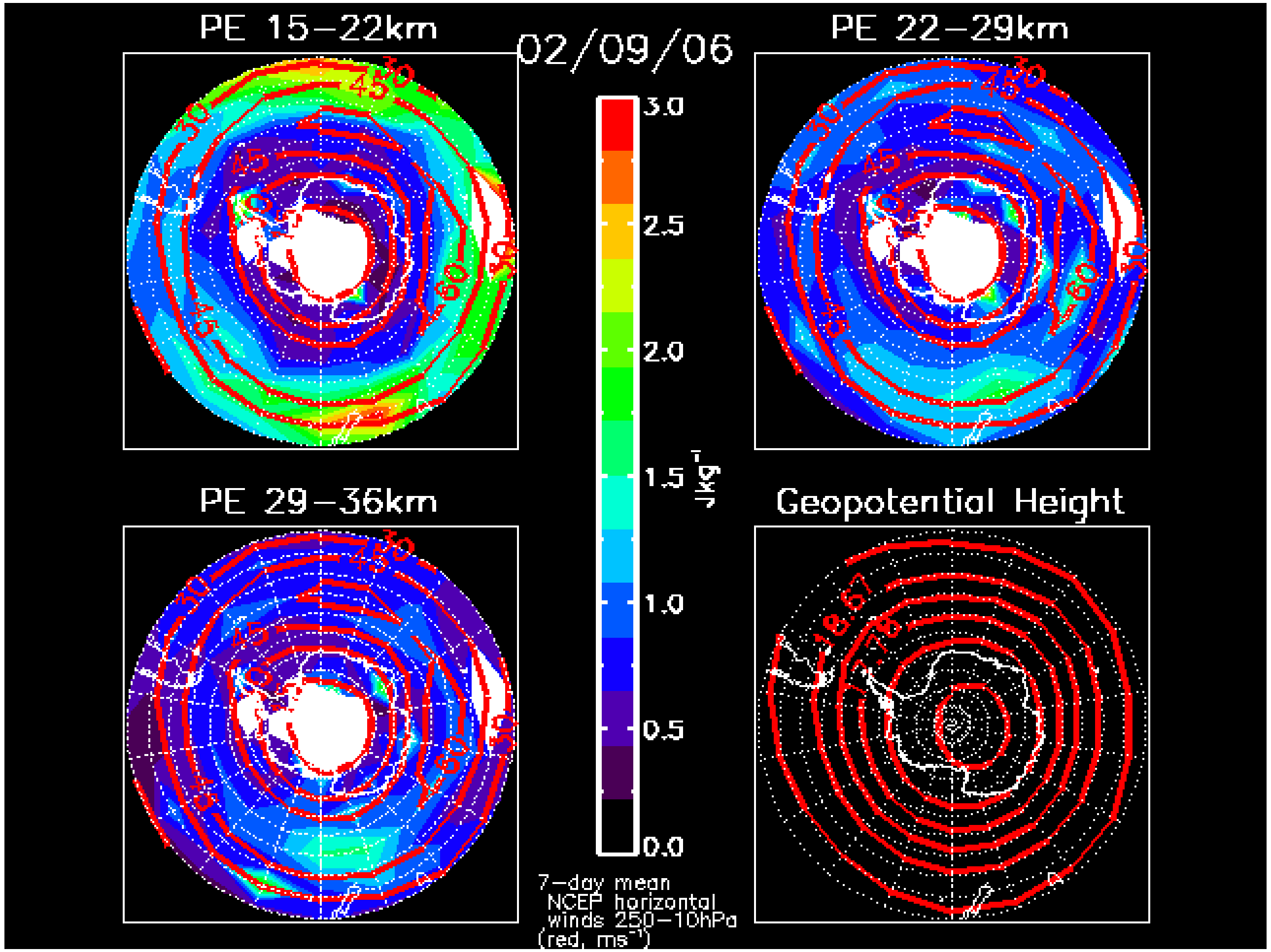
- Relatively large PE over Japan observed in SON, DJF, MAM, although strongest in winter
- Peak in PE observed above Rocky Mountains but in DJF also have large geostrophic source
- Himalayan peak clearest in DJF, MAM





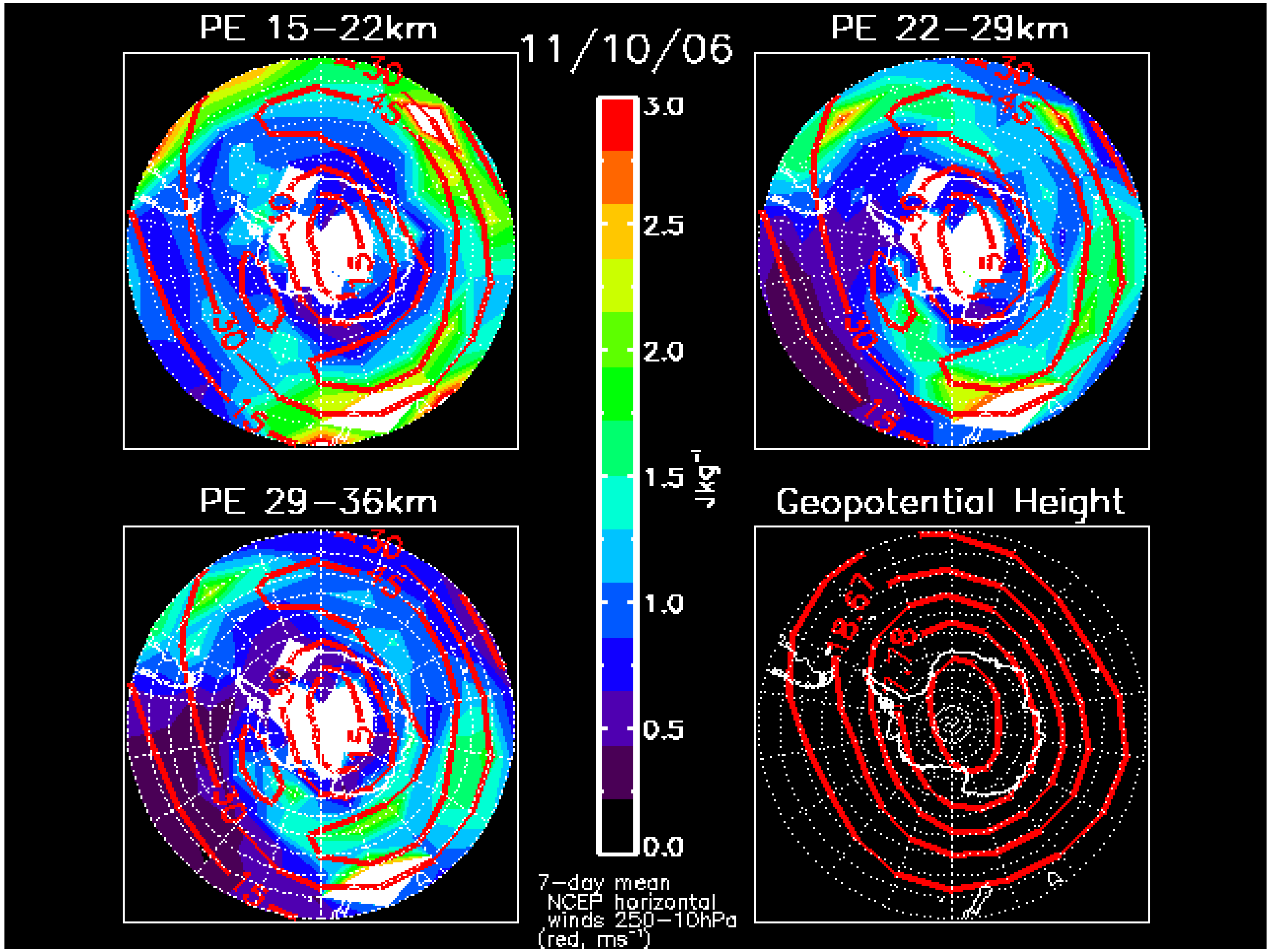
COSMIC Antarctic Polar Jet and Orographic Wave Generation – Preliminary Results

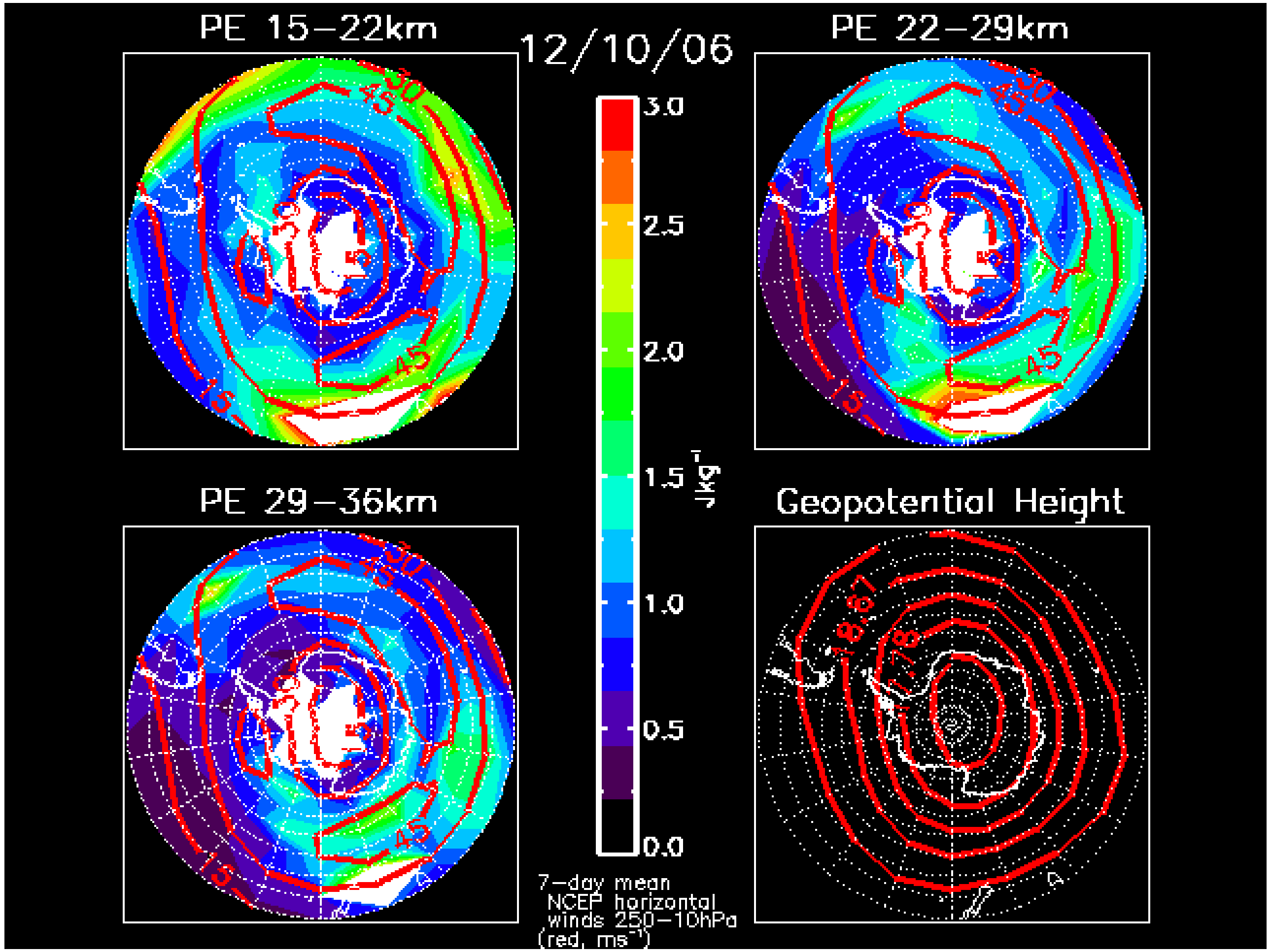
- Complementary to [Hei et al. JGR 2007 – in review] CHAMP five year climatological study but now have higher temporal resolution (7 days, stepped forward by one day), allowing the study of smaller scale phenomena
- Rotation of large PE with movement of polar night jet around the continent
- Preliminary results show large stratospheric PE associated with breakdown of polar jet in spring, but also large wave emission in winter – geostrophic adjustment
- Possible orographic generation of gravity waves by the Antarctic Peninsula during winter (source not yet confirmed)


PE 15-22km
02/09/06
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)

Movie

Enhancement of gravity waves near the edge of polar vortex – October 06




PE 15–22km
12/10/06
PE 22–29km
PE 29–36km
Geopotential Height
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2.5
2.0
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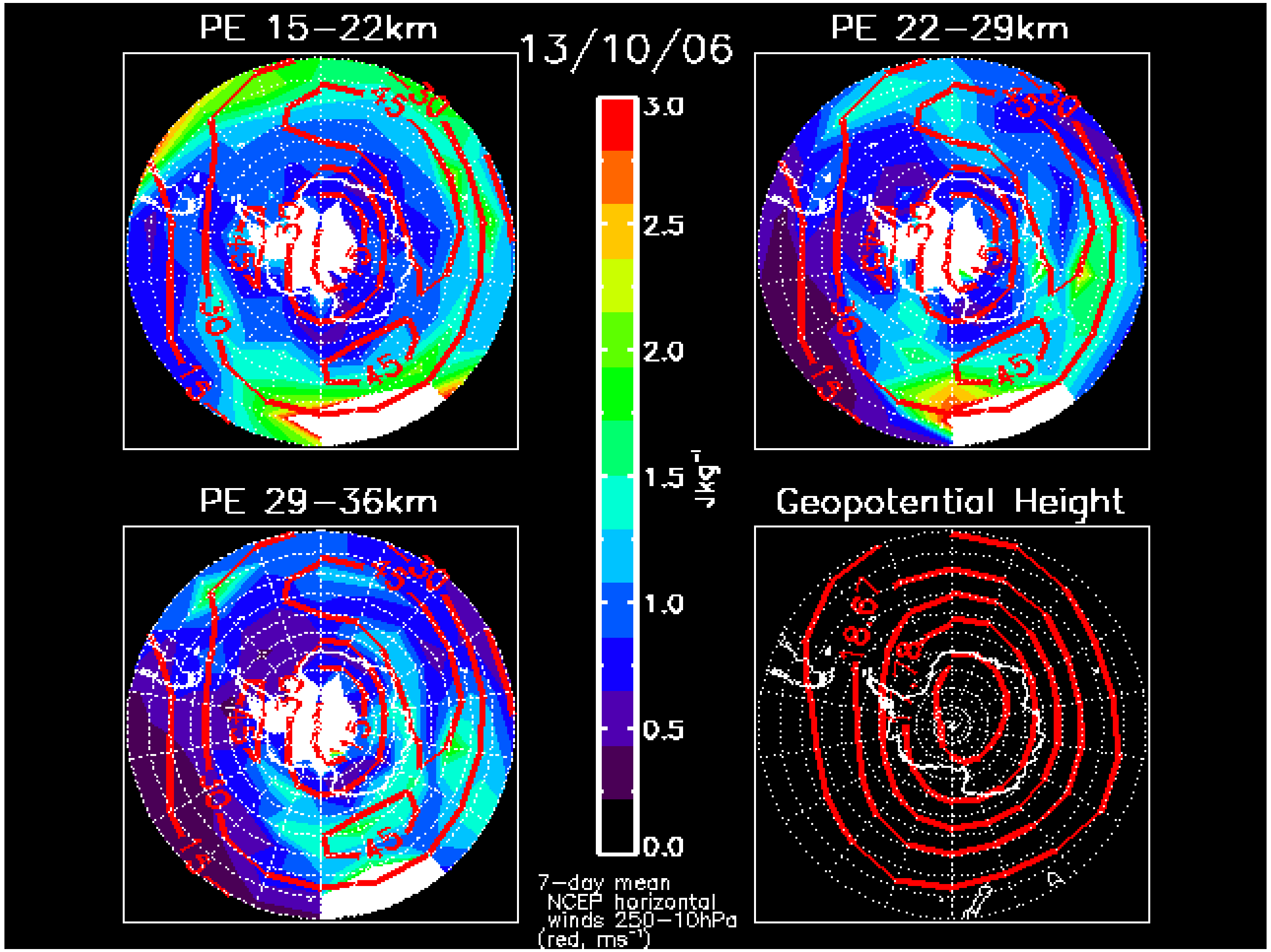
0.0
Jkg⁻¹
7–day mean
NCEP horizontal
winds 250–10hPa
(red, ms⁻¹)



PE 15-22km
13/10/06
PE 22-29km
PE 29-36km
Geopotential Height
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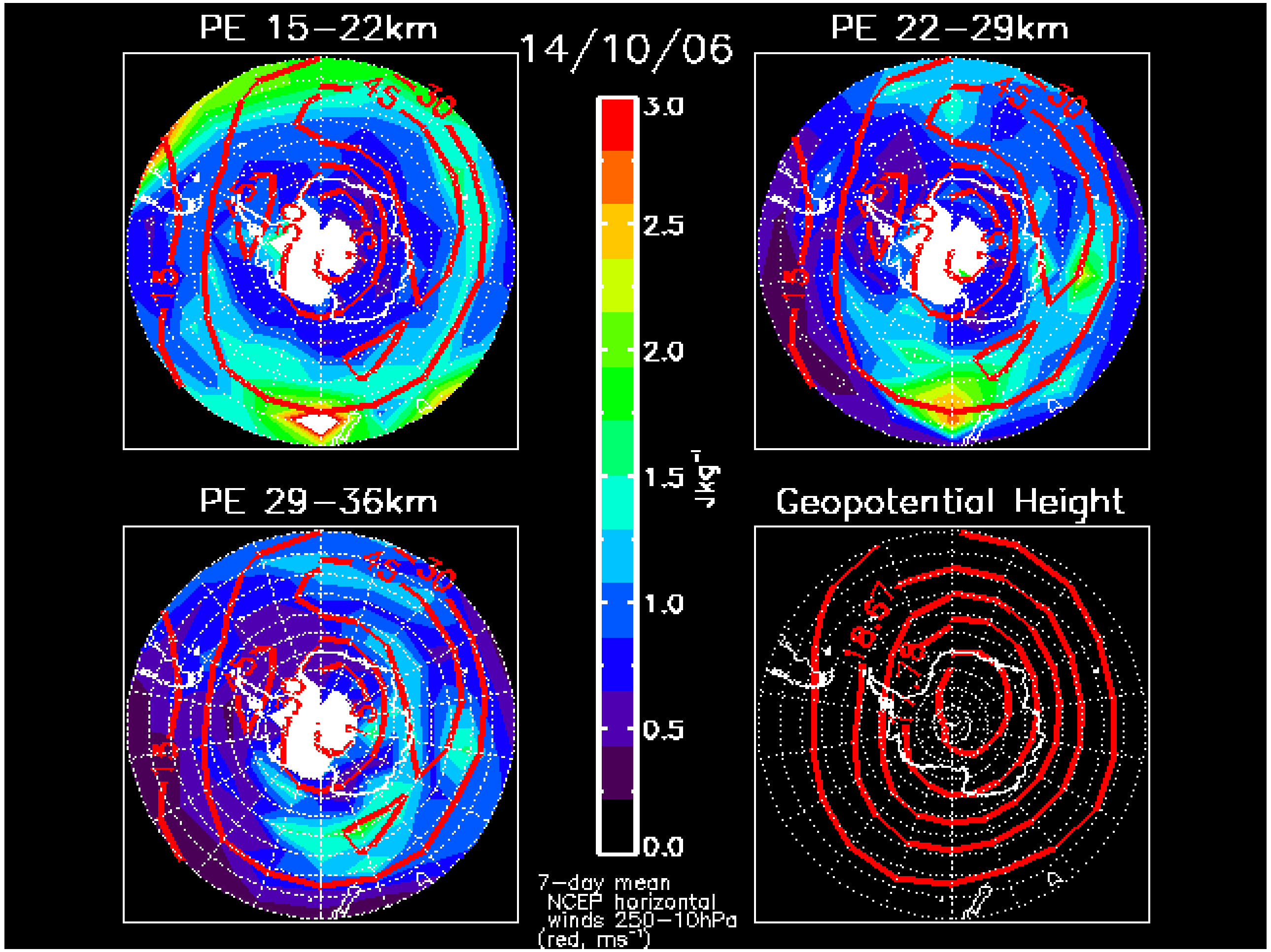
PE 15–22km
14/10/06
PE 22–29km
PE 29–36km
Geopotential Height
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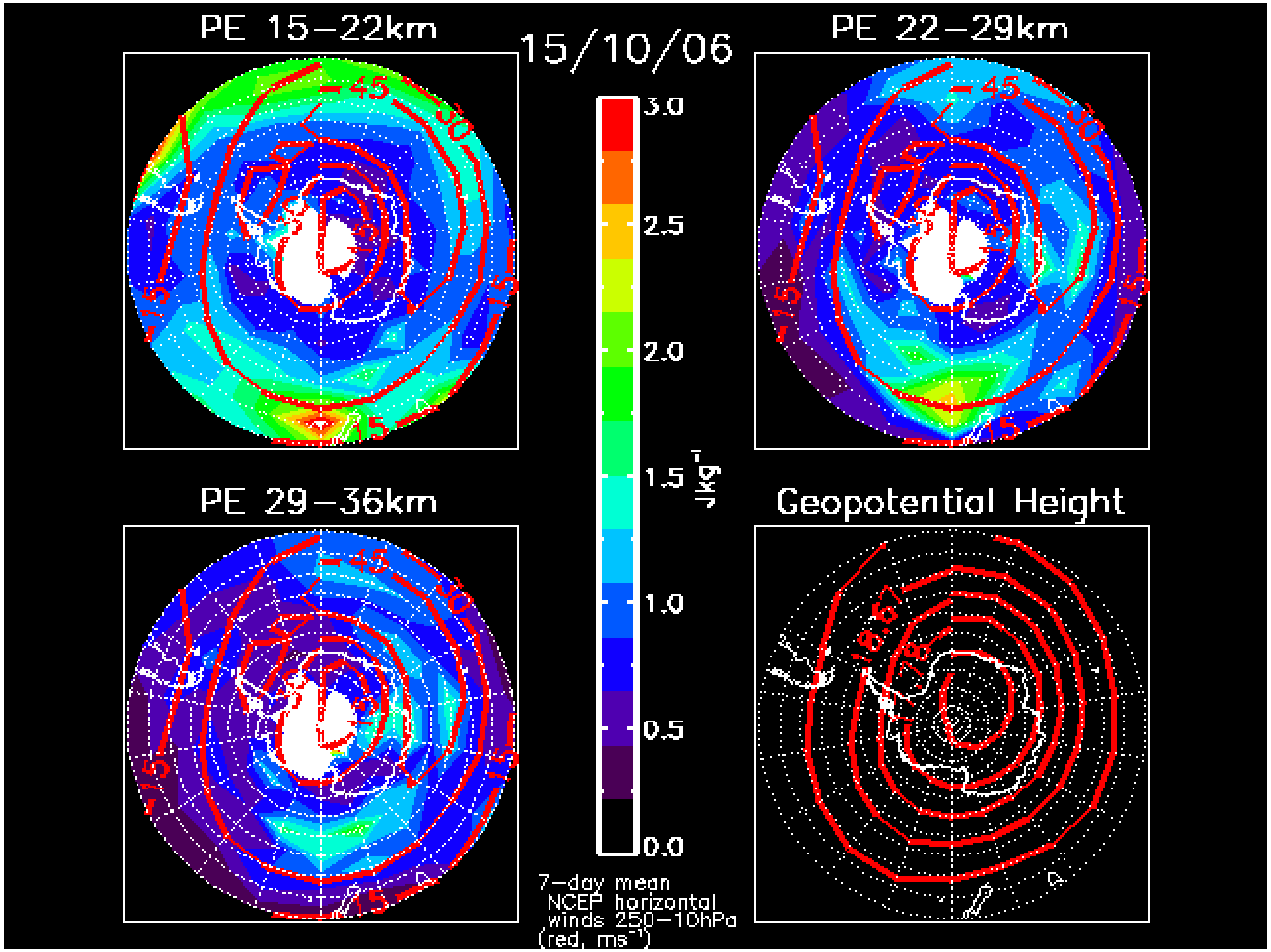

PE 15–22km
15/10/06
PE 22–29km
PE 29–36km
Geopotential Height
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2.5
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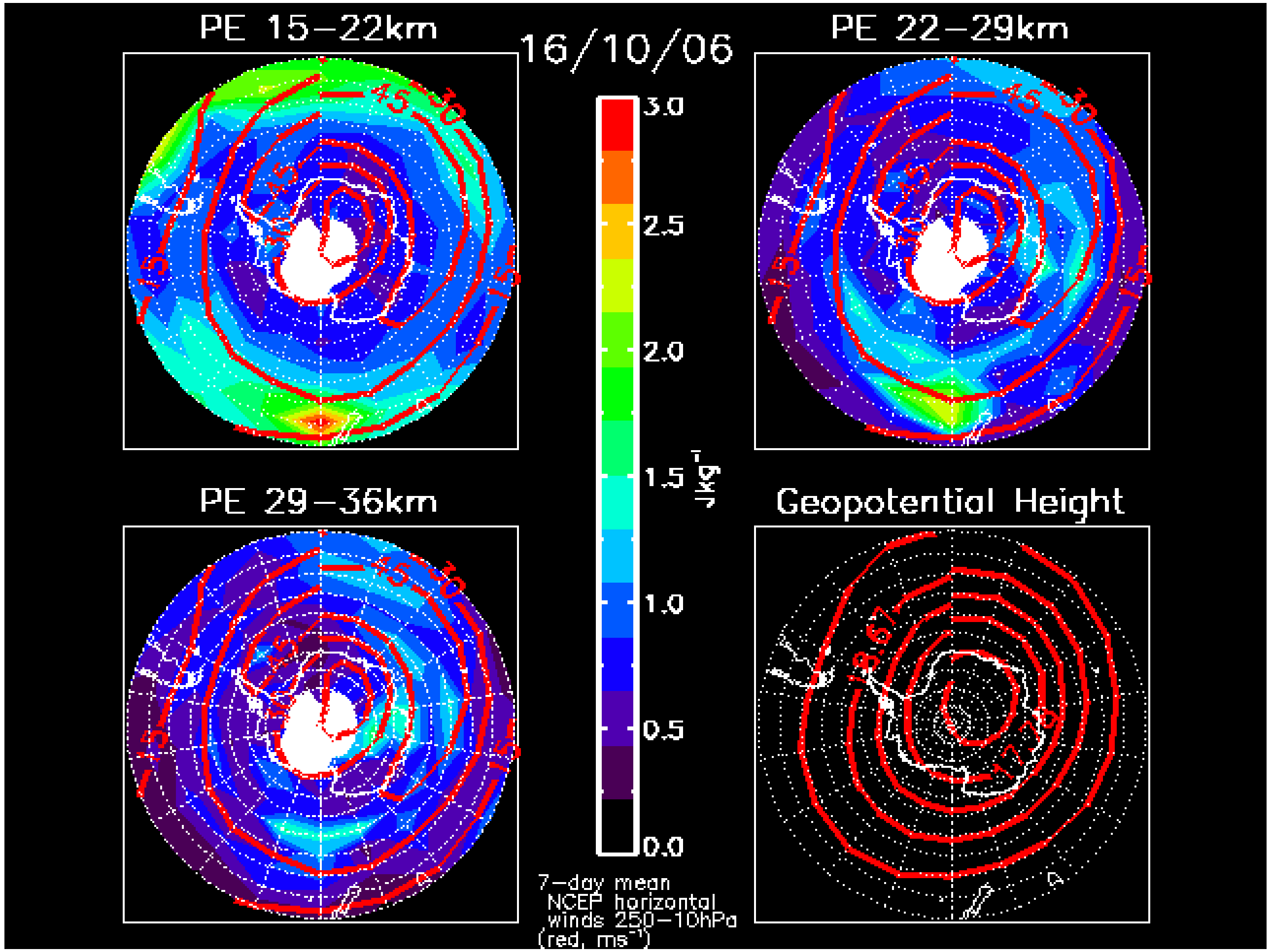

PE 15-22km
16/10/06
PE 22-29km
PE 29-36km
Geopotential Height
3.0
2.5
2.0
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0.5
0.0
Jkg⁻¹
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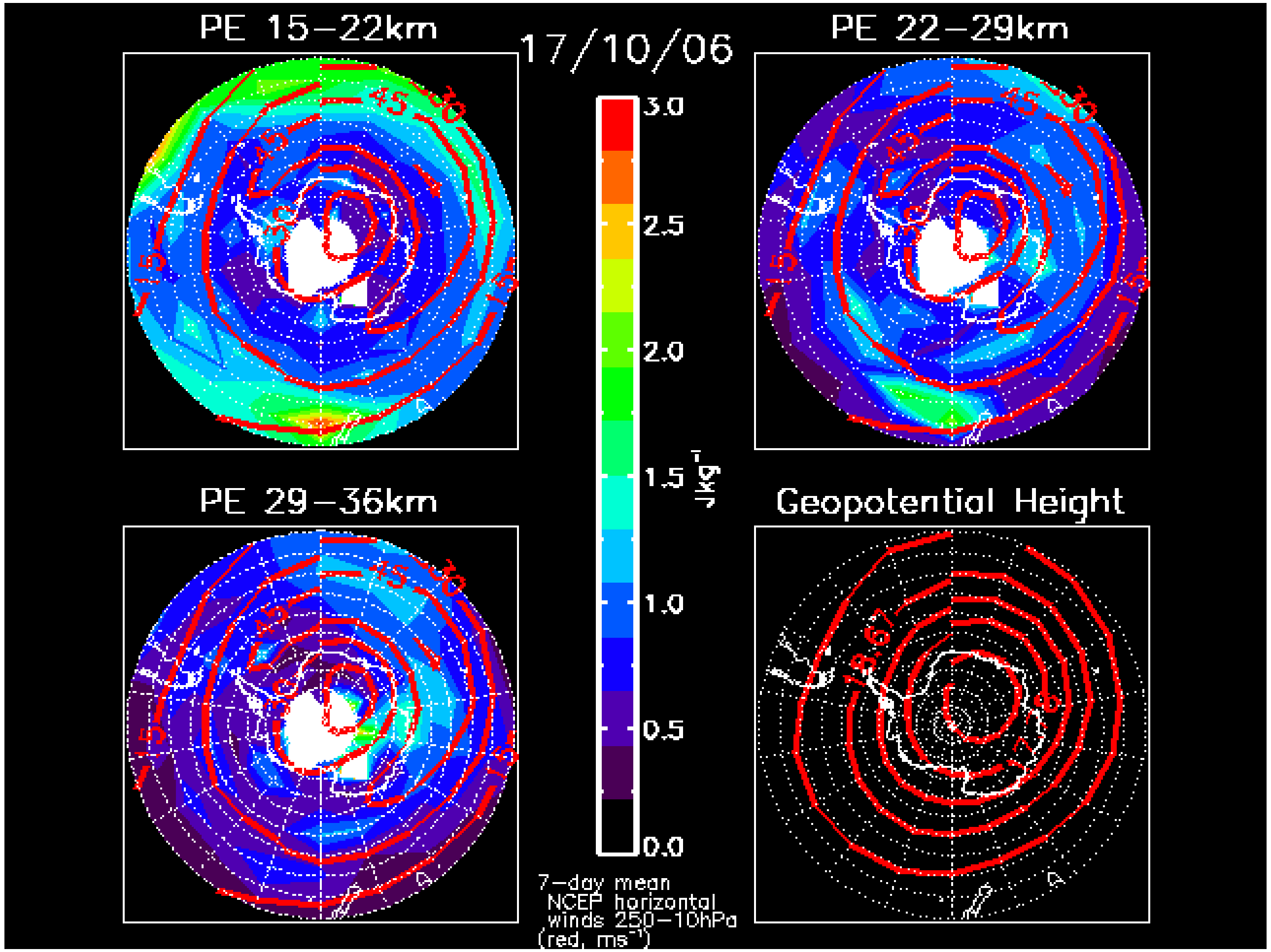
PE 15–22km
17/10/06
PE 22–29km
PE 29–36km
Geopotential Height
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1.0
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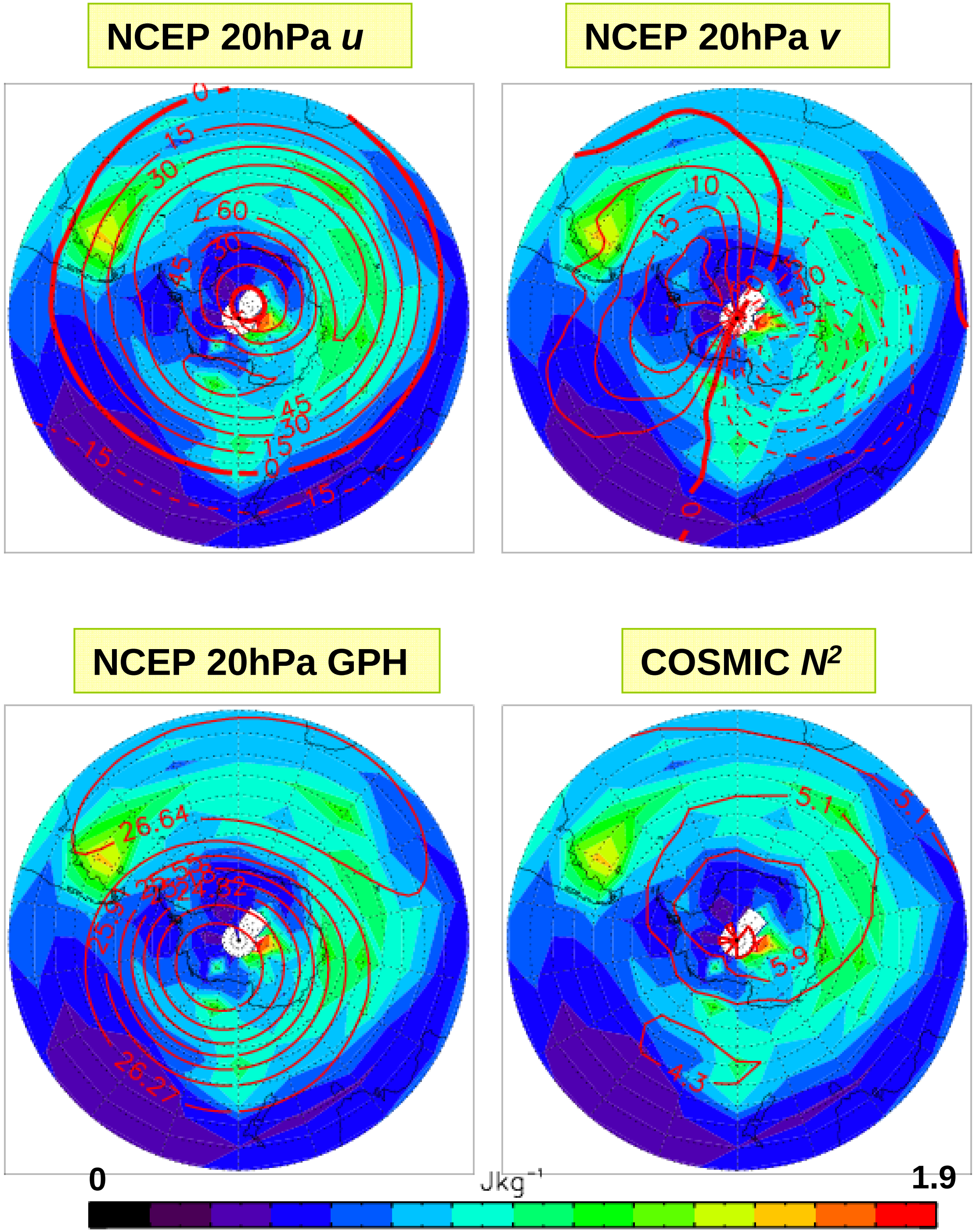
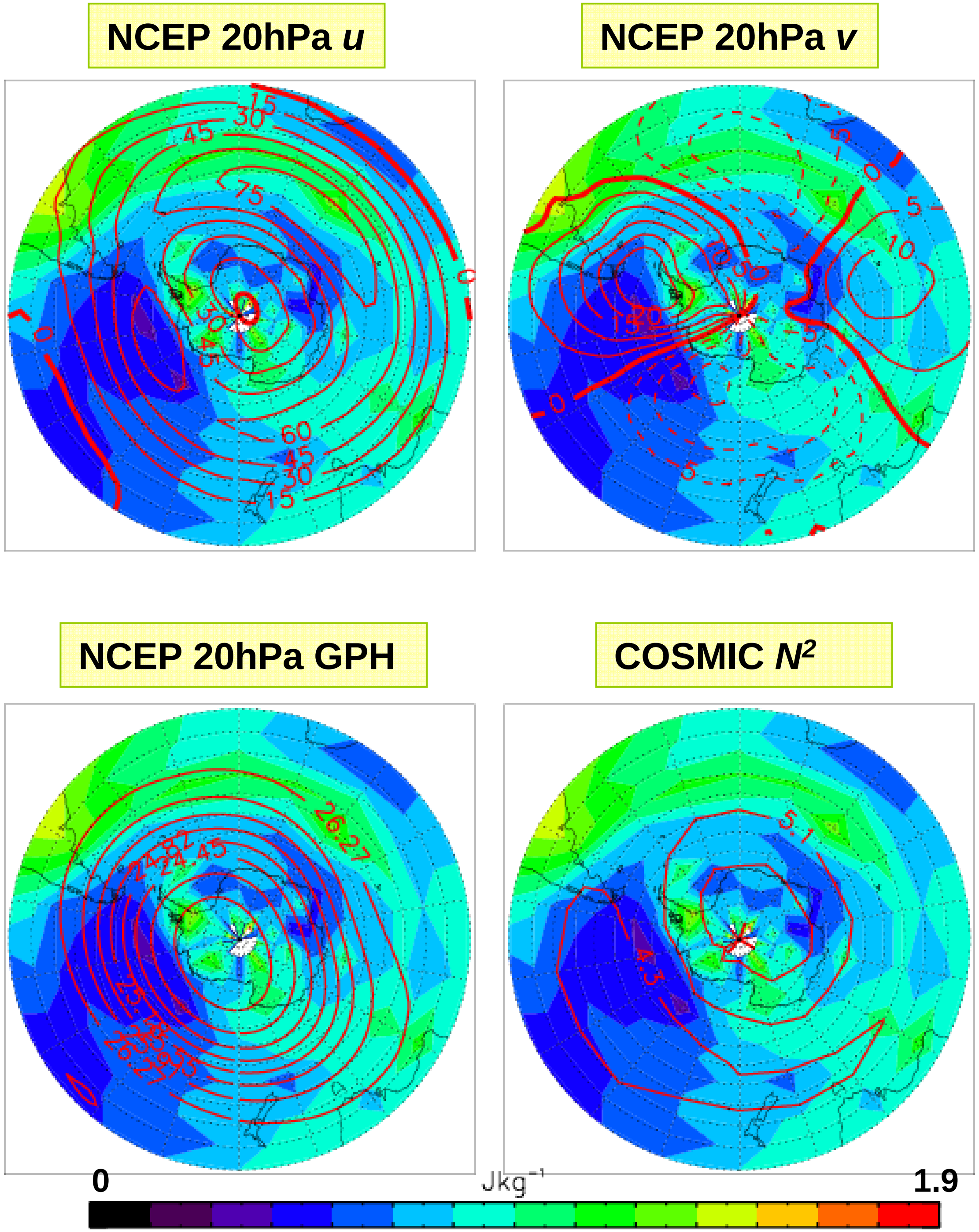
Jkg⁻¹
7–day mean
NCEP horizontal
winds 250–10hPa
(red, ms⁻¹)

October 2006 22 – 28km Antarctic PE



- October mean PE and NCEP parameters
- Break – up of the polar vortex
- Strong *u* associated with large PE: geostrophic adjustment
- Planetary wave 1 activity in *v*
- Asymmetric GPH
- Large PE downstream of Andes Mountains



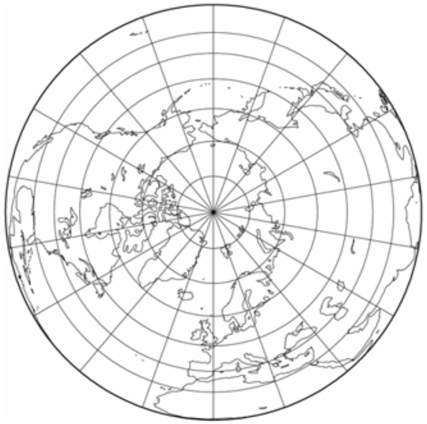
July 2007 22 – 28km Antarctic PE

- Large mean *u* and large shear in the Eastern Hemisphere – *u* exceeds $75ms^{-1}$
- Corresponding large PE
- Planetary wave 2 activity in *v*
- Symmetric GPH
- Large PE above and downstream of Antarctic Peninsula – observed in other winter 2007 months
- Also have large PE inside the continent either side of the Ross Sea – source is being investigated

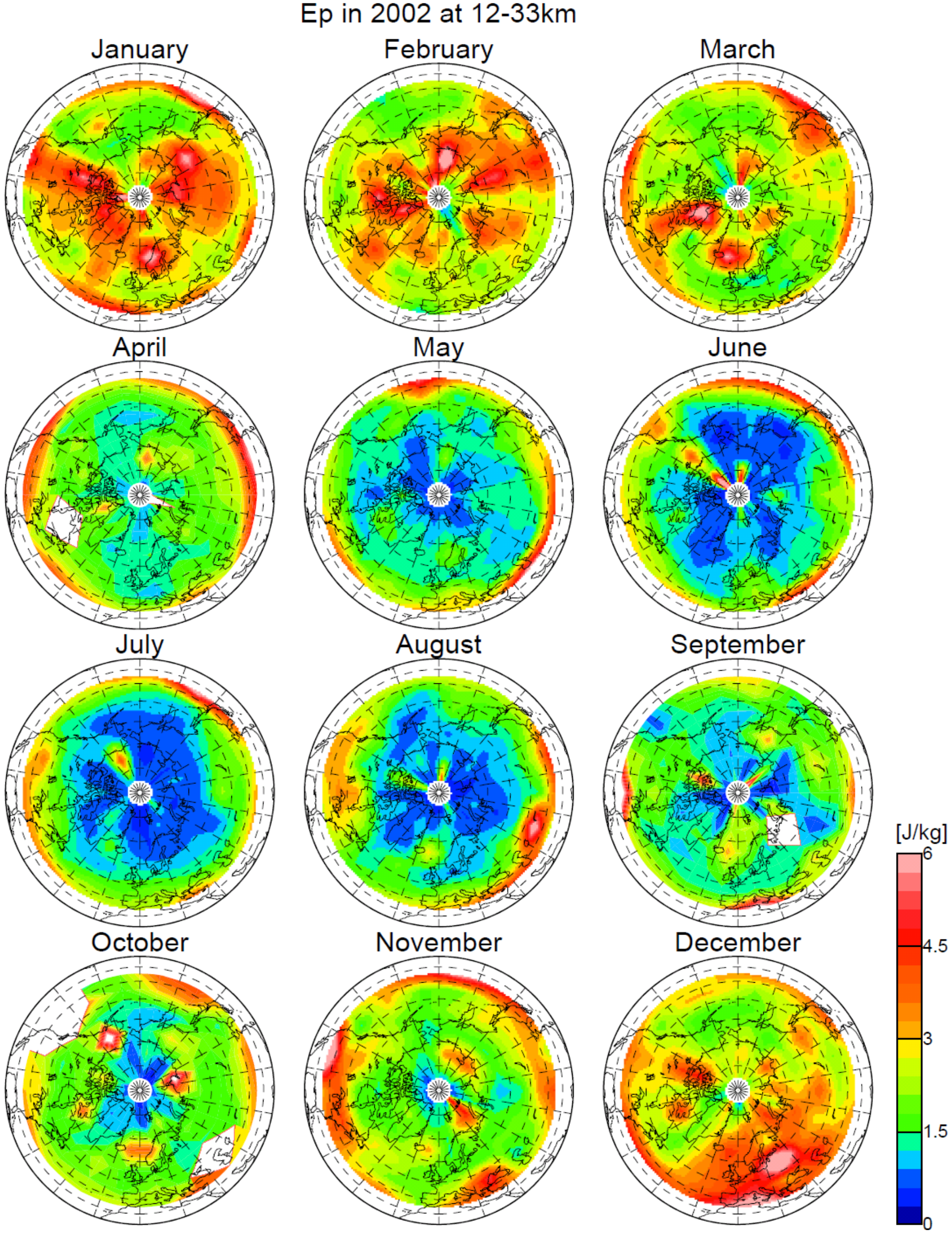
Horizontal distribution of monthly mean *Ep* in the Arctic region at 12-33km in 2002

CHAMP

Wave potential energy,
$Ep=1/2(g/N)2(T'/T0)2$
- ***g***; **acceleration of gravity,**
- ***N***; **Brunt-Vaisala frequency,**
- ***T'***; **temperature perturbation,**
- **T_0; background temperature**



CHAMP



Cell size (Longitude x Latitude):
- **$20^o \times 10^o$ for CHAMP**
- **$20^o \times 5^o$ for COSMIC**

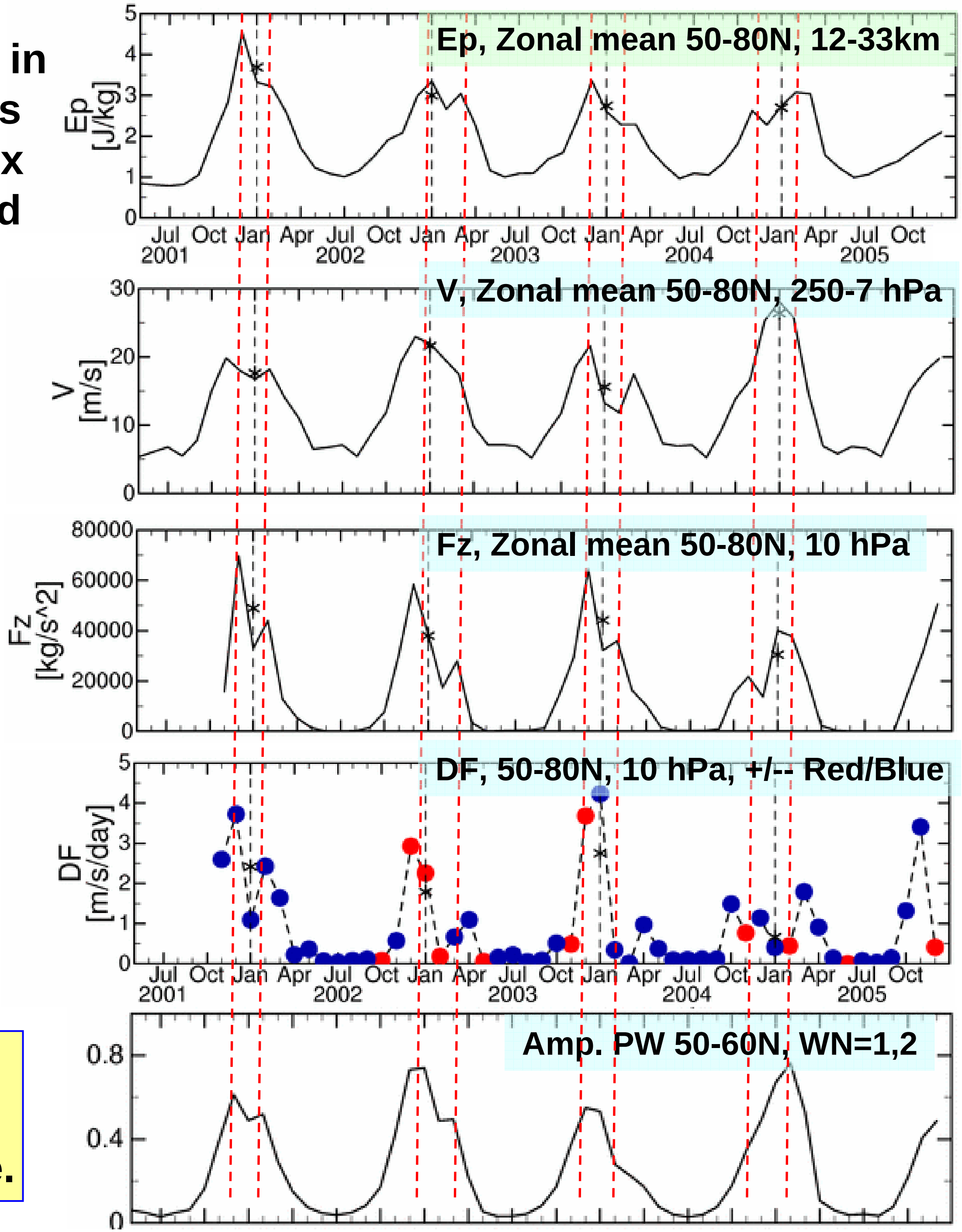
Monthly mean values of Ep (top) in the Arctic region and Mean winds V, Vertical component of E-P flux (Fz), E-P flux divergence (DF) and Planetary wave amplitudes.

Ep shows a clear annual cycle with a peak in winter months (December-February).

V also shows an annual cycle, but, it does not perfectly match with the Ep variation.

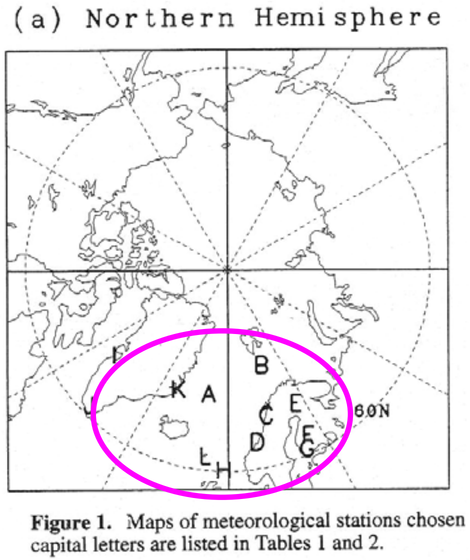
Fz peaks coincide well with Ep, and a general quantitative consistency is recognized, except in January 2003.
DF is also consistent.

Active planetary wave generates gravity waves through planetary wave breaking and/or transience.

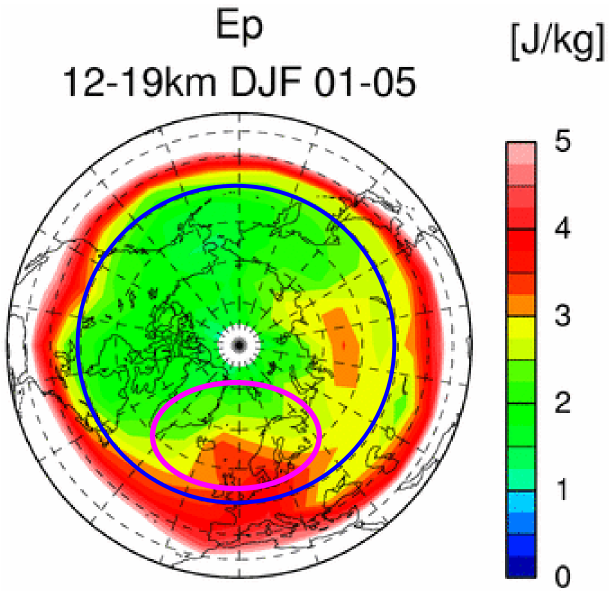


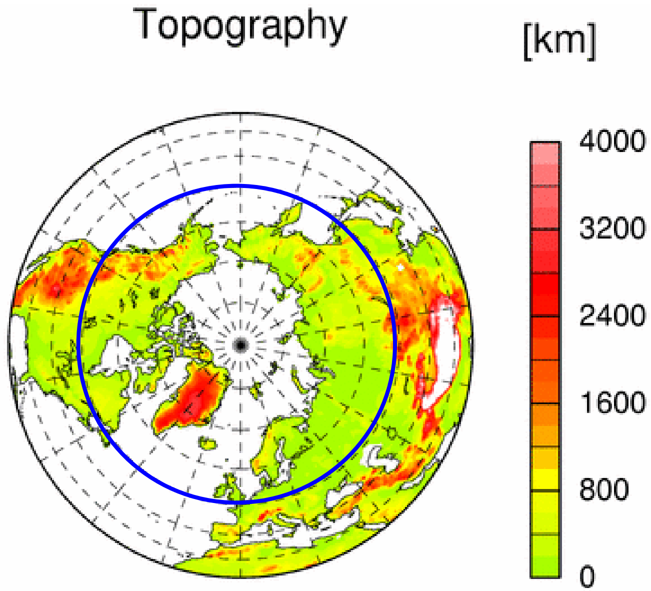
CHAMP

Horizontal distribution of Ep at 12-19 km (Middle) and topography (Right) in the Northern hemisphere. Ep is averaged in winter months (December – February) in 5 years: 2001-2005



Radiosonde sites used in Yoshiki and Sato (2000)



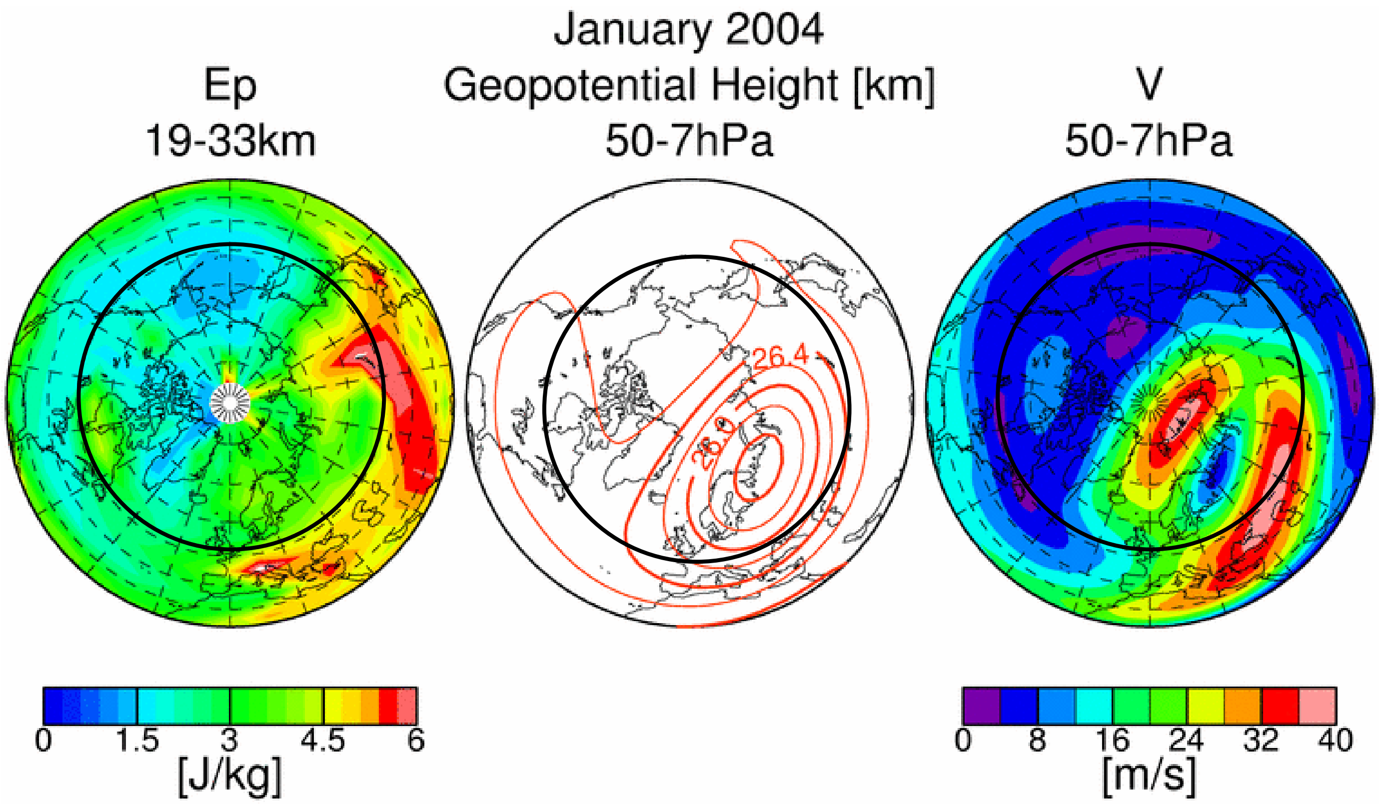


Yoshiki and Sato(2000) employed radiosonde data collected in the northern Europe and Greenaland, where gravity waves seem to be generated by orographic effects. But, it may not be a general case in the Arctic region.

Large Ep is found around Scandinavia peninsula, but Ep is not particularly enhanced over other mountain regions, like Rocky range. On the other hand, Ep is enhanced over the central Eurasia with relatively flat terrain.

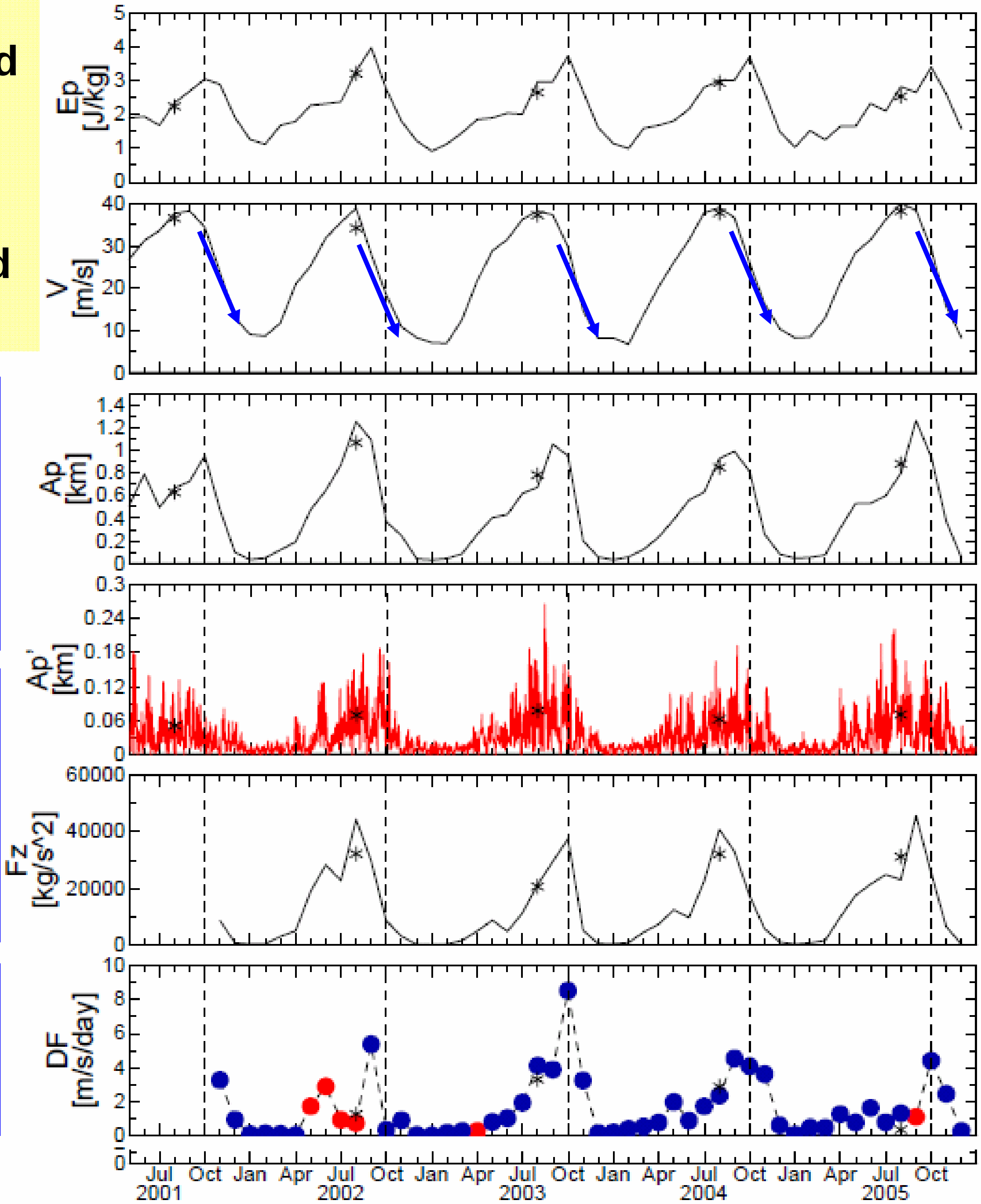
CHAMP

Horizontal distribution of Ep (19-33 km), geopotential height, φ (50-7hPa) and horizontal wind (V) in January 2004



This case study indicates that the horizontal distributions of Ep, Φ and V are generally consistent. It is further suggested that breaking and transience of the planetary waves could generate unbalanced flow, and emit gravity wave through geostrophic adjustment.

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).



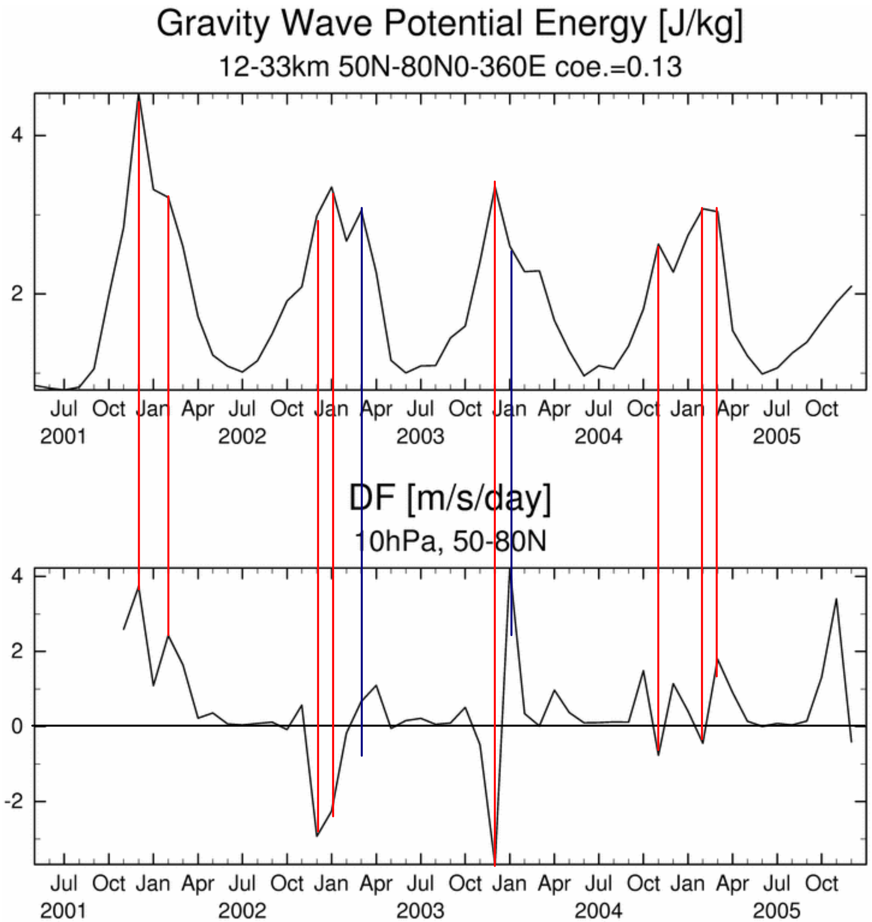
Ep gradually increases in winter (Sep-Oct), and it is largely enhanced in spring (Sep-Oct), then, it rapidly decreases.

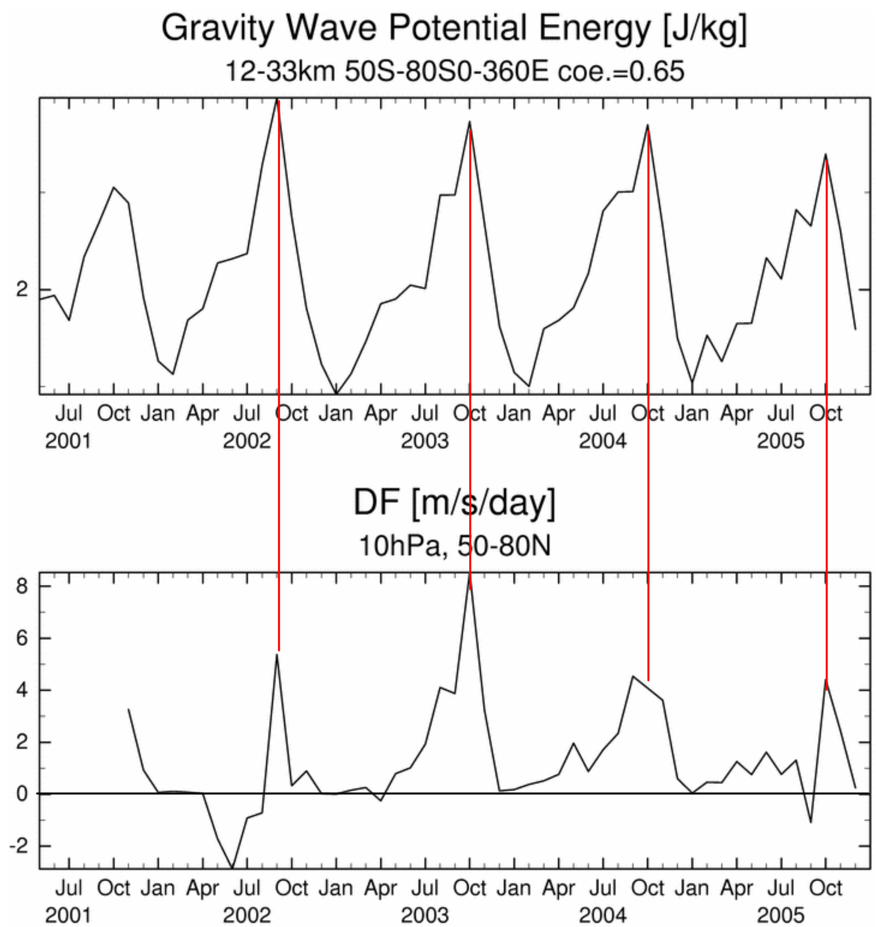
Maximum of V occurs one month earlier than Ep peak. dV/dt coincides with Ep peak, i.e., GW are enhanced during a decay phase of polar vortex.

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





COSMIC Tropical Region Wave Generation and Propagation

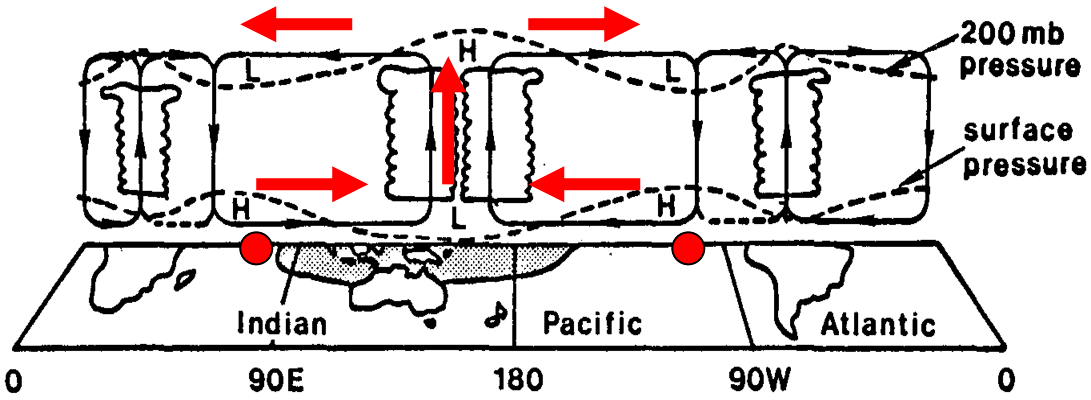
- Tropical regions' gravity wave emissions are mainly from deep convective activity

- Wide spectrum of waves generated: e.g. Kelvin waves, Mixed Rossby Gravity Waves, Gravity Waves…

- MJO and QBO related wave generation and filtering mechanisms studied

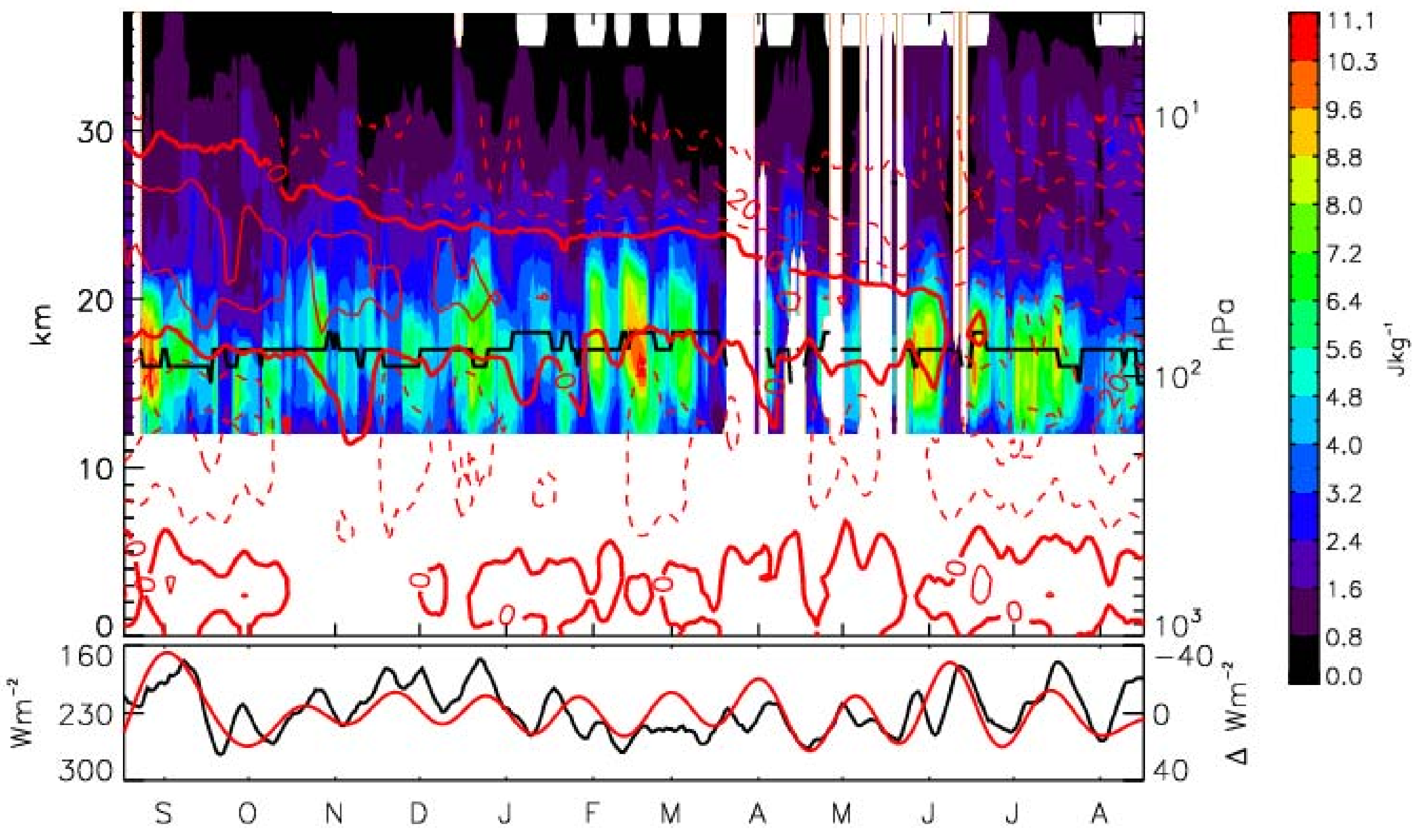
Walker Circulation

(Webster & Chang, JAS 1988)



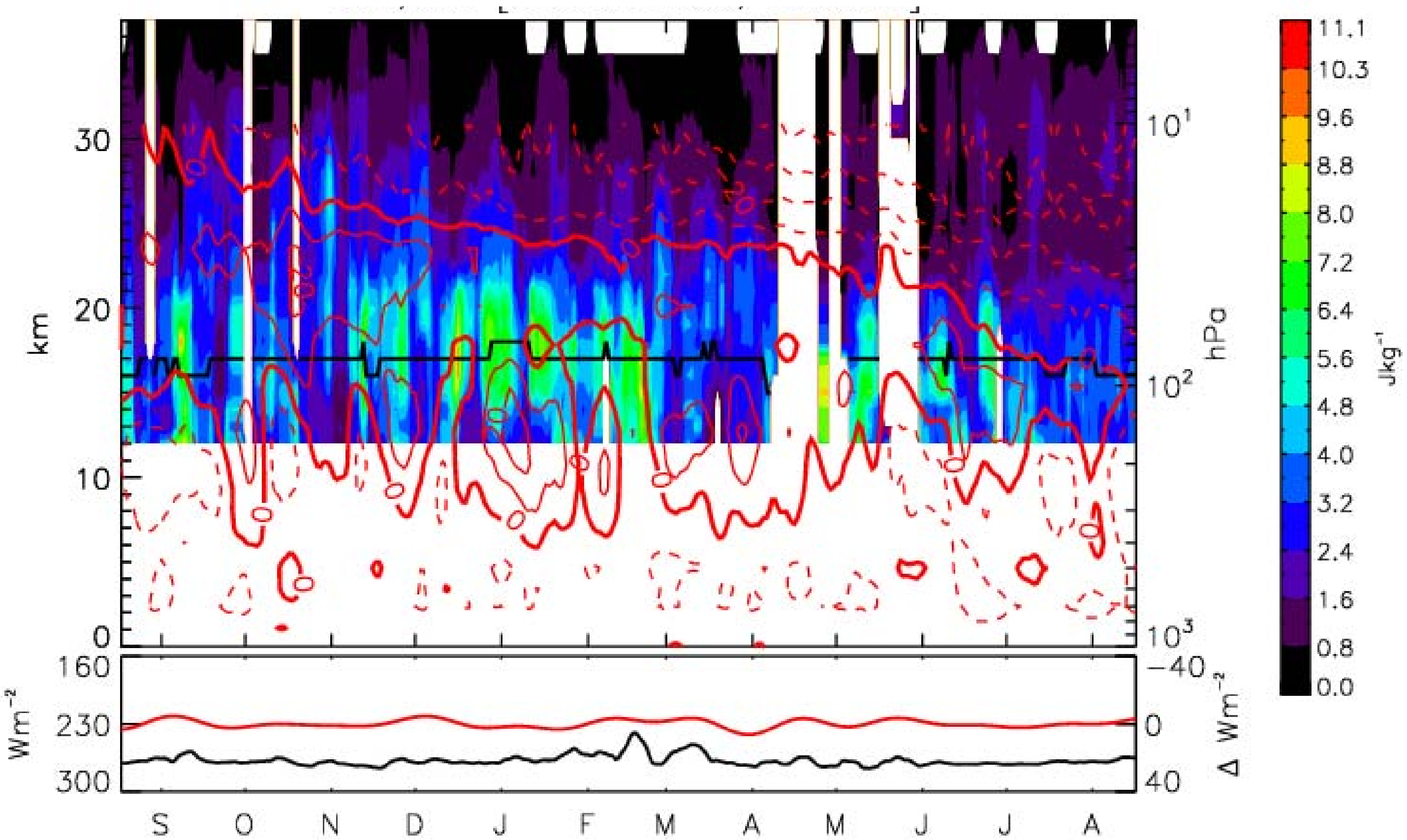
- Indian Ocean surface eastward, westward in upper troposphere
- Indonesian region’s *u* generally weak – deep convection
- Eastern Pacific often have upper level eastward winds
- Changing background wind structure around the equator may result in different wave generation sources and wave filtering

[80E,0S] Eastern Indian Ocean PE



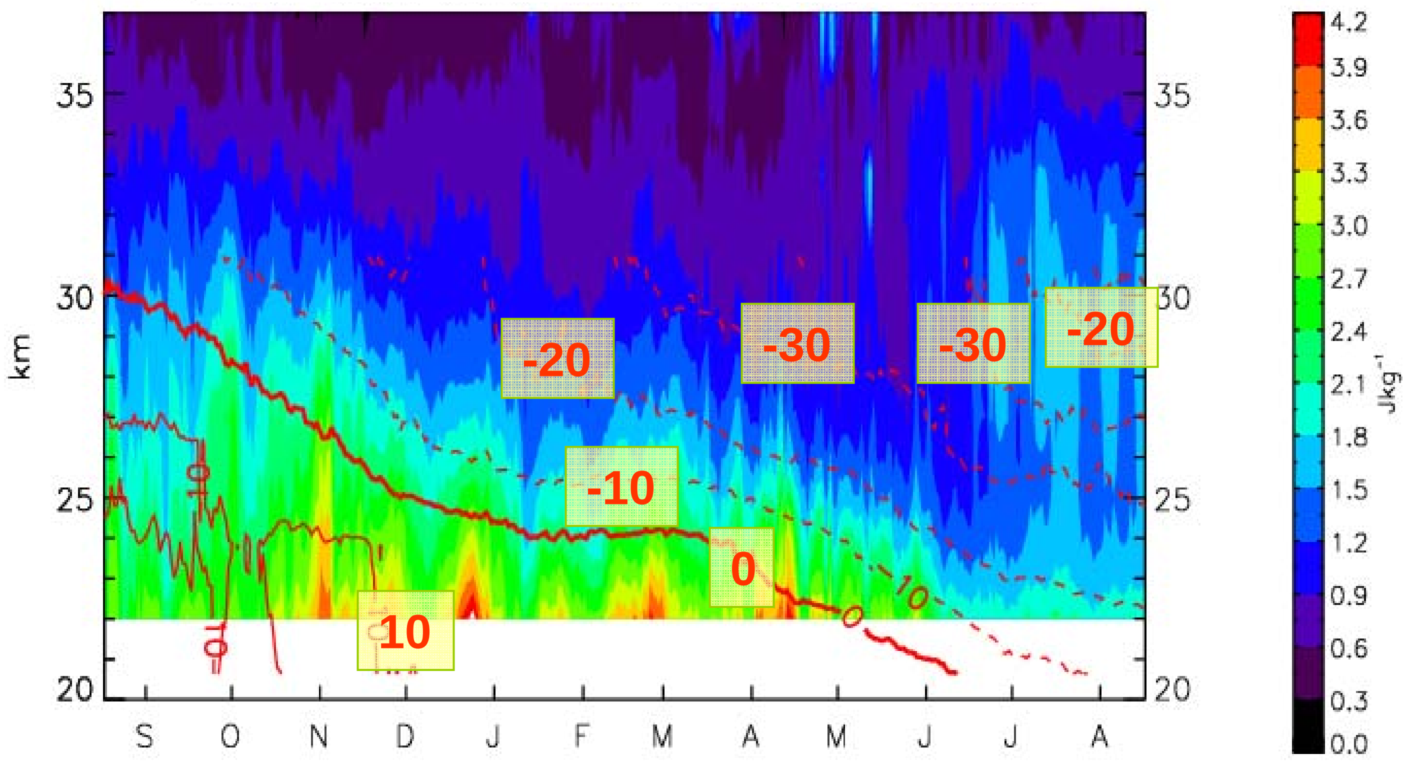
- Periodic increases in UTLS *Ep* often related to deep convective activity
- OLR averaged over same region, with 30-90 day bandpass shown in red (scale to right)
- *Ep* generally decreases with height in the stratosphere
- Increases in region 23-32km also noted, often at same time as UTLS (7km vertical averaging does not account for this) – more stratospheric wave energy during deep convection
- 1 – 2 J/kg stratospheric contours show a long-term downward trend – QBO filtering

[260E,0S] Eastern Pacific PE

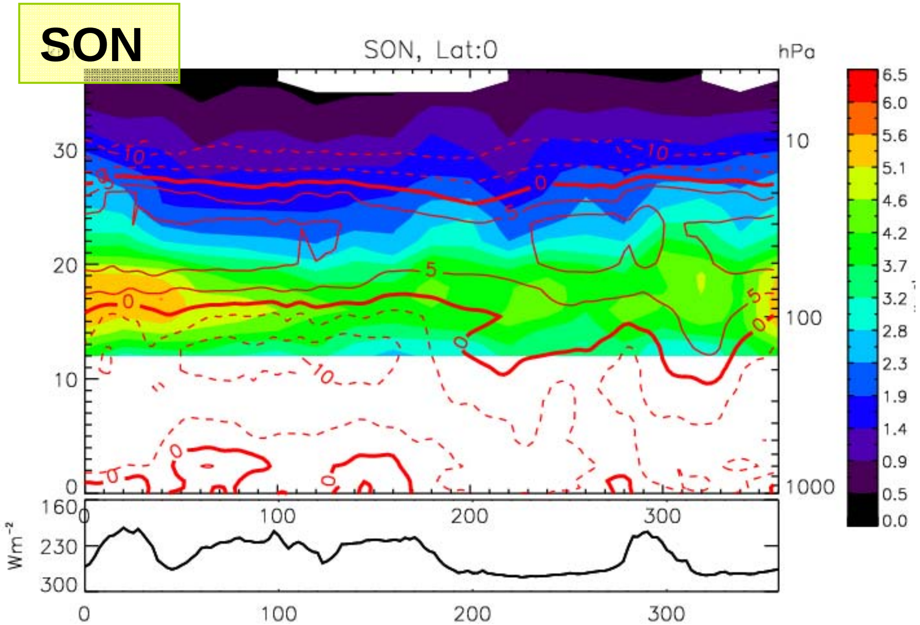


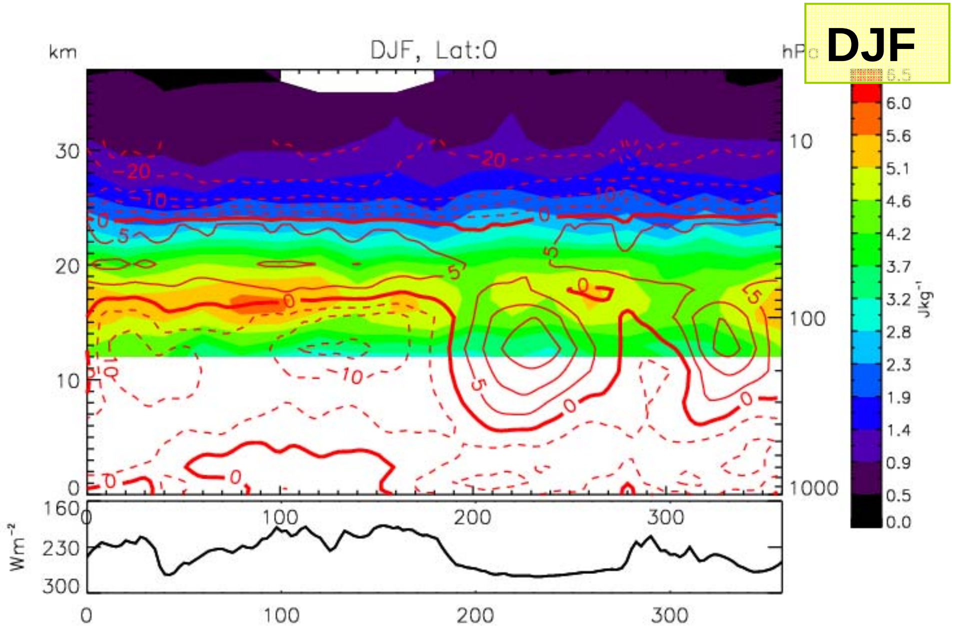
- Little convection in Eastern Pacific
- Lower tropopause 'PE' because of smaller gravity wave variances
- Walker circulation different too – e.g. DJF stronger eastward winds
- Periodic stratospheric increases in PE, but still have long term downward QBO trend

Stratospheric Zonal Mean Zonal Wind and PE (2.5S:2.5N)

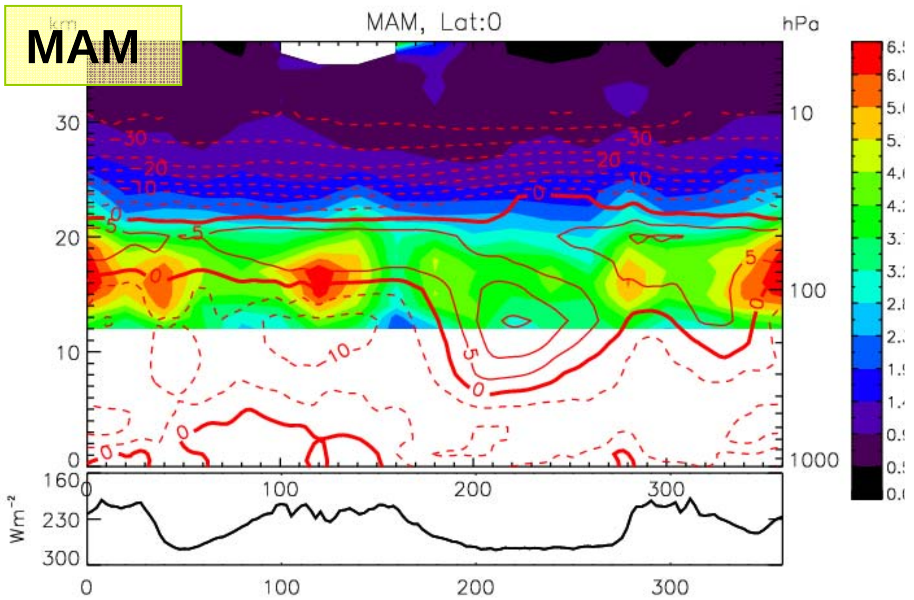


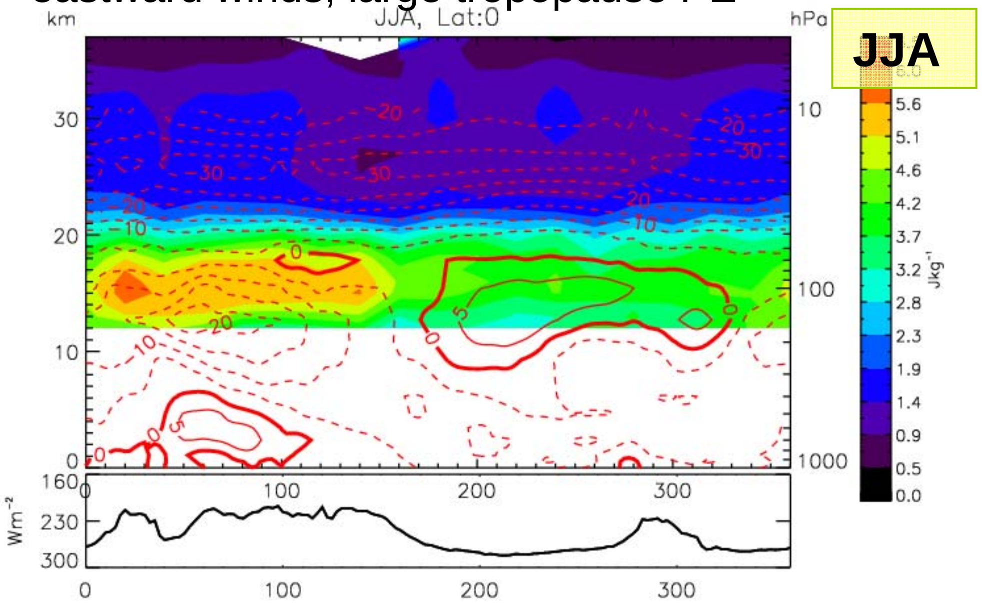
- Clear evidence of stratospheric filtering of wave energy with height
- Downward trend of the QBO winds through time acts to filter more waves, resulting in lower PE
- Note the larger PE at ~30km from July onwards

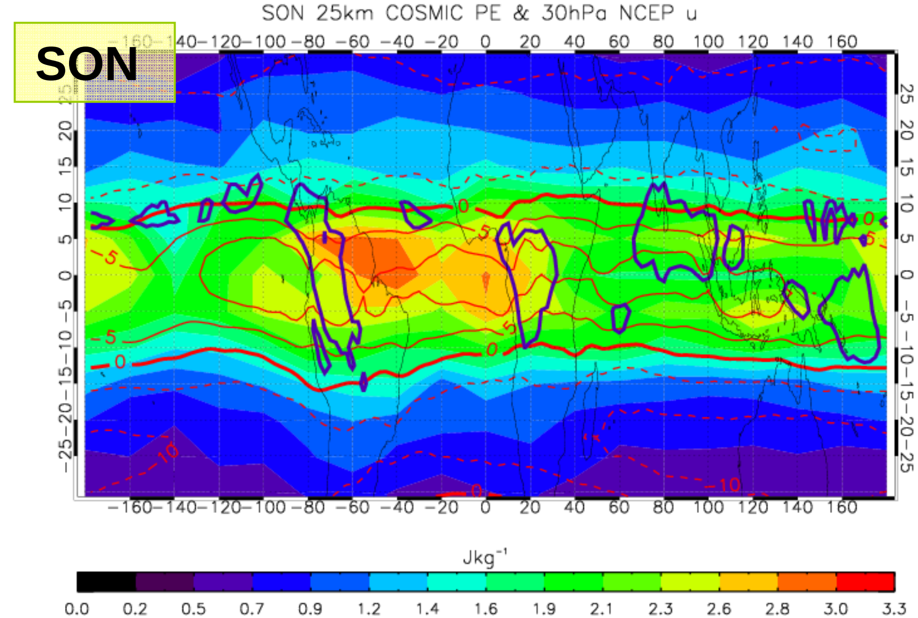


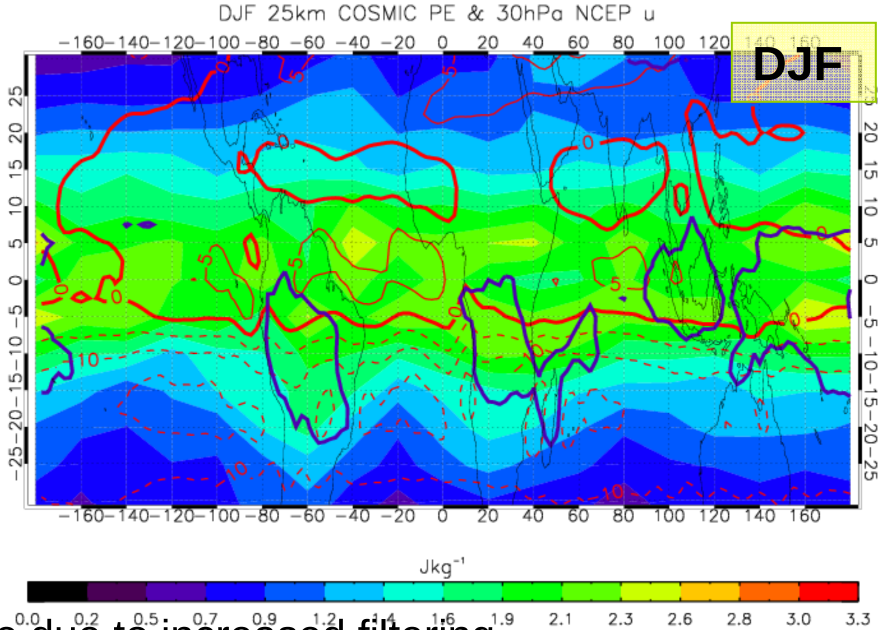


- OLR directly related to large tropopause variances (Africa, Indonesia, Amazon)
- PE decouples from source in stratosphere – zonally constant during DJF, MAM at 30km
- But in JJA, larger 30km PE above convection than in Pacific – less wave filtering by QBO
- Note also DJF Pacific Walker circulation – eastward winds, large tropopause PE

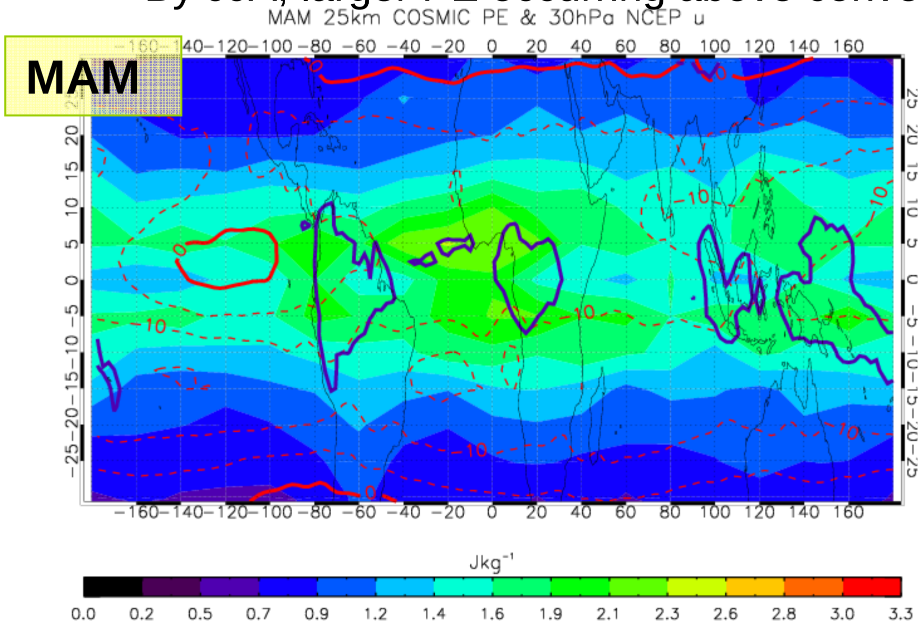


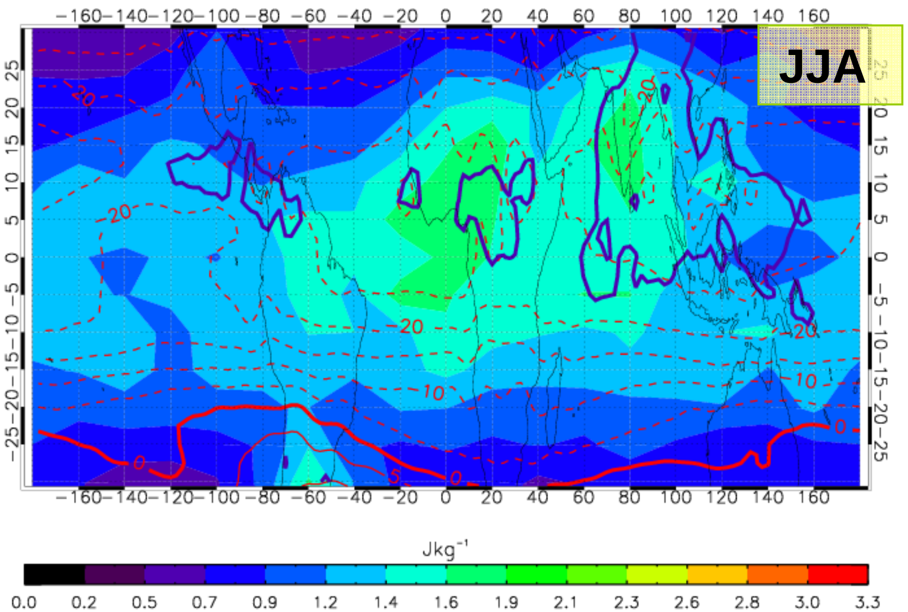






- 22 – 28km tropical PE decreases through time due to increased filtering
- 30hPa NCEP *u* plotted in red, solid eastward, dashed westward
- Note the split structure in MAM – peaks at 5° or 10° - may be MRGWs
- By JJA, larger PE occurring above convection (OLR @ 200Wm^{-2}) in India, Africa



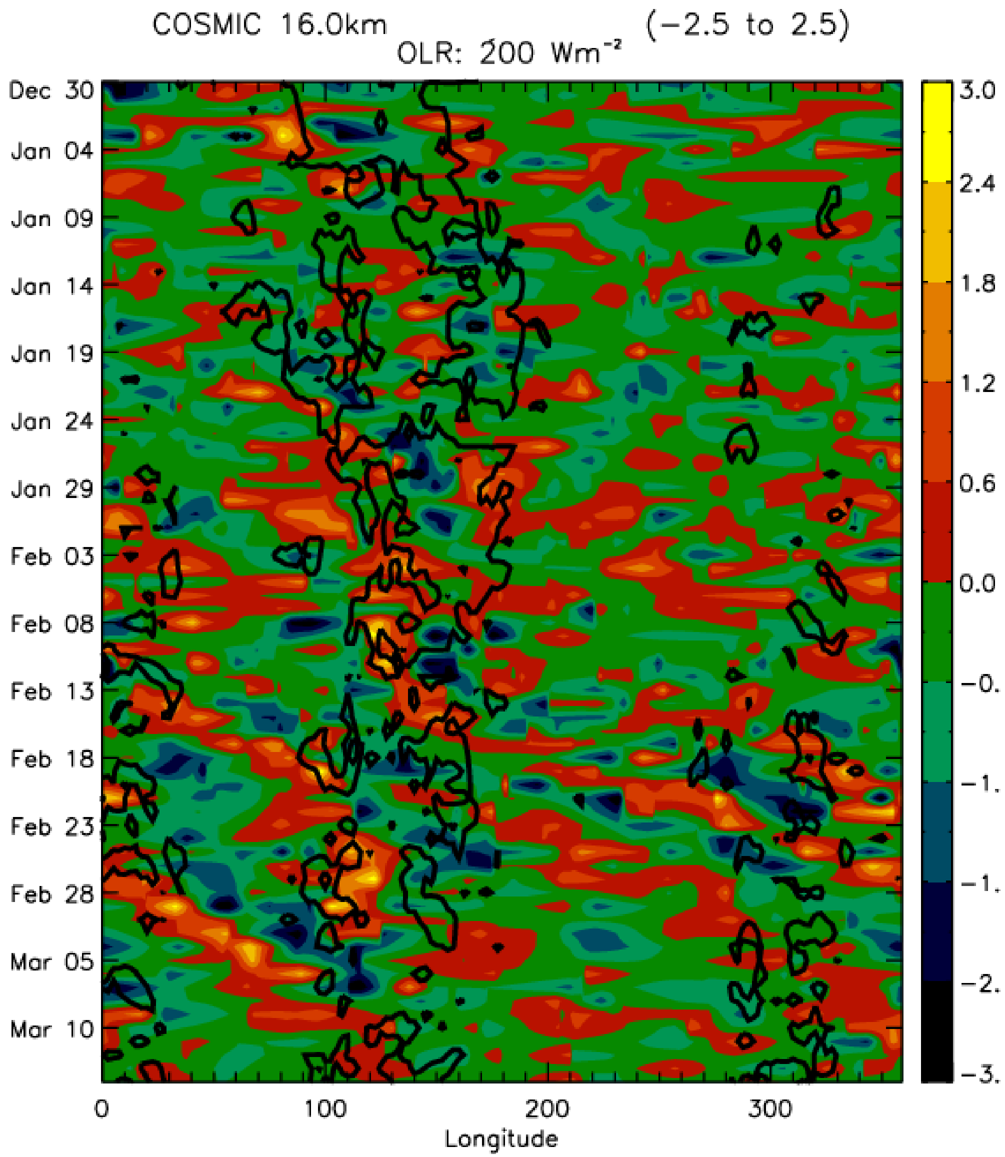


Zonal Higher Order Perturbations at the Equator

- Remove Kelvin wave 1, 2 components to look at *T'* due to:
  - Higher order wavenumber Kelvin waves
  - Kelvin-like gravity waves
  - Convectively coupled or freely propagating gravity waves
- Kelvin waves have periods of 10-20 days, so use 30 days of data to establish background mean temperature profile (stepping forwards by one day)
- Extract data from middle of this block to get 1 day's raw *T'* in each 20 x 5 degree grid cell, then remove the fitted Kelvin sine wave function:

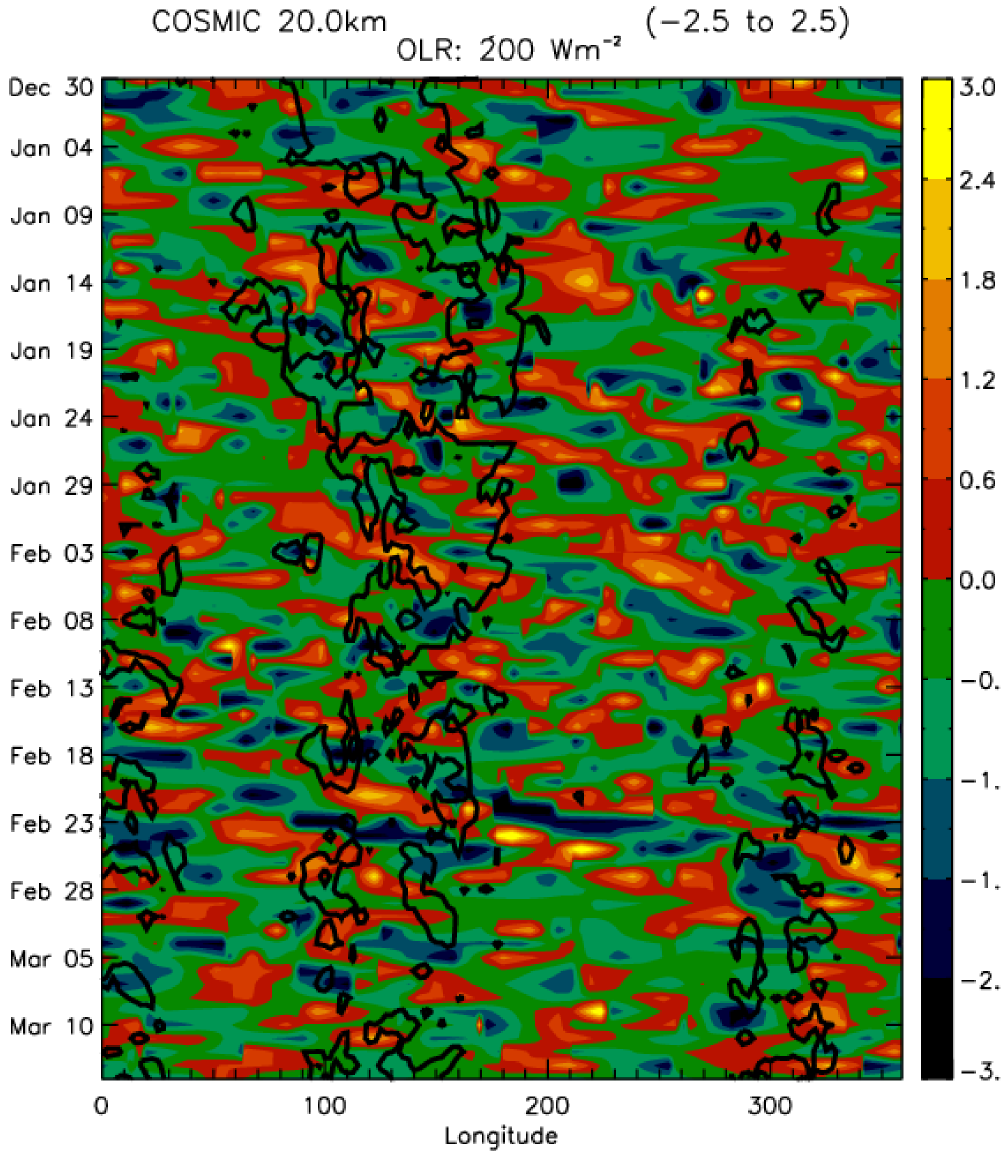
$$f(x) = \sum_{k=1}^{2} a_k \sin k(x - \phi_k)$$

16km *T'* after Kelvin Wave 1, 2 removal



- Below the tropopause
- Black open contours show 200W/m^2 OLR averaged over 2.5S:2.5N.
- Largest |*T'*| of over ±2K often occurred above the Western Pacific / Indonesian deep convection
- Eastward propagating waves often visible in e.g. February, may be k=3,4 Kelvin waves
- Waves do not appear to be convectively coupled

20km *T'* after Kelvin Wave 1, 2 removal



- 20km altitude, so waves probably mostly freely propagating
- Still regularly observe eastward propagation
- Sometimes have correspondence between amplitude & phase of these waves at 16km and 20km (e.g. early Feb)
- But at other times, waves have similar wavenumber but shorter period (late Feb)
- Largest |*T'*| not so clearly linked with deep convection

Summary

- GPS-RO is a very valuable technique for monitoring the atmosphere and studying the dynamics. COSMIC in particular allows a detailed analysis of wave energy hitherto not possible.

- Most of the polar regions' PE is due to geostrophic adjustment of the polar night jet and its springtime decay, although there are some local orographic effects in both hemispheres (Scandinavia, Antarctic Peninsula).

- The Northern Hemisphere mid-latitudes' winter-time PE is mainly due to sub-tropical jet geostrophic adjustment, although there are important orographic effects which enhance PE above the Himalayas, Canadian Rockies, the Alps and Japan.

- Tropical generation of PE is related to the MJO and deep convective activity, while stratospheric PE is affected by wave filtering which depends upon the phase of the QBO.