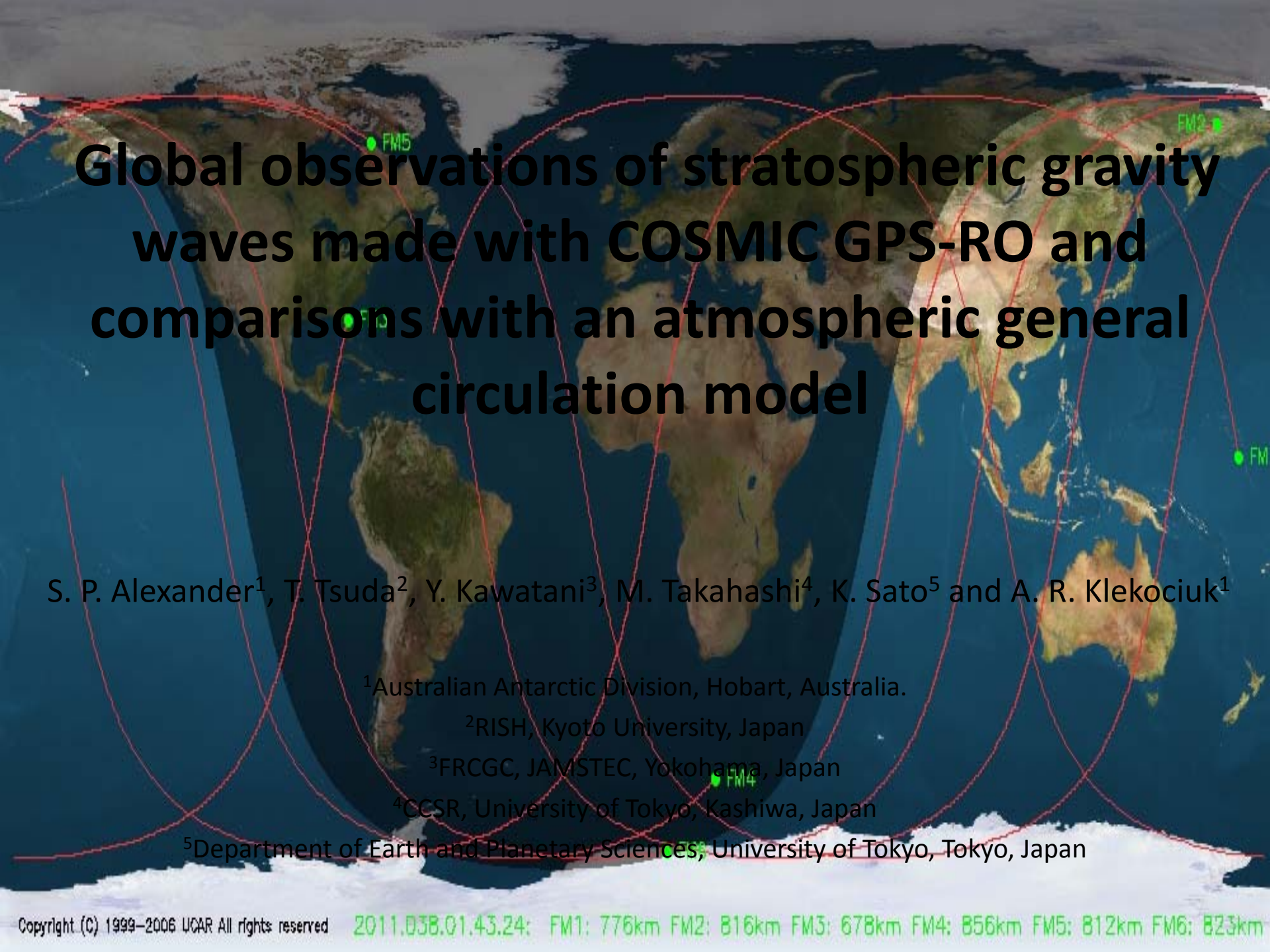


Global observations of stratospheric gravity waves made with COSMIC GPS-RO and comparisons with an atmospheric general circulation model

S. P. Alexander[1], T. Tsuda[2], Y. Kawatani[3], M. Takahashi[4], K. Sato[5] and A. R. Klekociuk[1]

[1]Australian Antarctic Division, Hobart, Australia.

[2]RISH, Kyoto University, Japan

[3]FRCGC, JAMSTEC, Yokohama, Japan

[4]CCSR, University of Tokyo, Kashiwa, Japan

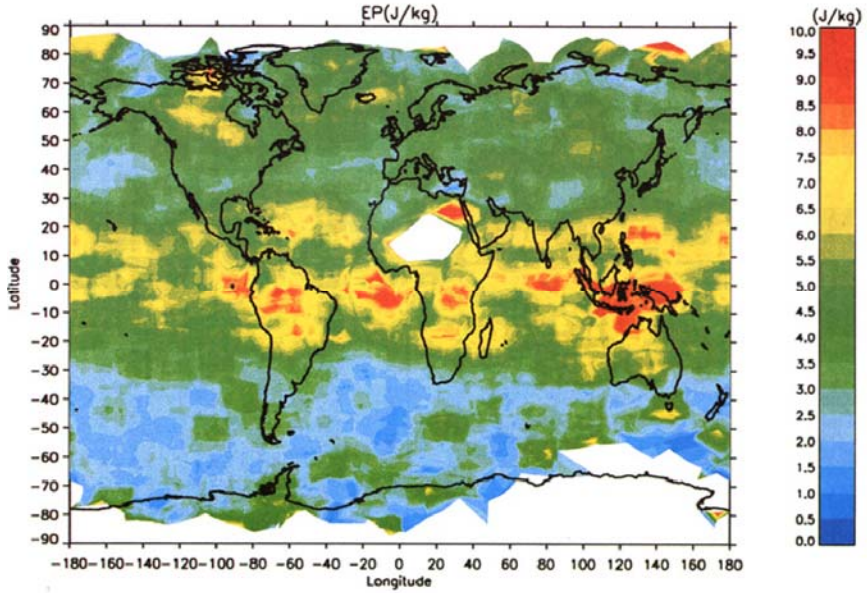
[5]Department of Earth and Planetary Sciences, University of Tokyo, Tokyo, Japan

Outline

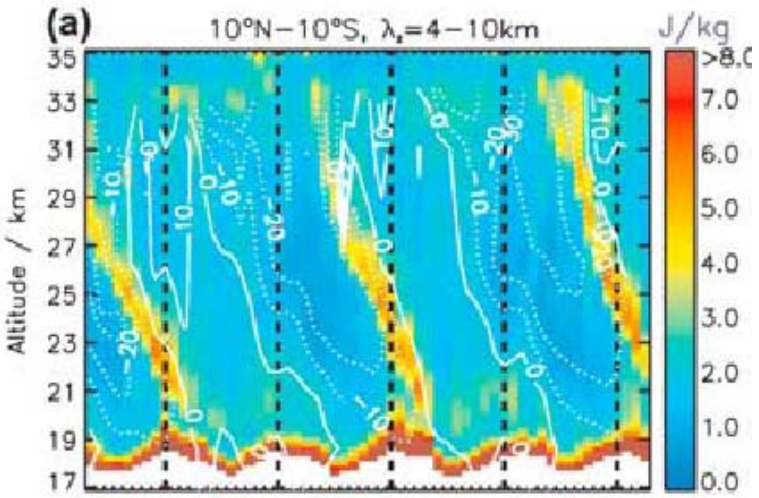
- GPS-RO background: GPS/MET and CHAMP
- COSMIC and T106L60 model comparisons
- Tropical gravity waves
- Equatorially-trapped waves
- Extra-tropical gravity waves
- Gravity waves in the polar regions
- Orographic-gravity waves and Polar Stratospheric Clouds (PSCs)

GPS-RO: Setting the scene… (1/2)

- GPS/MET in the mid-90s provided the first global picture of gravity-wave activity using GPS-RO
- CHAMP provided a multi-year dataset for wave analyses
- GPS Radio Occultations are more likely to capture gravity waves with slow vertical group velocities and with short vertical wavelengths (contrast with e.g. MLS)



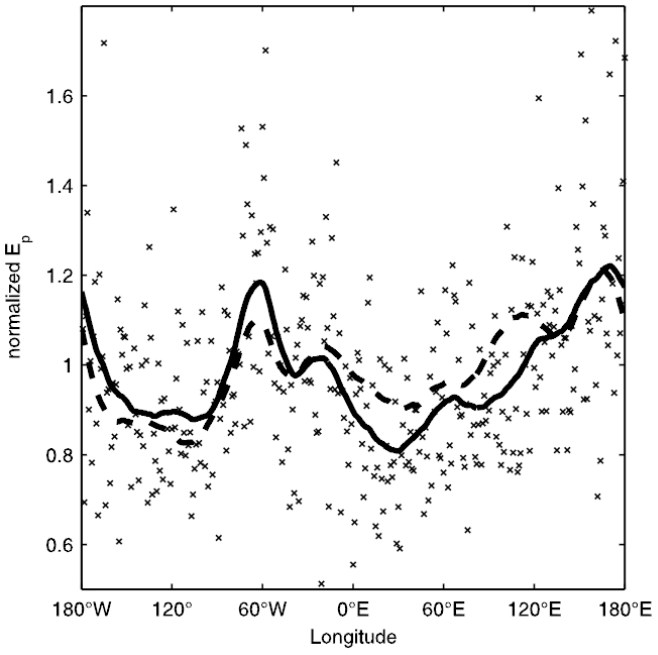
Tsuda et al., 2000



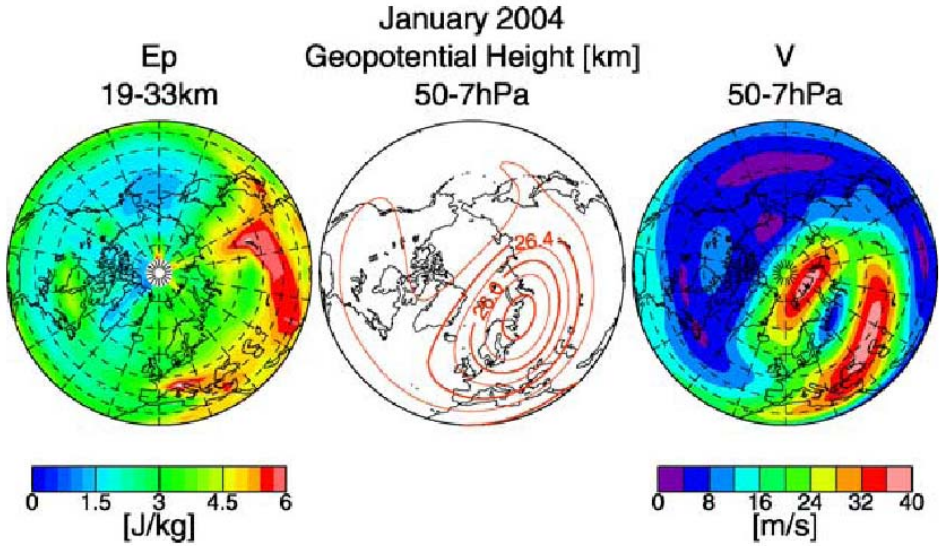
de la Torre et al., 2006

GPS-RO: Setting the scene… (2/2)

- Polar observations using CHAMP showed large orographic gravity wave activity above the Peninsula and Trans-Antarctic Mountains as well as the relationship between large gravity-wave activity and strong winds



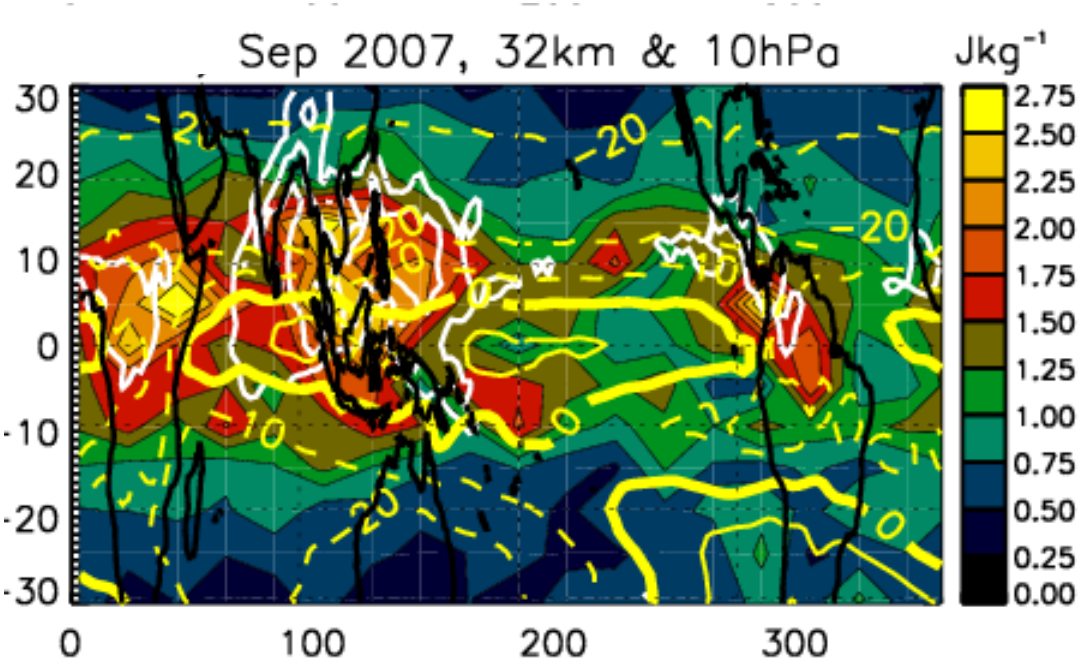
Baumgaertner & McDonald, 2007



Hei et al., 2008

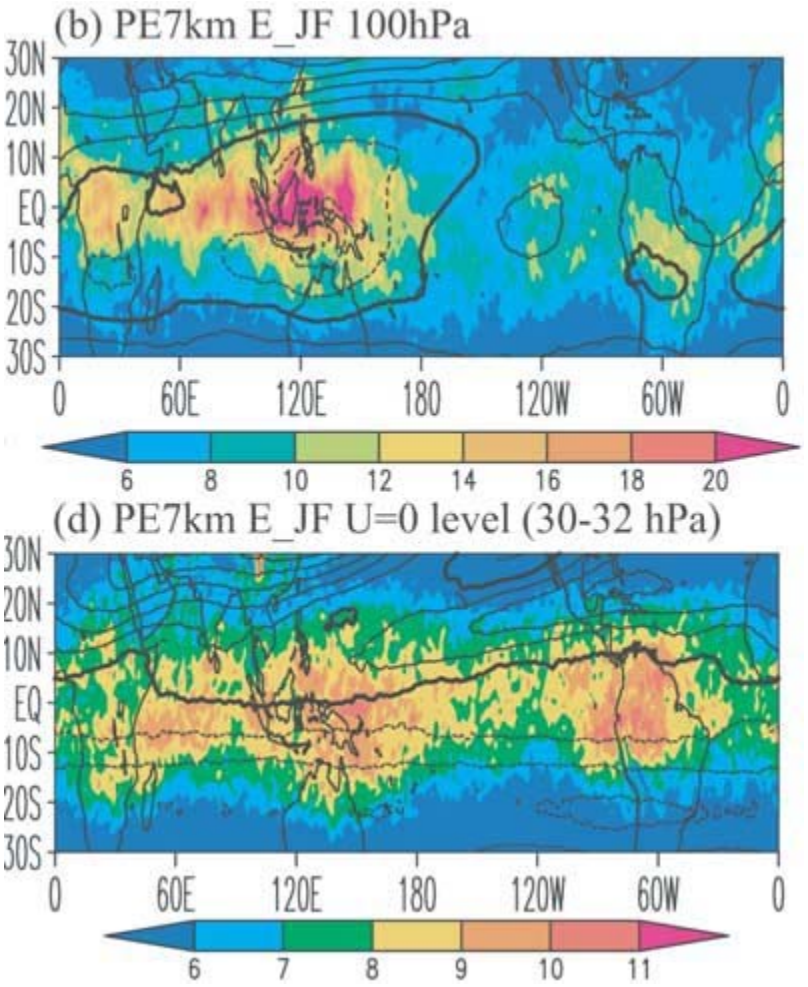
Tropical gravity waves

- COSMIC results for September 2007
- Winds were westward below 32km
- Large potential energy is visible directly above deep convective activity.
  - Slow $c_x > 0$ waves are encountering their critical level (group velocities also decrease close to critical levels, increasing the chance of wave observation.)



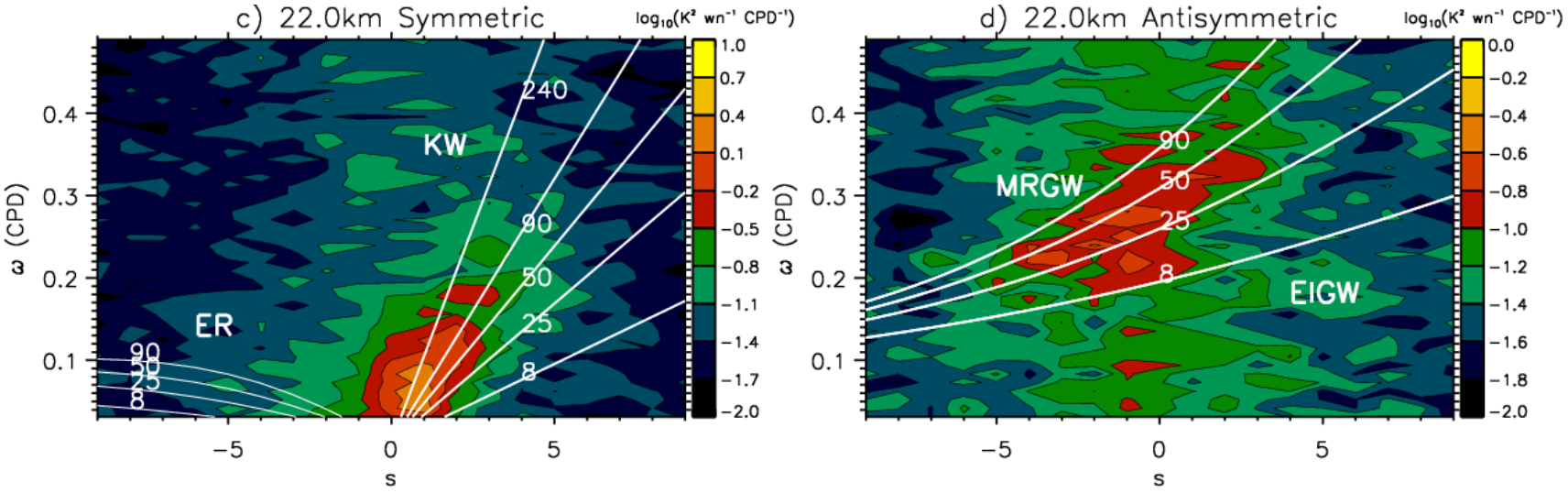
Tropical gravity waves

- Model results of PE in westward QBO shear phase shown (model incorporates wider range of GWs than COSMIC)
- Top panel shows distribution at 100hPa
- Bottom panel shows PE near the u = 0 m s^{-1} line: increased PE above deep convective regions

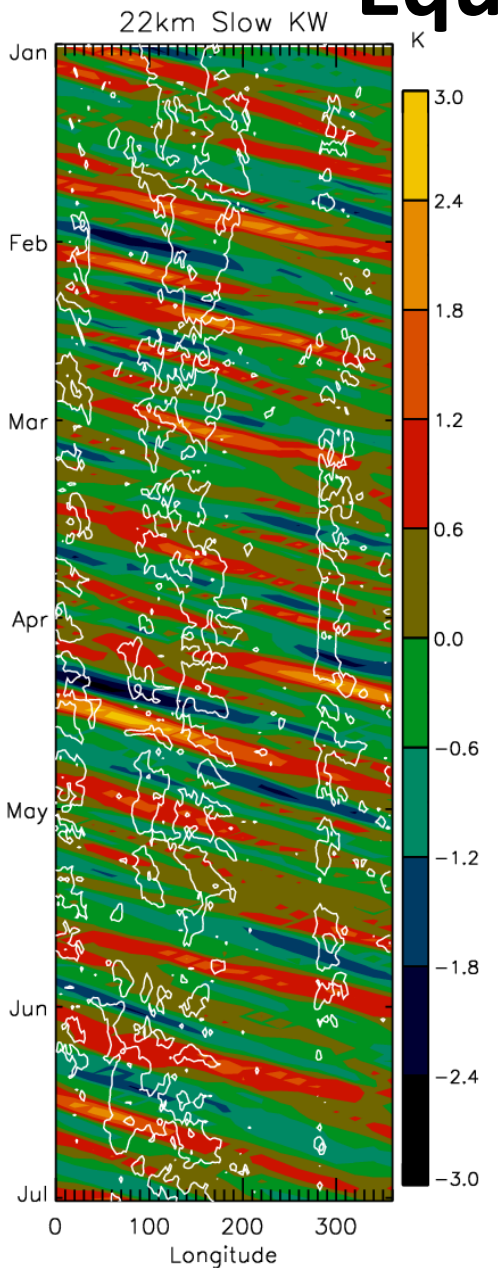


Equatorially-trapped waves

- Investigate with COSMIC data:
  - 'slow' Kelvin waves with $8 < h_e < 90$ m, corresponding to λ_z less than ~8 km ($h_e = 90$ m corresponds to $c_x = 30$ ms^{-1})
  - MRGWs with $8 < h_e < 90$ m.
  - While we can theoretically observe n=1 ER and n=0 EIGW, the resultant wave structures appear noisy and / or show little height consistency (there isn't much power in these bands)

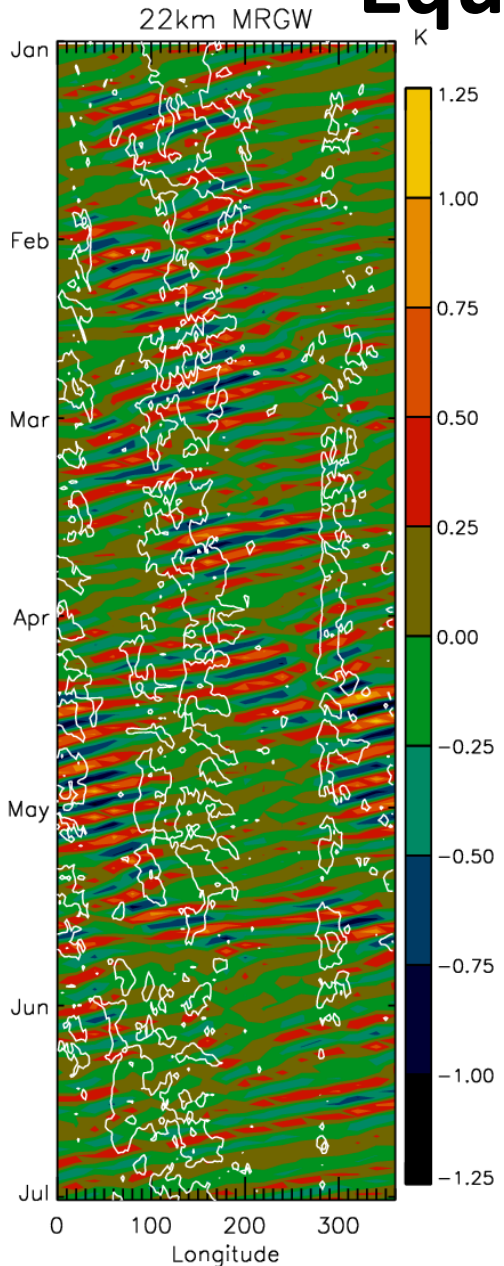


Equatorially-trapped waves



- 22km slow Kelvin waves observed by COSMIC for January – July 2007
- OLR 220 W m^{-2} marked in white
- Kelvin waves are mostly k = 1, 2 with periods ~ 10 – 20 days and c_x ~ 15 – 30 m s^{-1}

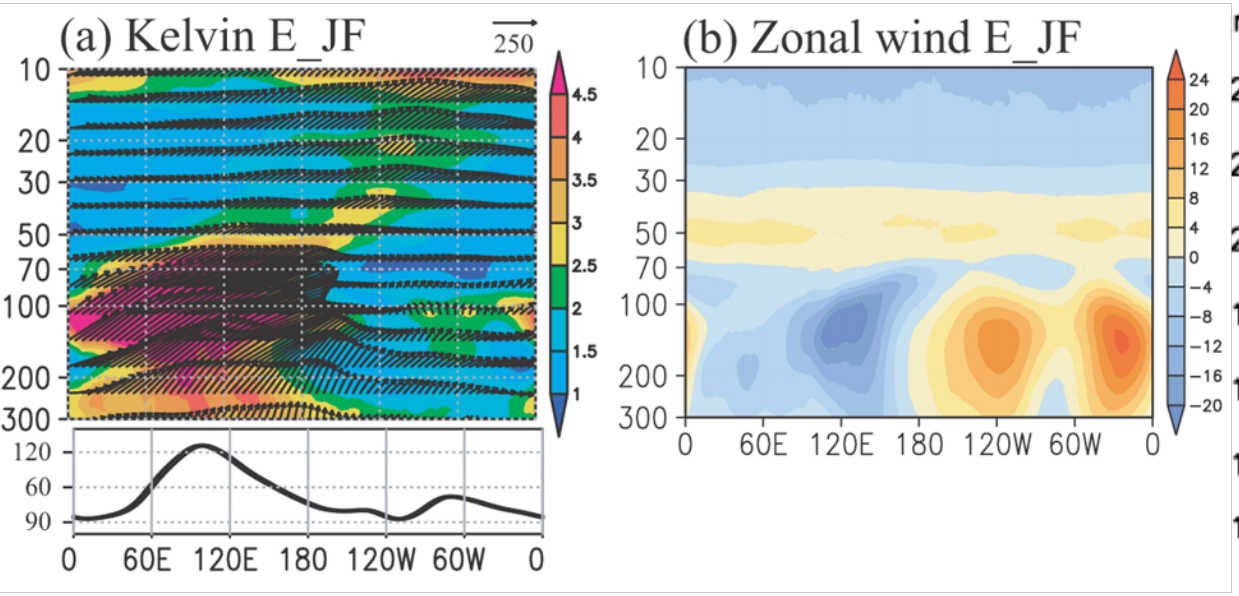
Equatorially-trapped waves

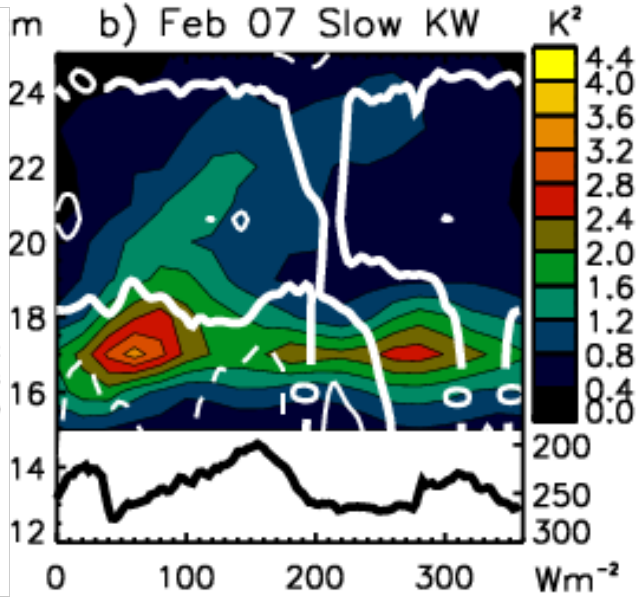


- 22km Mixed Rossby-Gravity Waves observed by COSMIC for January – July 2007 (these waves are visible in the unfiltered anti-symmetric data although there may be some GW contamination)
- Wave-packet behaviour evident: packets propagate eastward while the waves propagate westward
- Decrease in amplitudes after May: QBO is westward after this time thus removing MRGWs
- Periods 3 – 5 days, amplitudes up to ~1.2K, c_x ~ 20 – 30 m s^{-1}, k > -5

Equatorially-trapped waves

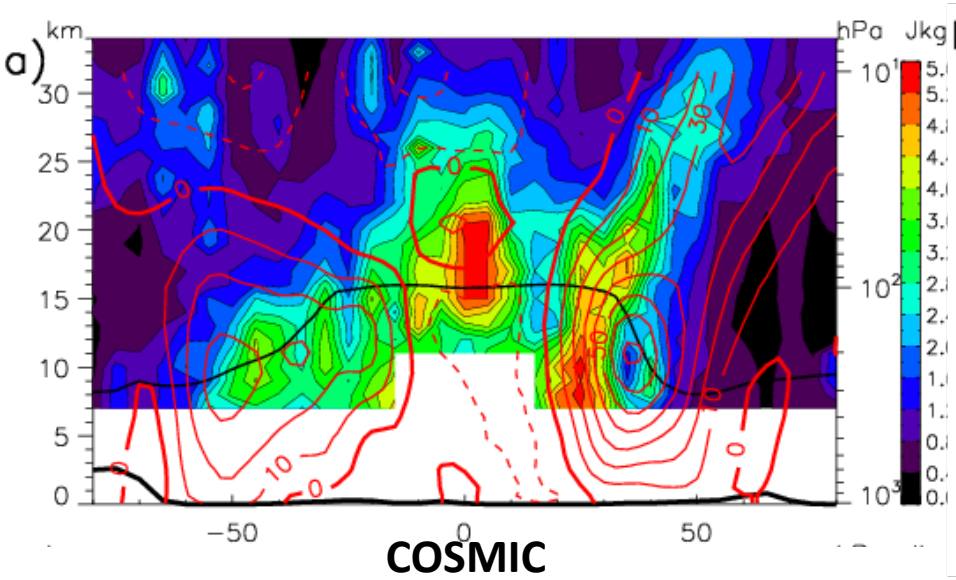
- Both model (LHS) and observations (RHS) show Kelvin waves propagating upward and eastward during QBO westward shear phase in the lower stratosphere
- The model's arrows are the energy flux, which are parallel to intrinsic group velocity

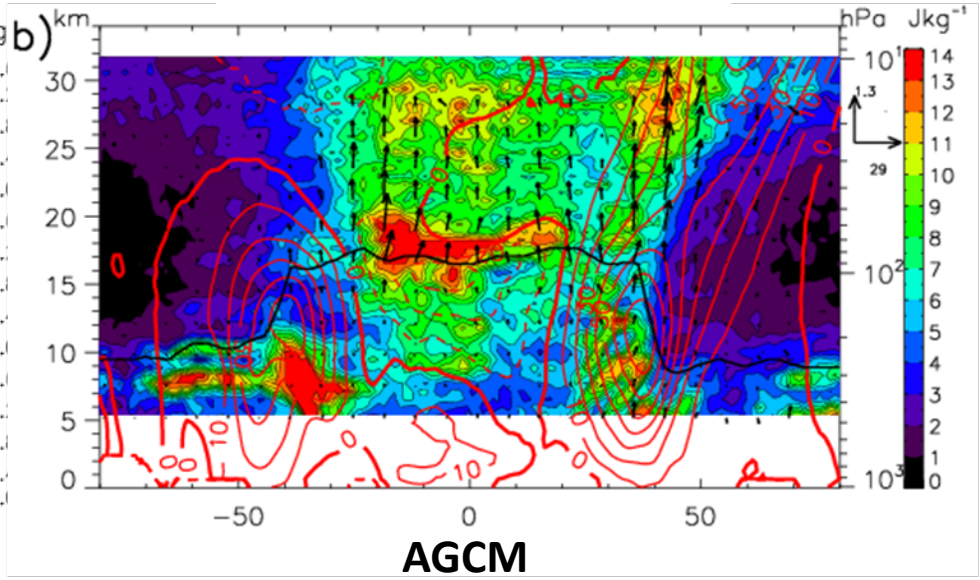




Extra-tropical gravity waves

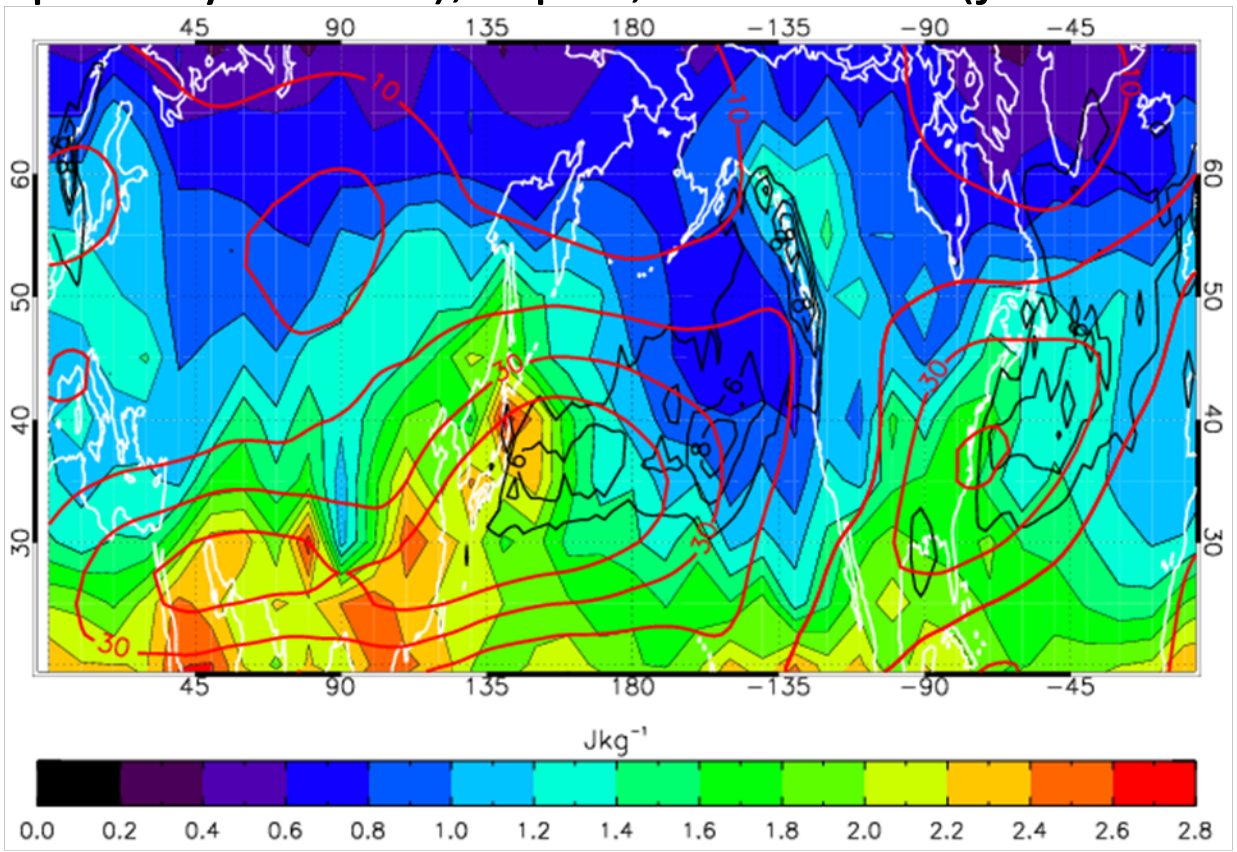
- COSMIC E_p (LHS) for 12-18 Dec 2006 at 140E
- AGCM E_p (RHS) for 1-7 Jan (similar wind conditions): vectors show meridional and vertical energy fluxes due to $\lambda_z < 7$km
- Large PE along the equatorward side of observed and modeled jet from mid-troposphere up to polar night jet





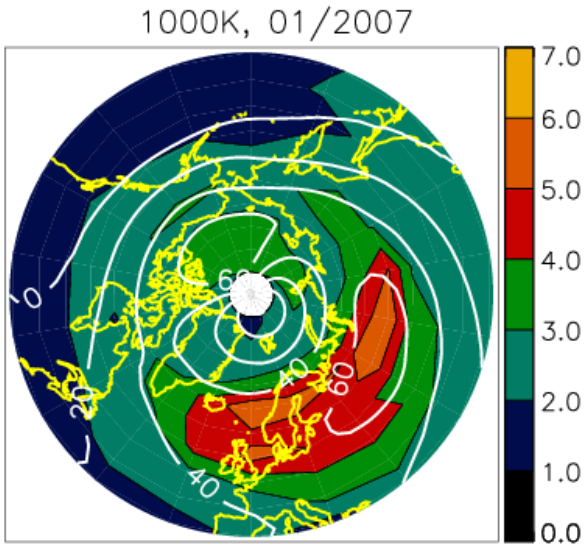
Extra-tropical gravity waves

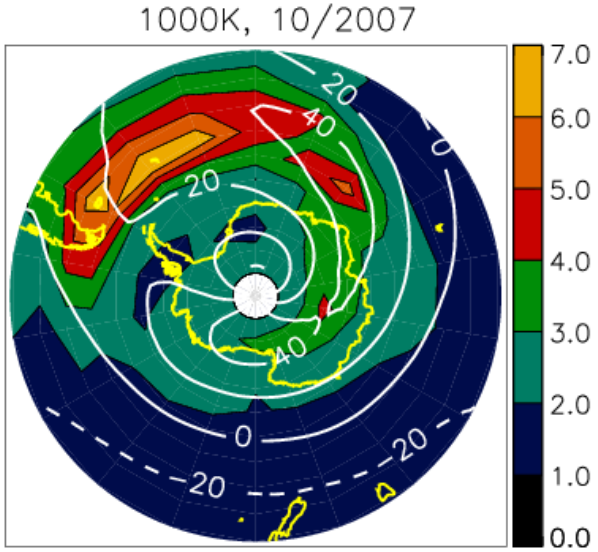
- COSMIC NH winter 2006-07 mean E_p at 20km (colour); NCEP 500 – 100hPa *u* (red); precipitation (mm/day, black)
- Enhanced E_p above the Canadian Rockies, Scandinavia (orographically-related); Japan, eastern US (jet-related)



Gravity waves in the polar regions

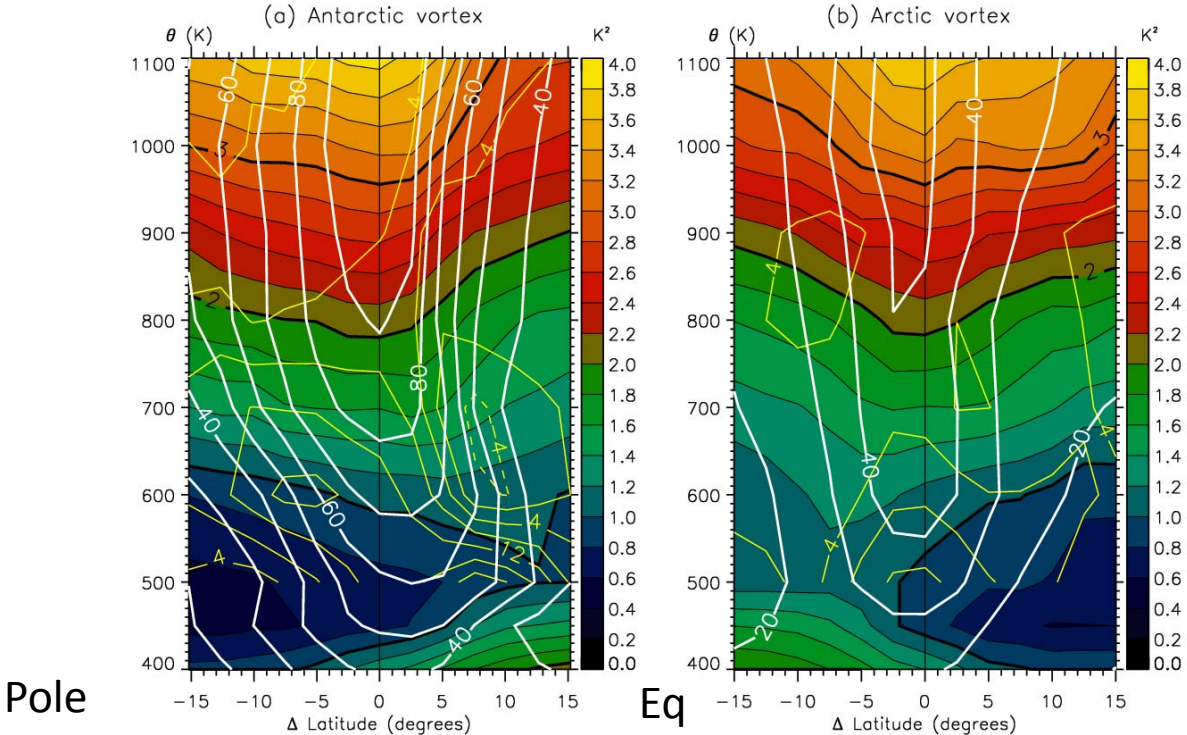
- COSMIC resolves more intermittent orographic waves than CHAMP due to the larger amount of occultation events
- Evidence of gravity-wave Doppler shifting and orographic-wave activity in monthly averages





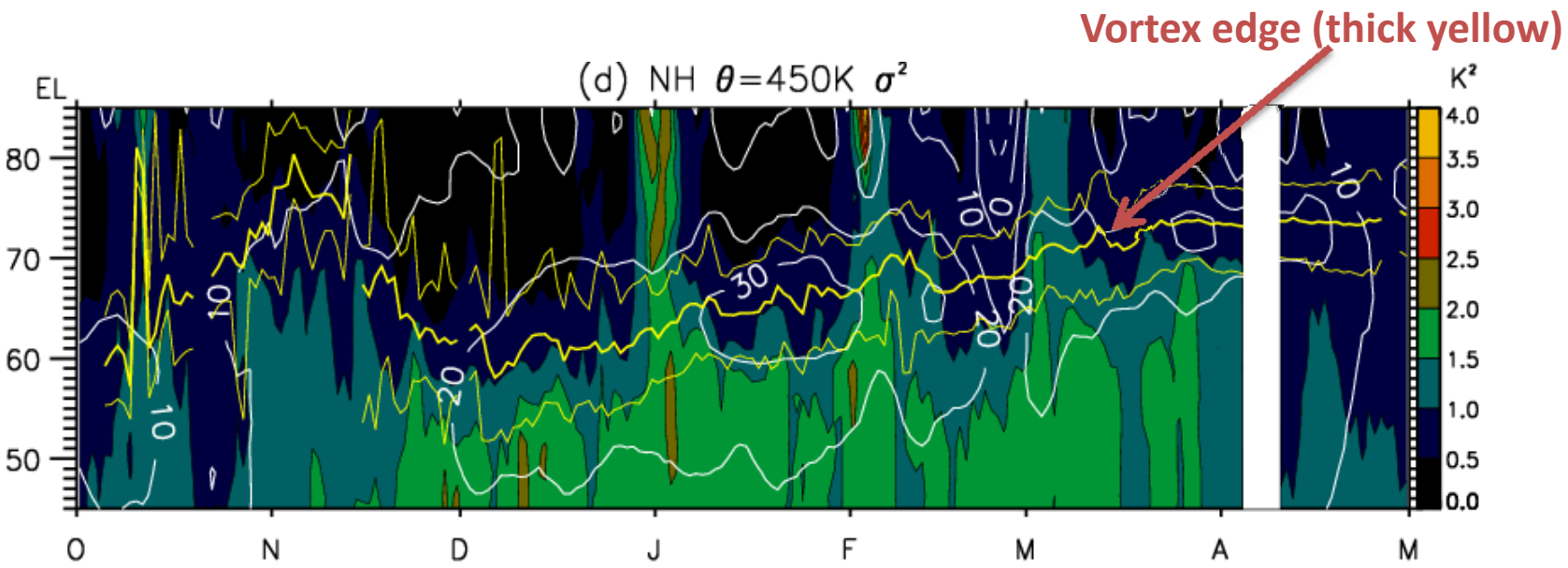
Gravity waves in the polar regions

- The σ^2 relative to the vortex edge on isentropic surfaces
  - Above 600K, the largest σ^2 correspond to the strongest winds at the vortex edge (Doppler shifting)
  - Below 600K, larger σ^2 occur equatorward of the vortex edge, suggesting sub-tropical or mid-latitude wave sources.



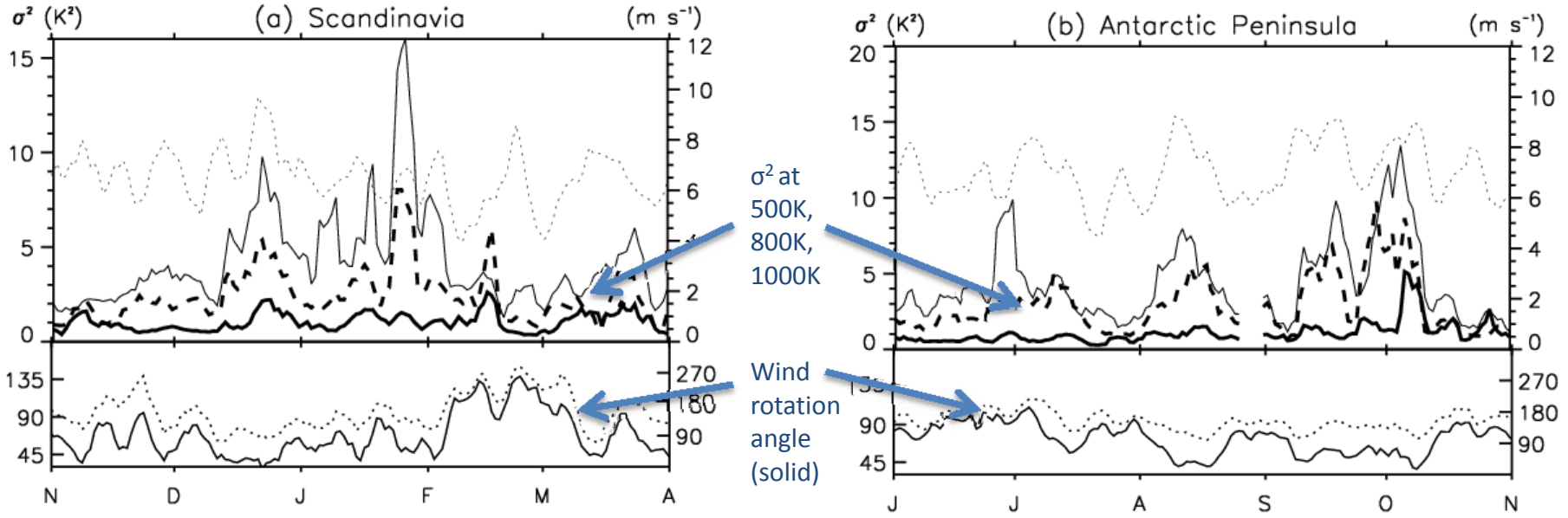
Gravity waves in the polar regions

- Time series of 2006-07 NH σ^2 in equivalent latitudes at 450K:
  - The poleward movement of the vortex edge during winter and the poleward movement of large σ^2 is seen, indicating poleward propagation of waves which are then likely focussed upward and into the stratospheric jet
  - Large increases in σ^2 inside the vortex at the start of Jan and Feb at times of minor SSWs



Gravity waves in the polar regions

- Large stratospheric σ^2 above mountain ranges are observed intermittently throughout winter, when there is relatively low wind rotation angle in the troposphere.
- Scandinavia (LHS) and the Antarctic Peninsula (RHS):



Orographic-gravity wave activity and Polar Stratospheric Clouds (PSCs)

- Question: Given that with COSMIC we can observe relatively short (< 1 week) variations in orographic-gravity wave activity above the Antarctic Peninsula, are these observable waves likely responsible for initiating the production of any PSCs?
- **Answer: YES!**



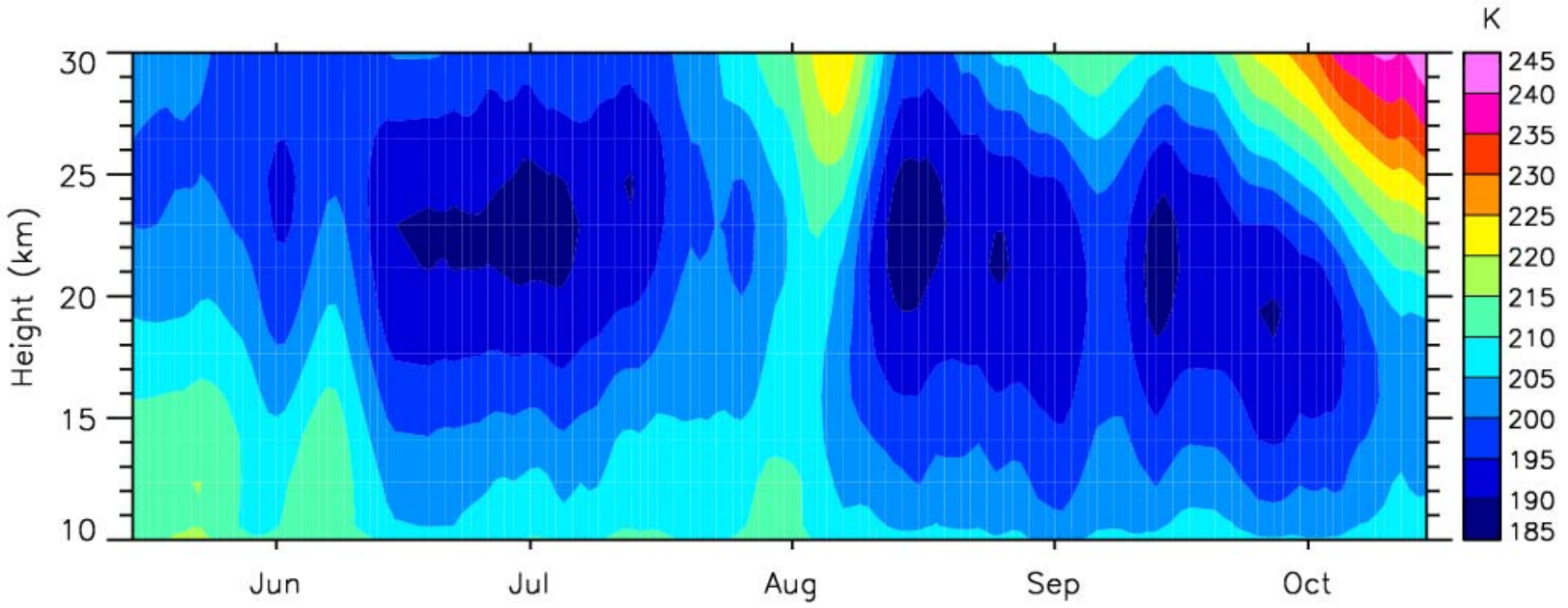


Orographic-gravity wave activity and Polar Stratospheric Clouds (PSCs)

- Alexander, Klekociuk, Pitts, McDonald and Arevalo-Torres, JGR (2011), in press
- Poster on Tuesday afternoon
- But, just to recap…
- Obtain PSC composition classes from CALIPSO lidar data (H_2O ice, STS, and two liquid / NAT mixed classes) during the 2007 austral winter.
- Then combine PSC results with COSMIC gravity wave σ^2 and MLS (for $T-T_{ice}$ and $T-T_{NAT}$)

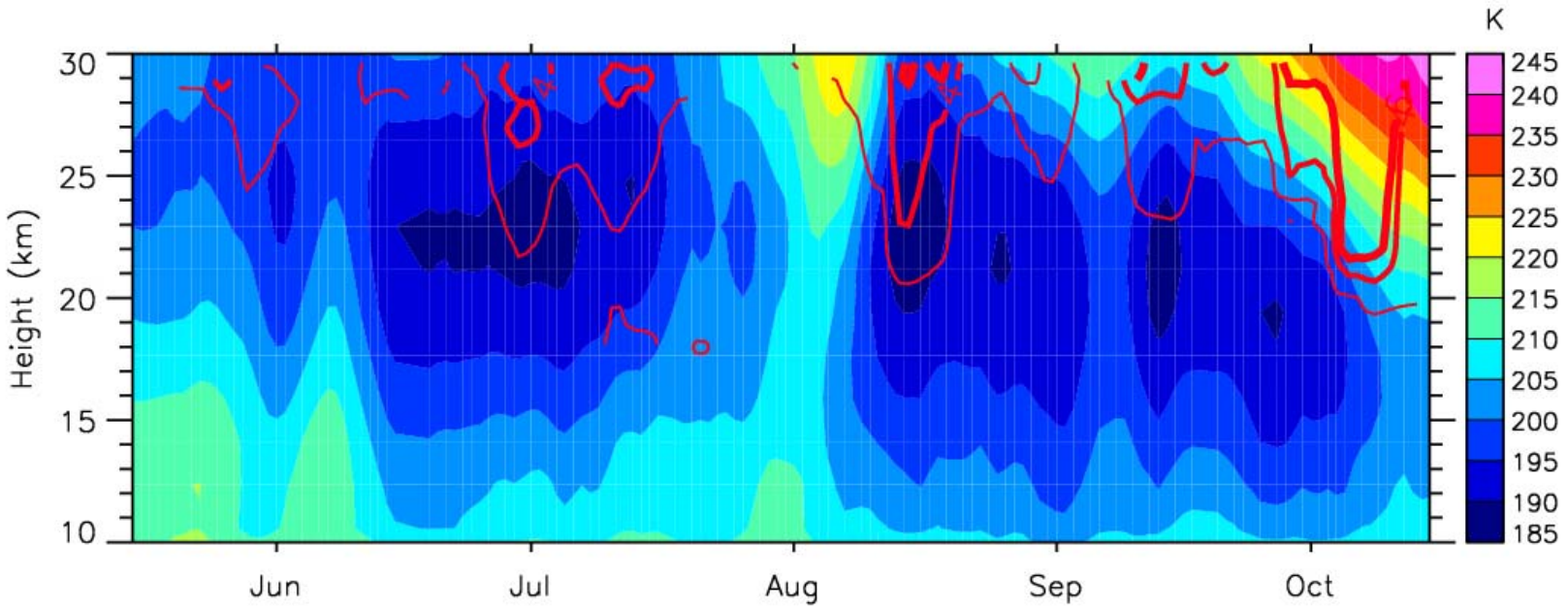
Orographic-gravity wave activity and Polar Stratospheric Clouds (PSCs)

- Antarctic Peninsula at 60-70S: mid-May to mid-October 2007
  - COSMIC temperatures (colour contour)



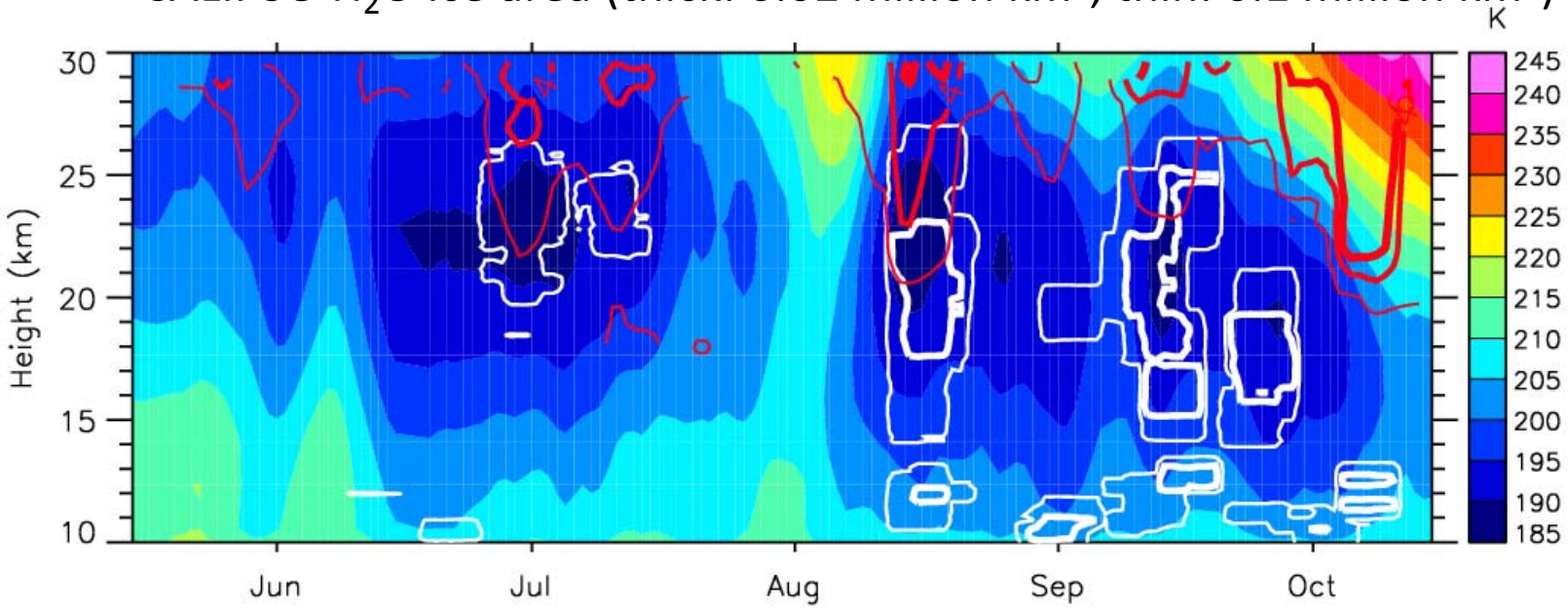
Orographic-gravity wave activity and Polar Stratospheric Clouds (PSCs)

- Antarctic Peninsula at 60-70S: mid-May to mid-October 2007
  - COSMIC temperatures (colour contour)
  - COSMIC σ^2 (red lines, units of K^2) – intermittent, large orographic waves



Orographic-gravity wave activity and Polar Stratospheric Clouds (PSCs)

- Antarctic Peninsula at 60-70S: mid-May to mid-October 2007
  - COSMIC temperatures (colour contour)
  - COSMIC σ^2 (red lines, units of K^2) – intermittent, large orographic waves
  - CALIPSO H_2O ice area (thick: 0.02 million km^2, thin: 0.1 million km^2)

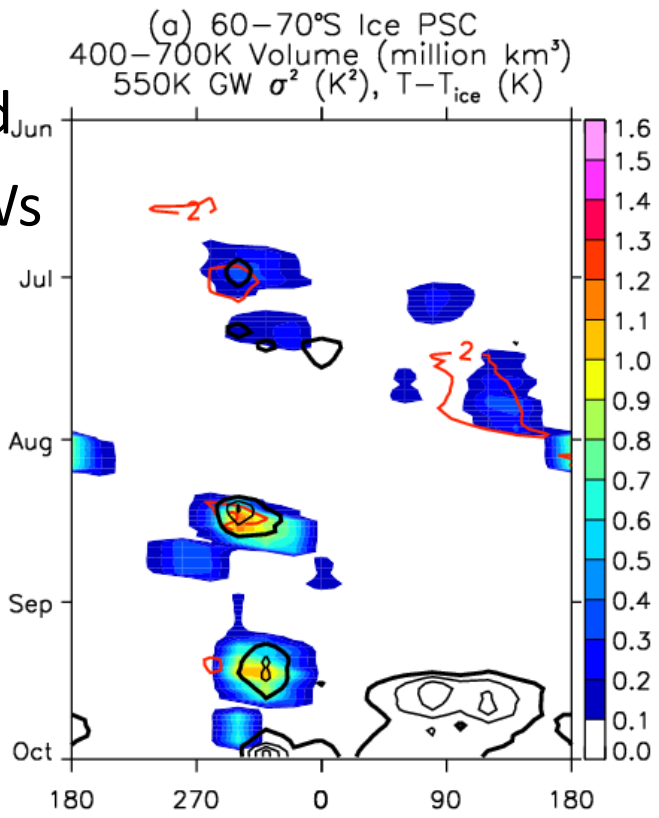


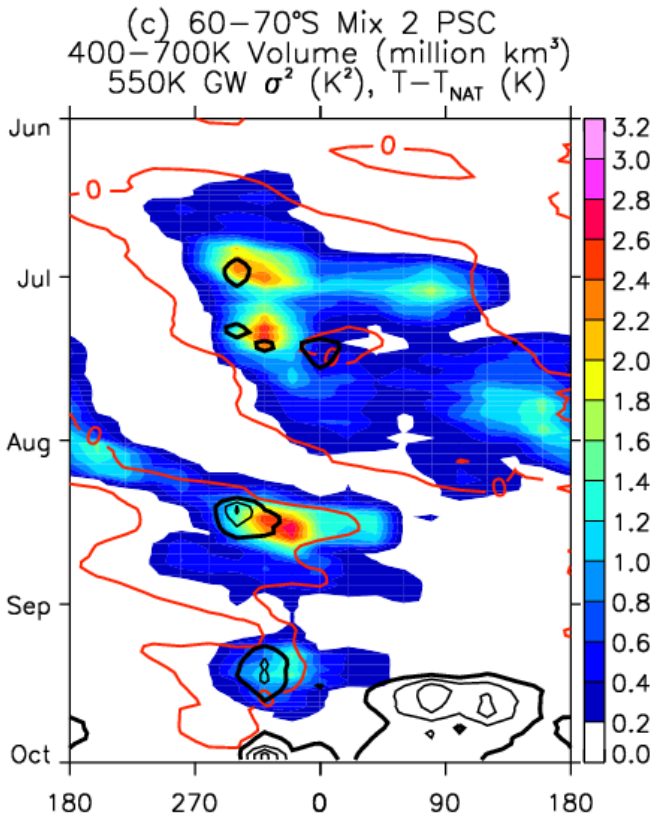
Orographic-gravity wave activity and Polar Stratospheric Clouds (PSCs)

- Large H_2O ice volumes above Peninsula when have large orographic gravity wave σ^2
- Increased NAT volumes for considerable distances downstream
- OGWs needed

in addition to PWs

to explain PSCs





Summary

- COSMIC observations and T106L60 model studies of equatorially-trapped waves and convectively-generated gravity waves in the tropics show good agreement. COSMIC observes gravity waves directly above convection, Kelvin waves and Mixed Rossby Gravity Waves.
- Gravity waves observed by COSMIC and generated in the mid-latitudes are likely focussed into the winter stratospheric jets. Doppler shifting of waves by the background winds occurs.
- The regional variability of orographic and non-orographic waves in the polar regions is seen with COSMIC, over sub-weekly time-scales.
- Orographic gravity waves above the Antarctic Peninsula induce the formation of polar stratospheric clouds (water ice and then NAT downstream) in the lower stratosphere.

References

- Alexander, S. P., T. Tsuda and Y. Kawatani (2008), 'COSMIC GPS Observations of Northern Hemisphere Winter Stratospheric Gravity Waves and Comparisons with an Atmospheric General Circulation Model', *Geophysical Research Letters*, **35**, L10808, doi:10.1029/2008GL033174
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