# Tropical Waves in Satellite Observations and Reanalyses

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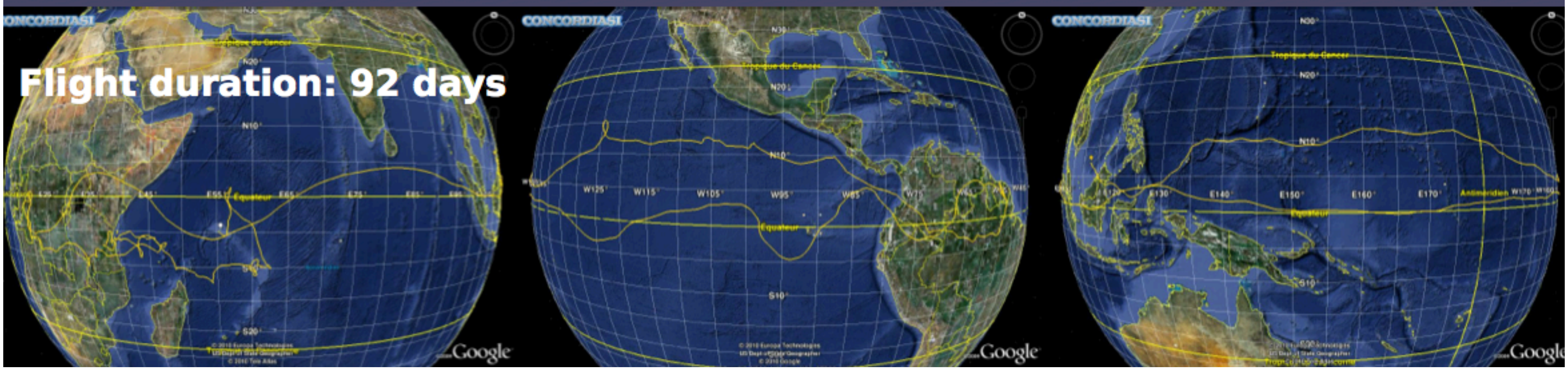
# Motivation

- Pre-Concordiasi, Seychelles Is., Feb-May 2010: 3 balloons




**Super-pressure balloons drifted at 60hPa measuring tropical winds for several months.**

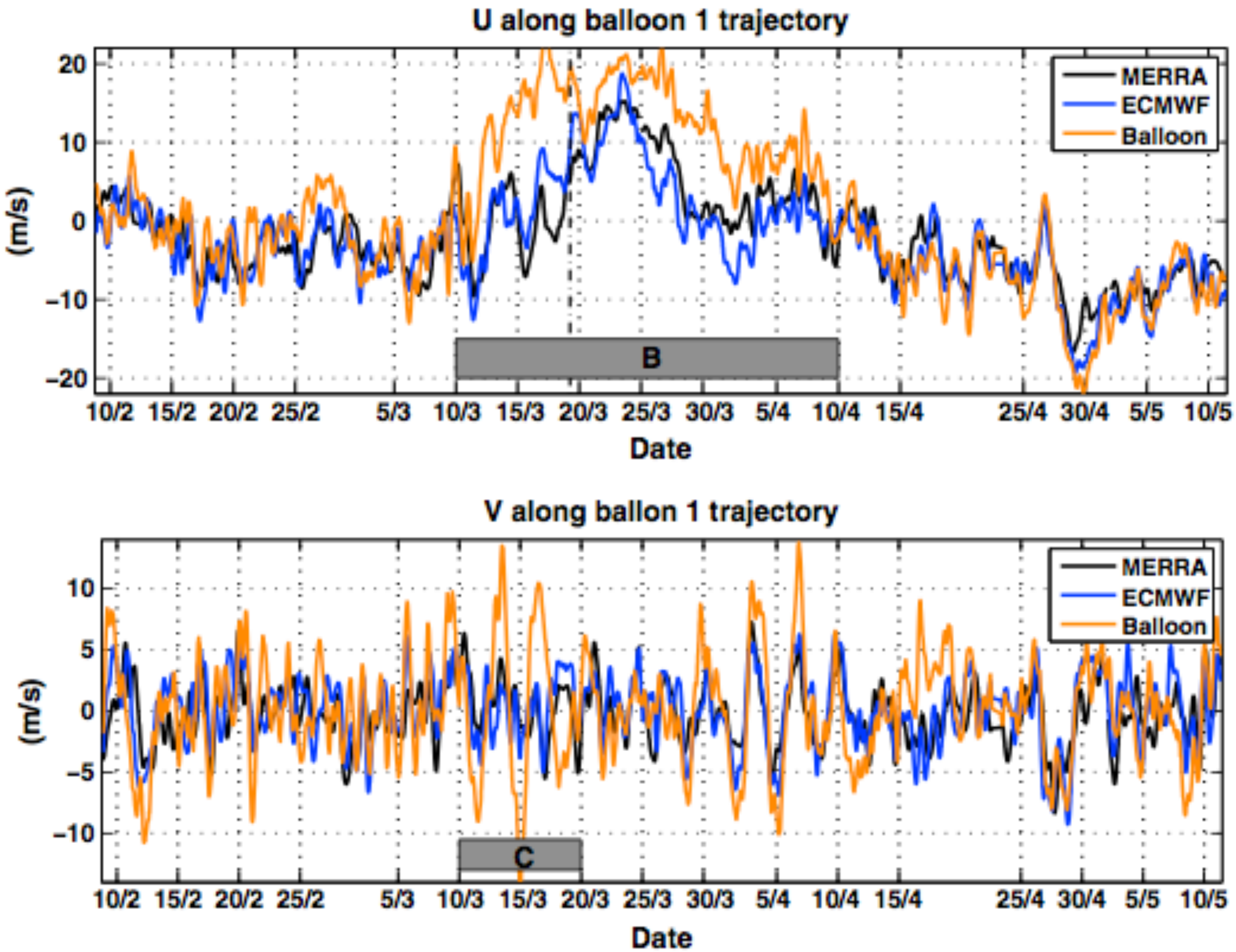
**Podglagen et al [2014] use these measurements to assess the accuracy of tropical analyses.**

# Motivation

**[Podglagen et al 2014]**

**MERRA and ECMWF analysis sampled along the balloon track showed large errors in winds 10-20m/s.**

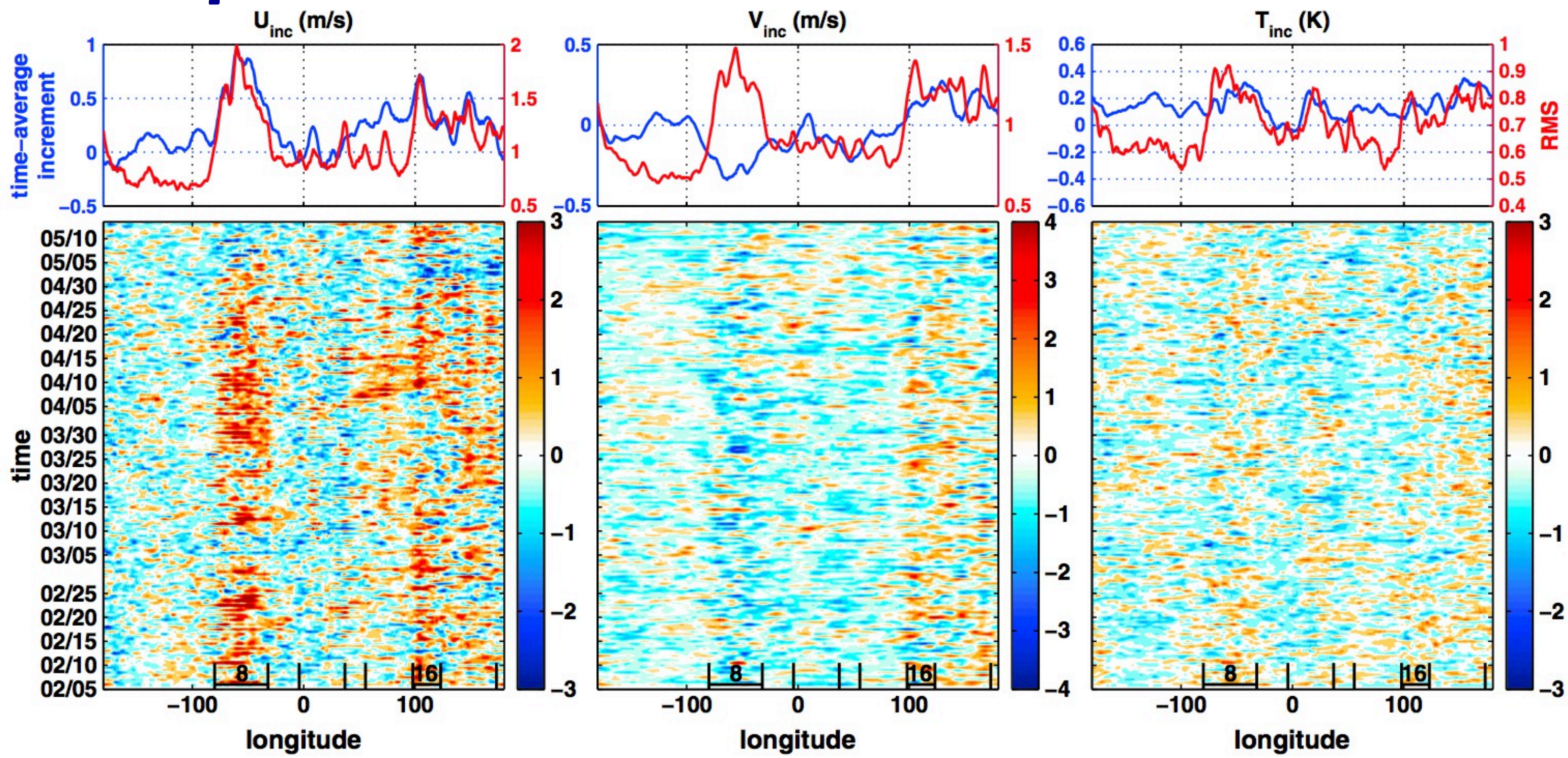
**Errors traced to Kelvin and Yanai waves over the Indian Ocean and Eastern Pacific.**



# Motivation

**[Podglagen et al 2014]**

**Analysis increments**




- **Tropical analysis wind increments are clustered in longitude where radiosondes are located.**
- **Temperatures increments are more uniformly distributed (GPS is assimilated).**
- **Temperatures and winds are not properly coupled, so tropical waves may be misrepresented.**

# Tropical Waves in Satellite Observations

**Using high-resolution satellite observations for independent examination of tropical wave properties.**

**High Resolution Dynamics Limb Sounder (HIRDLS) provided 3 years of measurements; over 5500 temperature profiles per day.**

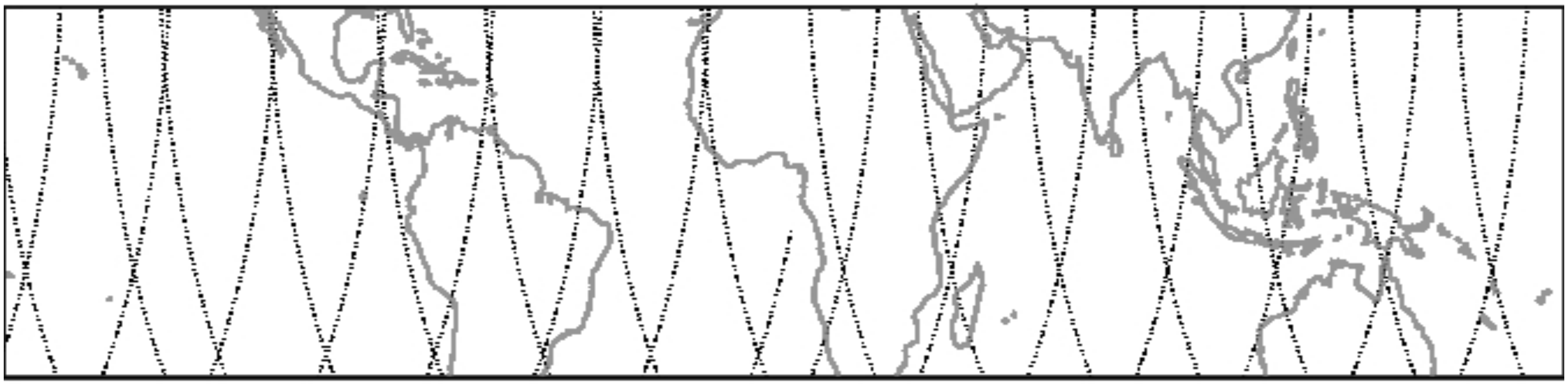
**HIRDLS observed in the IR, so only measurements above clouds.**

**Using the Salby [1982] method for asynoptically sampled satellite data to derive spectral properties of waves as** $\exp(-i\omega t + is\lambda)$ **at high vertical (~1 km) and latitudinal (~1$^{o}$) resolution.**

# High Resolution Dynamics Limb Sounder

**Advantage of HIRDLS Sampling: Comparison to SABER and GPS**

**Example: single day of HIRDLS profile measurements**



| | HIRDLS | SABER | GPS |
|---|---|---|---|
| Vertical Resolution | 1.2 km | ~2-2.5km | 1 km |
| Zonal resolution | wn ~ 7 | wn ~ 7 | wn<8? |
| 10S-10N profiles/day | ~650 | ~200 | ~200* |

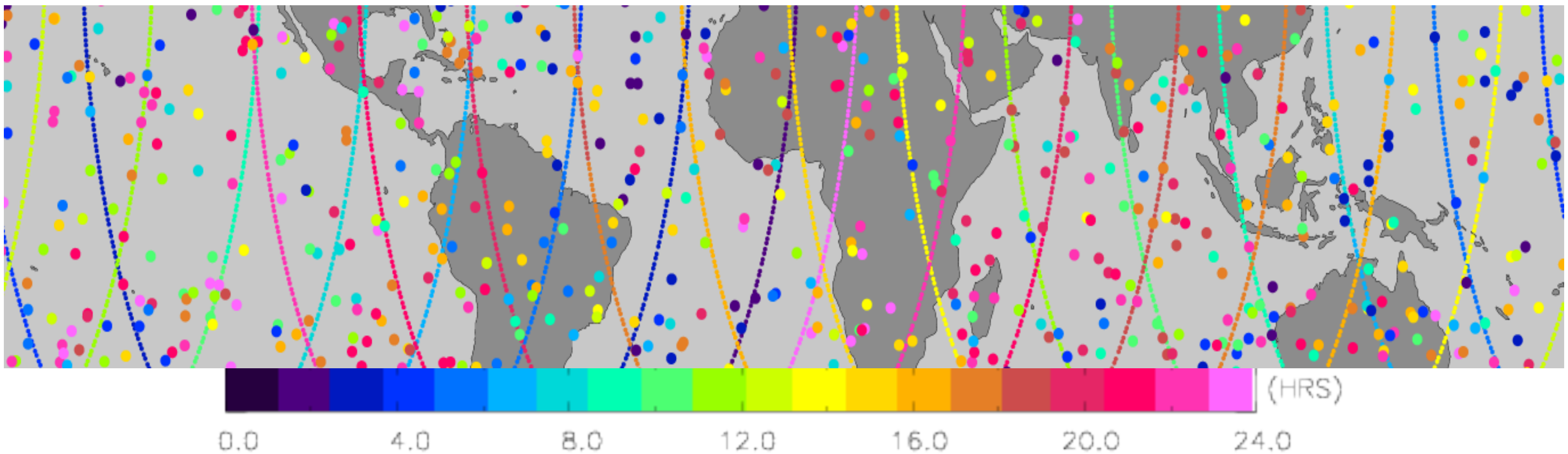
* Champ + COSMIC

- **HIRDLS vertical resolution like GPS; much higher 1° latitudinal resolution**
- **3 years of observations: January 2005 – March 2008**

# High Resolution Dynamics Limb Sounder

## Advantage of HIRDLS Sampling: Comparison to SABER and GPS

### Example: single day of HIRDLS profile measurements

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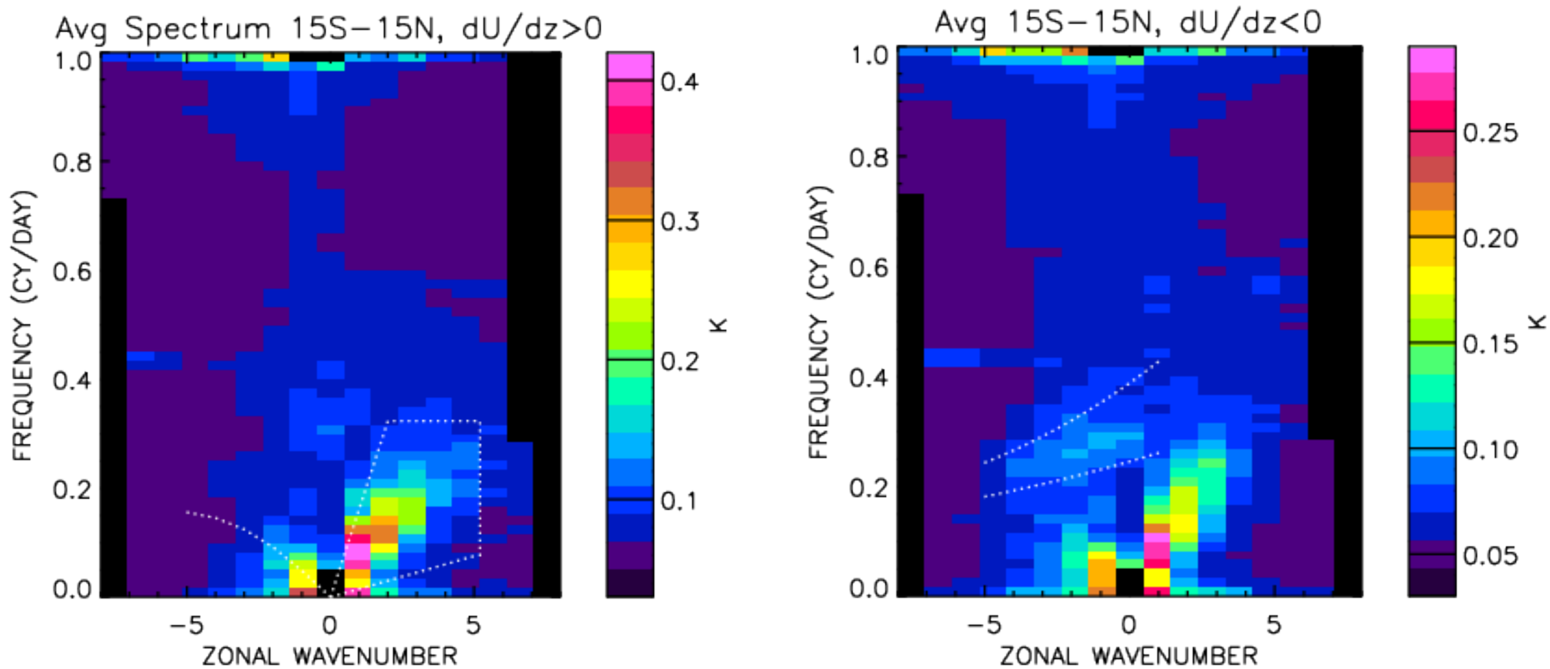
- **HIRDLS sampling is advantageous for wavenumber-frequency analysis of tropical waves.**

# Asynoptic Fourier Analysis (Salby Method)

## HIRDLS Temperature Spectra

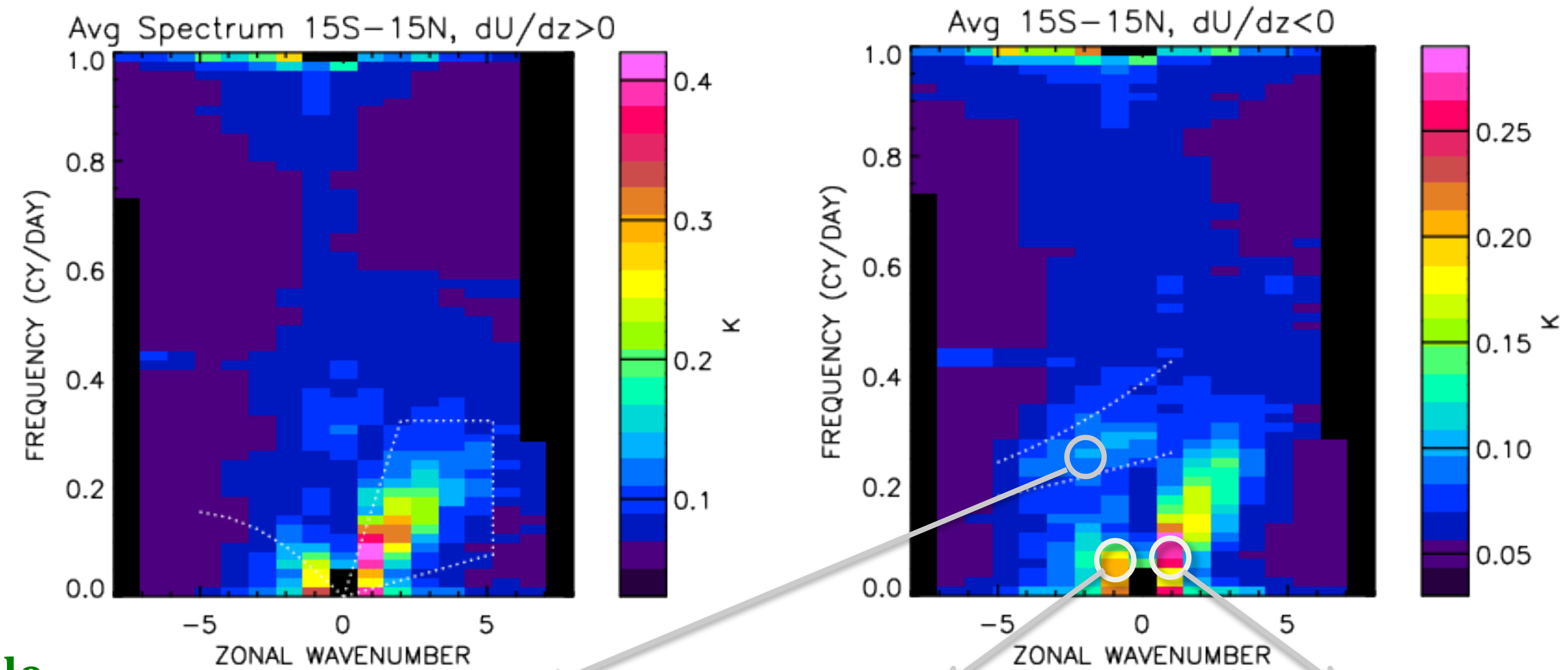



**Wavenumber-frequency spectrum of HIRDLS temperatures, z=15-32 km**
**Wave periods 1-60 days**
**Averaged: 15$^o$S-15$^o$N; 3 years January 2005-2008.**

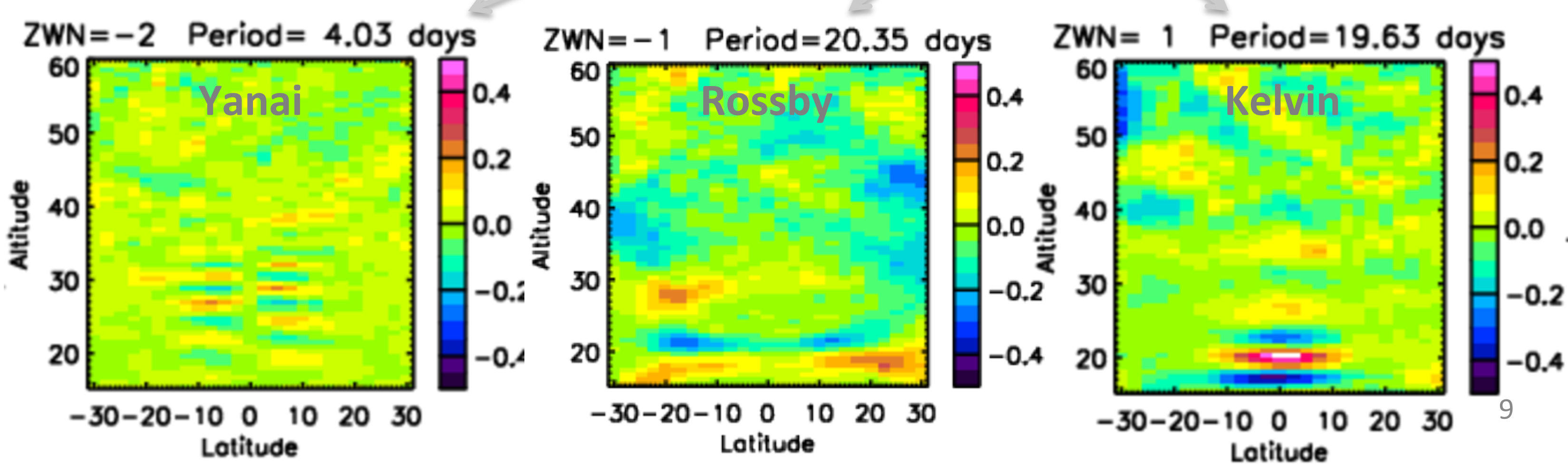
**Left: Eastward shear with U < 8m/s**
**Right: Westward shear with U >-20m/s**

# Asynoptic Fourier Analysis (Salby Method)

## HIRDLS Temperature Spectra

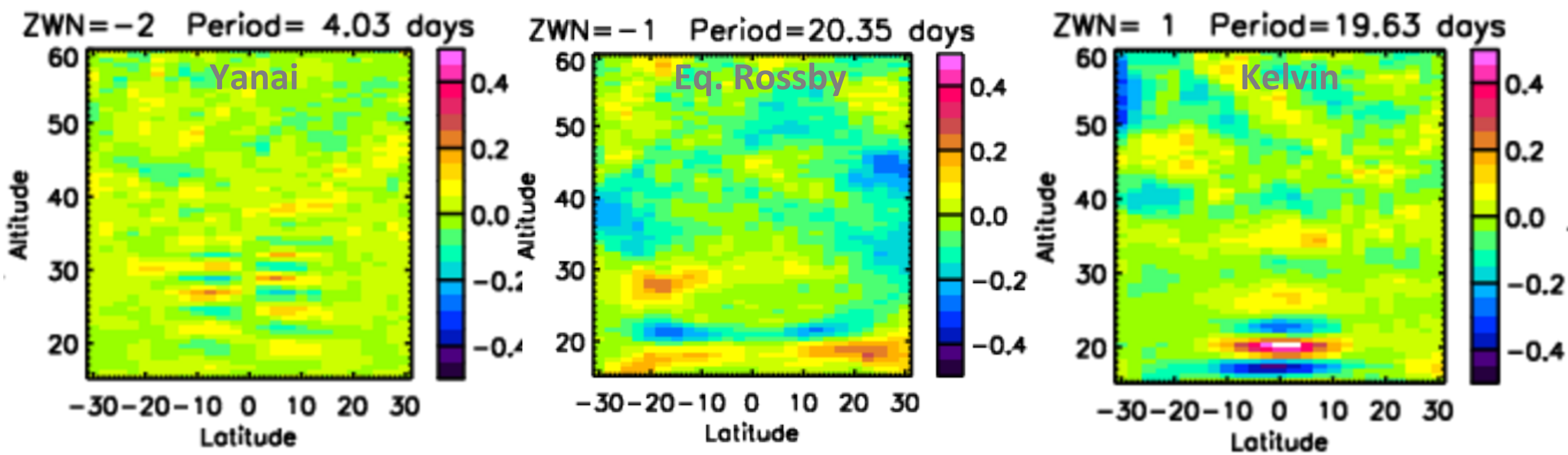



**Sample modes:**



# Asynoptic Fourier Analysis (Salby Method)

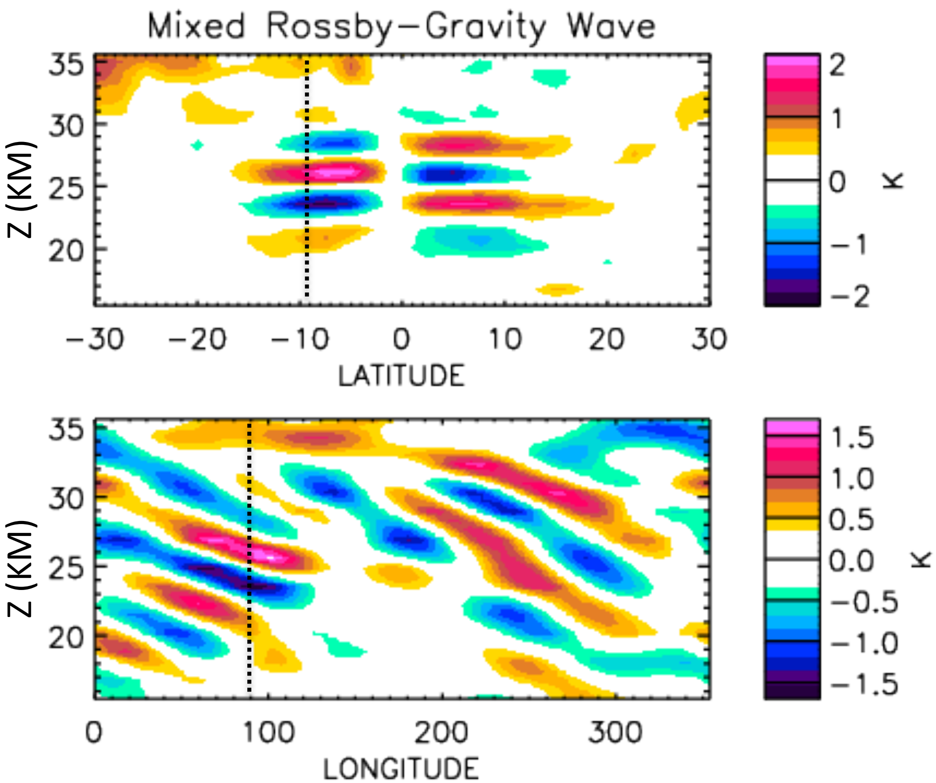
**Modal Latitude-Height Structures**




- Individual spectral points from a 60-day time series.
- Color shows real part of the complex amplitude.
- Each point in latitude and height in these plots results from a completely independent spectral analysis.
- Symmetric/asymmetric structures confined to the tropical latitudes validate the interpretation of these signals.
- Vertical wavelengths near the limits of resolution are clearly visible.

# Example Wave Events

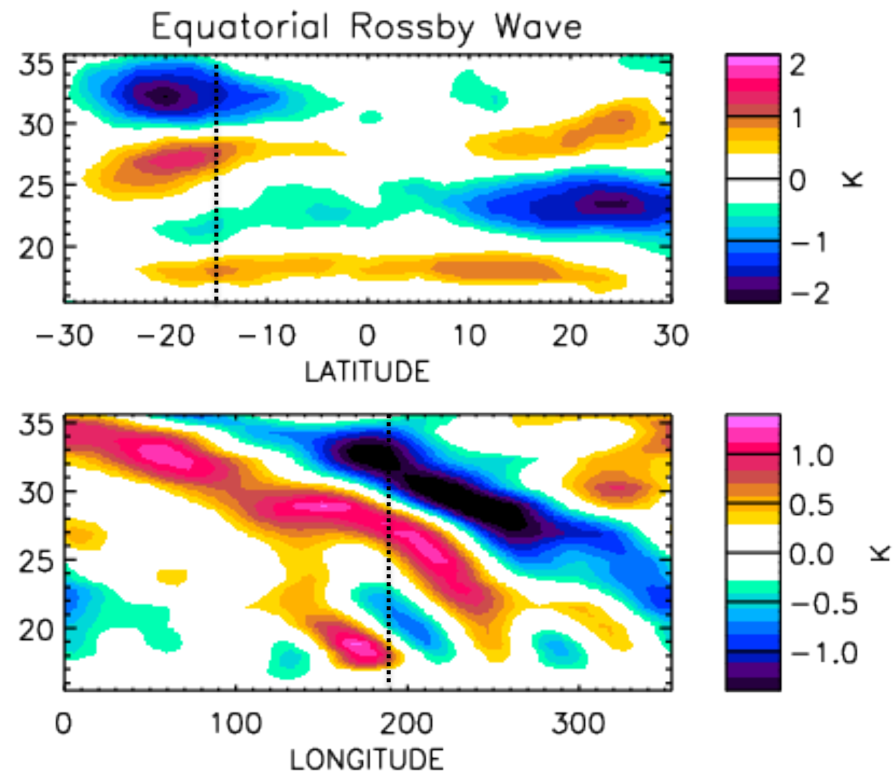
**Yanai wave**
**Day 305 2006**




**Filter: $s$ = -5 to 0; $\lambda_z$ = 4-10km**

Mixed Rossby-gravity strong event with $wn$ ~ 3, although these waves appear weak in averaged spectrum.

**Equatorial Rossby wave**
**Day 354 2006**

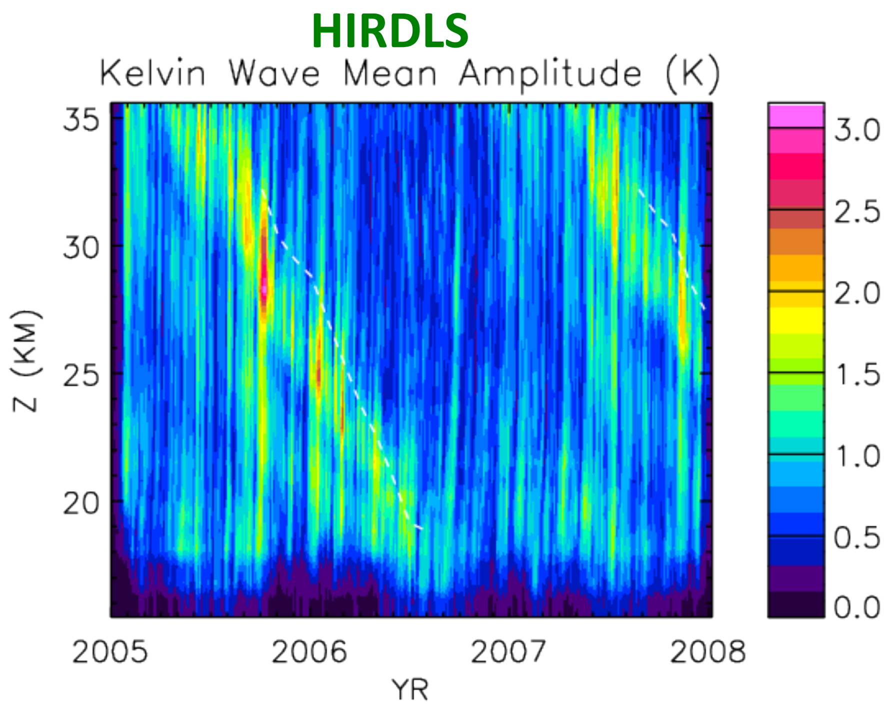


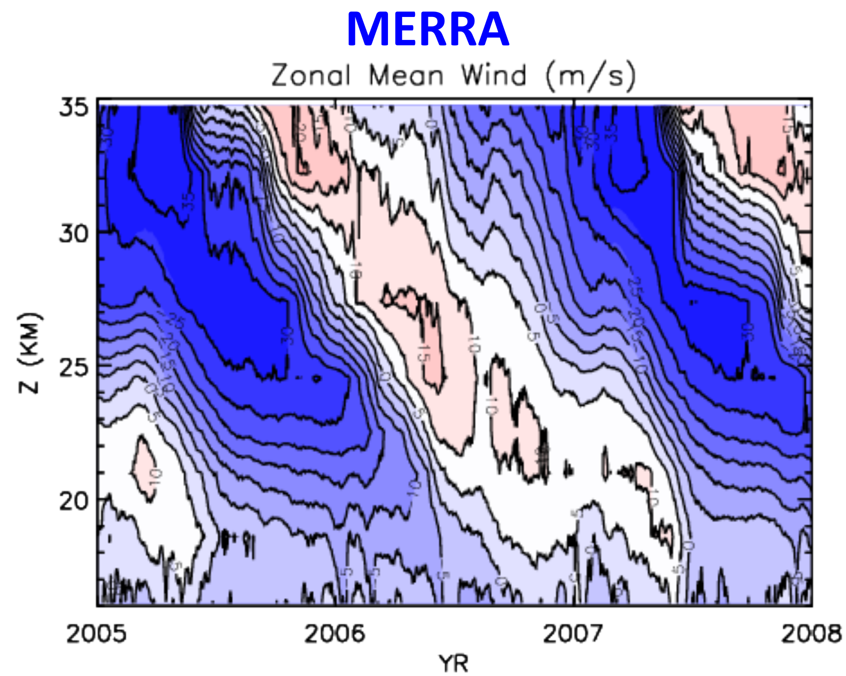

**Filter: $s$ = -5 to -1; $\lambda_z$ < 20km; Pd > 32d**

Example displays clear $n$=1 symmetric equatorial Rossby wave structure with $wn$ ~ 2-4

# Kelvin Waves

**Filter: *s* = 1-5, Pd = 3-20 days, *c* = 7-75 m/s**




- **Bursts of activity associated with faster descent of QBO westerlies.**

# Kelvin Waves

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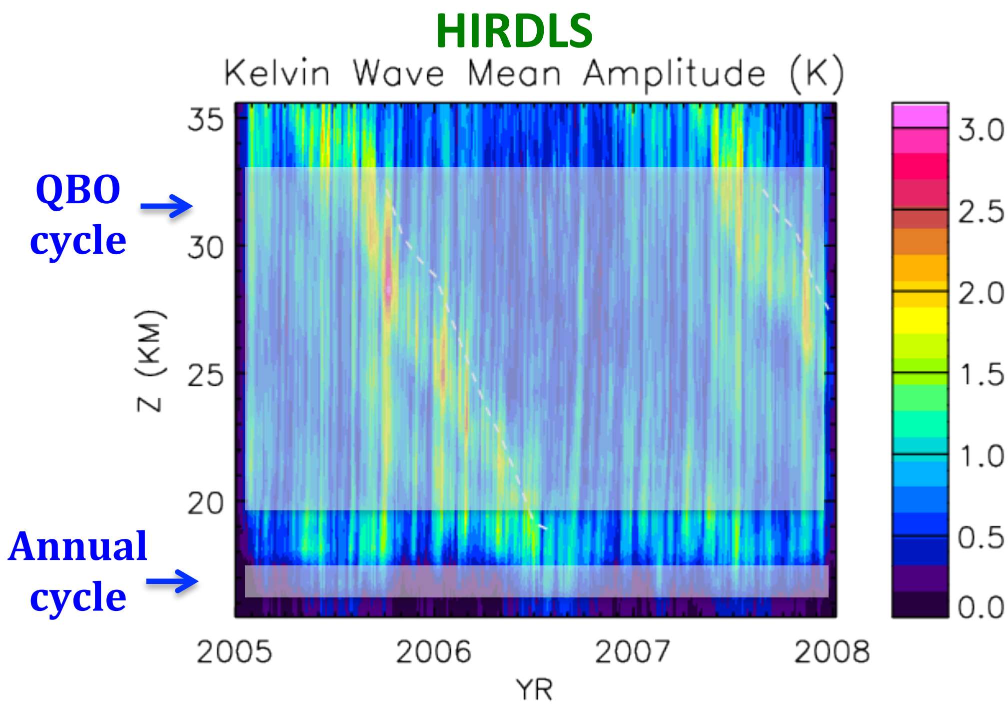
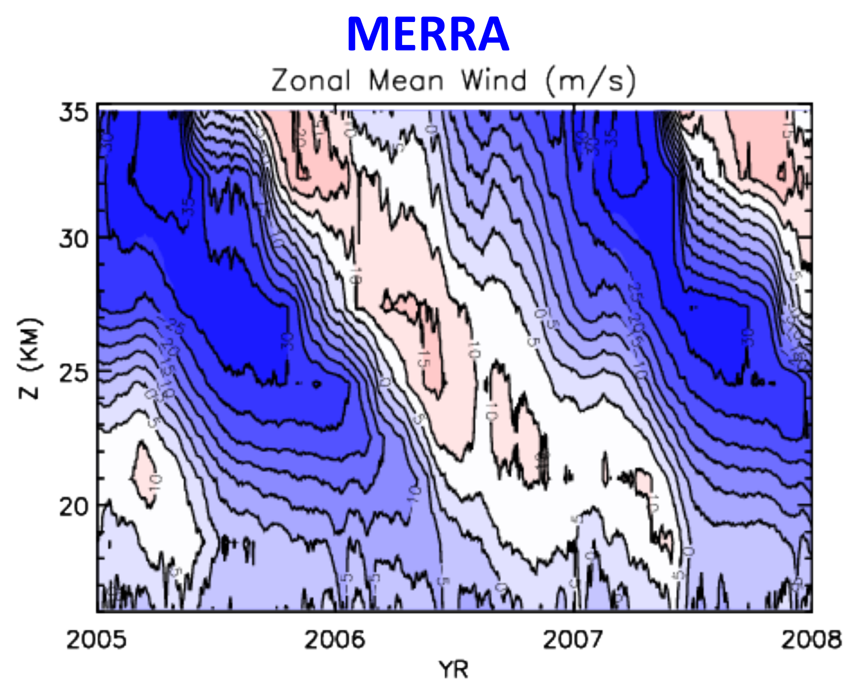


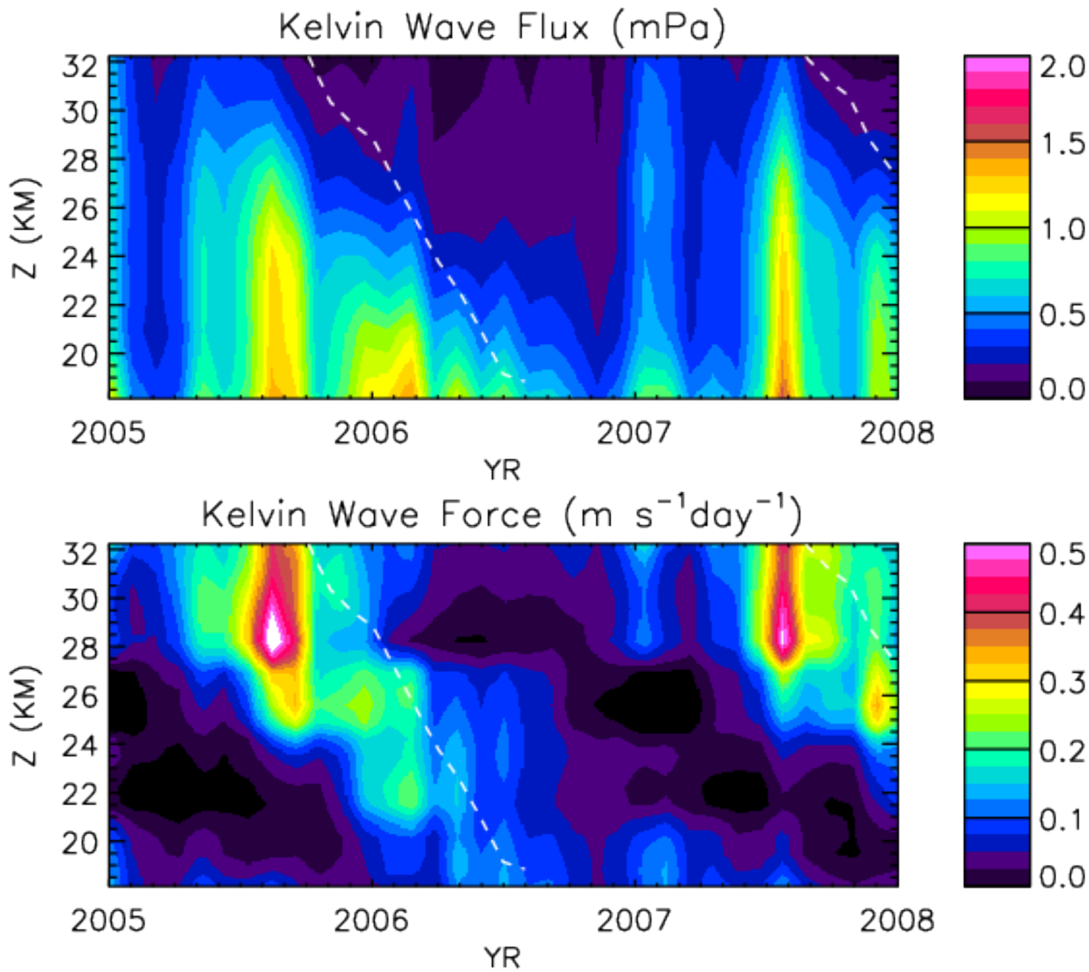




- **Bursts of activity associated with faster descent of QBO westerlies.**
- **Amplitude variations switch from annual cycle near the tropopause to a QBO variation above 70 hPa.**

# Kelvin Wave Forcing of the QBO

**Kelvin wave momentum flux from HIRDLS**

$$M = \frac{\rho}{2}\frac{k}{m}\left(\frac{g\tilde{T}}{N\overline{T}}\right)^2$$




Vertical wavenumber from the Kelvin wave dispersion relation:

$$m(z) = N(z)k/(\omega - U(z)k)$$

Force driving the QBO:

$$F = \frac{-1}{\rho}\frac{\partial M}{\partial z}$$

**Force derived from HIRDLS temperatures:**

**Kelvin waves provide 50% of the total force needed to drive descent of QBO westerlies**

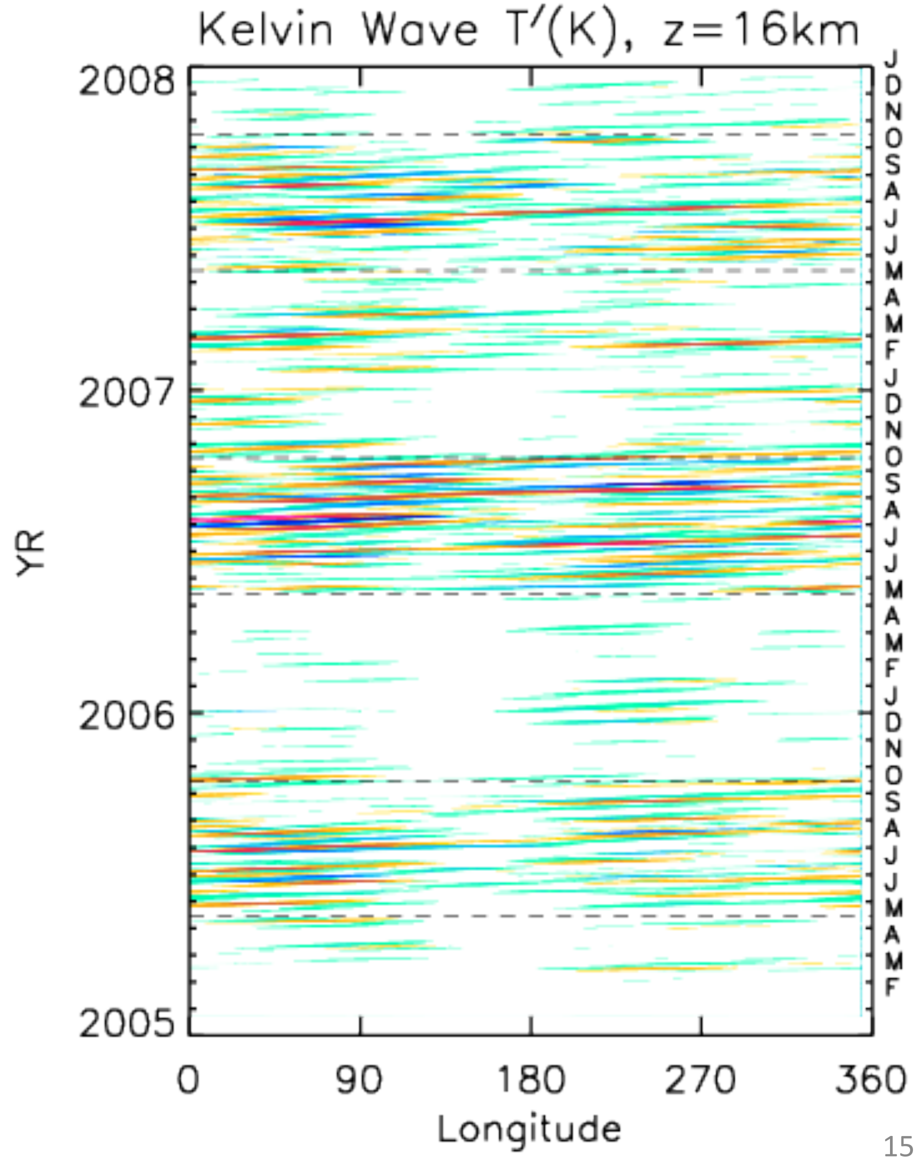
# Kelvin Waves

## HIRDLS Kelvin Waves near the tropopause

Longitude-time Kelvin wave perturbations at the equator.

Annual cycle with maximum amplitudes in Boreal summer at this altitude, gives way to QBO cycle above ~18 km.

Largest perturbations often appear over equatorial Africa and Indian Ocean.



# Eliassen-Palm Flux from HIRDLS

## Generalized formula for all HIRDLS-resolved tropical modes

**Vector EP-flux**

$$F^{(z)} = \rho a \cos\theta \left[ \frac{\bar{Z}}{N^2} \overline{v'\Phi'_z} - \overline{w'u'} \right]$$

$$F^{(y)} = \rho a \cos\theta \left[ \frac{\bar{u}_z}{N^2} \overline{v'\Phi'_z} - \overline{v'u'} \right]$$

$$\bar{Z} = f - (a\cos\theta)^{-1} (\bar{u}\cos\theta)_\phi$$

$$\bar{f} = f + (\bar{u}\tan\theta)/(2a)$$

**For waves of the form** $\exp(-i\omega t + is\lambda + \phi(\theta, z))$

$$F^{(z)} = \frac{\rho s}{2N^2} Re[i\hat{\Phi}\hat{\Phi}^*_z]$$

$$F^{(y)} = \frac{\rho s}{2(\tilde{\omega}^2 - \bar{f}\bar{Z})} Re[i\hat{\Phi}\hat{\Phi}^*_y]$$

$$y = a\theta$$

$$\tilde{\omega} = \omega - s\bar{u}$$

**For single mode assume the phase** $\phi(y, z) = \exp(imz + \phi_0(y))$

***EP-flux in terms of temperature and wave properties***

$$F^{(z)} = \frac{\rho s}{2m} \frac{g^2}{N^2} \frac{|\hat{T}|^2}{\bar{T}^2}$$

$$F^{(y)} = \frac{\rho s g^2 \partial_y \phi}{2m^2(\tilde{\omega}^2 - \hat{f}\bar{Z})} \frac{|\hat{T}|^2}{\bar{T}^2}$$

***All observed by HIRDLS and zonal mean wind from reanalysis***

# Eliassen-Palm Flux from HIRDLS

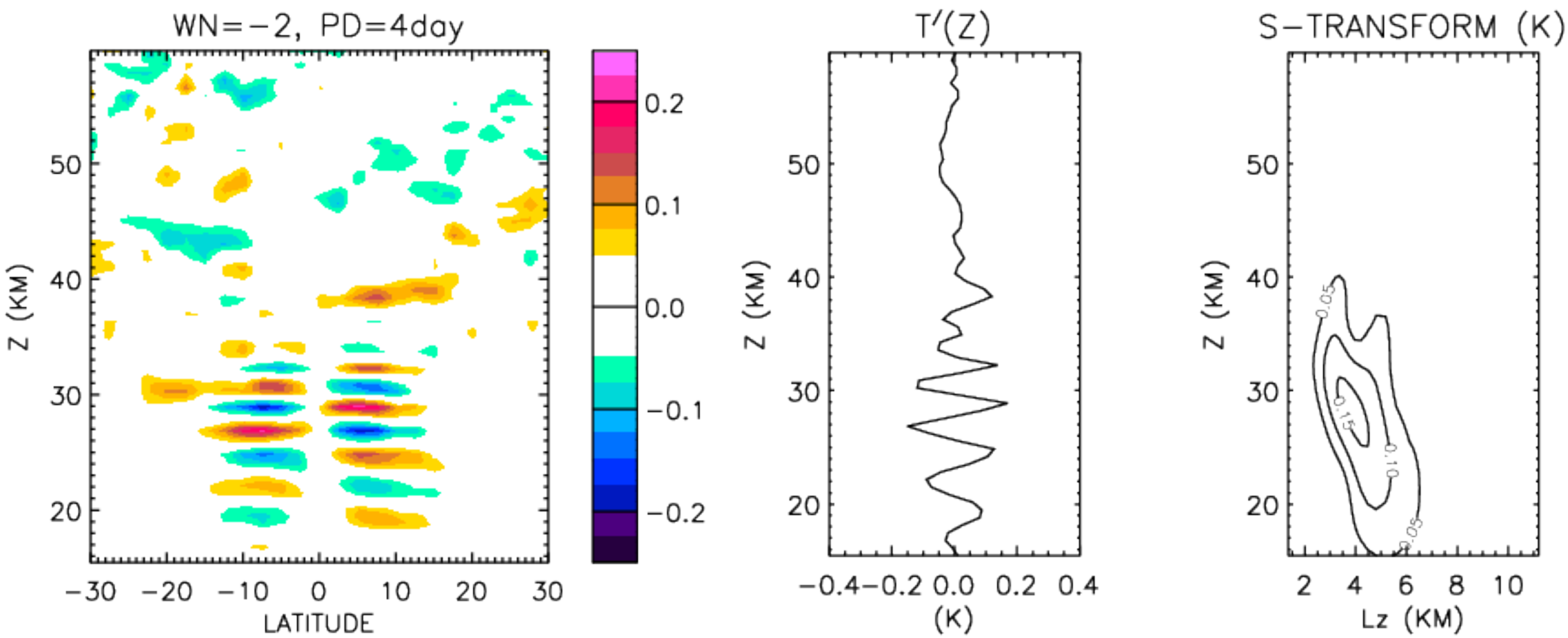
## Compute *m(z)* for vertical EP-flux $F^{(z)}$ with S-Transform

[Stockwell et al. 1996]

$$F^{(z)} = \frac{\rho s}{2m}\frac{g^2}{N^2}\frac{|\hat{T}|^2}{\bar{T}^2}$$

**Single Mode *(s, ω)***

**Amplitude *(m,z)***

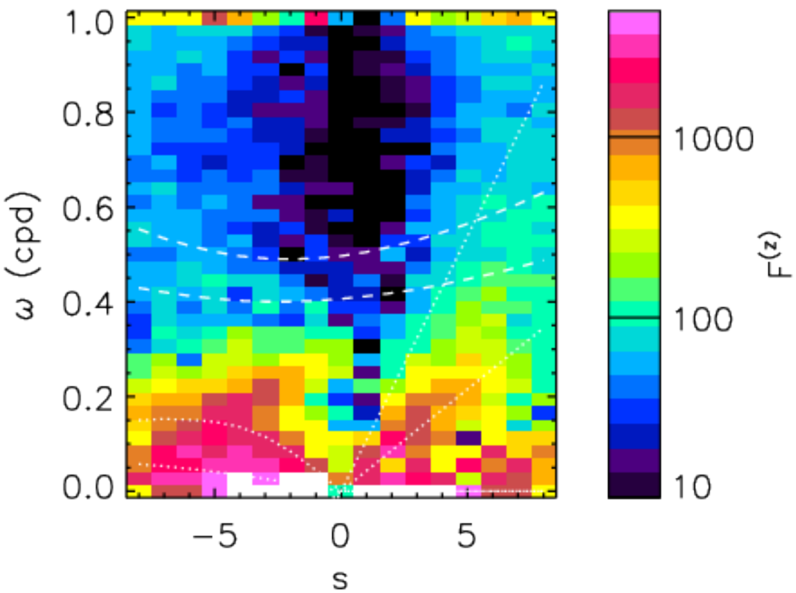


# Vertical EP Flux in MERRA 100hPa

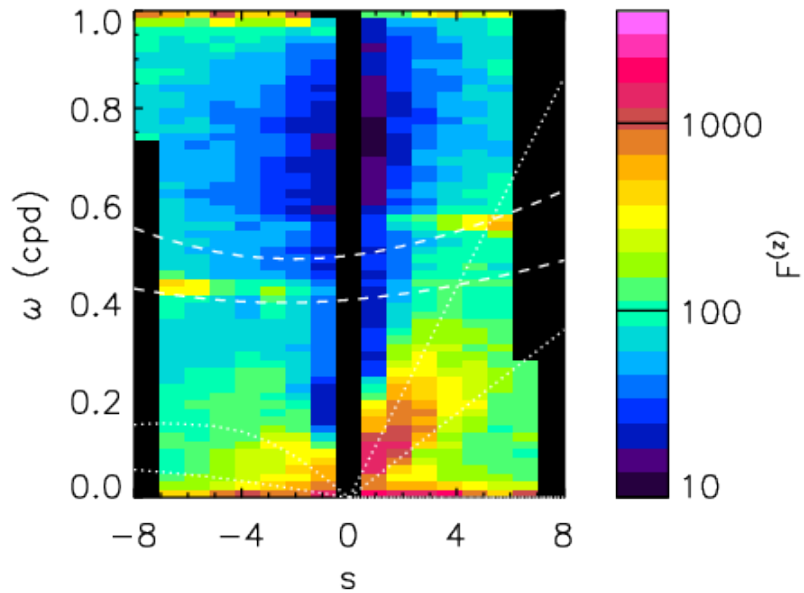
$$F^{(z)} = \rho a \cos\theta \left[ \frac{\bar{Z}}{N^2} \overline{v'\Phi'_z} - \overline{w'u'} \right]$$

$$F^{(z)} = \frac{\rho s}{2m} \frac{g^2}{N^2} \frac{|\hat{T}|^2}{\bar{T}^2}$$

**With MERRA winds and temperatures**




**MERRA temperatures-only sampled like HIRDLS**



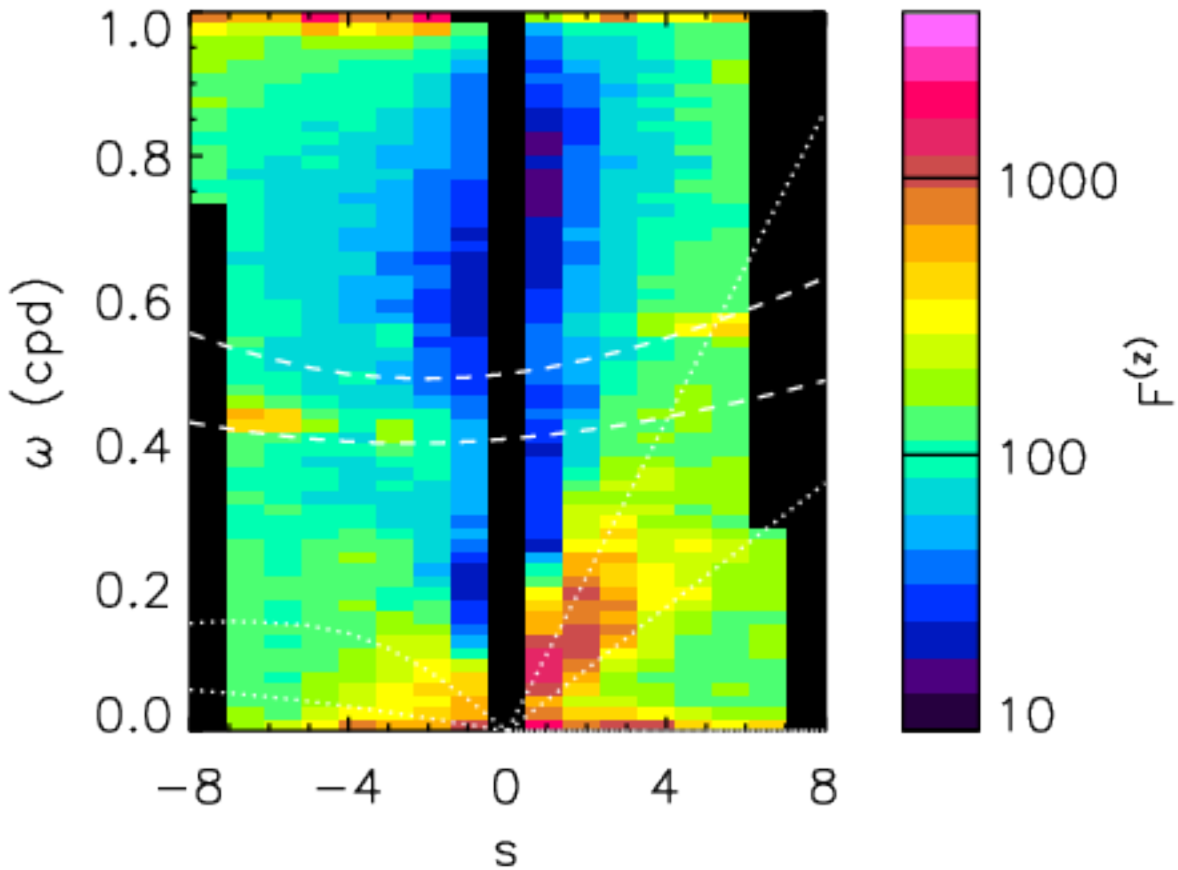

- Equatorial Rossby modes are severely under-represented with T only
- Method is localized in height by using S-Transform to compute m(z), but not localized to an individual level.

# Eliassen-Palm Flux Spectrum

**Vertical EP-flux *F*$^{(z)}$**

$$F^{(z)} = \frac{\rho s}{2m}\frac{g^2}{N^2}\frac{|\hat{T}|^2}{\bar{T}^2}$$

**HIRDLS Spectrum 16-18km**

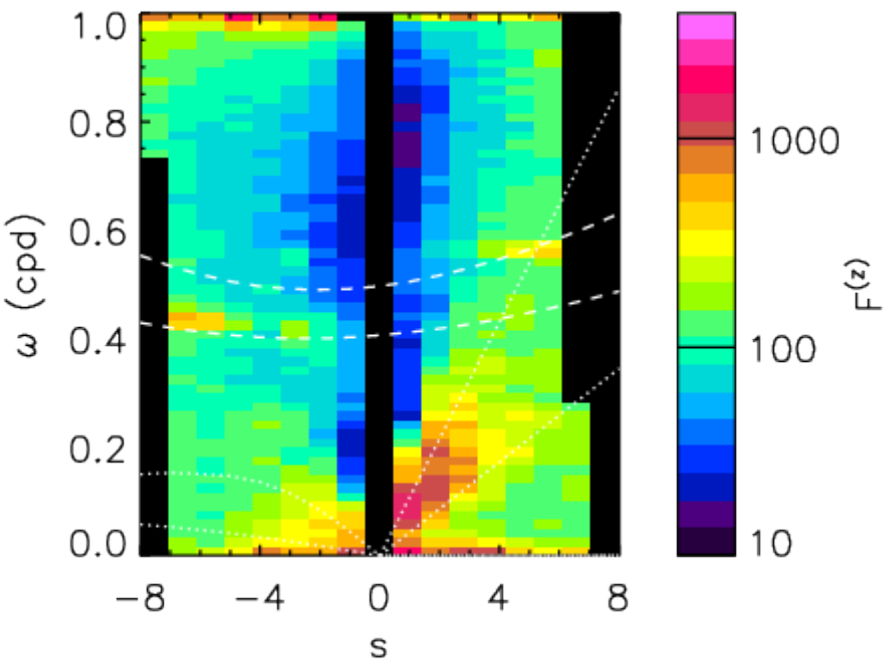


# Eliassen-Palm Flux Spectrum

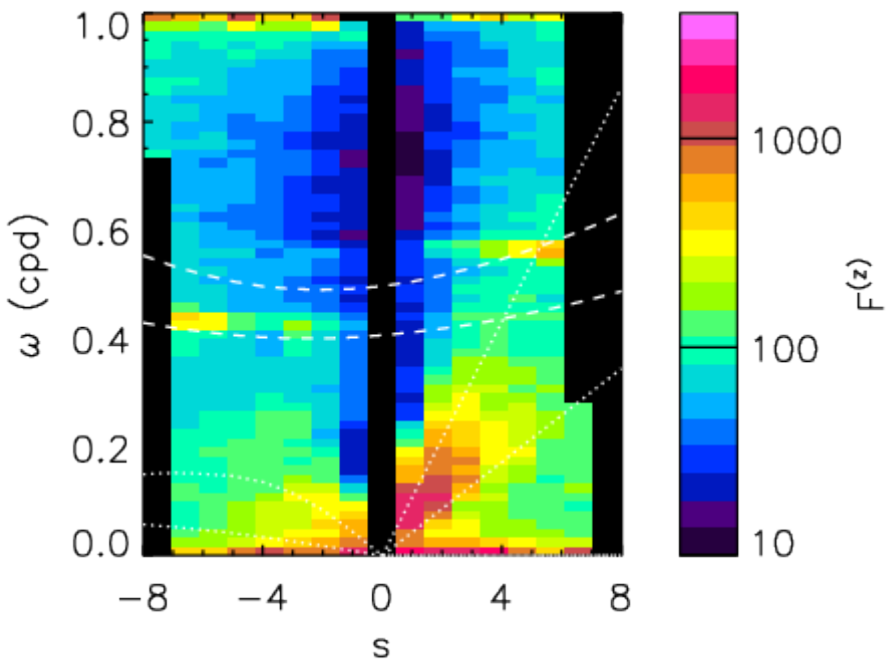
**Vertical EP-flux $F^{(z)}$**

$$F^{(z)} = \frac{\rho s}{2m}\frac{g^2}{N^2}\frac{|\hat{T}|^2}{\bar{T}^2}$$

**HIRDLS**




**MERRA sampled like HIRDLS**

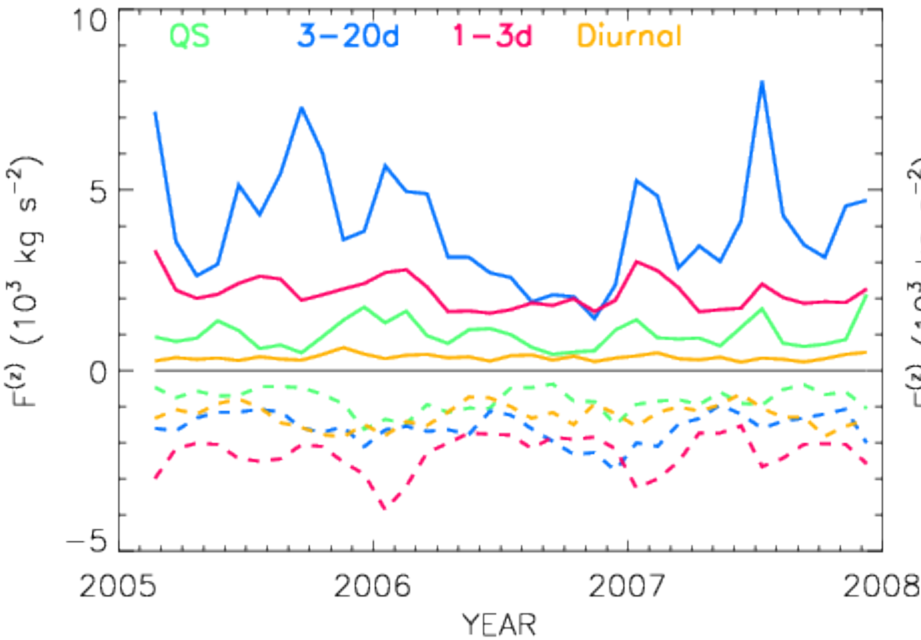


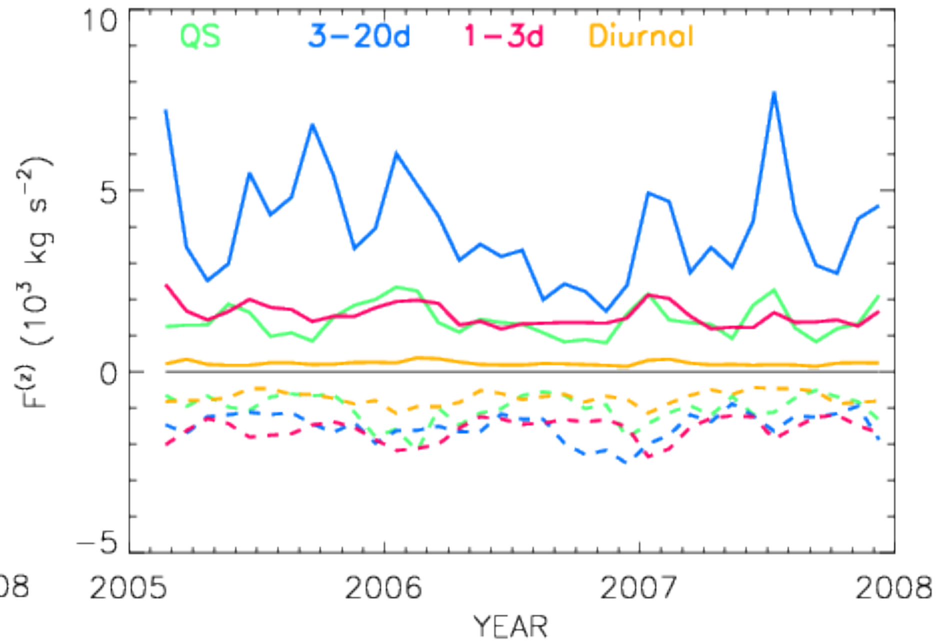
# Eliassen-Palm Flux Spectrum

## Vertical EP-flux $F^{(z)}$ versus time

**HIRDLS** **MERRA sampled like HIRDLS**

Equatorial Rossby Kelvin Inertia-gravity Tides



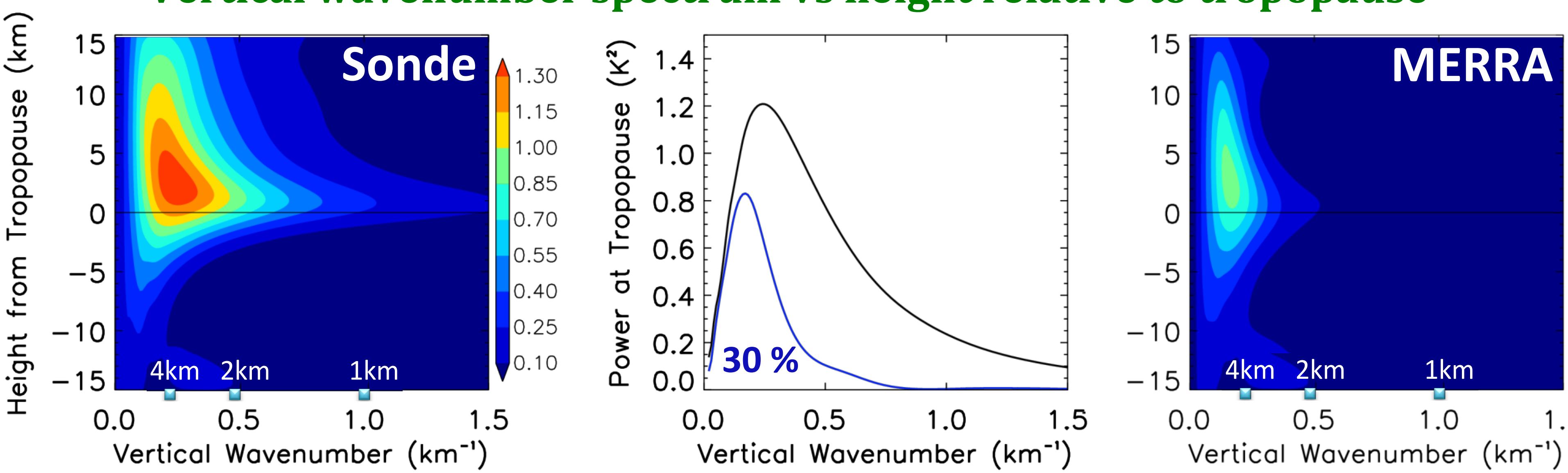

- Primary difference appears in the **inertia-gravity wave** band.
- HIRDLS fluxes are 50% larger and rival Kelvin wave fluxes at times!
- Why aren't these large-scale wn=1-6 waves better represented?

# Wave Vertical Structure

## Tropical radiosondes

[Kim et al. 2015 (in preparation)]

### Vertical wavenumber spectrum vs height relative to tropopause

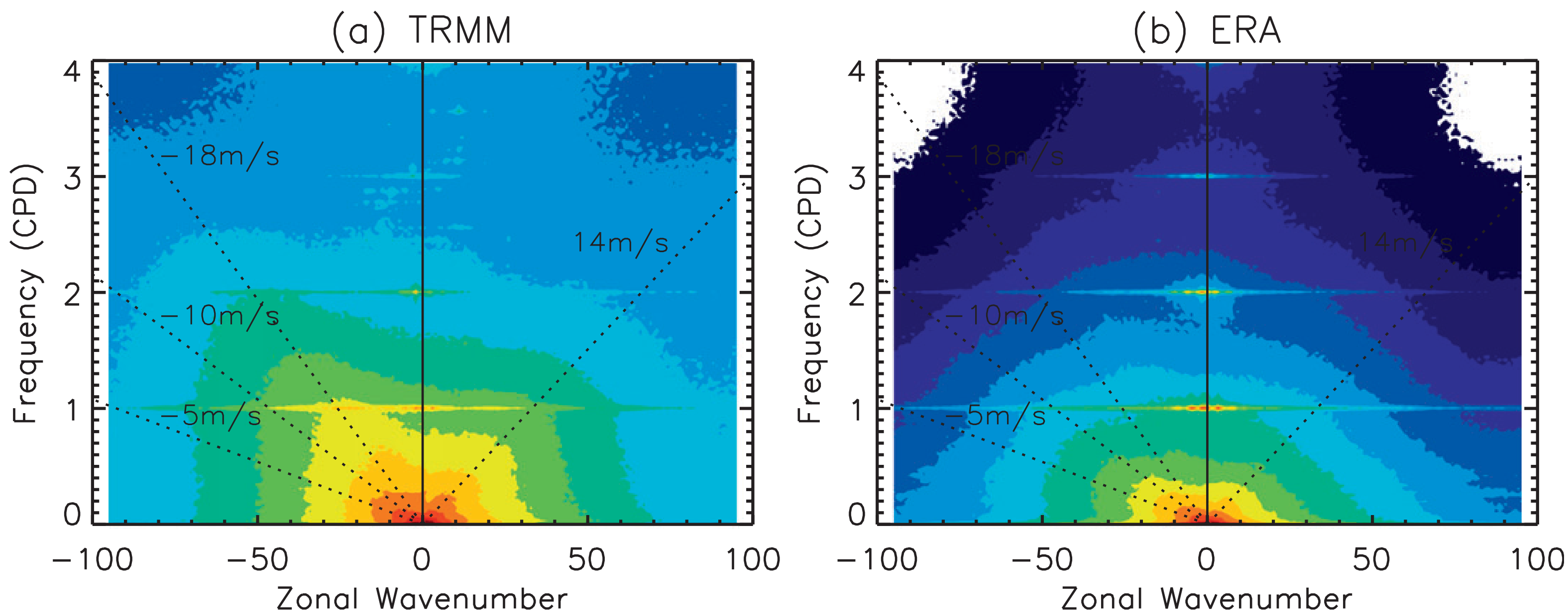



- Similar result for ERA-Interim
- Short vertical scales are marginally resolved even in today's ECMWF analyses

# Precipitation Variability in Reanalyses

Kim and Alexander [2013]

**Wavenumber-Frequency Spectrum of Tropical Precipitation**




- Precipitation variability at higher frequencies is lacking in reanalyses
- Indicates sources of tropical inertia-gravity waves are under-represented

# Summary & Conclusions

- **Analysis and reanalysis fields sometimes show large errors associated with misrepresentation of tropical waves.**
- **Wn=1-6 eastward and westward inertia-gravity waves are generally under-represented in reanalyses.**
- **Causes of these errors are likely associated with underlying model vertical resolution and under-representation of precipitation variability.**

# References


- Alexander, M. J. and D. A. Ortland, 2010: Equatorial waves in High Resolution Dynamics Limb Sounder (HIRDLS) data, *J. Geophys. Res.-Atmos.,* **115**, D24111, doi:10.1029/2010JD013860.

- Alexander, M. J., D. A. Ortland, and J.-E. Kim, 2015: Spectrum of tropical wave Eliassen-Palm flux: Comparison of satellite and reanalysis data, *(in preparation)*.