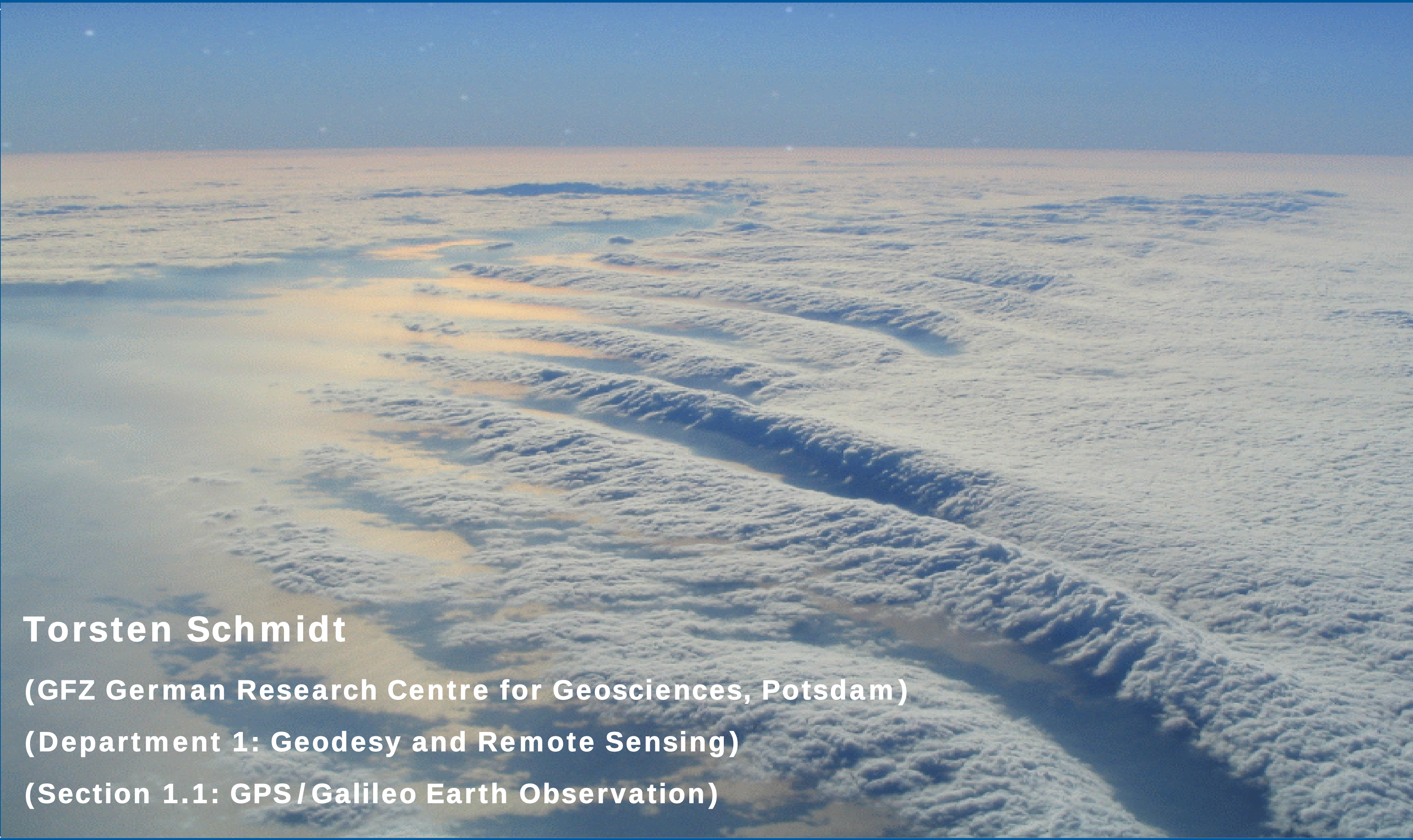
# Gravity wave studies using GPS RO



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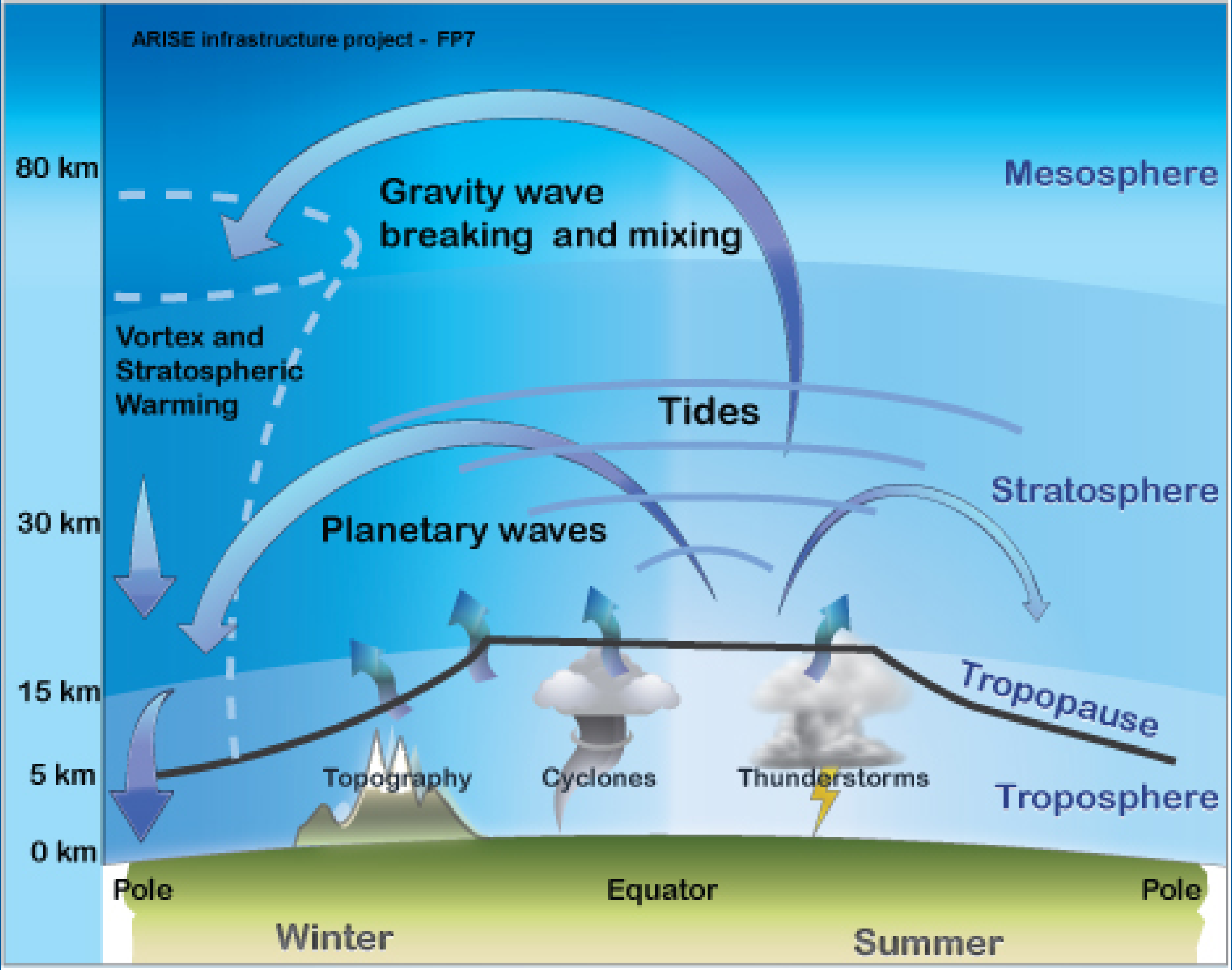
# Acknowledgement

I would like to acknowledge EUMETSAT ROM SAF for the financial support provided to attend the workshop.

# Outline

- Motivation
- Generation of gravity waves and gravity wave parameters
- Gravity wave detection by satellites
- Previous RO-GW studies
- New aspects from COSMIC and Metop
- Summary and outlook

# Motivation




Dynamics of the troposphere-stratosphere-mesosphere exchange

***arise-project.eu*** *(Atmospheric dynamics research infrastructure in Europe)*

# Occurrence of atmospheric waves

"If it were possible to see these waves and to greatly speed up their motions, we would see a wide variety of wave shapes moving in many directions.
Hines (1974) presents a "surrealistic" representation of these waves, which is reproduced in Fig. 1.1."

FIGURE 1.1 A surrealistic representation of atmospheric gravity waves. (From *The Upper Atmosphere in Motion*, C.O. Hines, Am. Geophys. Union, Washington, DC, 1974, p. 194.)

From Nappo (2002): An Introduction to Atmospheric Gravity Waves

# Classification of atmospheric waves

**From *Andrews et al. (1987): Middle Atmosphere Dynamics***

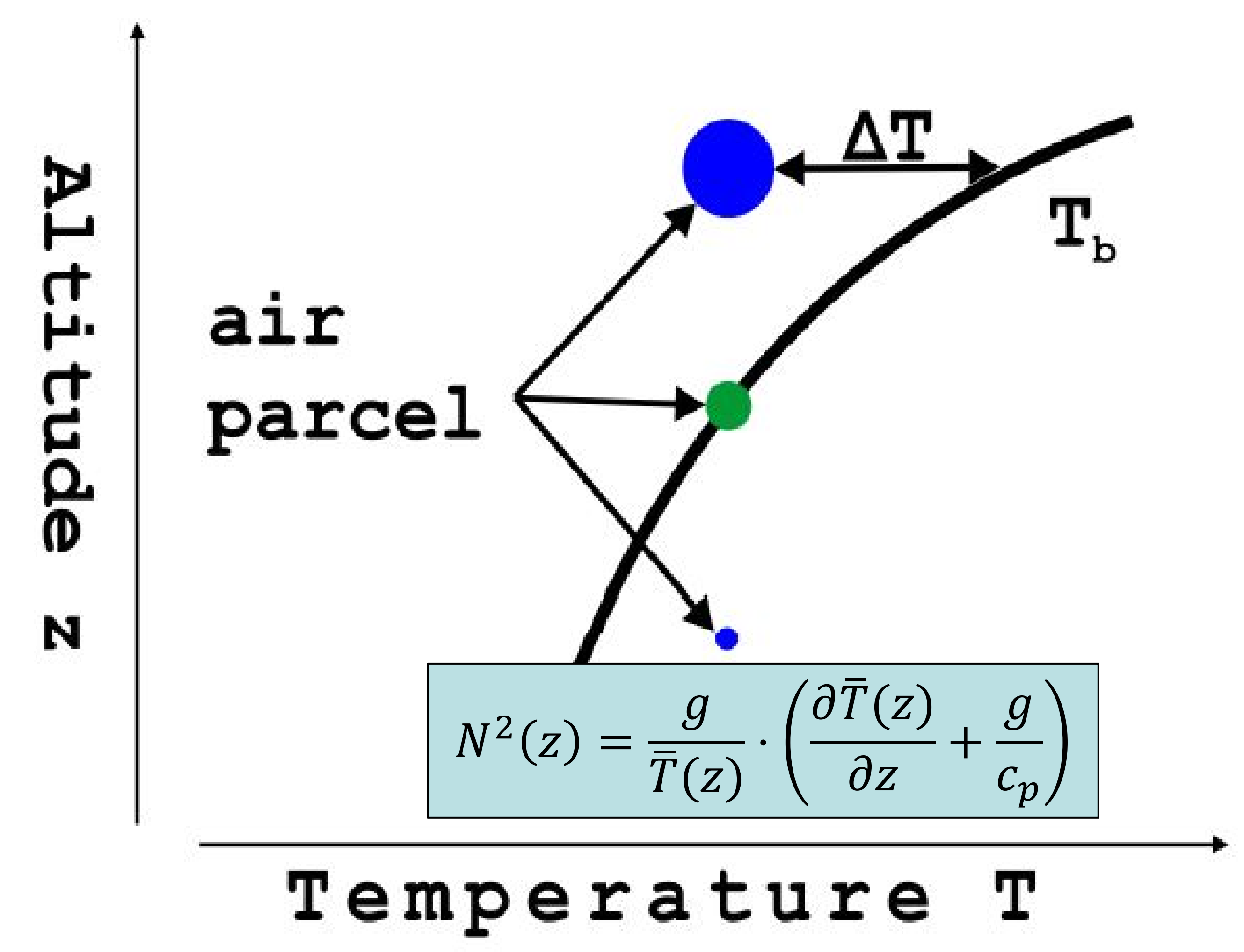
**e.g., after the restoring mechanism**

- Atmospheric stratification, stability
  ***Gravity (buoyancy) waves***

- Combination of stratification and Coriolis effects
  ***Inertio-gravity waves***

- Beta-effect or the northward potential vorticity gradient
  *Planetary or Rossby waves*

# Generation of gravity waves




$$N^2(z) = \frac{g}{\bar{T}(z)} \cdot \left( \frac{\partial \bar{T}(z)}{\partial z} + \frac{g}{c_p} \right)$$

**Atmospheric gravity waves are an oscillation characterized by a restoring force by buoyancy**

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

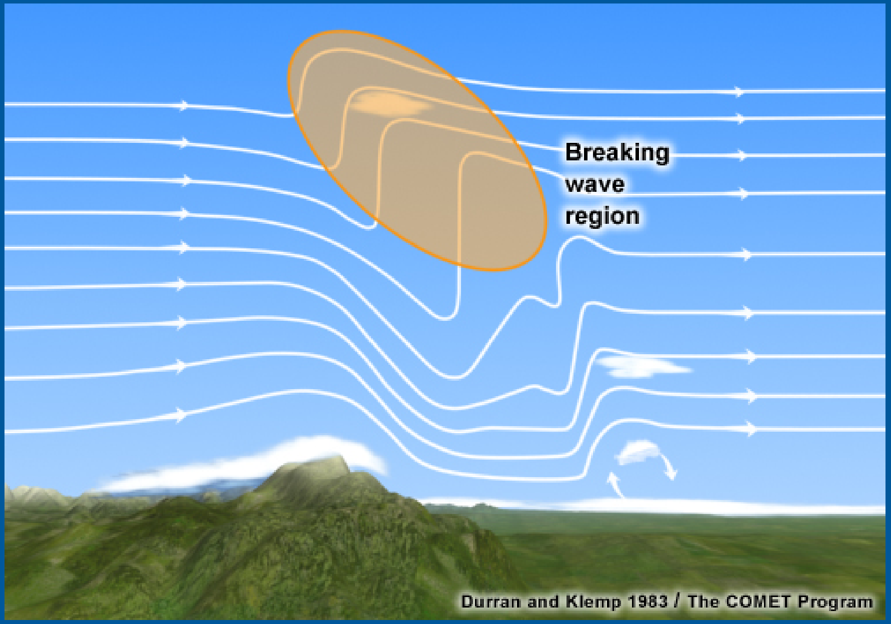
Vertical wavelength:
up to 20-30 km or even larger

Horizontal scale:
few tens to thousands km

# Generation of gravity waves

## Generation mechanisms of atmospheric gravity waves

- meteorological disturbances, typhoons, cyclones, fronts, etc.
- convection in the tropics
- unstable behavior of jet stream, like wind shear, geostrophic adjustment, etc.
- interaction of surface winds and topography (orographic or mountain waves)



# Gravity wave detection from space

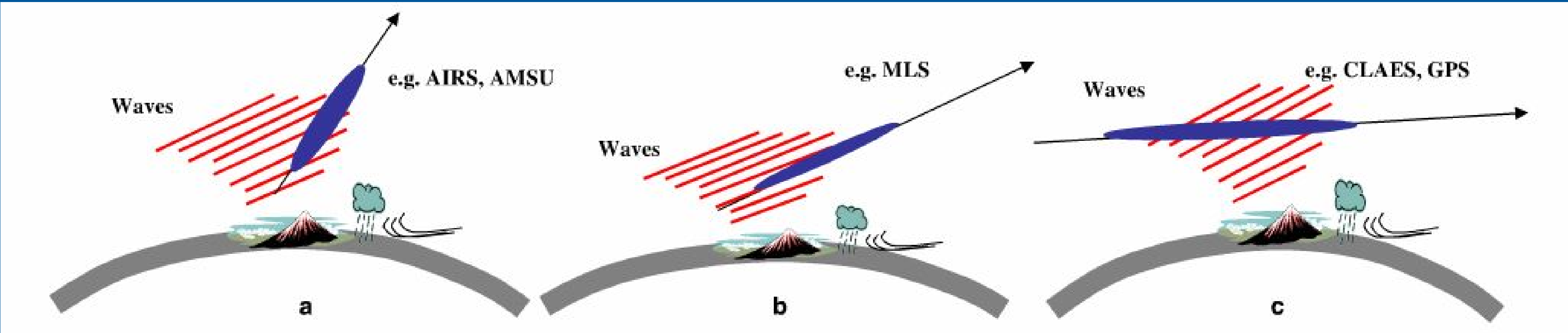



Fig. 1. Three types of satellite viewing geometry where GW-induced temperature perturbations can be measured: (a) nadir/slant path; (b) opaque limb path; (c) transparent limb path. Each has different sensitivities in horizontal and vertical wavelengths.

*Wu et al. (2006, ASR)*

## Sensitive to gravity waves

$with\ large\ \frac{\lambda_z}{\lambda_h}$

whose phase fronts
are roughly in parallel
to the LOS

$with\ small\ \frac{\lambda_z}{\lambda_h}$

RO: $\lambda_{z,min} > 2\ km\ for\ z < 30\ km$ [*Marquardt and Healy (2005, JRMSJ)*]
$\lambda_{h,min} > 100 - 200\ km$ [*Jacobi and Lange (2003)*]

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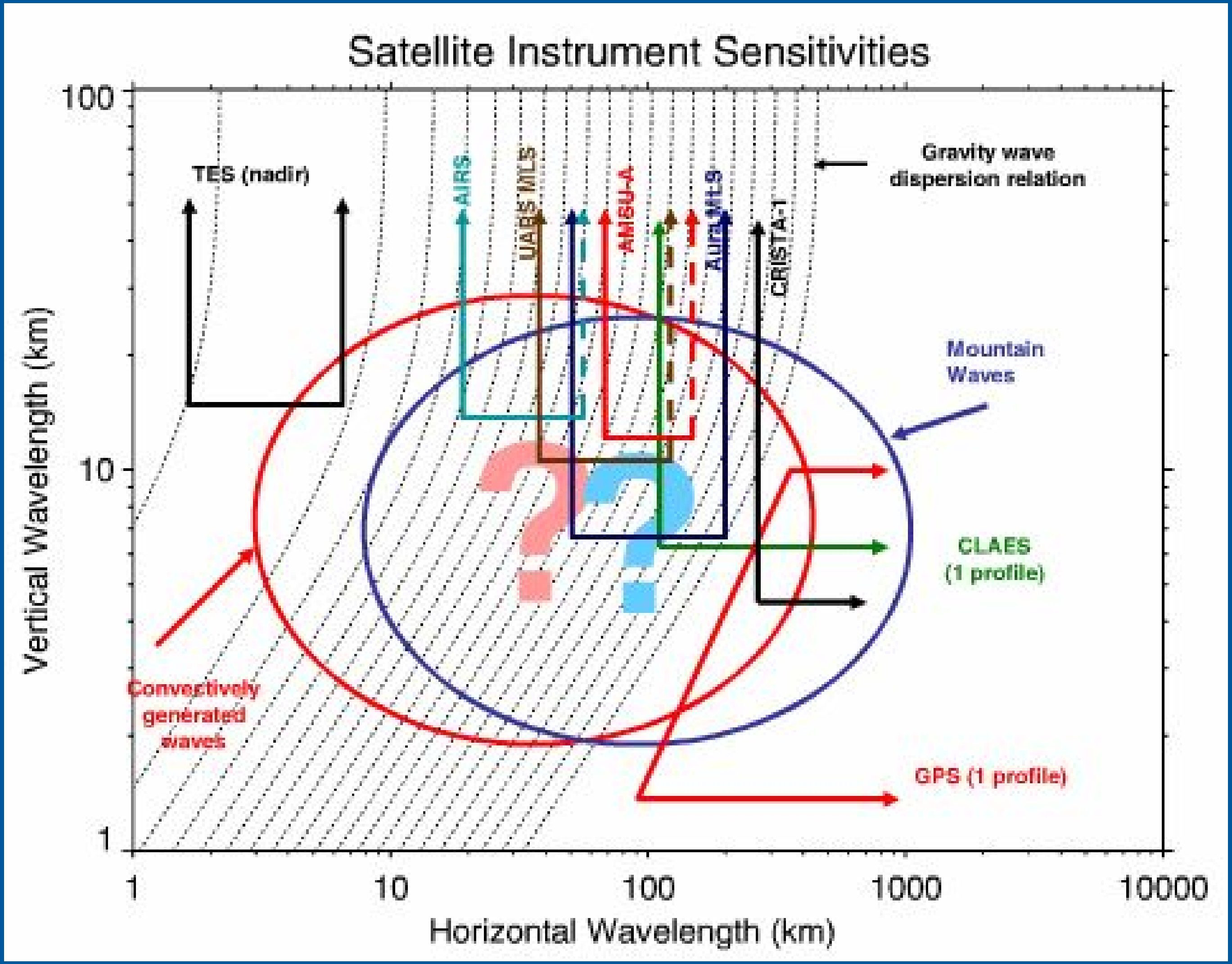
# Observational window for GW detection




*From Wu et al. (2006, ASR)*

# GW detection with RO

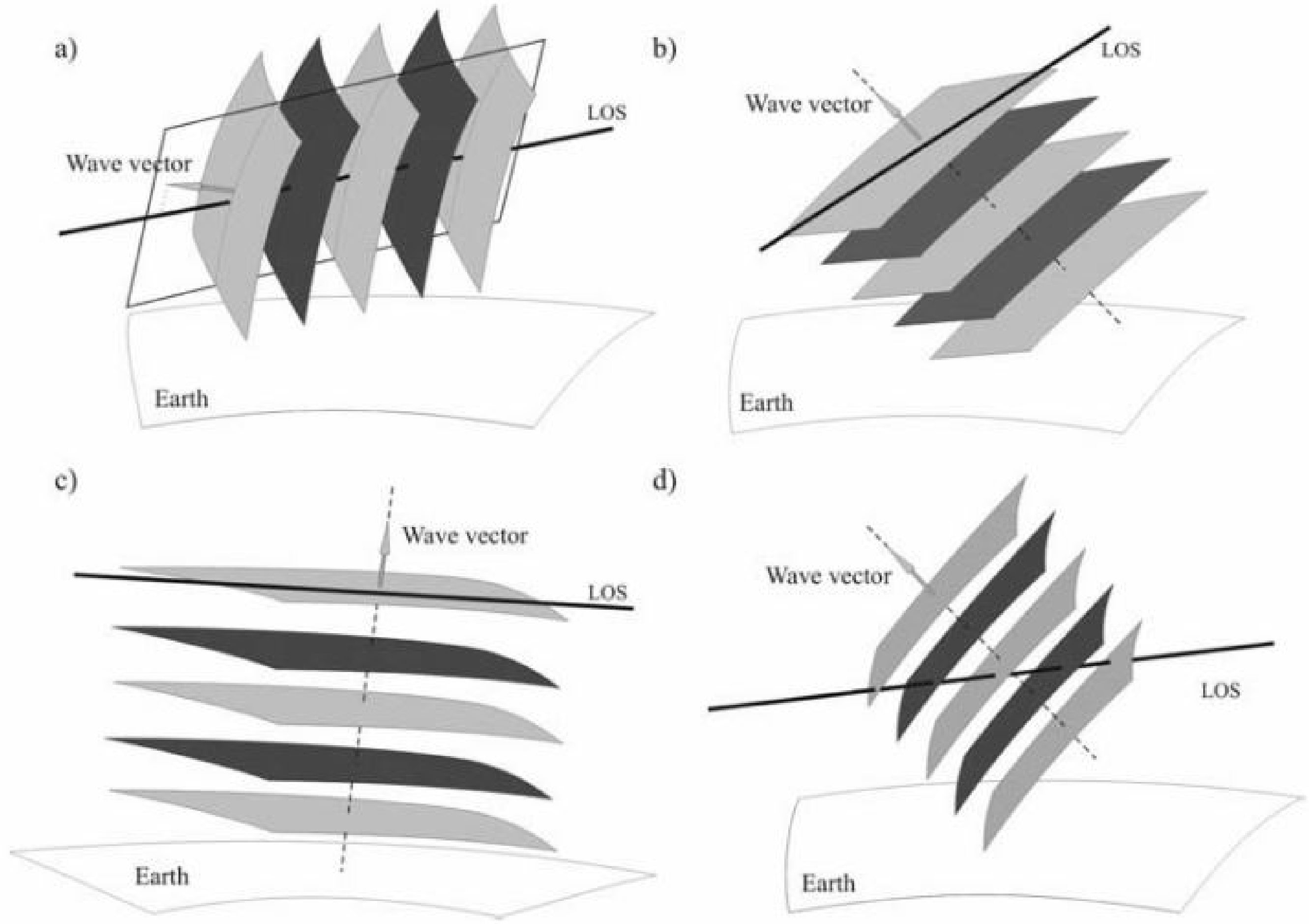



**Figure 2.** Representation of the relative orientation of wave and LOS in three simple cases (a) horizontal component of wave vector parallel to LOS, (b) LOS contained in wavefront and (c) horizontal wavefronts, whereas Figure 2d shows the most general situation.

*From P. Alexander et al. (2008, JGR)*

# GW detection with RO

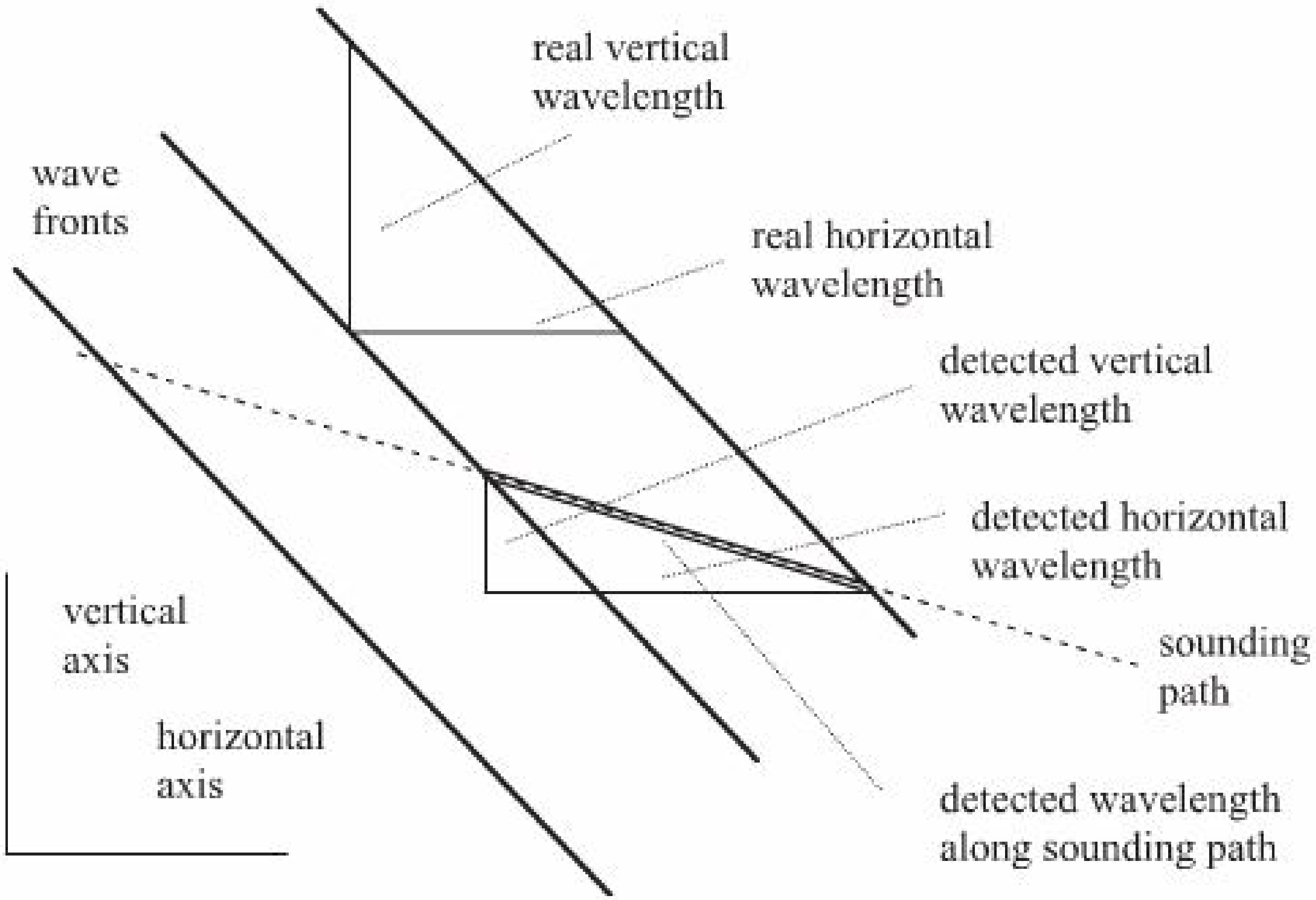



FIG. 1. A 2D diagram showing the possible differences between detected and real wavelengths.

*From P. Alexander and de la Torre (2010, JApplMetClim)*

# Dispersion relation

$$\hat{\omega}^2 = \frac{N^2 k_h^2 + f^2(m^2 + \alpha^2)}{k_h^2 + m^2 + \alpha^2}$$

$$k_h = (k^2 + l^2)^{1/2} \qquad \alpha = \frac{1}{2H_\rho}$$

$$\hat{\omega} = \omega - \vec{v} \cdot \vec{k}$$

Heigh frequency waves: $\hat{\omega} \gg f$
Low-frequency waves: $\hat{\omega} \sim f$
Mid-frequency waves: $N \gg \hat{\omega} \gg f$

The dispersion relation relates the wave frequency to the wave‘s spatial characteristics and to the background atmosphere properties $N$ and $\vec{v}$.

For vertically propagating gravity waves, $(k, l, m)$ are real, and the intrinsic frequency is limited to

$$N > |\hat{\omega}| > |f|$$

## Simplifications for the middle atmosphere

$N \gg f$
$m \gg k_h$
$m \gg \alpha$
$k_h = k$

$$\longrightarrow \hat{\omega}^2 = \frac{N^2 k^2}{m^2} \longrightarrow \hat{c}^2 = \frac{N^2}{m^2} = \frac{N^2 \lambda_z^2}{4\pi^2}$$

$$\hat{\omega} = \omega - uk$$
$$\hat{c} = c - u$$

# Potential energy and momentum flux

**Potential energy** as a proxy for gravity wave activity

$$E_p(z) = \frac{1}{2}\left(\frac{g}{N}\right)^2 \left(\frac{\hat{T}}{\bar{T}}\right)^2$$

*e.g., Tsuda et al. (2000, JGR)*

The **vertical flux of horizontal momentum** that can be carried by gravity waves:

$$F(z) = \frac{\rho}{2}\frac{\lambda_z}{\lambda_h}\left(\frac{g}{N}\right)^2 \left(\frac{\hat{T}}{\bar{T}}\right)^2$$

*e.g., Fritts and J. Alexander (2003, RG)*

## Challange: The background determination

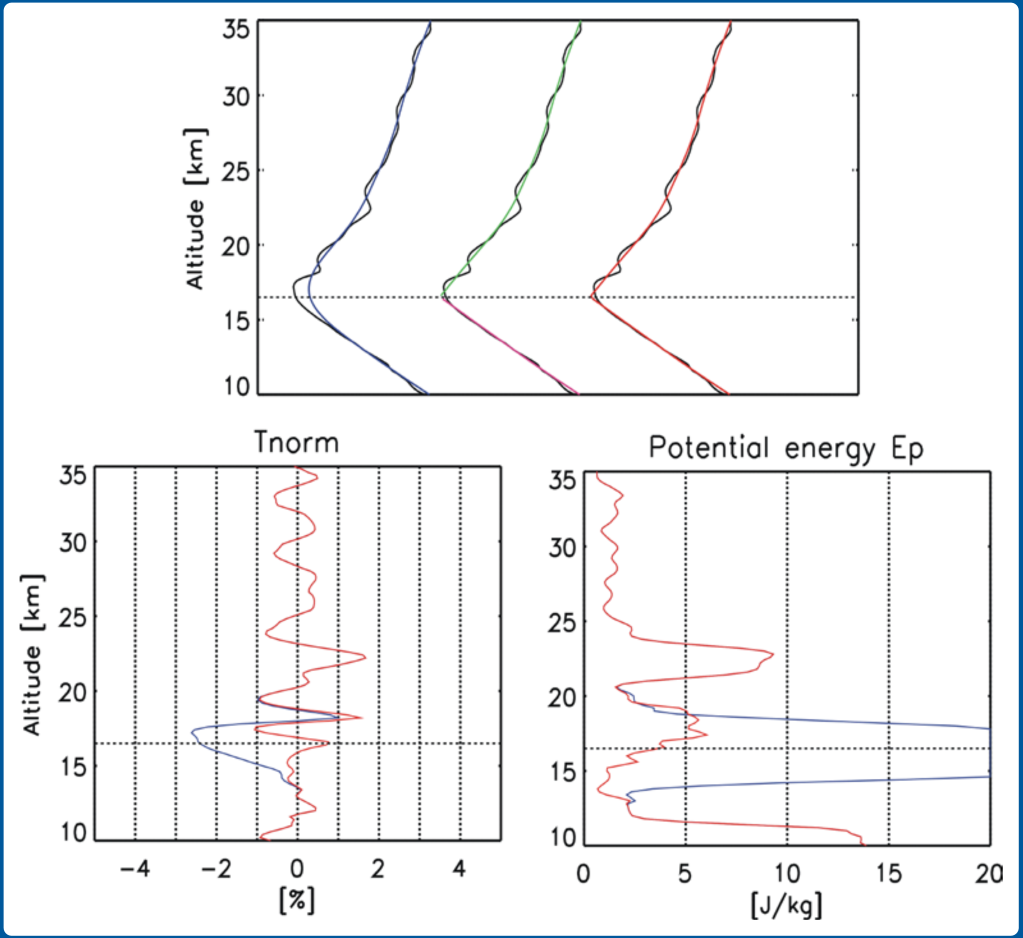
$$T'(z) = T(z) - \bar{T}(z)$$

Independent from data source (radiosondes, LIDAR, satellites)

$\bar{T}$ must include large-scale structures

# Background determination

## Vertical detrending




*From Schmidt et al. (2008, GRL)*

$$T'(z) = T(z) - \bar{T}(z)$$

$\bar{T}(z)$: large-scale temperature

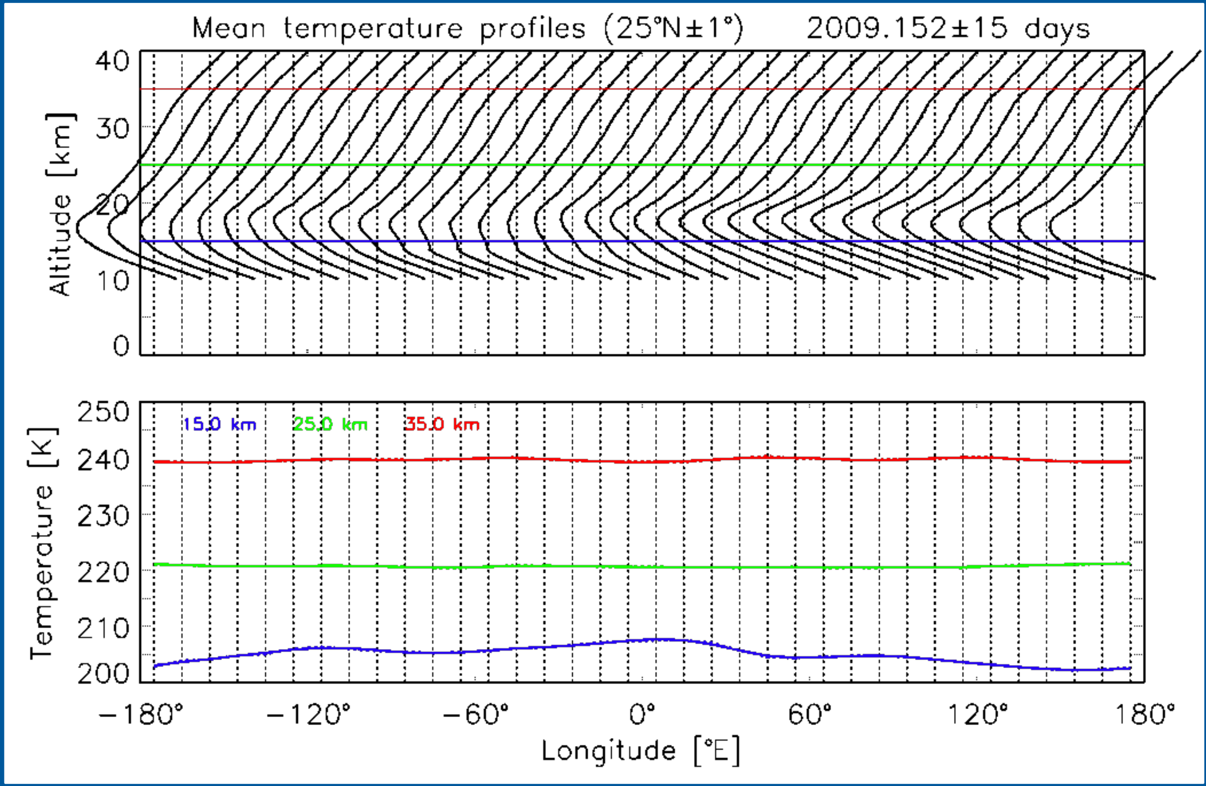
Methods:
- high-pass filtering
- polynomial
- other fits

**Problems** especially in the tropopause region

- separate filtering (*Schmidt et al., GRL, 2008*)
- double filtering (*P. Alexander et al., AMT, 2011*)

# Background determination

## Horizontal detrending




**Temperature background (large-scale temperature)**

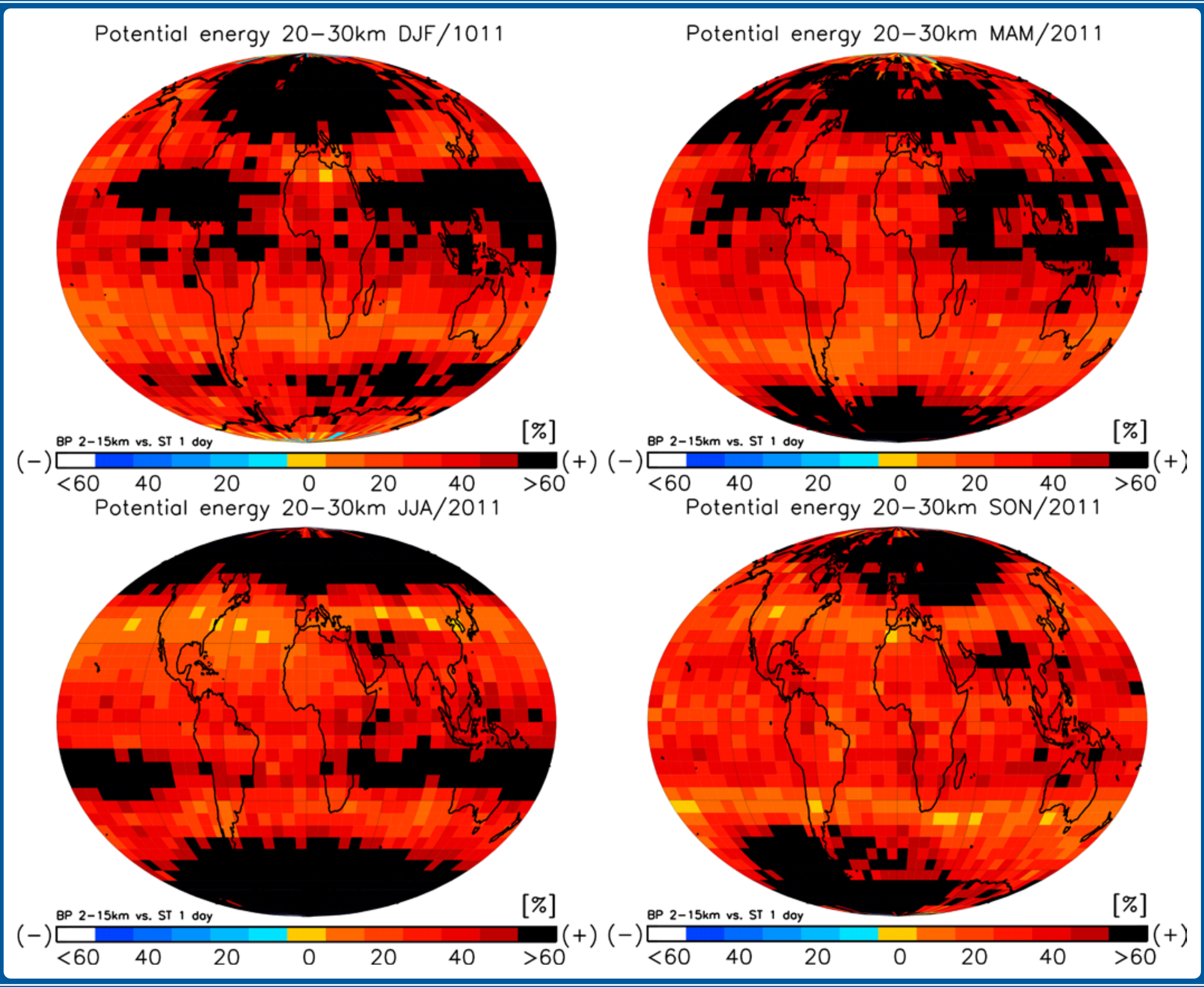
Dynamical RO climatologies
Δt=1 day (10°x15° lat/lon)
Δt=±3 days (10°x15° lat/lon)
Δt=±7 days (10°x15° lat/lon)
Δt=±15 days (2°x10° lat/lon)
(*Yan et al.*, 2010 for HIRDLS)

WN 1-6 from the longitudinal variations at each altitude (10-40 km, Δz=100m) are determined using a FFT and finally WN 0-6 define the temperature background
(*J. Alexander et al.*, 2008 for HIRDLS)

$T''(z) = T(z) - \bar{T}(z)$ : large-scale (dependent on Δt) plus small-scale structures superposed

$T'(z) = [T'']_{band-pass(2-15km)}$ : isolated small-scale structures addressed to GW

# Horizontal vs. vertical detrending: $E_p$




$$\frac{BP(2-15km)-1\ day\ clim}{1\ day\ clim}$$

# Previous work: GW detection and RO

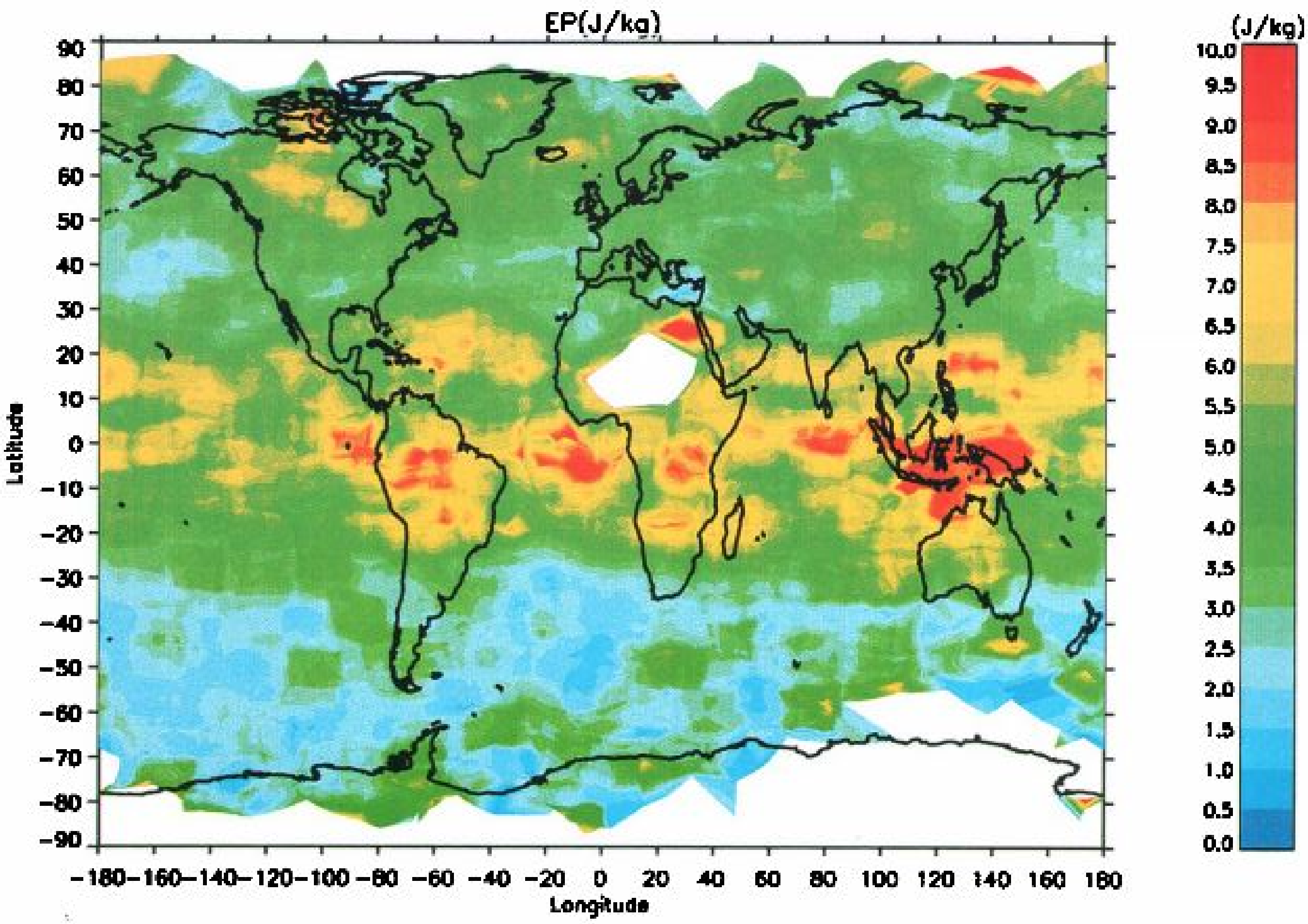


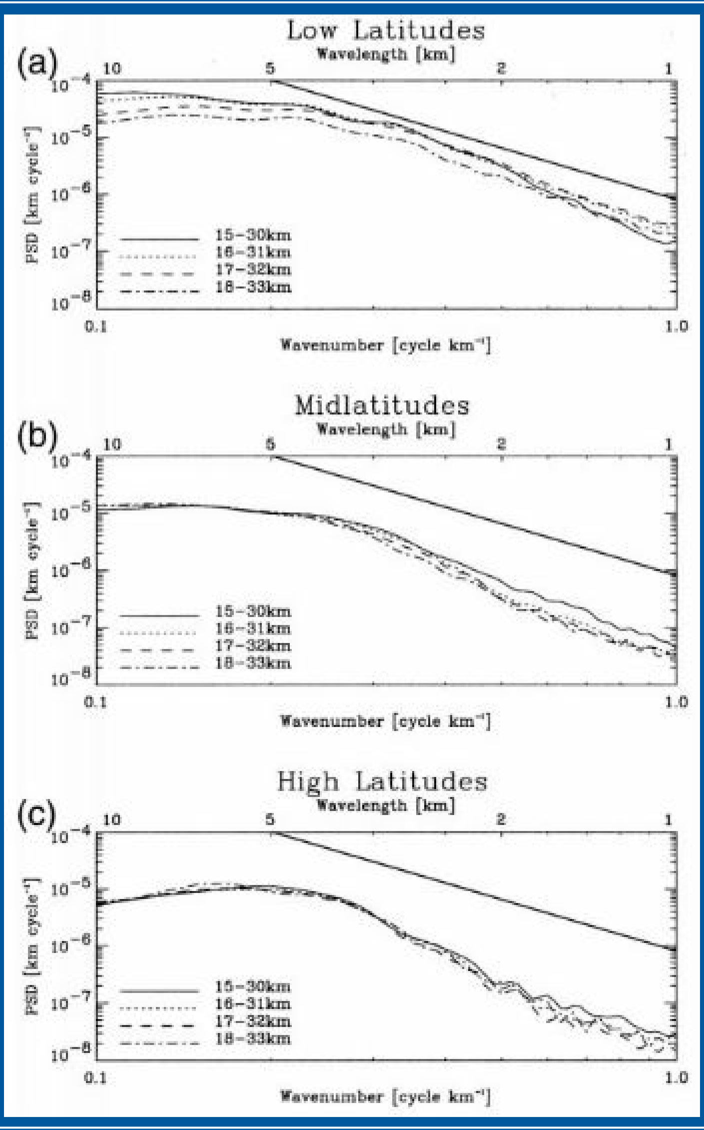

Plate 1. Global distribution of $E_p$ from the GPS/MET data at 20-30 km in November–February. The $E_p$ value is averaged in an area extending 10° and 20° in latitude and longitude, and the center coordinates are shifted every 1° and 2°, respectively.

Potential energy distribution from GPS/MET

20-30 km
Nov-Feb

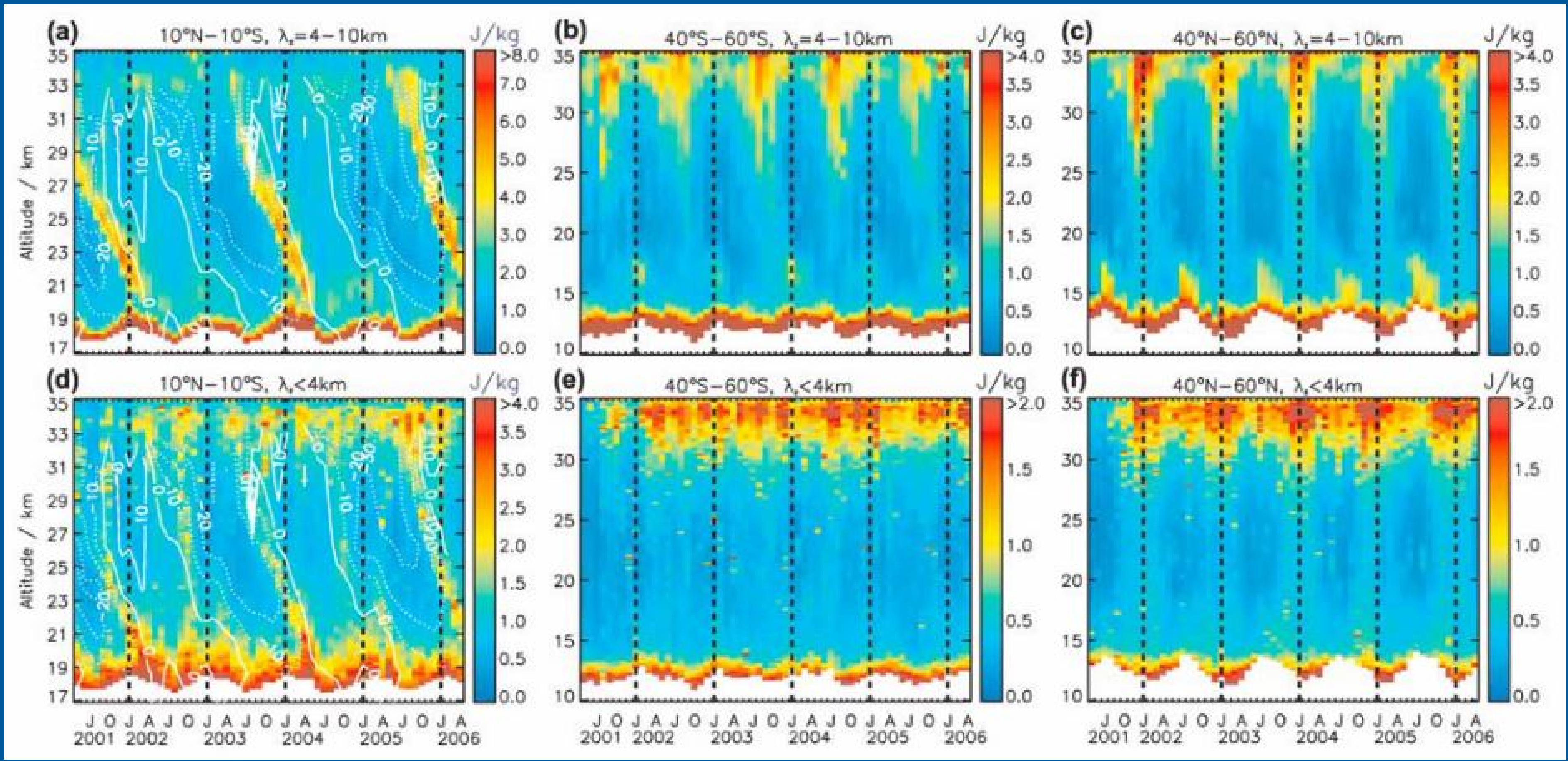
*From Tsuda et al. (2000, JGR)*

# Gravity wave spectra from GPS / MET



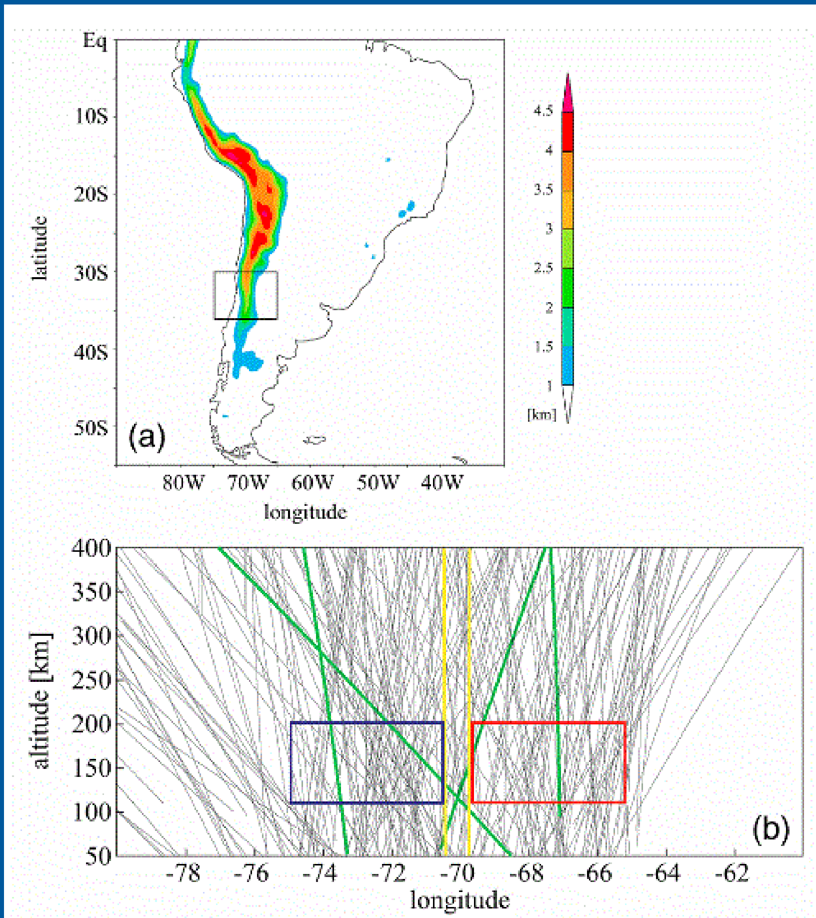

*From*
*Steiner and Kirchengast (2000, JAtmOceanTech)*

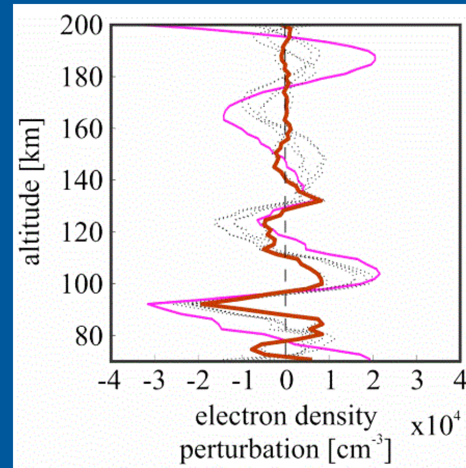
# Gravity wave activity from RO



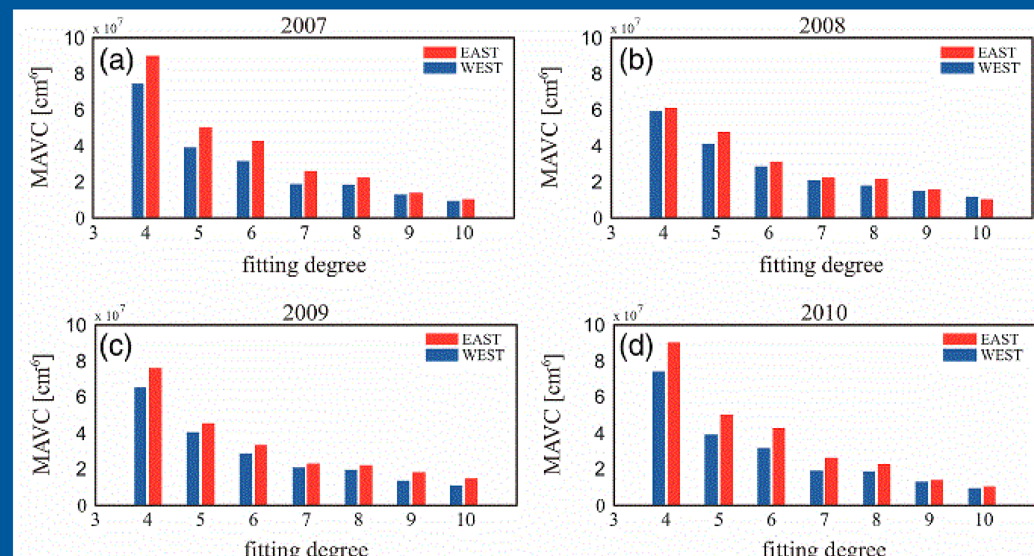

*From de la Torre et al. (2006, GRL)*

# Wave activity in the ionosphere



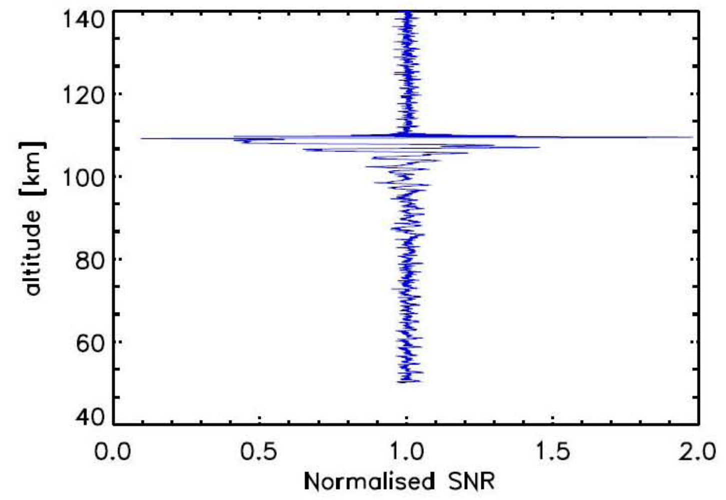




$$\mathrm{MAVC} = \frac{1}{M}\sum_{k=1}^{M}\frac{1}{z_2 - z_1}\int_{z_1}^{z_2}(\delta N_{e_k})^2 dz.$$

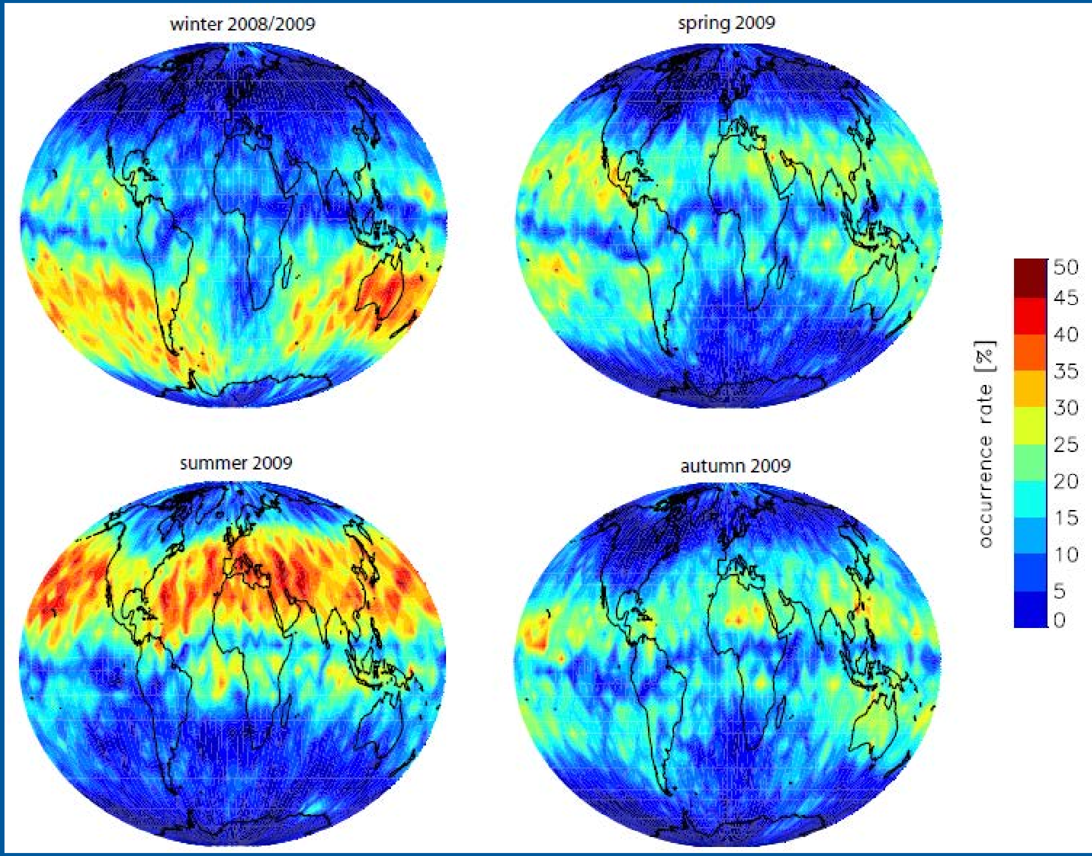



*From de la Torre et al. (2013, JGR)*

# Sporadic E layer studies



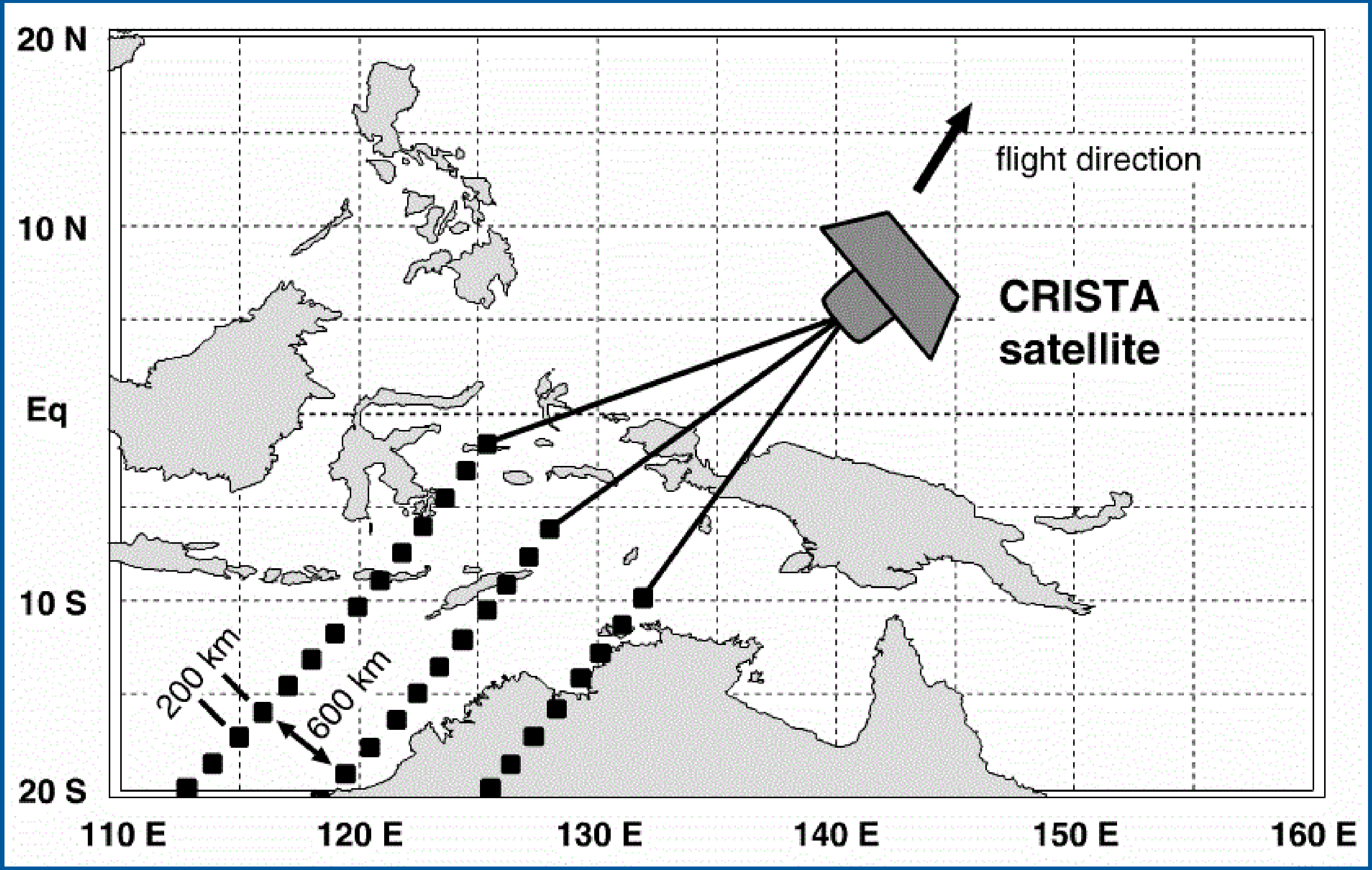

*From Arras et al. (2008, GRL)*




**There were much more GW studies using RO data, but until the availability of COSMIC data no paper to momentum flux determination.**

# Momentum flux determination

Method from *Ern et al. (2004, JGR)*: $k_h = \frac{\Delta\phi_{ij}}{\Delta r_{ij}}$ or $\lambda_h = 2\pi \frac{\Delta r_{ij}}{\Delta\phi_{ij}}$




**HIRDLS (2005)**
(NASA‘s Aura sat.)
along-track distance between profiles of ~75-100 km

**SABER (2002)**
(NASA‘s TIMED sat.)
along-track profile spacing of ~370 km

**All:** limb-scanning infrared radiometer

# Momentum flux determination

Method from *Ern et al. (2004, JGR)*: $k_h = \frac{\Delta\phi_{ij}}{\Delta r_{ij}}$ *or* $\lambda_h = 2\pi \frac{\Delta r_{ij}}{\Delta\phi_{ij}}$

Monochromatic wave $\quad T'(x_h, z, t) = \hat{T}(z) \cdot \sin(k_h x_h + mz - \omega t)$

Phase $\quad kx + ly + mz - \omega t = \phi$

Phase difference at the altitude z (e.g. S transform) $\quad \Delta\phi_{ij} = k(x_i - x_j) + l(y_i - y_j) - \omega(t_i - t_j)$

Neglect time $\quad \Delta\phi_{ij} = k(x_i - x_j) + l(y_i - y_j)$

**need at least three profiles**

Horizontal wavelength $\quad \lambda_h = \frac{2\pi}{|\vec{K}|} \rightarrow F = \frac{\rho}{2} \frac{\lambda_z}{\lambda_h} \left(\frac{g}{N}\right)^2 \left(\frac{\hat{T}}{\bar{\bar{T}}}\right)^2$

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# Model vs. Observation

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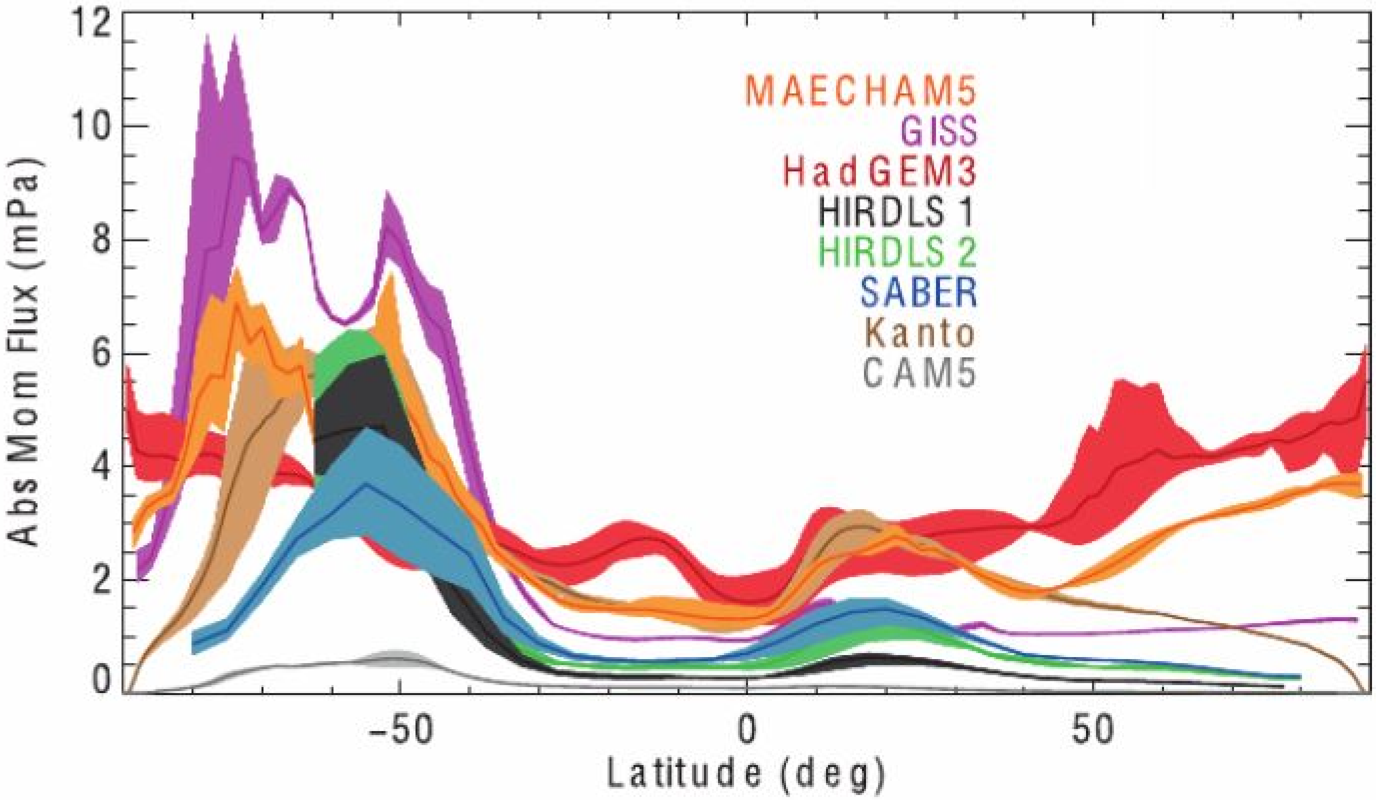
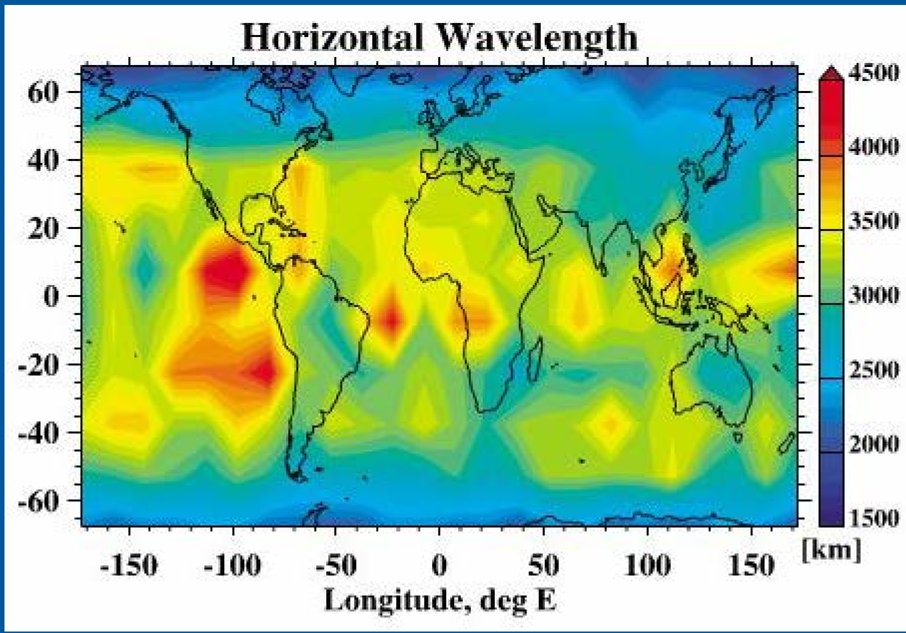


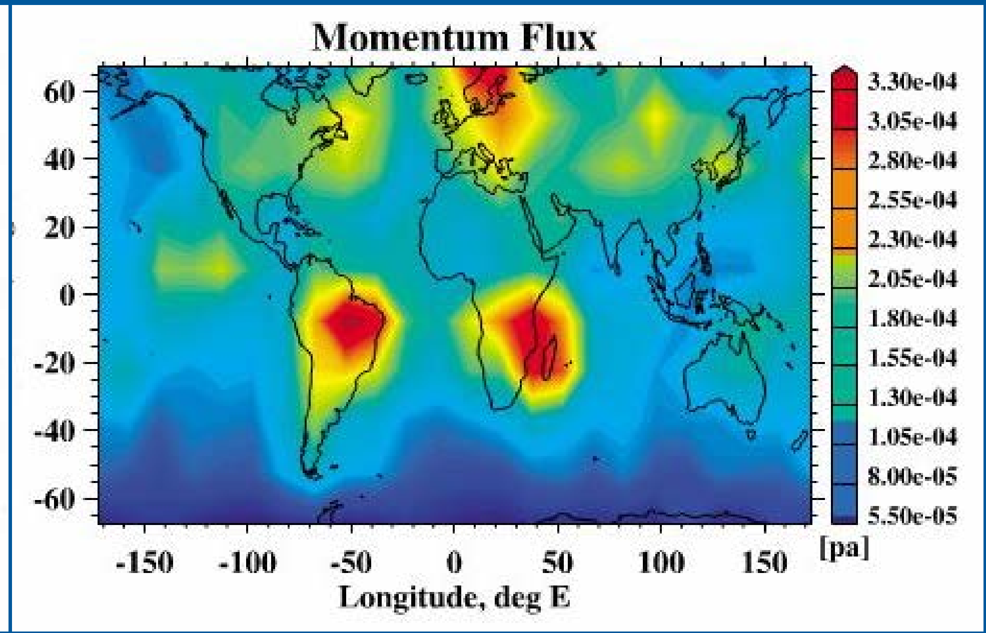

FIG. 8. Interannual variability of the zonal-mean absolute momentum flux for July of 2005, 2006, and 2007 at 20 km. The color denotes the model or observations and the shaded regions denote the range of variability for these three Julys.

From *Geller et al. (2013, JClim)*

# *Wang & J. Alexander (2010, JGR)*

## Dec 2006-Jan 2007, 18-23 km

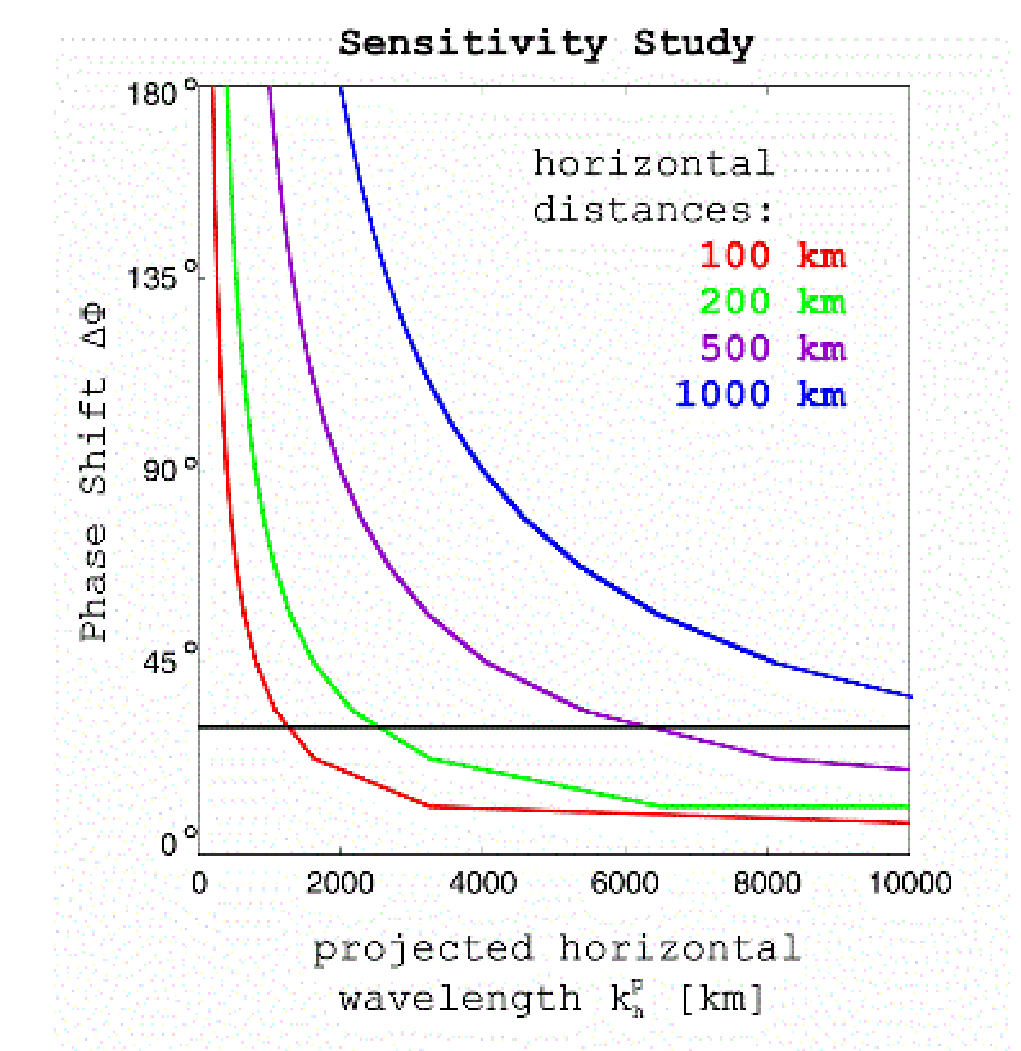



To derive horizontal wavelength $\lambda_H$, we partition the GPS RO data into 15° × 15° × 4hr longitude × latitude × time cells. For

Sampling pattern too large → unrealistic values !

# Limitations




From *Faber et al. (2013, AMT)*

$$\lambda_h = 2\pi \frac{\Delta x_{ij}}{\Delta \phi_{ij}} \quad \Delta\phi_{ij} = 0 \ldots \pm\pi$$

PhD work (2009-2013)

- 10° lat/lon and 2 hrs
- Phase shift limitation (>0.5 rad or ~28°)

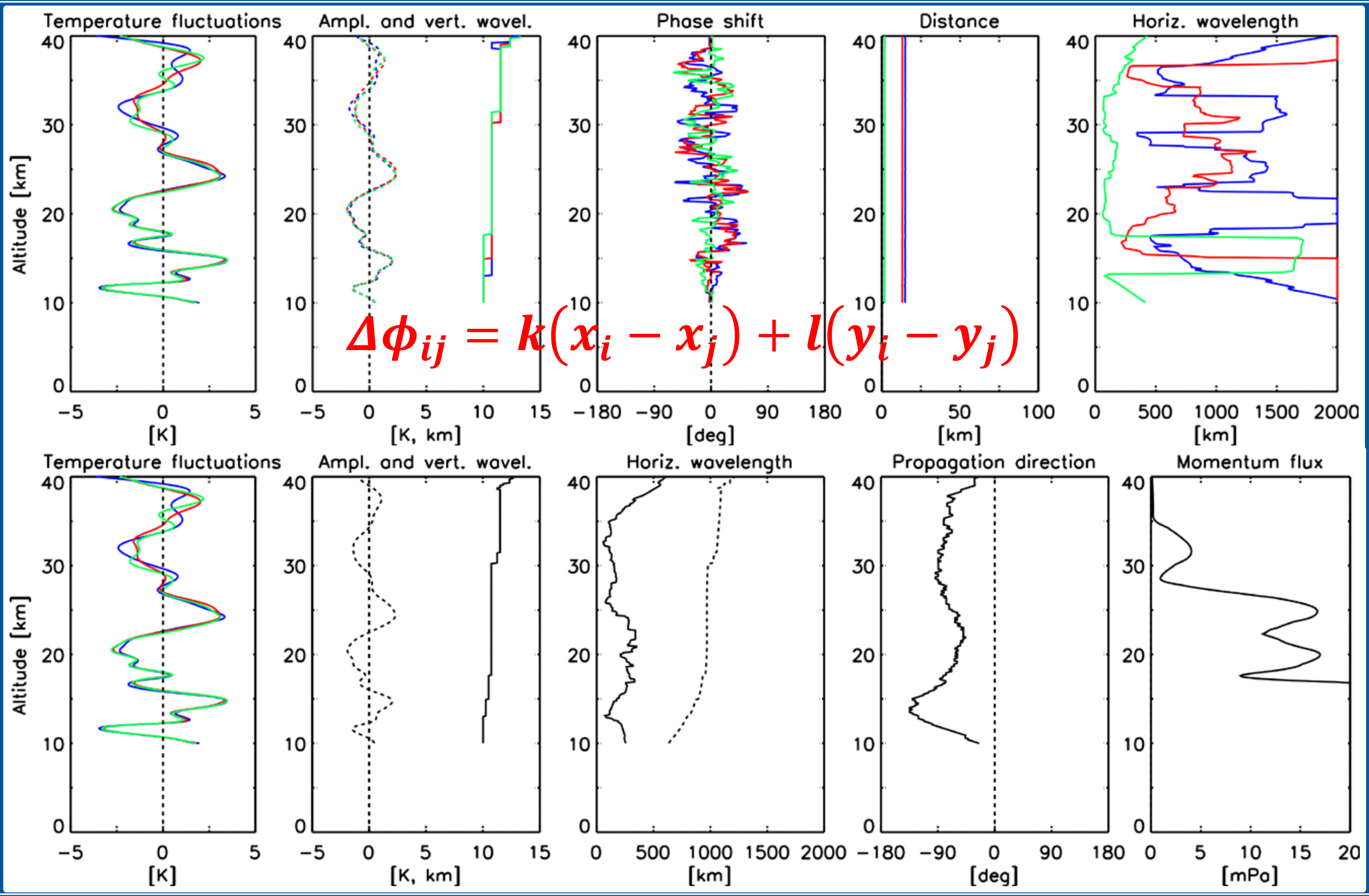
Better:
250 km and 15 minutes ?

and with $\hat{\omega}/f = 3$

$$\lambda_{h,max} = \frac{N \cdot \lambda_z}{3 \cdot f}$$

$\lambda_{h,min} = 2 \cdot \Delta x_{ij}$ (Nyquist)

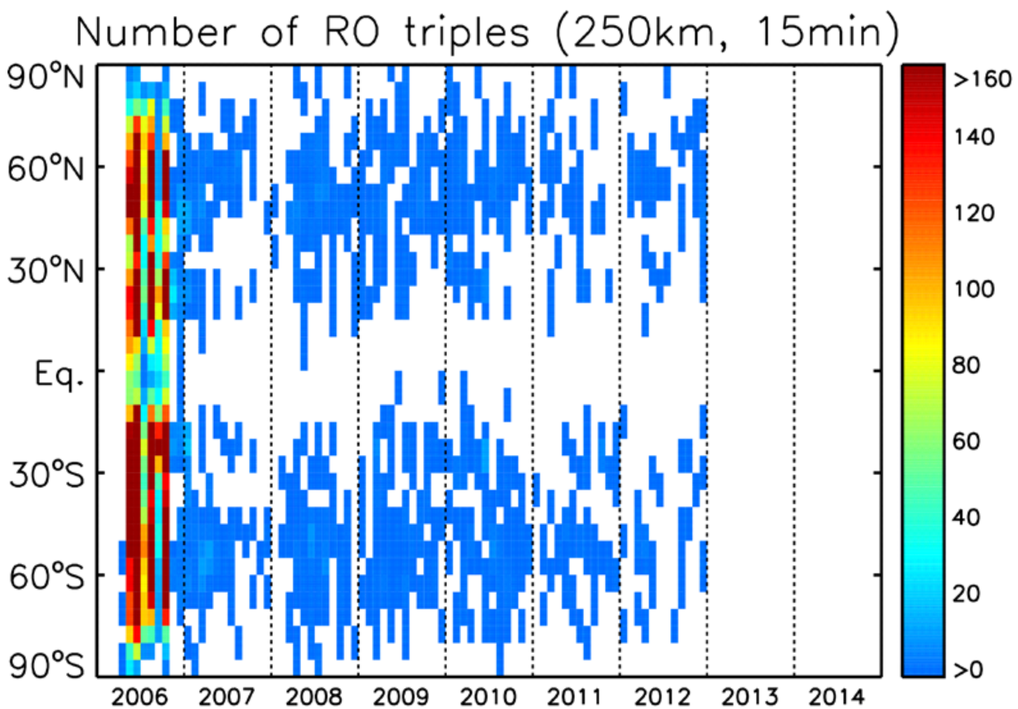
# Example for data analysis

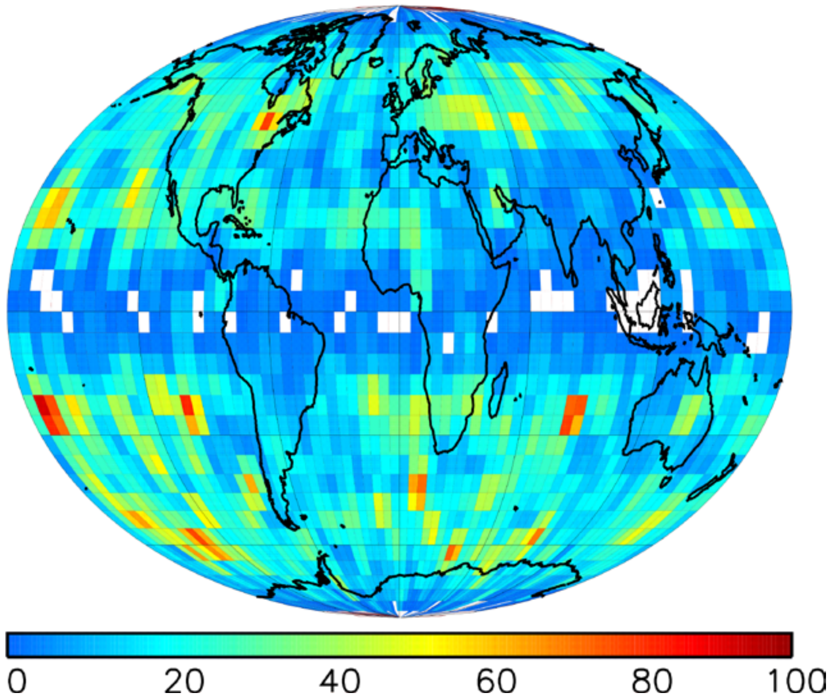



$$\Delta\phi_{ij} = k(x_i - x_j) + l(y_i - y_j)$$

# Number of triples

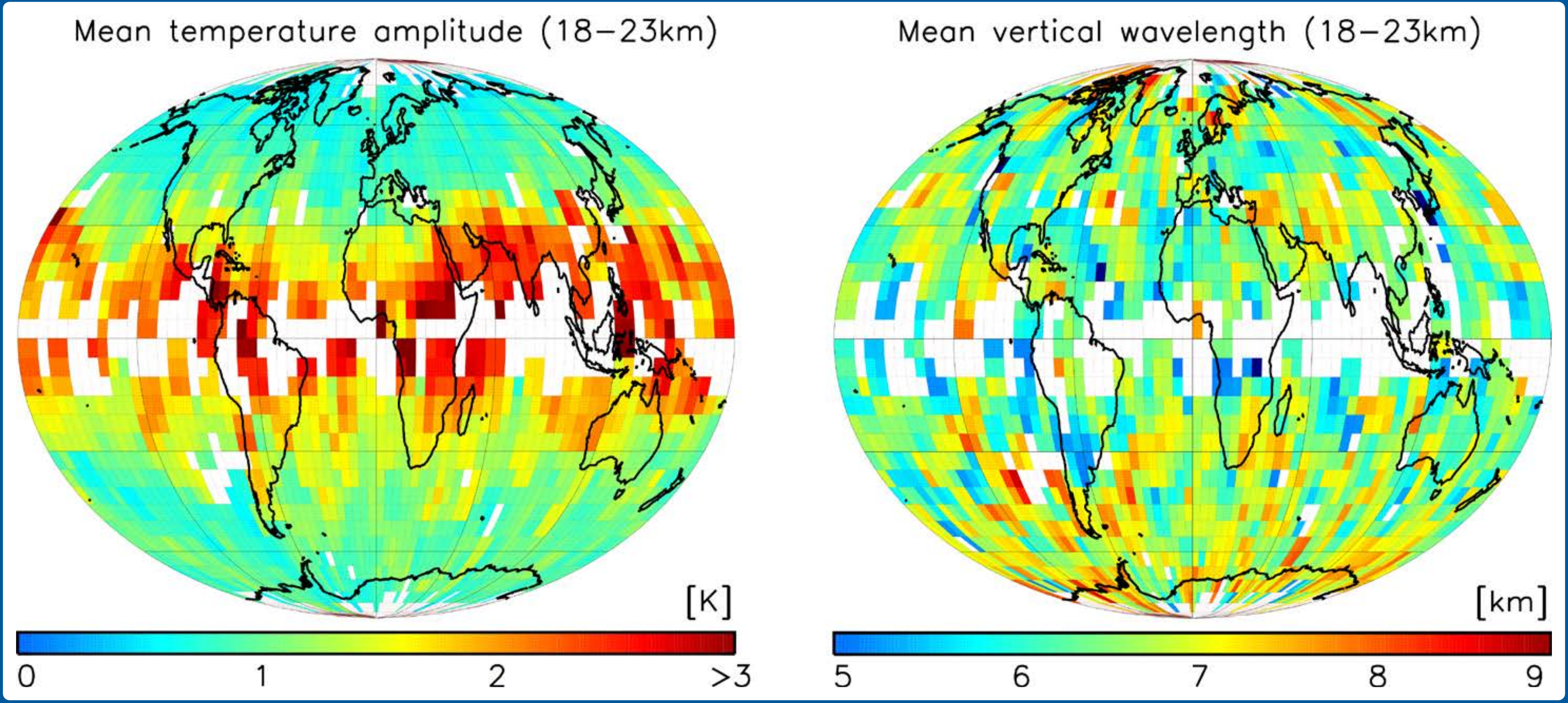
April 2006 – December 2012



# Results

## May 2006 – October 2006



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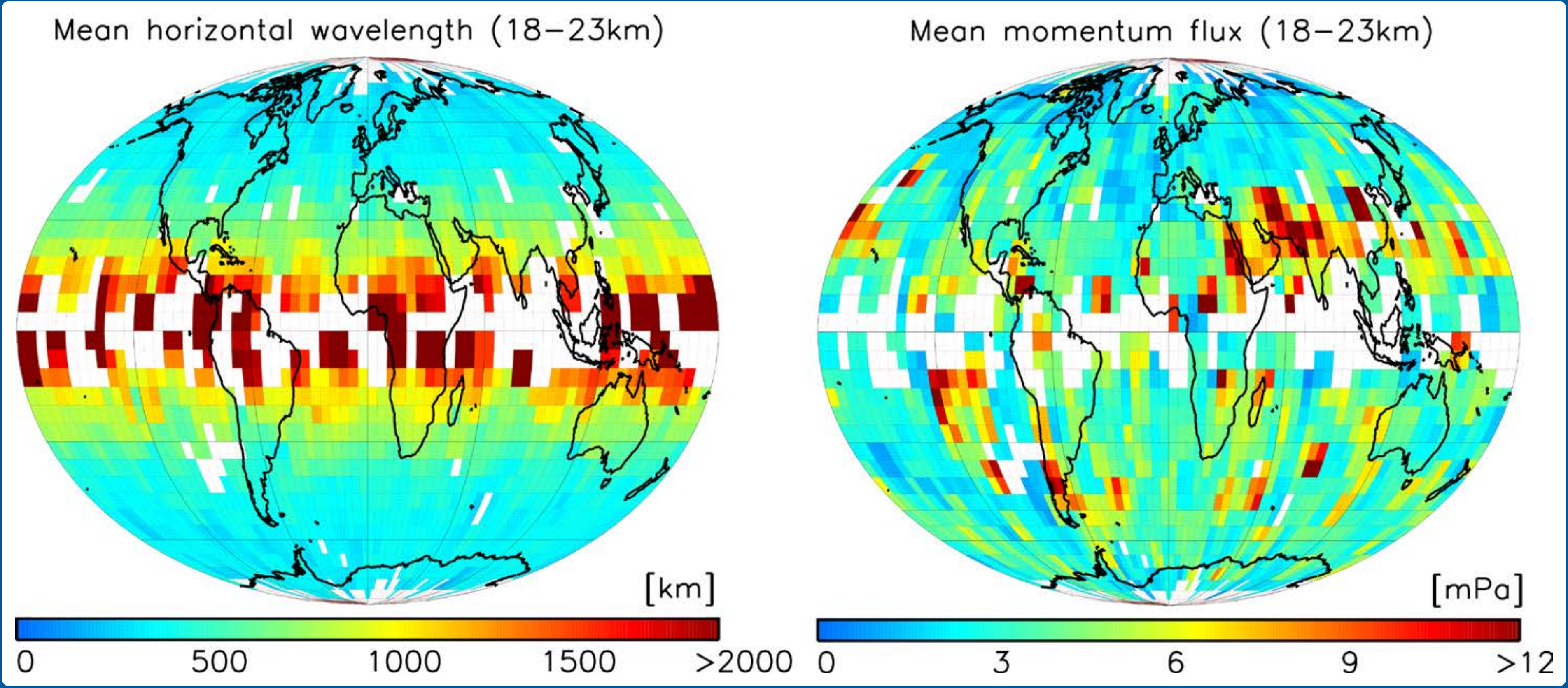
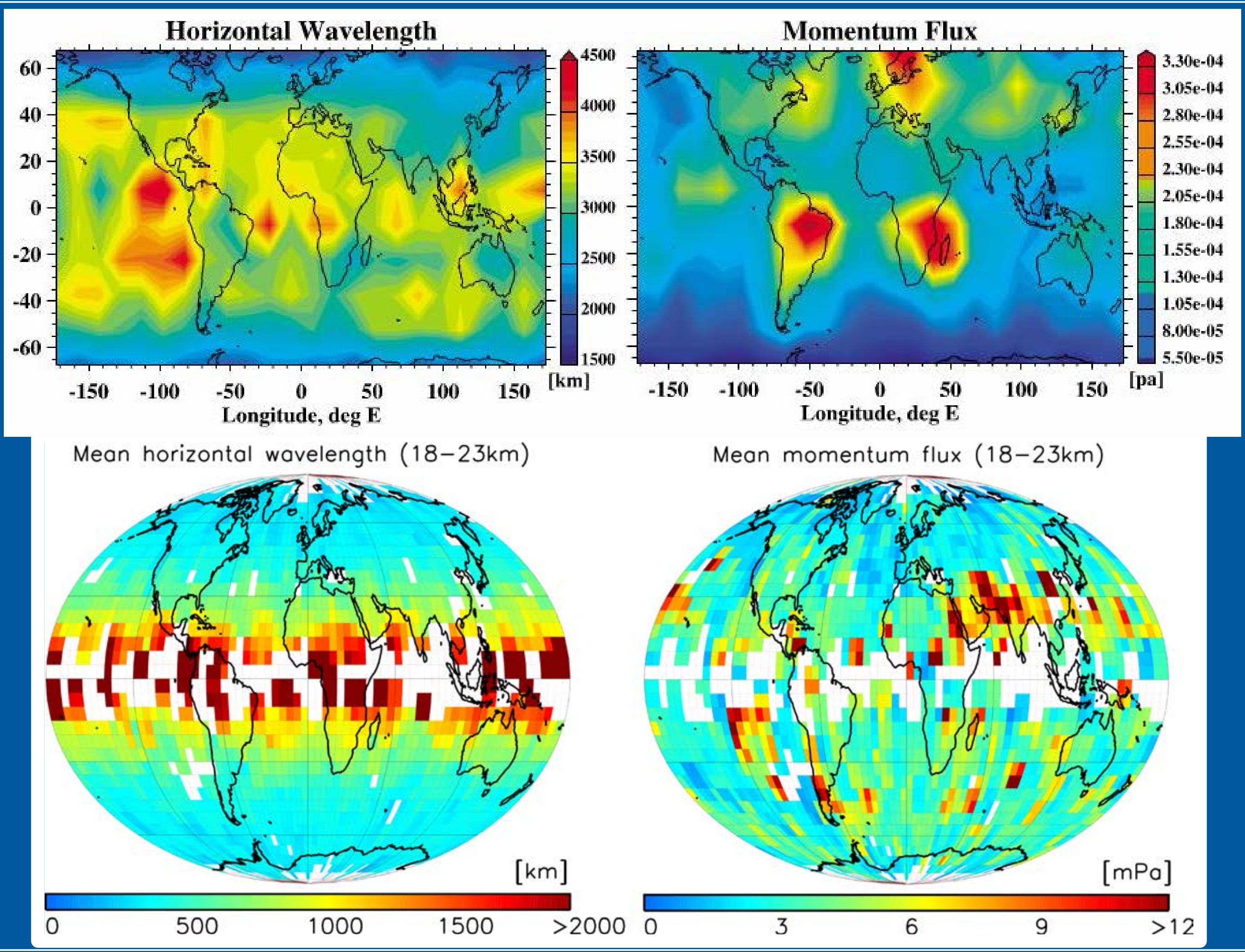
May 2006 – October 2006



# Results




***Wang & J. Alexander***

**DJF 2006/7**

**18-23 km**

**15°x15°x2hrs**

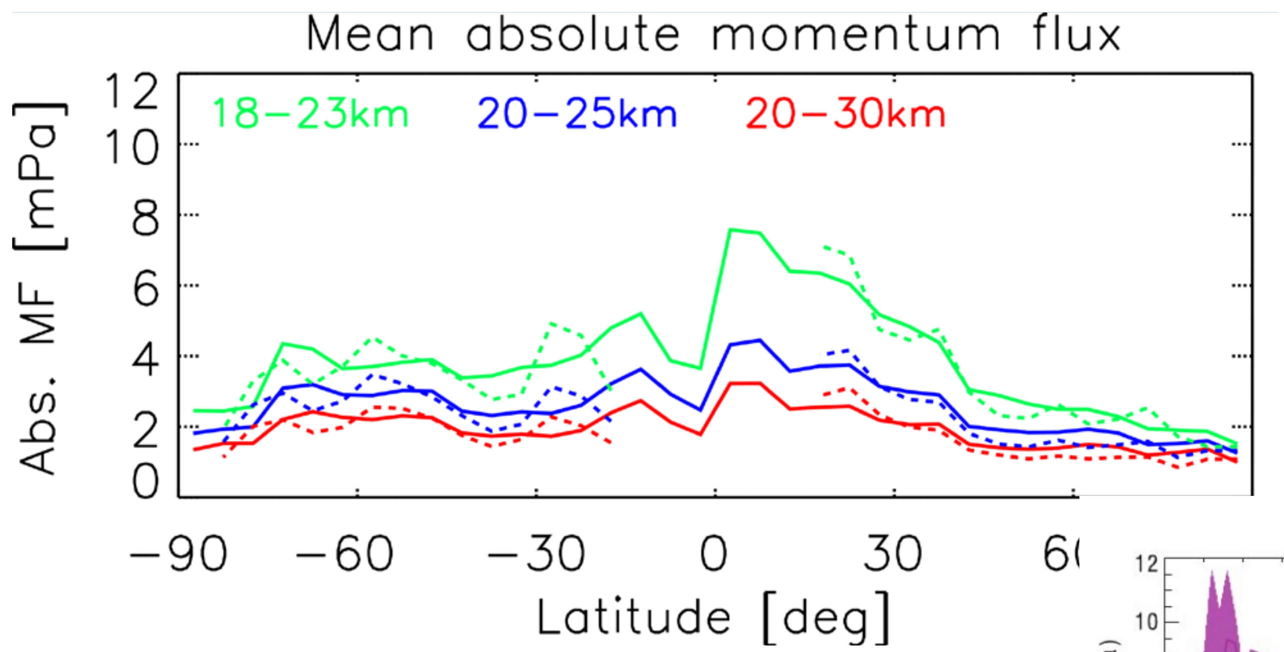
**May-Dec 2006**

**18-23 km**

**250 km**
**15 minutes**

**Different time scale!**

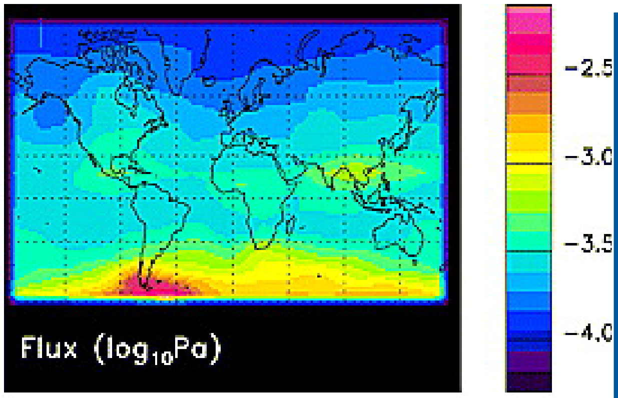
# Model vs. Observation




**GPS RO**
**Apr 2006- Dec 2012**

*solid: all data*
*dotted: July data only*

*Geller et al. (2013, JClim)*




**HIRDLS**
**20-30 km**
**May 2006**

*J. Alexander et al. (2008, JGR)*

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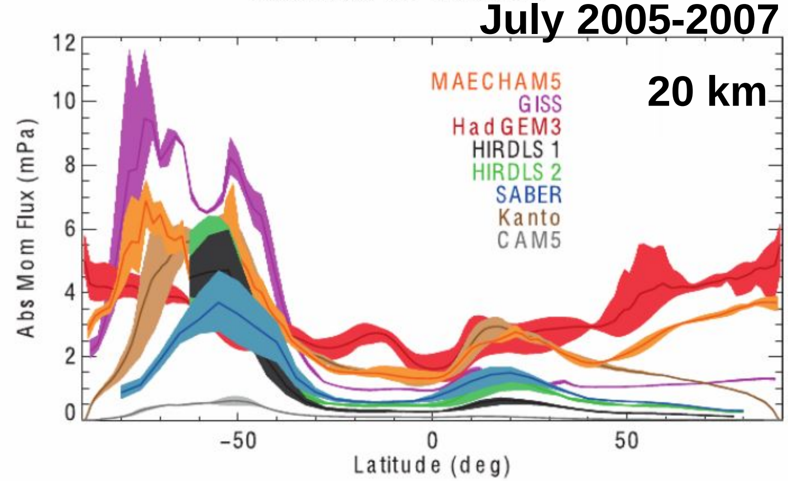
**July 2005-2007**

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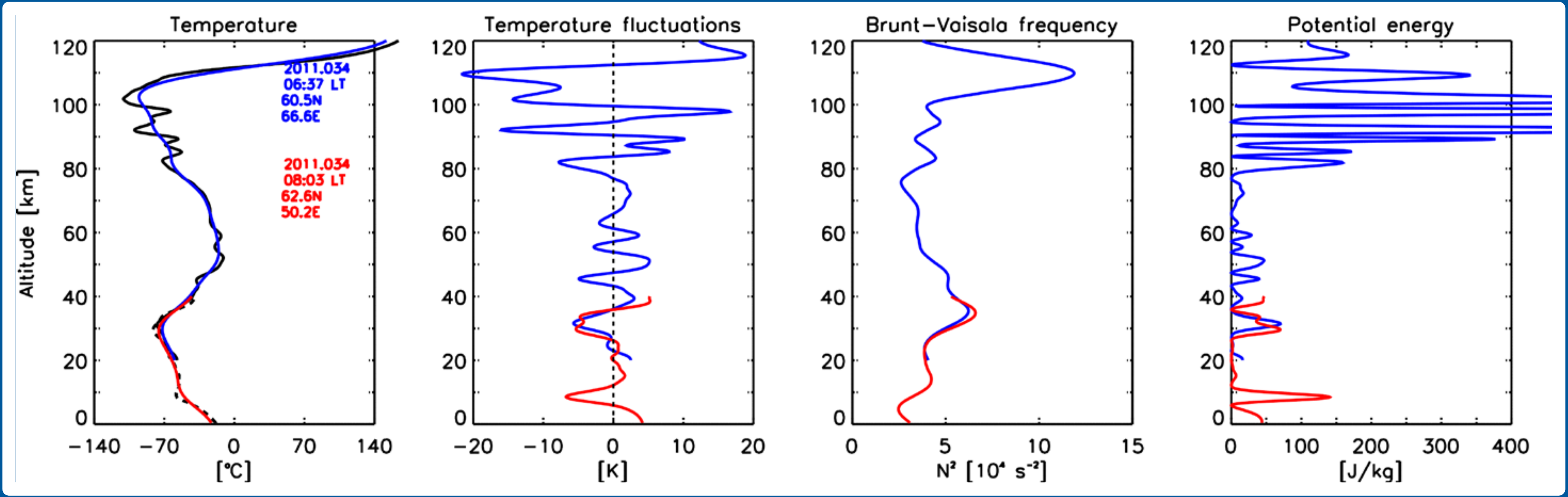
# Summary and Outlook

- RO measurements provide an excellent data base for the study of tradionally gravity wave parameters.
- The general challange for all GW observing systems are the background determination (detrending) and planetary wave removal.
- Absolute GW momentum fluxes are possible from RO data, but are limited due to the temporal and spatial data availability. First results are promising.
- A constellation as to the beginning of the COSMIC mission would be favourably.
- A combination of different datasets (COSMIC+Metop and RO+SABER) for GW analysis and coupling studies is reasonable.

# RO and SABER data




**Can fill the gap in RO data between 40 km and 90 km**

**A good continuity from the RO data to higher altitudes**

**Cover a large altitude interval**

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- A constellation as to the beginning of the COSMIC mission would be favourably.
- A combination of different datasets (COSMIC+Metop and RO+SABER) for GW analysis and coupling studies is reasonable.
- COSMIC-2 with GPS and Glonass tracking could improve the requirements for MF determination.