Large-scale equatorial waves in the middle-atmosphere of the ECMWF model

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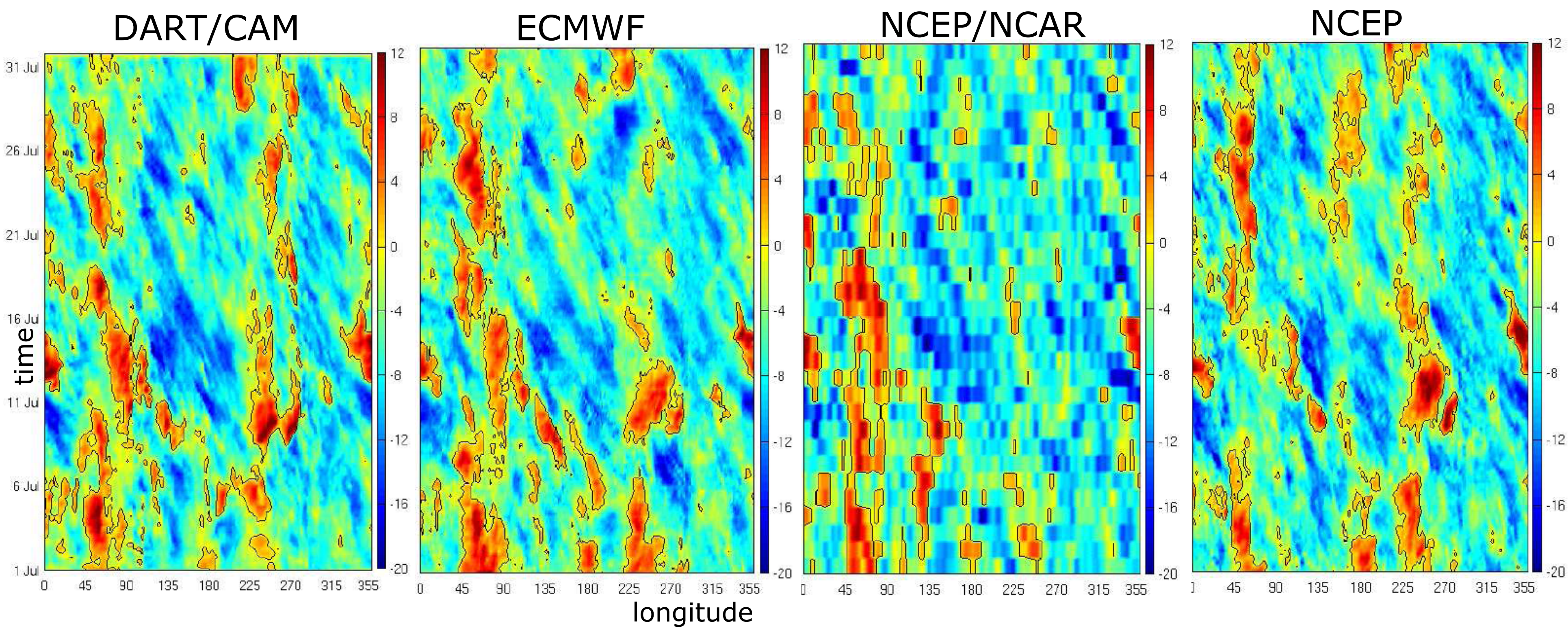
Tropical winds in 4 analysis datasets in July 2007 at 370 hPa along 5ºN



Divergent tropical circulations crucial, but unreliable from present (re)analysis.

Motivation:

Large-scale equatorial inertio-gravity waves in recent years have been diagnosed from different mass-field observations. Quantification of their variance and dynamical relevance still not understood well.

Goal:

Climatology of large-scale equatorial waves in the middle atmosphere by analyzing mass and wind fields simultaneously (normal-mode function expansion)

Spatio-temporal quantification of the wave variance due to various waves

This talk: Kelvin wave

Dataset:

ECMWF: operational analyses, 12-hour 4D-Var system, T799 interpolated to N64 grid, 91 vertical level up to 0.01 hPa. Period 2007-2009, analyses every 6 hours

ERA Interim reanalysis of ECMWF, 1989-2009
ERA40 reanalysis of ECMWF, 1989-2009

Methodology: normal mode functions

Kasahara and Puri, 1981

Linearization of primitve equations around the mean state (vertically stratified in N_z σ levels and at rest

- New mass variable P: $P=gz+RT_o(\sigma)q$ $q=\ln(p_s)$ $\sigma=p/p_s$

assume separation of variables
introduce vertical dependence function $\Psi(\sigma)$

$$\begin{vmatrix} u(\lambda,\theta,\sigma) \\ v(\lambda,\theta,\sigma) \\ g^{-1}P(\lambda,\theta,\sigma) \end{vmatrix} = \begin{vmatrix} u'(\lambda,\theta) \\ v'(\lambda,\theta) \\ g^{-1}P'(\lambda,\theta) \end{vmatrix} \Psi(\sigma)$$

$$\int_0^1 \Psi_i \Psi_j \, d\sigma = \delta_{ij}$$

Equations for horizontal motion:

$$\frac{\partial u}{\partial t} - 2\Omega\mu v + \frac{g}{a}\left(1-\mu^2\right)^{-1/2}\frac{\partial h}{\partial \lambda} = 0$$

$$\frac{\partial v}{\partial t} + 2\Omega\mu u + \frac{g}{a}\left(1-\mu^2\right)^{1/2}\frac{\partial h}{\partial \mu} = 0$$

$$\frac{\partial h}{\partial t} + \frac{H_{eq}}{a}\left[\frac{\partial u}{\partial \lambda} + \frac{\partial}{\partial \mu}\left(\left(1-\mu^2\right)^{1/2} v\right)\right] = 0\,.$$

Stability parameter: $\Gamma_o = \frac{\kappa T_o}{\sigma} - \frac{dT_o}{d\sigma}$

Boundary conditions: $\frac{d\Psi}{d\sigma} = \text{finite at } \sigma = 0$

$$\frac{d\Psi}{d\sigma} + \frac{\Gamma_o}{T_o}\Psi = 0 \text{ at } \sigma = 1$$

Vertical structure equation:

$$\frac{d}{d\sigma}\left(\frac{\sigma g}{R\Gamma_o}\frac{d\Psi}{d\sigma}\right) + \frac{1}{H_{eq}}\Psi = 0$$

H_{eq} - “equivalent depth”

Vertical eigenstructures for CAM (26 levels)

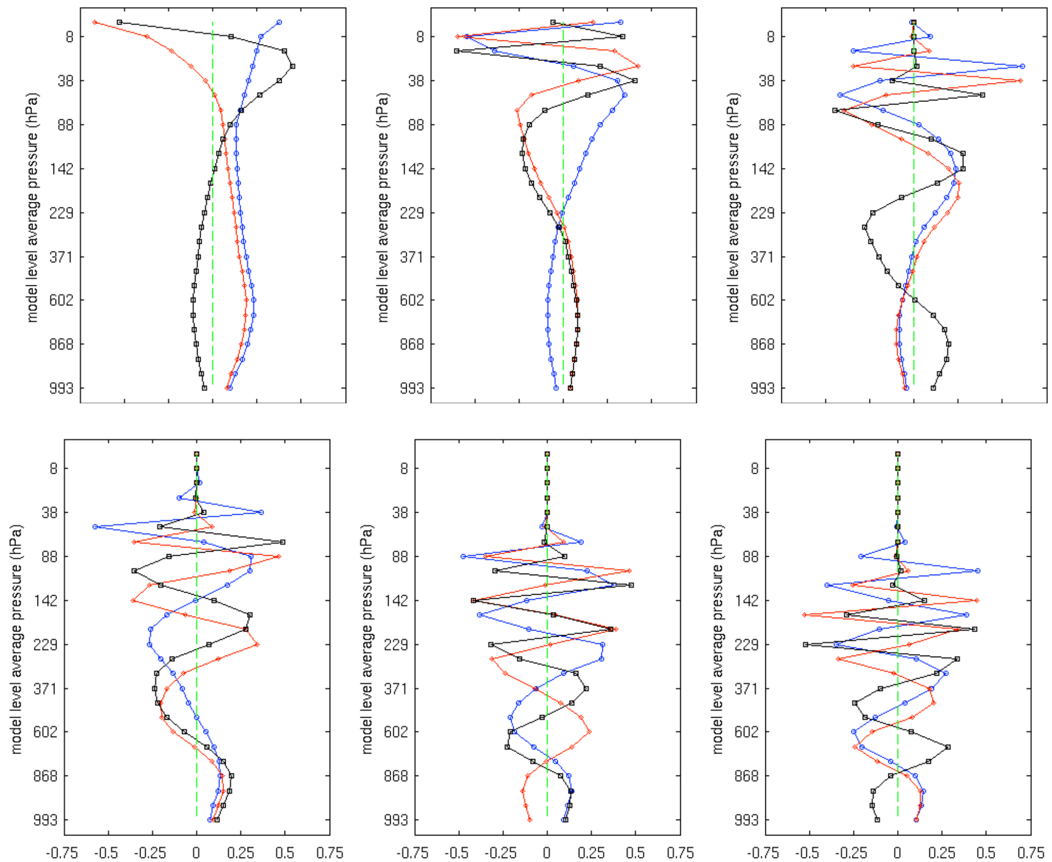
Vertical structure equation:

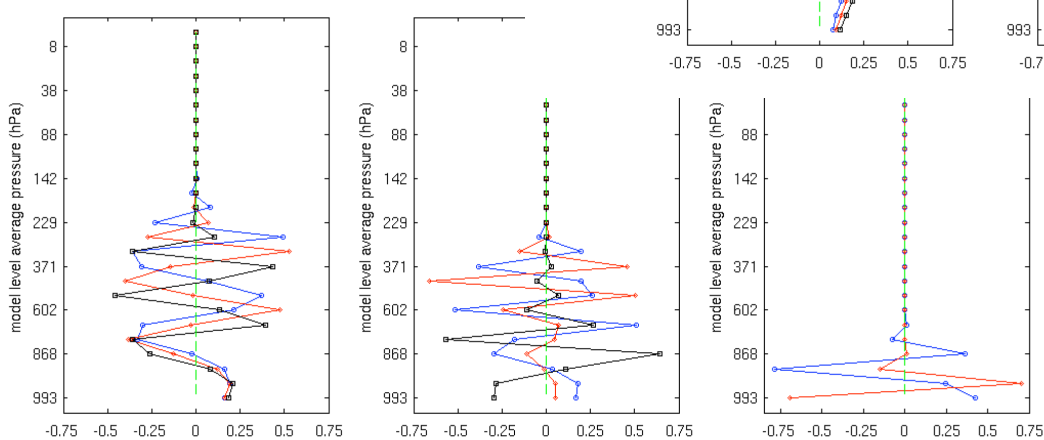
$$\frac{d}{d\sigma}\left(\frac{\sigma g}{R\Gamma_o}\frac{d\Psi}{d\sigma}\right)+\frac{1}{H_{eq}}\Psi=0$$

H_{eq} - "equivalent depth"

Finite difference solution

Input information: vertical discretization, temperature profile, stability profiles





H_{eq} from 10 km to 0.3 m

10 km, 6.2 km, 2.2 km, 985 m, 572 m, 379 m, 250 m, 162 m, 107 m

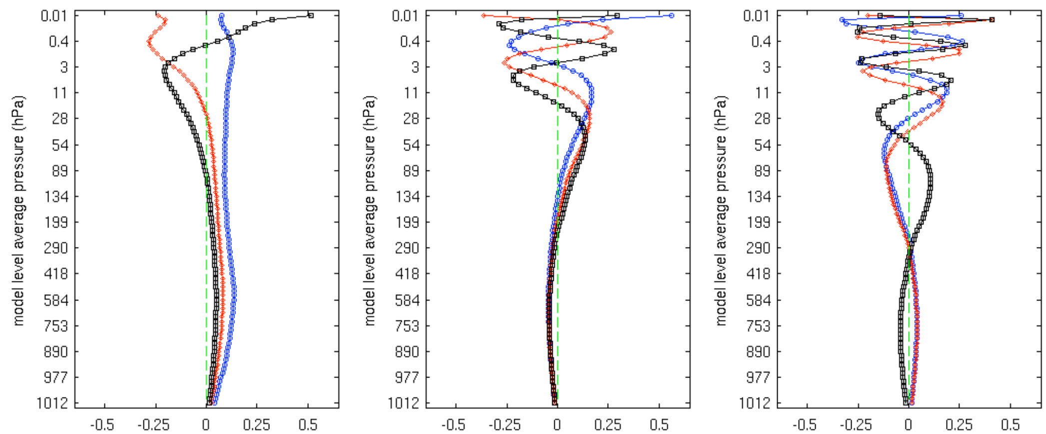
Modes 10-26 have H_{eq} below 100 m

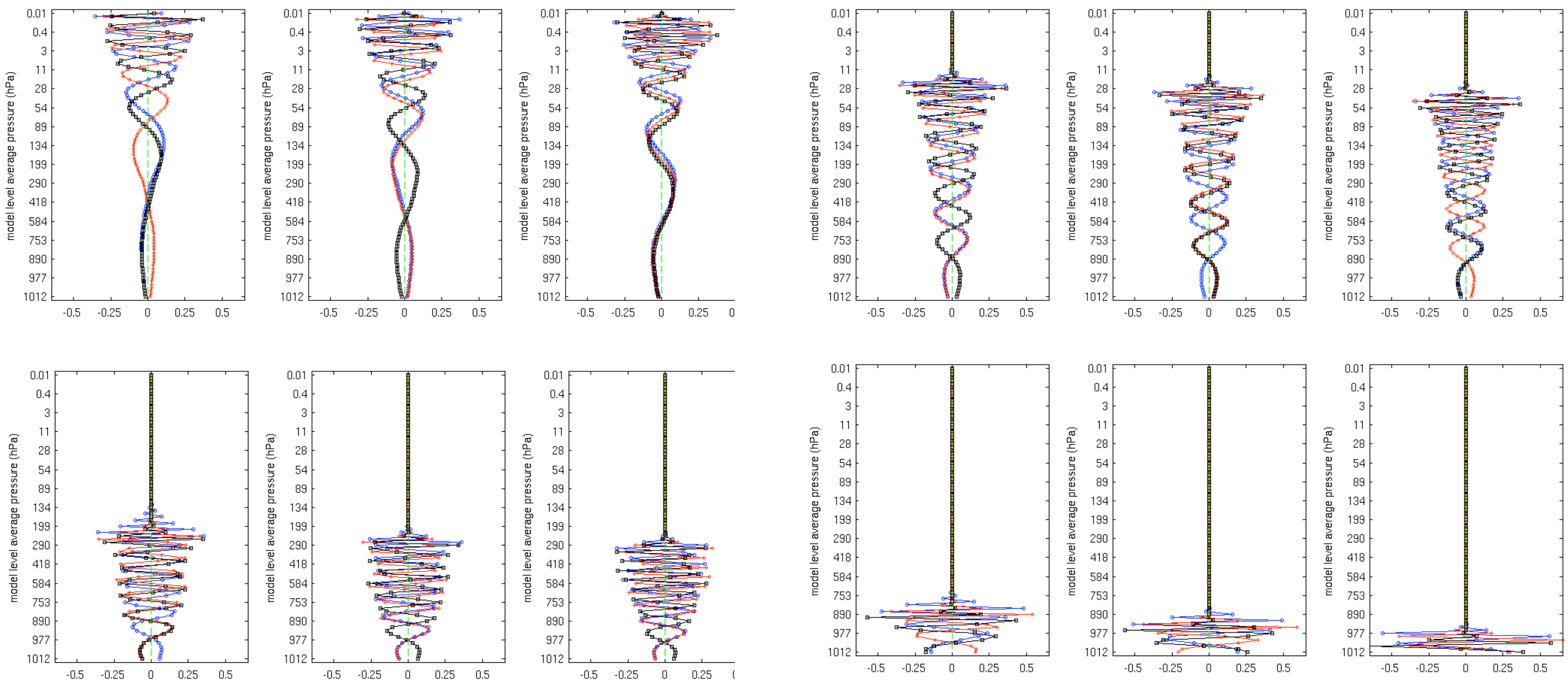
Vertical eigenfunctions for the L91 ECMWF system

H_{eq} from 10 km to 8 mm

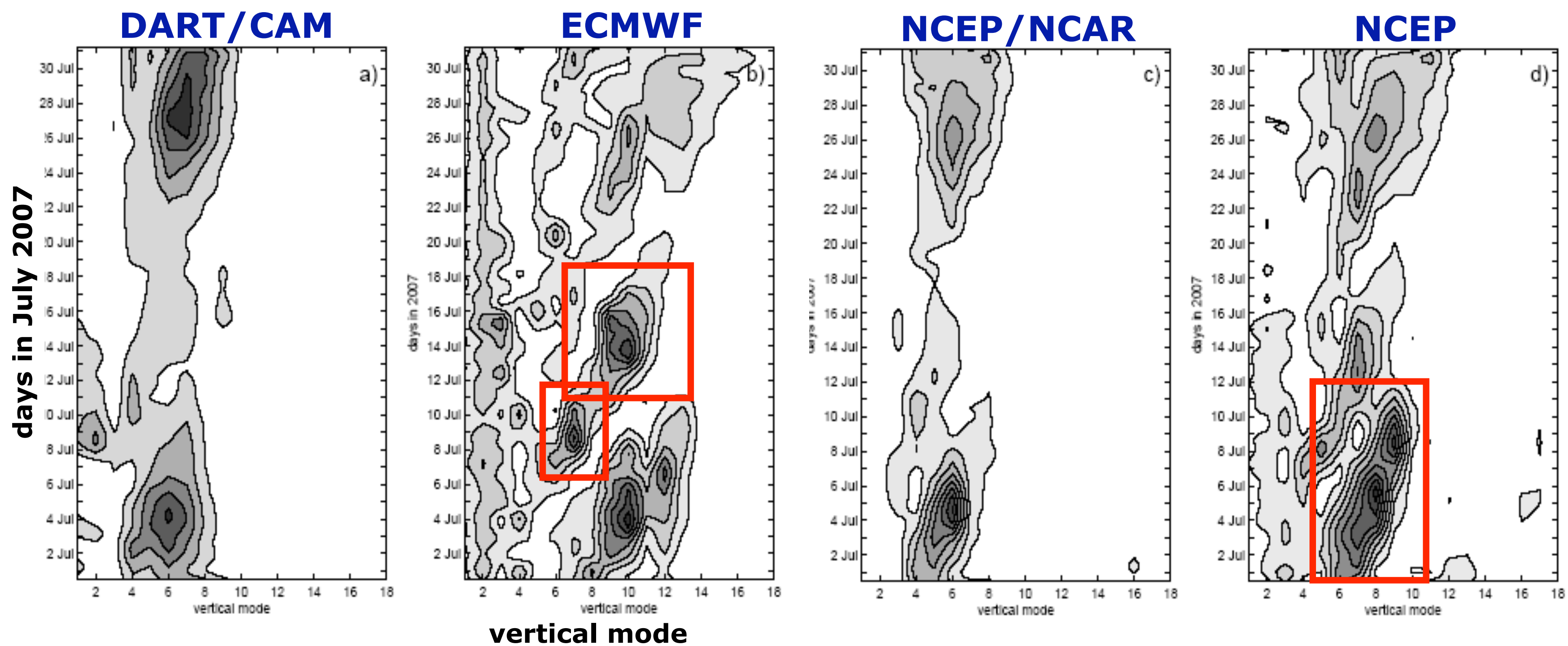
First 18 with H_{eq} > 100 m

Modes 19-38 between 100 m and 10 m, 39-66 between 10 and 1 m, and 66-91 below 1 m.





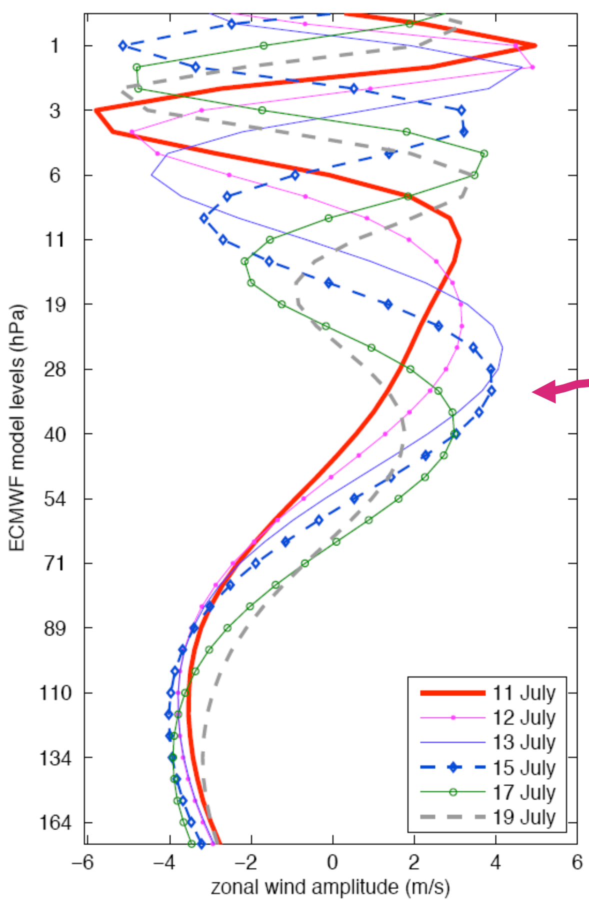
Modal-space diagnosis of the vertical energy propagation by the Kelvin waves



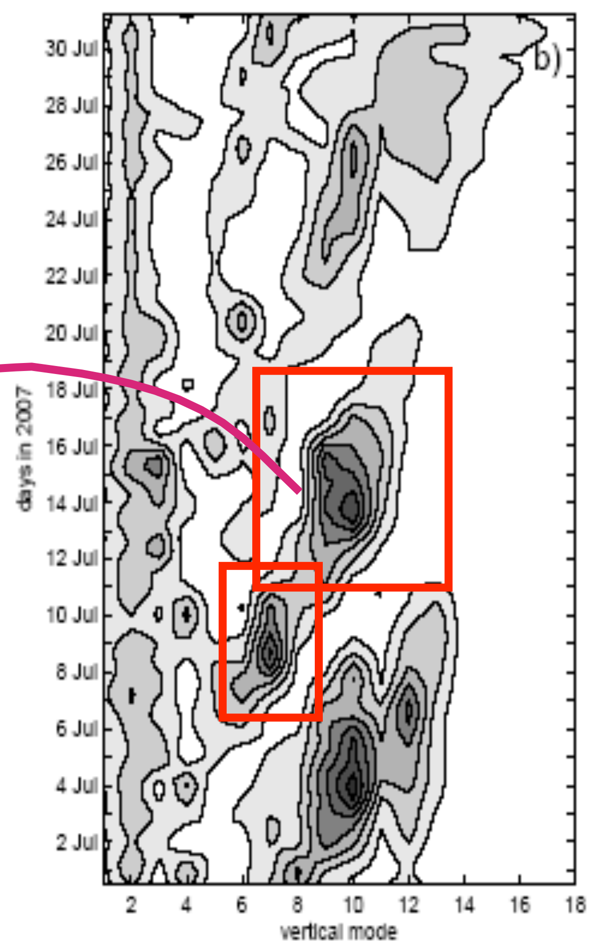
Evolution of the zonal wavenumber k=1 Kelvin wave in July 2007, filtered for periods shorter than 36 hours.

The best agreement between the datasets exists for the Kelvin wave.

Modal-space diagnosis of the vertical energy propagation by the Kelvin waves



ECMWF



The zonal wind component in the Kelvin wave at subsequent days (left) shows the downward phase propagation (upward energy propagation).

The difference in the depth of the atmosphere in DART/CAM and NCEP/NCAR on one hand and ECMWF and NCEP on the other appears to be one reason for different propagation properties as well as energy levels in datasets.

(Zagar et al., 2009)

Horizontal normal-mode solutions:

Beauty of physical significance

Kasahara 1976, 1978

System of equations for the horizontal structure of modes

$$\frac{\partial u}{\partial t} - 2\Omega\mu v + \frac{g}{a}\left(1-\mu^2\right)^{-1/2}\frac{\partial h}{\partial \lambda} = 0$$
$$\frac{\partial v}{\partial t} + 2\Omega\mu u + \frac{g}{a}\left(1-\mu^2\right)^{1/2}\frac{\partial h}{\partial \mu} = 0$$
$$\frac{\partial h}{\partial t} + \frac{H_{eq}}{a}\left[\frac{\partial u}{\partial \lambda} + \frac{\partial}{\partial \mu}\left(\left(1-\mu^2\right)^{1/2} v\right)\right] = 0\,.$$

Solutions

$$(u, v, h)^{\mathrm{T}} = \mathbf{S}_m \mathbf{H}^p_{k,n}(\lambda, \theta, m)\, e^{-\mathrm{i}\,\omega_{k,n,m} p\, t}$$

$$\mathbf{S}_\mathbf{m} = \begin{pmatrix} (gH_{eq})^{1/2} & 0 & 0 \\ 0 & (gH_{eq})^{1/2} & 0 \\ 0 & 0 & gH_{eq} \end{pmatrix}$$

Hough functions

$$\mathbf{H}^p_{k,n}(\lambda, \theta, m) = \mathbf{H}^p_{k,n}(\theta, m)\, e^{-\mathrm{i}\,k\,\lambda}$$

$$\mathbf{H}^p_{k,n} \equiv \begin{bmatrix} U^p_{k,n,m}(\theta) \\ -\mathrm{i}V^p_{k,n,m}(\theta) \\ Z^p_{k,n,m}(\theta) \end{bmatrix}$$

m - vertical mode index

k - zonal mode index

n - meridional mode index

σ – eigen frequency

Energy partitioned into balanced (ROT) and inertio-gravity (IG) motions (eastward-EIG and westward-WIG) for each vertical mode

3D normal mode expansion: discrete form

Inverse projection:

common expansion coefficient

$$\mathbf{X}(\lambda,\theta,\sigma) = \sum_{m=1}^{N_m} \mathbf{S}_m \left(\sum_{p=1}^{3} \sum_{n=0}^{N_n} \sum_{k=-N_k}^{N_k} \chi_{knm}^{p} \mathbf{H}_{knm}^{p}(\sigma) e^{ik\lambda} \right) \Pi_m(\sigma)$$

normalization matrix

Hough functions

vertical eigenfunctions

Basic idea: select the expansion basis which provides the best fit (best correlation and variance fit to the input grid-point fields) ⬄ tuning of the truncation parameters N_k, N_n , N_m

Number of degrees of freedom per motion type: N_k * N_n * N_m

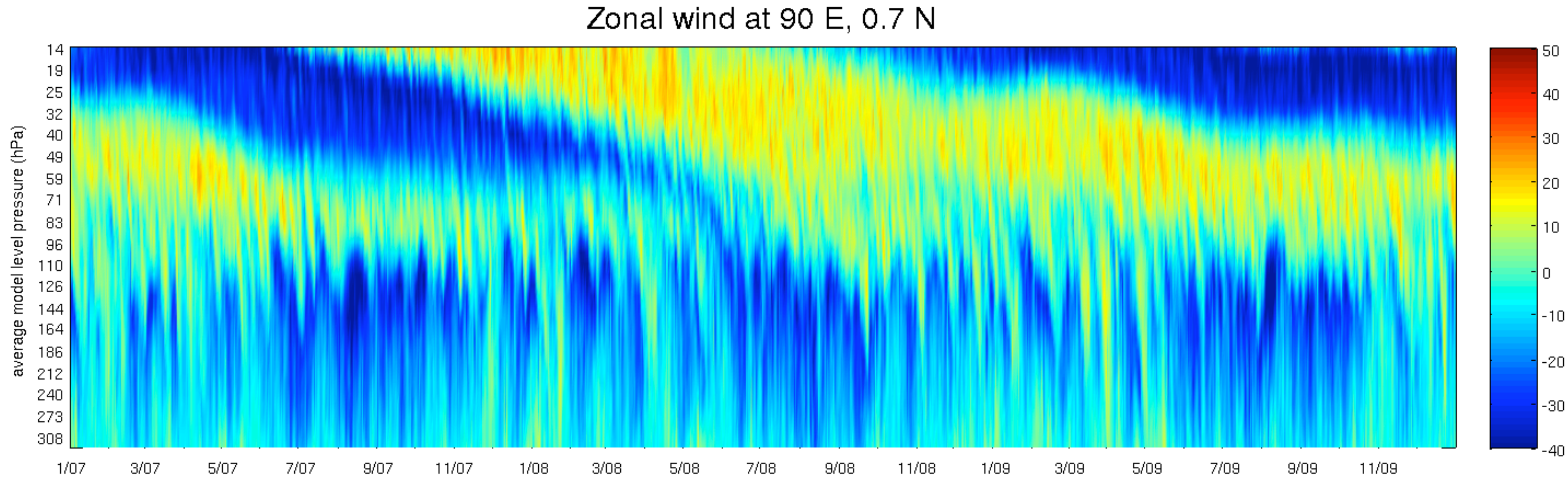
Selected values:

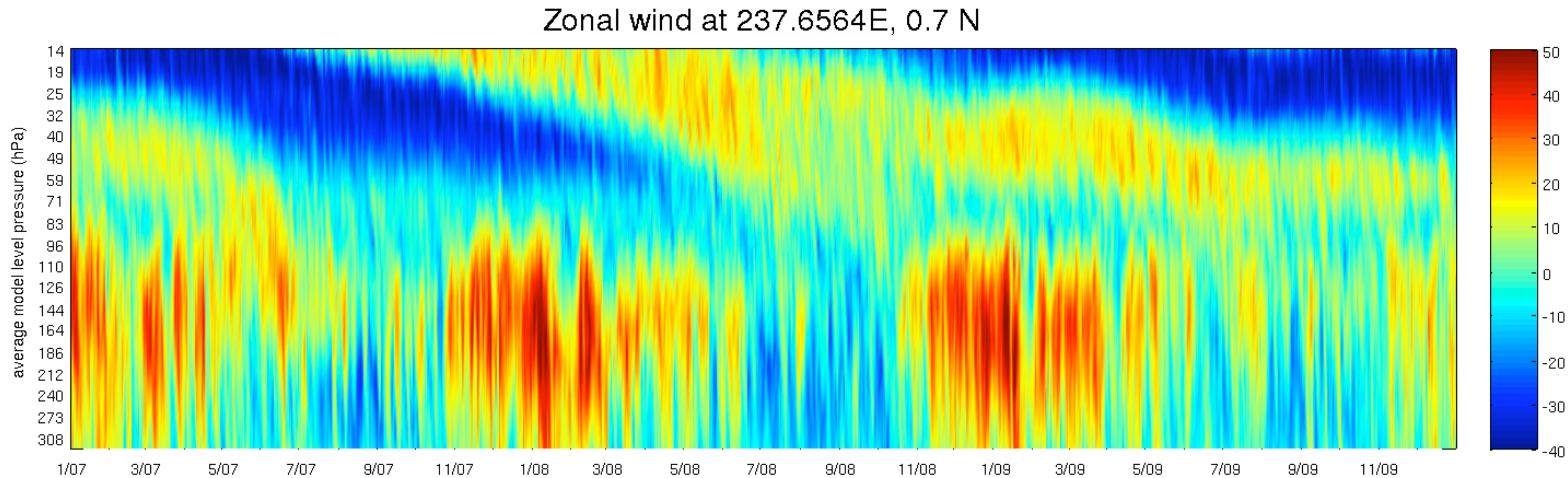
N_k =54, N_n=3 x 18, N_m =70

Total energy per mode (k,n,m) per unit mass:

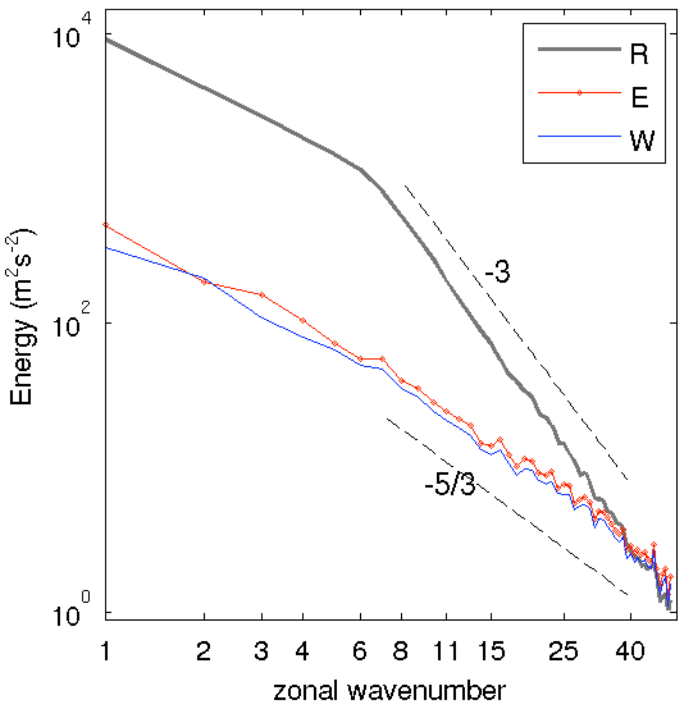
$$\sum_k \sum_n \sum_m g H_{eq} \left| \chi_{knm} \right|^2$$

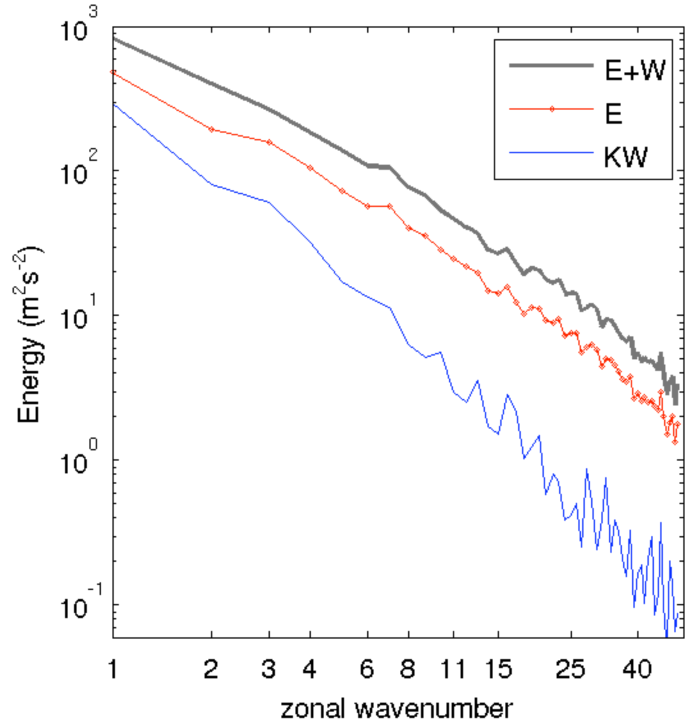
On the input dataset: zonal winds 2007-2009





Wave energy spectra



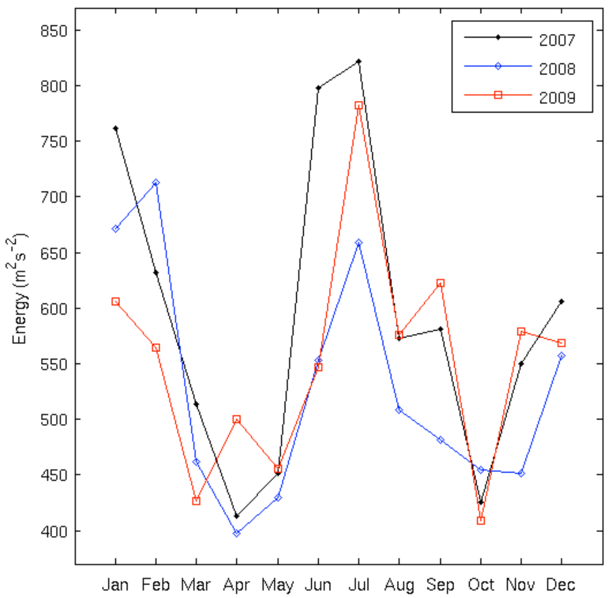


Energy spectra from 3-yr analysis data:

Around 10% of wave energy belong to IG and there is about 1% more EIG than WIG

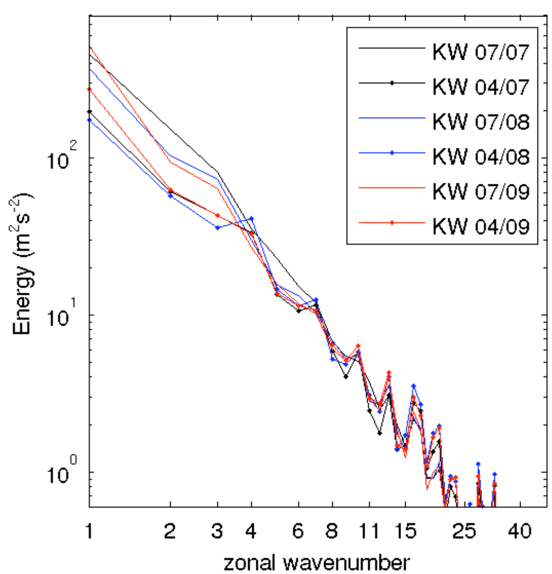
Kelvin wave (KW) makes 20% of IG energy, little over 1/3 of EIG

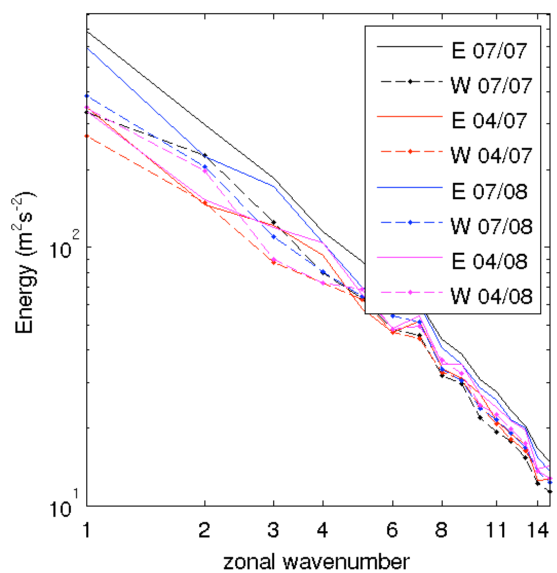
Energy spectra for Kelvin waves



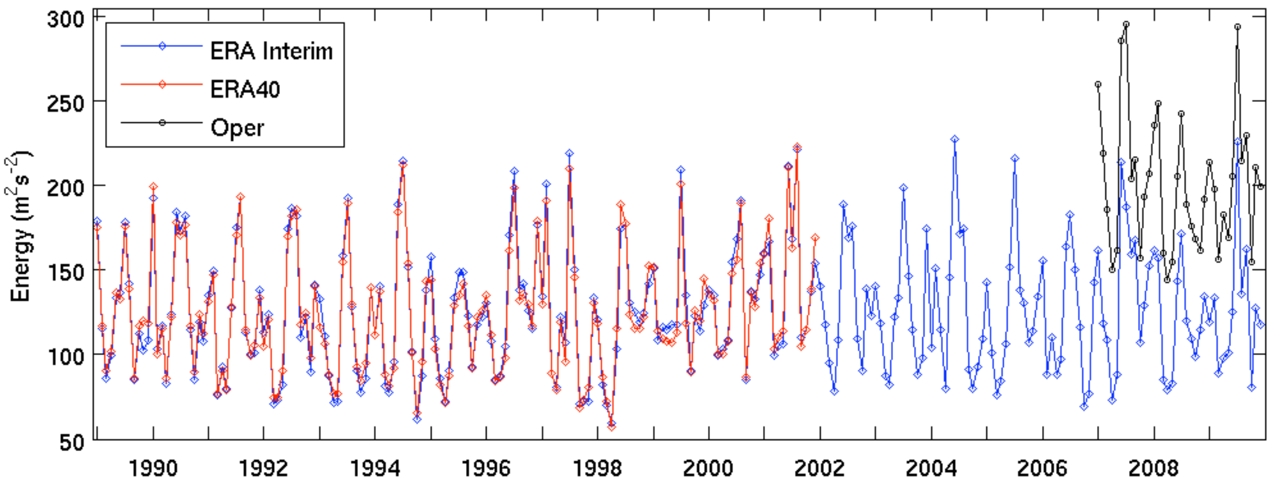
Annual cycle for the KW energy due to zonal wave numbers 1-4

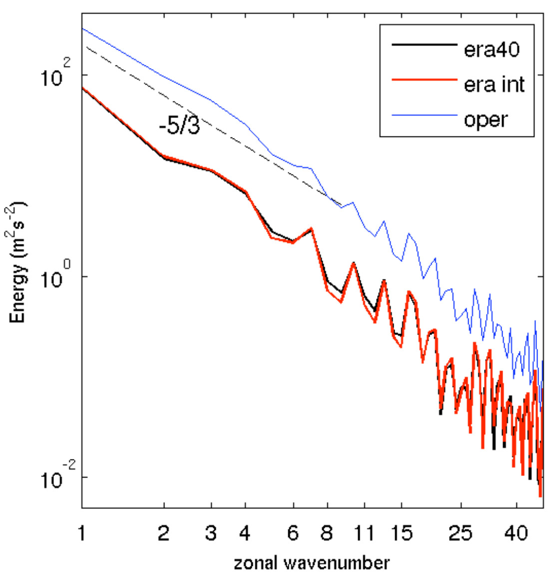
Reduced summer maximum in the westerly phase of QBO

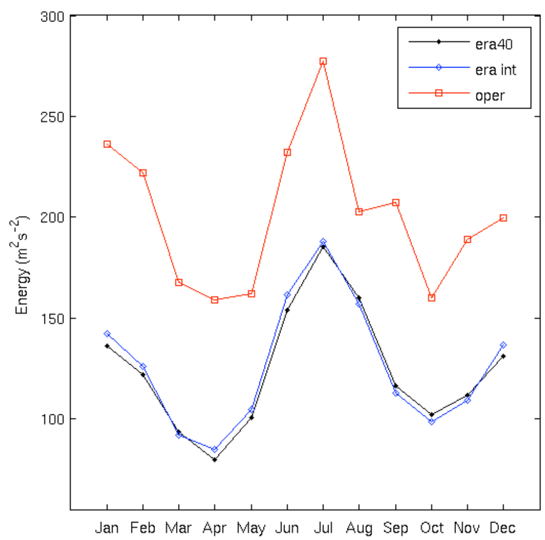




Intercomparison of 3 analysis datasets

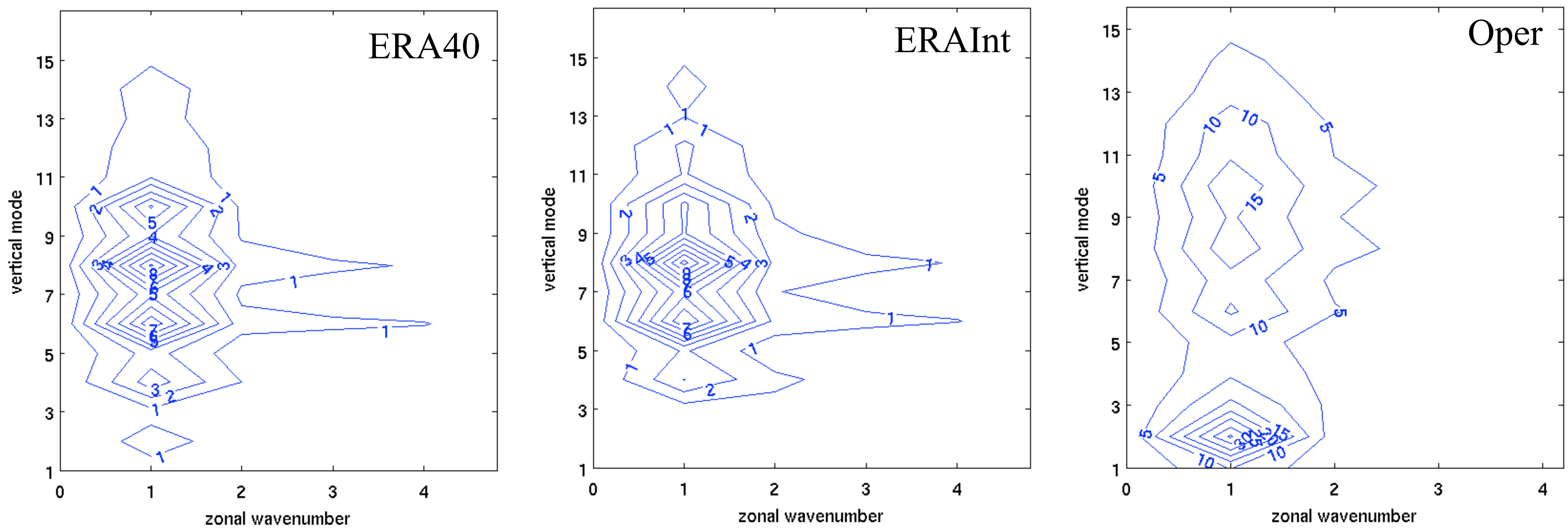






Differences due to vertical model depth

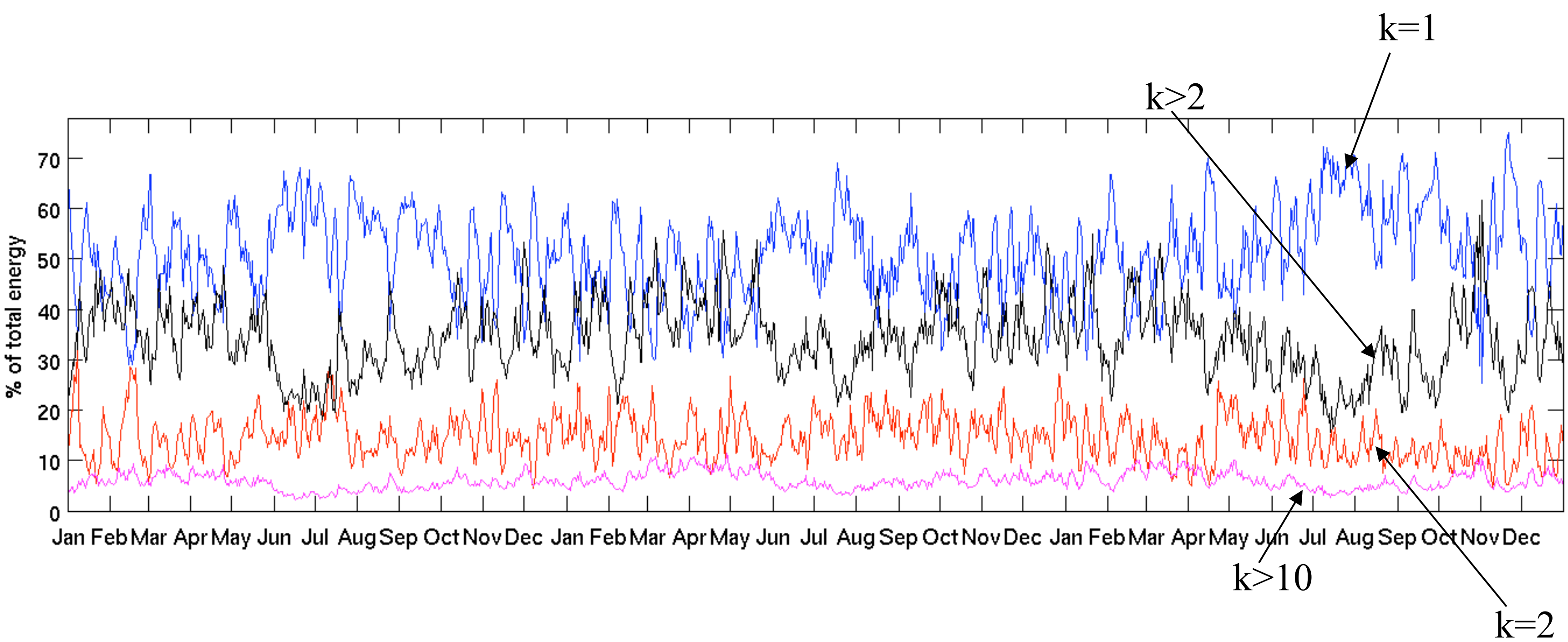
Intercomparison of 3 analysis datasets



Vertical energy distribution changed between ERA40 and ERA Interim

Adding more vertical depth resulted in m=2 (upper stratosphere/ mezosphere)

Kelvin wave: energy vs. scale



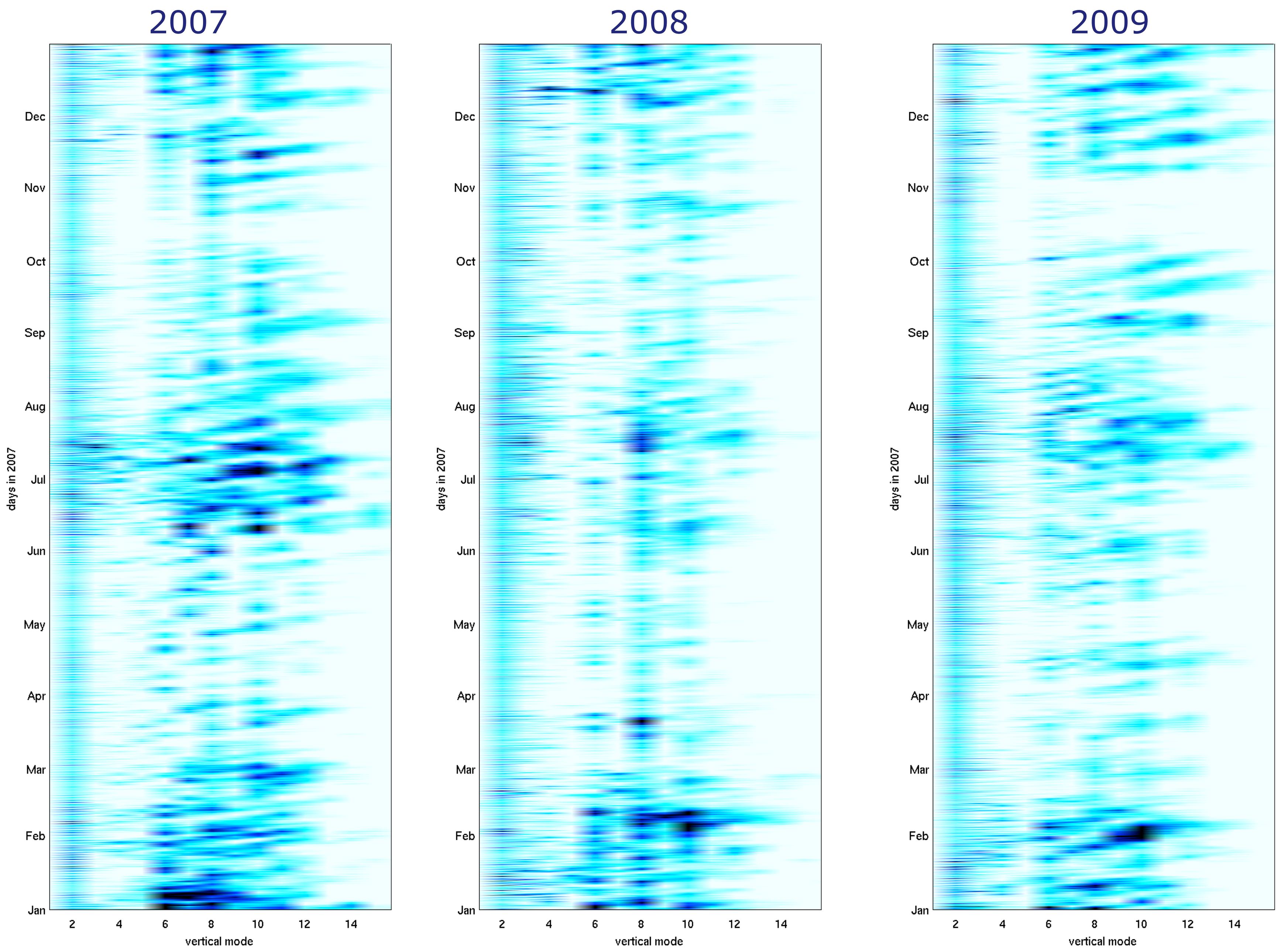
On average, about half of energy is in k=1

Different sign of tendencies in k=1 and higher k

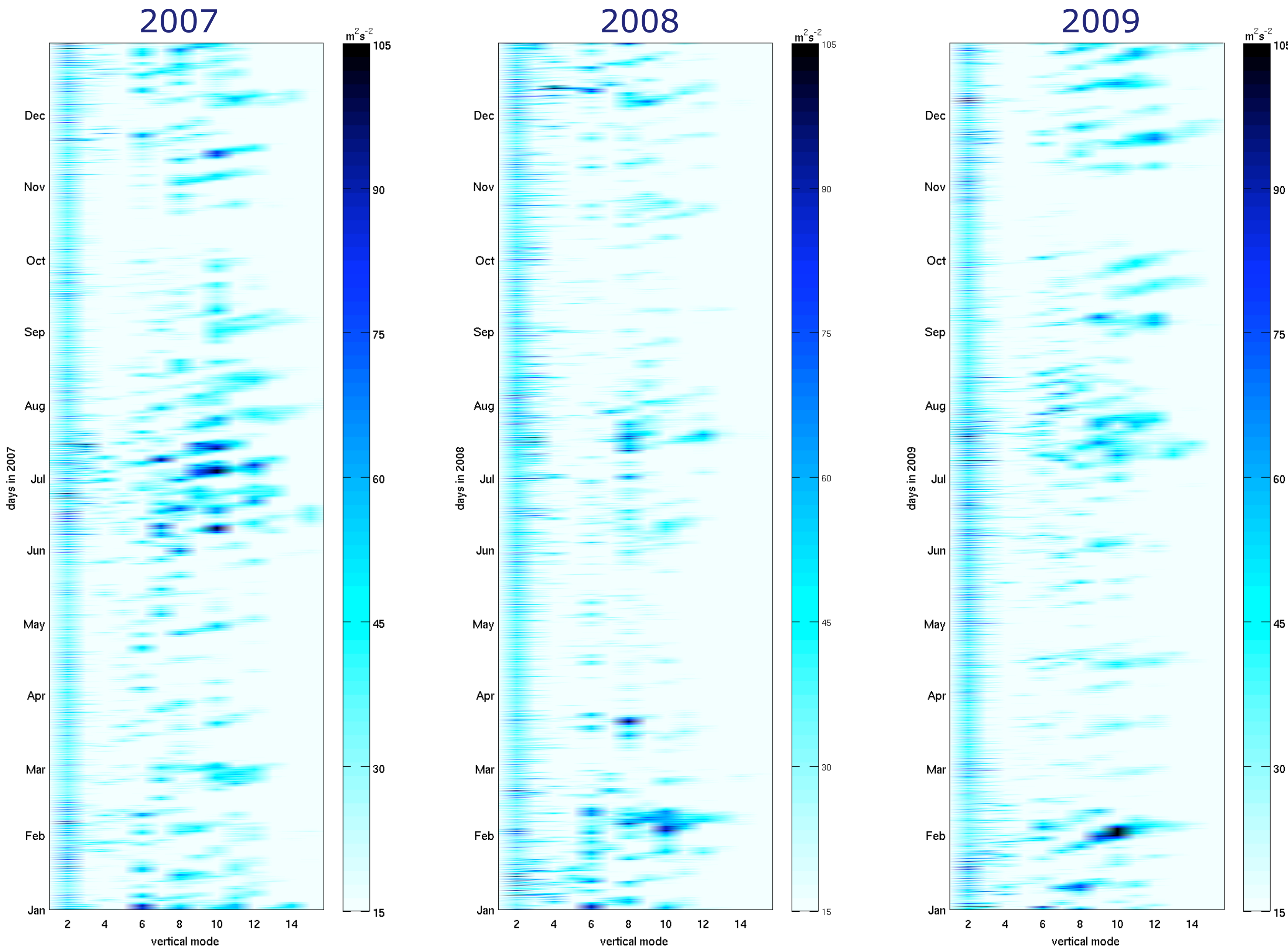
Spectral analysis has peak at periods ~T=16 days

6-hr data show strongly diurnal tide (m=2)

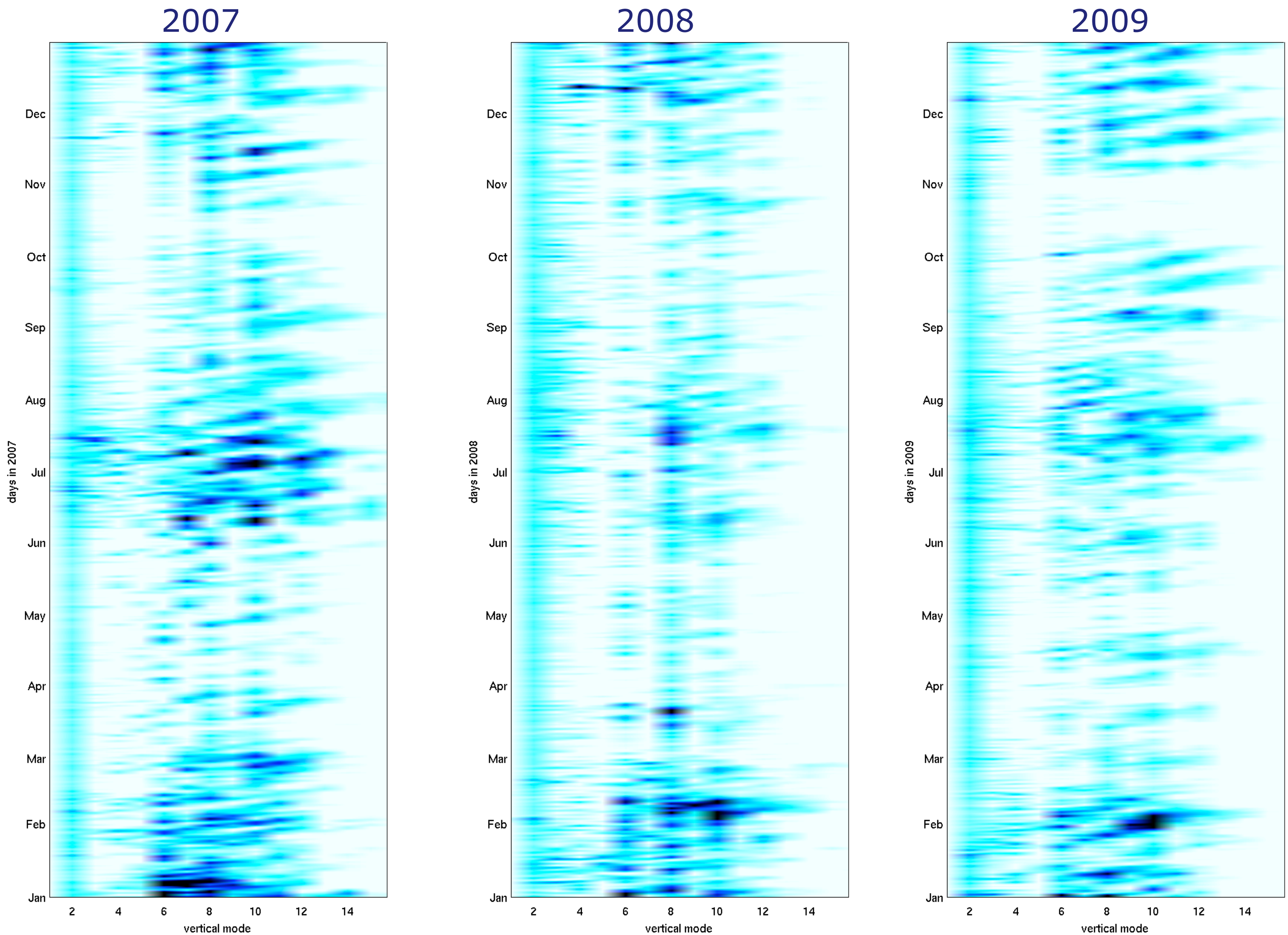
KW: all (k,m)


2007
2008
2009
Dec
Nov
Oct
Sep
Aug
Jul
Jun
May
Apr
Mar
Feb
Jan
days in 2007
2
4
6
8
10
12
14
vertical mode

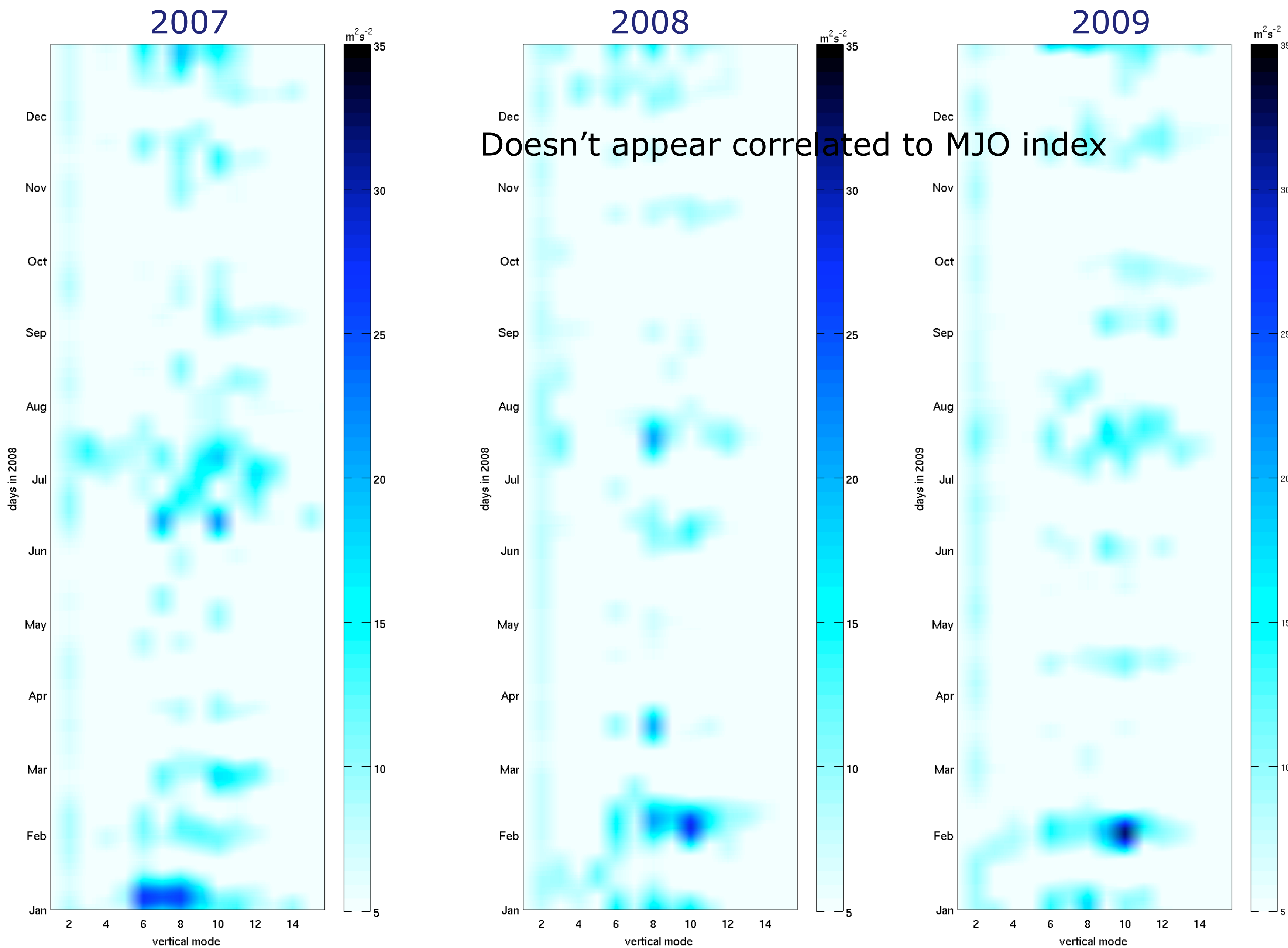
KW: k=1


2007
2008
2009
m^{2}s^{-2}
105
90
75
60
45
30
15
Dec
Nov
Oct
Sep
Aug
Jul
Jun
May
Apr
Mar
Feb
Jan
days in 2007
days in 2008
days in 2009
2
4
6
8
10
12
14
vertical mode

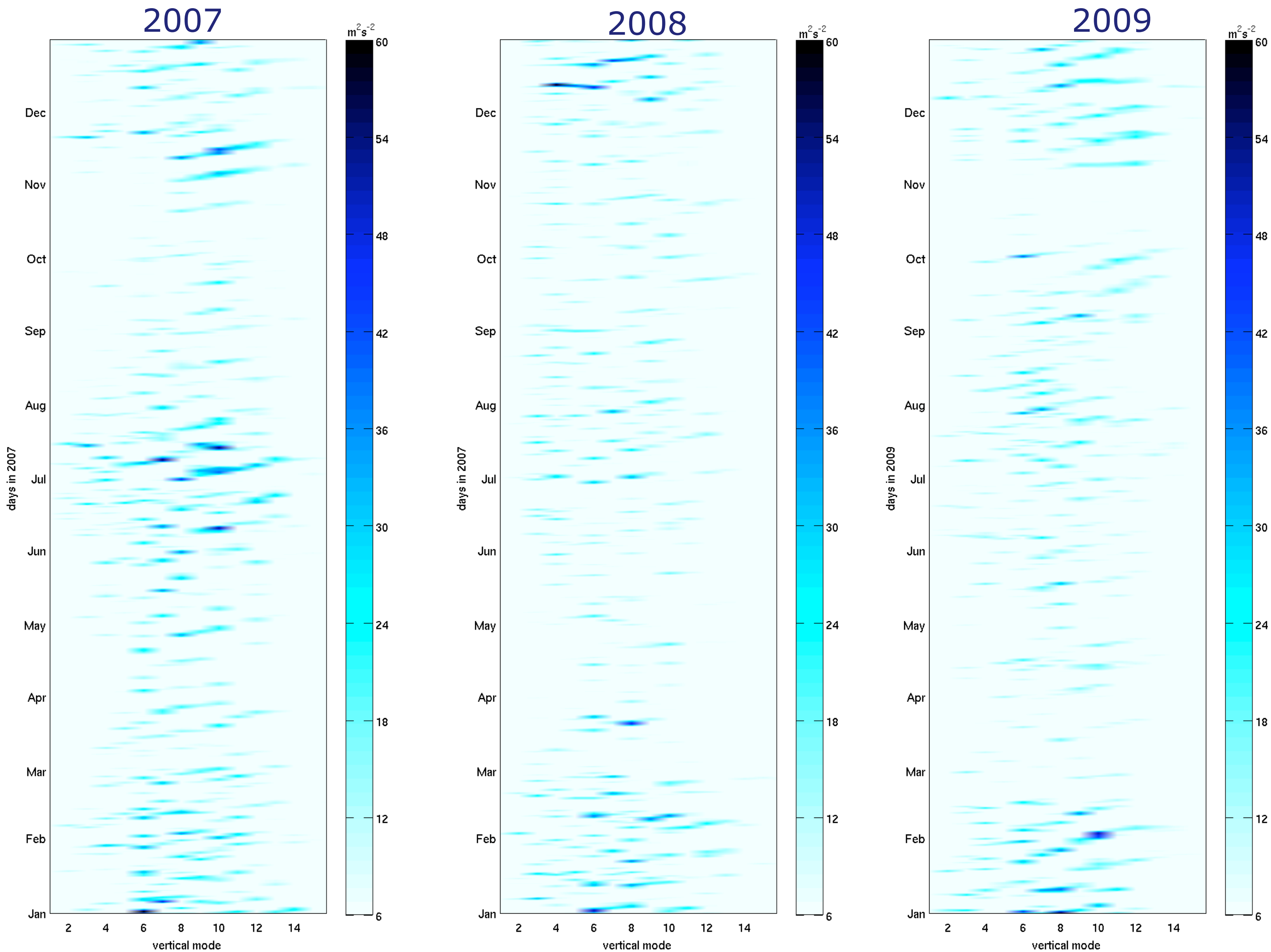
KW: all (k,m), filtered for T< 1.5 days

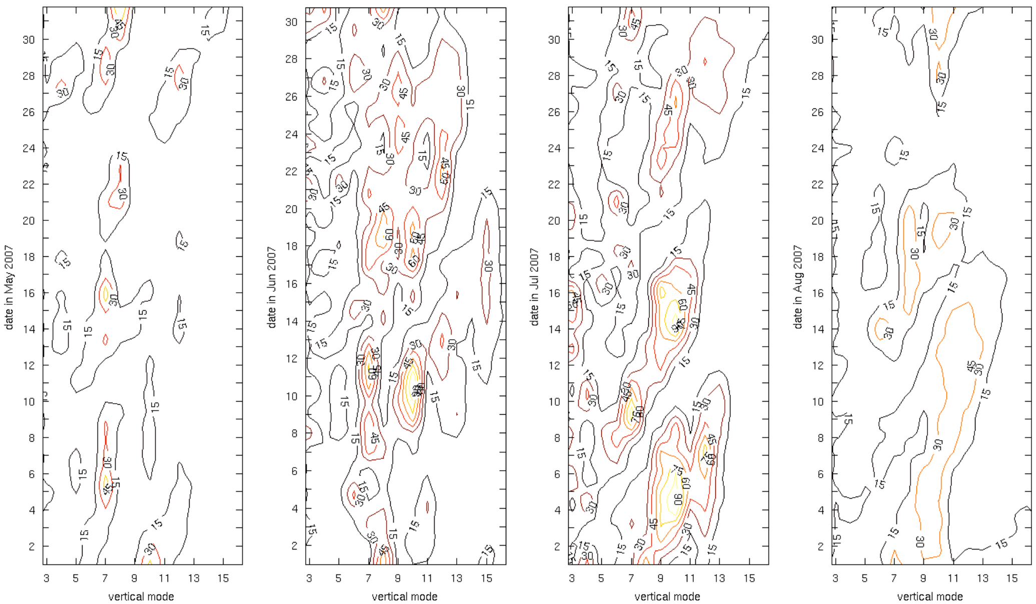


KW: MJO filtered (40<T<60 days)



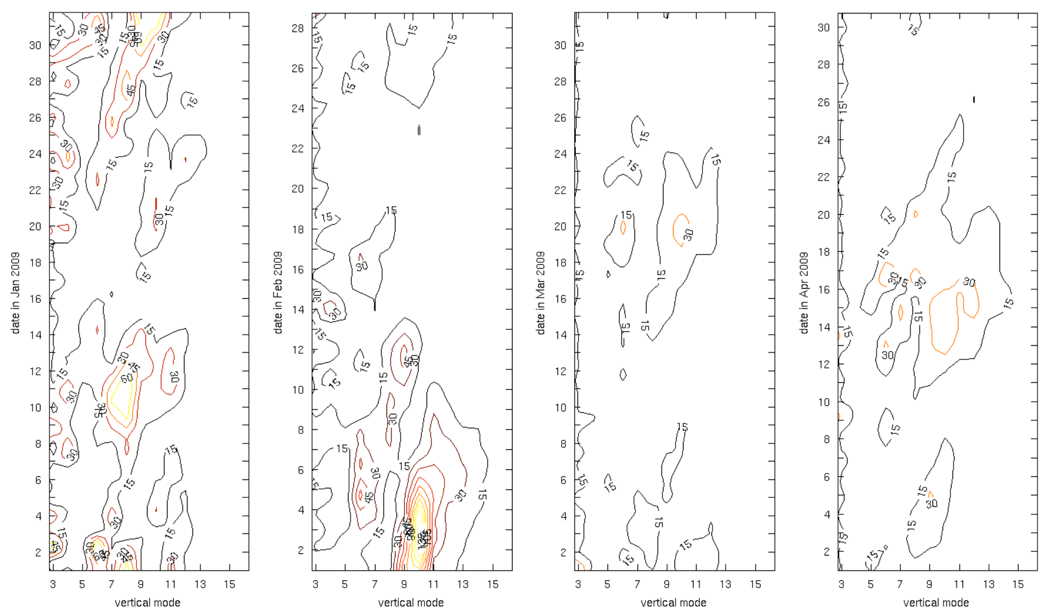
KW: 2-15 days filtered

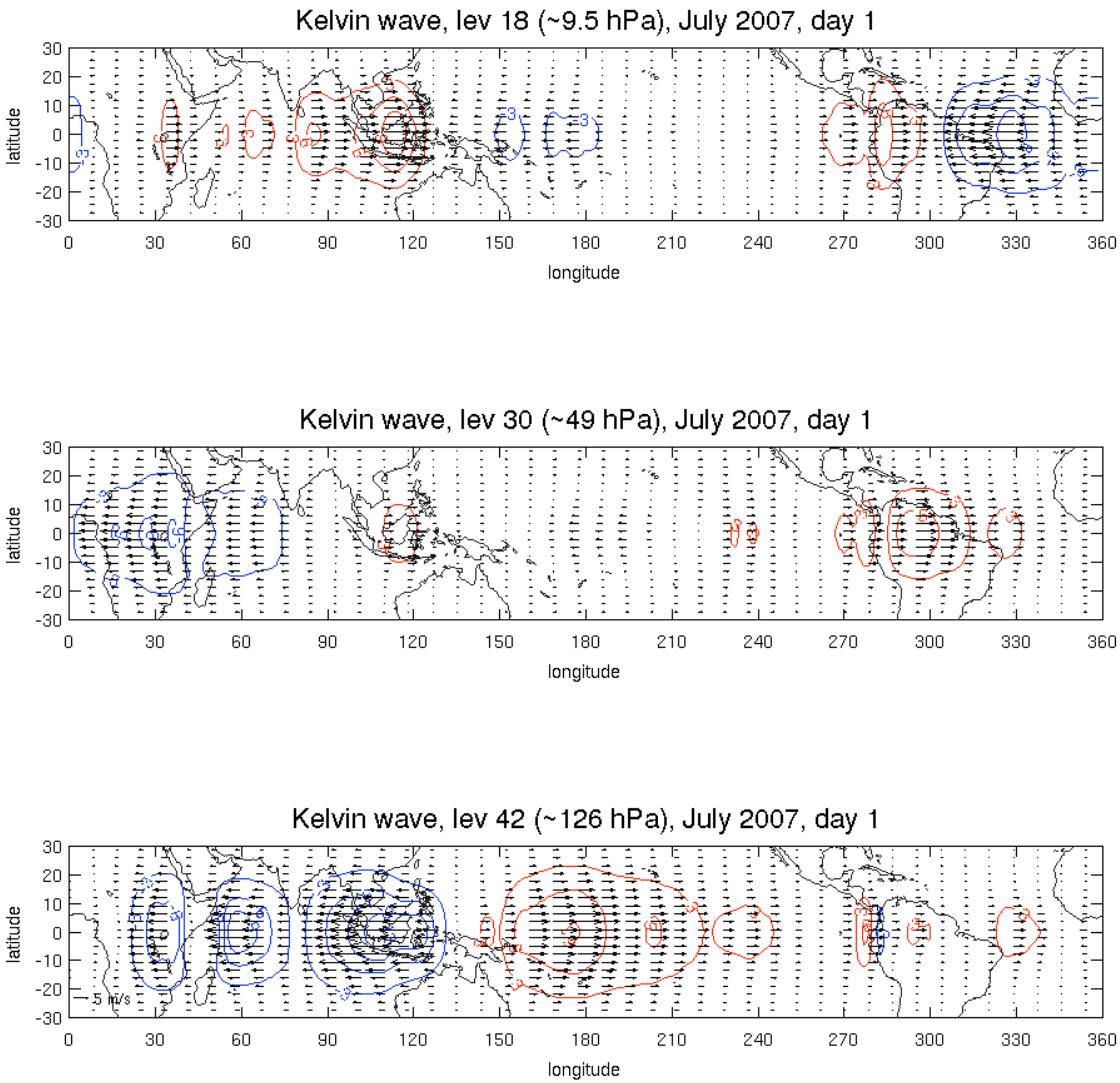




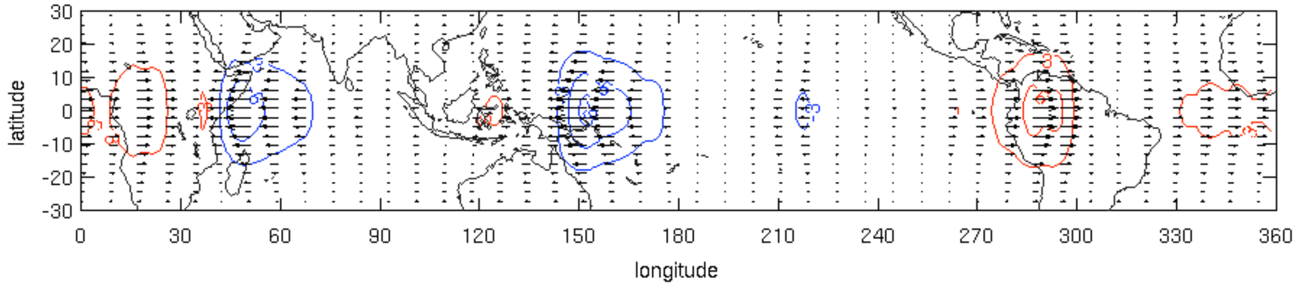
Most transient events last between 10 and 20 days and occupy space m=5-15

Filtering back to physical space shows that events occur in the upper troposphere and the stratosphere

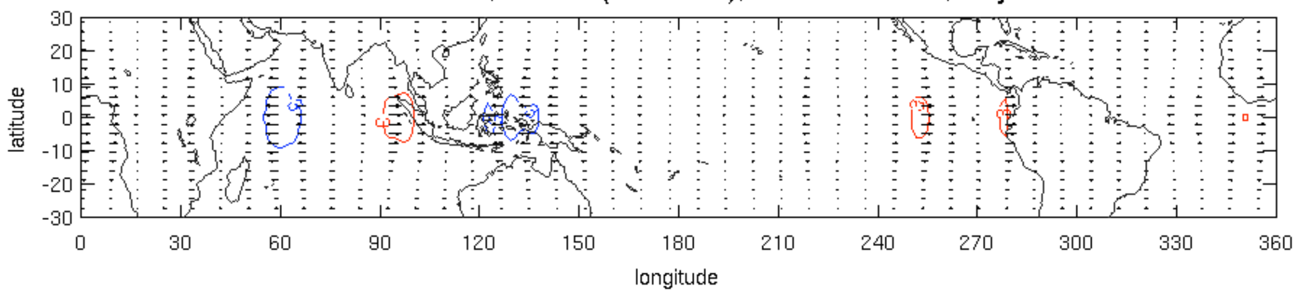



Kelvin wave, lev 18 (~9.5 hPa), July 2007, day 1
latitude
longitude
Kelvin wave, lev 30 (~49 hPa), July 2007, day 1
latitude
longitude
Kelvin wave, lev 42 (~126 hPa), July 2007, day 1
latitude
longitude
5 m/s

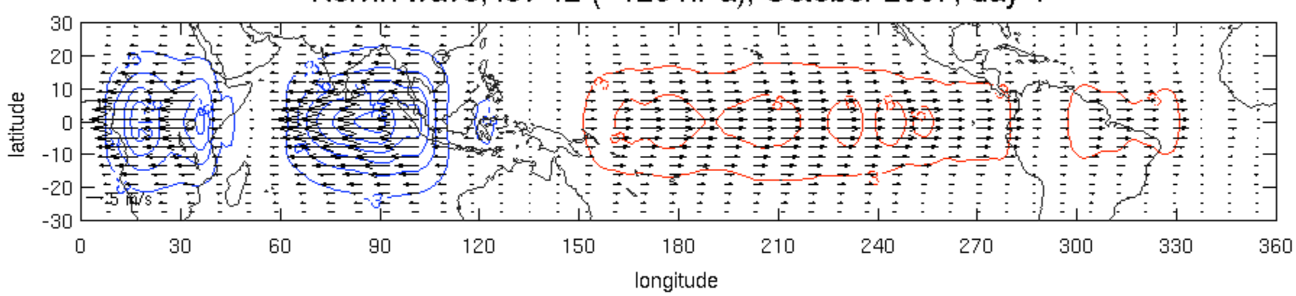
Kelvin wave, lev 18 (~9.5 hPa), October 2007, day 1



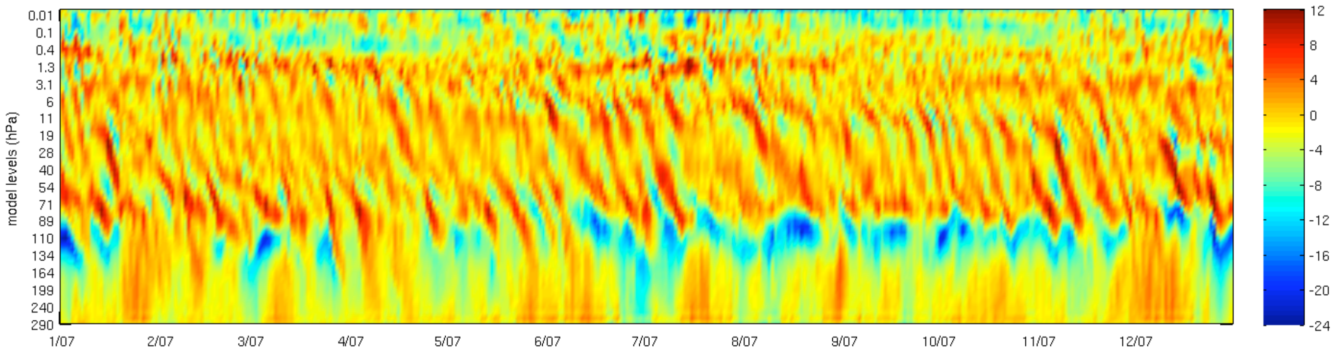
Kelvin wave, lev 30 (~49 hPa), October 2007, day 1



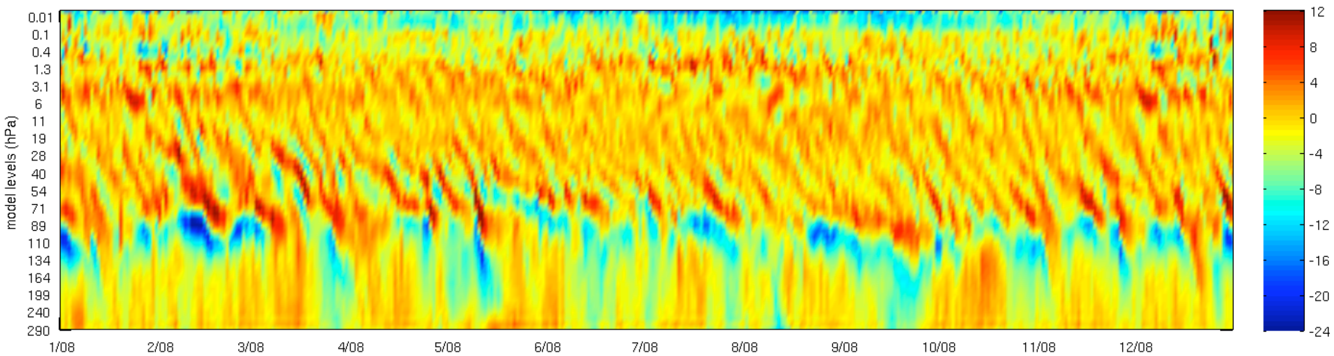
Kelvin wave, lev 42 (~126 hPa), October 2007, day 1



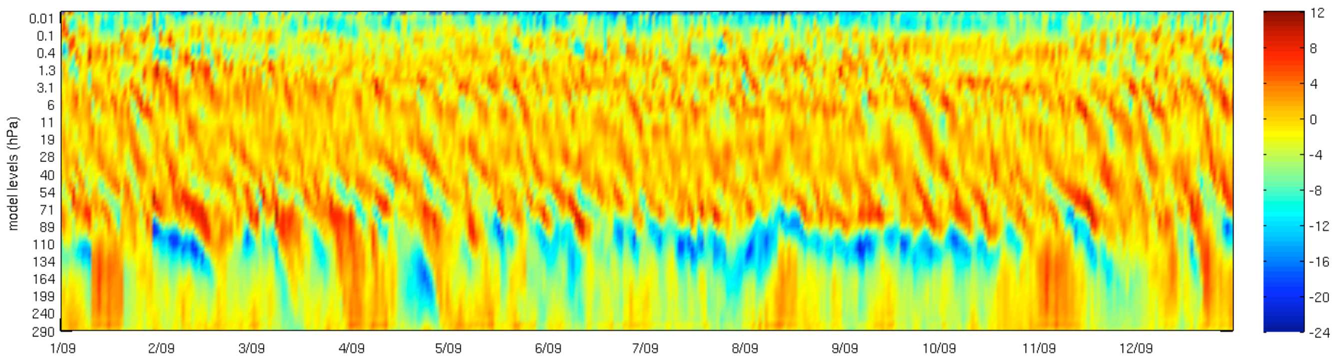
Diagnostics in physical space: u wind at 90 E



2007

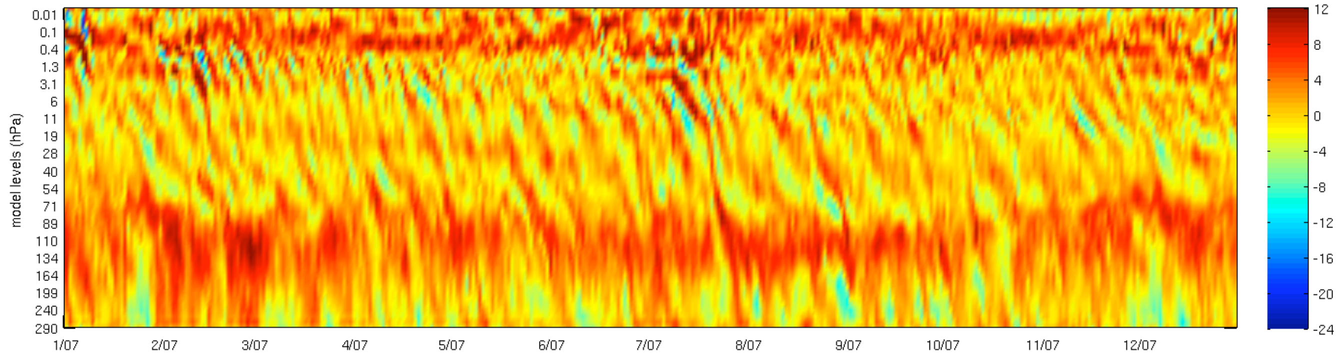


2008

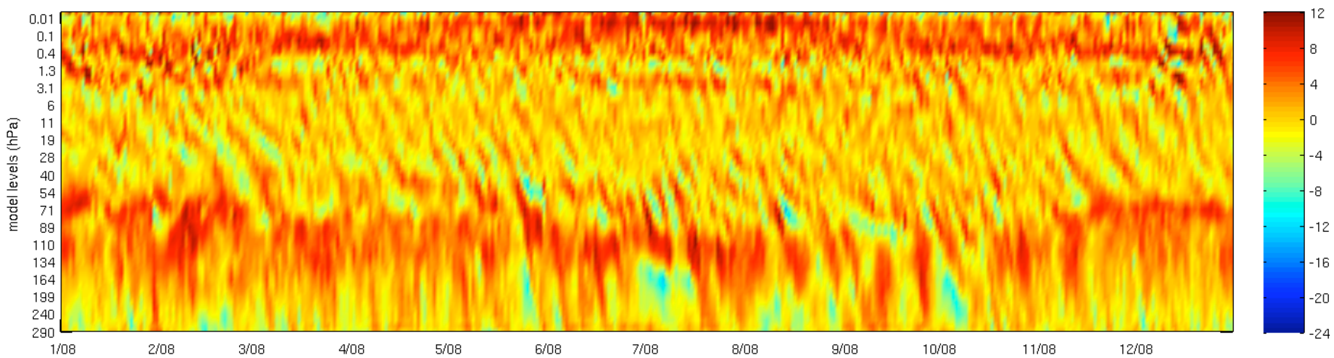


2009

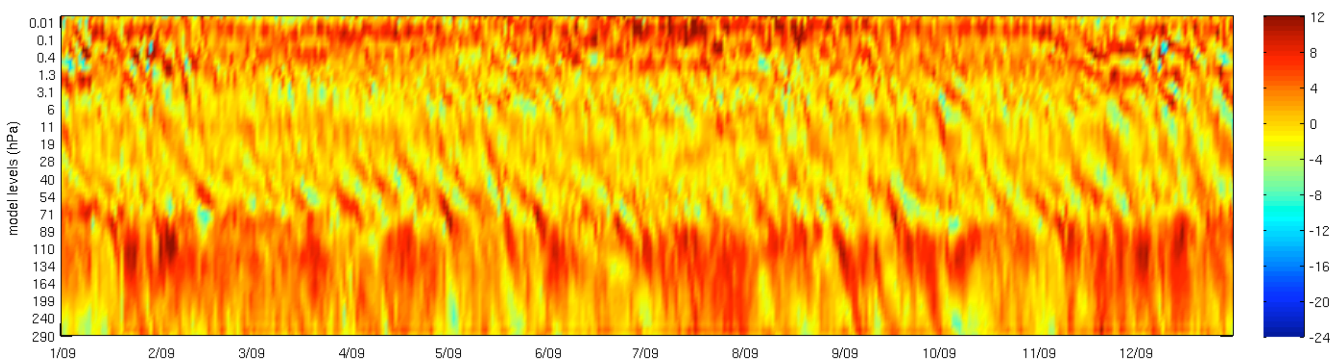
Diagnostics in physical space: u wind at 240 E



2007



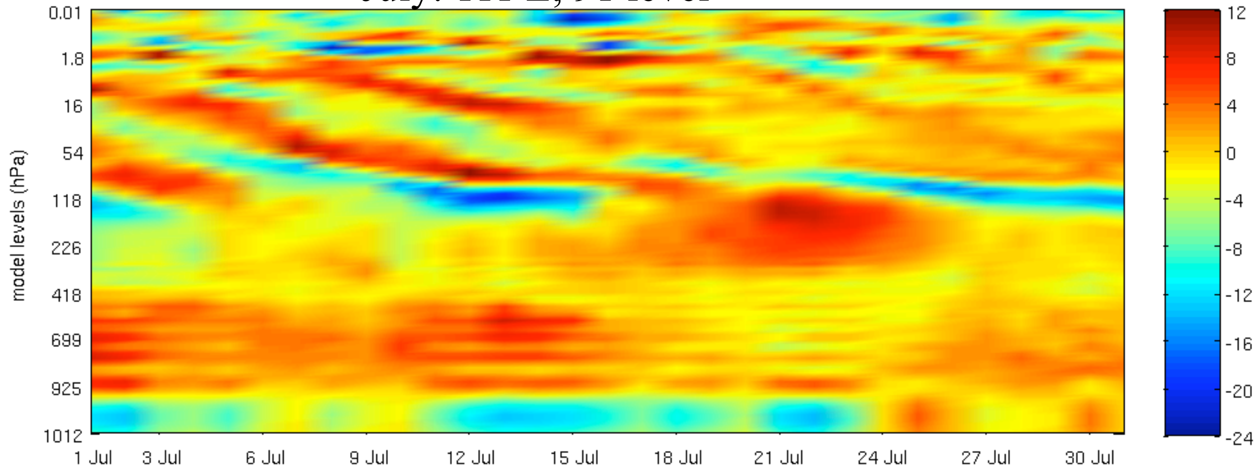
2008



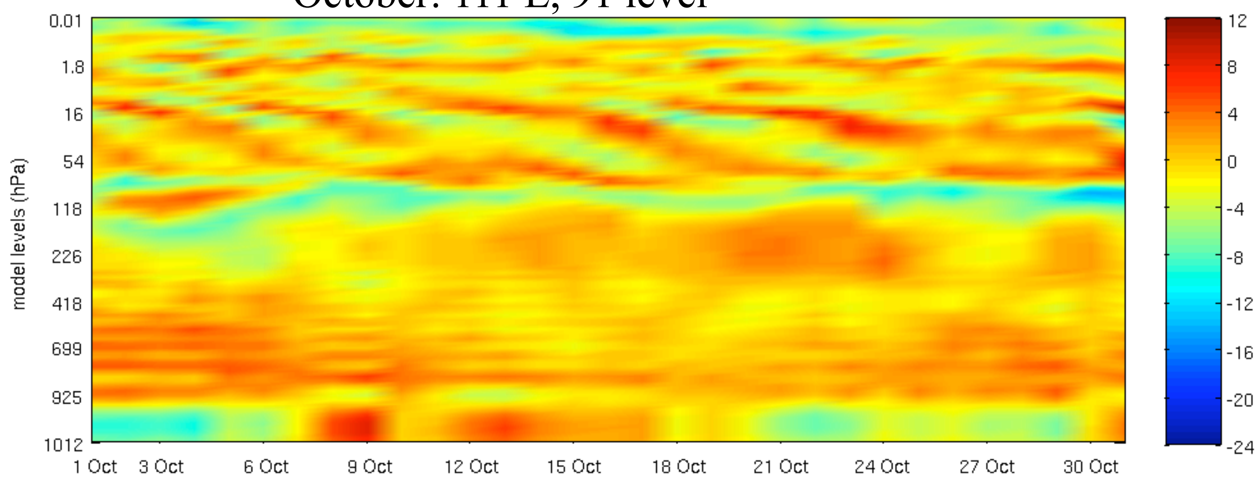
2009

Diagnostics in physical space: July vs. October 2007

July: 111 E, 91 level

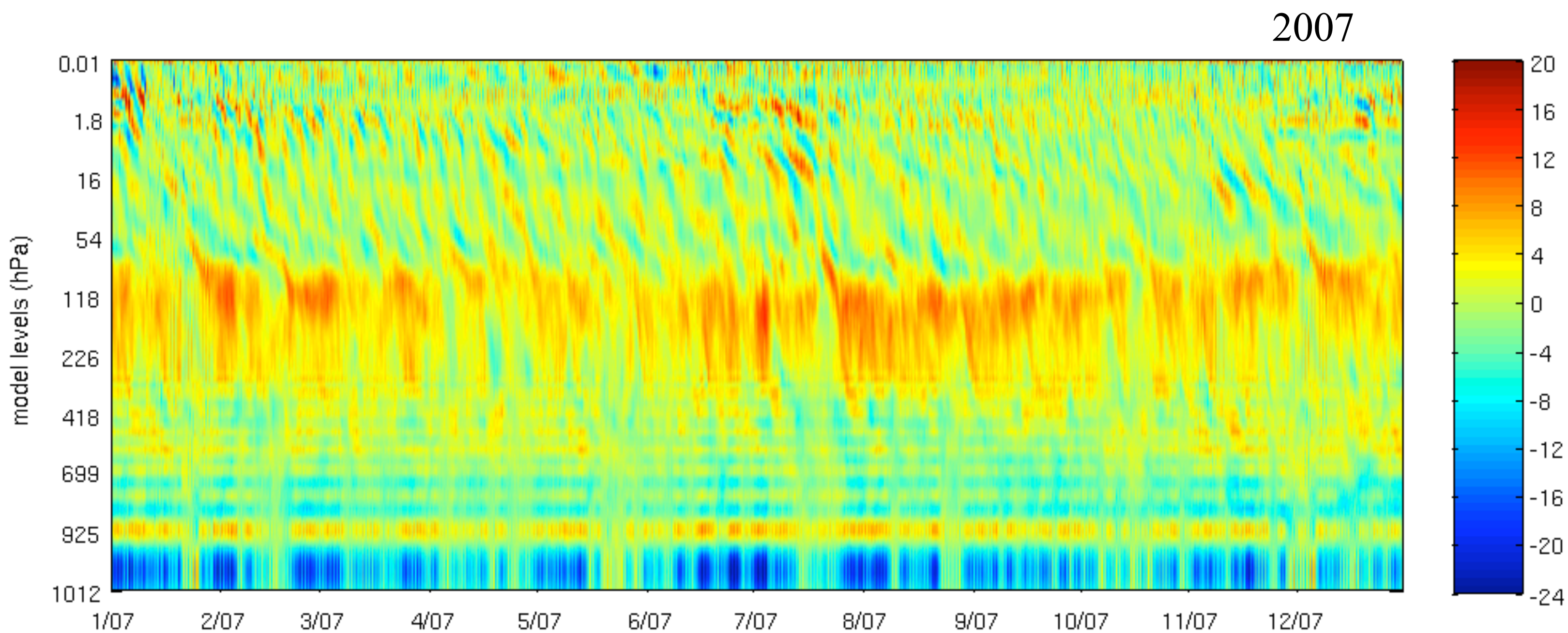


October: 111 E, 91 level



Intensity, not the structure changes throughout the year

Diagnostics in physical space: u wind at 200 E

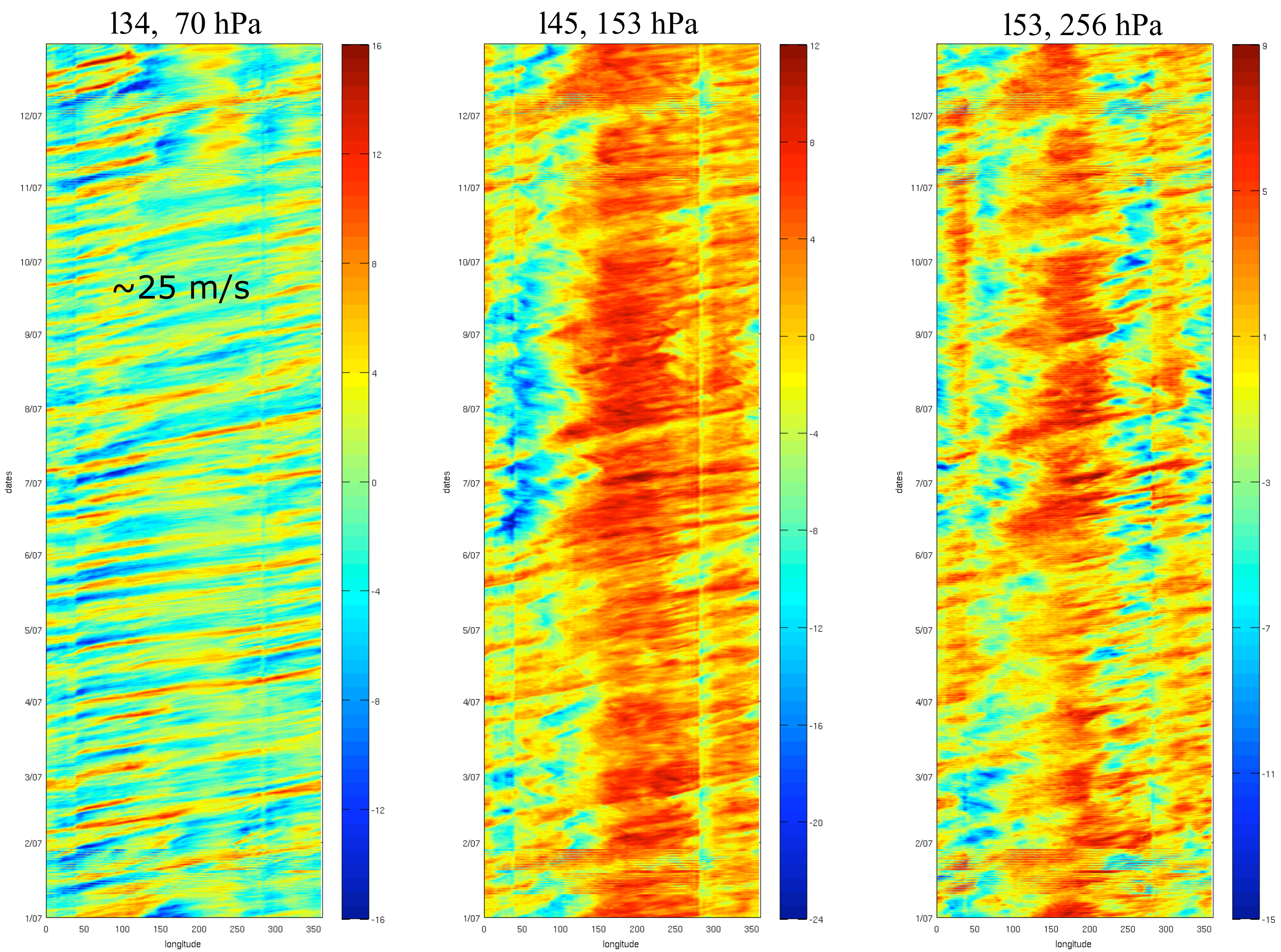


Pacific: Maximal intensity around tropopause region, between 50 hPa and 150 hPa

Westerlies in the boundary layer project to KW

Diagnostics in physical space: u wind

2007



Summary

- Normal modes offers a way to diagnose features of large-scale circulations such as vertical energy propagation by various waves and its seasonal and spatial variability

- ECMWF analyses in 2007-2009 period contain stratospheric Kelvin waves which propagate energy upward with periods about 16 days. Horizontal phase speeds are between 20 m/s and 30 m/s. Maximal KW activity is around the tropopause region in the Pacific

- Benefits of the study: comparison with wave properties derived from a single data type (wind or mass) in observations or models; testing the impacts of changes in the model physics and in the assimilation scheme on the vertical energy propagation and wave properties

- Only preliminary results are presented. Looking for collaborators interested in using the wave datasets in physical and modal space for further studies