The seasonal cycle of Kelvin waves in the ECMWF analyses

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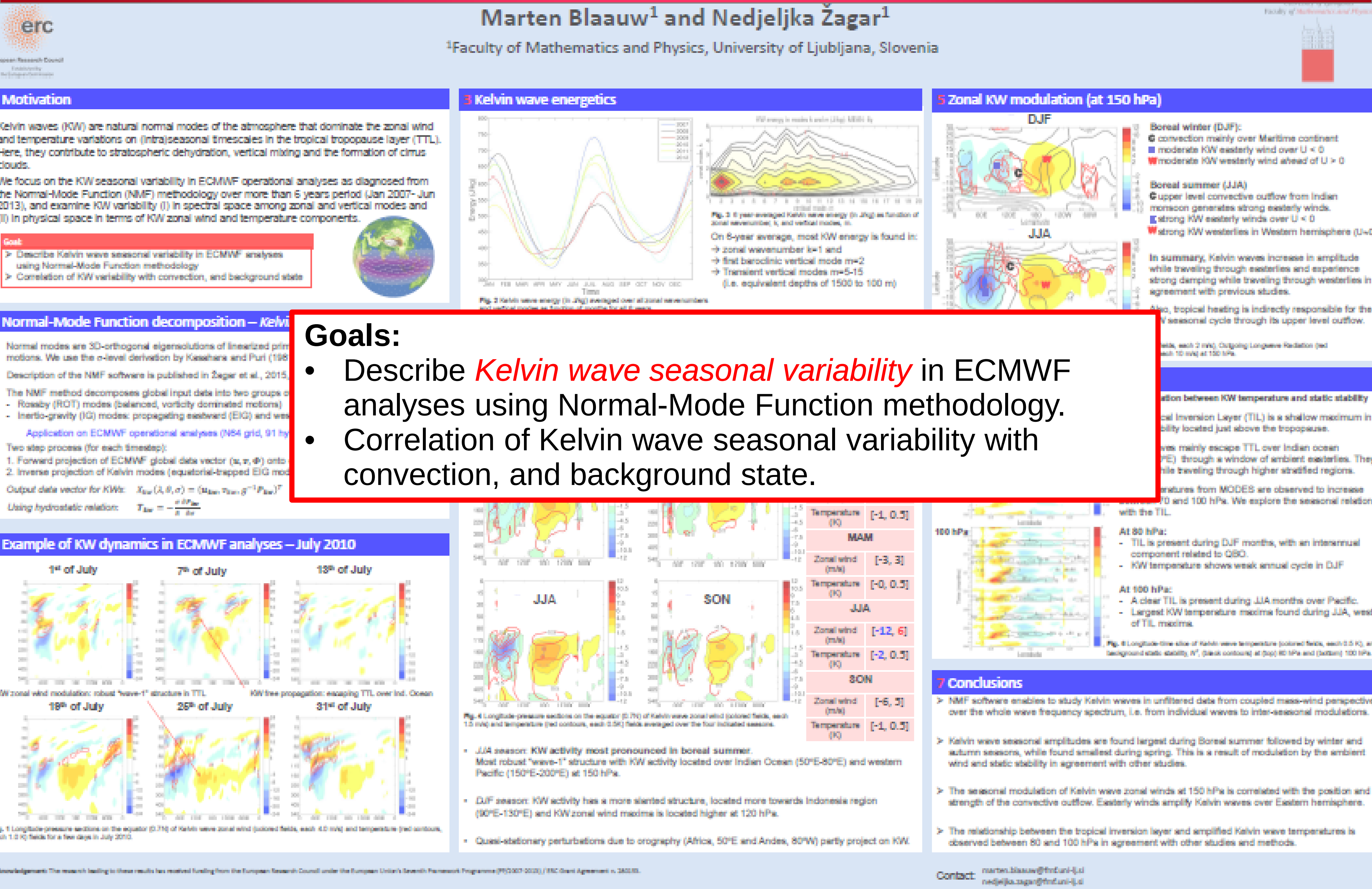
Introduction



Goals:

- Describe *Kelvin wave seasonal variability* in ECMWF analyses using Normal-Mode Function methodology.
- Correlation of Kelvin wave seasonal variability with convection, and background state.

Data and methodology

ECMWF operational analyses

Data from operational archive is extracted from January 2007 till June 2013

Resolution: Gaussian grid N64 and 91 vertical hybrid levels.

NMF analysis with MODES software (Žagar et al., 2015, Geosci. Mod. Dev.) has been applied from day to day for all 6,5 years.

Output: Kelvin wave zonal wind, U_{kw}, and modified geopotential, P_{kw}

Use of hydrostatic formulation in σ-coordinates to express P_{kw} in terms of Kelvin wave temperature, T_{kw}.

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Next: three movies demonstrating Kelvin wave seasonal cycle

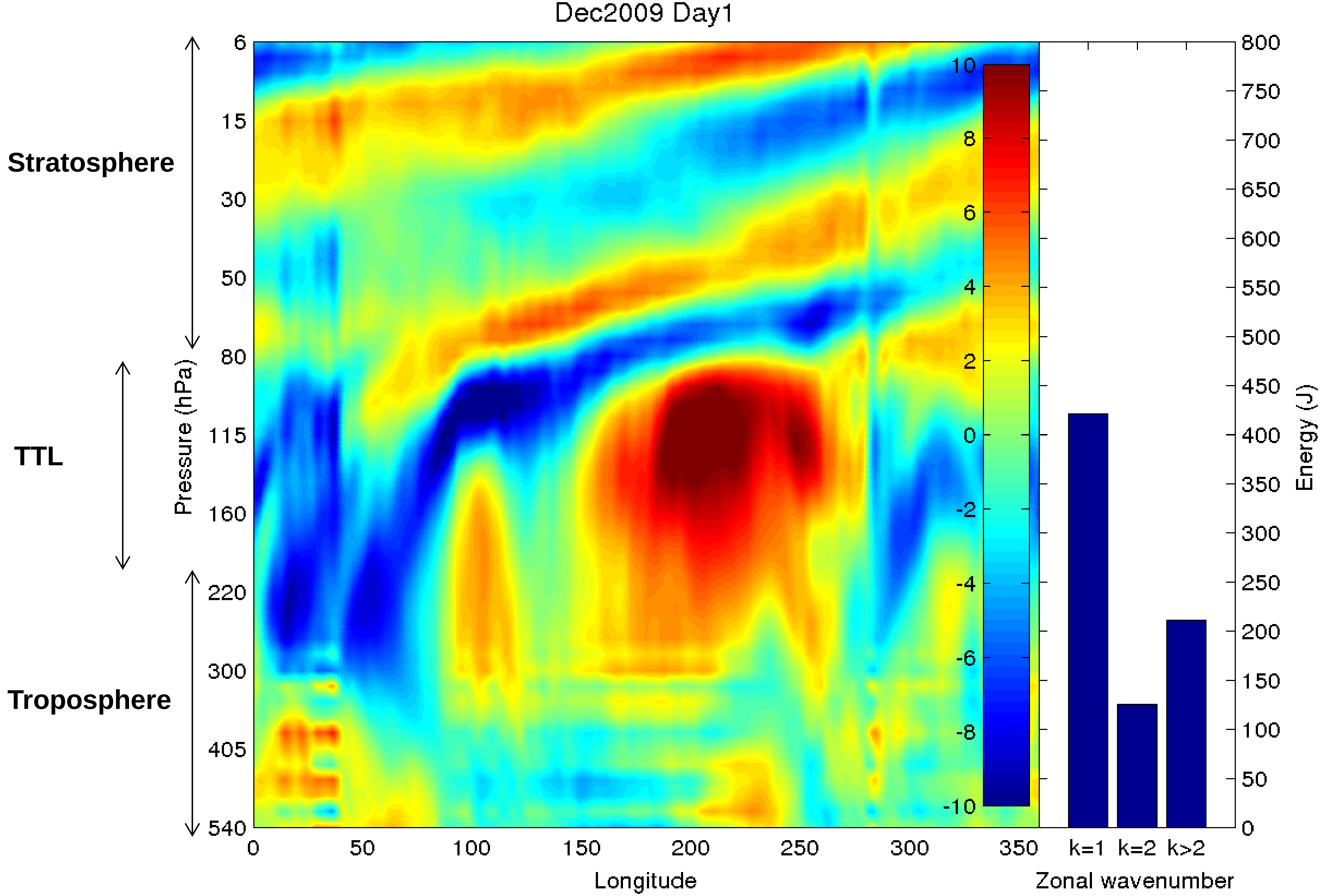
(i) Daily snapshots of U_{kw} throughout 2010.

(ii) Seasonal cycle of U_{kw} and T_{kw} over 6,5 years.

(iii) Mapslices at 150 hPa of seasonal cycle U_{kw} and full zonal wind, and OLR.

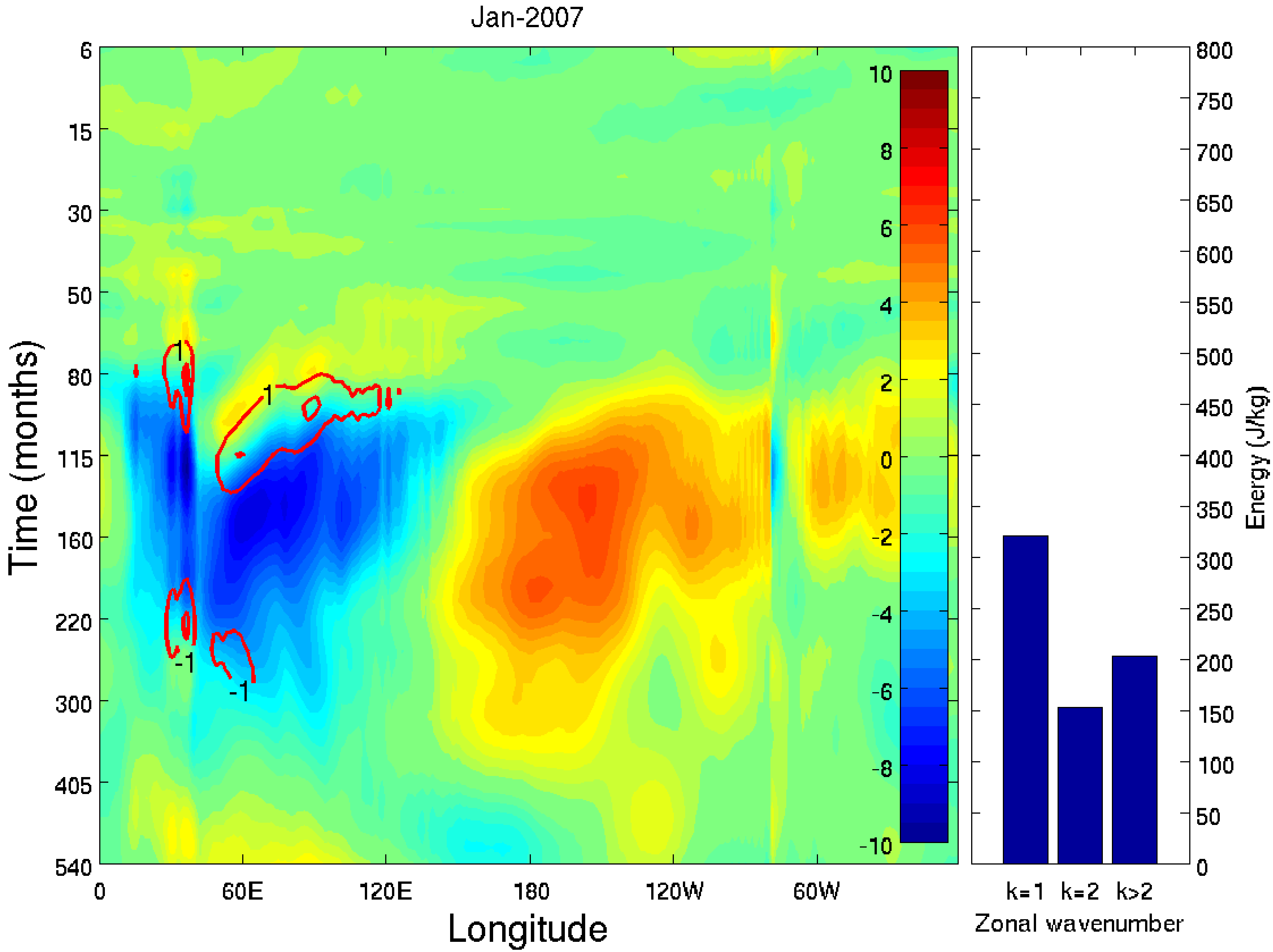
(i) Daily snapshots of U_{kw}

→ Low-pass filter applied with cut-off period of **7 days**

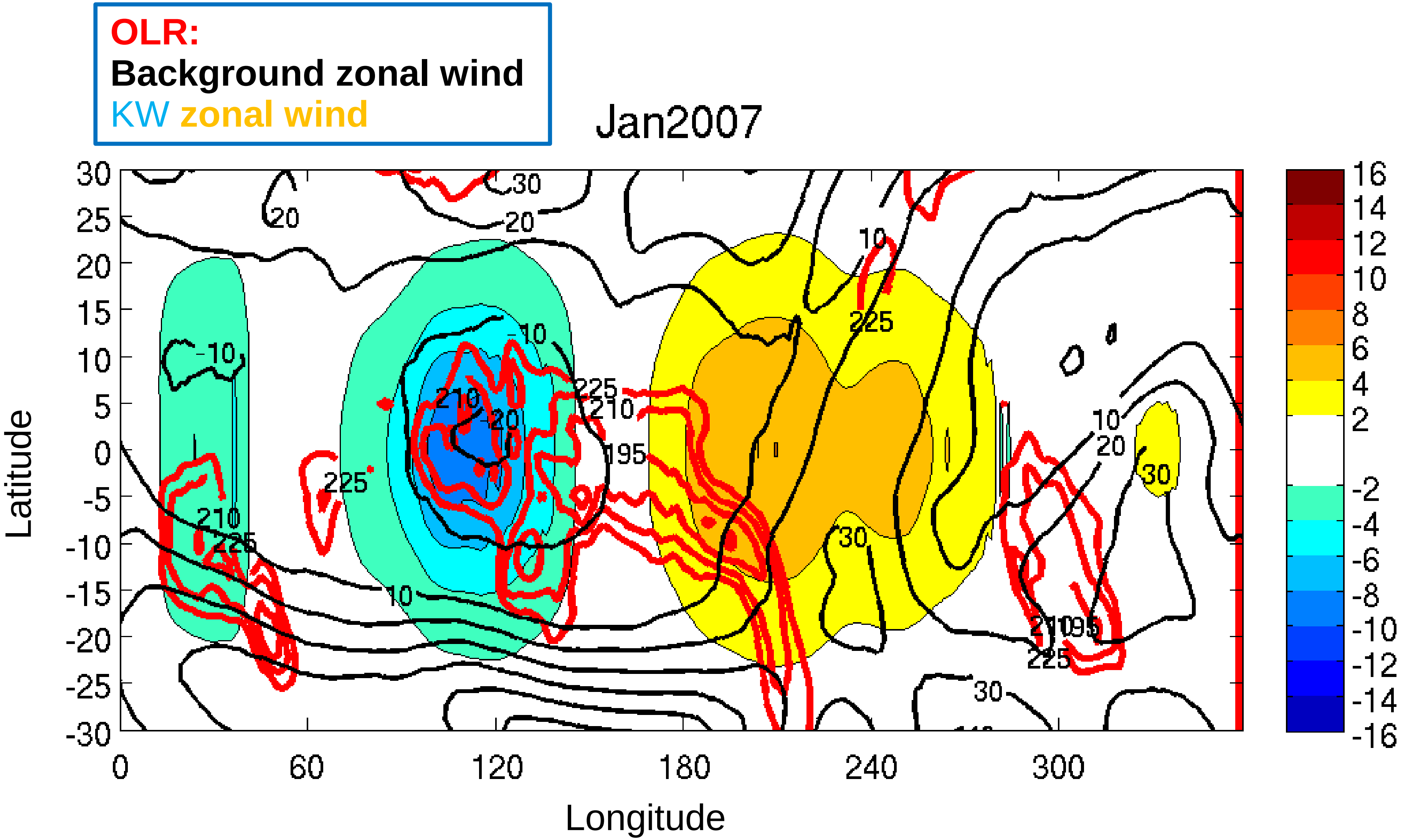


(ii) Seasonal cycle, U_{kw} & T_{kw}

→ Low-pass filter applied with cut-off period of **90 days**



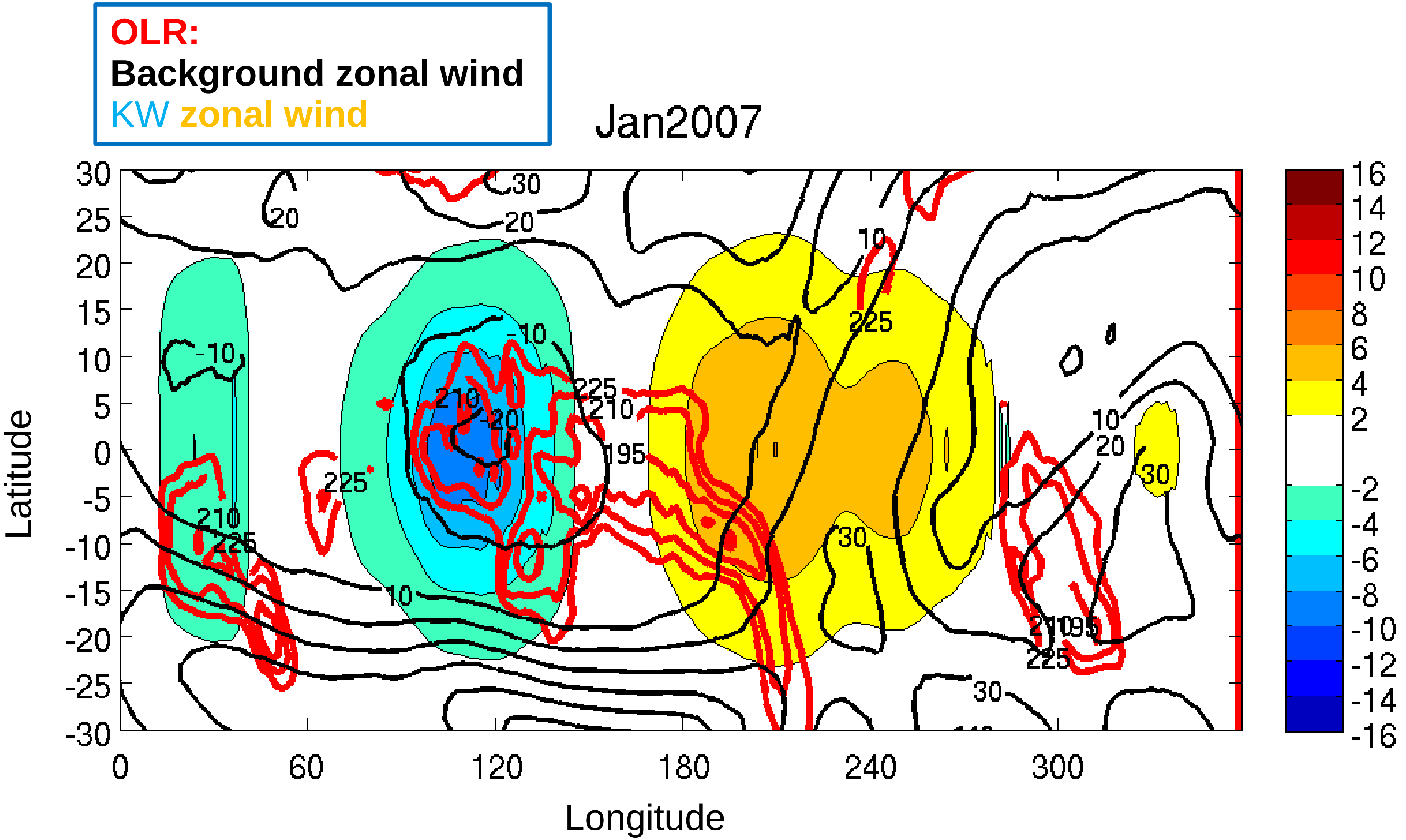
(iii) Map slices at 150 hPa



<u>Gill-type response</u>

Convective outflow projects on robust “wave-1” structure of Kelvin wave. Especially during MJO.

(iii) Map slices at 150 hPa

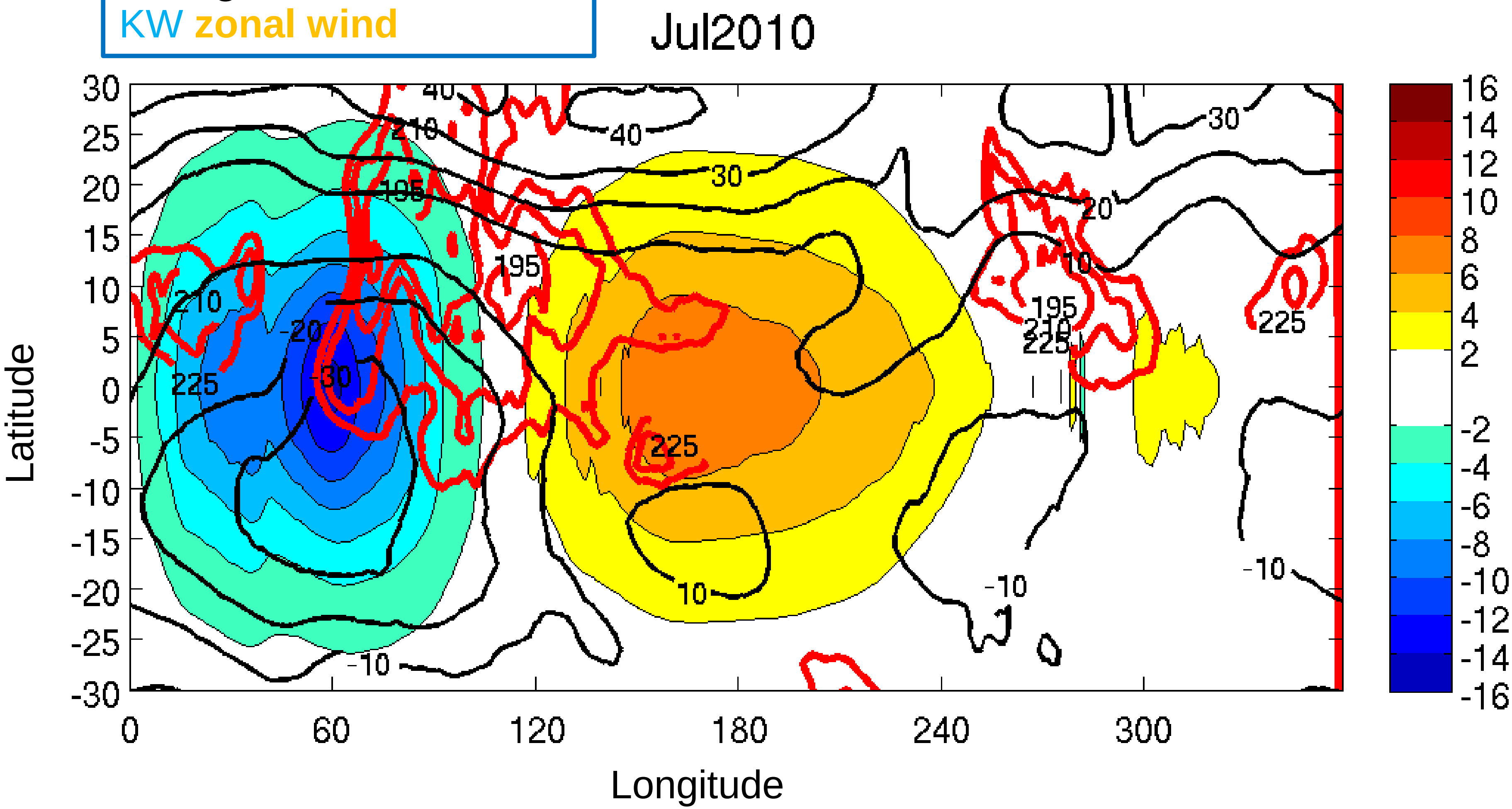


Kelvin wave zonal wind modulation:

DJF: Convection concentrated over Maritime continent → Outflow with moderate easterlies → Additional amplification of KW easterlies over Eastern hemisphere.

(iii) Map slices at 150 hPa

OLR:
Background zonal wind
KW **zonal wind**



<u>Kelvin wave zonal wind modulation:</u>

JJA: Indian summer monsoon → strong easterlies over equator → strong KW winds

Conclusions

- NMF software enables to study Kelvin waves in unfiltered data from coupled mass-wind perspective over the whole frequency spectrum, i.e. from individual waves to inter-seasonal modulations.
- Kelvin waves seasonal amplitudes are found largest during Boreal summer followed by winter and autumn seasons. This is a result of modulation by the ambient wind and static stability in agreement with other studies.
- The seasonal modulation of Kelvin wave zonal winds at 150 hPa is correlated with the position and strength of the convective outflow. Easterly winds amplify Kelvin waves over Eastern hemisphere.
- The relationship between the tropical inversion layer and amplified Kelvin wave temperatures is observed between 80 and 100 hPa in agreement with other studies and methods (see poster).

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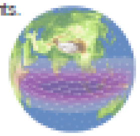
Motivation

Kelvin waves (KW) are natural normal modes of the atmosphere that dominate the zonal wind and temperature variations on (intra)seasonal timescales in the tropical tropopause layer (TTL). Here, they contribute to stratospheric dehydration, vertical mixing and the formation of cirrus clouds.

We focus on the KW seasonal variability in ECMWF operational analyses as diagnosed from the Normal-Mode Function (NMF) methodology over more than 6 years period (Jan 2007- Jun 2013), and examine KW variability (i) in spectral space among zonal and vertical modes and (ii) in physical space in terms of KW zonal wind and temperature components.

Goal:
- ➢ Describe Kelvin wave seasonal variability in ECMWF analyses using Normal-Mode Function methodology
- ➢ Correlation of KW variability with convection, and background state



Normal-Mode Function decomposition – *Kelvin waves*

Normal modes are 3D-orthogonal eigensolutions of linearized primitive equations of atmospheric motions. We use the σ-level derivation by Kasahara and Puri (1981, Mon. Wea. Rev.)

Description of the NMF software is published in Žagar et al., 2015, Geosci. Model. Dev.

The NMF method decomposes global input data into two groups of eigensolutions:
- Rossby (ROT) modes (balanced, vorticity dominated motions)
- Inertio-gravity (IG) modes: propagating eastward (EIG) and westward (WIG)

Application on ECMWF operational analyses (N64 grid, 91 hybrid levels) for Kelvin waves

Two step process (for each timestep):
1. Forward projection of ECMWF global data vector (u, v, Φ) onto eigensolutions in spectral space
2. Inverse projection of Kelvin modes (equatorial-trapped EIG modes) to physical space

Output data vector for KWs: $X_{kw}(\lambda, \theta, \sigma) = (u_{kw}, v_{kw}, g^{-1}P_{kw})^T$ where P_{kw} is modified geopotential

Using hydrostatic relation: $T_{kw} = -\frac{\sigma}{R}\frac{\partial P_{kw}}{\partial \sigma}$

Example of KW dynamics in ECMWF analyses – July 2010

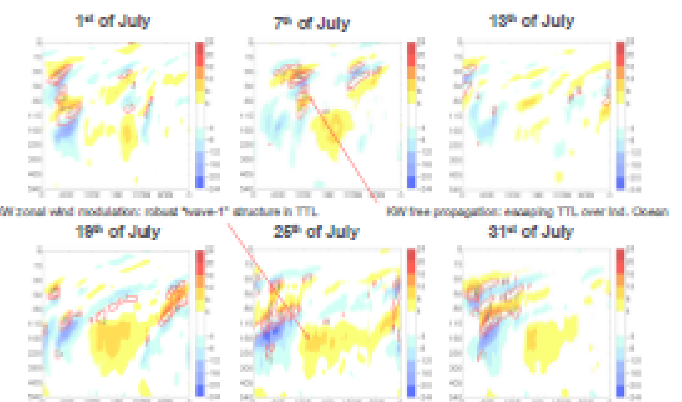


Fig. 1 Longitude-pressure sections on the equator (0.7°N) of Kelvin wave zonal wind (colored fields, each 4.0 m/s) and temperature (red contours, each 1.0 K) fields for a few days in July 2010.

3 Kelvin wave energetics

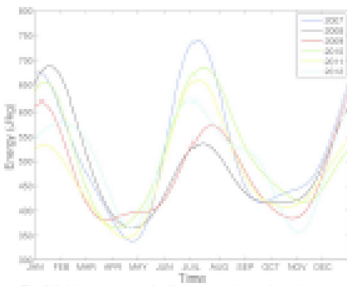


Fig. 2 Kelvin wave energy (in J/kg) averaged over all zonal wavenumbers

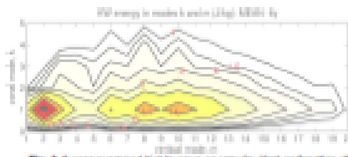


Fig. 3 6-year averaged Kelvin wave energy (in J/kg) as function of zonal wavenumber k, and vertical modes, m.

On 6-year average, most KW energy is found in:
- → zonal wavenumber k=1 and
- → first baroclinic vertical mode m=2
- → Transient vertical modes m=5-15 (i.e. equivalent depths of 1500 to 100 m)

Thank you!

4 Seasonal averages

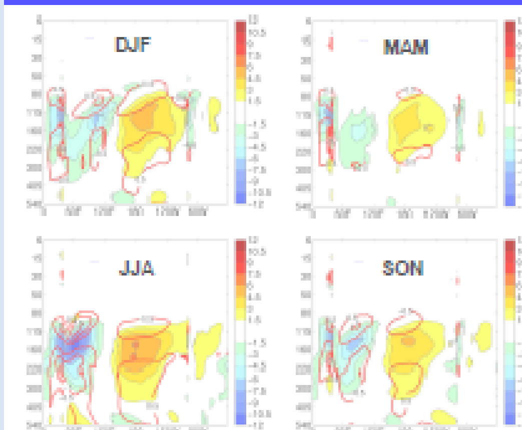


Fig. 4 Longitude-pressure sections on the equator (0.7°N) of Kelvin wave zonal wind (colored fields, each 1.5 m/s) and temperature (red contours, each 0.5K) fields averaged over the four indicated seasons.

Seasonal amplitudes	
DJF	
Zonal wind (m/s)	[-6, 5]
Temperature (K)	[-1, 0.5]
MAM	
Zonal wind (m/s)	[-3, 3]
Temperature (K)	[-0, 0.5]
JJA	
Zonal wind (m/s)	[-12, 6]
Temperature (K)	[-2, 0.5]
SON	
Zonal wind (m/s)	[-6, 5]
Temperature (K)	[-1, 0.5]

- *JJA season:* **KW activity most pronounced in boreal summer.** Most robust "wave-1" structure with KW activity located over Indian Ocean (50°E-80°E) and western Pacific (150°E-200°E) at 150 hPa.
- *DJF season:* KW activity has a more slanted structure, located more towards Indonesia region (90°E-130°E) and KW zonal wind maxima is located higher at 120 hPa.
- Quasi-stationary perturbations due to orography (Africa, 50°E and Andes, 80°W) partly project on KW.

5 Zonal KW modulation (at 150 hPa)

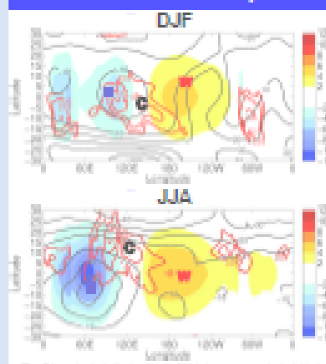


Fig. 5 Longitude-latitude slices of Kelvin wave zonal wind, U, (colored fields, each 2 m/s), Outgoing Longwave Radiation (red contours, each 10 W/m²) and background zonal wind (black contours, each 10 m/s) at 150 hPa.

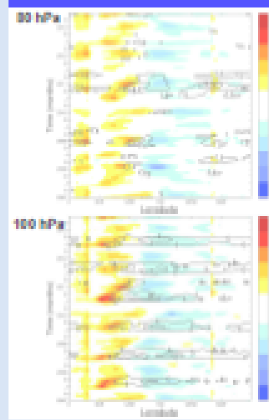
Boreal winter (DJF):
- C convection mainly over Maritime continent
- ■ moderate KW easterly wind over U < 0
- W moderate KW westerly wind ahead of U > 0

Boreal summer (JJA)
- C upper level convective outflow from Indian monsoon generates strong easterly winds.
- E strong KW easterly winds over U < 0
- W strong KW westerlies in Western hemisphere (U>0)

In summary, Kelvin waves increase in amplitude while traveling through easterlies and experience strong damping while traveling through westerlies in agreement with previous studies.

Also, tropical heating is indirectly responsible for the KW seasonal cycle through its upper level outflow.

6 Vertical KW modulation



On the relation between KW temperature and static stability

The Tropical Inversion Layer (TIL) is a shallow maximum in static stability located just above the tropopause.

Kelvin waves mainly escape TTL over Indian ocean (60°E-100°E) through a window of ambient easterlies. They amplify while traveling through higher stratified regions.

KW temperatures from MODES are observed to increase between 70 and 100 hPa. We explore the seasonal relation with the TIL.

At 80 hPa:
- TIL is present during DJF months, with an interannual component related to QBO.
- KW temperature shows weak annual cycle in DJF

At 100 hPa:
- A clear TIL is present during JJA months over Pacific.
- Largest KW temperature maxima found during JJA, west of TIL maxima.

Fig. 6 Longitude-time slice of Kelvin wave temperature (colored fields, each 0.5 K), and background static stability, N^2, (black contours) at (top) 80 hPa and (bottom) 100 hPa.

7 Conclusions

- ➢ NMF software enables to study Kelvin waves in unfiltered data from coupled mass-wind perspective over the whole wave frequency spectrum, i.e. from individual waves to inter-seasonal modulations.
- ➢ Kelvin wave seasonal amplitudes are found largest during Boreal summer followed by winter and autumn seasons, while found smallest during spring. This is a result of modulation by the ambient wind and static stability in agreement with other studies.
- ➢ The seasonal modulation of Kelvin wave zonal winds at 150 hPa is correlated with the position and strength of the convective outflow. Easterly winds amplify Kelvin waves over Eastern hemisphere.
- ➢ The relationship between the tropical inversion layer and amplified Kelvin wave temperatures is observed between 80 and 100 hPa in agreement with other studies and methods.

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