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The Importance of Background State for the Climatology of Equatorial Kelvin Wave Propagation into the Stratosphere

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Introduction

Kelvin waves dominate the intraseasonal temperature variability in the tropical tropopause layer (TTL), and therefore have implications for cirrus cloud formation and vertical mixing in the TTL. Kelvin waves are generated in the troposphere, and propagate upwards into the stratosphere where they contribute to the QBO. In observations, we find that Kelvin waves exhibit pronounced spatial structure; in particular there is a **maximum in wave temperature variance over the Indian Ocean** in boreal summer, and a **minimum in wave variance over the Pacific** in boreal winter.

Here, we will

- Describe the climatology of Kelvin wave activity in the TTL region
- Explain this climatology using **ray tracing** calculations applied to realistic zonal wind structures

1. Observed wave propagation

Observations show striking climatological zonally asymmetric structure. ERA Interim captures this well.

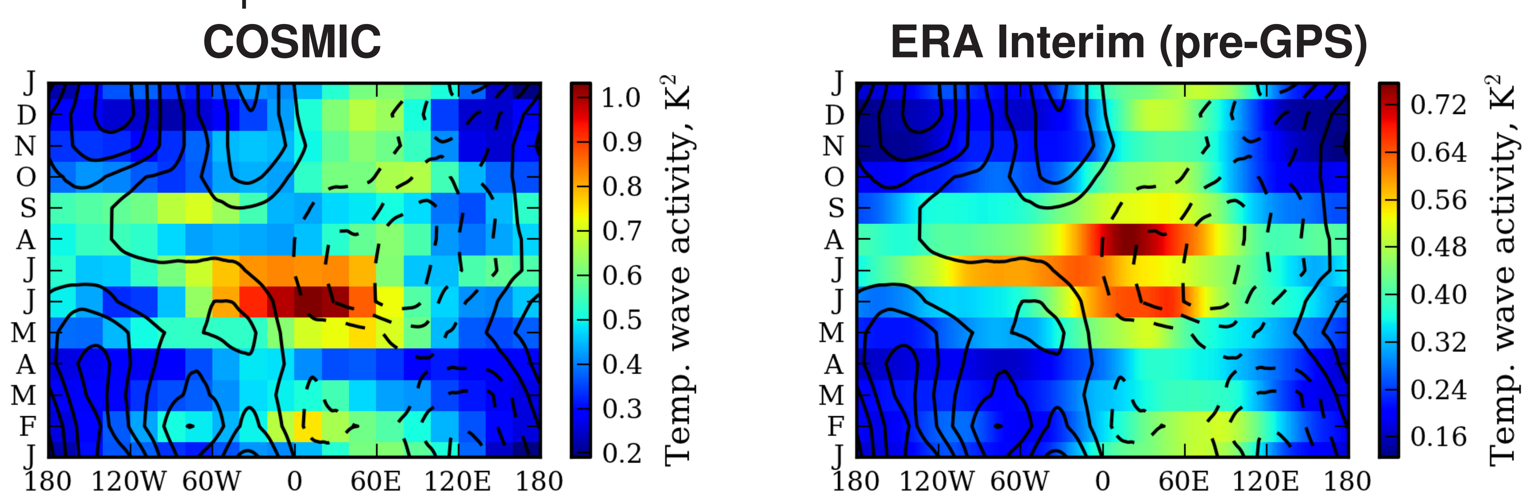

Figure 1 : Climatological annual cycle of WK-99 filtered temperature data on the 113 hPa, using a) COSMIC data from 1 October 2006 to 1 October 2011, and b) ERA Interim data from 1 January 1989 to 1 January 2001.

We have developed a method for tracking waves both horizontally and vertically through the TTL. This allows us to robustly separate the number of waves from wave amplitude, and gives a better insight into propagation.

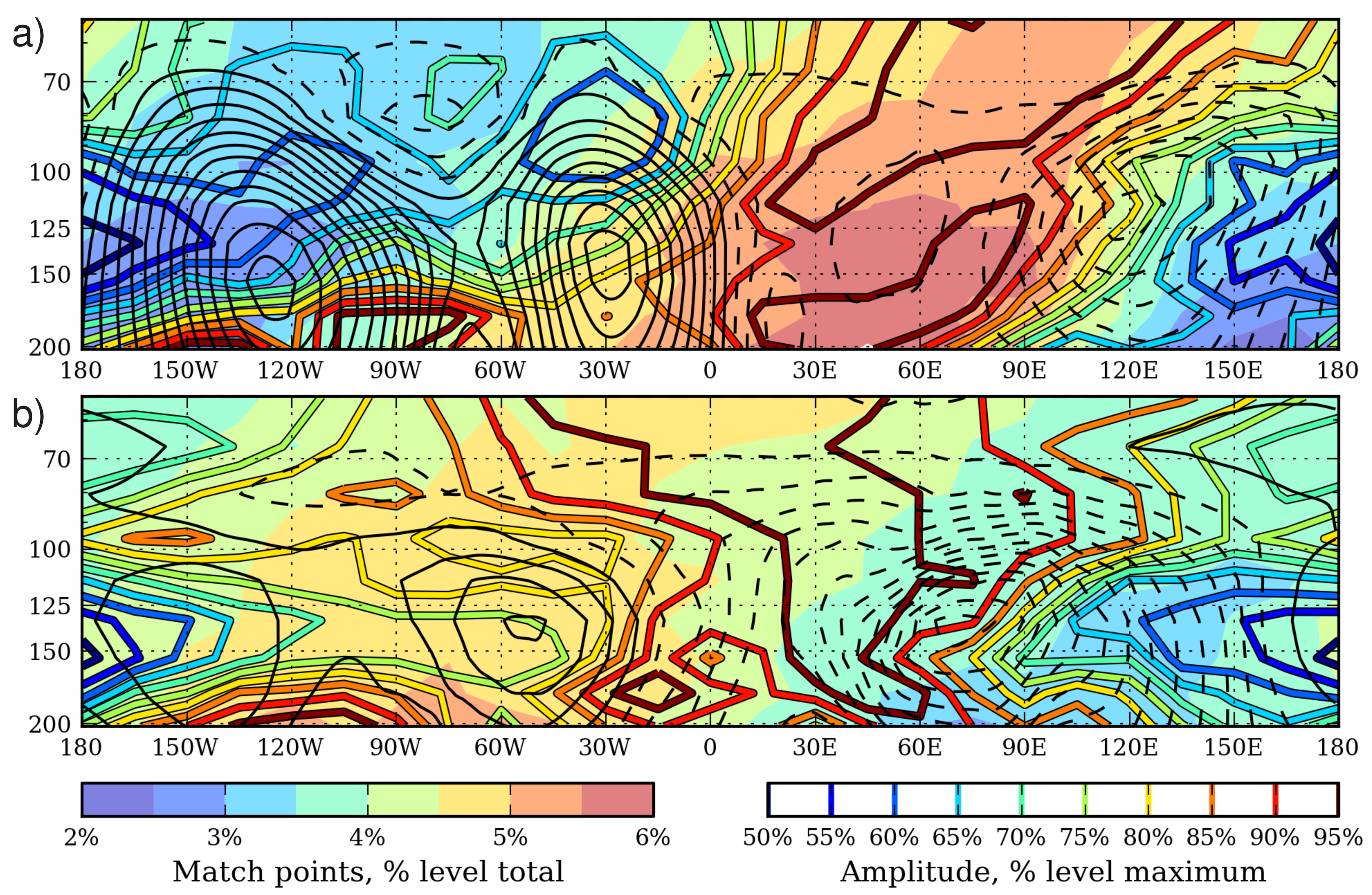

Figure 2 : Results of tracking waves from 200 hPa to 65 hPa during a) DJF and b) JJA. Shading shows the number of waves passing through each location, and colored contours show average wave amplitude. Black contours show zonal wind (2 ms^{-1} spacing.)

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2. Ray tracing theory

Ray tracing finds **rays** – trajectories of group velocity. Rays are governed by a set of ODEs (the ray tracing equations) defining how background conditions influence the direction of wave propagation. The ray tracing equations are defined by the dispersion relation of the wave.

Wave action is used to find amplitude along rays:

$$\frac{d_g A}{dt} + A\nabla \cdot c_g = \text{non-conservative effects}$$

- Wave properties are a function of the history of the ray
- Ray tracing is therefore non-local
- Ray convergence increases wave action – waves grow in amplitude when rays get closer together

3. Ray tracing examples

Rays initialised on 388 hPa with

- initial **zonal wavenumber** $k = 3$ (varied in Figure 5)
- initial **phase speed** $c = 20\ \mathrm{m\,s^{-1}}$
- **constant** initial **wave energy density** ($E_0 = 1$)
- Sensitivity to these parameters discussed in *Flannaghan and Fueglistaler (2013)*; results don't change much

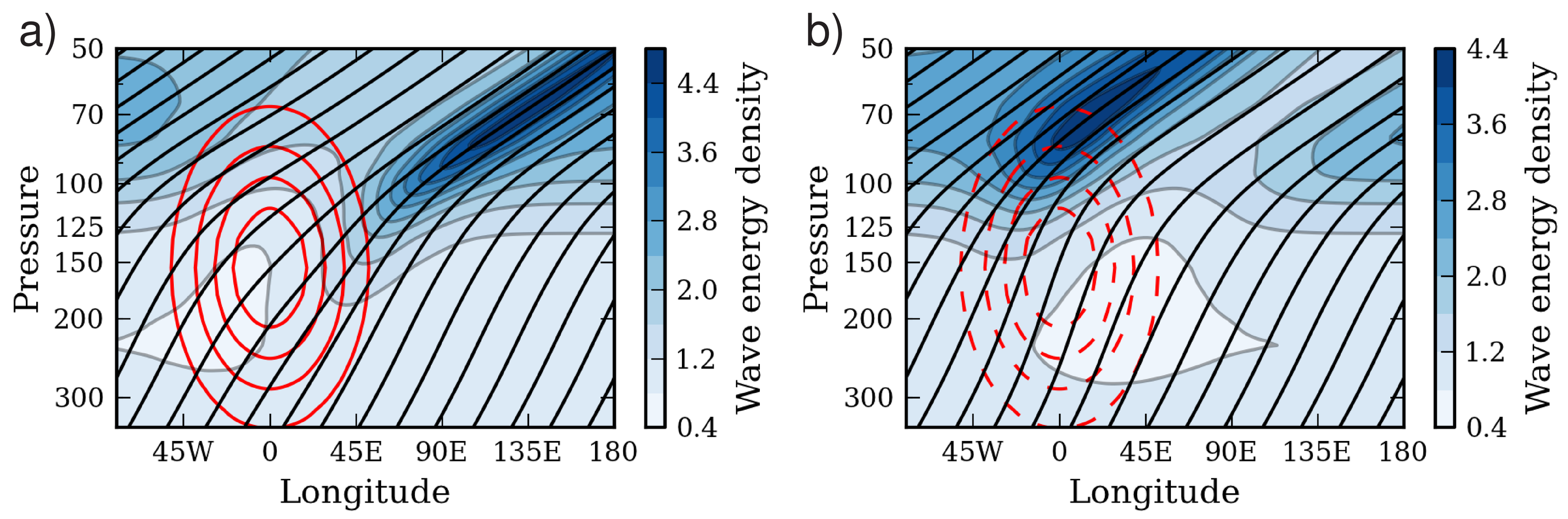

Figure 3 : Results of ray tracing applied to a) positive and b) negative wind anomaly (red contours, 1 ms^{-1} spacing) with 5 ms^{-1} amplitude. Rays (black lines) are initialized at 5° intervals (shown every 20°). Energy density is shown with shading relative to the initial value at 350 hPa. An average N^2 profile is used (independent of longitude).

- Rays deflected by zonal wind – band of wave activity above wind anomaly
- Stronger winds lead to stronger wave activity
- Location of wave activity anomaly approx fixed

4. Ray tracing with observed winds

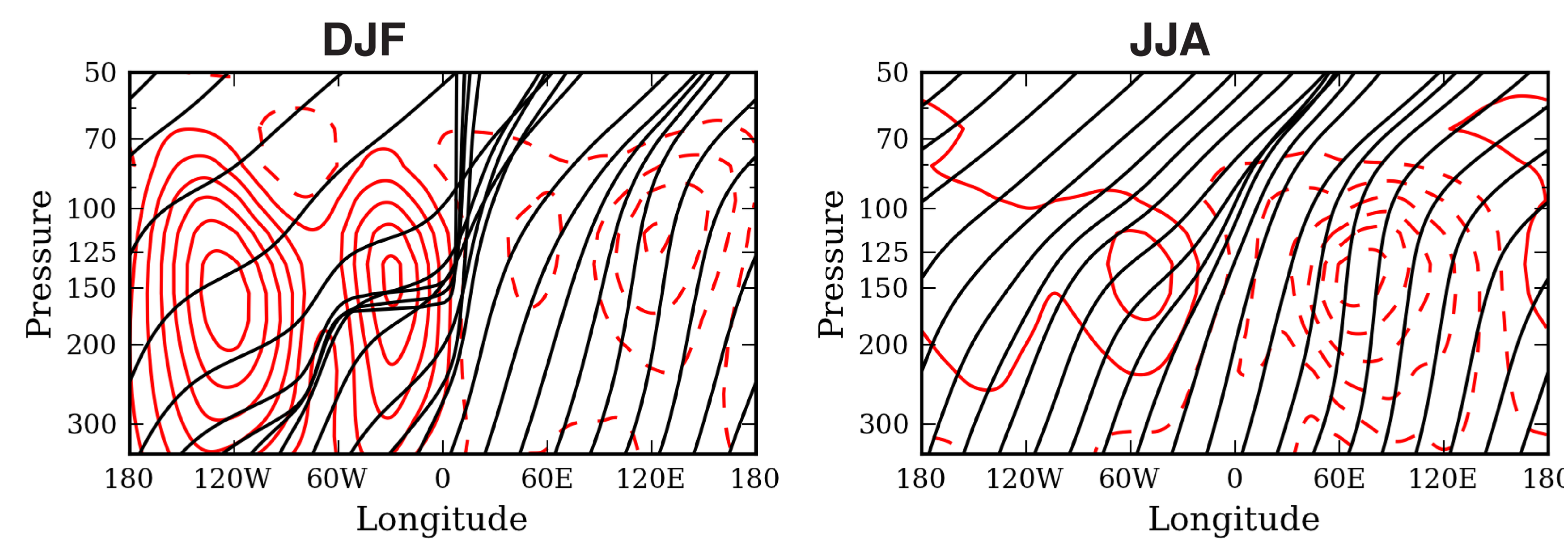

Figure 4 : Ray tracing applied to climatological DJF and JJA zonal wind (shown in red contours) and temperature fields. Rays are shown in black.

- Strong winds cause rays to intersect
- Ray tracing equations break down
- However, retains qualitative structure similar to Figure 3

5. Ray tracing with reduced winds

We can apply ray tracing theory to the observed background conditions, but this leads to ray intersections (see box 4). We therefore *rescale zonal wind to 25% amplitude*. This will affect wave activity but the structure will **remain qualitatively similar**.

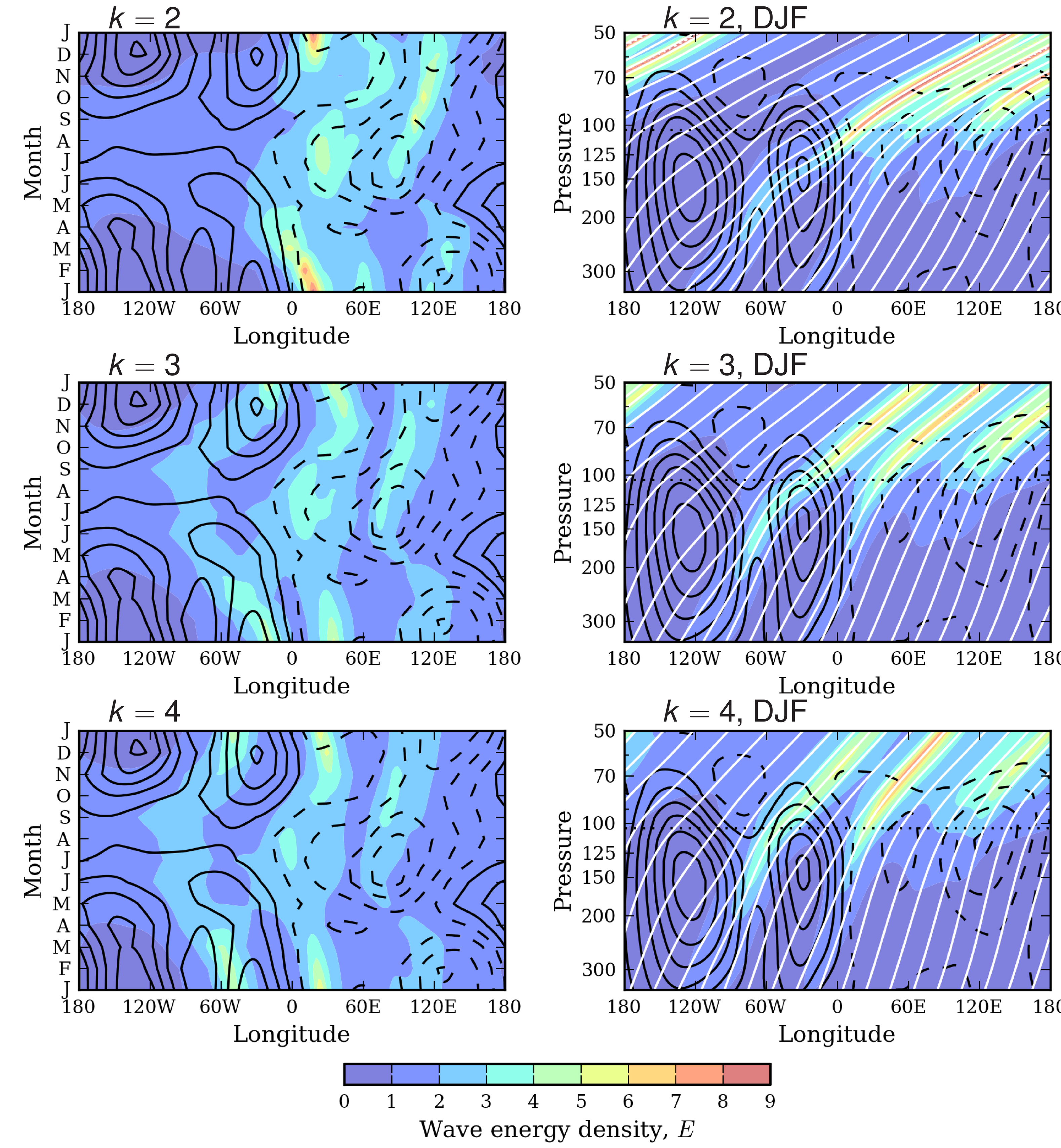

Figure 5 : Energy density on 104 hPa (left) and DJF energy density (right) for ray tracing with climatological zonal winds for different zonal wavenumbers k. Black contours show zonal wind. White lines (right) show selected rays.

- Three bands of high wave activity – one for each extremum in zonal wind
- Response similar to simple examples in Figure 3
- Wave energy density maximum in summer Indian Ocean
- N^2 variation $\Longrightarrow$ temperature wave variance highest in summer

Conclusions

- **Ray tracing captures many features of the Kelvin wave climatology**
- **Most of the observed spatial structure is due to background wind** (N^2 plays a secondary role)
- TTL wave activity controlled by conditions in TTL, with **little influence of tropospheric wave activity**.
- TTL background conditions control wave activity above the TTL in the stratosphere (also dependant on QBO)

Papers:

Flannaghan, T. J. and S. Fueglistaler (2013), The importance of the tropical tropopause layer for equatorial Kelvin wave propagation, JGR

Flannaghan, T. J. and S. Fueglistaler (2012), Tracking Kelvin waves from the equatorial troposphere into the stratosphere, JGR