Diagnosing tropical waves

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RESEARCH ARTICLE

The intricacies of identifying equatorial waves

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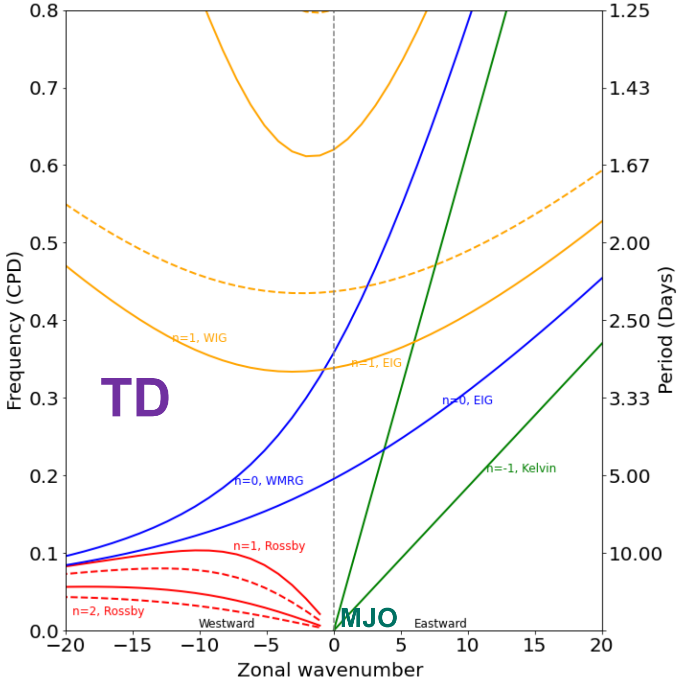
What are tropical waves?

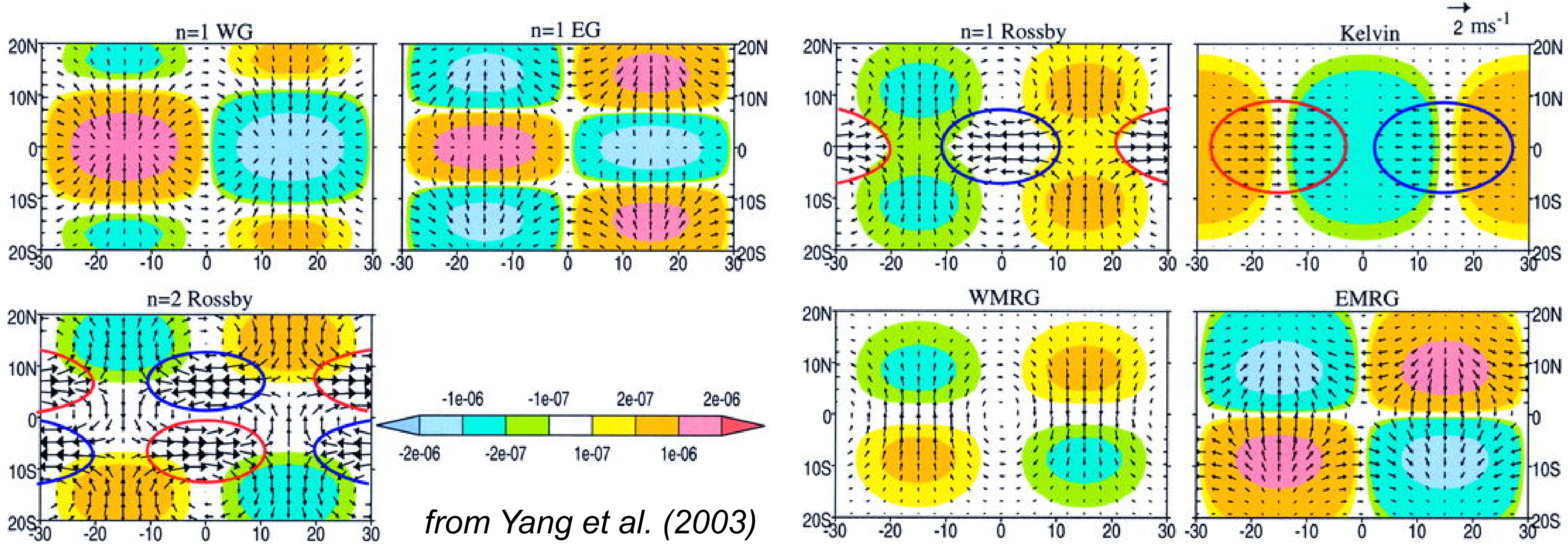
- Zonally propagating, synoptic- to planetary-scale disturbances with frequencies from a few days to several weeks
- Dynamical solutions to linear wave theory ("equatorial waves", *Matsuno 1966*)
  - Kelvin waves (KW)
  - equatorial Rossby waves (ER)
  - mixed-Rossby gravity waves (MRG)
  - inertio-gravity waves (IG)
- Other modes: Tropical disturbances (TDs), Madden-Julian Oscillation (MJO), …
- Coupling with convection creates link to clouds / rainfall



Solutions to rotating, linearized shallow-water equations on tropical β-plane (D=8m & 90m)

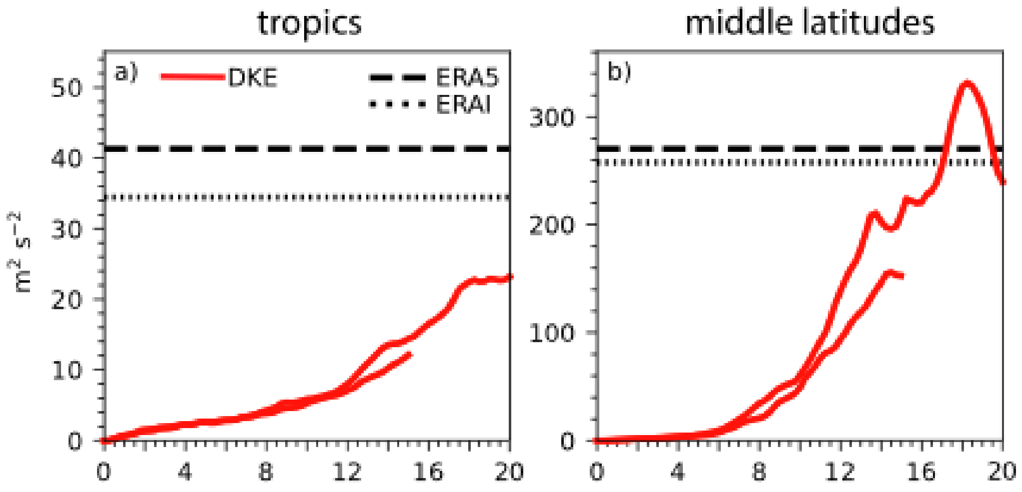
Spatial structures

- Linear modes have **theoretical** patterns in wind, geopotential and convergence.
- The other modes (TD, MJO etc.) only have **empirical** patterns!



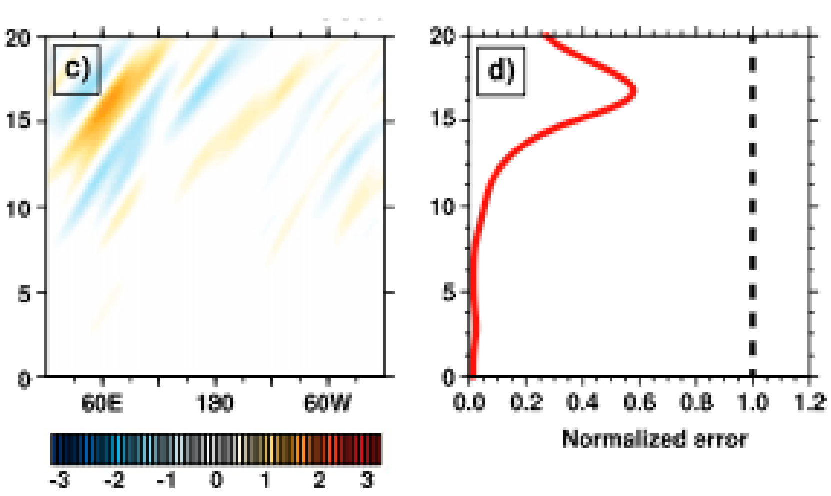
from Yang et al. (2003)

Why do tropical waves matter?



from Judt (2020) based on "identical-twin predictability" experiments with 4km grid spacing (convection permitting)

Error in Kelvin wave winds



How to identify tropical waves?

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emphasize spatial characteristics

can be applied to short time-series

Broad filter windows (space only)

3DS-HF — [u,v,ϕ] $(x,y_n,\sigma_m/p_m)$
3D SPATIAL PROJECTION
USING HOUGH FUNCTIONS
Žagar et al. (2009b, 2016), Castanheira & Marques (2015), Ogrosky & Stechmann (2015, 2016), Marques & Castanheira (2018)

Broad filter windows (time & space)

2DS-PCF — u/v/ϕ (x,y_n,t)
2D SPATIAL PROJECTION
USING PARABOLIC CYLINDER FUNCTIONS
Yang et al. (2003), Yang et al. (2007a,b,c), Yang & Hoskins (2013), Ferrett et al. (2020)

Intermediate filter windows (time & space)

2DS-EOF — OLR (x,y,t)
2D SPATIAL PROJECTION
USING TIME-EXTENDED EMPIRICAL ORTHOGONAL FUNCT.
Roundy & Schreck (2009), Roundy (2012)

Narrow filter windows (time & space)

FWF-PCF — Scalar (x,y_n,t)
FREQUENCY-WAVENUMBER FILTERING
USING PARABOLIC CYLINDER FUNCTIONS
Gehne & Kleeman (2012), Li & Stechmann (2020)

FWF-FFT — Scalar $(x,\bar{y},t)$
FREQUENCY-WAVENUMBER FILTERING
USING FAST-FOURIER TRANSFORM
Takayabu (1994a,b), Wheeler & Kiladis (1999), Kiladis et al. (2009), Roundy (2020)

FWF-Wavelet — Scalar $(x,\bar{y},t)$
FREQUENCY-WAVENUMBER FILTERING
USING WAVELETS
Wong (2009), Kikuchi & Wang (2010), Kikuchi (2014), Dias & Kiladis (2014), Roundy (2018)

emphasize propagation characteristics

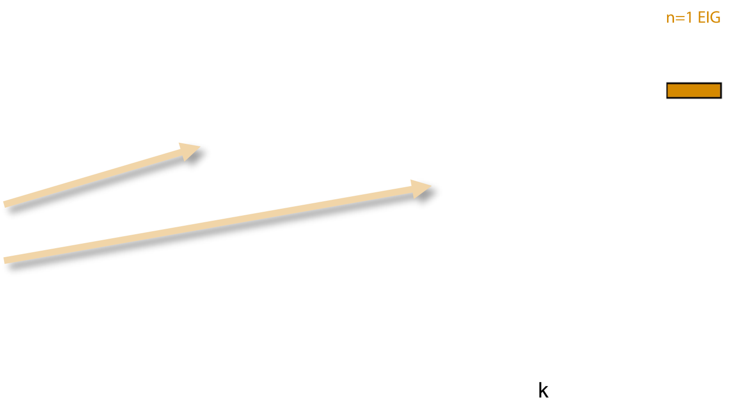
can only be applied to long time-series

from Knippertz et al. (2022)

3D Spatial Projection – Hough Functions

3DS-HF *Žagar et al. (2016)*

- **Hough Functions** (HFs) are **3D** solutions of the rotating, linearized shallow-water equations on the **sphere**
- Full **multivariate, instantaneous projection** of dynamical fields **(u,v,Z)**
- Restrict zonal wavenumber to $1 \leq |k| \leq 15$
- Time filtering ($2d \leq |T| \leq 30d$) after re-projection into physical space



2D Spatial Projection – Parabolic Cylinder Funct.

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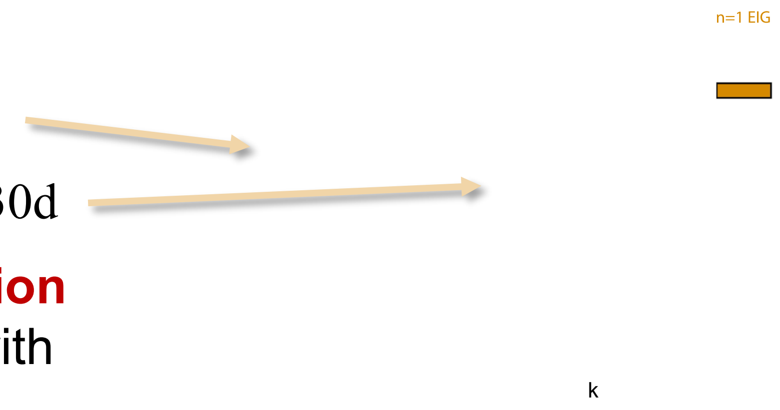
2DS-PCF *Yang et al. (2003)*

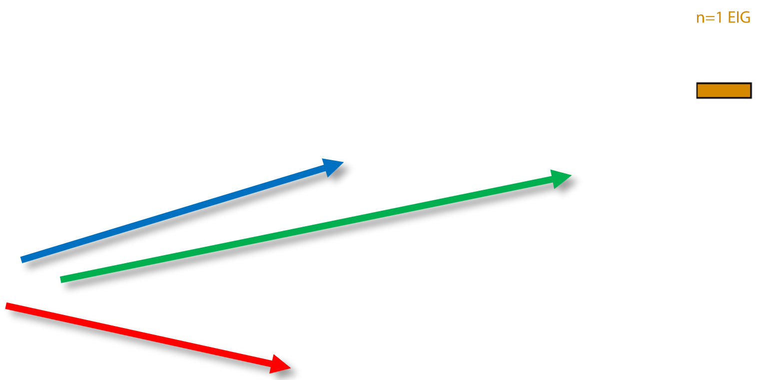
- **Parabolic Cylinder Functions** (PCFs) are the meridional basis of solutions of the rotating, linearized shallow-water equations on the **tropical β-plane**
- Fourier filter for wavenumber $1 \leq |k| \leq 15$
- Fourier filter for wave periods $2d \leq |T| \leq 30d$
- **Single-variate, instantaneous projection** of dynamical fields **(u,v,Z) onto PCFs** with fixed meridional scale of 6°



2D Spatial Projection – Time-Extended EOFs

2DS-EOF *Roundy & Schreck (2009)*

- Define empirical wave patterns using past fields of Outgoing Longwave radiation **(OLR)** and **Time-Extended Empirical Orthogonal Functions** (EEOFs)
- Use **Fast Fourier Transform (FFT)** to filter for **broad frequency-wavenumber (ω-k) windows** specific for individual wave types
- Project OLR fields of interest onto EEOFs



Freq.-Wavenumber Filtering – Fast Fourier Transf.

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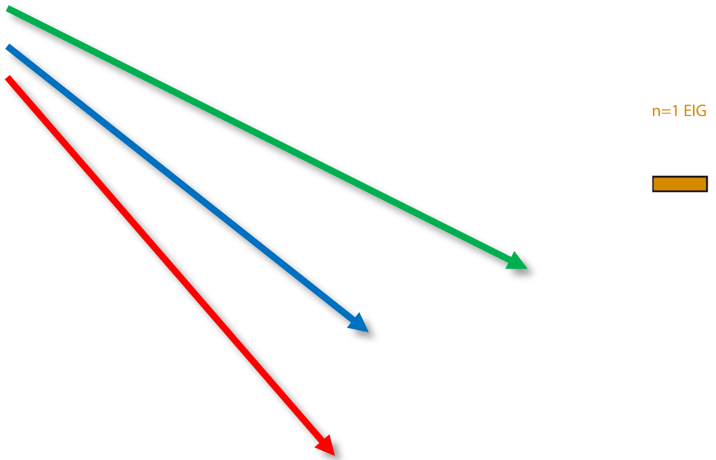
FWF-FFT *Wheeler & Kiladis (1999)*

- Use **Fast Fourier Transform (FFT)** to filter for **narrow ω-k windows** specific for individual wave types
- These filter windows have been defined on basis of spectral peaks in OLR
- They can be applied to **any scalar**!
- Average fields meridionally to obtain equator-symmetric (for KW & ER) and -antisymmetric (for MRG) signals



Freq.-Wavenumber Filtering – Wavelets

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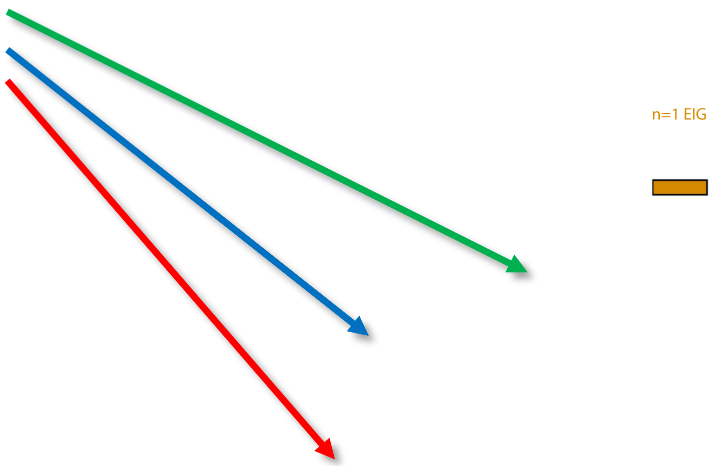
FWF-wavelet *Kikuchi (2014)*

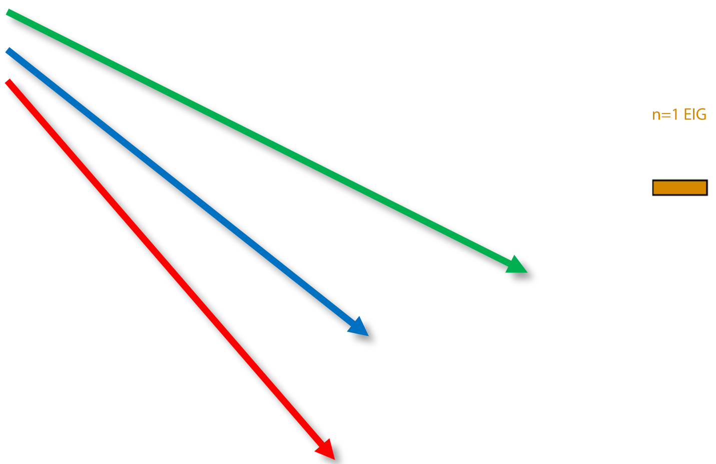
- Use **wavelets** to filter for **narrow ω-k windows** specific for individual wave types
- Wavelets allow localization in longitude and time
- They can be applied to **any scalar**!
- Average fields meridionally to obtain equator-symmetric (for KW & ER) and -antisymmetric (for MRG) signals



Freq.-Wavenumber Filtering using PCFs

FWF-PCF *Gehne & Kleeman (2012)*

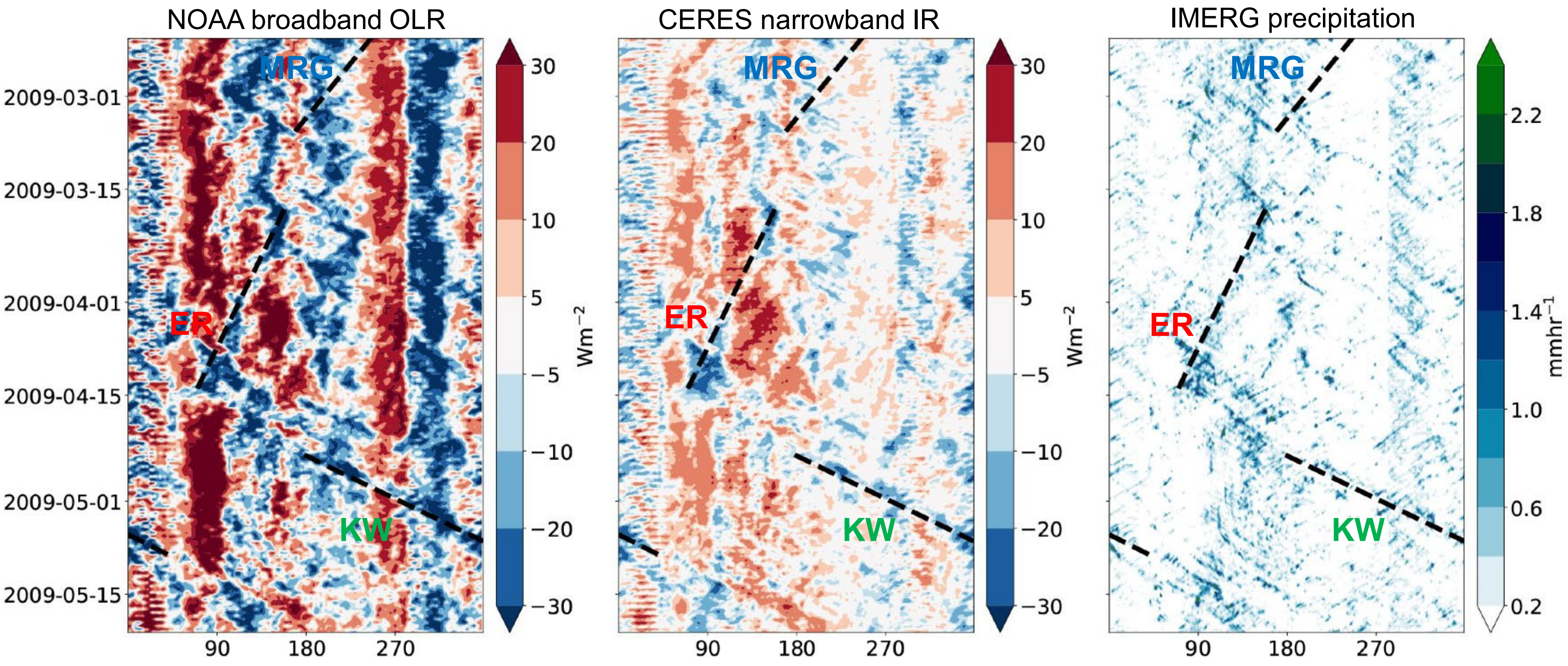
- Project fields on **Parabolic Cylinder Functions** (PCFs) to obtain equator-symmetric (for KW & ER) and -antisymmetric (for MRG) signals of different meridional wavelength
- They can be applied to **any scalar**!
- Use **Fast Fourier Transform (FFT)** to filter for **narrow ω-k windows** specific for individual wave types



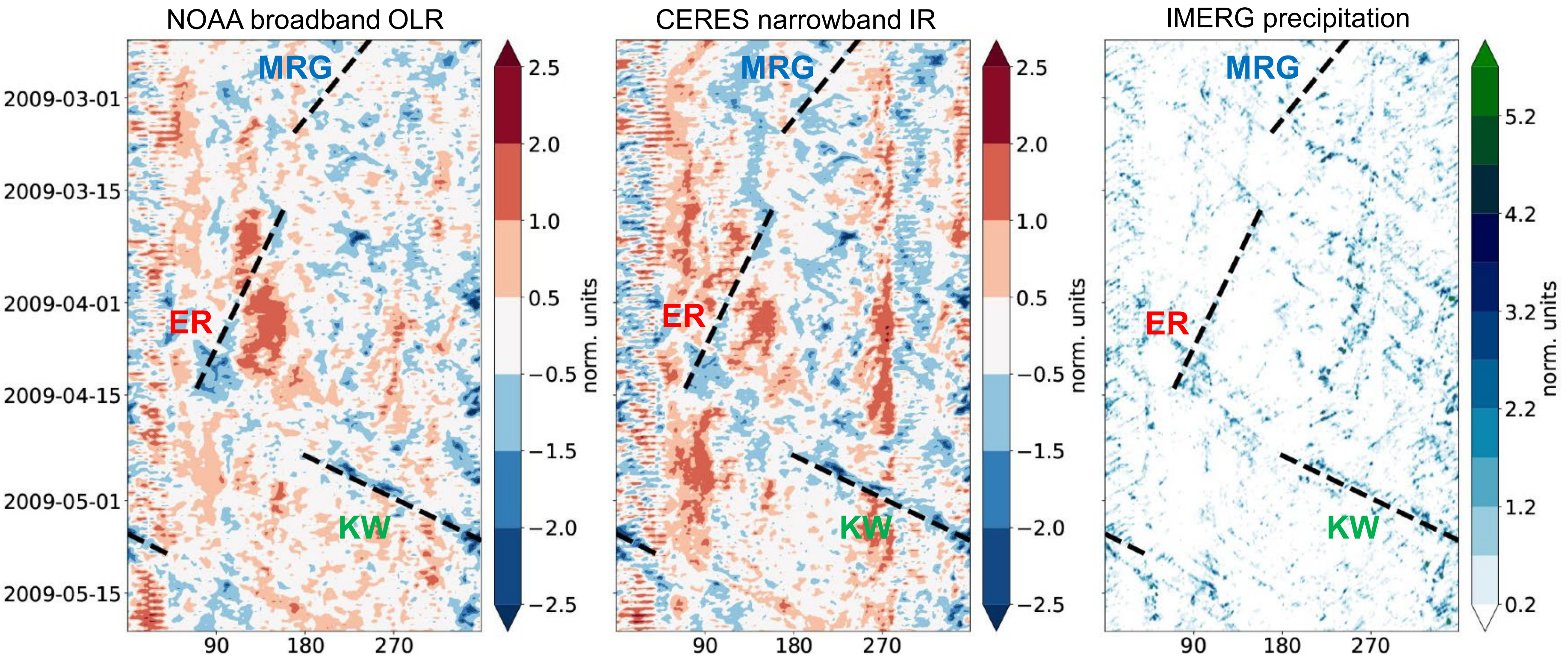
Case study 20 February – 20 May 2009

(also discussed in “Year of Tropical Convection” overview paper [*Waliser et al. 2012*])

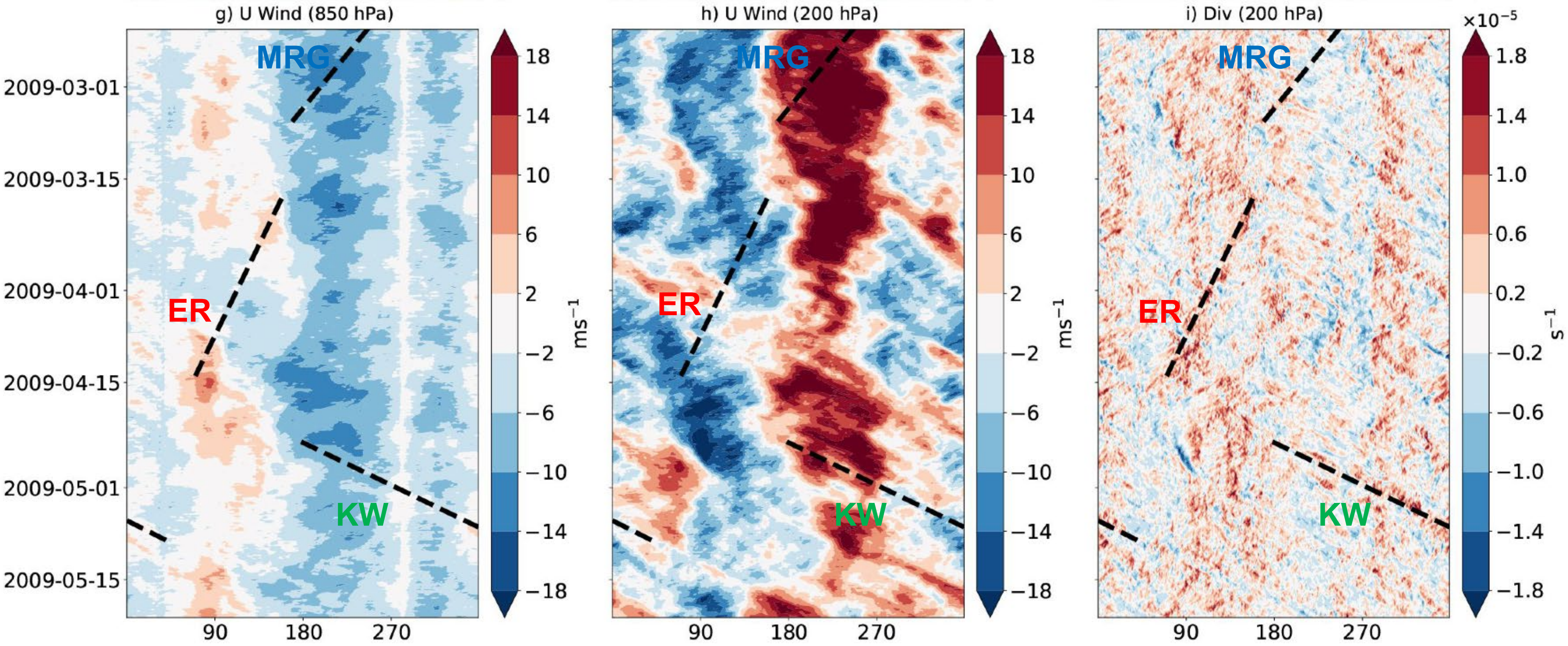
Unfiltered anomalies – clouds & rain



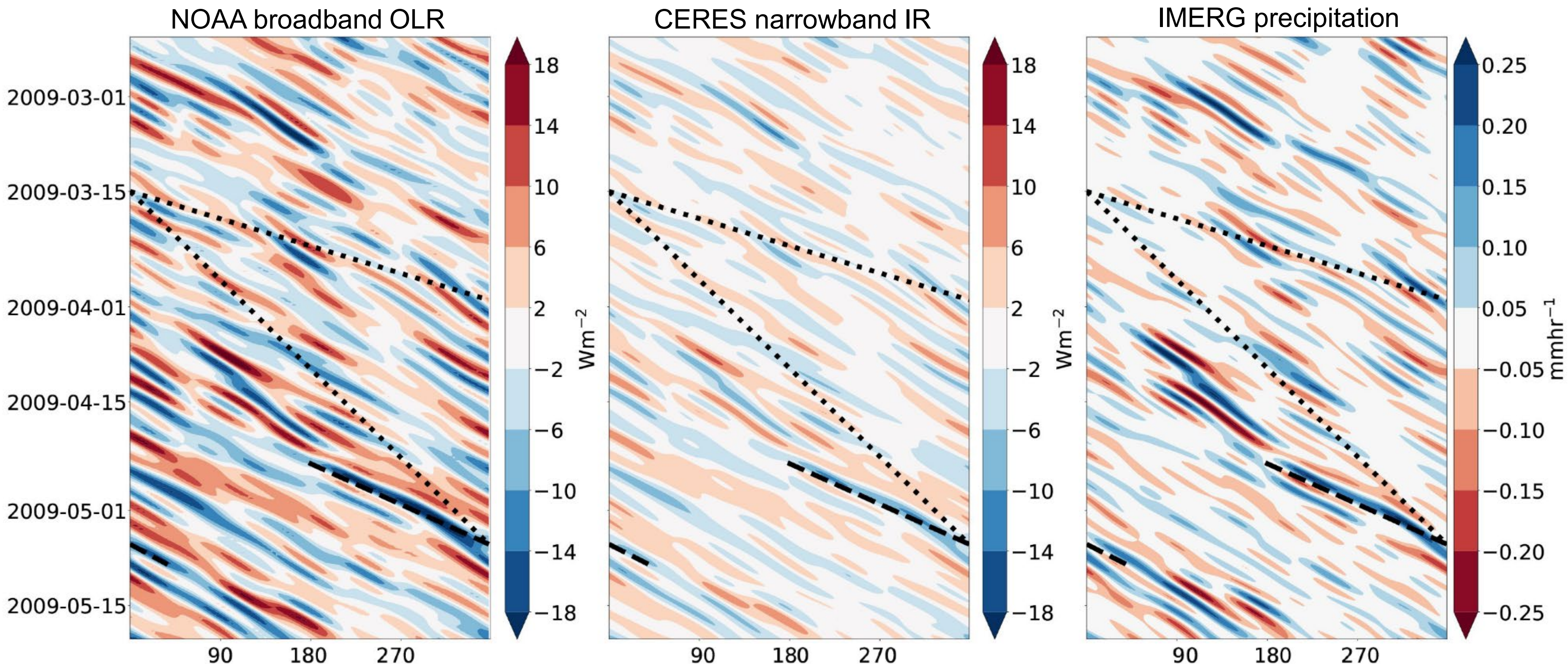
Unfiltered normalized anomalies – clouds & rain



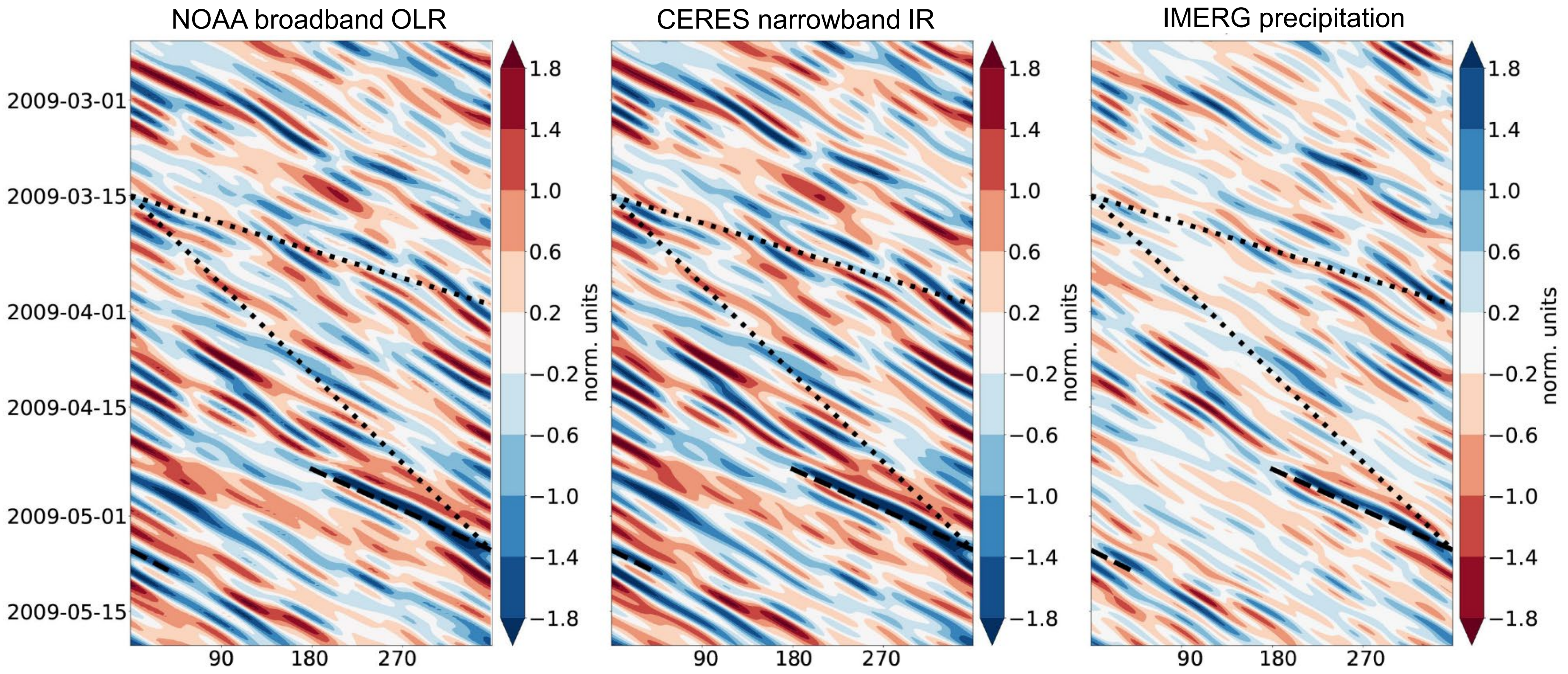
Unfiltered full fields – U wind & divergence



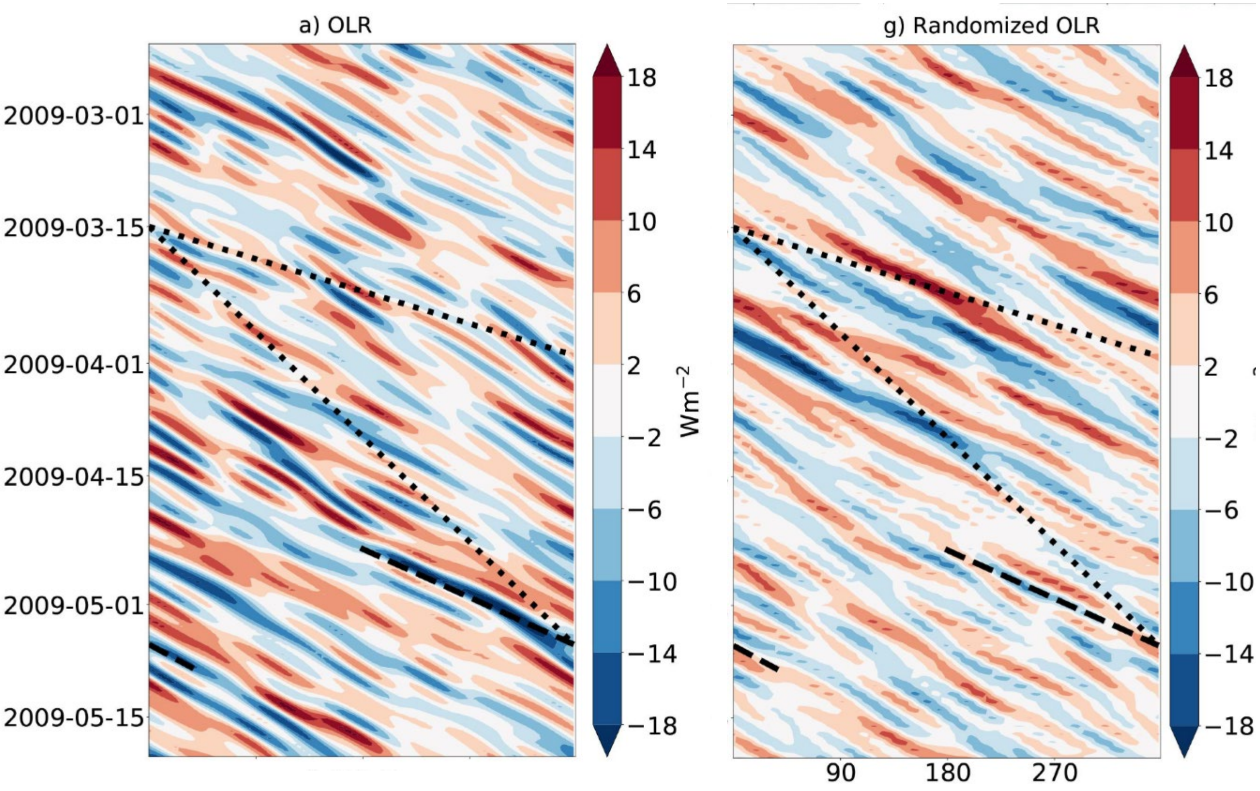
KW – FWF-FFT – clouds & rain



KW – FWF-FFT – clouds & rain (normalized)

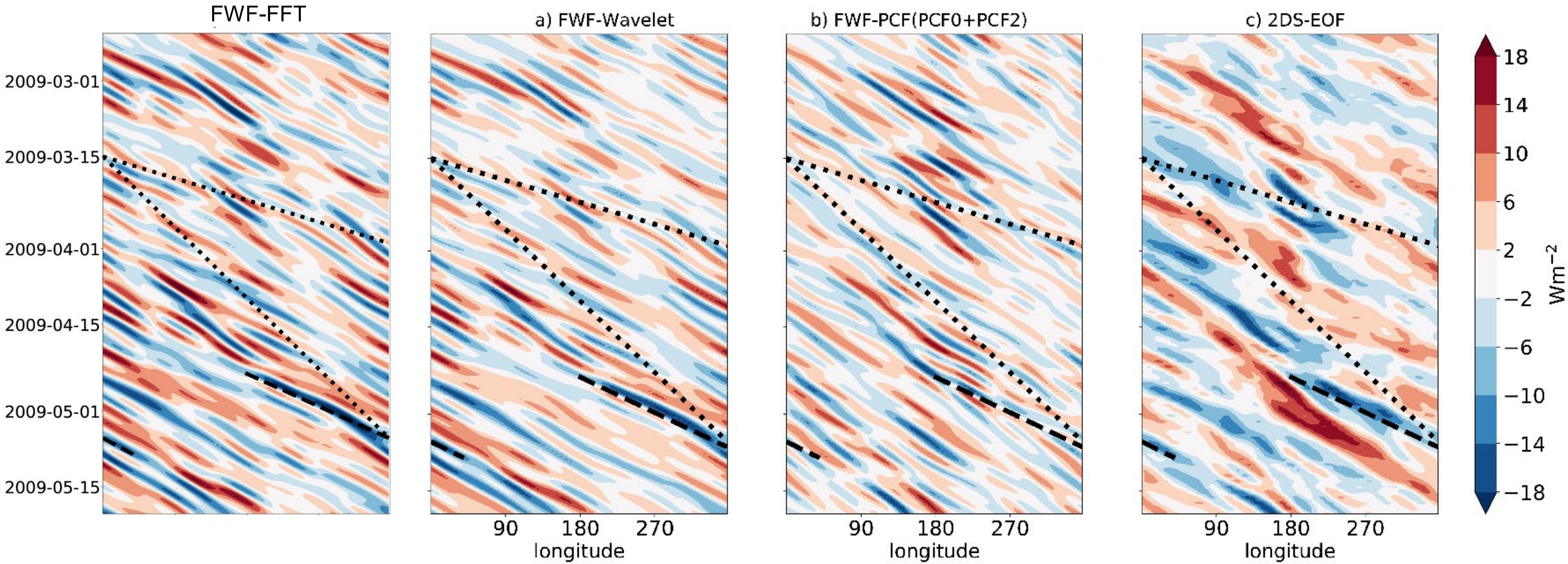


KW – OLR – Randomization

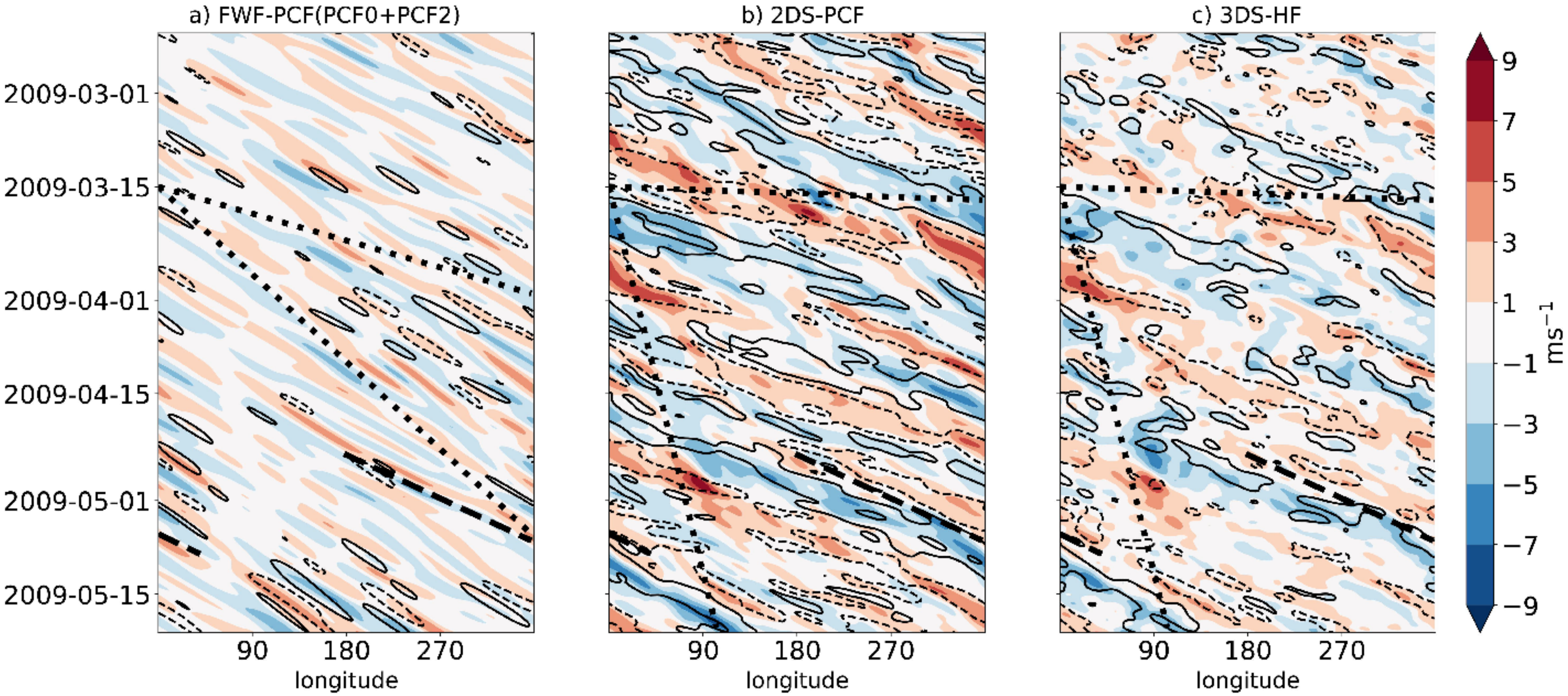


Beware of overinterpreting noise!!

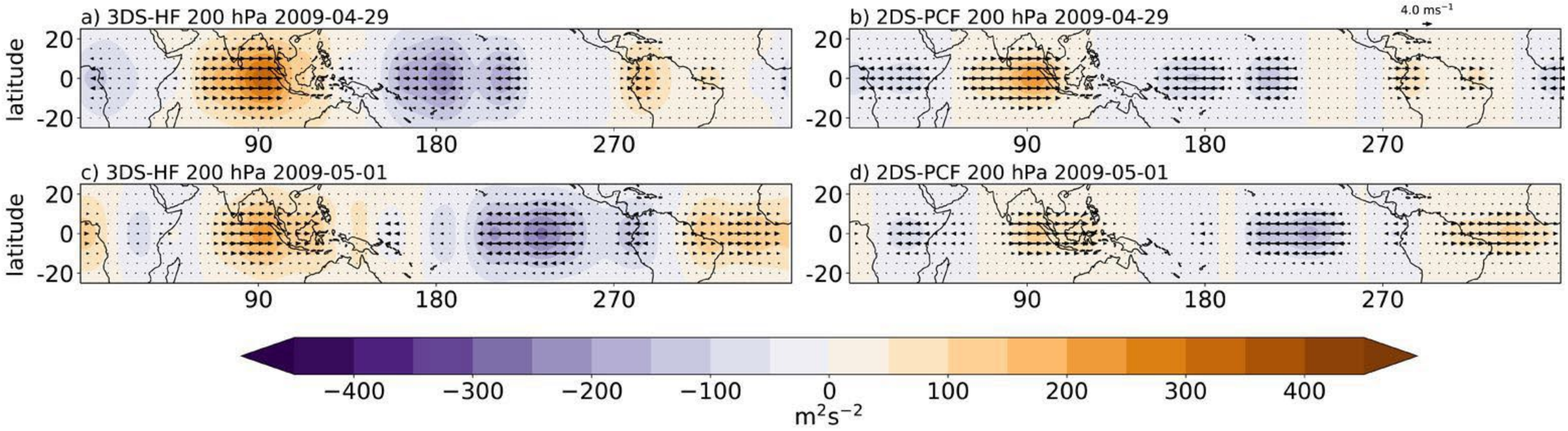
KW – OLR – Comparison of methods



KW – U wind – Comparison of methods

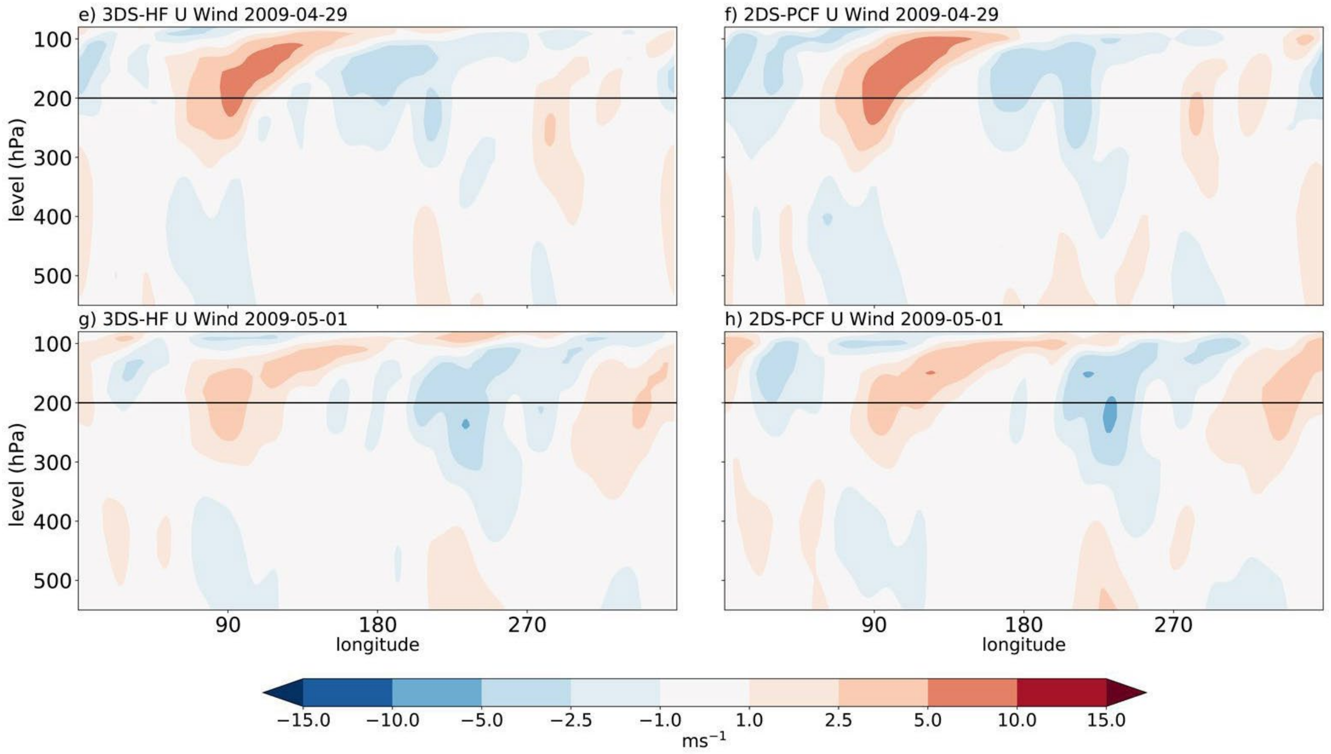


KW – U wind & Z – Comparison of methods

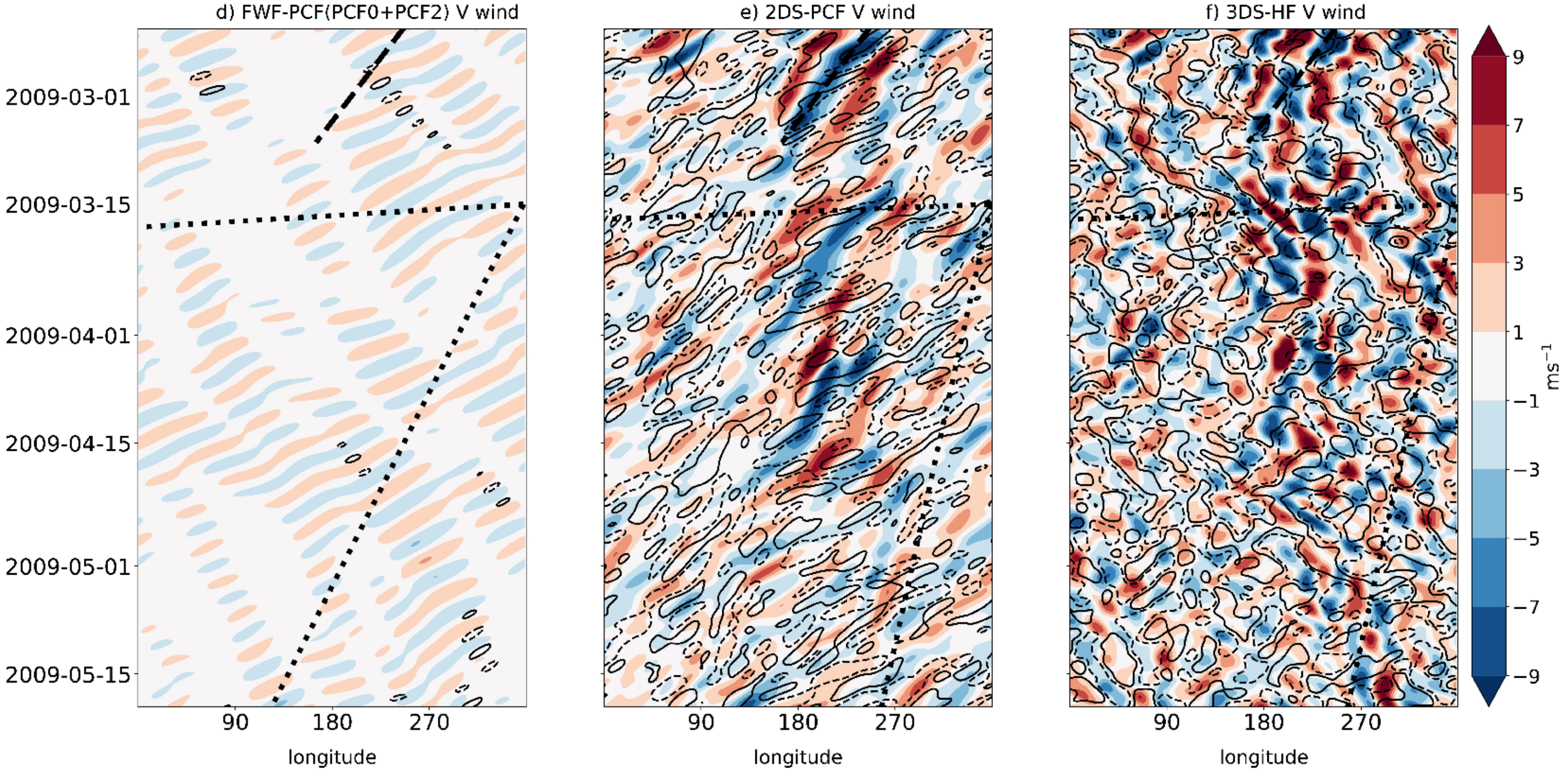


Setting a meridional scale in 2DS-PCF confines signal to inner tropics!

KW – U wind & Z – Comparison of methods



MRG – V wind – Comparison of methods



Explained variance for climatological period 2001–2018

(method is based on squared correlation between wave-filtered signals and variance in raw data [*Schlueter et al. 2019*])

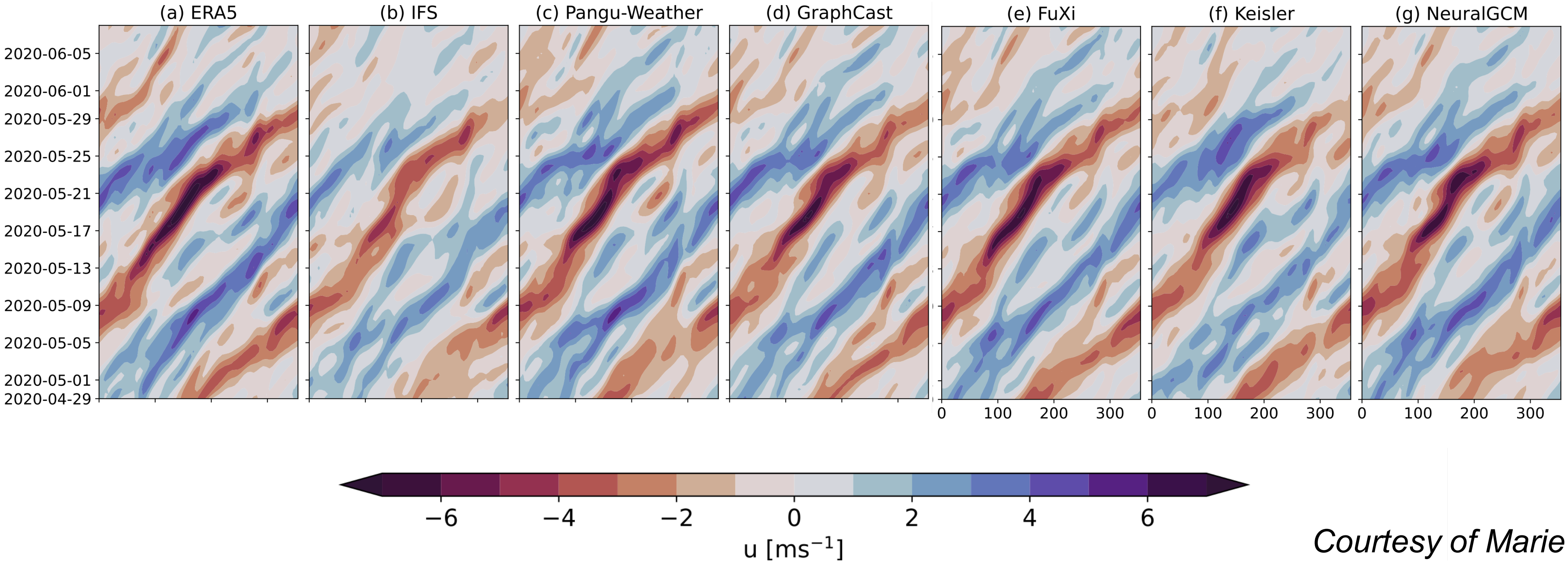
Equator-symmetric variance in OLR

Africa

Forecast evaluation

(comparison of model vs. data-driven forecasts based on the BSc thesis of *Marie Müller* at KIT)

5-day forecasts of KW in U_{850hPa} (FWF-FFT)



Courtesy of Marie Müller (KIT)

Conclusions

- Tropical waves shape synoptic- to planetary variability in the tropics with important ramifications for predictability (and data assimilation).
- Here we presented the first ever systematic comparison of the six most common objective identification methods.
- A case study and a climatological analysis show considerable differences with respect to amplitude, spatial scale, and phase speed.
- KW: Frequency-wavenumber filter (FWF) methods show more fine-scale structure and slower propagation than spatial projection methods
- MRG (& ER): Generally large discrepancies between methods
- **Combine time-space filtering & spatial projection methods for robust results!**
- **Think about underlying assumptions when interpreting discrepancies!**