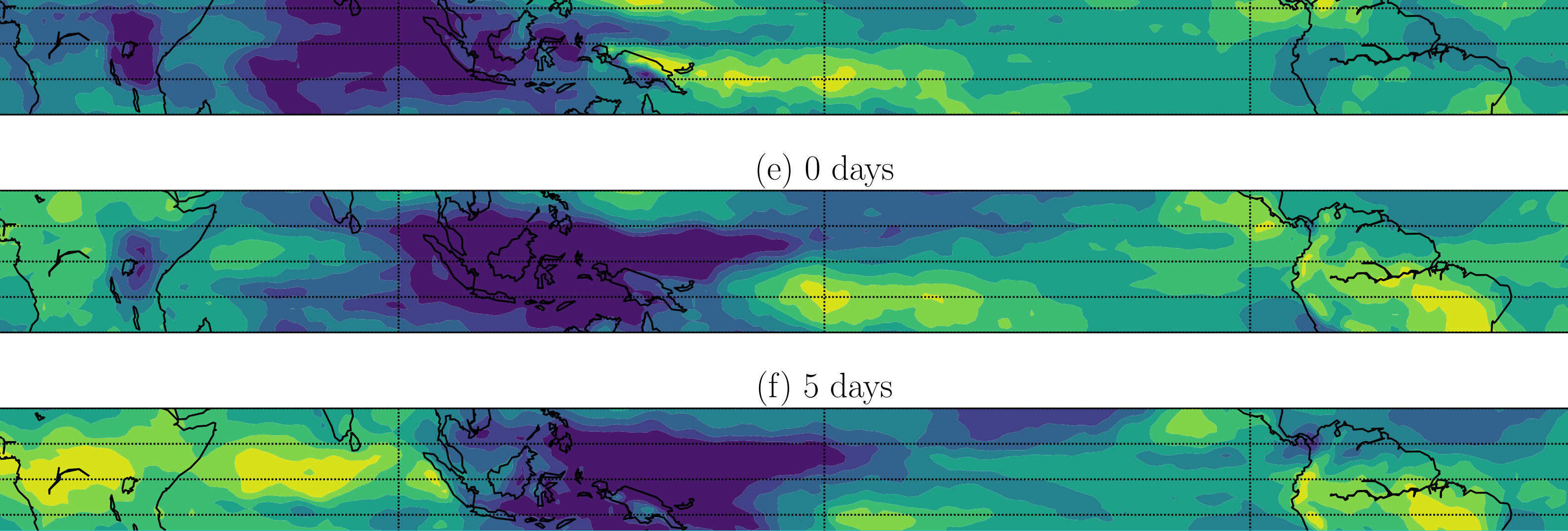

Application of normal mode functions for the improved balance in the CAFE data assimilation system and characterisation of modes of variability

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CLIMATE ANALYSIS FORECAST ENSEMBLE system

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Approach

- Will focus on the characterisation of the **Madden Julian Oscillation (MJO)** via a **Normal Mode Functions (NMF)** decomposition of JRA55, and discuss implications for **Normal Mode Inialisation (NMI)**.
- MJO is a mode of variability resulting from coupled tropical deep convection and atmospheric dynamics.
- Use key MJO properties to identify representatives NMFs:
  - Eastward propagating
  - Dominant variance over intra-seasonal timescales: 30-90 days.
  - Tropics centric dynamics.
  - Horizontal velocity field has a dominant longitudinal wave of $k = 1$.
  - Dominant component of the zonal velocity is symmetric about the equator.
- Using one such mode we produce phase and conditional averages of:
  - velocity potential to illustrate atmospheric dynamics
  - outgoing longwave radiation to illustrate convection
- Acknowledge Žagar for sharing the NCAR NMF code, **MODES**.

What are Normal Mode Functions ?

- Decompose 3D (λ, ϕ, σ) velocity (u, v) and geopotential height (h) fields into **horizonal** and **vertical scales**, and **mode type**, using the eigensolution of the linearised primitive equations on a sphere.
- Each scale decomposed into: Balanced Component (**BAL**) ; Eastward Inertial Gravity Wave (**EIG**) ; Westward Inertial Gravity Wave (**WIG**).
- Vertical Structure Functions (VSF), G_m in σ coordinates.
- Longitudinal (λ) waves $e^{\mathrm{i}k\lambda}$
- Meridional (ϕ) Horizonal Structure Functions (HSF) of wind and height (U, V, H) for EIG, WIG and BAL modes.

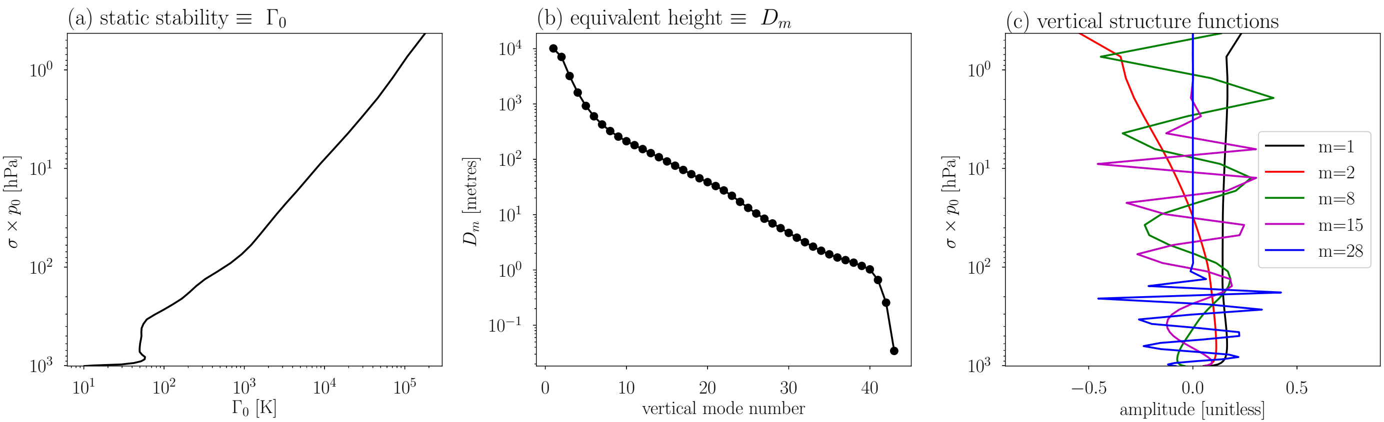
$$\begin{bmatrix} u(\sigma,\lambda,\phi,t) \\ v(\sigma,\lambda,\phi,t) \\ h(\sigma,\lambda,\phi,t) \end{bmatrix} = \sum_{m=1}^{M} G_m(\sigma) \begin{bmatrix} \sqrt{gD_m} & 0 & 0 \\ 0 & \sqrt{gD_m} & 0 \\ 0 & 0 & gD_m \end{bmatrix} \sum_{k=-K}^{K} e^{\mathrm{i}k\lambda}$$

$$\sum_{n=0}^{N} \sum_{p}^{\text{EIG,WIG,BAL}} \begin{bmatrix} U(\phi) \\ -\mathrm{i}V(\phi) \\ H(\phi) \end{bmatrix}_{knm}^{p} \chi_{knm}^{p}(t)$$

- Complex coefficients, $\chi_{knm}^{p}(t)$, represent contributions of each component.

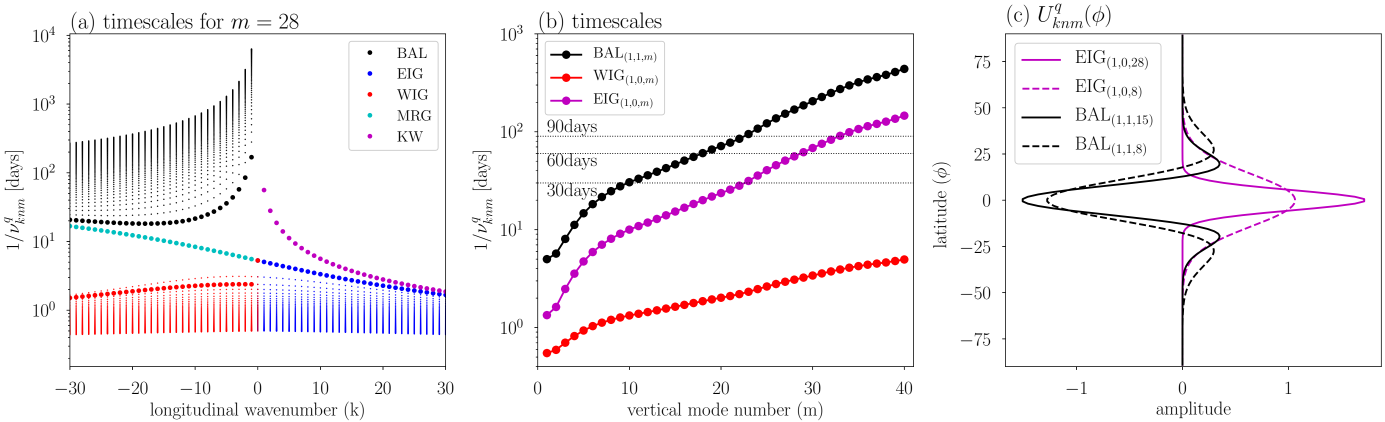
Vertical Structure Functions

- VSF given by solution of the VSF eigenvalue problem (EVP).
- VSF EVP requires only a time and horizontally averaged static stability profile in σ coordinates.
- Equivalent heights D_m (eigenvalues) are indicative of vertical scale.
- VSF $G_m(\sigma)$ (eigenvectors) have $m-1$ zero crossings. G_1 is the barotropic, G_2 the first baroclinic, G_3 the second baroclinic, ...
- For large m, the VSF represent boundary layer processes.



Horizontal Structure Functions

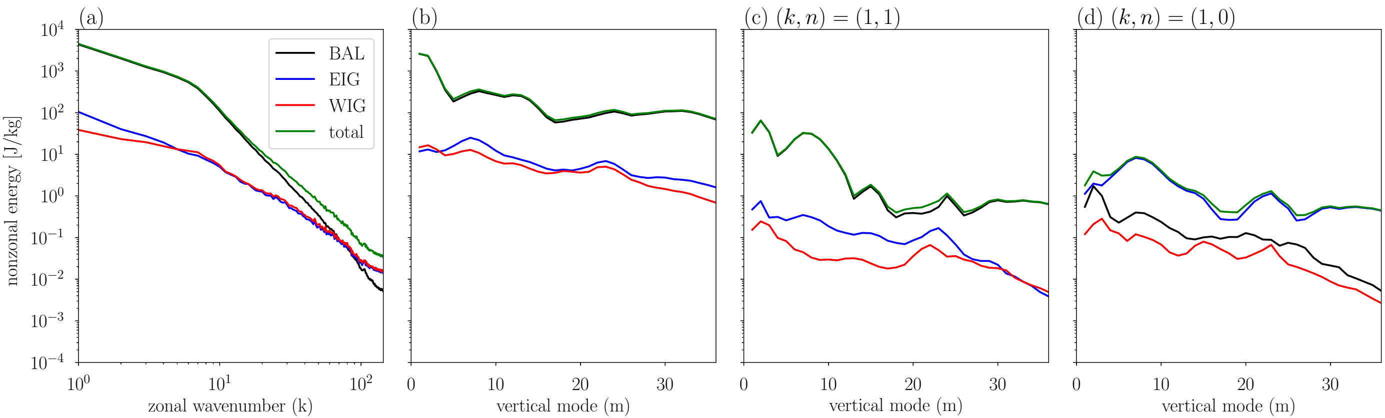
- HSF given by solution of a HSF EVP for each equivalent height (D_m).
- Eigenvectors give meridional dependence, with mode types (EIG, WIG, BAL) defined by symmetry properties.
- Frequency ν (eigenvalue) is indicative of temporal scale.



- Recall for MJO: $k = 1$; tropics centric; U is symmetric
- Only the EIG $n = 0$, WIG $n = 0$, and BAL $n = 1$ are tropics centric with the appropriate symmetries.
- EIG $m = 23 - 32$; BAL $m = 11 - 22$ have intra-seasonal timescales.

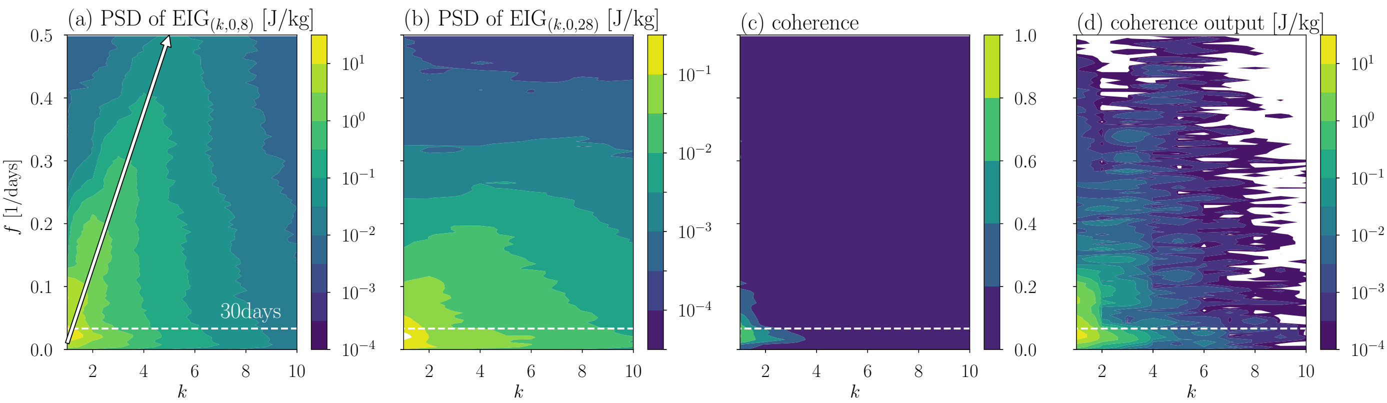
Energy Contribution $\overline{\chi^{p}_{knm}(t)\chi^{p*}_{knm}(t)}$ of NMFs in JRA55

- BAL dominates for low k, IG dominate for high k
- BAL dominates for all vertical modes m
- For $(k,n) = (1,1)$ BAL HSF eigenvectors have MJO-like properties:
  - BAL $(k,n,m) = (1,1,2)$ and $(1,1,2)$ local peaks in energy, but too fast
  - BAL $(k,n,m) = (1,1,15)$ has HSF eigenvalue of 46 days.
- For $(k,n) = (1,0)$ EIG HSF eigenvectors also have MJO-like properties:
  - EIG $(k,n,m) = (1,0,8)$ has most energy, but timescale too fast
  - EIG $(k,n,m) = (1,0,28)$ has HSF eigenvalue of 56 days.



Cross-spectral Analysis of Candidate NMFs

- All candidate modes are tropics centric and have the appropriate symmetries.
- Only EIG $(k, n, m) = (1, 0, 28)$ has an intra-seasonal timescale, and propagates eastward, but has low energy.
- Cross-spectral analysis identifies only slow intra-seasonal timescales are coherent between EIG $(k, n, m) = (1, 0, 28)$ and the more energetic modes.
- Fast Kelvin wave removed from energetic EIG $(k, n, m) = (1, 0, 8)$.



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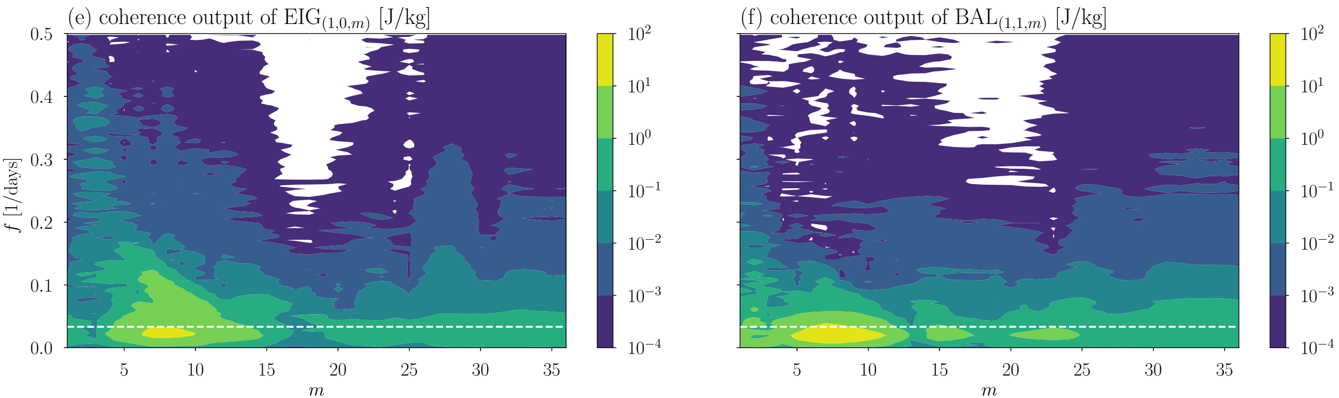
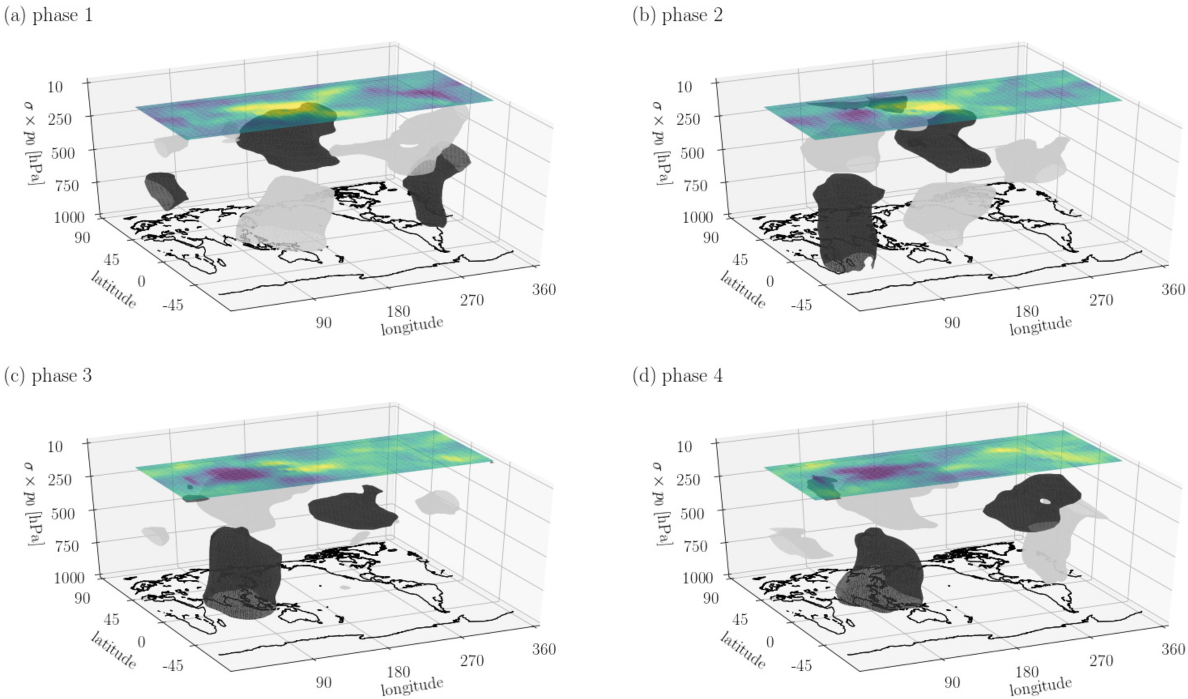
- Cross-spectral analysis identifies only slow intra-seasonal timescales are coherent between EIG $(k, n, m) = (1, 0, 28)$ and the more energetic modes.
- Repeated for all vertical scales (m) with $k = 1$ for BAL and EIG.



- Other candidate modes highlighted in coherence output clusters.

Phase Average on Basis of EIG $(k, n, m) = (1, 0, 28)$

- Phase angle calculated from complex χ^p_{nmk}. Dates associated with each phase angle octant averaged. All modes contribute to phase averages.



- Velocity potential is a propagating longitudinal wave, with a vertical sign change representing upper level divergence and lower level convergence.

Phase Average on Basis of EIG $(k, n, m) = (1, 0, 28)$

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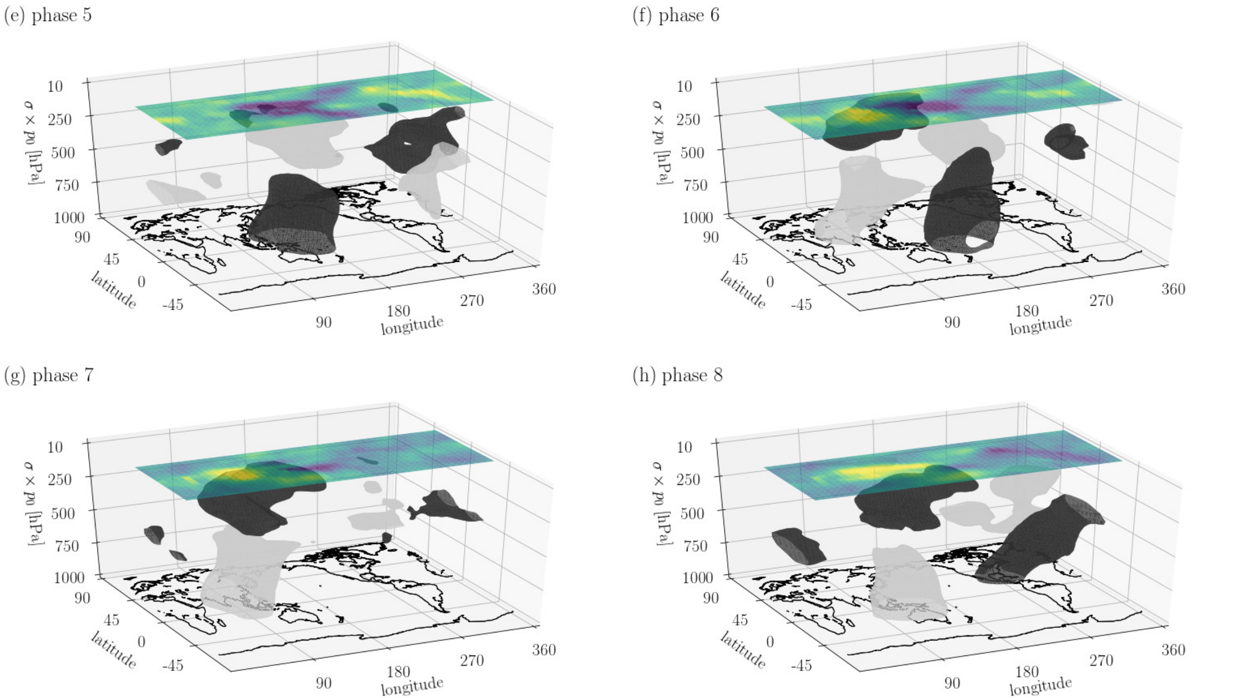
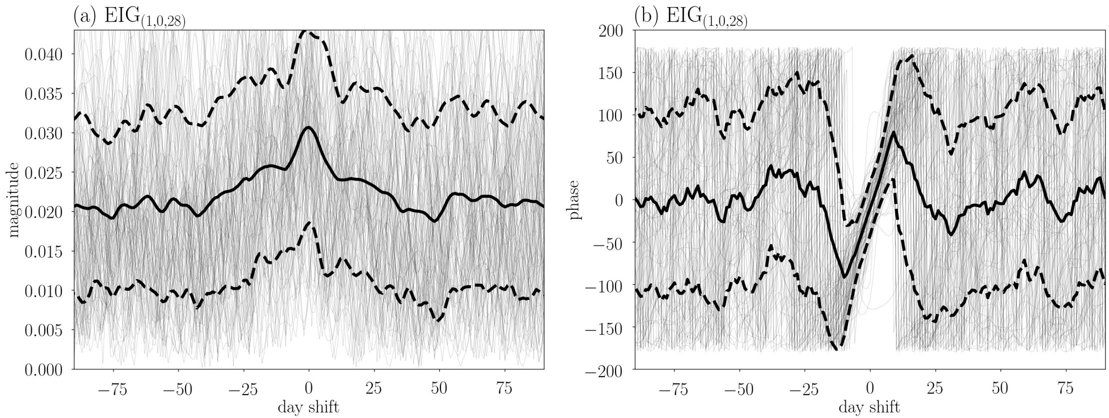


- OLR has a dipole pattern over the maritime continent, tracking with velocity potential of like sign.

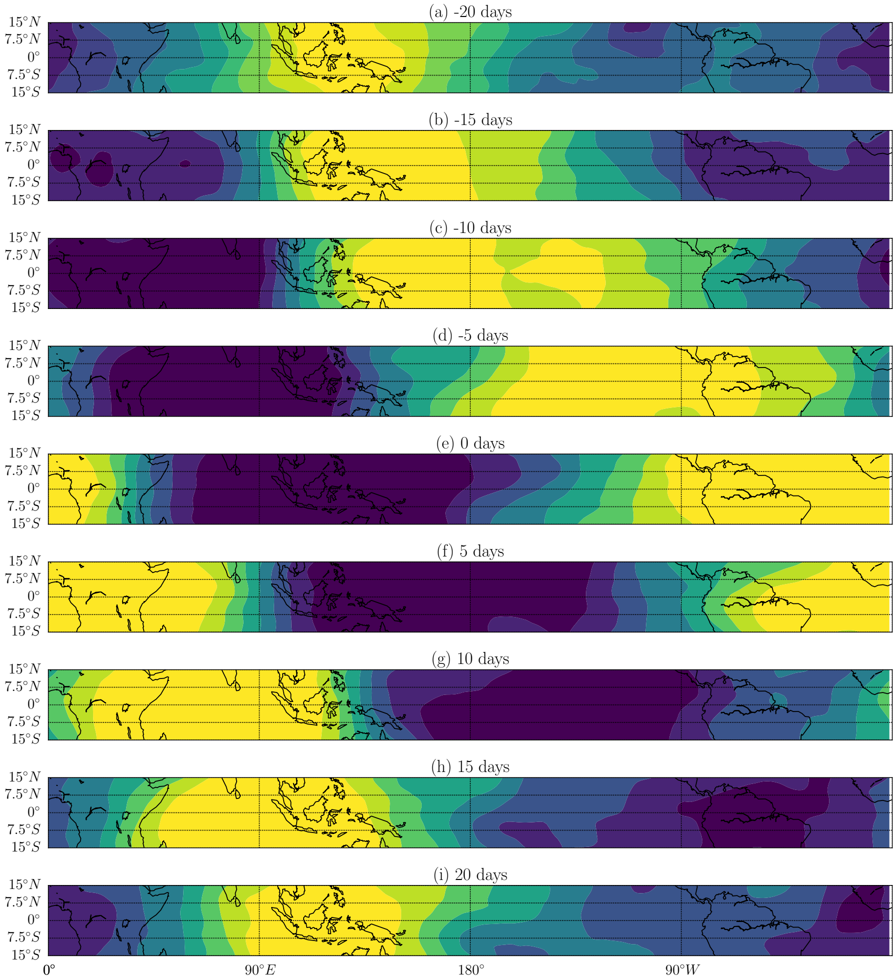
Large and Persistent MJO Events

- Start and end of each event defined as discontinuities in phase angle of EIG $(k, n, m) = (1, 0, 28)$.
- Persistent events have a continuous phase for longer than $270°$.
- Large events have a magnitude in the upper quartile.
- Composite average magnitude is greater than background for 20 days before and after day 0.
- Composite average phase angle indicates eastward propagation.

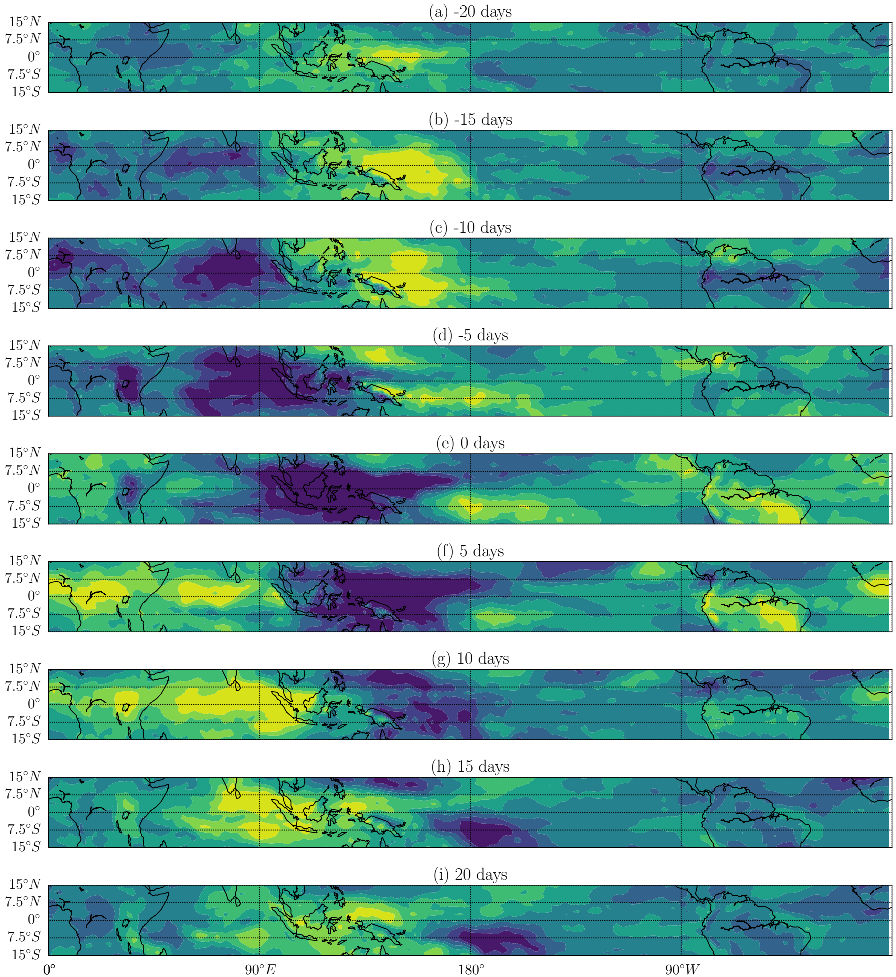


- Dates associated with each phase shift identified and averaged to produce composite fields of velocity potential and outgoing longwave radiation.

Velocity Potential at 200hPa - Wave Like

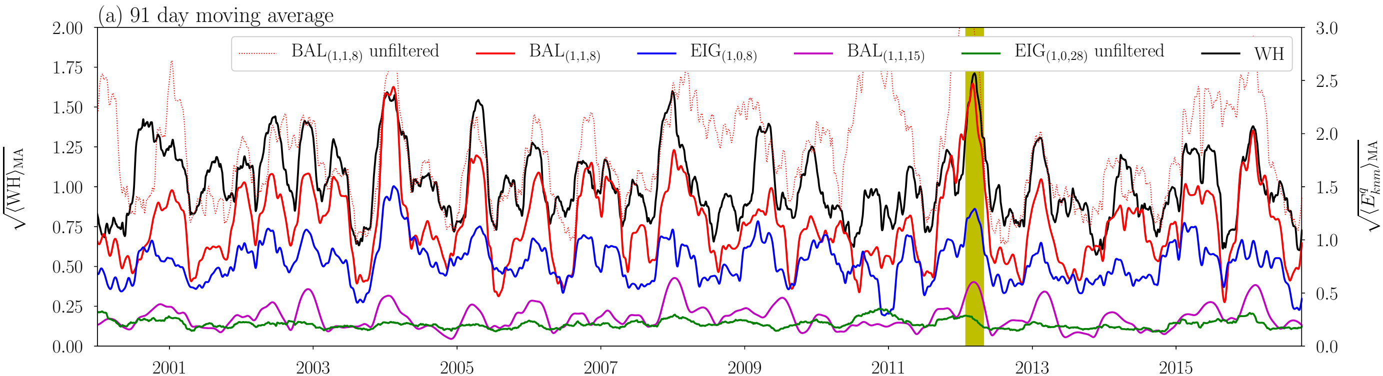


Outgoing Longwave Radiation at 200hPa - Dipole Like



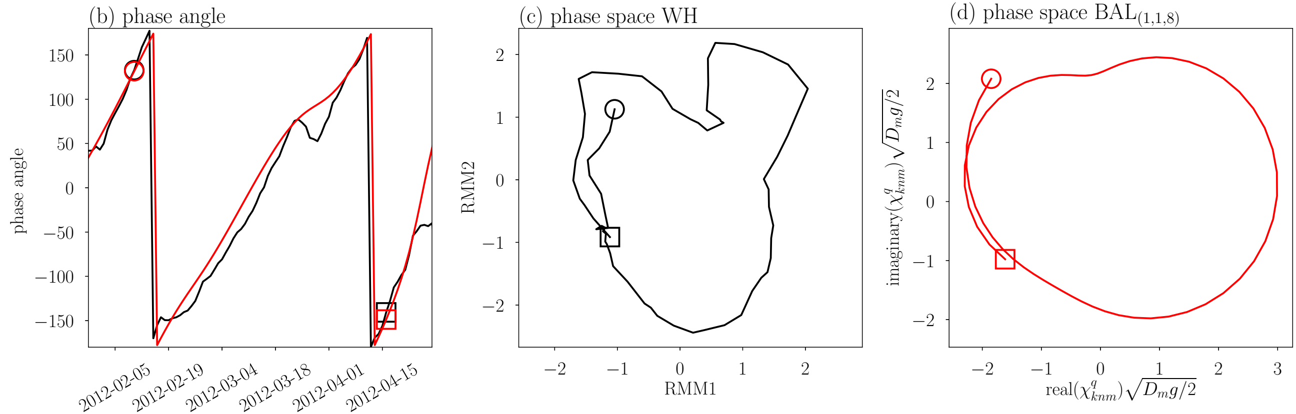
Instantaneous Comparison of NMFs and WH

- Wheeler & Hendon index based on first two PCs of meridionally averaged u at 200hPa, 850hPa and OLR within $15°S$ and $15°N$.
- Compare to tropics centric NMFs, with MJO-like symmetries:
  - BAL$(k, n, m) = (1, 1, 8)$: energetic, but westward, timescale too fast.
  - EIG$(k, n, m) = (1, 0, 8)$: energetic, but timescale too fast.
  - BAL$(k, n, m) = (1, 1, 15)$: intra-seasonal timescale, but westward.
  - EIG$(k, n, m) = (1, 0, 28)$: intra-seasonal timescale, eastward, not energetic.
- Correlation of BAL $(k, n, m) = (1, 1, 8)$ with WH when filtered to retain temporal scales coherent with EIG $(k, n, m) = (1, 0, 28)$ is 0.78.



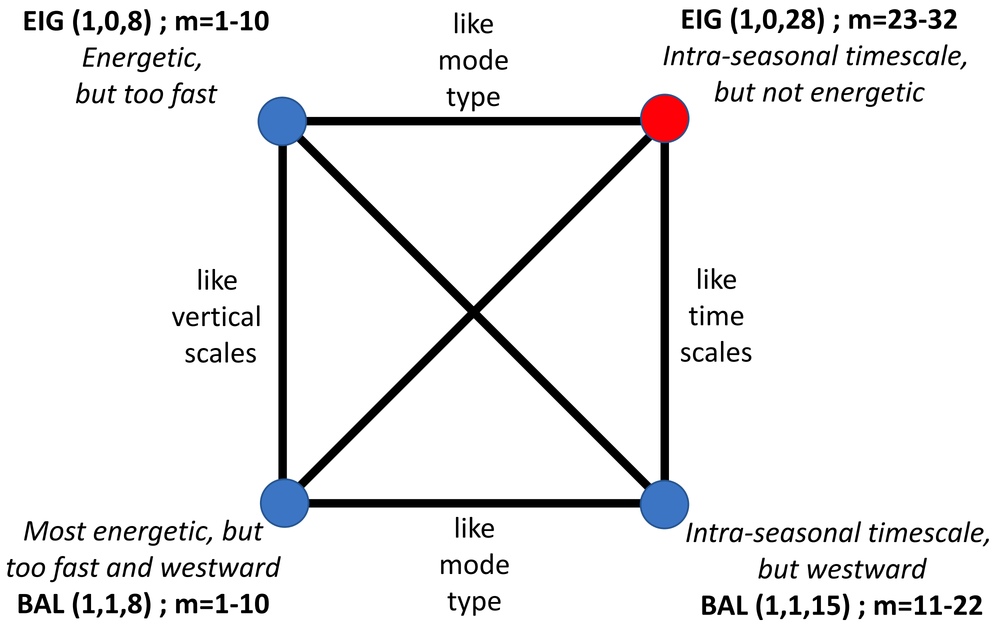
Instantaneous Comparison of NMFs and WH

- Wheeler & Hendon index based on first two PCs of meridionally averaged u at 200hPa, 850hPa and OLR within $15°S$ and $15°N$.
- In comparision to WH, coherence filtered BAL$(k, n, m) = (1, 1, 8)$ mode exhibits:
  - high correlation in magnitude over the entire time series (1958-2016)
  - consistent phase propagation for a specific event (Jan 2012)
  - consistent spiralling in for a specific event in phase space



Proposed MJO Skeleton

- Nonlinear interactions of these modes generates an energetic MJO of eastward propagation and correct phase period.
- All modes have MJO-like longitudinal and meridional structure.



- Interaction strength inferred from cross-spectral analysis.
- In the future will calculate the nonlinear transfer terms explicitly.

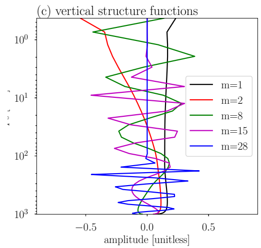
Concluding Remarks

- NMFs decompose a 3-D atmospheric geopotential height and horizontal velocity field into scale (**zonal, meridional, vertical**) and mode class (**BAL, EIG, WIG**).
- MJO-like NMF modes and their interactions were isolated in the **JRA-55**.
- A skeleton physical model of the MJO was proposed.

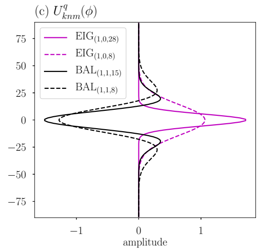
- Implications for **Normal Modes Initialisation**:
  - Since the IG waves have shorter timescales, they are potentially less predictable over a multi-year period.
  - Naively one would think that filtering the IG waves would improve predictability.
  - However, the EIG waves (even of small vertical scale and low energy) are shown here to be dynamically important for the MJO.

Questions

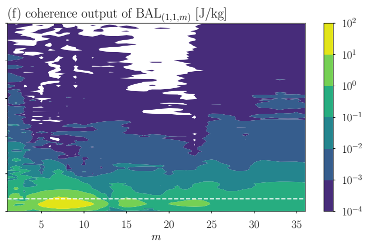
Vertical Structure Functions



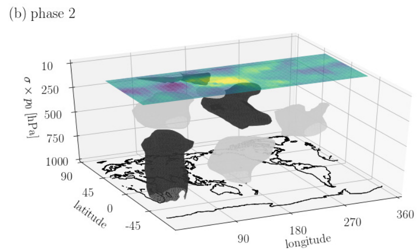
Horizontal Structure Functions



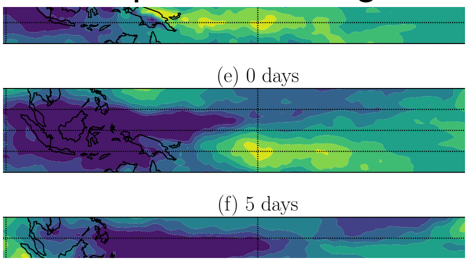
Cross-Spectral Analysis



Phase Averages

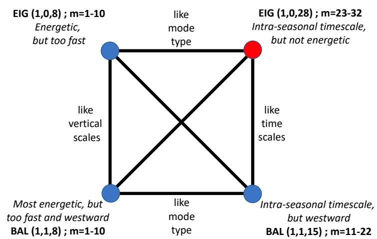


Composite Averages


(e) 0 days

(f) 5 days

Skeleton Physical Model



Thank You

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