Tropical Waves

Large-scale tropical circulation: Equatorial waves and the Madden-Julian Oscillation (MJO)

Linda Hirons | 24th July 2019

Learning Objectives

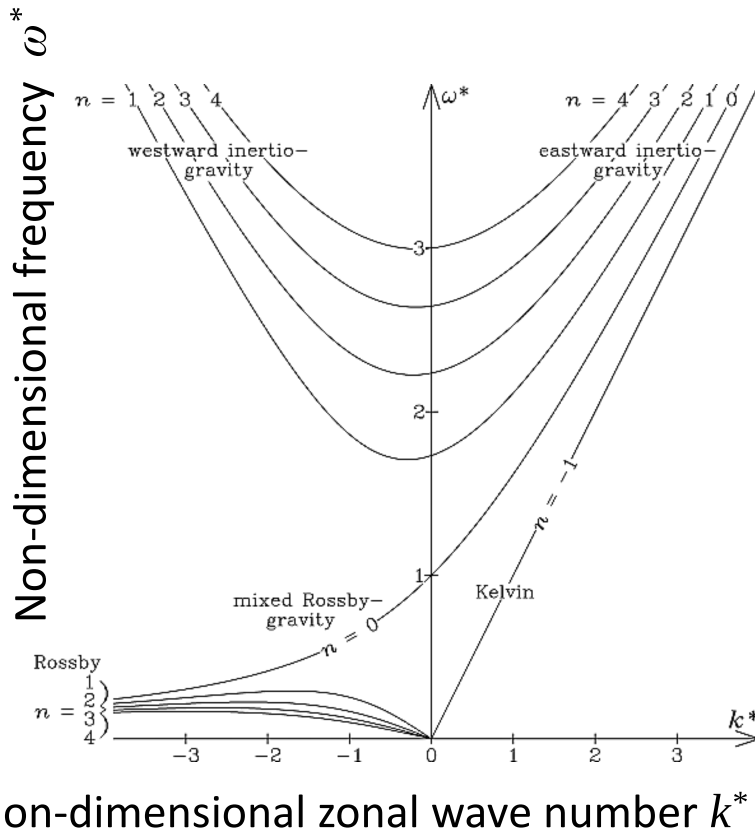
- Describe the structure and propagation characteristics of equatorial trapped waves and their relationship to the shallow water equations
- Relate the theoretical waves structures to the observed variability
- Describe the structure and propagation characteristics of the MJO
- Use the RMM indices to describe the convective signal of the MJO
- Describe some of the impacts of the MJO on tropical weather and climate

Convectively Coupled Equatorial Waves

- Convectively Coupled Equatorial Waves (CCWE) control a considerable fraction of tropical rainfall variability.
- However, their simulation in Global Circulation Models (GCMs) is far from perfect and a complete understanding of CCEWs remains a challenge for tropical meteorology.

- The horizontal structures and dispersion characteristics of these waves correspond to Matsuno (1966) solutions of the *shallow water equations* on an equatorial beta plane.
    - The *shallow water equations* govern motions in a layer of constant density fluid when the restoring forces are gravity and a linearly varying Coriolis parameter.
    - The solutions of this system correspond to waves of the equatorial atmosphere and ocean: **Kelvin**, **equatorial Rossby (ER)**, **westward and eastward inertio-gravity (WIG and EIG**) and **mixed Rossby-gravity (MRG) waves**.

See Kiladis (2009) for an overview.

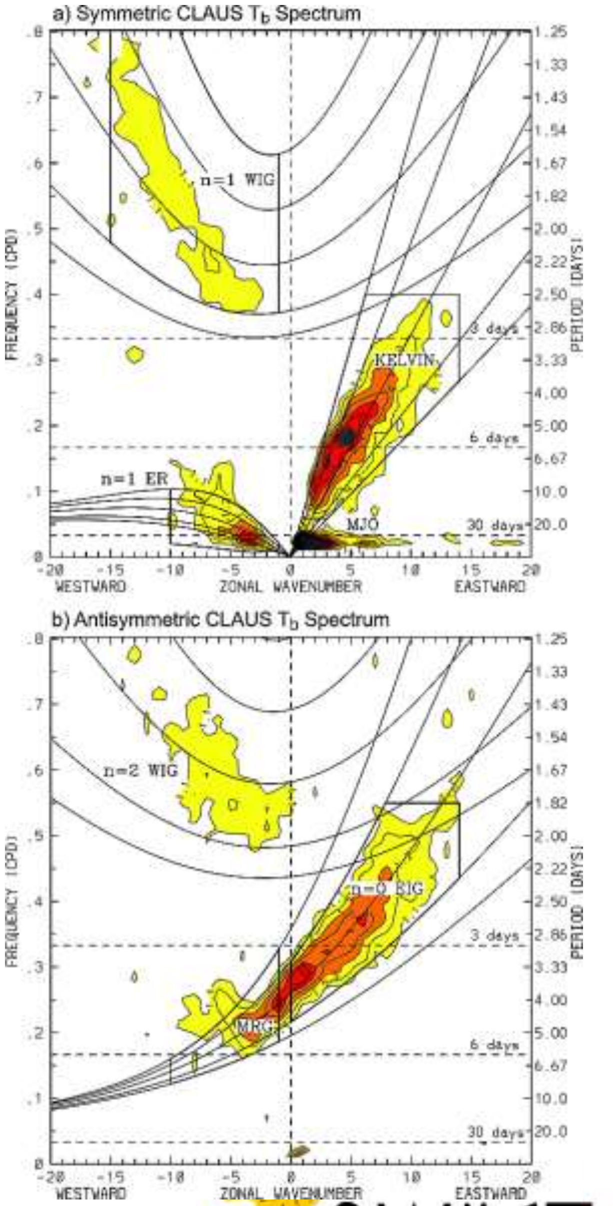


Dispersion curves for equatorial waves up n=4, as a function of non-dimensional zonal wave number (k^*) and frequency (ω^*), Reproduced from Kiladis et al. (2009)

Observing CCEWs

Space-time power spectrum of a long record of tropical cloudiness.

- E.g., Wavenumber-frequency power spectrum of equatorial (15N-15S) brightness temperature.
- As you can see, prominent spectral peaks from observations are orientated along the dispersion curves of Matsuno's (1966) theory for equatorially trapped wave modes.
- There is also a considerable spectral peak at eastward propagating wavenumbers 1-3 and period 30-60 days – this is the signal of the Madden-Julian Oscillation (MJO).



- Even without considering the potential effects of (i) the basic state flow and (ii) coupling to convection, remarkably the dispersion characteristics and structure of these CCWEs broadly correspond to linear theory (Figure).
  - Notable differences: observed phase speed of CCWEs are considerably slower than their dry counterparts.

Wavenumber frequency power spectrum of (a) symmetric and (b) antisymmetric brightness temperature (T_b) summed from 15°N to 15°S, plotted as the ratio between the T_b power and the power in a smoothed red noise background. Lines show theoretical dispersion curves on a resting basic state for equivalent depths of 8,12,25,50,90m, for a variety of equatorially trapped modes. Reproduced from Kiladis et al. (2009).

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Theory of CCEWs

- Consider inviscid *shallow water equations* linearized about a motionless basic state (see Kiladis 2009).
  Assumption valid for tropics: Coriolis parameter f is linearly proportional to distance from the equator (i.e., $f=\beta y$).

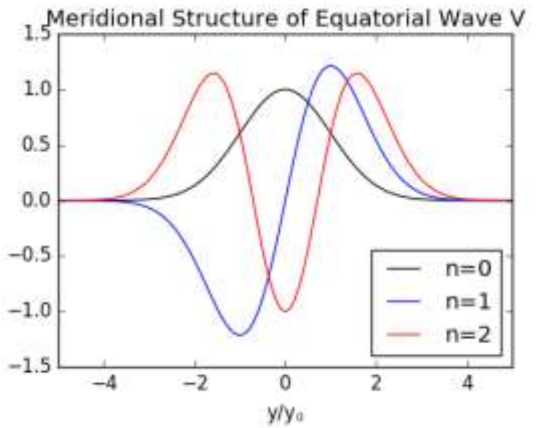
(1) $$\frac{\partial u_l}{\partial t} - \beta y v_l = -\frac{\partial \phi_l}{\partial x},$$

(2) $$\frac{\partial v_l}{\partial t} + \beta y u_l = -\frac{\partial \phi_l}{\partial y},$$

(3) $$\frac{\partial \phi_l}{\partial t} + g h_e \left(\frac{\partial u_l}{\partial x} + \frac{\partial v_l}{\partial y} \right) = 0.$$

- (1),(2): horizontal momentum equations. (3): consequence of mass conservation
- u_l and v_l : zonal and meridional velocities. Φ_l: geopoential, g: acceleration due to gravity, h_e: depth of undisturbed layer of fluid.
- These equations model the horizontal (x and y) and time (t) varying components of the flow. i.e., they govern the motions of a particular vertical mode, l, for which an appropriate choice of h_e must be made.
- For a single layer of fluid phase speed (c) is given by: $c^2=gh_e$. Typical c values for dry tropical wave from theory are ~50ms^{-1} compared with observed CCEWs phase speeds of ~15-20ms^{-1}.

Theory of CCEWs – Meridional Structure



- Seek zonally propagating wave solutions to these equations of the form (4) :

(4) $$\begin{pmatrix} u_l \\ v_l \\ \phi_l \end{pmatrix} = \begin{pmatrix} \hat{u}(y) \\ \hat{v}(y) \\ \hat{\phi}(y) \end{pmatrix} \exp[i(kx - \omega t)],$$

k: zonal wave number, ω: frequency.

- Seeking solutions for the meridional wind which are wave-like in the longitudinal direction.
- Therefore, combining these horizontal equations, substitution and rearrangement yields a second-order differential equation for the meridional velocity:

$$\frac{d^2\hat{v}}{dy^2} + \left(\frac{\omega^2}{gh_e} - k^2 - \frac{k}{\omega}\beta - \frac{\beta^2 y^2}{gh_e}\right)\hat{v} = 0. \quad (5)$$

- Solutions to (5) take the following form:

$$\frac{\sqrt{gh_e}}{\beta}\left(\frac{\omega^2}{gh_e} - k^2 - \frac{k}{\omega}\beta\right) = 2n + 1 \qquad n = 0,\ 1,\ 2, \ldots. \quad (6)$$

- (6) gives a relation between zonal wavenumber (k) and frequency (ω), for each positive integer n, thus defining the horizontal dispersion relation for the waves.

n: meridional mode number as it corresponds to the number of nodes in the meridional profile of v (Figure).

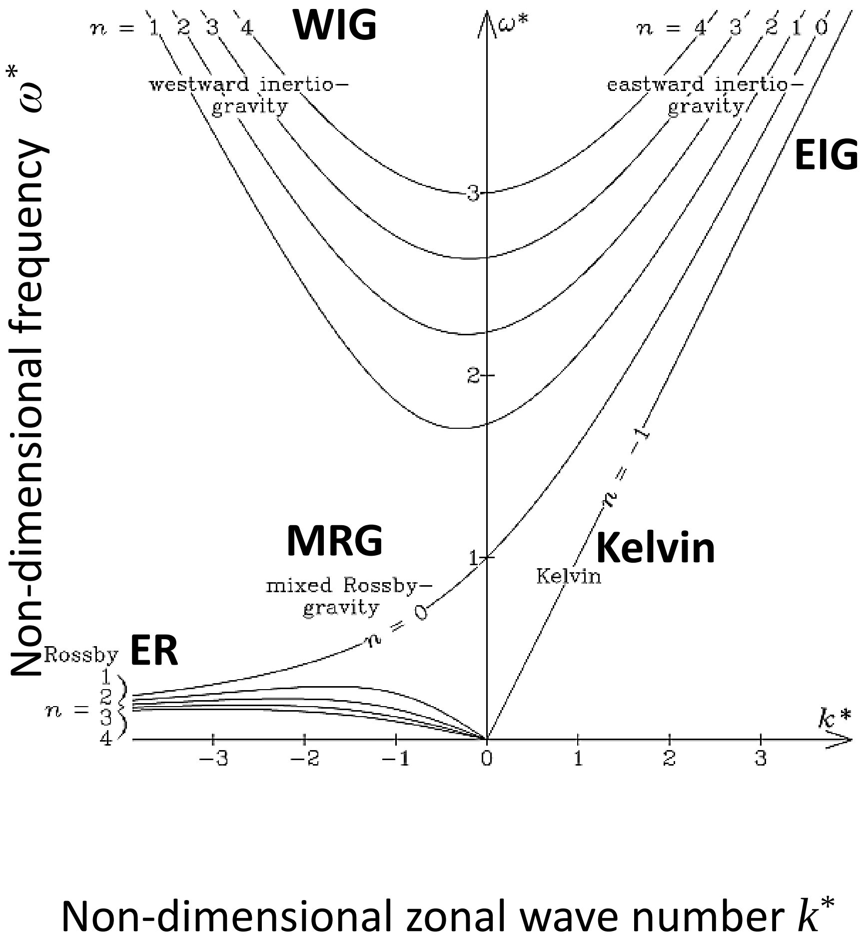
Theory of CCEWs – Dispersion Relation

$$\frac{\sqrt{gh_e}}{\beta}\left(\frac{\omega^2}{gh_e} - k^2 - \frac{k}{\omega}\beta\right) = 2n+1 \qquad n = 0,\ 1,\ 2, \ldots . \qquad (6)$$

- Equation (6) is cubic in ω with solutions corresponding to the **EIG**, **WIG** and **ER** waves.
- Special case of $n=0$ corresponds to **MRG.**
    - Westward moving MRG waves are low frequency and behave more like ER.
    - Eastward moving MRG waves are high frequency and behave more like EIG.

- **Kelvin** wave is an additional solution to equations (1)-(3) for which $\tilde{v}=0$ for all y. For consistency with (6) this tends to be noted as $n=-1$.

- Non-dimensional frequency $\omega^*=\omega/(\beta\sqrt{gh_e})^{1/2}$, non-dimensional wavenumber $k^*=k(\sqrt{gh_e}/\beta)^{1/2}$



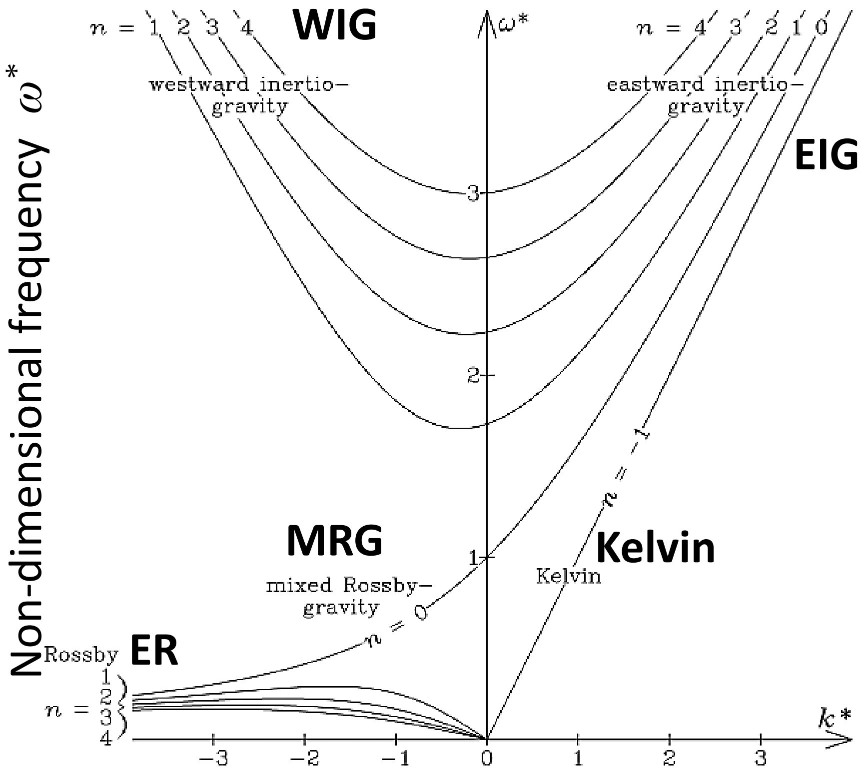
Dispersion curves for equatorial waves up n=4, as a function of non-dimensional zonal wave number (k^*) and frequency (ω^*), Reproduced from Kiladis et al. (2009).

Theory of CCEWs – Phase Speed and Group Velocity

Phase speed: the speed of the wave front
Group velocity: the propagation of the entire wave packet.

- The **phase speed** of the Kelvin wave, a non-dispersive wave, is $c=\sqrt{gh_e}$. The phase speeds of WIG and EIG asymptotically approach this magnitude for large k.
- The horizontal energy dispersion of waves is governed by the **group velocity** $c^{(x)}_g=\partial\omega/\partial k$. MRG wave, for example, has westward phase speed (*speed of wave front;* ω/k is negative) but eastward energy dispersion (*speed of wave packet;* $c^{(x)}_g$ is positive).
- Rossby waves have westward phase speed, and long waves have westward group veolocity but short waves have eastward group velocity.

- The equatorial *Rossby radius of deformation*, which governs the rate of decay of solutions with distance from the equator, is given by $R_e=(\sqrt{gh_e}/\beta)^{1/2}$. For CCEWs R_e is ~ 10° of latitude.



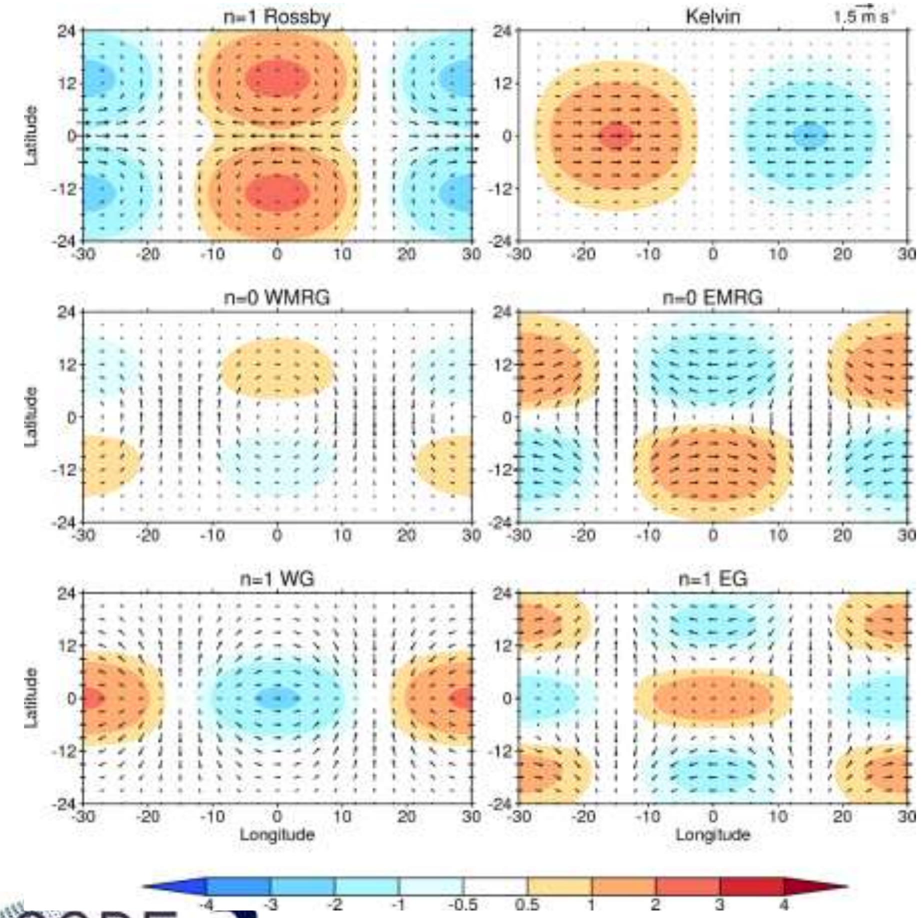
Non-dimensional zonal wave number k^*

Dispersion curves for equatorial waves up n=4, as a function of non-dimensional zonal wave number (k^*) and frequency (ω^*), Reproduced from Kiladis et al. (2009).

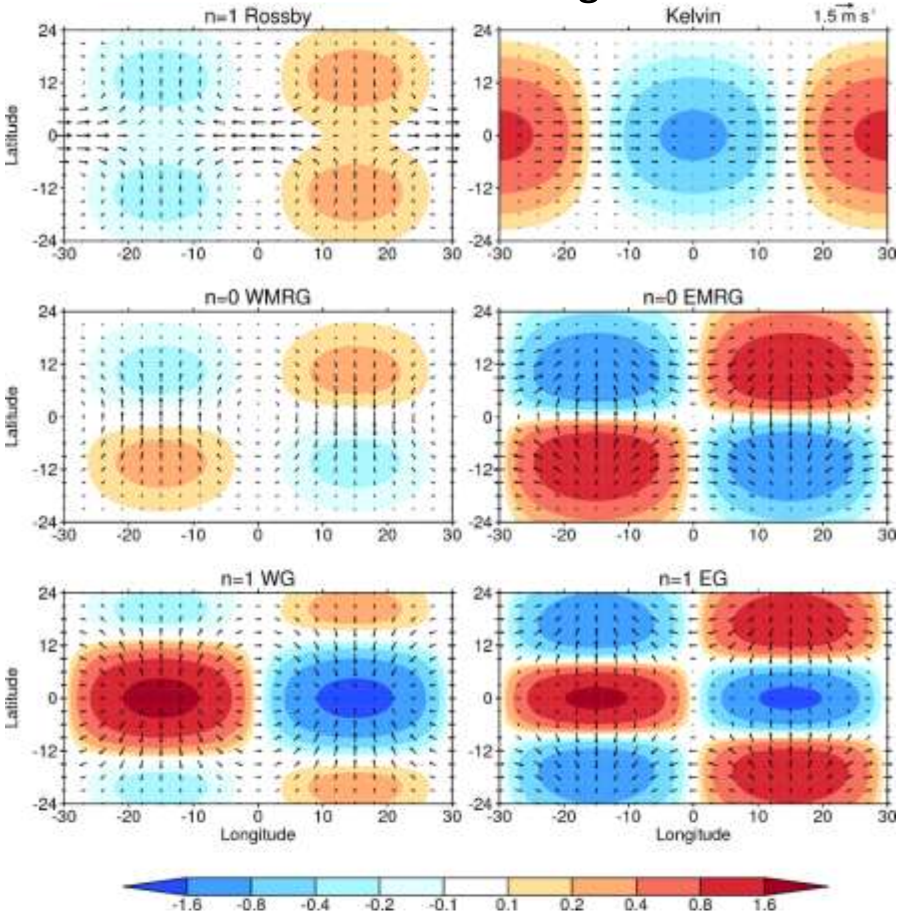
Theory of CCEWs – Horizontal Structure

- Substituting for the meridional structure along with the dispersion relation back into the *shallow water equations* reveals the horizontal structure of these theoretical waves.

Winds and Geopotential Height



Winds and Divergence



- Kelvin, IG and eastward-moving MRG waves are more divergent in nature
- ER and westward-moving MRG waves are more rotational in nature
- Kelvin, n=1 ER and IG waves are **symmetric** about the equator in geopotential, divergence and zonal wind and **asymmetric** in meridional wind
- MRG, n=2 ER and IG waves (not shown) are **asymmetric** about the equator in geopotential, divergence and zonal wind and **symmetric** in meridional wind

Horizontal Structure for wavenumber 6 equatorial waves, (with a trapping scale of ~8.4°; c~ 20 ms^{-1}; H~40m)

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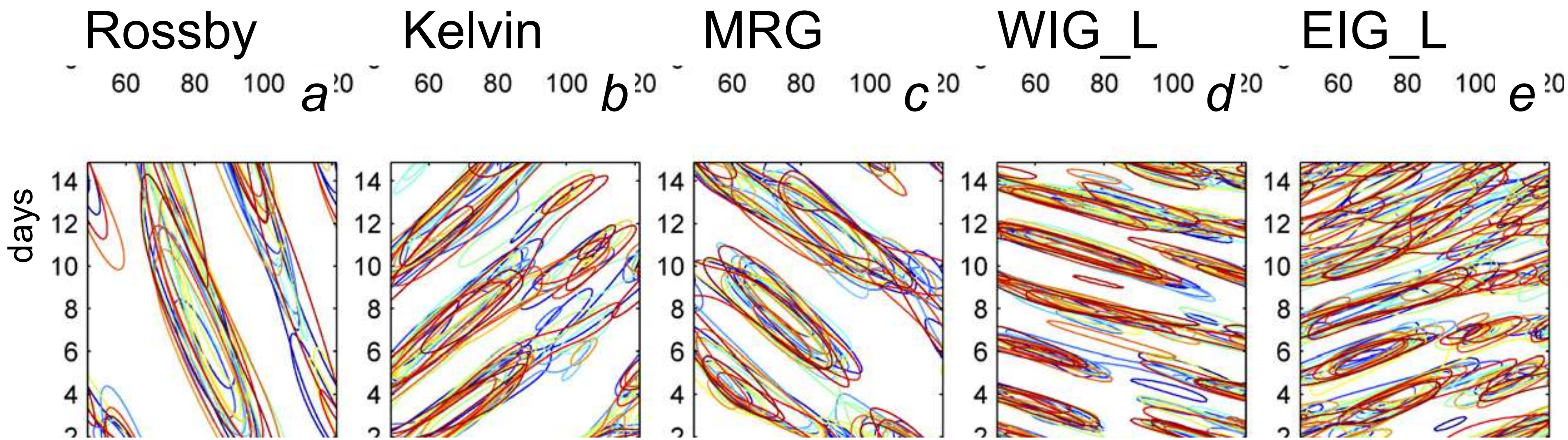
Theory of CCEWs – propagation characteristics

Phase speed: the speed of the wave front
Group velocity: the propagation of the entire wave packet.



Longitude-time filtered precipitation plots for 0°-5°N. Shading every 1mm/day from -10 to 10 mm/day. (Ying and Zhang 2017).

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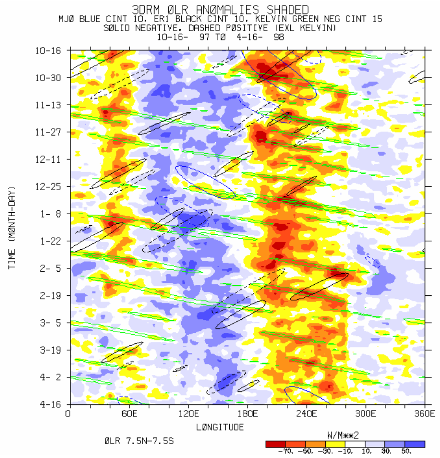
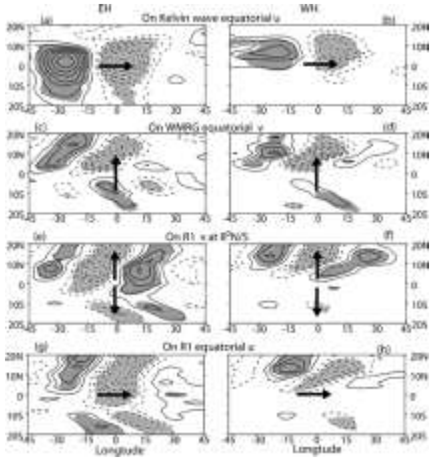
Identifying CCEWs in observations

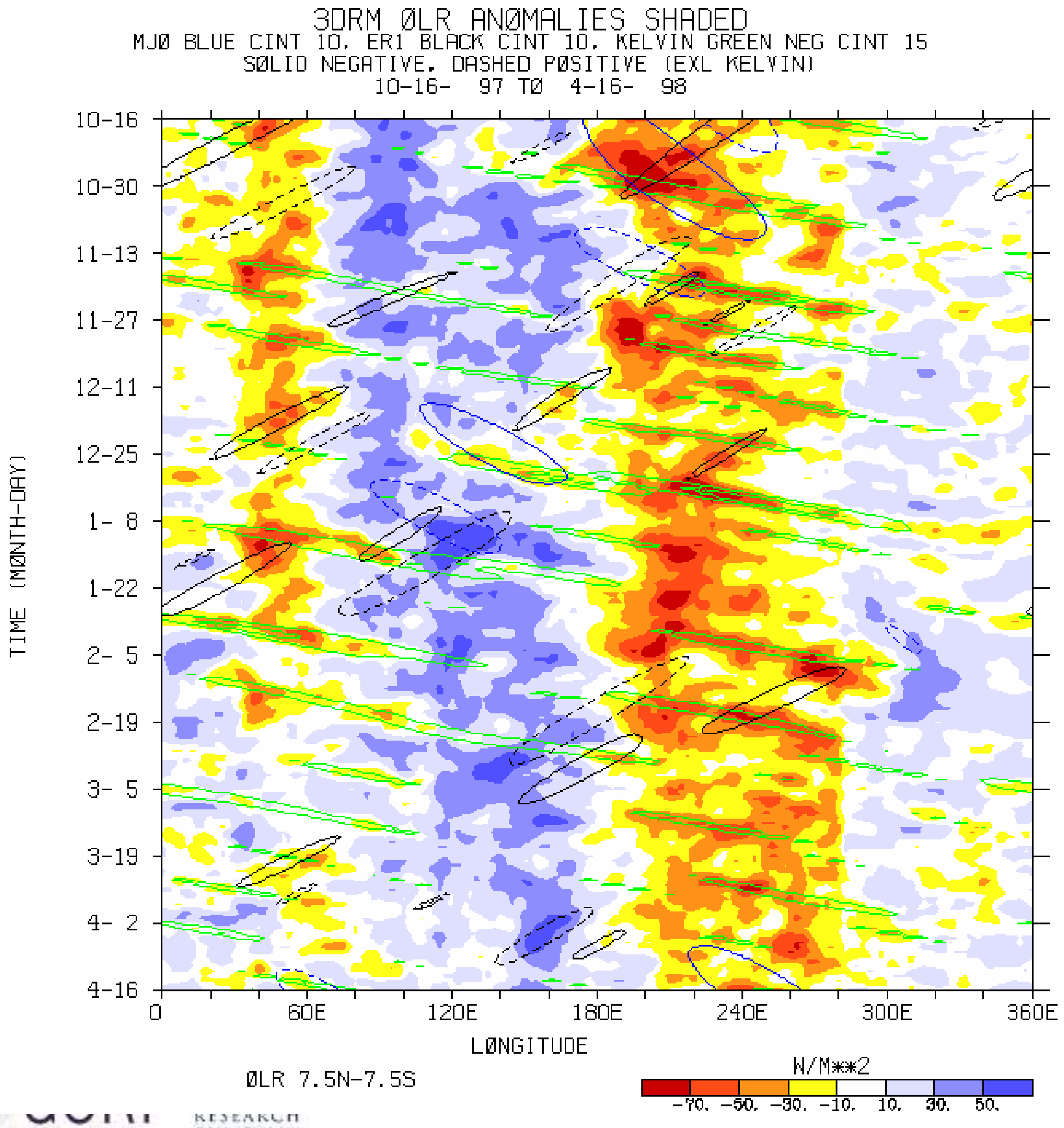
- **Wave-number frequency filtering (e.g. Wheeler and Kiladis 1999)**
  - Isolate particular regions in wave-number frequency space associated with theoretical dispersion curves for waves and filter e.g. OLR, brightness temperature.
  - Easy to do, but cannot account for Doppler shifting by mean wind.



- **Projection onto dynamical fields (e.g. Yang et al. 2003)**
  - Project winds and geopotential onto theoretical dynamical structures of the waves.
  - More complex, but doesn’t depend on dispersion relation and hence isn’t affected by Doppler shifting by mean wind.



Identifying CCEWs in observations



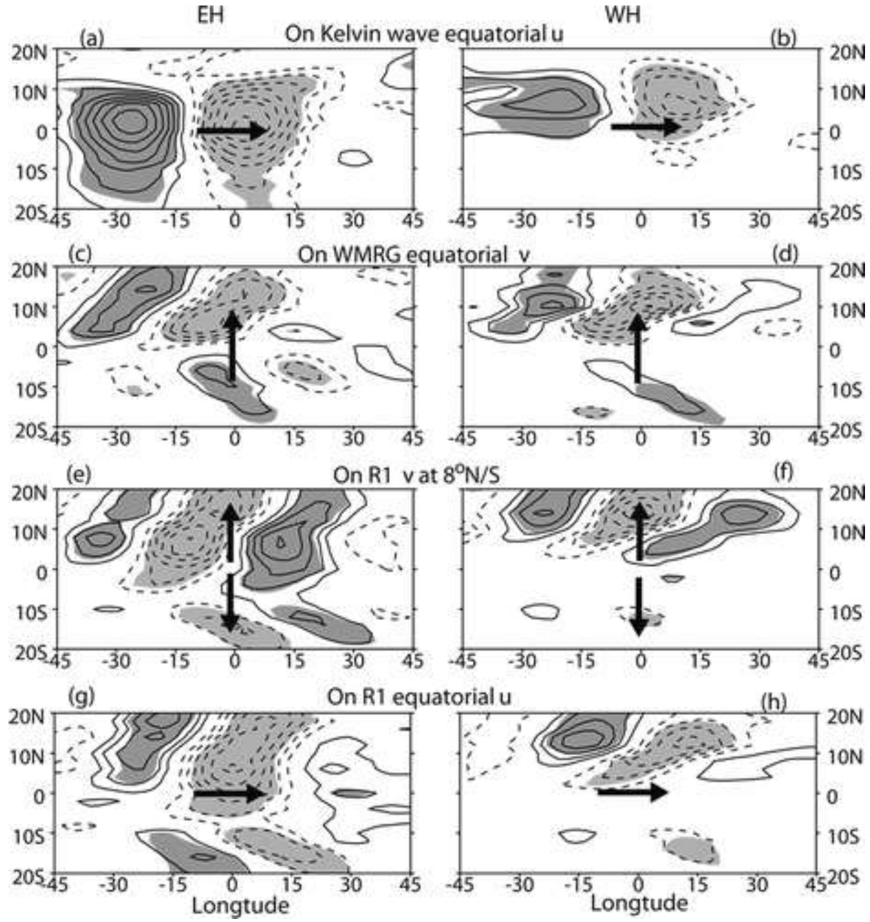
Wave number frequency filtering

Image shows 7.5°N-7.5°S averaged OLR anomalies overlaid with filtered anomalies using Wheeler and Kiladis method for winter 97-98

- MJO in blue
- Kelvin Wave in Green
  - Much faster than MJO
- n=1 Equatorial Rossby Wave in Black
  - Note evidence of eastward group velocity e.g. 20 Nov over East Pacific
- No MRG waves as this OLR is symmetric about equator

Image from NOAA Earth System Research Laboratory at https://www.esrl.noaa.gov/psd/map/clim/olr_modes/PASTIMAGES/9798hovEa.gif

Identifying CCEWs in observations



Projection onto dynamical fields

- Identifying waves by projecting dynamical fields onto theoretical structures following Yang et al. (2003) and regress other fields on to winds associated with particular wave modes
- Brightness temperature shows convective signal associated with waves
- Differences between behaviour in the western (dry) and eastern (moist) hemisphere
- Hemispheric asymmetry in convection associated with the wave
- Convection not necessarily associated with low-level convergence
- Vertical structure (not shown) reveals e.g. westward tilt with height for Kelvin wave

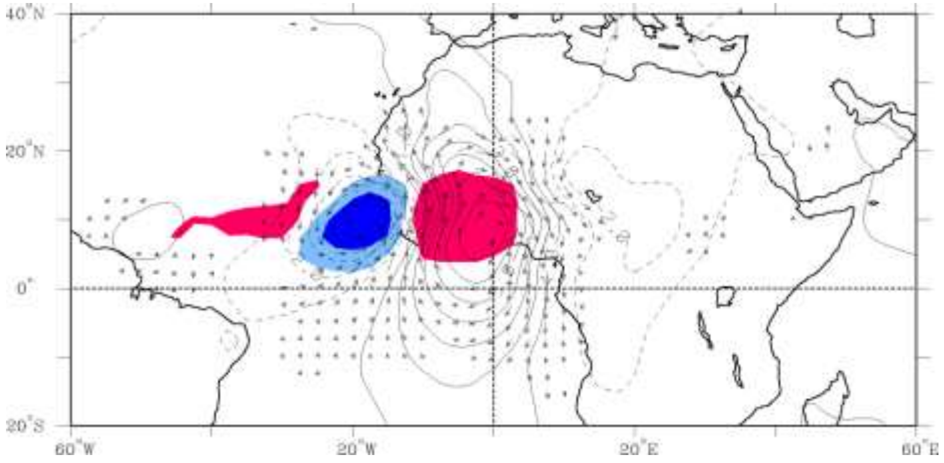
Brightness (T_b) regressed on various equatorial wave mode winds at 850 hPa:
Arrows schematically show the winds of the various waves to be regressed. Brightness temperatures eastward/westward filtered as appropriate for wave. Dashed (solid) contours denote negative (positive) $T_{b.}$-
Reproduced form Yang et al. (2007)

Influence of tropical waves on Africa

- Two other major wave types have been observed in the tropical belt that are not obtained from the shallow-water equations:
  - Madden Julian Oscillation (MJO)
  - Tropical Disturbances (TDs)
- TDs are observed in the entire tropics but over northern tropical Africa these can be thought of as African Easterly Waves (AEWs) and modulate precipitation on 2-6 day timescales.

- AEWs are the dominant weather maker in West Africa - about one third of total variance in deep convection can be explained by AEWs.
- Produce significant rainfall for the region – more than 60% of squall lines in W. Africa are associated with AEWs.
- Modulate hurricane activity over the Atlantic basin

Regression against TD-filtered OLR at 10°N, 10°W



Shadings: OLR (shadings)

Contours: 850 hPa flow

Vectors: 850-hPa wind

+/- 6 W s^{-2}; 10^5 m^2 s^{-1}; m s^{-1}

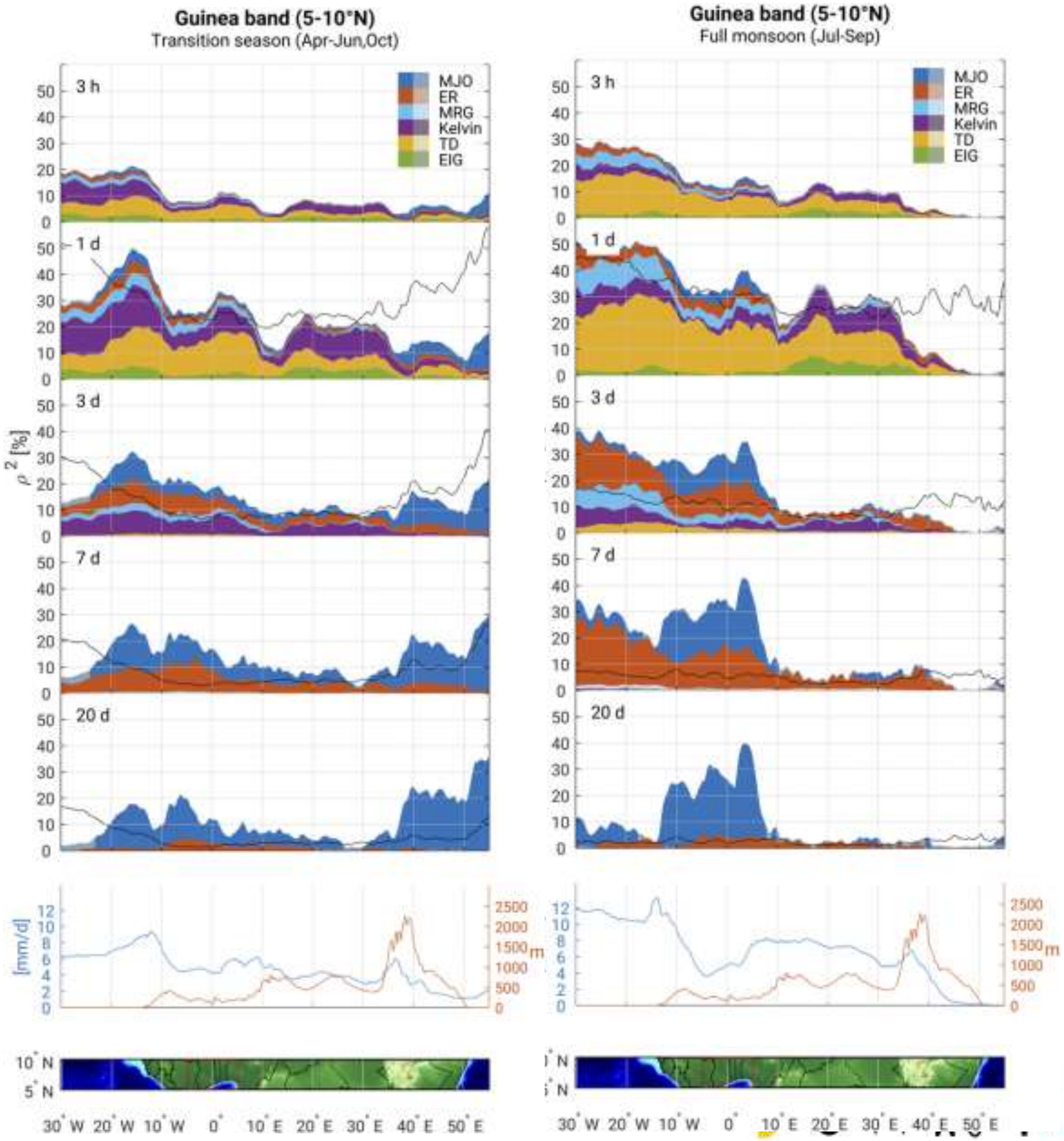
Kiladis et al. (2006)

Influence of tropical waves on African rainfall

How much variance in African precipitation is explained by these waves?

- On short timescales (3hrly – daily) Kelvin waves and African easterly waves (AEWs; TD in figure) dominate explaining 10-30% of local rainfall variance

- On longer timescales (7-20 days) only the MJO and Equatorial Rossby waves modualte variability in rainfall explaining up to 40%.



Relative importance of tropical wave signals for TRMM precip over Guinean band (5N-10N) during Transition season (Apr-Jun,Oct; left) Monsoon season (Jul-Sep; right). Sum of all lines = max variance explained by all wave types. Significant correlations indicated by saturated colours. Black line: variance of precip at that timescale as percentage of total variance in raw (3h) data. Bottom panel: ban- averaged daily precip and surface height (Schleuter et al 2019).

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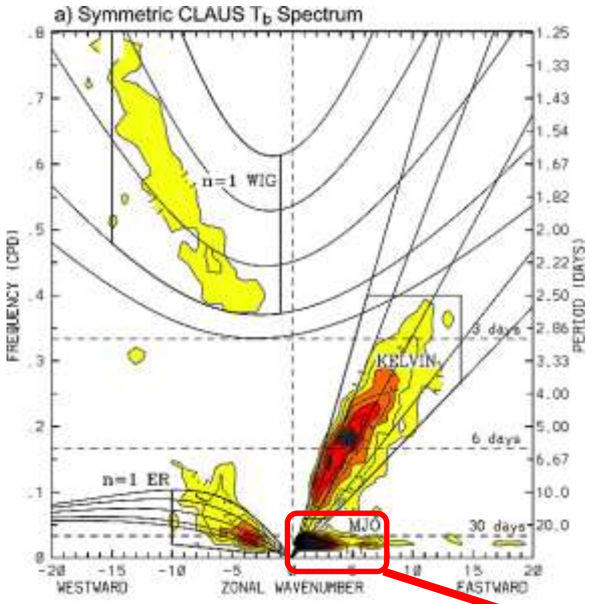
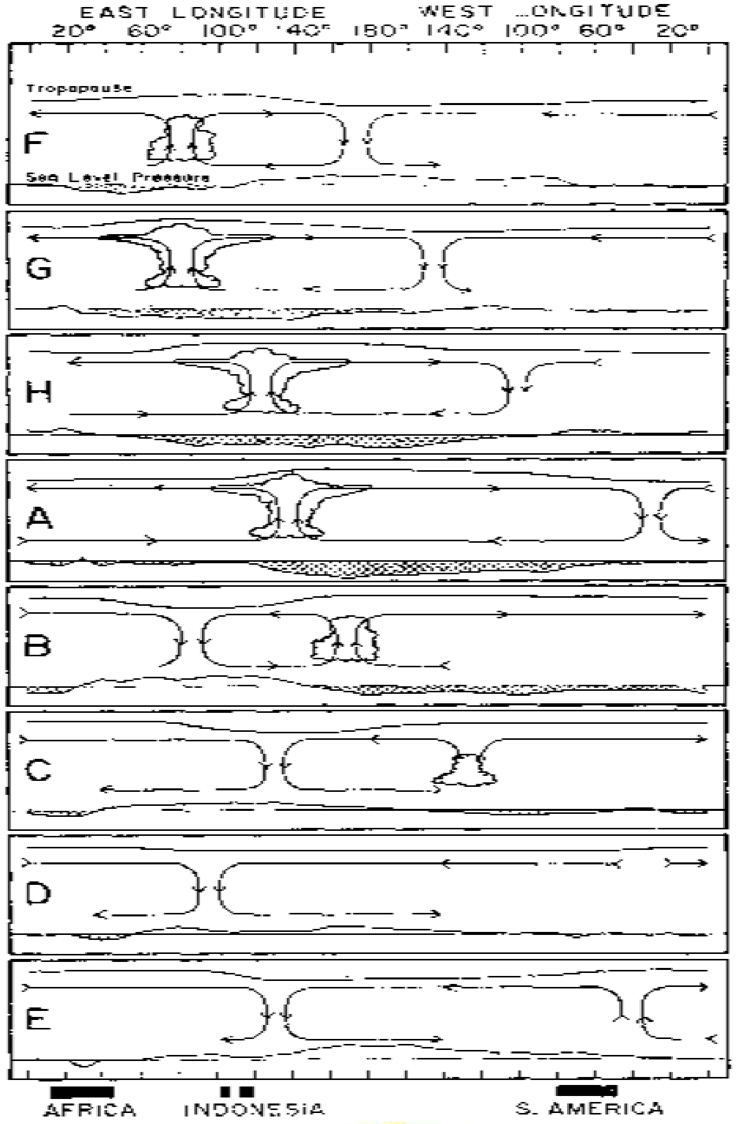
The Madden Julian Oscillation



- Madden-Julian Oscillation first identified by Madden & Julian (1971,1972) by spectral analysis of upper level winds
- They described it as "*an eastward movement of large-scale circulation cells oriented in the equatorial (zonal) plane*'".
- From analysis of the divergent winds Madden and Julian were able to hypothesise the convective signal associated with the MJO.

- Its characterised by planetary scale structure (zonal wavenumbers 1-3) and a period of 30-60 days (although you will see anything from 20-100 days quoted).
- Main convective envelope (*active phase)* propagates slowly eastward (~5m/s), with large regions of suppressed convection ahead and behind *(suppressed phase).*



Schematic description of the variations (zonal and time) associated with the 40-50day oscillation. Reproduced from Madden and Julian (1972)

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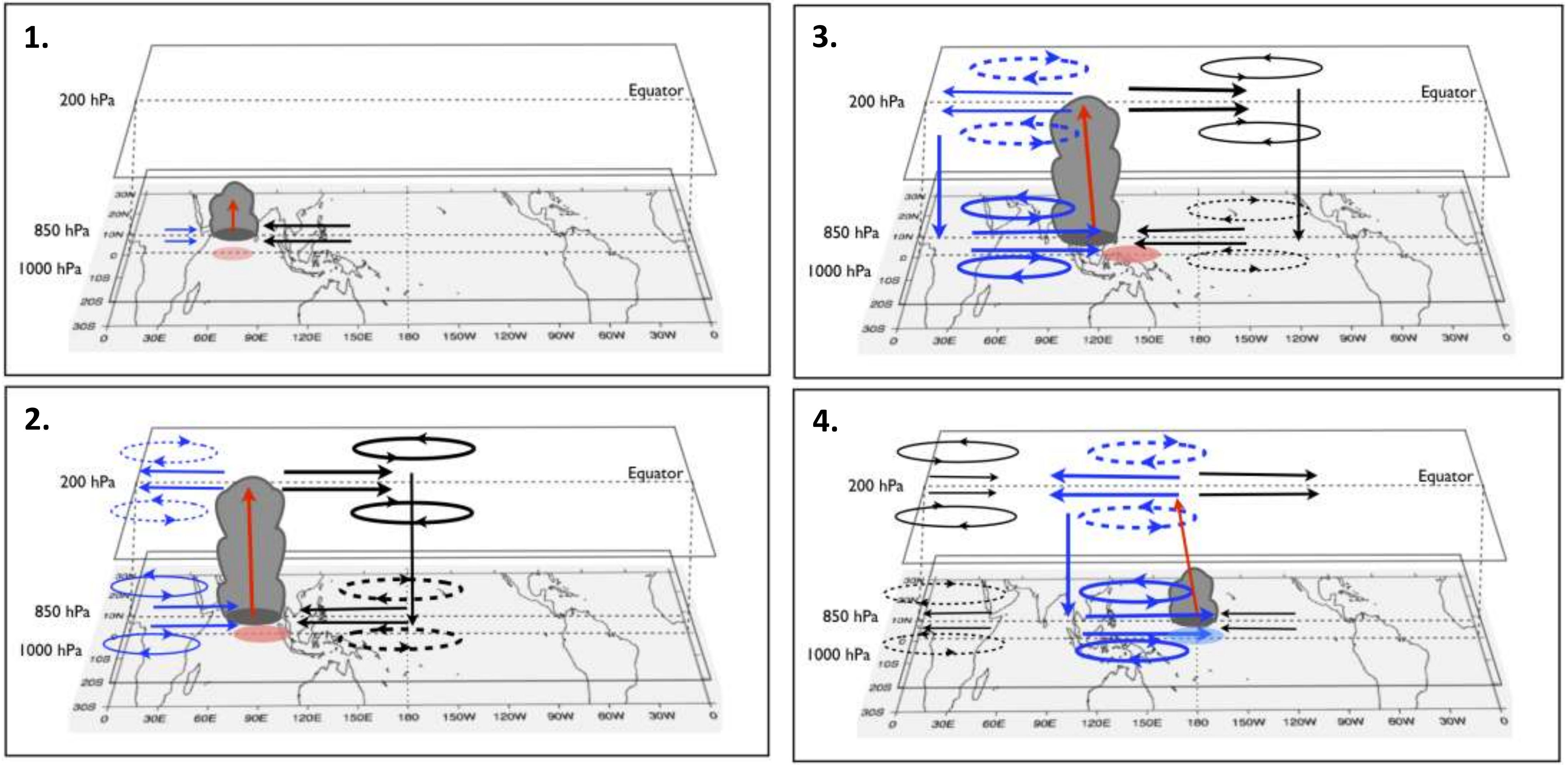
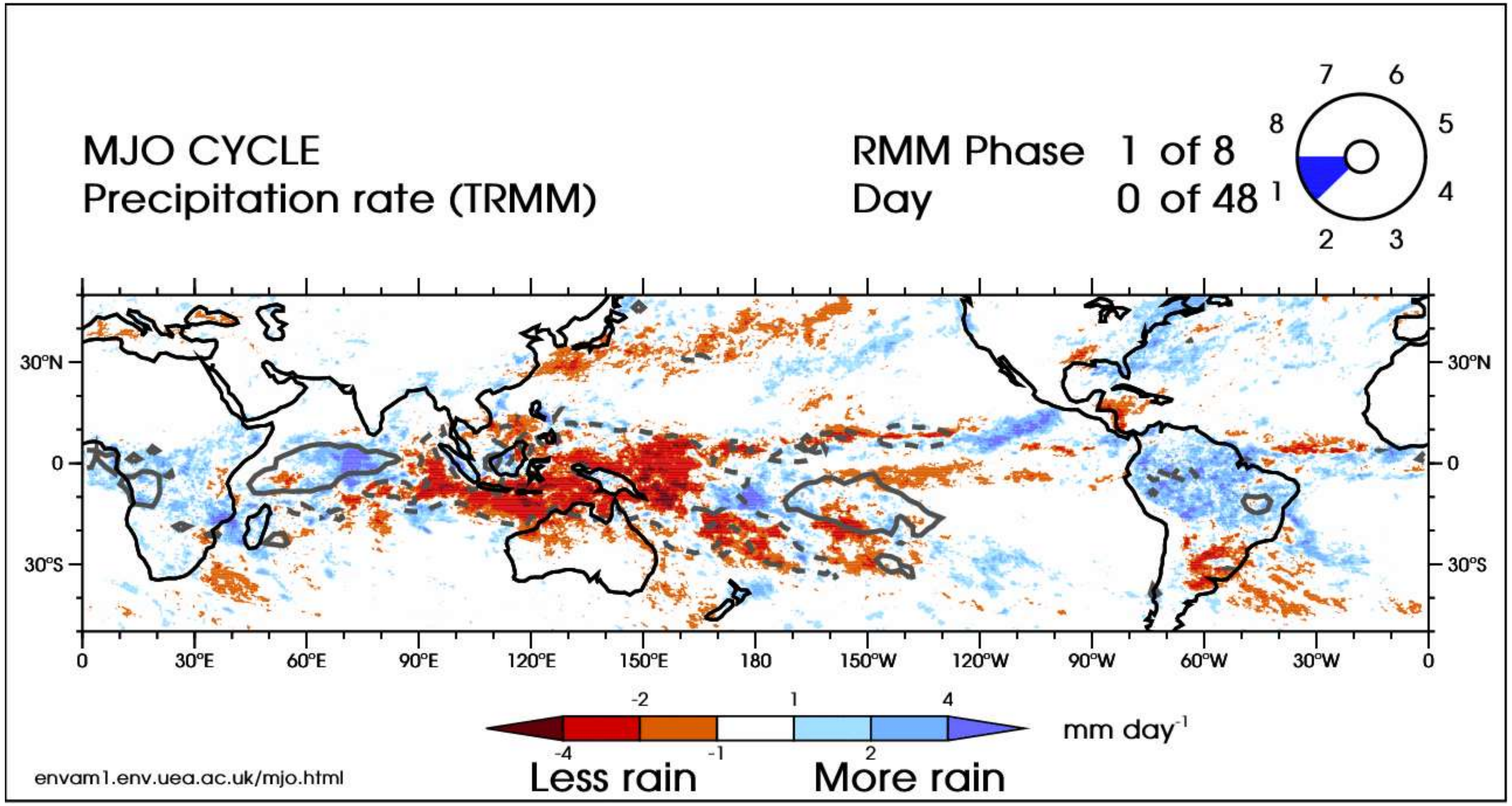
The Madden Julian Oscillation

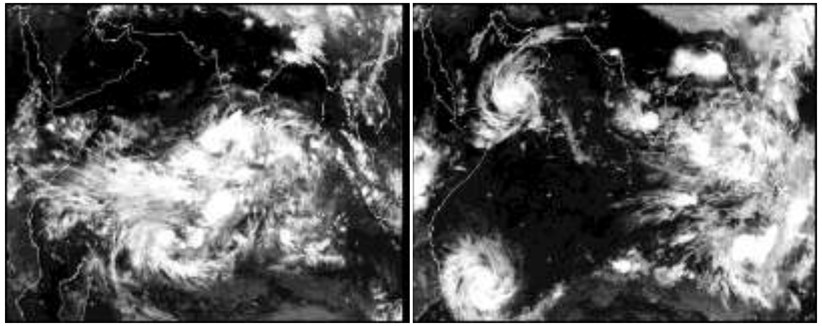


1-4. Schematic representation of the MJO. Reproduced from Hirons (2012).

MJO – Composite Behaviour

- Animation shows an "average MJO" cycle in terms of rainfall from TRMM (shading) and CMAP (contours) associated with MJO events from Nov-Apr.





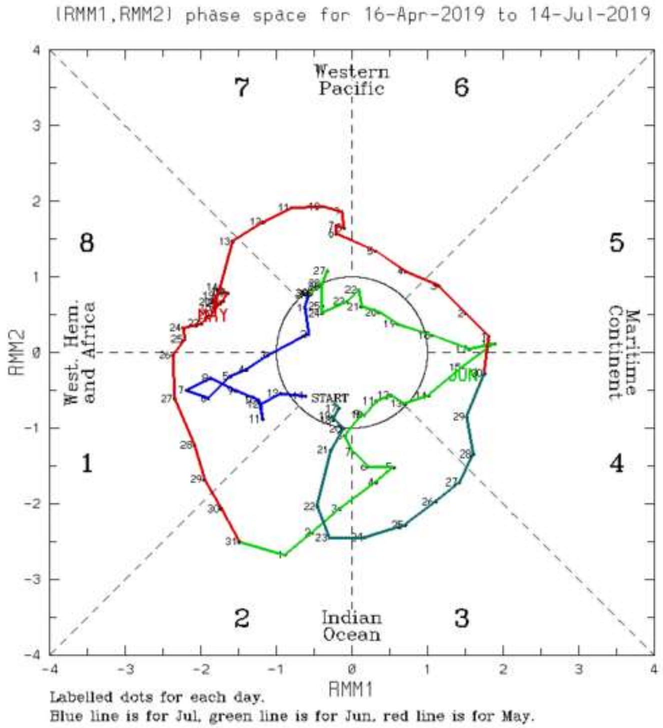
(a) May 2nd 2002 (b) May 9th 2002

Figure 2.6 *EUMETSAT Infrared (IR) images of the multiscale organisation of tropical convection associated with an MJO over (a) the Indian Ocean on 2nd May 2002 and (b) the Maritime Continent on 9th May 2002 with twin trailing tropical cyclones.*

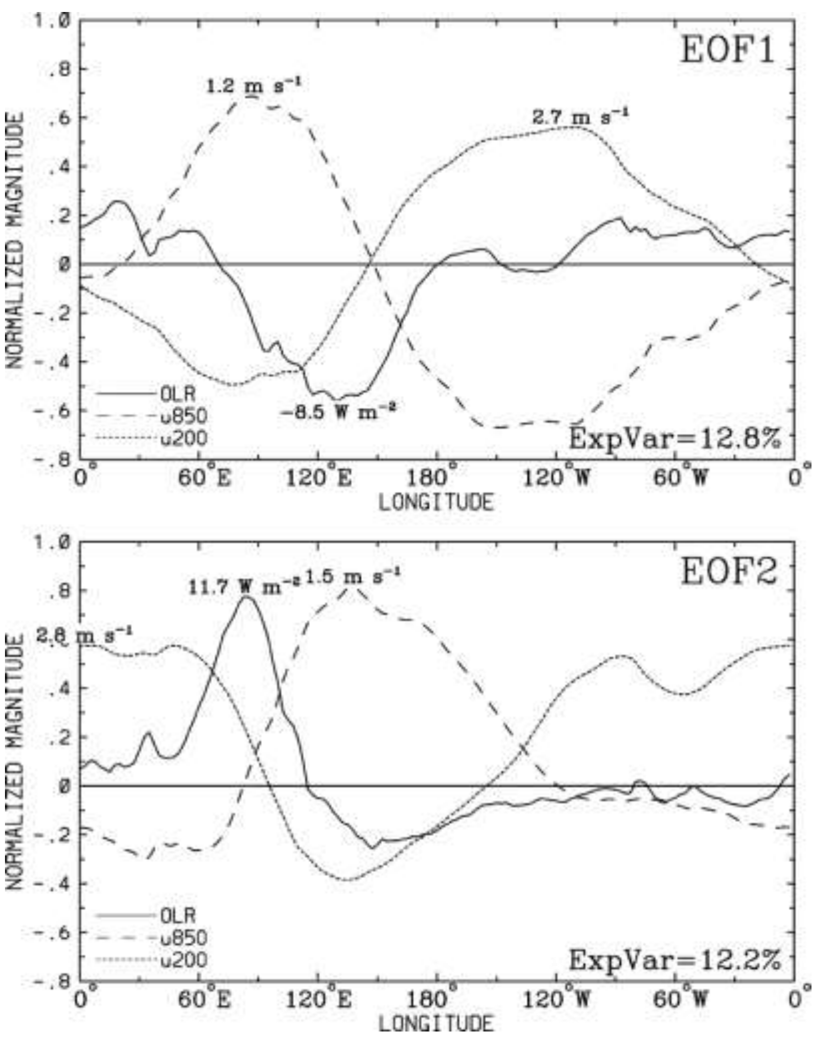
Animation from Adrian Matthews at http://envam1.env.uea.ac.uk/mjo.html

MJO – characterising the MJO

- Characterising the MJO requires a method for isolating the MJO signal in observations
- Early analysis of the MJO relied heavily on filtering in time (and sometimes space) the OLR signal to identify the MJO.
  - Time filtering doesn't allow for easy application in real time.
- Wheeler and Hendon (2004) developed a Real-time Multivariate MJO (RMM) Index, based on a combined EOF of zonal wind at upper and lower levels and OLR to identify the MJO without the need for time filtering
- The RMM Index is widely used, especially in operational forecasting, to describe the observed and forecast MJO



MJO – RMM index



Spatial structures of EOFs 1 and 2 of the combined analysis of OLR and 850hPa and 200hPa zonal wind (u850, u200). Reproduced from Wheeler & Hendon (2004)

- Combined Empirical Orthogonal Functions (EOFs) of 15°N-15°S averaged 200hPa and 850hPa zonal wind and OLR
    - Anomalies from smooth seasonal cycle
    - Average of previous 120 days removed to remove interannual variability (particular ENSO which projects strongly onto the MJO EOFs)
- EOF1 describes active or supressed convection over the Maritime Continent
- EOF2 describes dipole of active/supressed convection over the Indian Ocean and West Pacific
- Baroclinic Structure of the Winds is clearly evident in near quadrature with the convective signal
- RMM indices calculated by projecting daily anomalies onto EOFs

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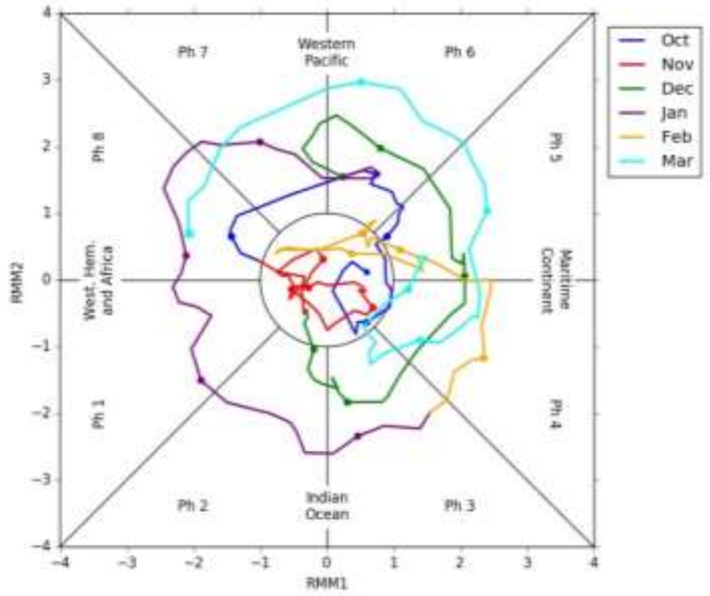
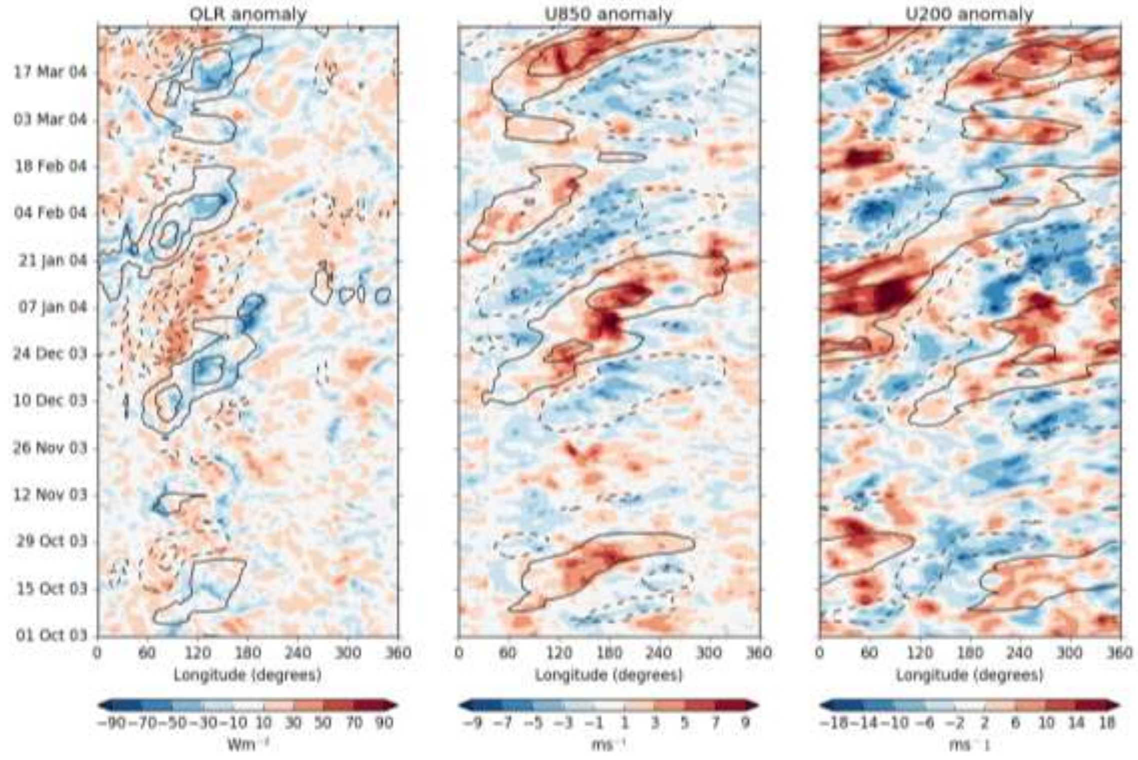
MJO – Example Season 2003-2004





- Plotting RMM Indices as x-y coordinates produces MJO Phase diagram with the MJO progressing anti-clockwise around the diagram, areas inside the unit circle are weak MJO activity
- RMM phase diagram typically divided into 8 phases which describe the location of active convection
- Hovmöller diagrams of 15°N-15°S averaged OLR and winds show eastward moving convective signals associated with the MJO
- "MJO anomalies" can be reconstructed by multiplying the RMM indices by the un-normalized EOFs (the contours in the hovmöller diagram)

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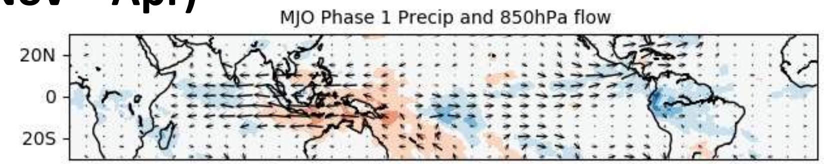
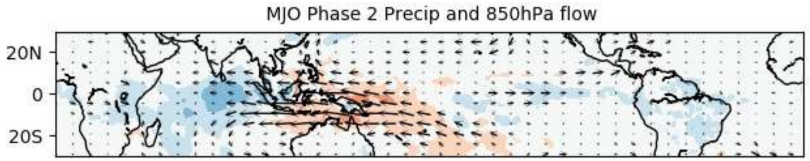
MJO – Seasonality

(Nov – Apr)





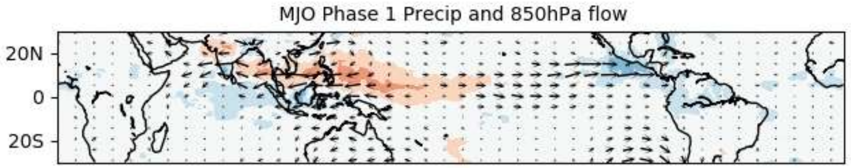
Boreal Winter (Nov – Apr)

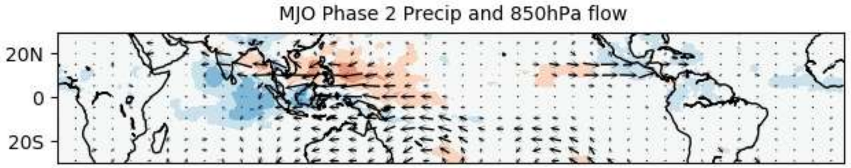
- MJO Variability is strongest during Boreal Winter (Nov – Apr).
- During Boreal Winter the MJO convection tends peak south of the equator
- Propagation is mainly eastward

Boreal Summer (Jun – Sep)

- In Boreal Summer (Jun – Sep) the MJO circulation interacts with the Asian Summer Monsoon and there is both a Northward and Eastward Propagation.
- Boreal Summer MJO is closely linked with active-break cycles of the Asian Summer Monsoon; Wang and Rui (1990) found about 50% of northward moving active break cycles were associated with MJO events.
- The close connection between the Active/Break Cycles and the MJO has led to a number of studies which consider the summer manifestation of the MJO to be a separate mode of variability usually known as the Boreal Summer Intraseasonal Oscillation (BSISO).

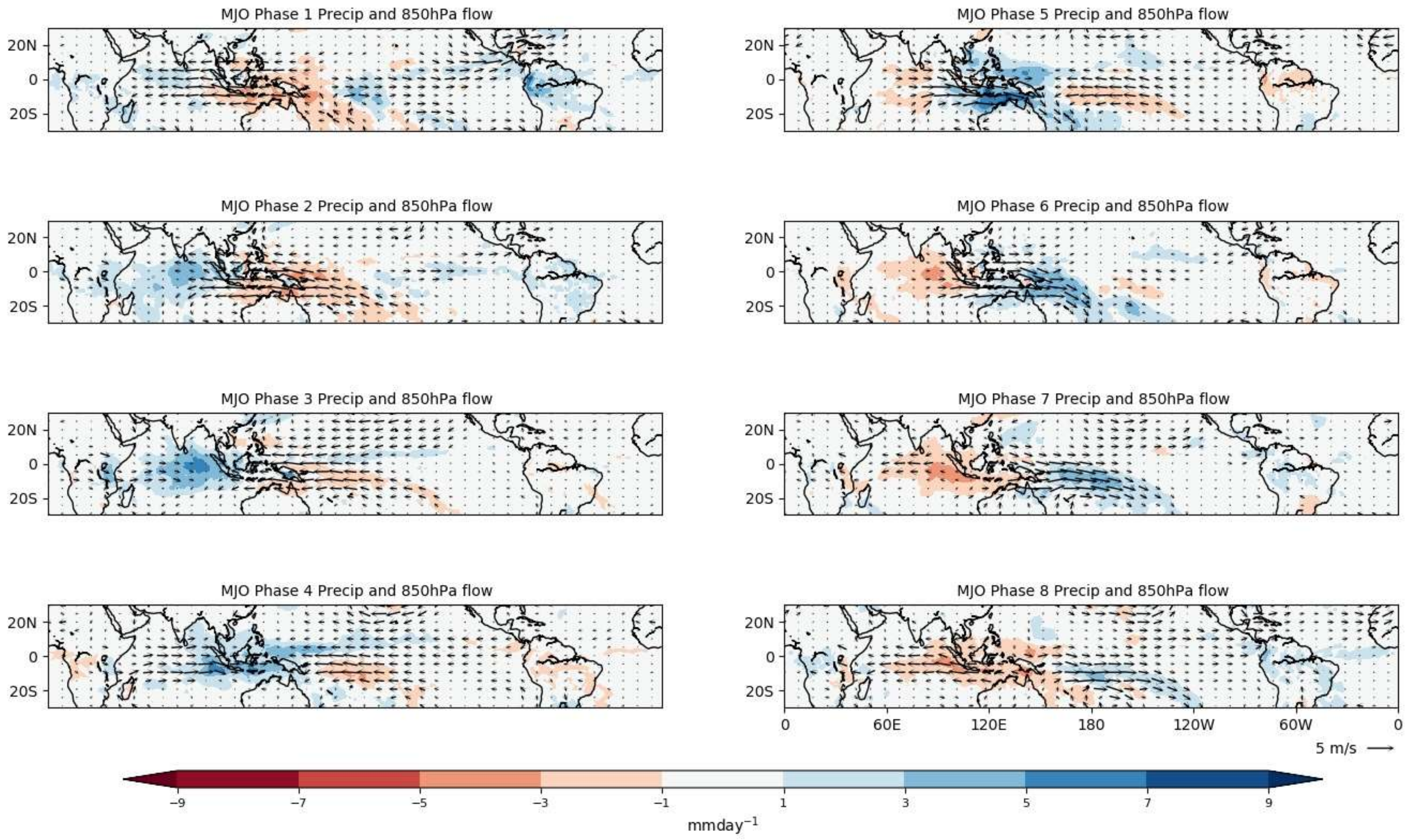
(Jun-Sep)





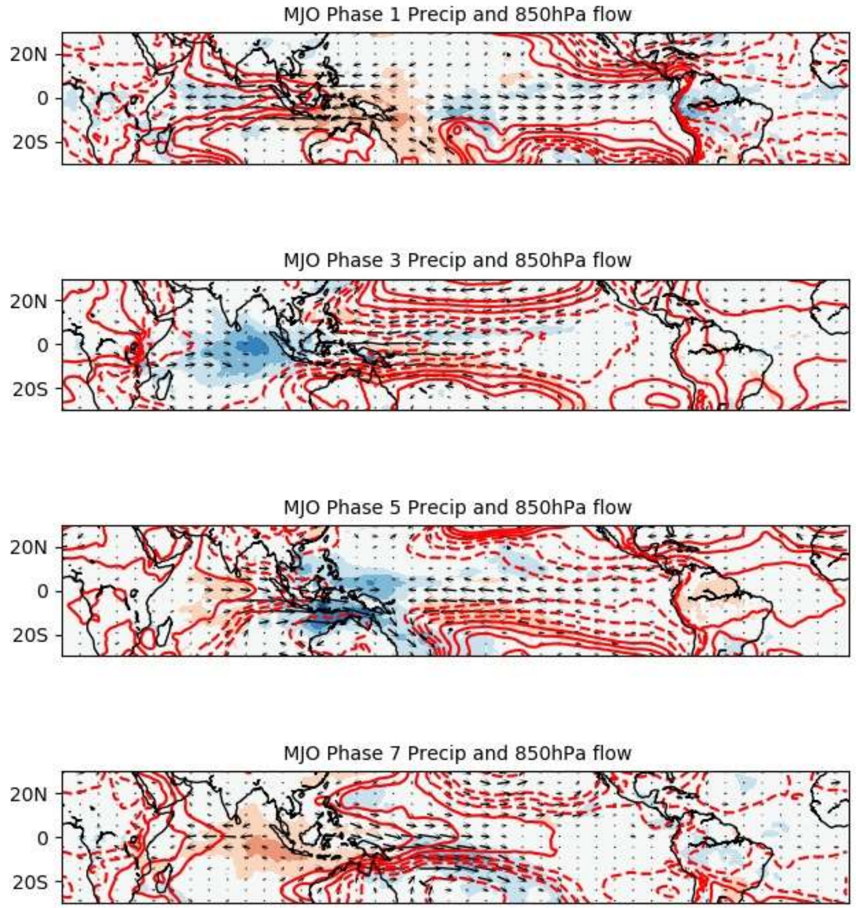
MJO – Composite behaviour (Nov-Apr)

Averaging over days in a particular MJO phase produces a composite or average picture of the MJO in that phase although there is considerable inter-event variation.



Precip (shading), 850hPa flow (vectors)

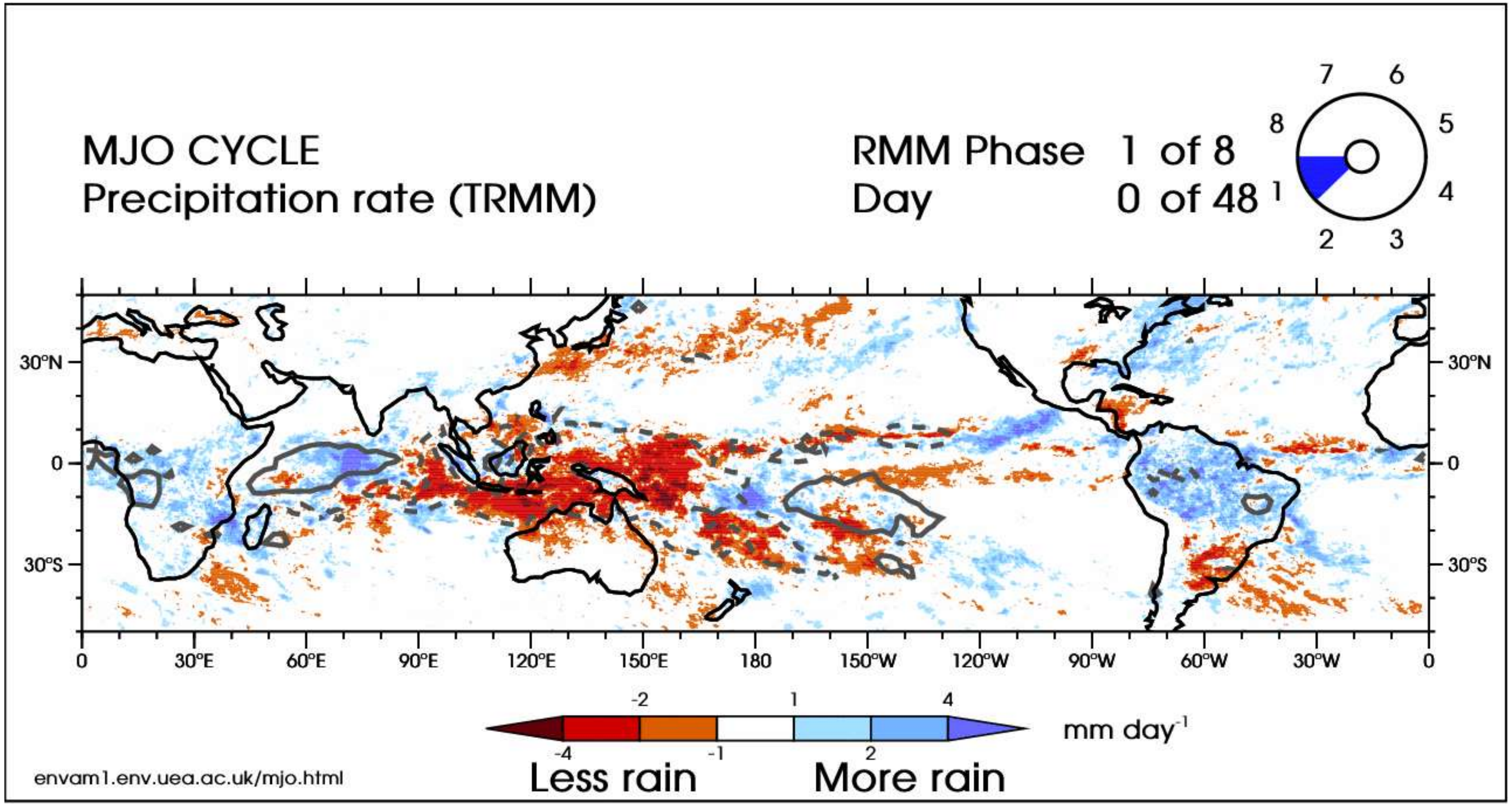
MJO – Composite Behaviour (Nov-Apr)



- Low level easterlies to the east of the enhanced convection and westerly to the west of the convection
- Tongue of low 850hPa geopotential (and surface pressure) which extends east of the enhanced convection reminiscent of the Gill (1980) response to tropical heating
- Low-level Rossby gyres to the west of the convection
- Although reminiscent of the Gill response extent of easterly anomalies is smaller, but stronger
- At upper levels the flow is reversed and the geopotential has a quadrupole response with a pair of anticyclones to the west and cyclones to the east
- Vertical structure has a westward tilt in humidty, vertical velocity and diabatic heating
- Gradual moistening and deepening of convection as the MJO transitions from suppressed to active convection
- Some longitudinal variations in detail of structure

Contours show geopotential anomalies ± 10,30,50,150,

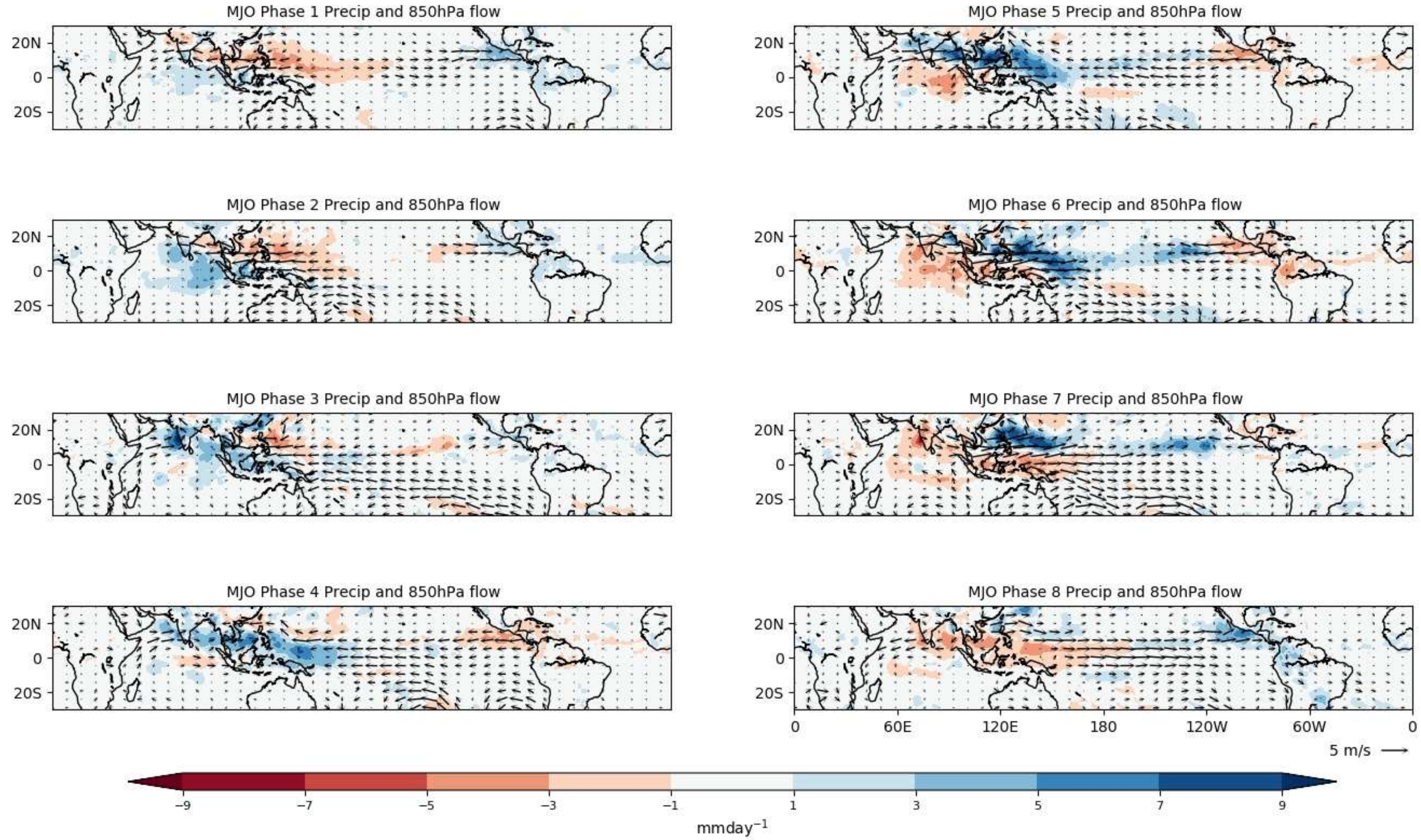
MJO – Composite Behaviour (Nov-Apr)



By linearly interpolating between these 8 phase composites we can construct an idealized MJO cycle (here with a period of 48 days, 6 days between each phase)

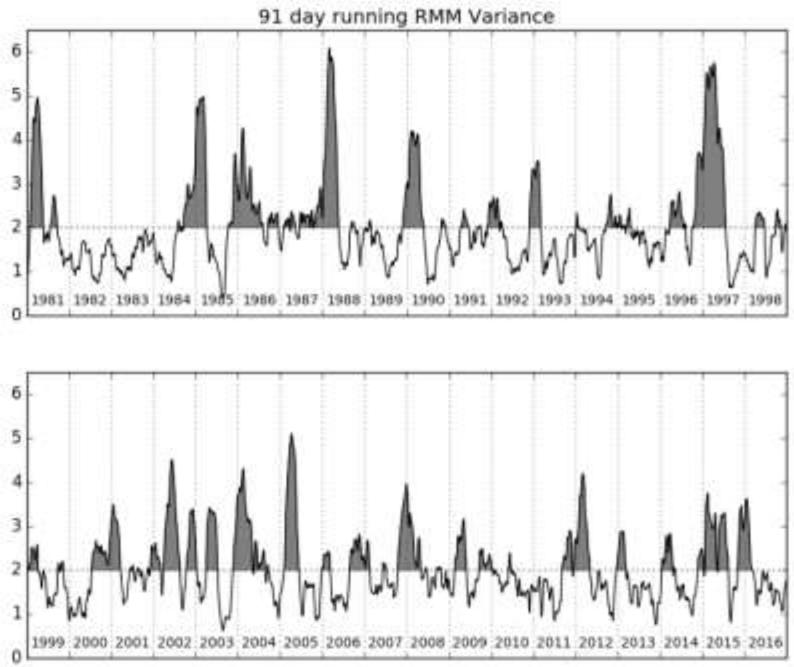
- Can nicely see that MJO convection over Islands of Maritime Continent peaks ~1 phase ahead of the convection around surrounding islands (e.g. Peatman et al., 2014)

MJO – Composite Behaviour (Jun-Sep)



- MJO variability is weaker in Boreal Summer
- In Boreal Summer the MJO circulation interacts with the Asian Summer Monsoon and in contrast to Boreal Winter there is both a Northward and Eastward Propagation

MJO – Interannual Variability



Running 91-day RMM variance ($RMM_1^2 + RMM_2^2$) showing the interannual modulation of MJO activity, after Wheeler & Hendon (2004)

- Considerable Interannual Variability in MJO activity
- No evidence of strength of MJO activity being related to ENSO overall
- Some evidence that MJO activity is enhanced in Central Pacific El Niños and reduced in Eastern Pacific El Niños (e.g. Feng et al, 2015; but note small sample size)
- MJO events do remain convectively active further into central Pacific during El Niño years (and conversely in La Niña years)
- Recent evidence the MJO activity is enhanced during Easterly phases of the Quasi-Biennial Oscillation (e.g. Yoo & Son, 2016 although mechanisms still not clearly understood

MJO – Maintenance and Propagation

- Since it's discovery there have been a number of theories and mechanisms for MJO propagation (see Wang, 2012 for a review) but there is still no clear consensus.
- Two key components for a theory of the MJO
  - A model for **the large-scale dynamical response** to the anomalous heating, primarily the latent heat release in **convection** but also **radiative** and **surface fluxes.**
  - A model for how the anomalous heating evolves in response to the anomalous circulation
- **The dynamical model**
  - Theories for the large-scale dynamical structure of the MJO are commonly based on a linearized set of equations of motion for tropical dynamics with simplified vertical structure, with or without a representation of the boundary layer
  - Some elements of this dynamical model are critical for how the convection evolves (e.g. the frictional convergence mechanism of Wang and Rui, 1990a depends on the inclusion of a boundary layer)

Major differences between most theories is how the heating evolves in response to the anomalous circulation

MJO – Maintenance and Propagation

Moisture Convergence Induced Heating

- Heating is related directly to the moisture convergence in the wave
  - Moisture convergence is linked to the dynamical convergence through a specified moisture field
  - Precipitation is proportional to the moisture convergence via a precipitation efficiency but moisture field does not evolve with flow
  - Free Tropospheric wave convergence (e.g. Lau and Peng, 1987)
    - Can't easily reproduce spatial or temporal scale of the MJO
  - Wave and Frictionally induced boundary layer convergence (Wang and Rui 1990a)
    - Preferentially destabilizes the planetary scales of the MJO

Moisture Mode

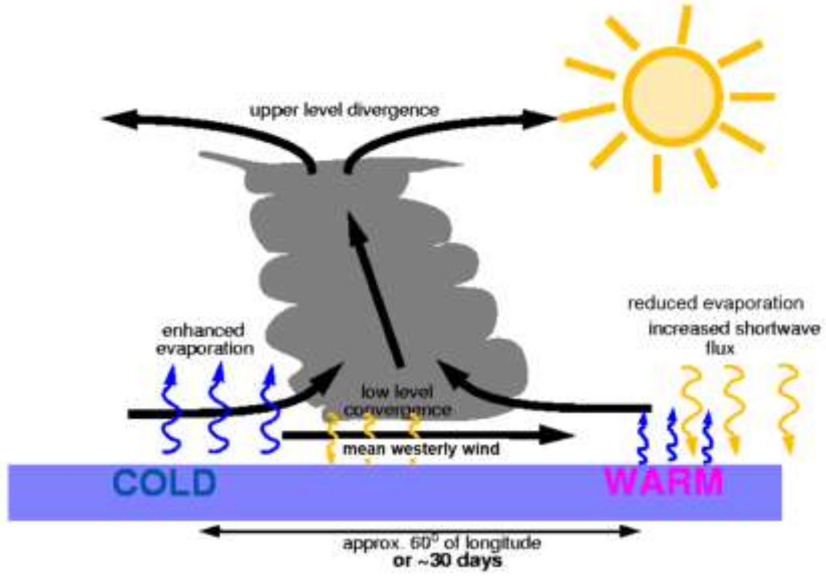
- Convection is related to the moisture (or moist static energy) variations (e.g. Adames and Kim 2016)
  - Precipitation is related to a measure of column humidity
  - Precipitation removes moisture but it is recharged by the **large-scale circulation** and **surface fluxes**
  - Jiang et al. (2017) find that advection of background moisture by the anomalous circulation is and important component of positive moisture tendency to the east of convection
  - Sobel et al. (2014) also find that the cloud radiative heating is has an important role in maintaining the MSE anomalies associated with the MJO and this can be interpreted as the radiative warming by the clouds driving ascent and moistening the column

MJO – Maintenance and Propagation

Air-sea interaction (see DeMott et al. 2015 for a review)

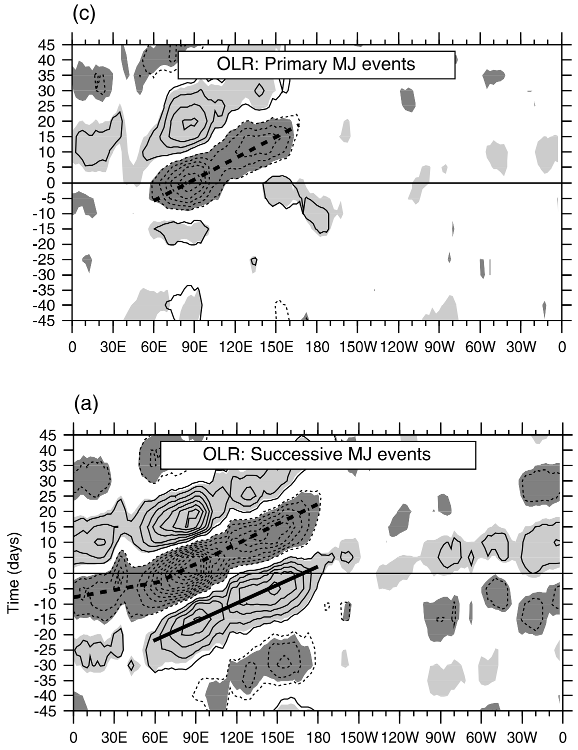
- Observations show modulation of SST by MJO
  - Reduced latent heat fluxes (due to reduced wind stress) and increased solar radiation warm ocean to east of active convection
    - Additional role of shoaling of mixed layer and increased diurnal cycle of SST

- Enhanced latent heat fluxes (due to enhanced wind stress) and reduced solar radiation cool ocean under and to west of convection
- Increased SST to east of convection "promotes" eastward propagation



MJO – Initiation

- Once underway the MJO can make several circuits of the globe
- However Matthews (2008) showed that about 40% of MJO events are “primary” i.e. not preceded by another MJO
- Indian Ocean slightly preferred for initiation of Primary MJO over other locations
- Several studies on MJO initiation with differing findings
  - A number of studies (e.g. Hsu et al,1990) found evidence of extra-tropical wave propagation into the tropics being important for MJO inititation
  - Matthews et al. (2008) found no such evidence of wave propagation for primary events in the Indian Ocean but that some but not all were preceded by an area of supressed convection which develops in situ
  - Straub (2013) found no supressed signal over the Indian Ocean but that although there was no convective signal the circulation was similar to that for successive events
- However there are significant differences in dates and locations of initiation depending on the choice of index and this makes diagnosing MJO precursors from observations difficult



MJO – Impacts

- The MJO is the dominant mode of intraseasonal variability in the tropical atmosphere, and hence is a major source of predictability for the tropical atmosphere on these timescales.
- As well as modulating precipitation directly the MJO is known to impact, e.g.
    - Tropical cyclogenesis
    - Monsoon onset
- Beyond the intraseasonal timescale the surface westerlies behind the active phase of the MJO are one of the main causes of westerly wind bursts associated with ENSO development
- The diabatic heating associated with the MJO acts as a source of Rossby waves which propagate globally and impact North and South America and the North Atlantic and Europe

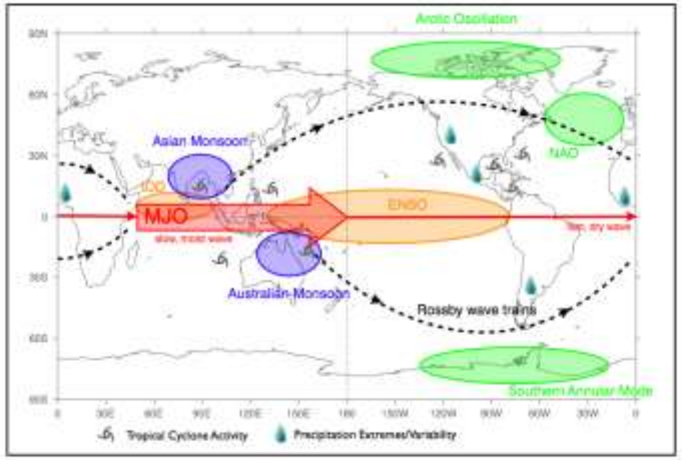
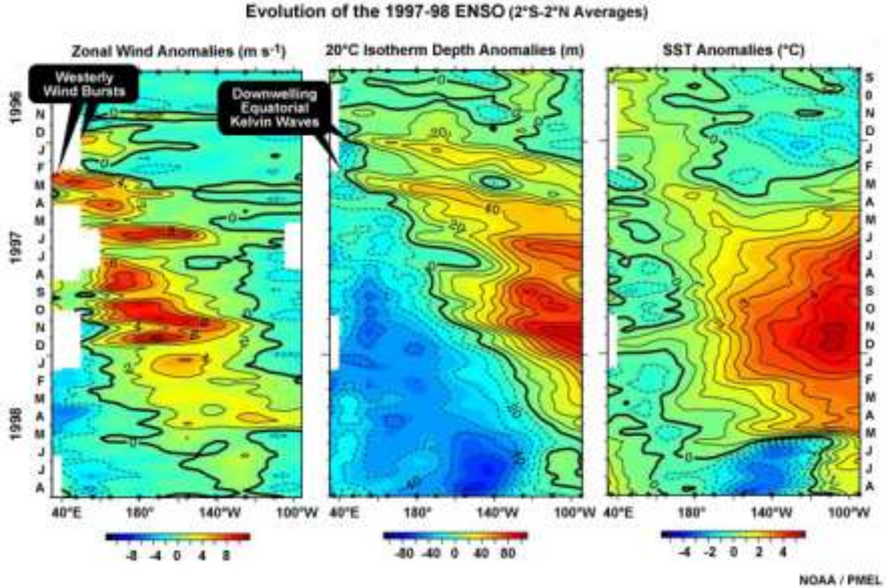


Figure 1.2 *Schematic representation of the global teleconnection patterns associated with the MJO. Adapted and extended from Lin et al. (2006).*

MJO global teleconnections (Hirons 2012)



MJO-ENSO interaction for 97/98 el Niño

MJO – African rainfall - Summary

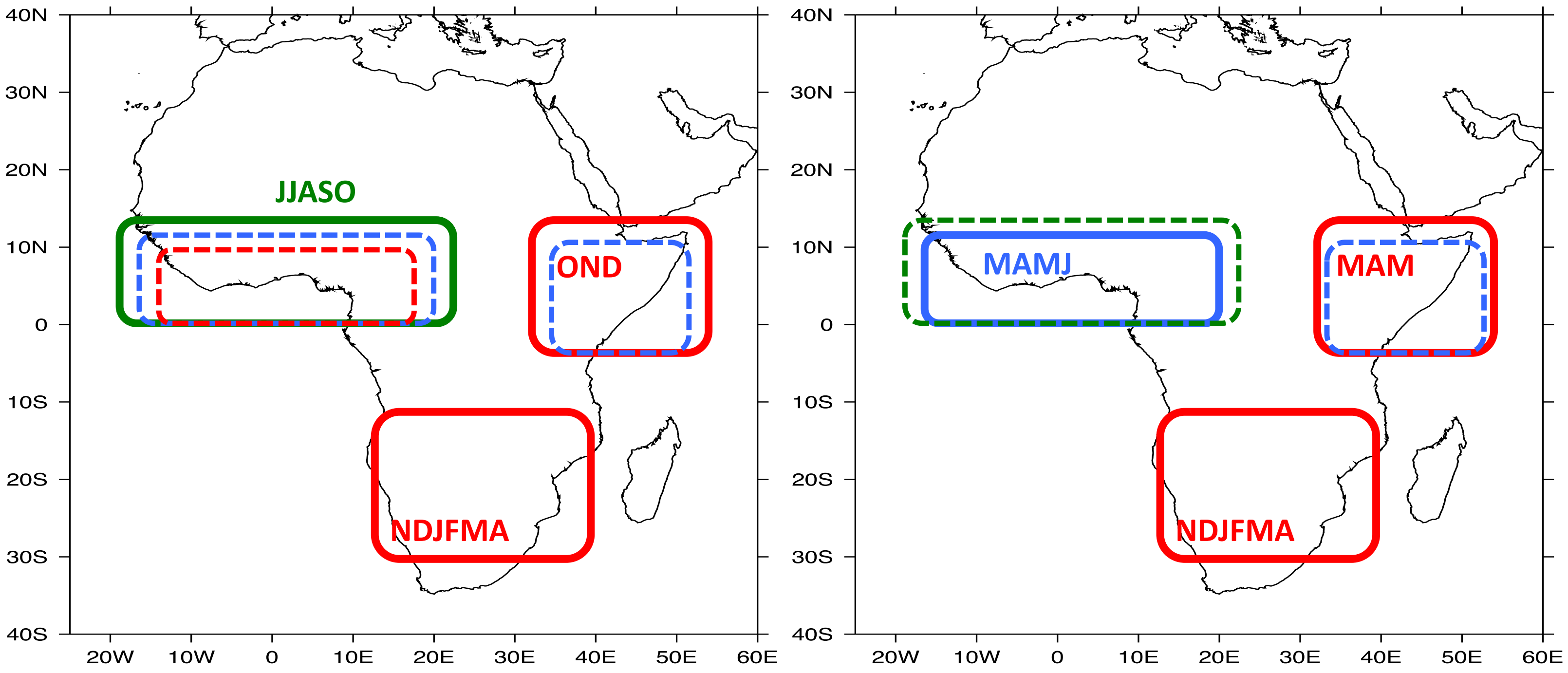
How does the MJO influence African rainfall?

(1) MJO convective core
(2) Indirect synoptic dynamics
(3) Kelvin and/or Rossby waves

- From a sub-seasonal to seasonal prediction perspective, the influence of the MJO is very important.

- For specific months, these associations have potential to be significant at up to four pentad lead time.

Summary of consensus from studies



Summary of the mechanisms of MJO influence that have been emphasized in studies of African precipitation, grouped by rainfall season and region. ***Solid line indicates the mechanism that has been identified most consistently across studies.*** *Dashed lines indicate other mechanisms at work. Note that mechanisms are not mutually exclusive. Months listed are approximate, as studies sometimes differ in their definitions of the rainy season. Adapted from Table in Zaitchik et al 2017.*

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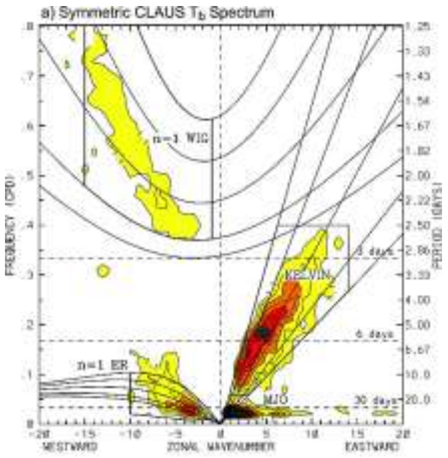
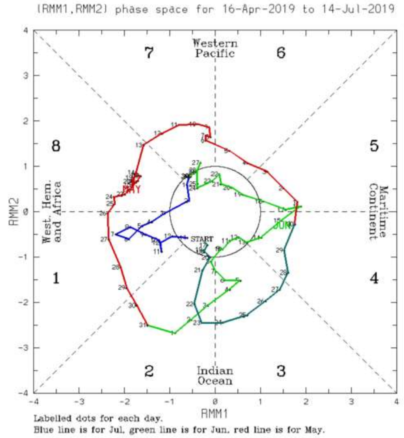
Summary

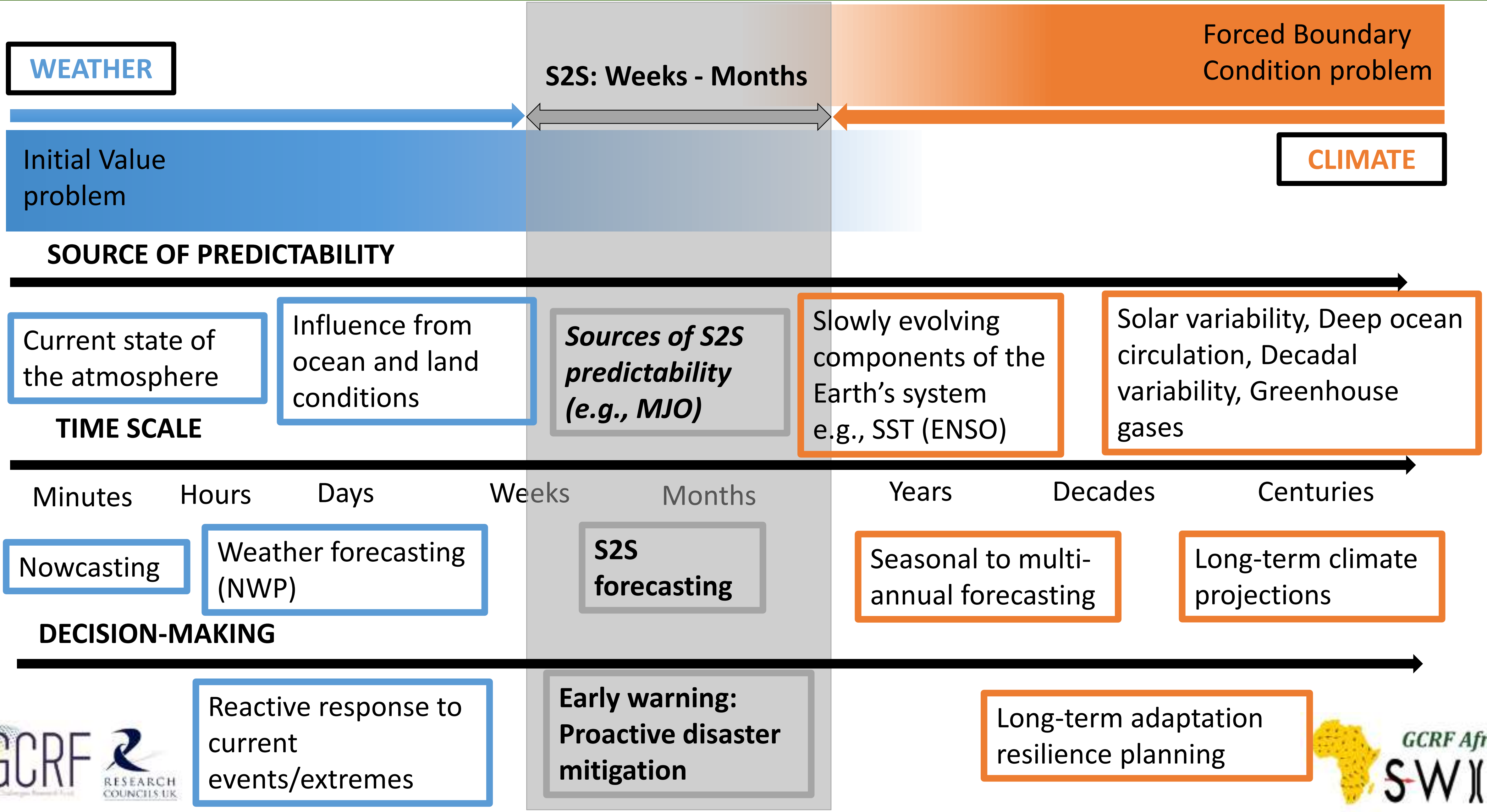
- Tropical Convection Organized on a range of spatial and temporal scales
  - Equatorially Trapped Wave Modes
    - Can be closely related to theory of shallow water equations
  - The Madden Julian Oscillation
    - Eastward moving convective envelope of convection with period of 30-60 days
    - Mechanisms not completely understood but depends on a complex interaction between convection and other diabatic process and the large-scale circulation

- Equatorial Waves and the MJO are important in modulating both the large-scale and local weather of the tropics including
  - Local precipitation
  - Monsoon Onset and active/break cycles
  - Tropical Cyclogenesis





Subseasonal to seasonal (S2S)



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The Madden Julian Oscillation

Final slide to acknowledge funder, see below

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