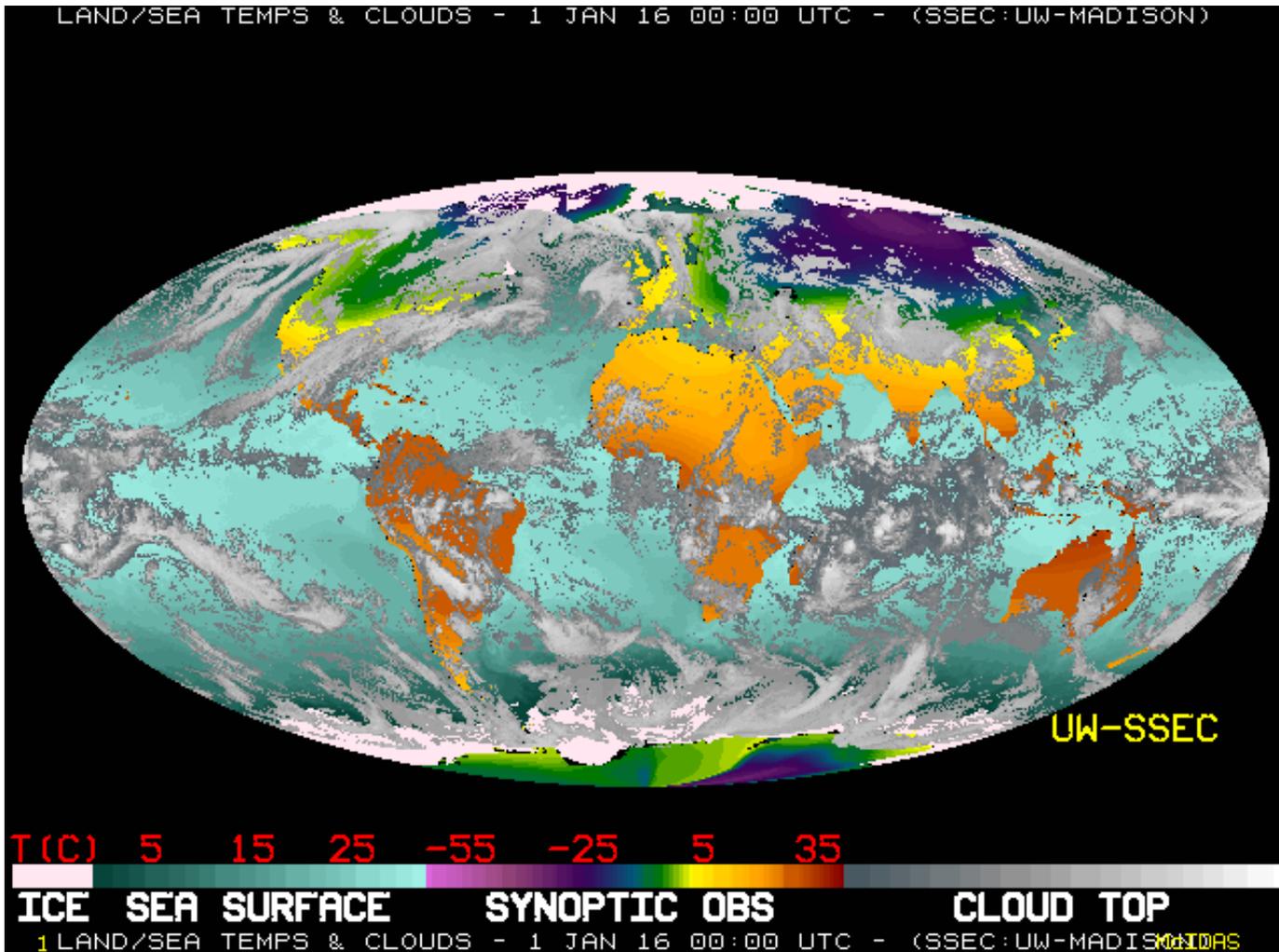


Tropical Variability

Steve Woolnough

National Centre for Atmospheric Science

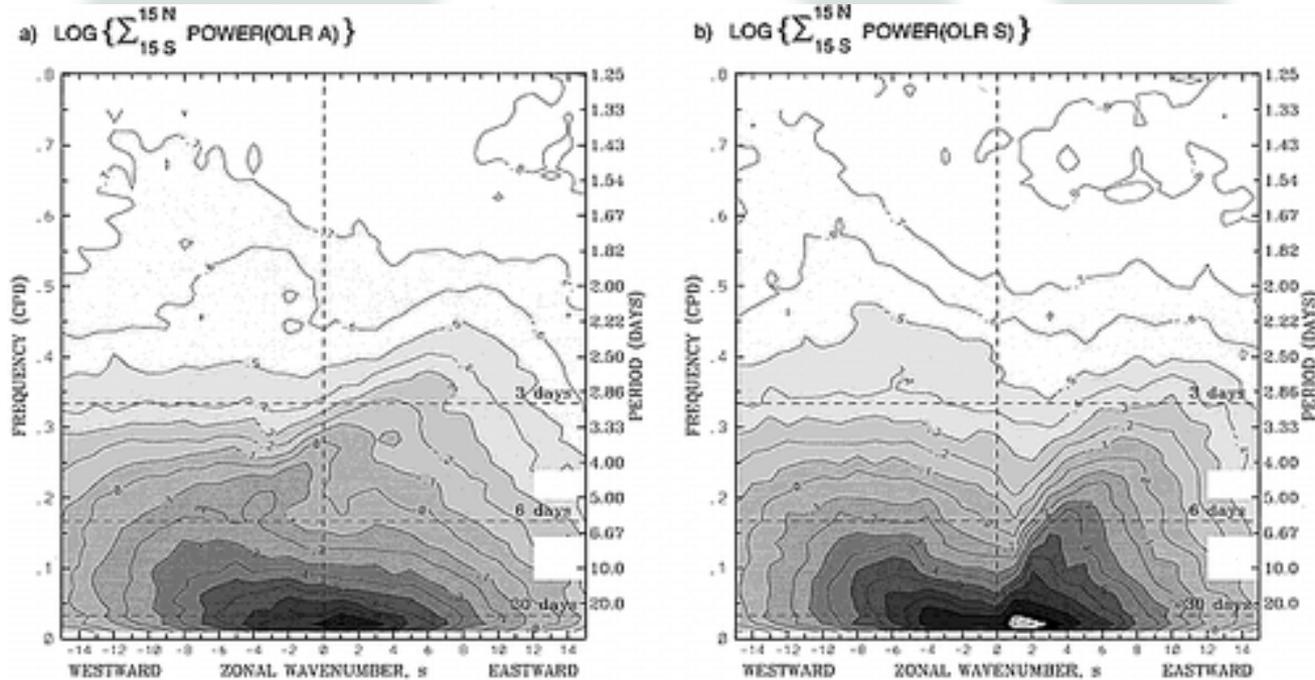
University of Reading



Images from University of Wisconsin-Madison Space Science and Engineering Centre
<http://www.ssec.wisc.edu/data/composites.html>

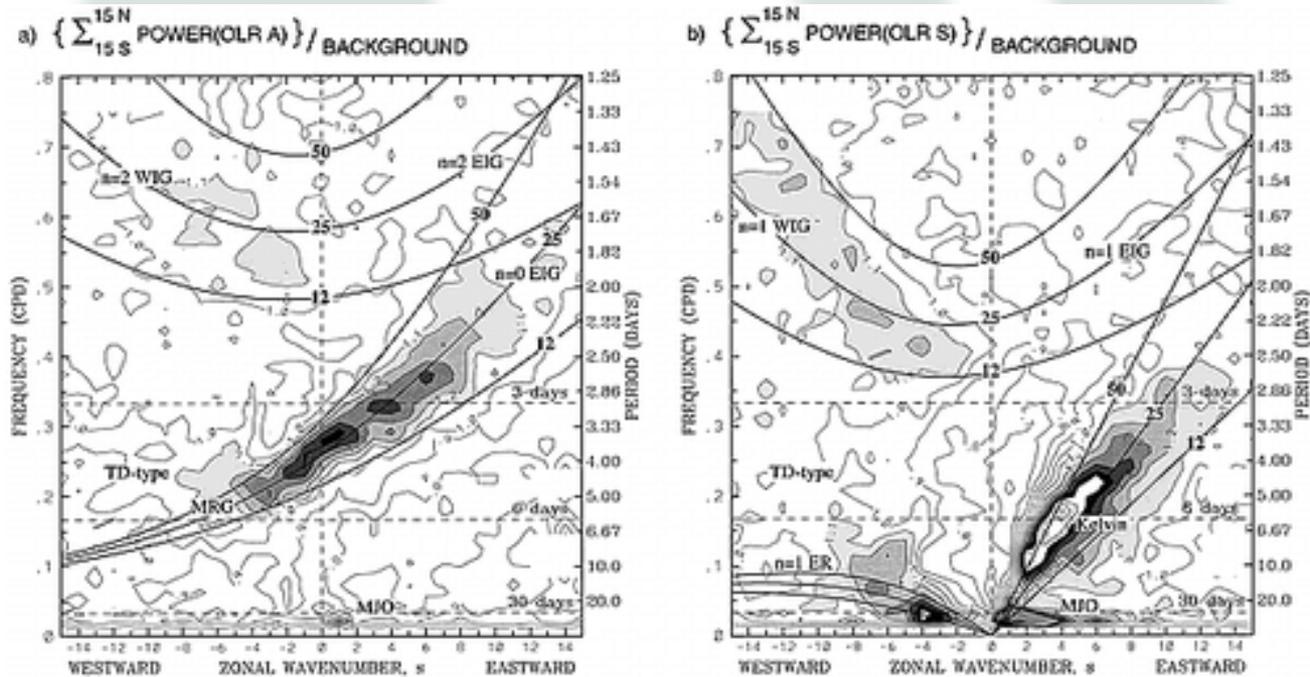
Power Spectra of Convective Variability

- Compute wave number frequency power spectra for OLR (e.g. Wheeler & Kiladis, *J. Atmos. Sci.* 1999)
- Broadly a red spectra, but with clear preferred regions in frequency wavenumber space



Power Spectra of Convective Variability

- Compute wave number frequency power spectra for OLR (e.g. Wheeler & Kiladis, *J. Atmos. Sci.* 1999)
- Broadly a red spectra, but with clear preferred regions in frequency wavenumber space
- Remove “smoothed” background spectra and plot ratio of full spectra to background spectra to identify “spectral” peaks



Wheeler & Kiladis
J. Atmos. Sci., 1999 Fig 3

Dry Equatorial Waves

For the dry, frictionless, adiabatic, primitive equations linearized about a resting basic state we can derive solutions for equatorially trapped waves that whose horizontal structures are governed by the shallow water equations on a β -plane

$$\frac{\partial u}{\partial t} - \beta y v = -\frac{\partial \phi}{\partial x}$$

$$\frac{\partial v}{\partial t} + \beta y u = -\frac{\partial \phi}{\partial y}$$

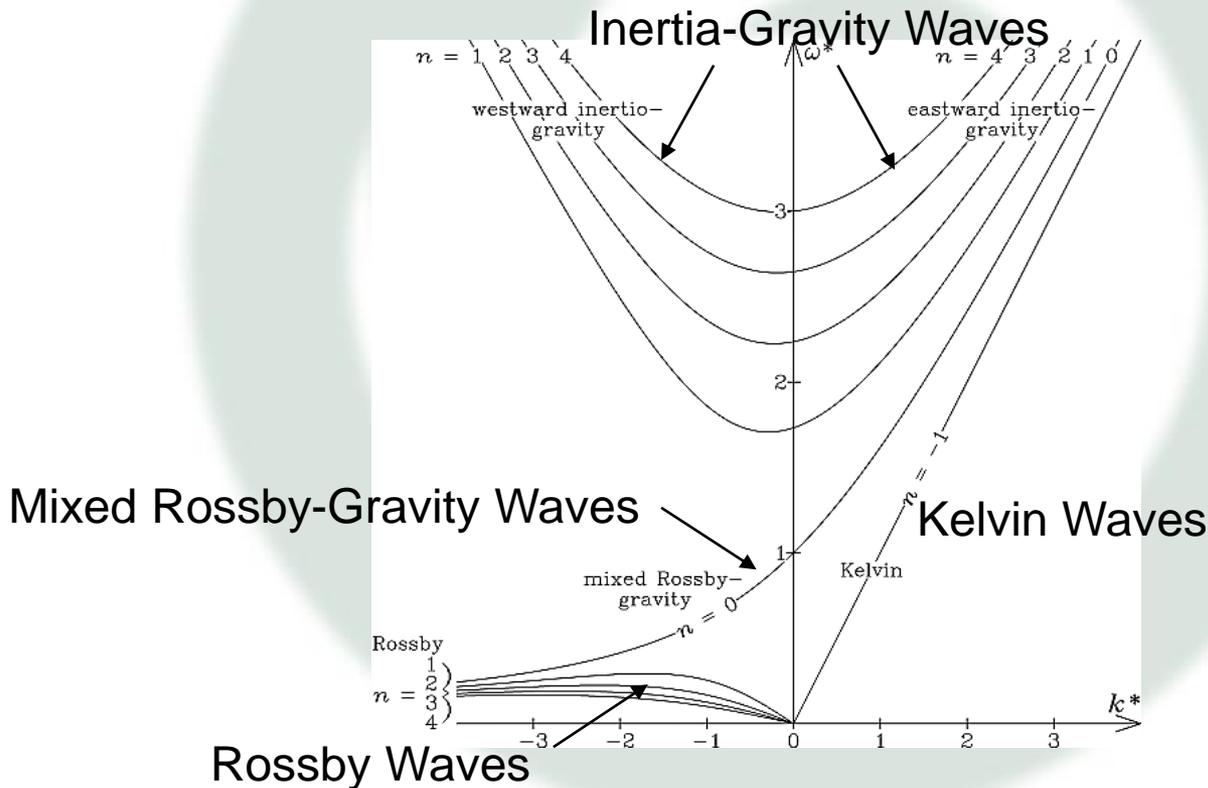
$$\frac{\partial \phi}{\partial t} + c^2 \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) = 0$$

Where, c , depends on the atmospheric static stability and the vertical wavenumber of the waves, such that c increases for deep waves or high static stability

Dry Equatorial Waves

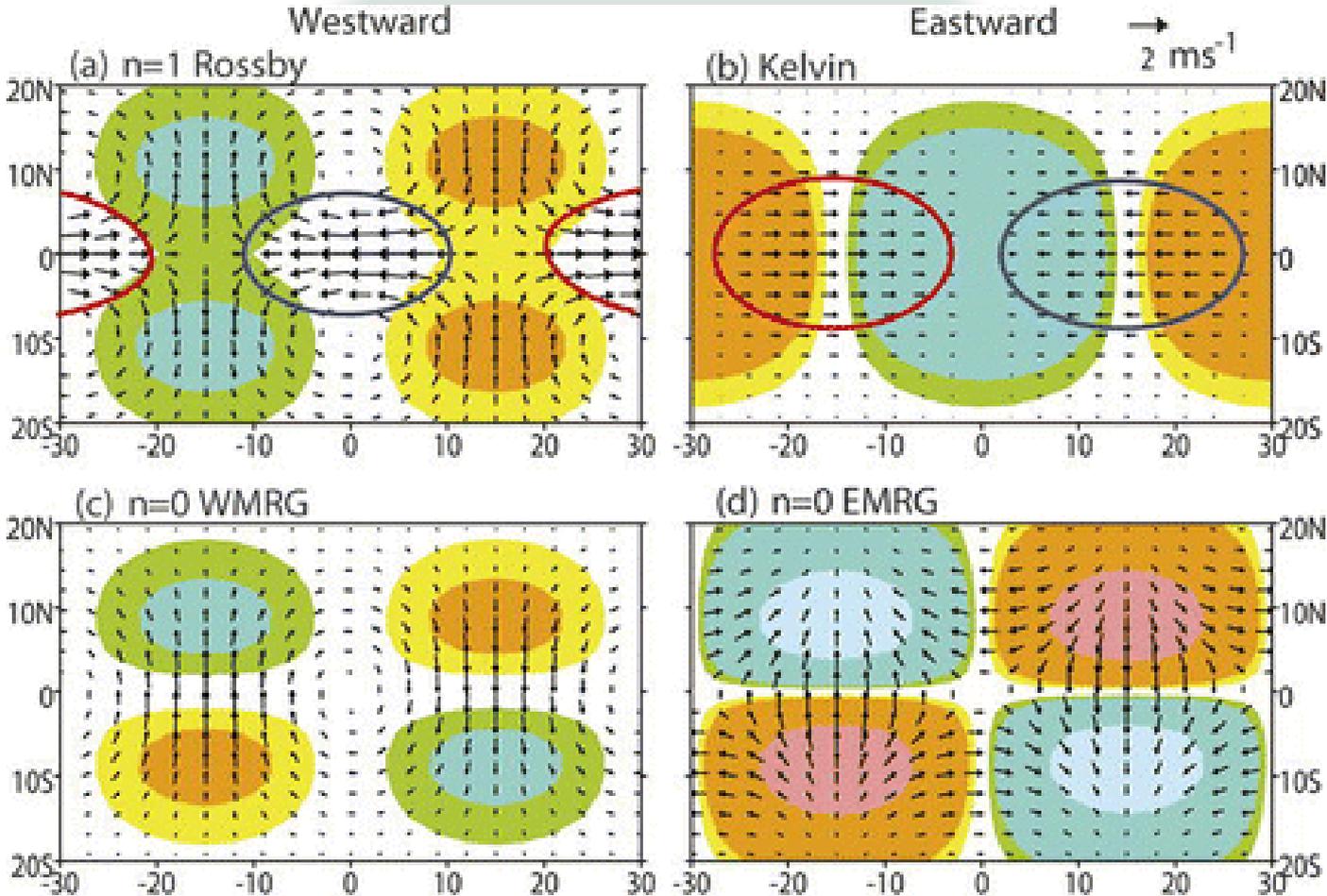
Equatorially trapped wave solutions to these equations satisfy the dispersion relation

$$\frac{c}{\beta} \left(\frac{\omega^2}{c^2} - k^2 - \frac{k}{\omega} \beta \right) = 2n + 1$$



Kiladis et al., Rev. of Geophys. 2009 Fig 2

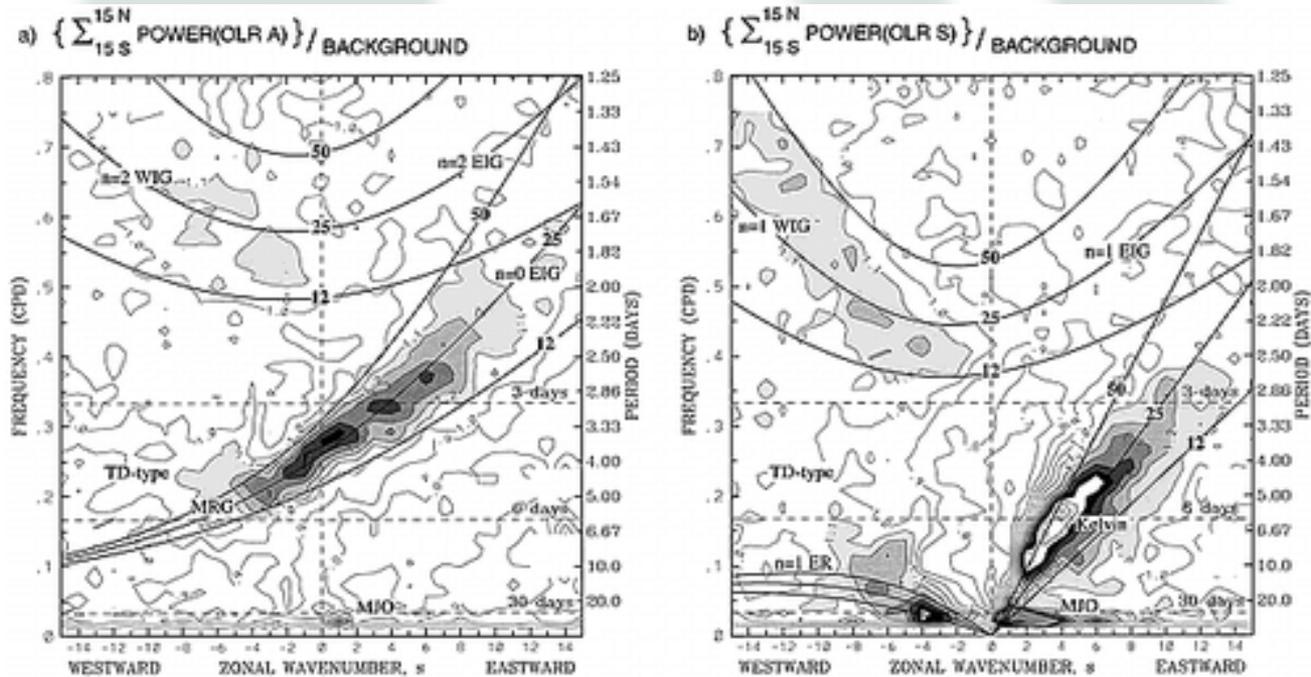
Horizontal Structures of Equatorial Waves



Yang et al. J.Atmos. Sci,
2007, Fig 1

Convectively Coupled Equatorial Waves

- Spectral peaks fall along dispersion curves for equatorial waves, but with speeds which are too slow for dry theory
- Convection is a strong source of heating in the wave, and modifies both the wave speed and structures



Wheeler & Kiladis
J.Atmos. Sci, 1999 Fig 3

Moist Equatorial Waves

Consider the thermodynamic equation,

$$\frac{\partial}{\partial t} \left(\frac{\partial \phi}{\partial z} \right) + wN^2 = Q$$

where N^2 is a measure of the dry static stability and Q is the diabatic heating

IF we make Q proportional to the vertical motion

$$Q = \alpha wN^2$$

The thermodynamic equation becomes

$$\frac{\partial}{\partial t} \left(\frac{\partial \phi}{\partial z} \right) + w(1 - \alpha)N^2 = 0$$

and we recover the dry system with reduced static stability and slower wave speeds

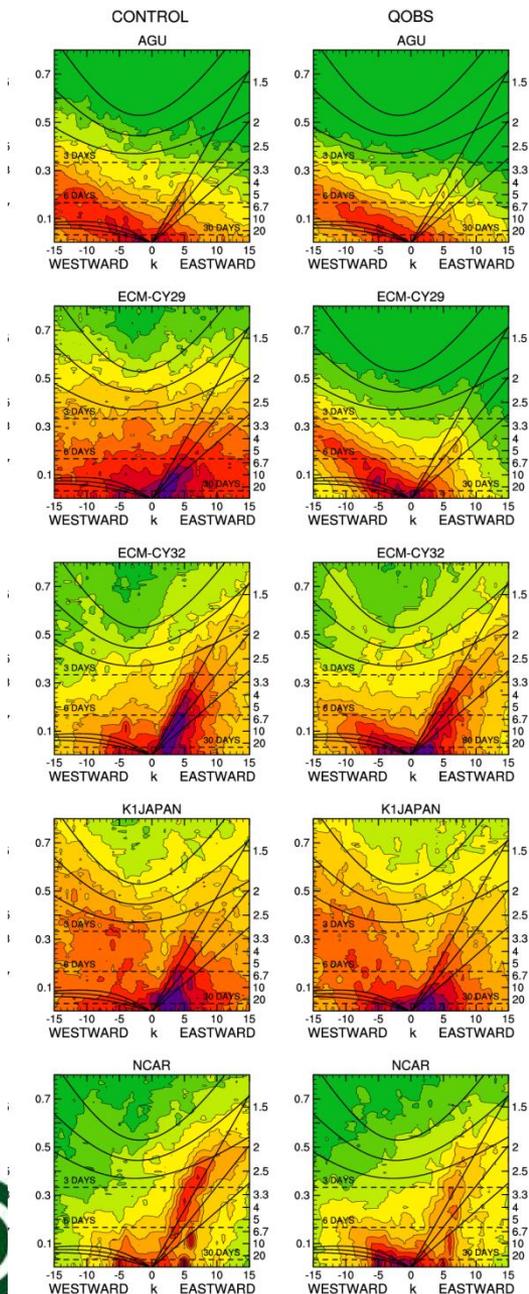
However convection isn't as simple as that

Convectively Coupled Waves

- Convective heating isn't directly related to the vertical motion
- Even if the amplitude of the heating is related to vertical velocity at a particular level, the vertical profile of the heating doesn't necessarily have the same structure as the vertical velocity which leads to coupling between vertical modes
- Typically α is related to the moisture convergence which will depend on the background moisture field and hence α will not be constant within the wave (particularly in the meridional direction)
 - e.g. Kang et al., *J. Clim.*, 2013, argue that equatorially peaked moisture profiles favour Kelvin waves over Rossby waves
- Moisture convergence depends on both the vertical velocity profile and the vertical humidity profile

The complicated relationship between convection and the large-scale dynamics makes developing a complete theory for equatorial waves (and other tropical variability) very difficult

Variety of Equatorial Waves in Aquaplanet GCMs



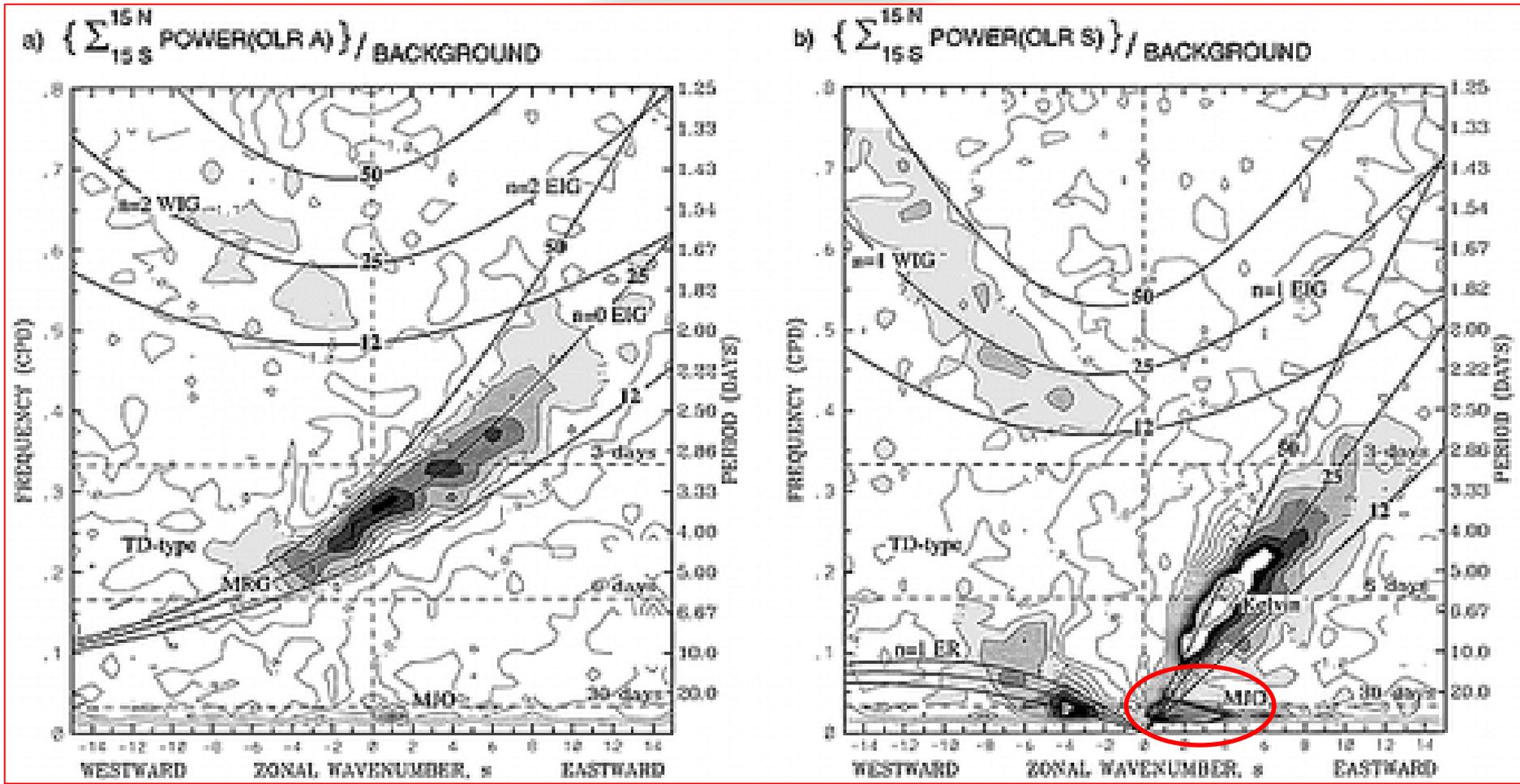
Power Spectra from the APE Project

- Variations in
 - Intensity
 - Dominance of eastward of westward moving waves
- With both
 - Model
 - SST profile

Highlights importance of both the basic state and model physics in determining the characteristics of waves



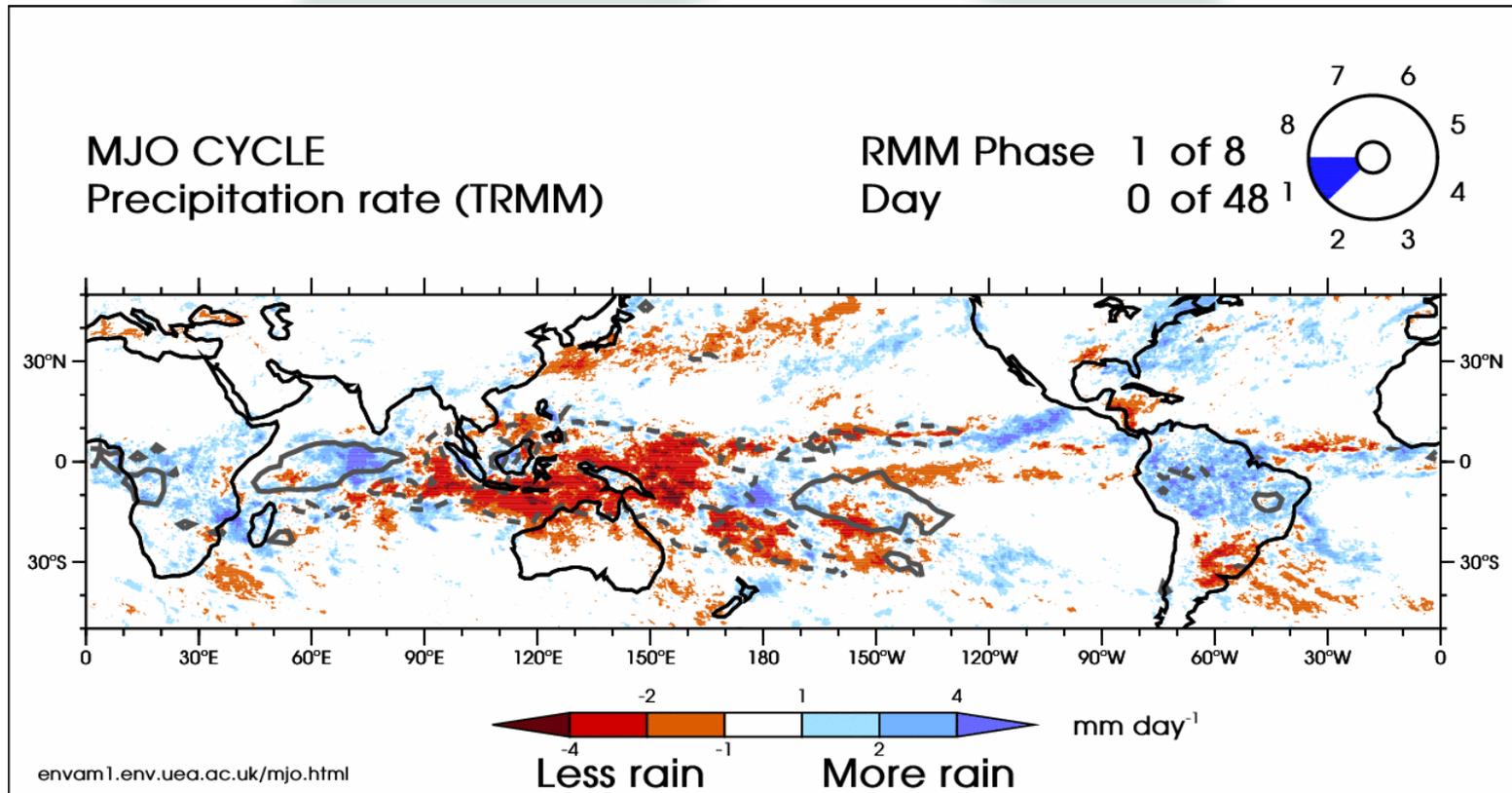
The Madden Julian Oscillation



Wheeler & Kiladis
 J.Atmos. Sci, 1999 Fig 3

The Madden-Julian Oscillation (MJO)

- The MJO is the largest mode of subseasonal variability in the tropics



Animation courtesy of Adrian Matthews <http://envam1.env.uea.ac.uk/mjo.html>

The Madden-Julian Oscillation (MJO)

- The MJO is the largest mode of subseasonal variability in the tropic, with significant tropics-wide and global impacts on sub-seasonal timescales (*see Zhang, 2013 in BAMS, for a nice review*)
- Linked to sub-seasonal variability of the major monsoon systems
- Associated tropical heating anomalies act as Rossby wave-source and provide teleconnections to extra-tropics (troposphere and stratosphere)
- Modulates tropical cyclone activity
- Westerly Wind Bursts important in development of El Niño events



MJO Global Teleconnections

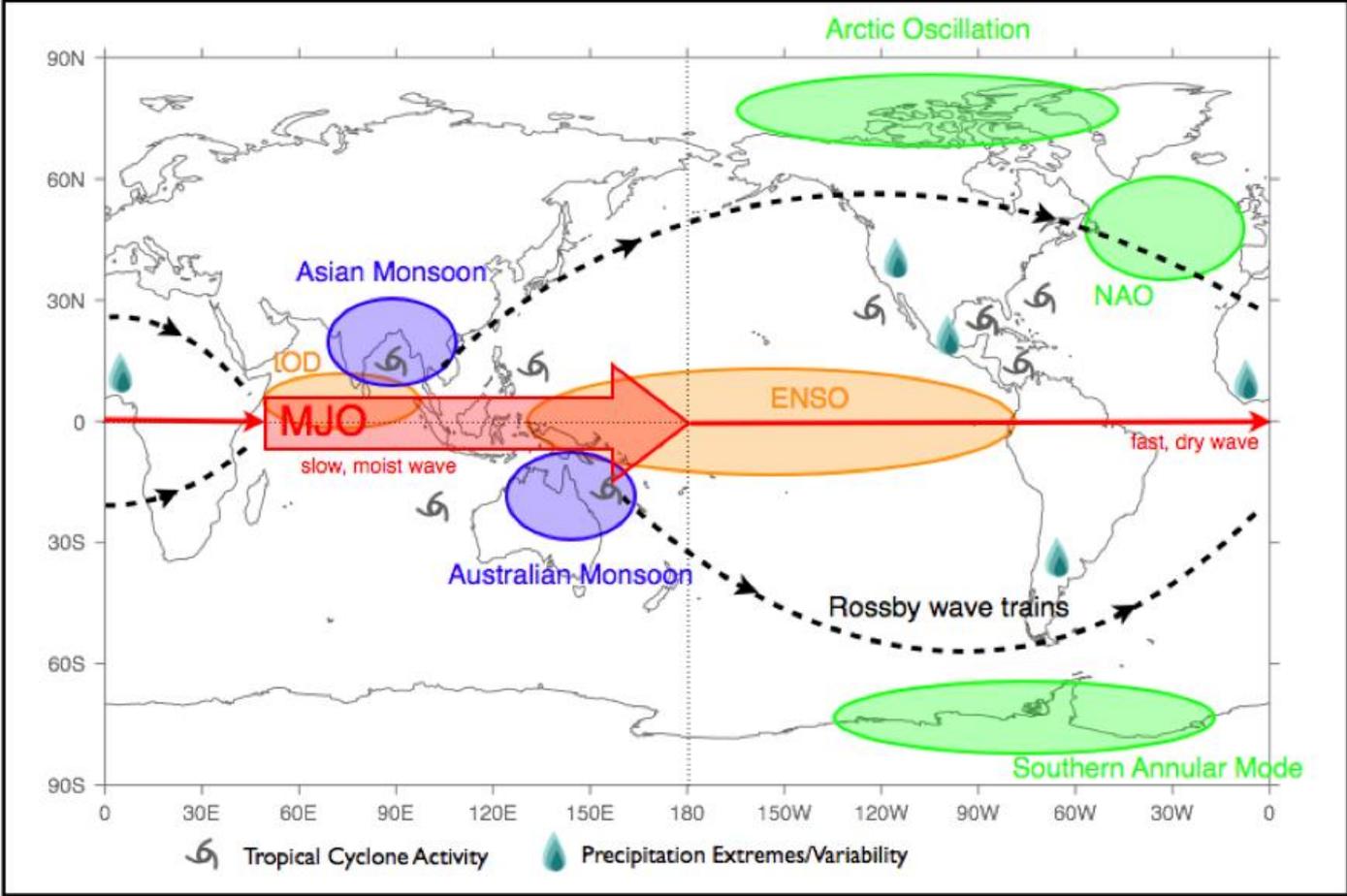


Figure 1.2 Schematic representation of the global teleconnection patterns associated with the MJO. Adapted and extended from Lin et al. (2006).

Courtesy of Linda Hiron

MJO maintenance and propagation

- A number of proposed mechanisms and theories for MJO maintenance and propagation, which are not necessarily mutual exclusive
 - Modification of linear equatorial waves, by convective heating
 - Wave-CISK, Frictional Wave-CISK
 - Moisture modes based around dynamical and diabatic processes influence on the moist static energy budget
 - Role of horizontal advection, longwave and surface heat fluxes, NGMS
 - Air-sea interaction
 - Scale interactions
 - Modulation of synoptic scale activity and their associated heat and momentum transports on the MJO scale flow

Underpinned by the interactions between convection and the large-scale circulation

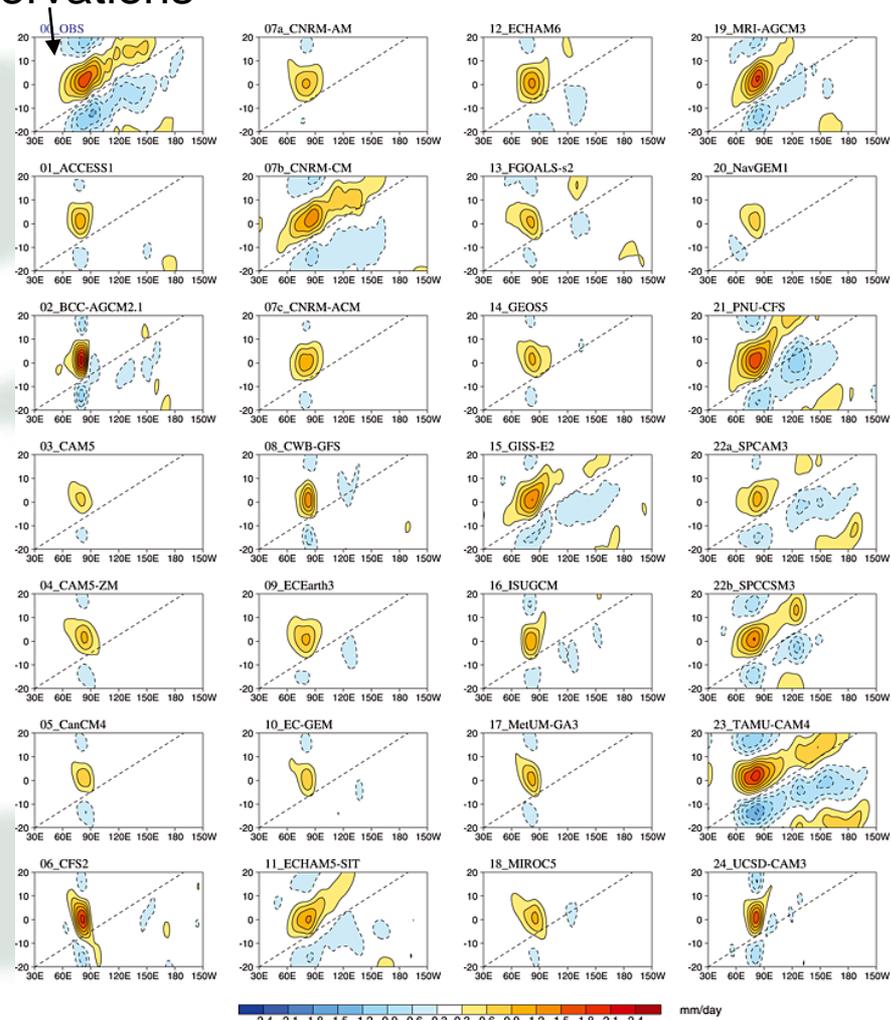
MJO in climate models

- Very few models able to simulate a realistic MJO
- Air-sea coupling can make a difference (see later)
- No obvious relationship between MJO simulation and model climatology

Results from companion papers (Klingaman et al. JGR, 2015a,b, Xavier et al. JGR, 2015) show

- Models which have good predictive skill do not necessarily have a good MJO in climate simulations and vice-versa
- Skill of models seems to be related to their representation of the relationship between column moistening and precipitation rate

Observations



Lag regression of precipitation with precipitation at a base point in the Indian Ocean from a range of climate models

Sensitivity to the representation of convection

- Global climate and NWP models cannot simulate individual convective clouds so the effect of these convective clouds is represented by the sub-grid parametrizations schemes, (in particular the convection scheme interacting with the boundary layer scheme)
- Convection is often represented by an “entraining plume” model where a parcel of air is lifted from the boundary layer entraining air from the environment as it goes, (and detraining air to the environment).
- This entrainment controls the vertical profile of convective mass flux, both directly and through the mixing with drier environmental air reducing its parcel buoyancy.
- The specification of this entrainment rate is one of the many choices you have to make in building a convection scheme and the representation of the tropical climate can be highly sensitive to it.
- We have performed a number of experiments exploring the sensitivity to the entrainment rate for deep convection in the Met Office Unified Model



Sensitivity of the MJO to Entrainment Rate

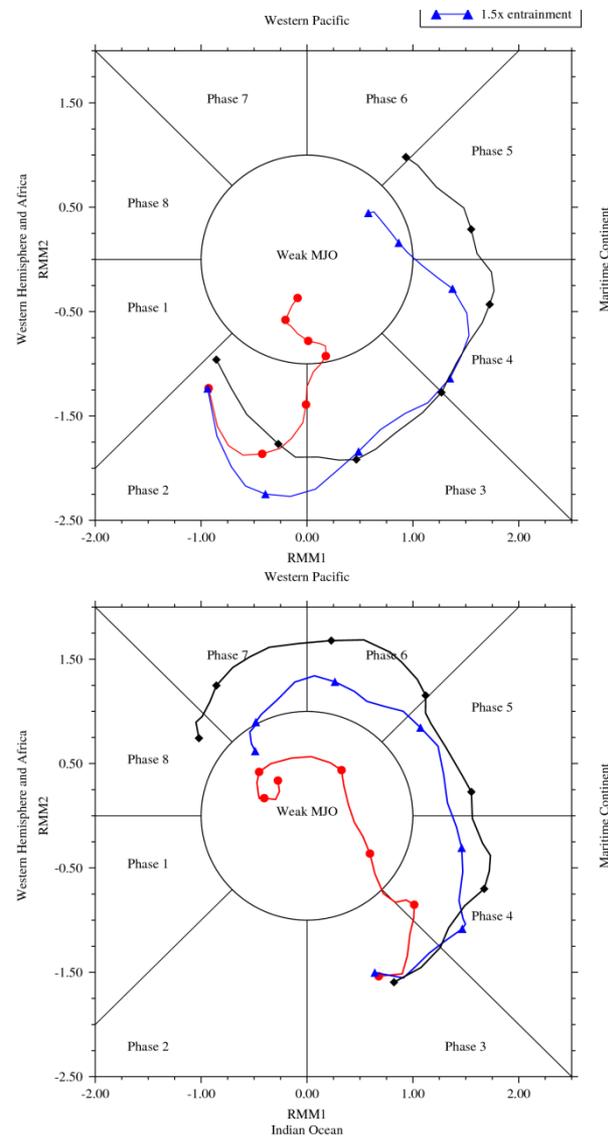
Set of hindcasts and climate simulations with the Met Office Unified Model

- with the control entrainment rate for deep convection, and
- enhanced entrainment (multiplied by a factor of 1.5)

(Klingaman & Woolnough, QJRMS 2014a)

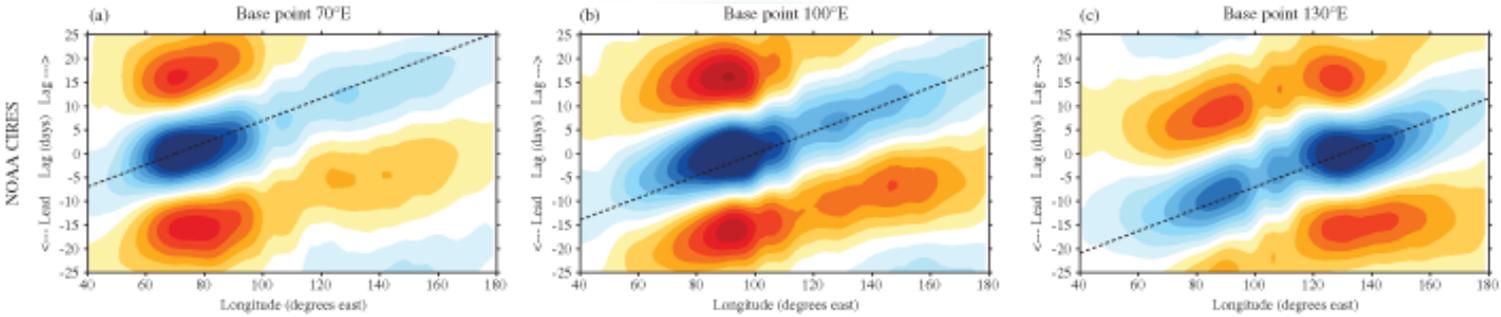
- High entrainment hindcasts show both improved amplitude and propagation compared to control case.

Composite RMM evolution of observations (black), control hindcasts (red) and 1.5x entrainment hindcasts (blue) for 14 hindcasts initialized with strong MJOs in Phase 2 and 10 days later.

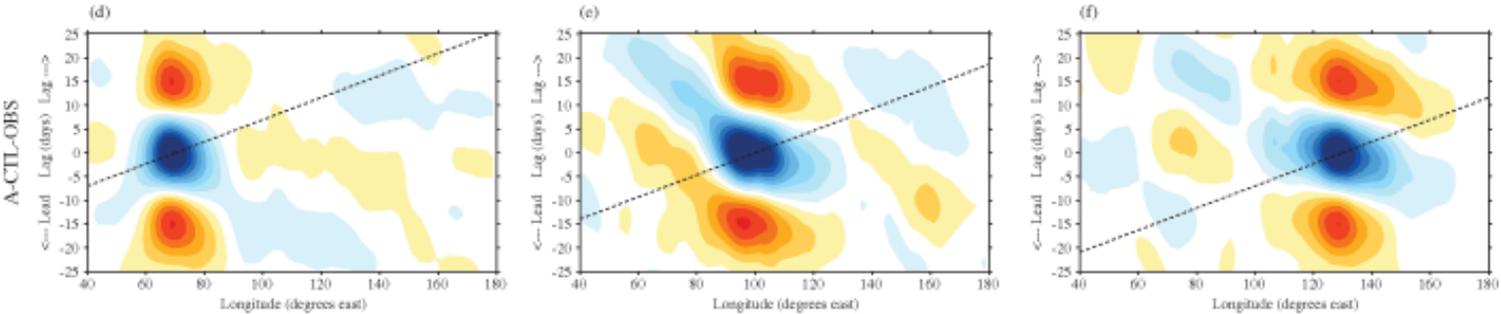


Sensitivity of the MJO to Entrainment Rate

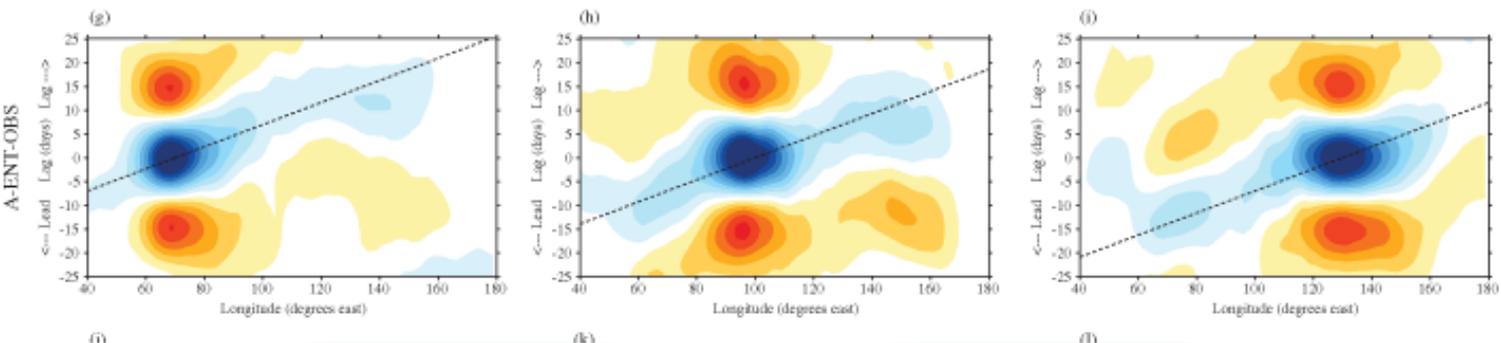
Observations



Control



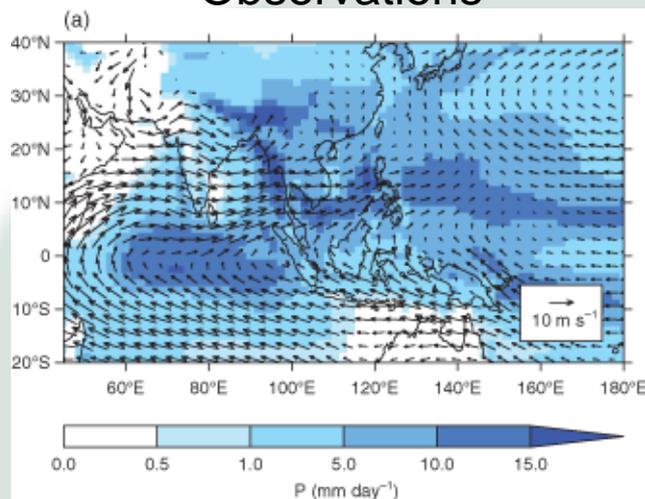
High entrainment



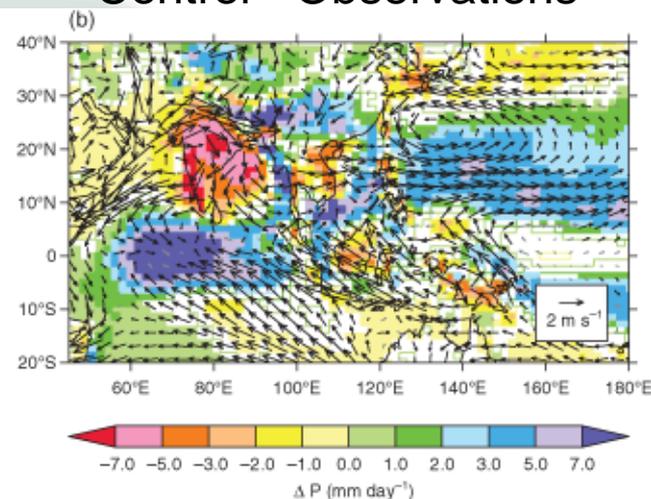
Lag regressions of 20-100 day bandpassed OLR from a 20 year climate simulation of the Met Office Unified Model

Sensitivity of the basic state to Entrainment Rate

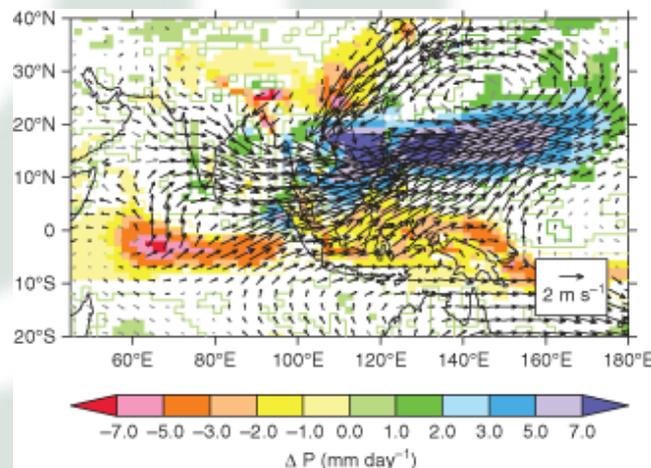
Observations



Control - Observations

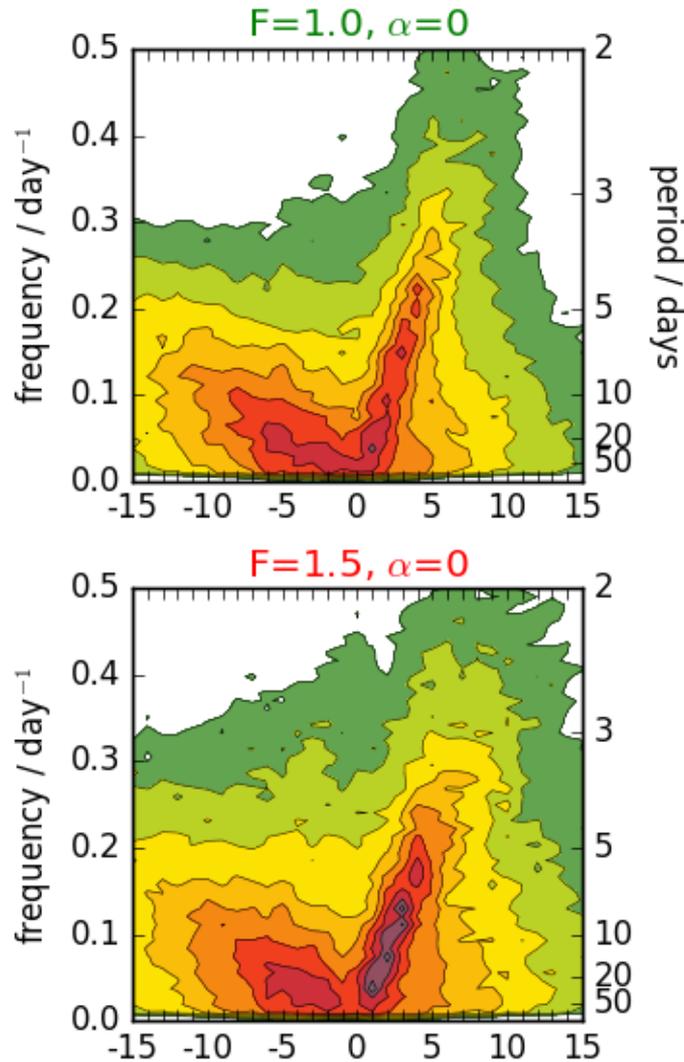


- Control has large biases compared to observations
- Sensitivity to entrainment rate is often comparable to the magnitude of the bias
- But increasing entrainment sometimes
 - Reduces bias (e.g. Indian Ocean)
 - Increases bias (e.g. West Pacific)



High entrainment - Control

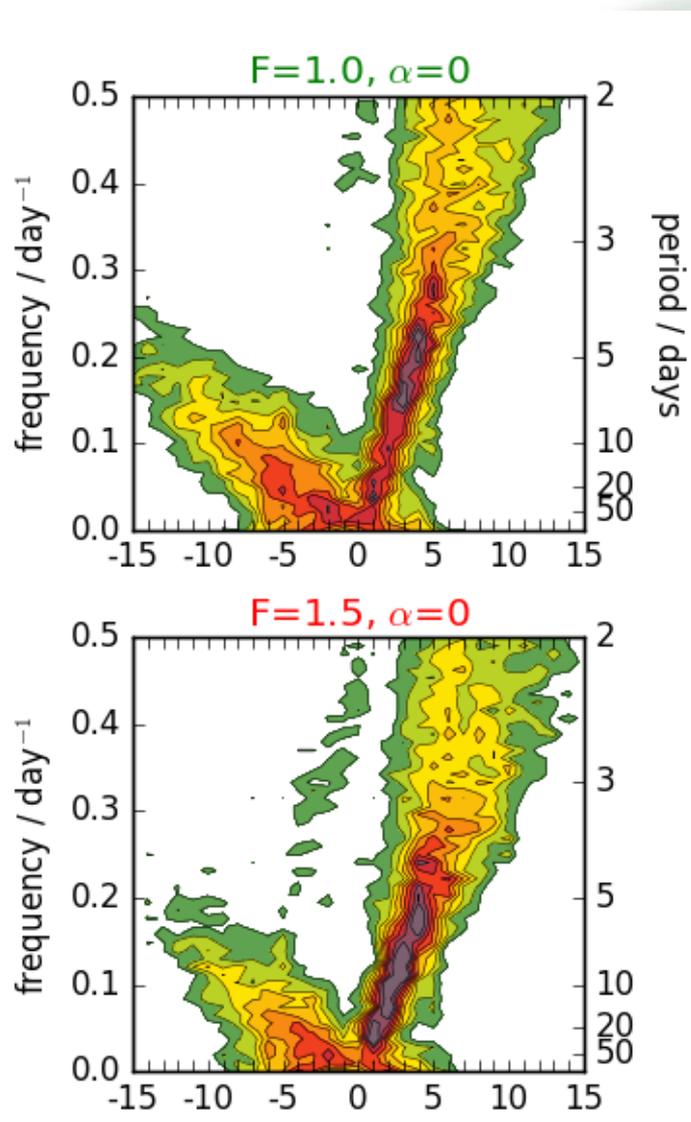
Sensitivity of Equatorial Waves to Entrainment rate



- Aquaplanet simulations of the UM with the default choice of entrainment rate ($F=1$) and enhanced entrainment rate ($F=1.5$)
- Slightly increased power at all wavenumbers and frequencies



Sensitivity of Equatorial Waves to Entrainment Rate



- Aquaplanet simulations of the UM with the default choice of entrainment rate ($F=1$) and enhanced entrainment rate ($F=1.5$)
- Slightly increased power at all wavenumbers and frequencies

Remove background by average across wavenumber

- Increased power (relative to background) for lower wavenumber Kelvin waves and reduced power for high wavenumbers
- Reduced power in westward moving modes relative to Kelvin Waves

Simon Peatman et al. in preparation



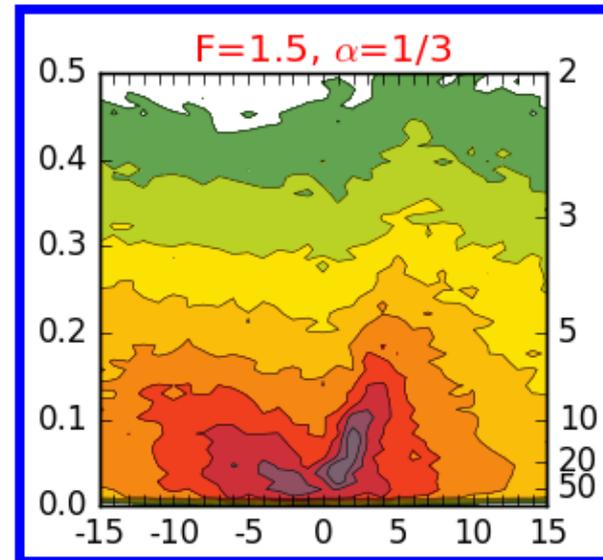
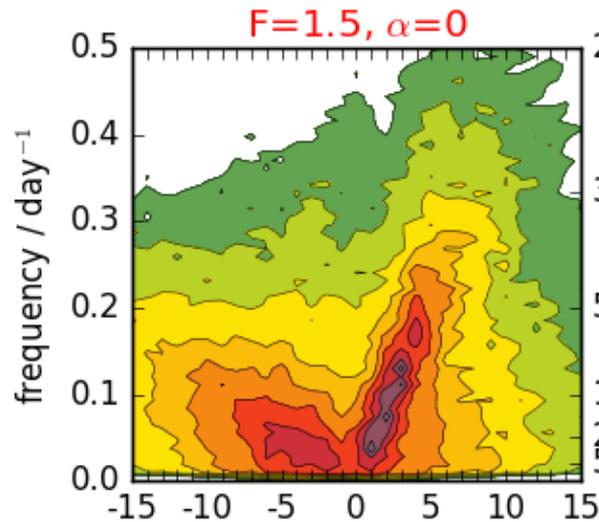
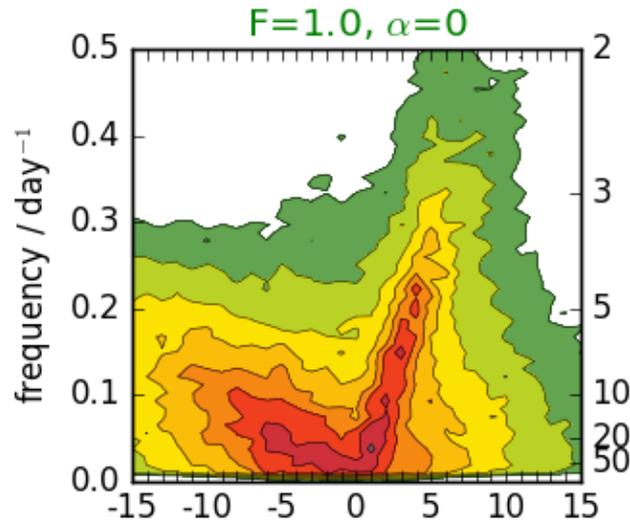
Sensitivity of Equatorial Waves to entrainment rate

- However changing the entrainment rate also leads to a change in the basic state, with more peaked equatorial precipitation and moisture – Are the changes in equatorial waves are response to
 - a) the changes in the basic state
 - b) the sensitivity of the wave convection to the environmental humidity
- Perform an experiment in which we modify the convection scheme so that it entrains the climatological basic state moisture at the higher entrainment rate ($F=1.5$), but the perturbations from the basic state at the lower entrainment rate (labelled, $F=1.5$, $\alpha=1/3$)
- If it behaves like
 - a) $F=1.5$ then the change is more likely due to the sensitivity to the basic state
 - b) $F=1$ then the change is more likely due to the sensitivity of the convection in the wave to the environmental humidity



Sensitivity of Equatorial Waves to Entrainment rate

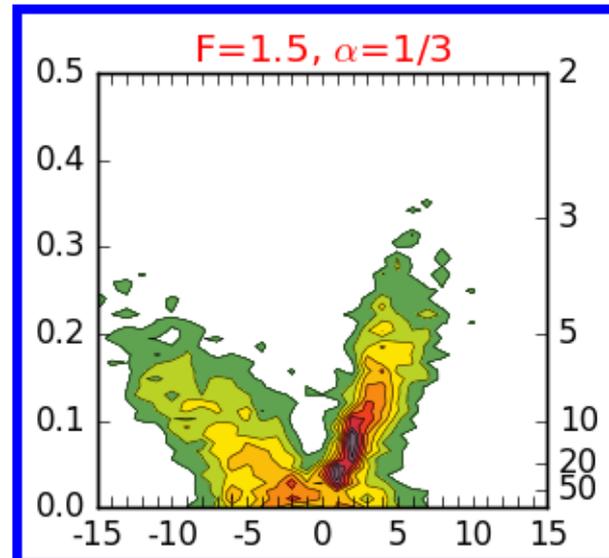
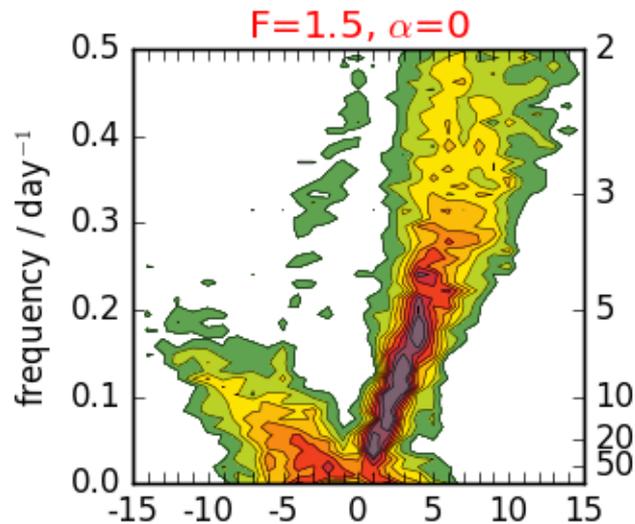
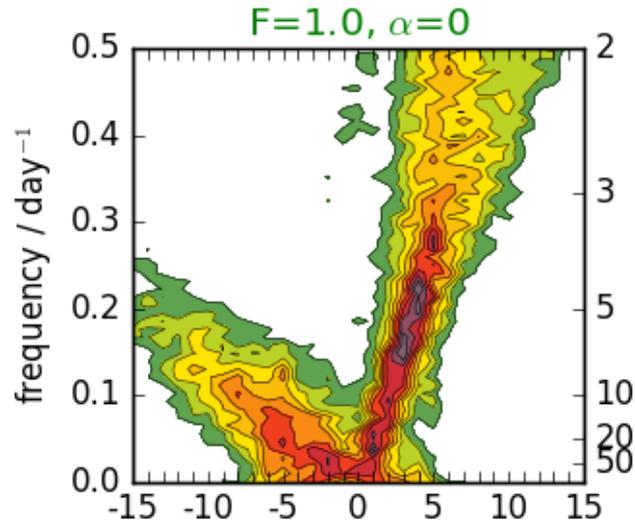
- Increased power in the background relative to $\alpha=0$ case



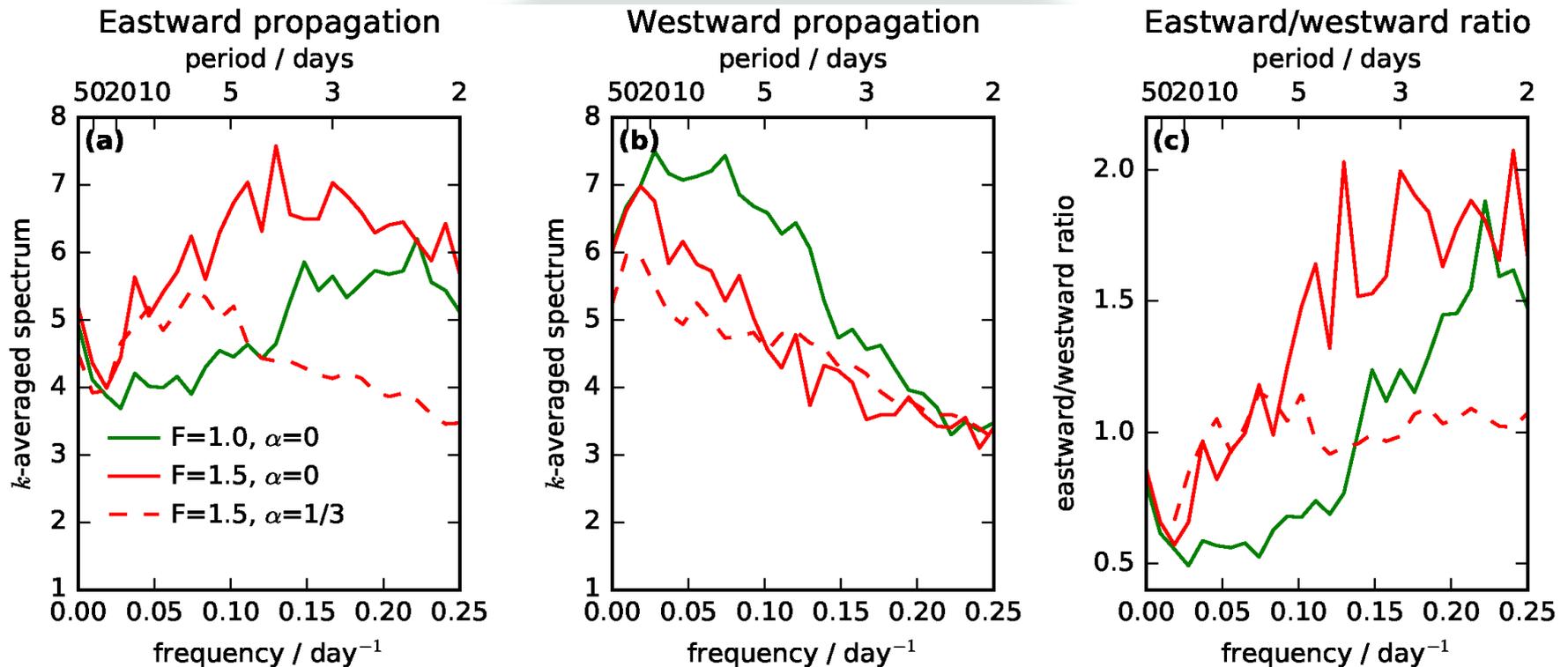
Sensitivity of Equatorial Waves to Entrainment rate

Remove background

- High wavenumber Kelvin waves become indistinct from background state
- Low wavenumber Kelvin Waves more like $F=1.5$
- East-west ratio more like $F=1.5$

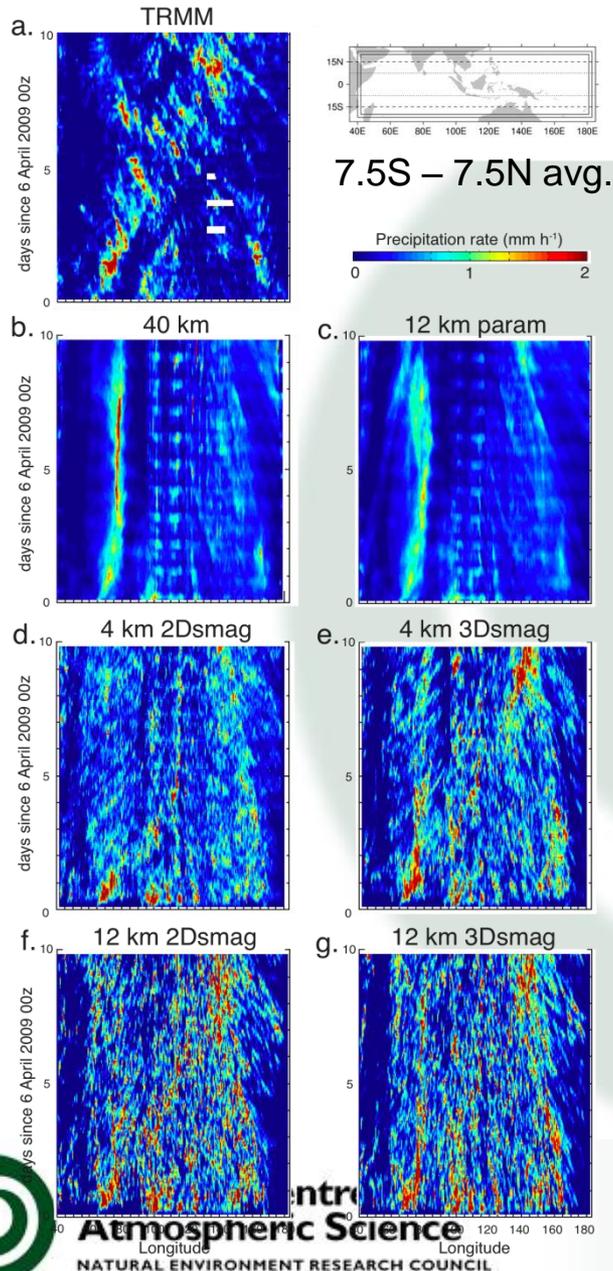


Sensitivity of Equatorial Waves to Entrainment Rate



- Not as clean as experiment as we would have liked, but
- Evidence suggests that the sensitivity of equatorial waves to entrainment rate arises largely due to changes in the basic state

Beyond Convective Parametrization



- Simulations of an MJO event in a limited domain, at a range of resolutions (*Holloway et al, J. Atmos. Sci 2013,2015*)
- explicit convection at 4km and 12km resolution
- parametrized convection at 12 and 40km resolution
- Much improved MJO simulation in most of the explicit simulations
- However
 - explicit simulations too “noisy”
 - Unrealistic grid-scale vertical velocities and precipitation rates
 - Under resolved explicit convection, there is still a parametrization problem



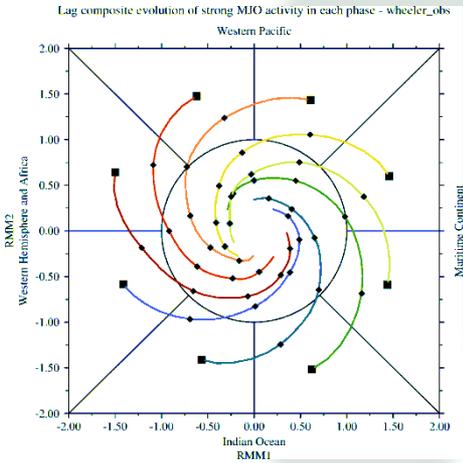
Air-sea interaction and the MJO

- There is an enormous amount of evidence that air-sea interaction is important in the MJO (*comprehensive review in DeMott et al., Rev. Geophys, 2015*)
- Woolnough et al., QJRMS 2007, using a 1D mixed layer model showed that
 - the impact of air-sea coupling is sensitive to the ability of the ocean mixing to reproduce the diurnal cycle of SST and shallow mixed layers during the suppressed phase of the MJO
 - requires both high vertical resolution in the ocean and sub-daily coupling
- Klingaman & Woolnough 2014b using a 1D mixed layered model showed that impact of air-sea coupling depends on representation of the MJO in the uncoupled model

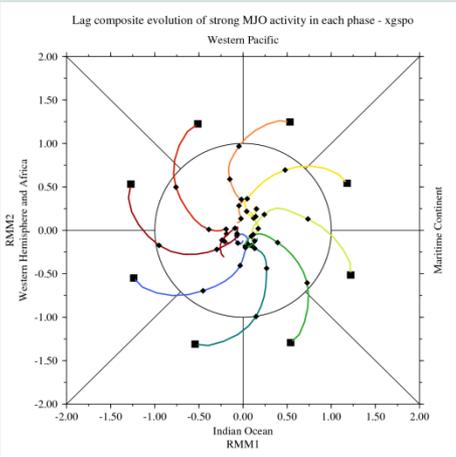


MJO in a climate model: sensitivity to ocean coupling

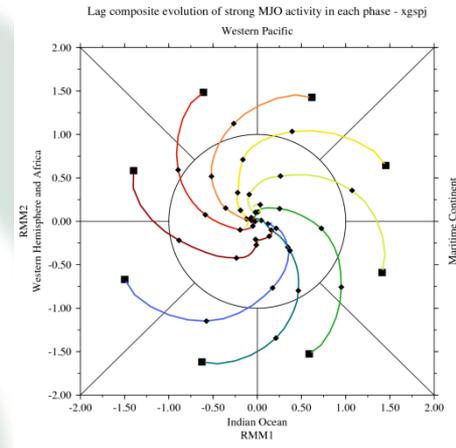
Observations



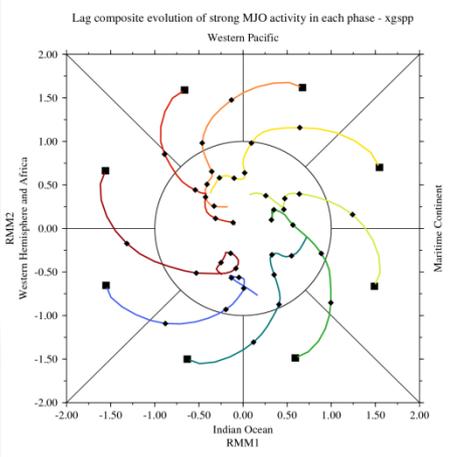
A-CTL



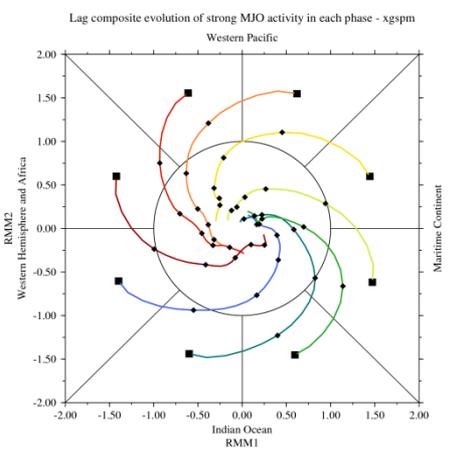
A-ENT



K-CTL



K-ENT



Air-sea interaction and the MJO

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 - requires both high vertical resolution in the ocean and sub-daily coupling
- Klingaman & Woolnough 2014b using a 1D mixed layered model showed that impact of air-sea coupling depends on representation of the MJO in the uncoupled model
- We have further shown that the biases which often arise when coupling to an ocean offset the positive benefits of coupling on the MJO



Summary

- Tropical climate is characterized by a tight coupling between the large-scale dynamics and convection across a range of temporal and spatial scales
- Coupling between convection and the dynamics makes extending theoretical models of the dry tropical atmosphere to include moisture very challenging
- Modes of tropical variability are highly sensitive to the basic state of the atmosphere

Summary

- Model simulations of tropical variability are highly sensitive to the representation of convection (*not just convection schemes*)
- The sensitivity of the basic state to the representation of convection can make interpreting the sensitivity of variability to the representation of convection very difficult
- Air-sea interaction is an important component of the MJO the major mode of sub-seasonal variability, but
 - Its impact in models is sensitive to the uncoupled simulation
 - Can be impacted by biases in the basic state introduced by coupling
- The sensitivity of model simulations of the tropical climate and its variability adds additional challenges when introducing more components to the system, e.g.
 - Interactive bio-geochemistry will be highly sensitive to errors in the basic state and variability (e.g. diurnal cycle, extended dry spells,...)

