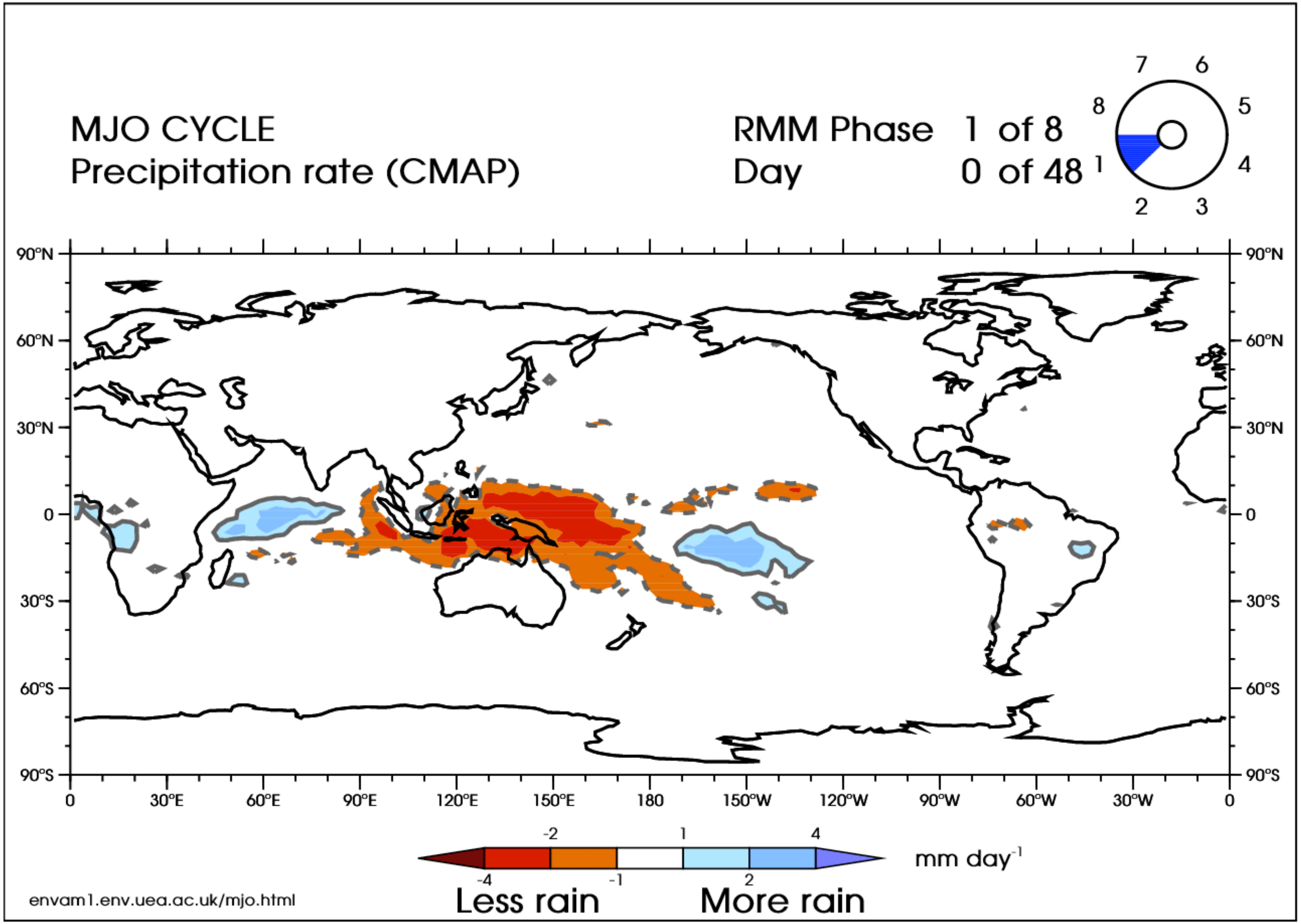
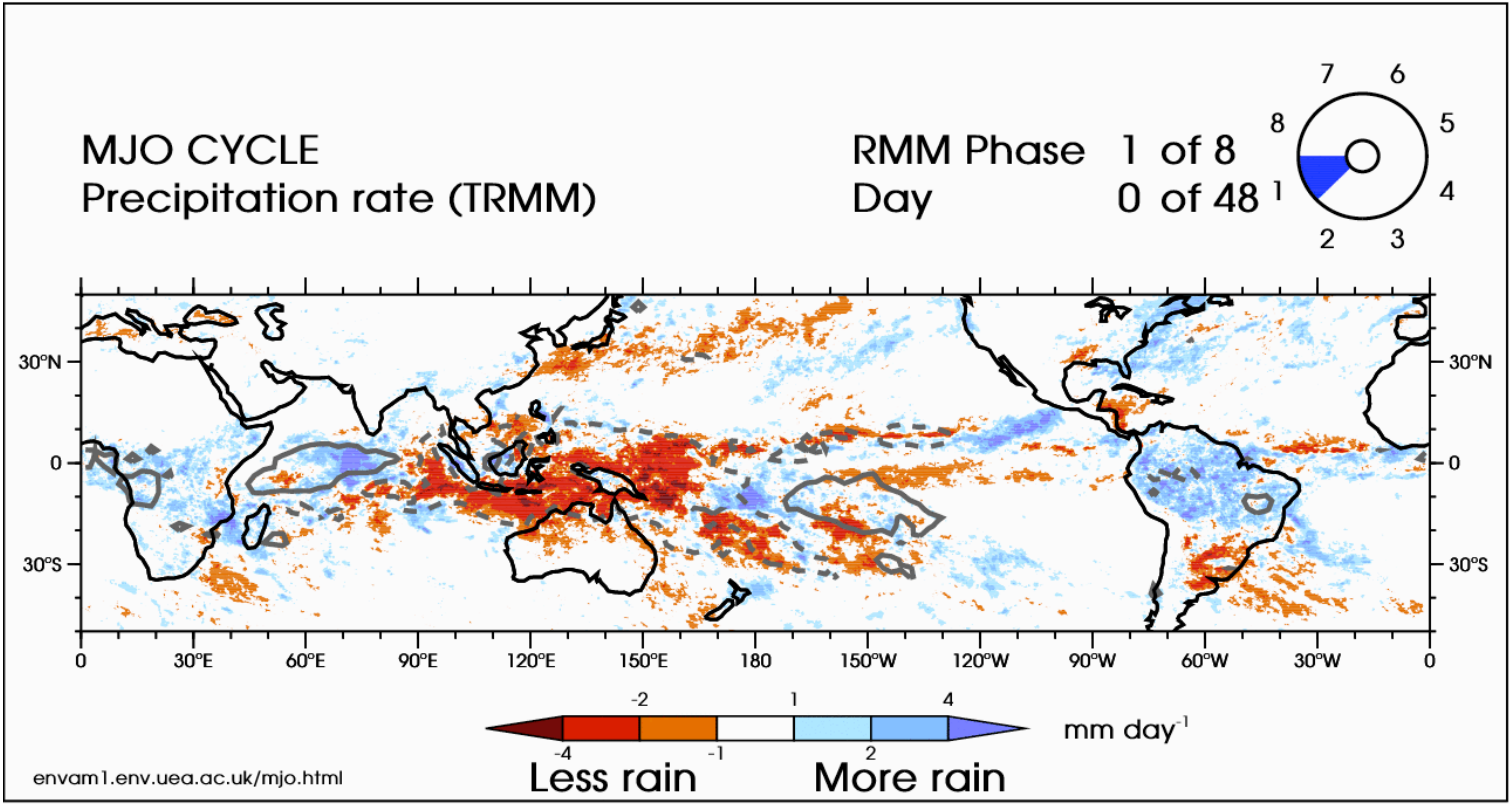
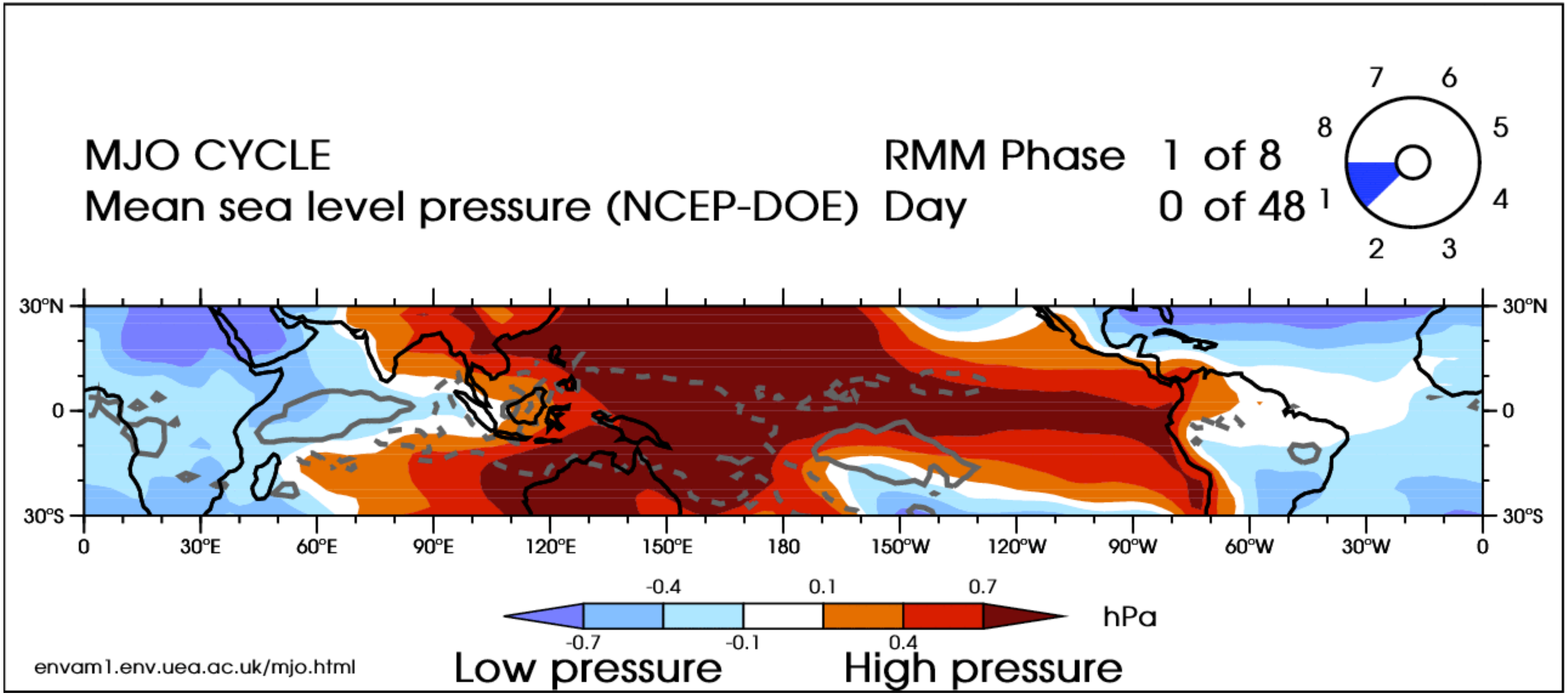
Atmosphere–Ocean Interactions

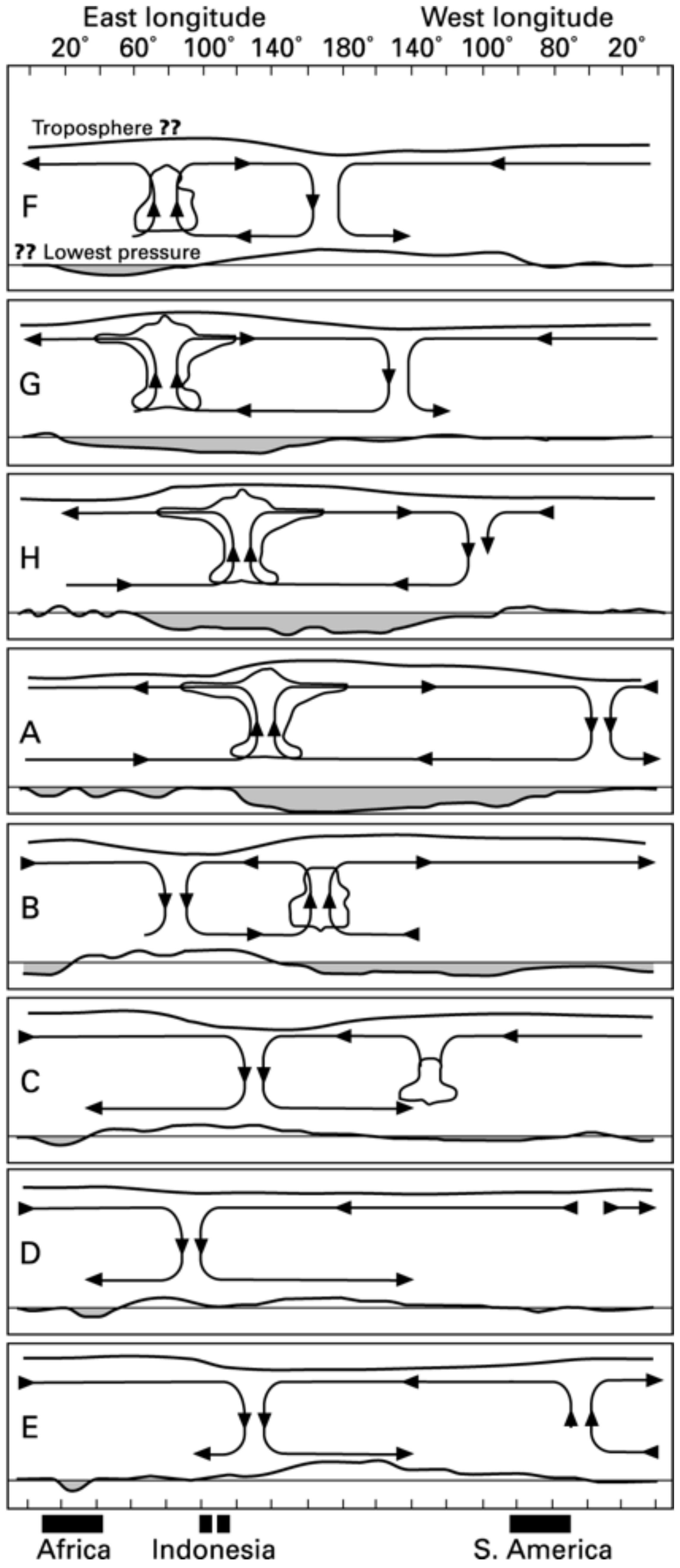
10. The Madden–Julian Oscillation

- Introduction and basic dynamical concepts
- What causes the MJO?
- Numerical modeling of the MJO
- Interactions between the MJO and other coupled atmosphere–ocean phenomena


MJO CYCLE
Precipitation rate (CMAP)
RMM Phase 1 of 8
Day 0 of 48
7 6 8 5 1 4 2 3
90°N
60°N
30°N
0
30°S
60°S
90°S
0 30°E 60°E 90°E 120°E 150°E 180 150°W 120°W 90°W 60°W 30°W 0
-4 -2 -1 1 2 4
mm day-1
Less rain
More rain
envam1.env.uea.ac.uk/mjo.html


MJO CYCLE
Precipitation rate (TRMM)
RMM Phase 1 of 8
Day 0 of 48
7 6
8 5
1 4
2 3
30°N
0
30°S
0 30°E 60°E 90°E 120°E 150°E 180 150°W 120°W 90°W 60°W 30°W 0
-2 1 4
-4 -1 2
mm day-1
Less rain
More rain
envam1.env.uea.ac.uk/mjo.html

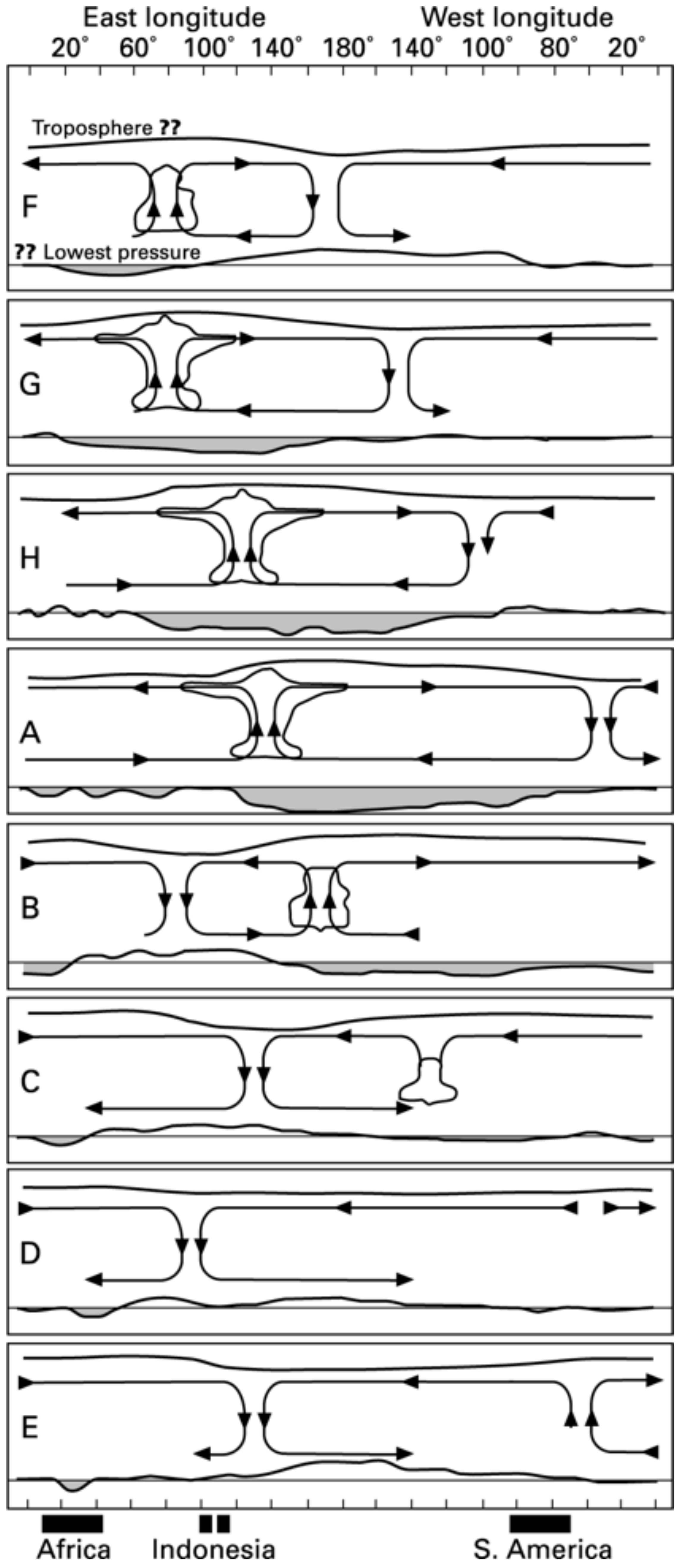

MJO CYCLE
Mean sea level pressure (NCEP-DOE)
RMM Phase 1 of 8
Day 0 of 48
7 6 8 5 1 4 2 3
30°N
0
30°S
0 30°E 60°E 90°E 120°E 150°E 180 150°W 120°W 90°W 60°W 30°W 0
-0.7 -0.4 -0.1 0.1 0.4 0.7
hPa
Low pressure
High pressure
envam1.env.uea.ac.uk/mjo.html



The MJO

A mode of natural variability in the tropical climate system characterized by planetary spatial scale, intraseasonal (30–60 day) time scale, and eastward propagation

Madden & Julian, *J. Atmos. Sci.* 1972



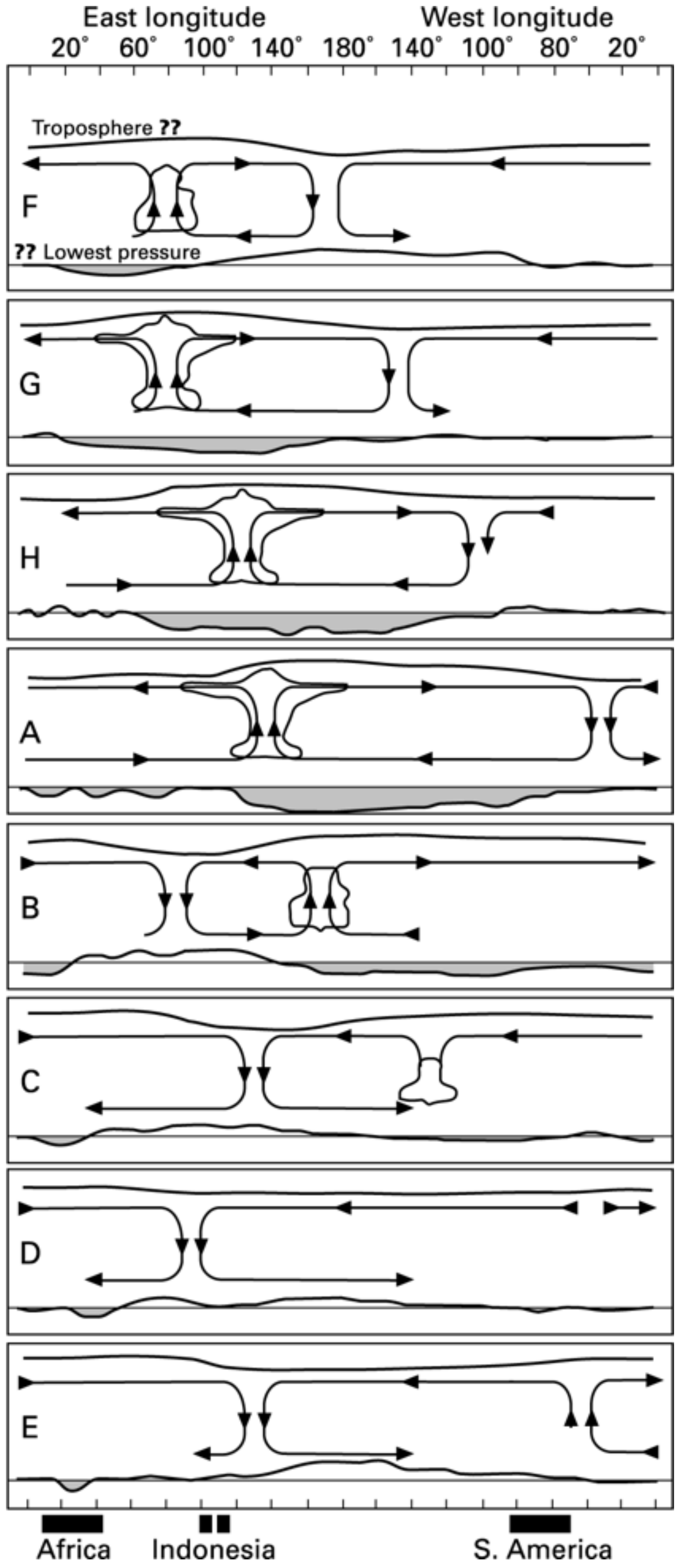
The MJO

A mode of natural variability in the tropical climate system characterized by planetary spatial scale, intraseasonal (30–60 day) time scale, and eastward propagation

a tendency of the climate system to vary in a particular way (generally an oscillation between two preferred states, rather than a permanent change).

The MJO is the dominant mode of intraseasonal variability in the tropics

Madden & Julian, *J. Atmos. Sci.* 1972

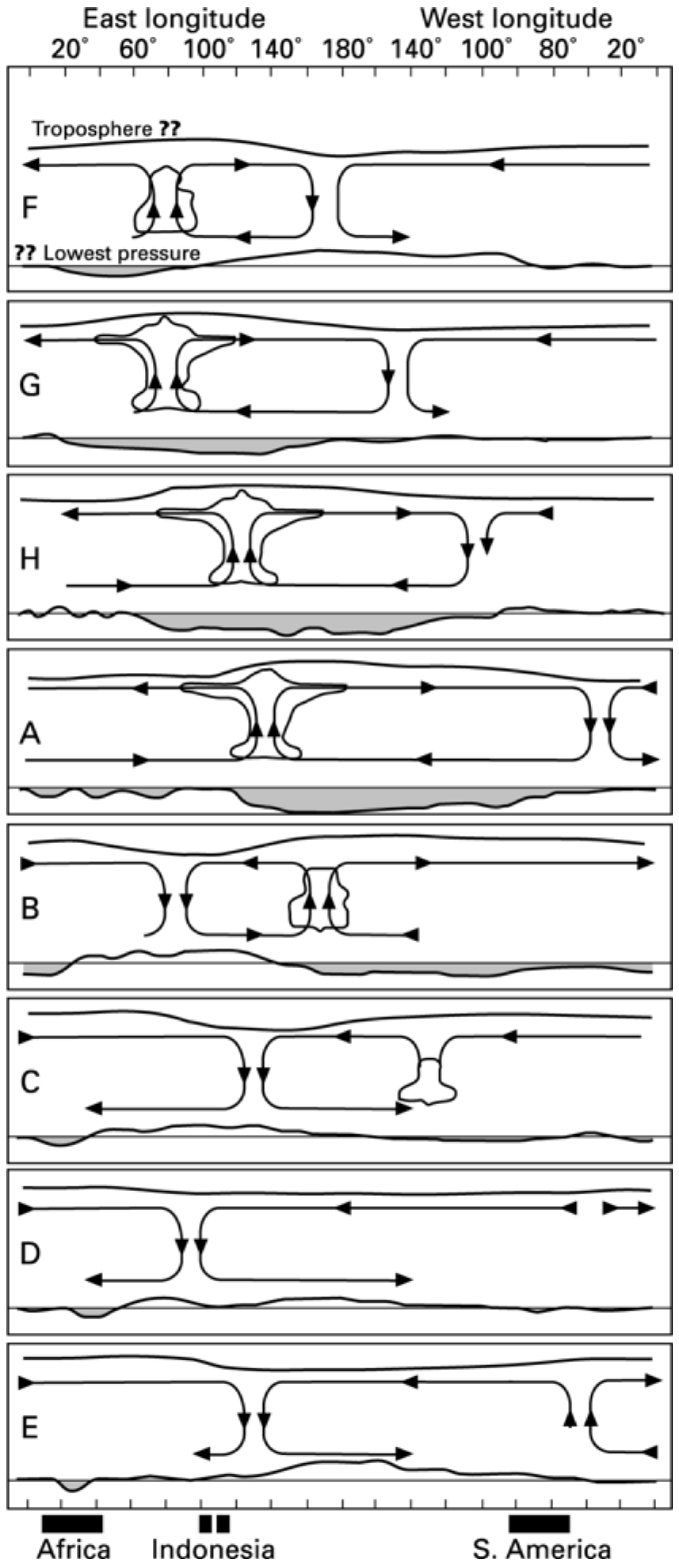


The MJO

A mode of natural variability in the tropical climate system characterized by planetary spatial scale, intraseasonal (30–60 day) time scale, and eastward propagation

The MJO is not caused by humans, although it may be modified by anthropogenic climate change

Madden & Julian, *J. Atmos. Sci.* 1972

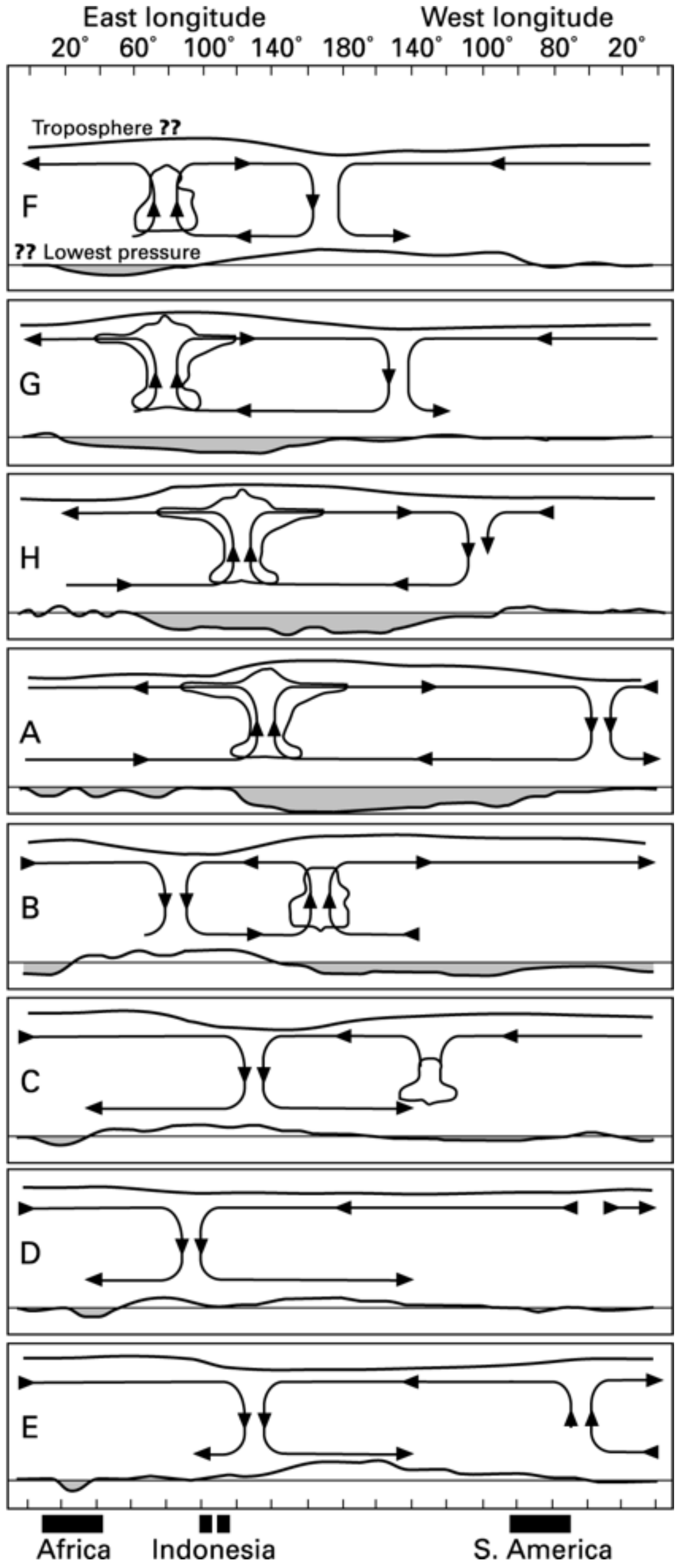


The MJO

A mode of natural variability in the tropical climate system characterized by planetary spatial scale, intraseasonal (30–60 day) time scale, and eastward propagation

The MJO occurs in the tropics, and both the atmosphere and ocean are involved.

Madden & Julian, *J. Atmos. Sci.* 1972

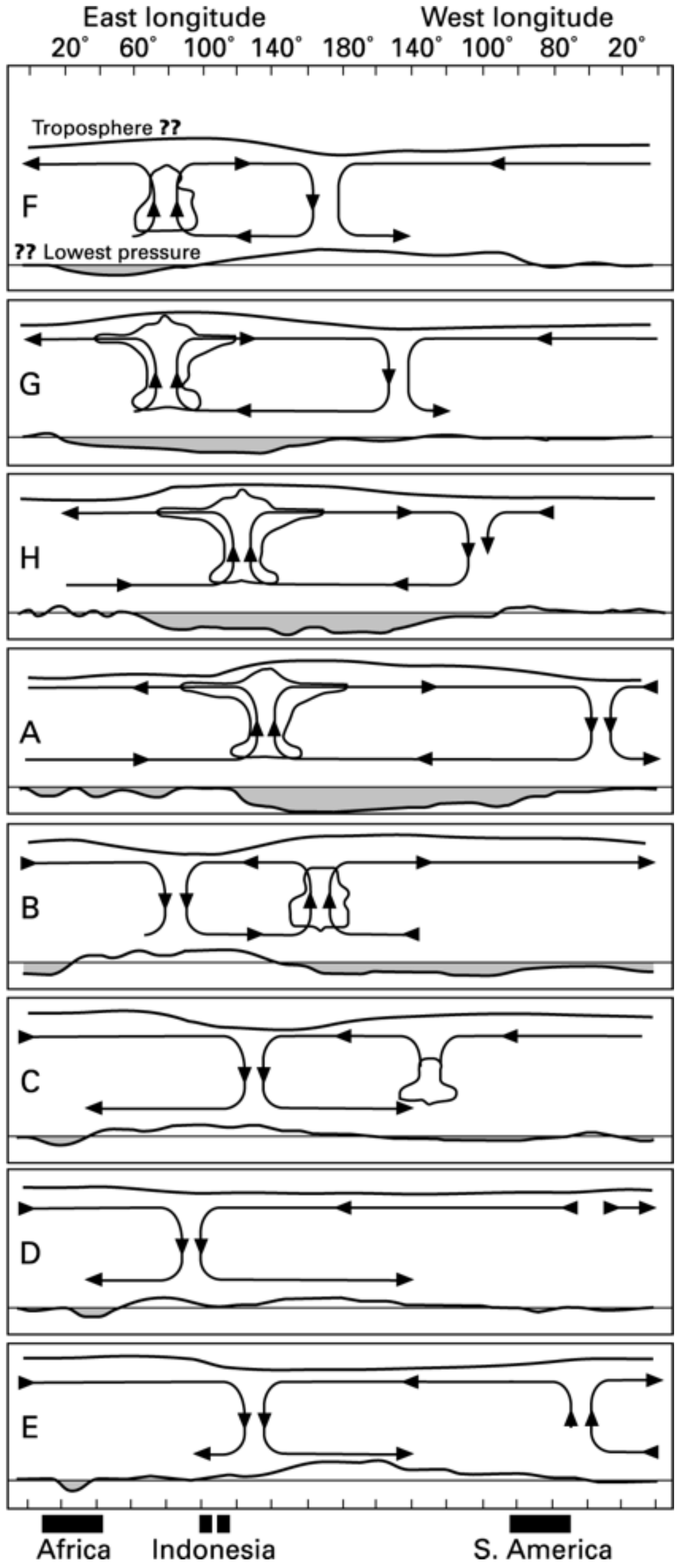


The MJO

A mode of natural variability in the tropical climate system characterized by planetary spatial scale, intraseasonal (30–60 day) time scale, and eastward propagation

The size of rainy or dry regions associated with the MJO (5,000–10,000 km) is not much smaller than the circumference of the Earth at the equator (40,000 km).

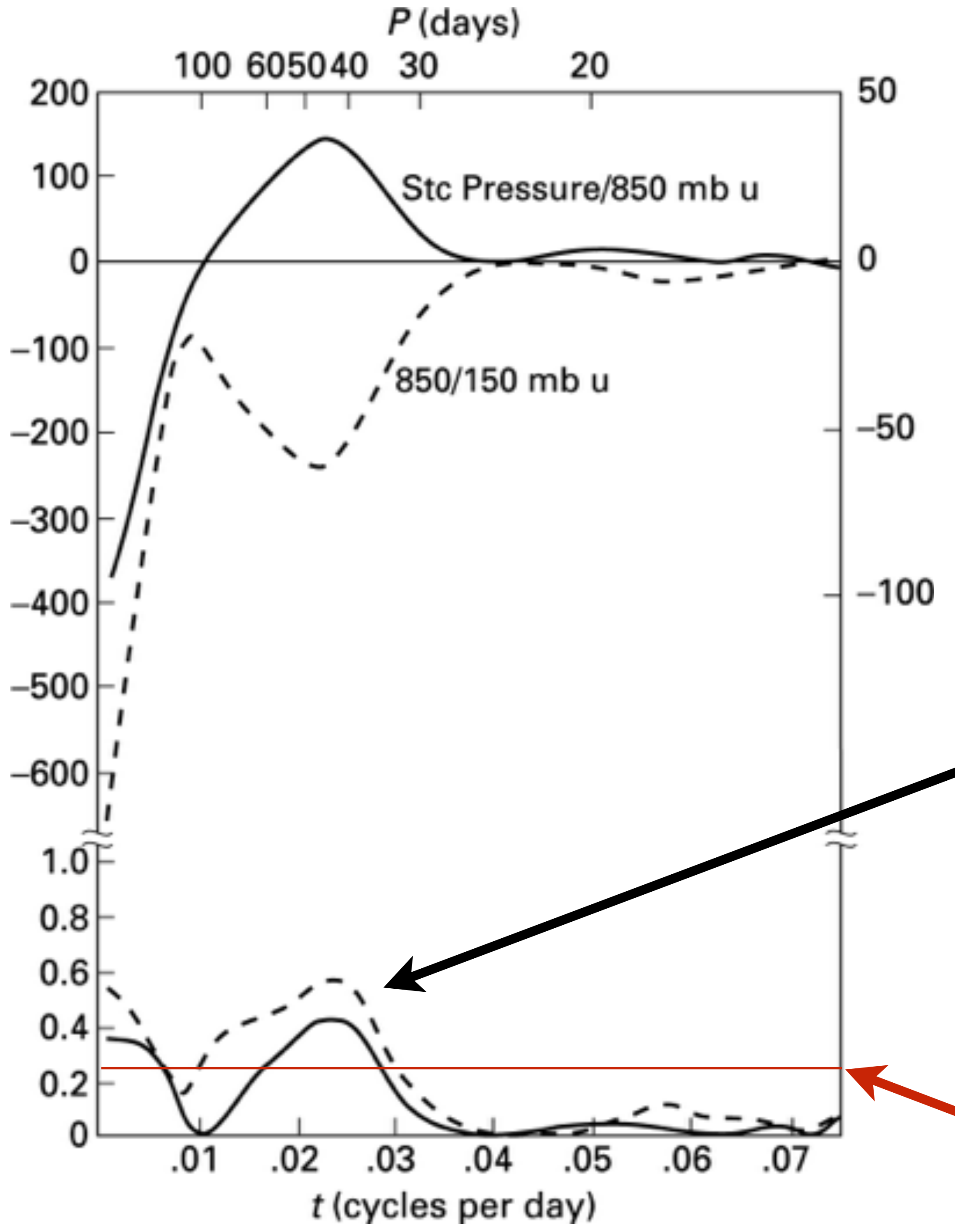
Madden & Julian, *J. Atmos. Sci.* 1972



The MJO

A mode of natural variability in the tropical climate system characterized by planetary spatial scale, intraseasonal (30–60 day) time scale, and eastward propagation

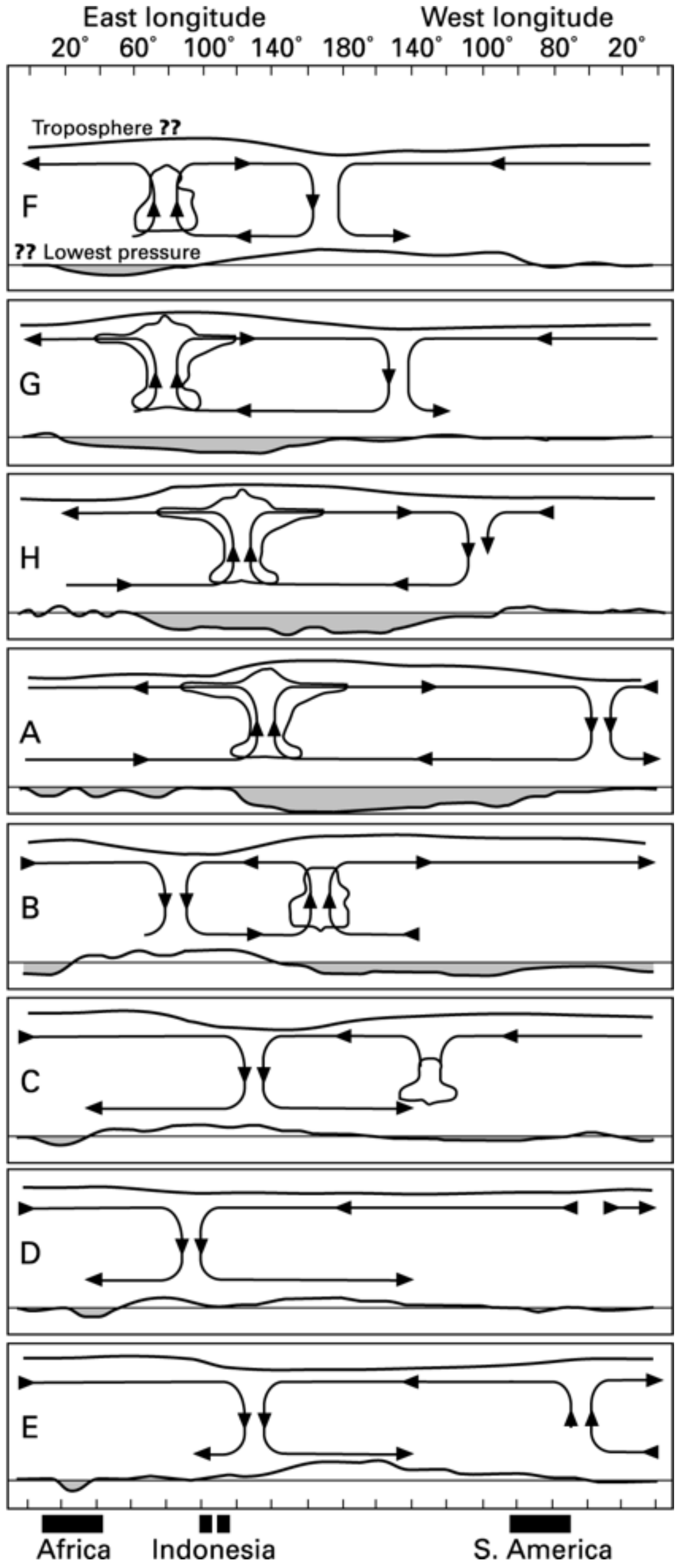
The phase of the MJO repeats itself (i.e., the MJO signal circles the globe) every ~30–60 days, a time period that is somewhat shorter than a season.



Coherence:
~1.5 to 3 cycles per 100 days

coherence is significant above this line

Madden & Julian, *J. Atmos. Sci.* 1972

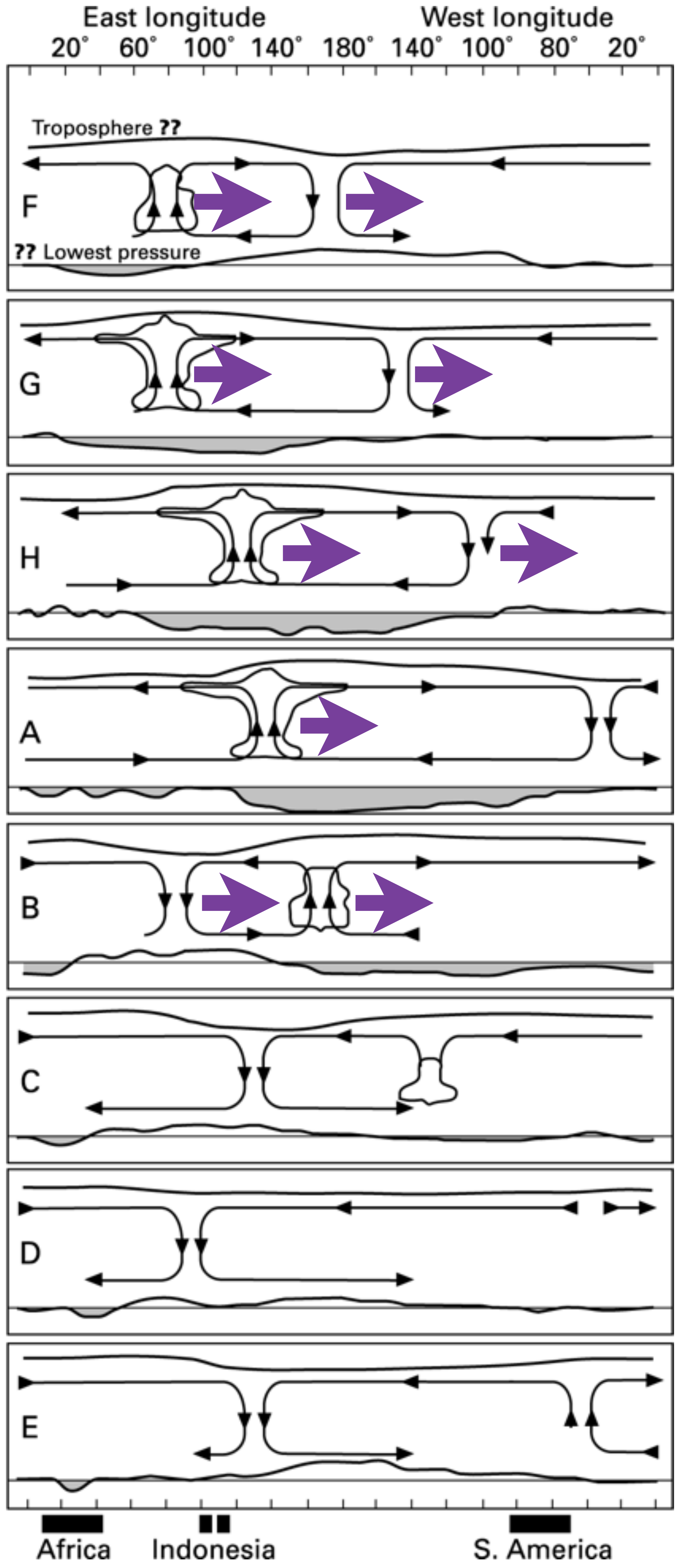


The MJO

A mode of natural variability in the tropical climate system characterized by planetary spatial scale, intraseasonal (30–60 day) time scale, and eastward propagation

The MJO is "quasi-periodic":
the period is not exactly regular

Madden & Julian, *J. Atmos. Sci.* 1972

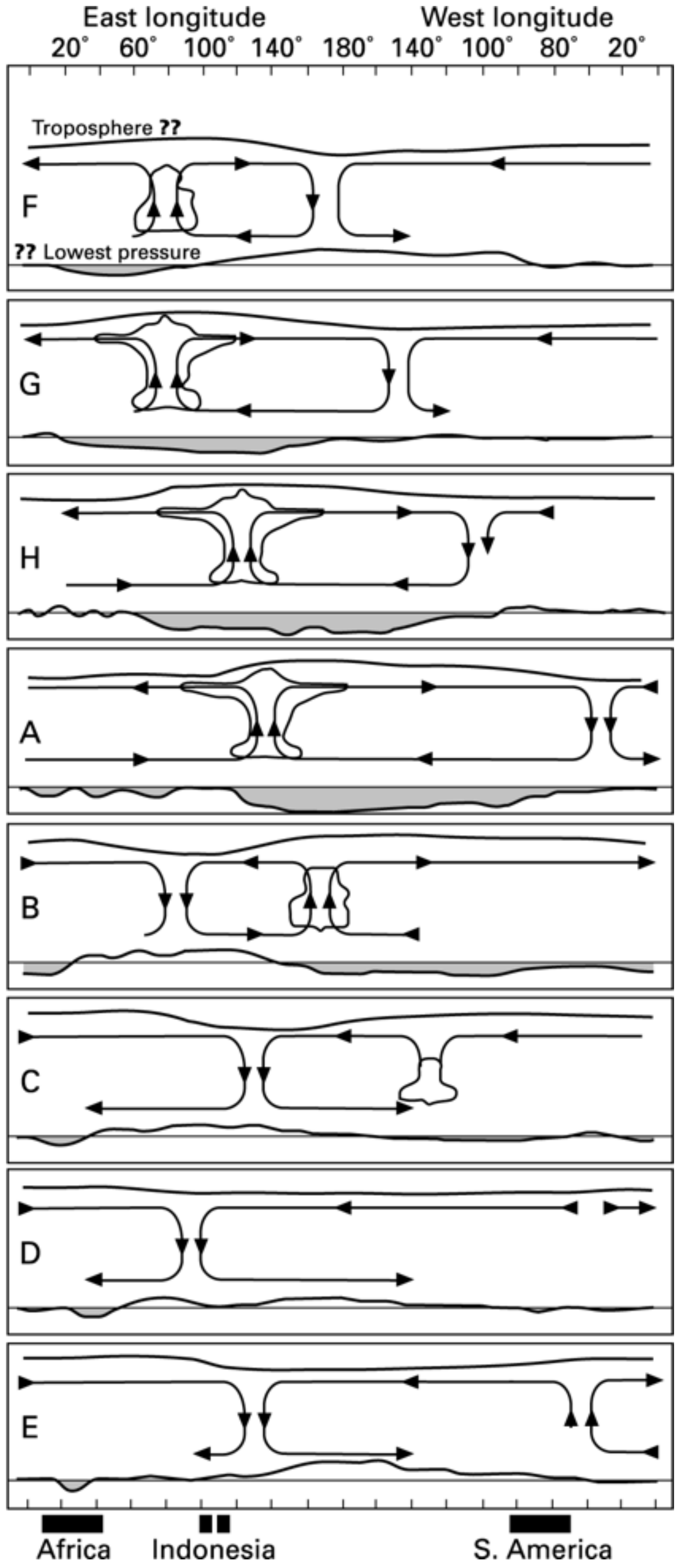


The MJO

A mode of natural variability in the tropical climate system characterized by planetary spatial scale, intraseasonal (30–60 day) time scale, and eastward propagation

The rainy and dry regions associated with the MJO move from west to east

Madden & Julian, *J. Atmos. Sci.* 1972

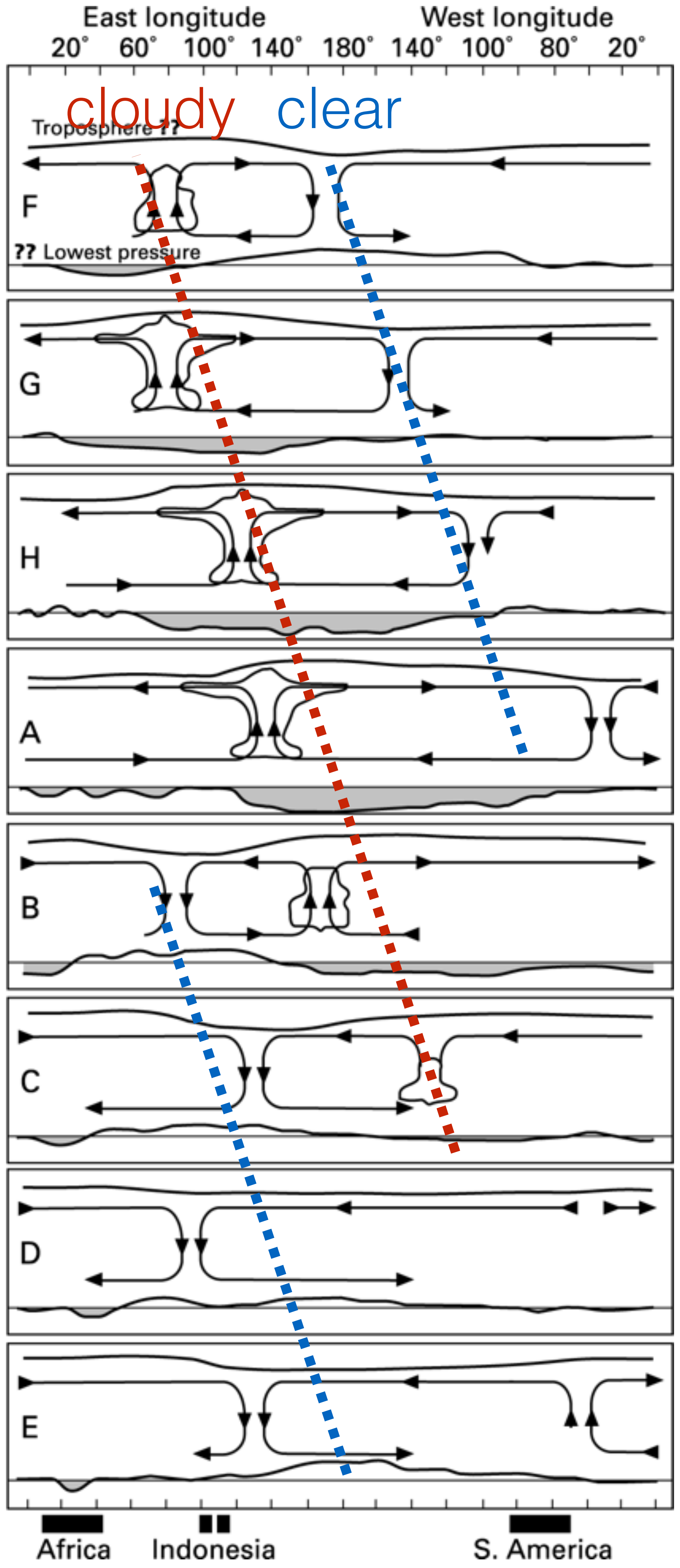


The MJO

A mode of natural variability in the tropical climate system characterized by planetary spatial scale, intraseasonal (30–60 day) time scale, and eastward propagation

Coherent variations in sea level pressure and winds, both near the surface and in the upper troposphere

Madden & Julian, *J. Atmos. Sci.* 1972



The MJO

A mode of natural variability in the tropical climate system characterized by planetary spatial scale, intraseasonal (30–60 day) time scale, and eastward propagation

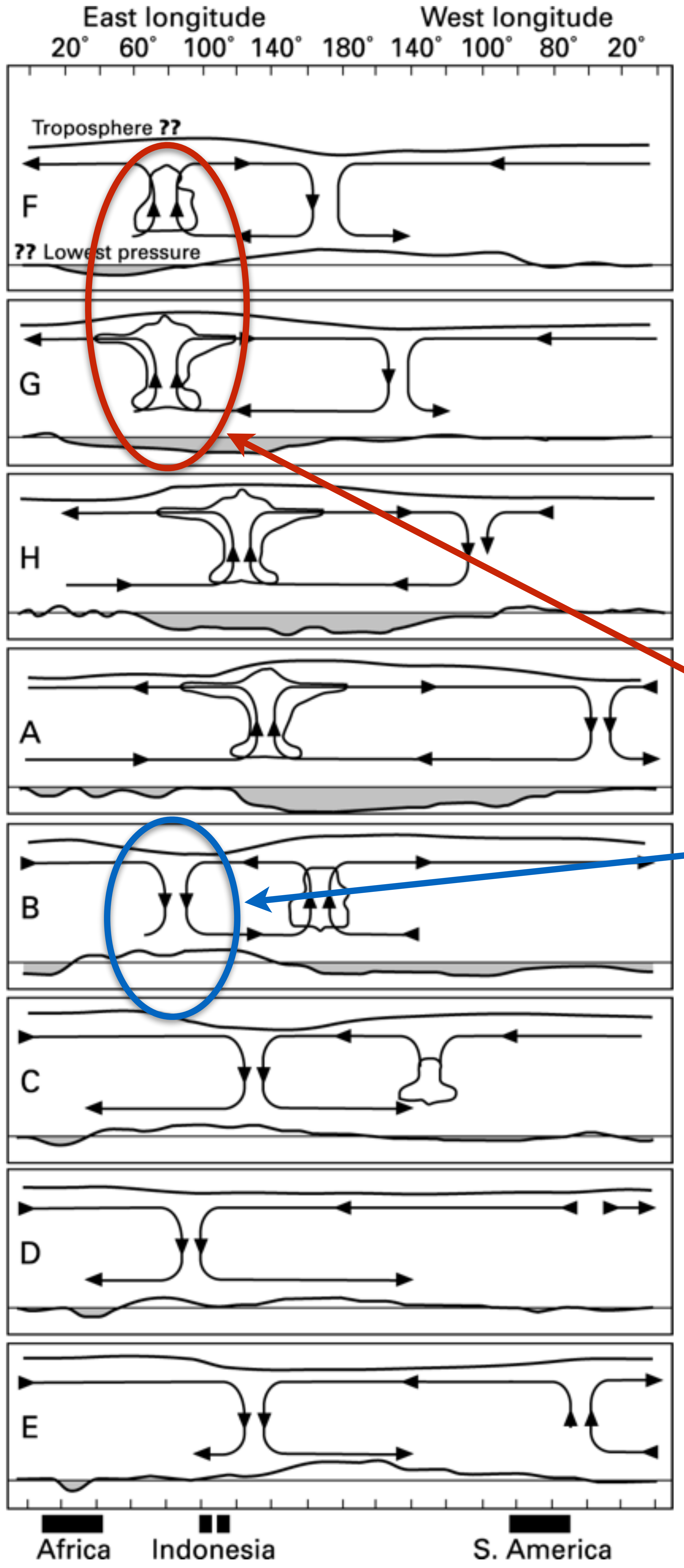
active phase

an eastward moving center of low pressure, strong deep convection, and precipitation

inactive phase

active phases are sandwiched by regions of high pressure, with weak deep convective activity and little precipitation

Madden & Julian, *J. Atmos. Sci.* 1972

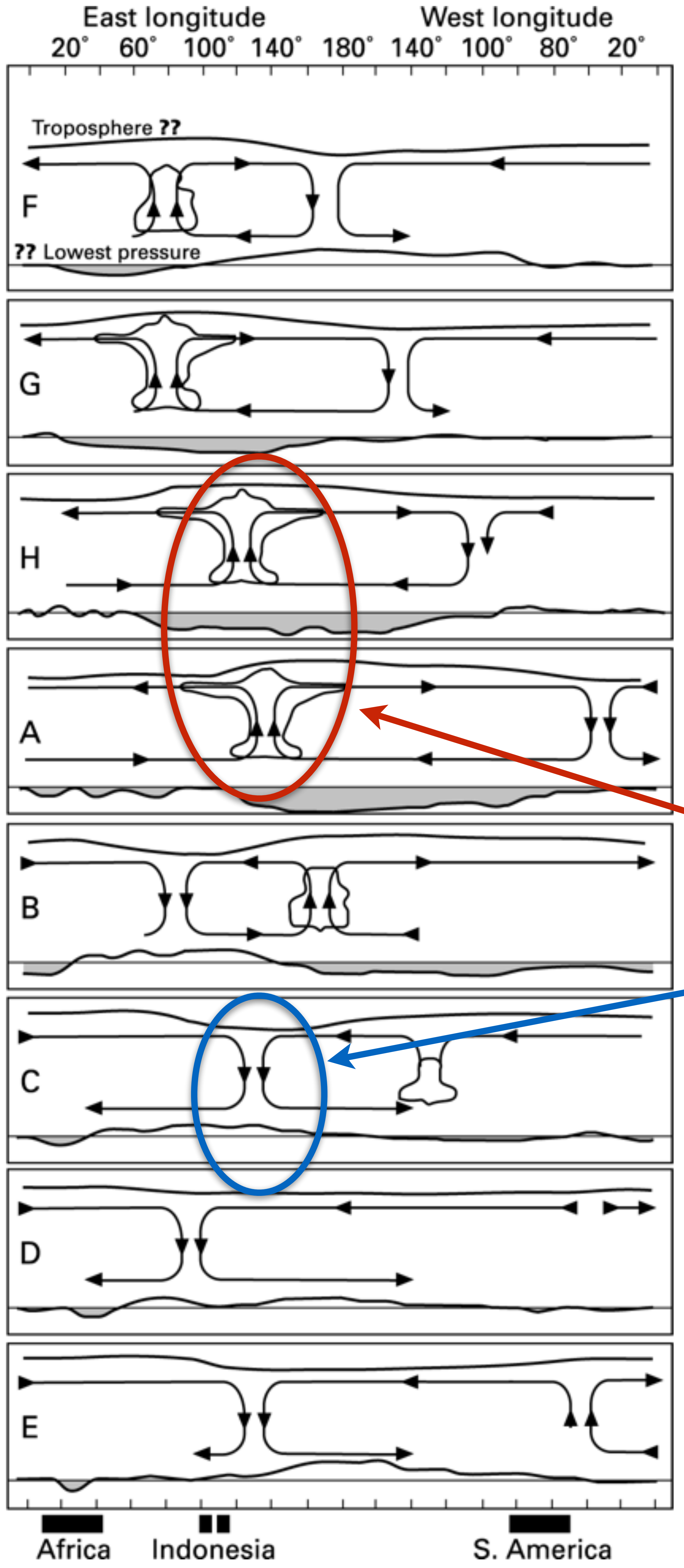


The MJO

A mode of natural variability in the tropical climate system characterized by planetary spatial scale, intraseasonal (30–60 day) time scale, and eastward propagation

both phases tend to initiate over the Indian Ocean…

Madden & Julian, *J. Atmos. Sci.* 1972



The MJO

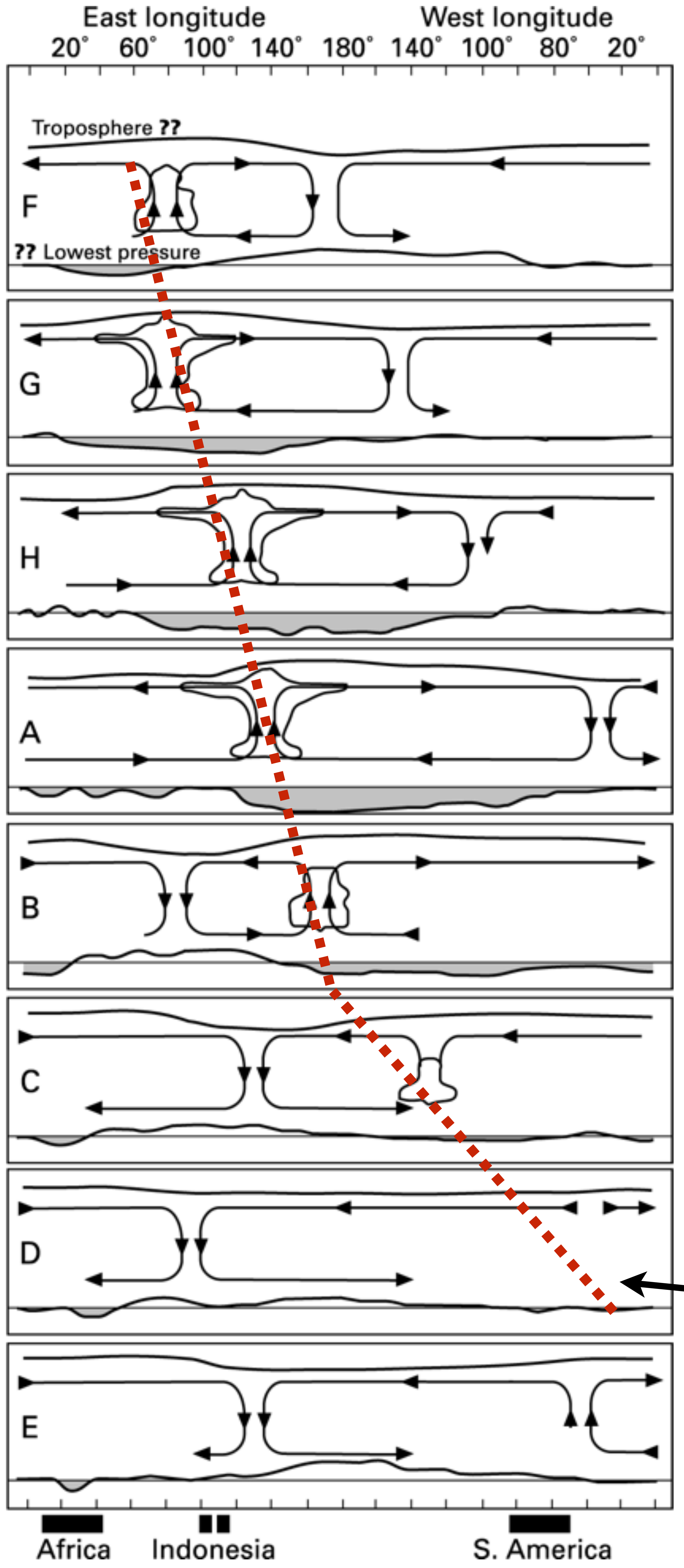
A mode of natural variability in the tropical climate system characterized by planetary spatial scale, intraseasonal (30–60 day) time scale, and eastward propagation

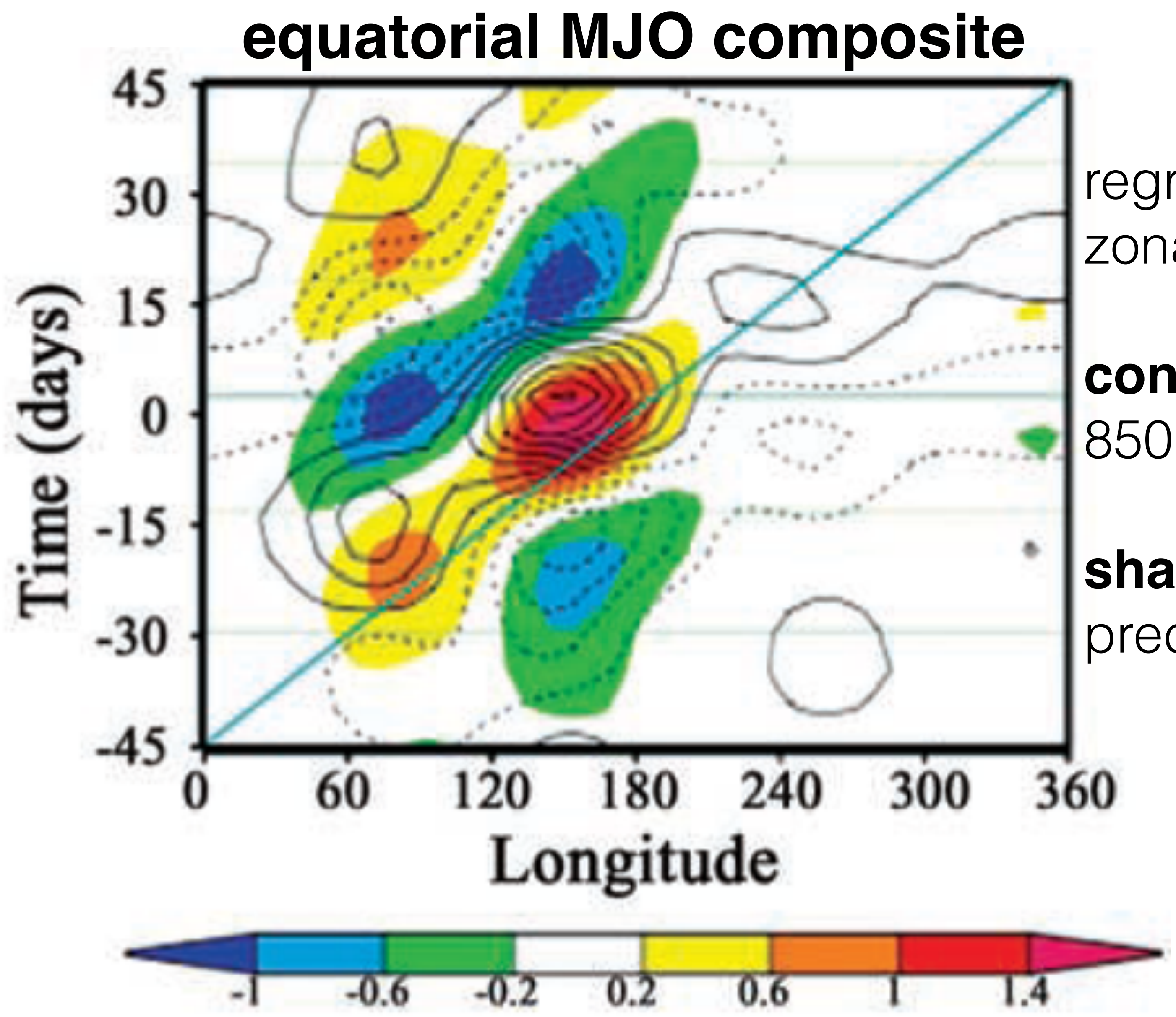
… and then propagate across Indonesia into the western Pacific at a speed of ~5 m s^{-1}

Madden & Julian, *J. Atmos. Sci.* 1972

The MJO

A mode of natural variability in the tropical climate system characterized by planetary spatial scale, intraseasonal (30–60 day) time scale, and eastward propagation





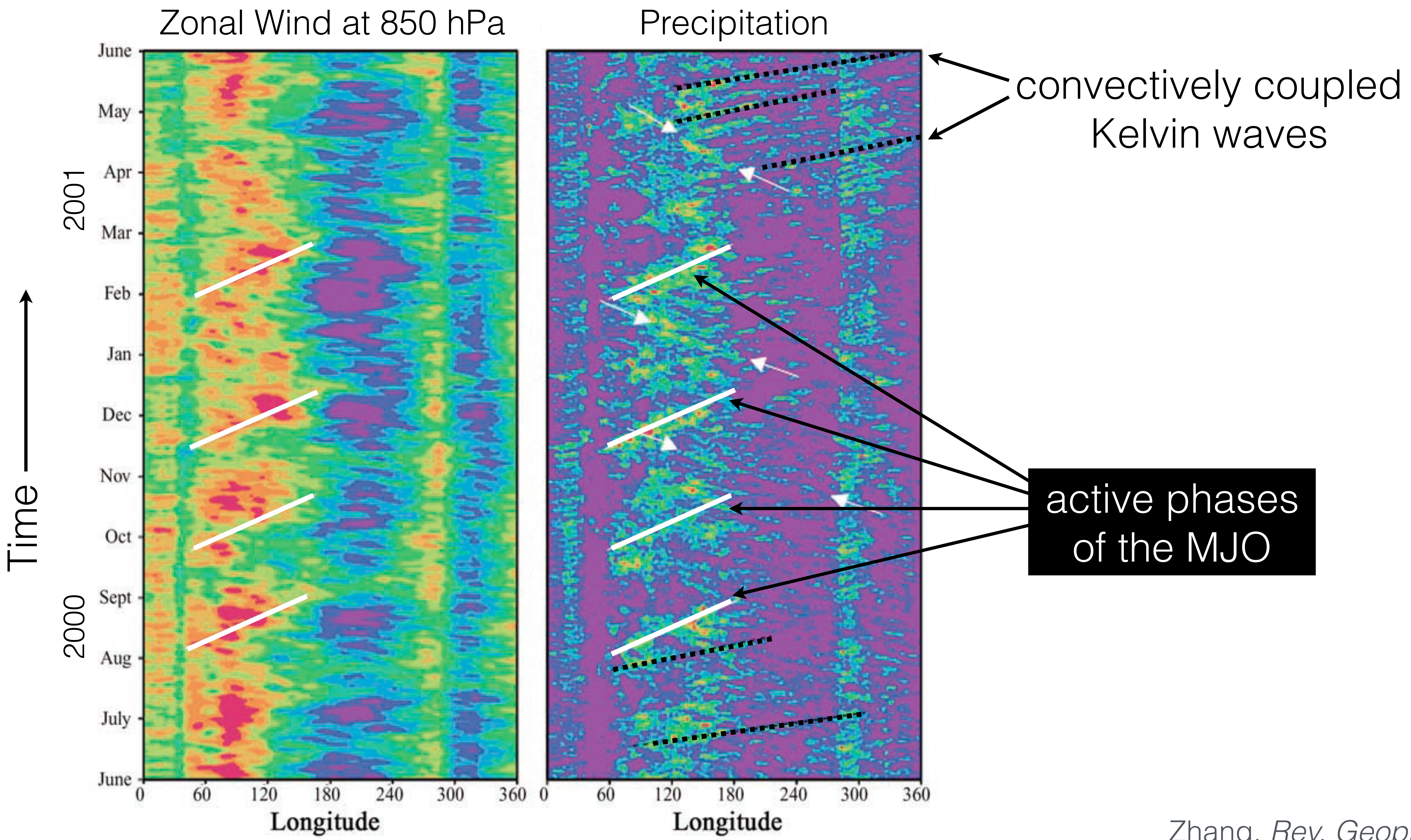
regressions against zonal wind at 160°E

contours: 850 hPa zonal wind

shading: precipitation

circulation anomalies continue moving eastward into the eastern Pacific, across the Americas, and into the Atlantic, but at a faster propagation speed (~15 m s^{-1}) and with smaller changes in rainfall.

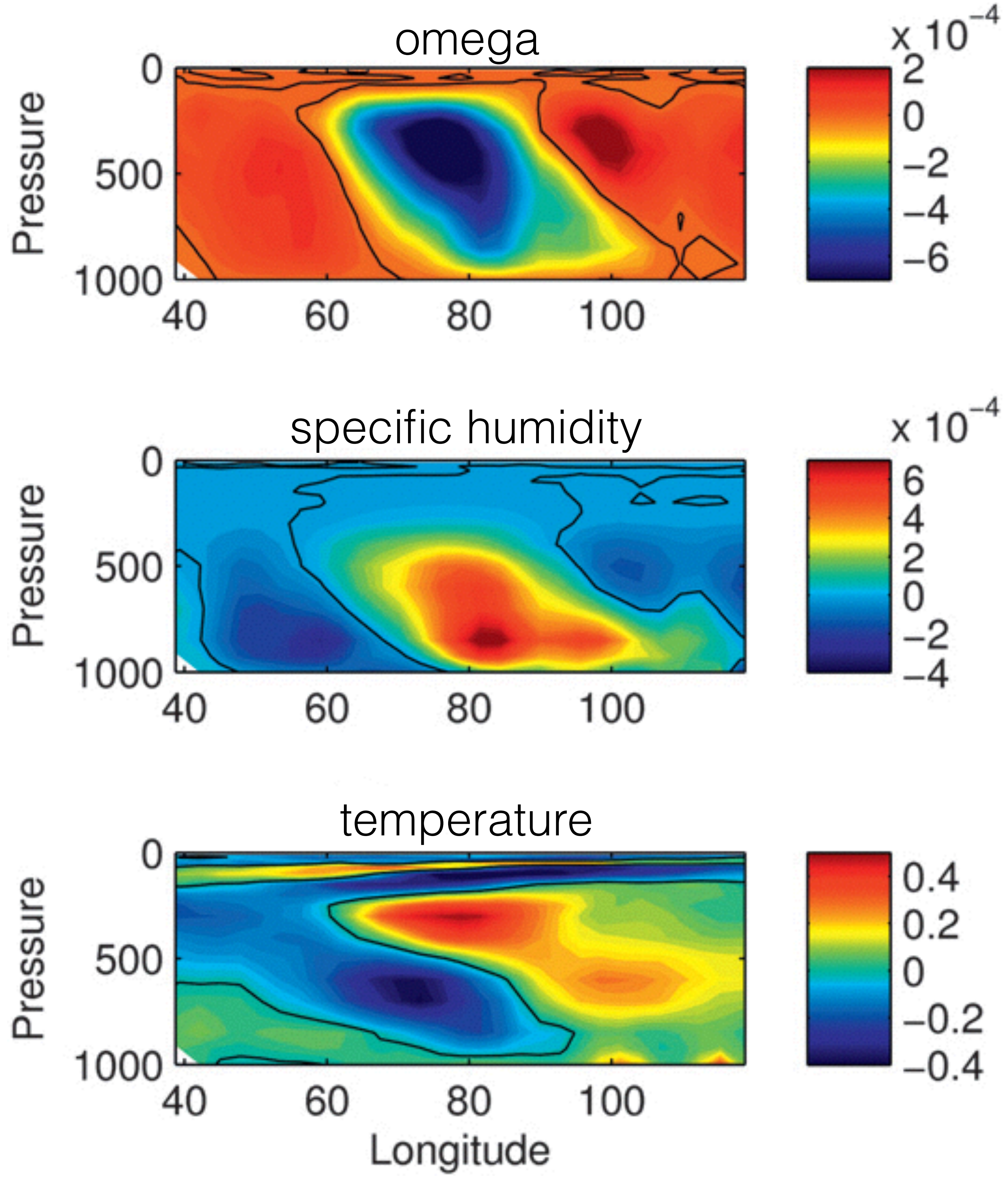
Madden & Julian, *J. Atmos. Sci.* 1972



Zhang, *Rev. Geophys.* 2005

Convectively Coupled Kelvin Waves

- equatorial waves characterized by eastward propagation and zero meridional velocity
- propagate by interactions between buoyancy and pressure gradients
- draw energy from interactions with tropical deep convection



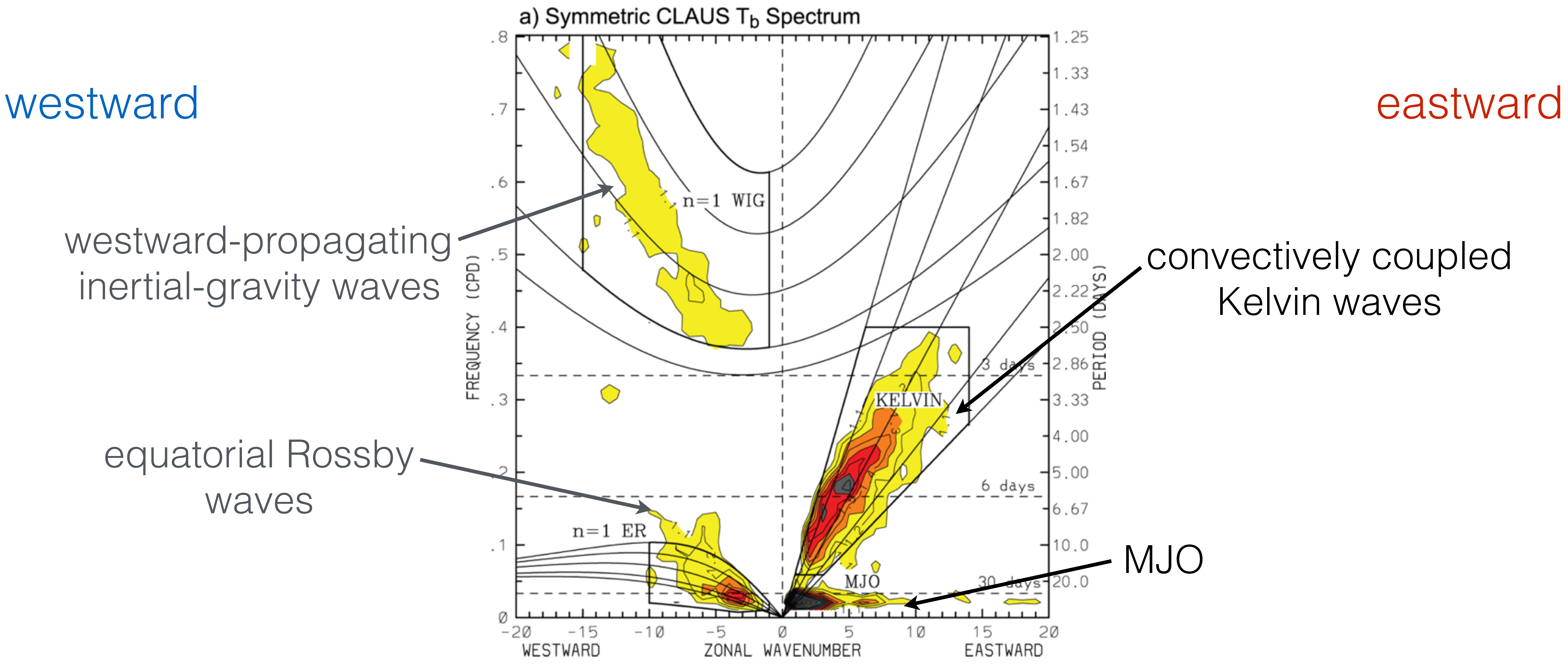
Kelvin wave composites

- anomalies around 78°E and equator
- convection and precipitation propagate with the wave, maintaining it
- moistening of boundary layer and middle troposphere
- warm over cold temperature anomalies
- baroclinic mode driven by diabatic heating
- similarities, but should not be mistaken for the MJO!

Frierson et al., *J. Atmos. Sci.* 2011

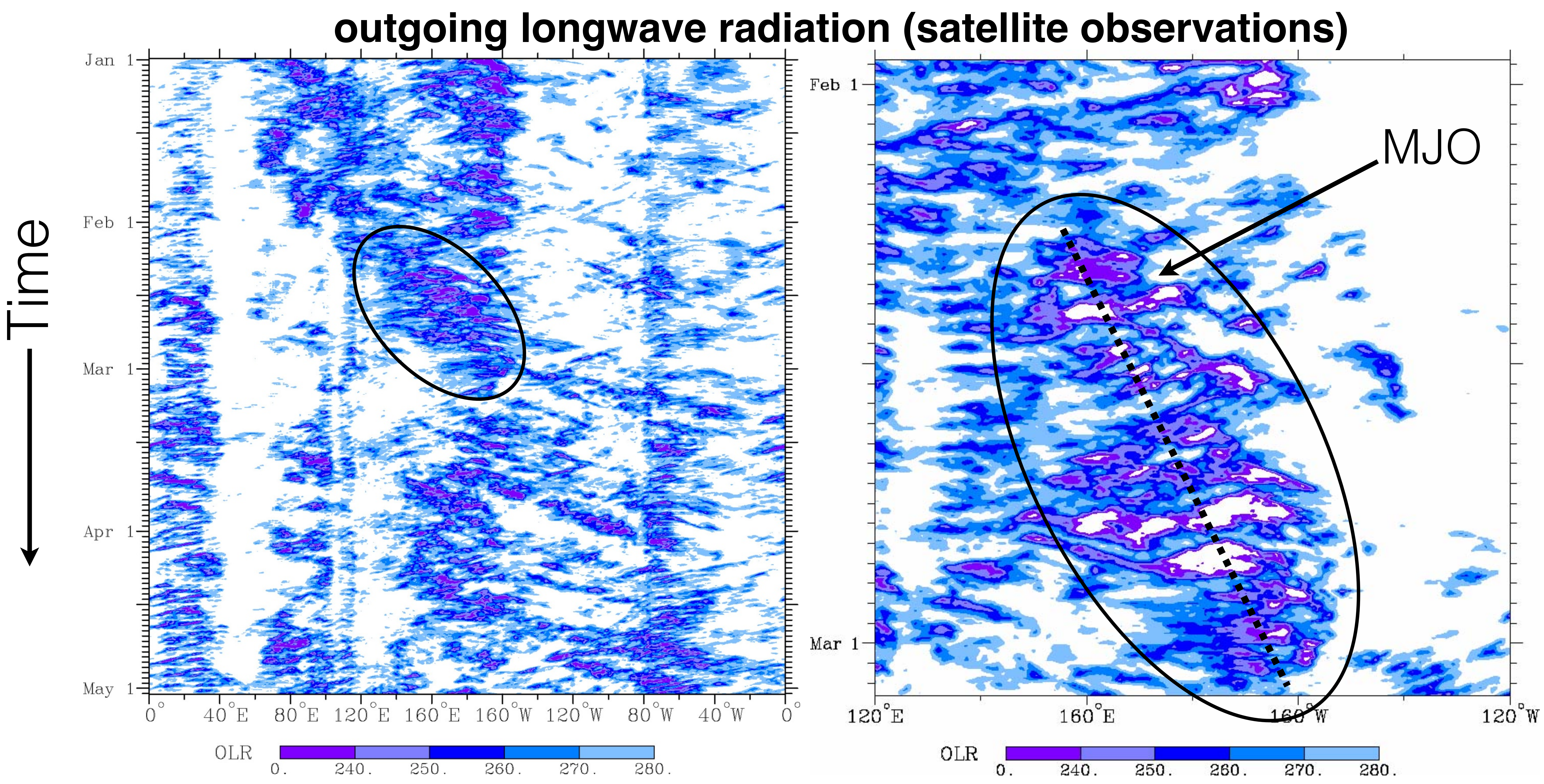
Convectively Coupled Kelvin Waves

- shorter periods, faster propagation, shorter wavelengths and larger wave numbers than the MJO



Kiladis et al., *Rev. Geophys.* 2009

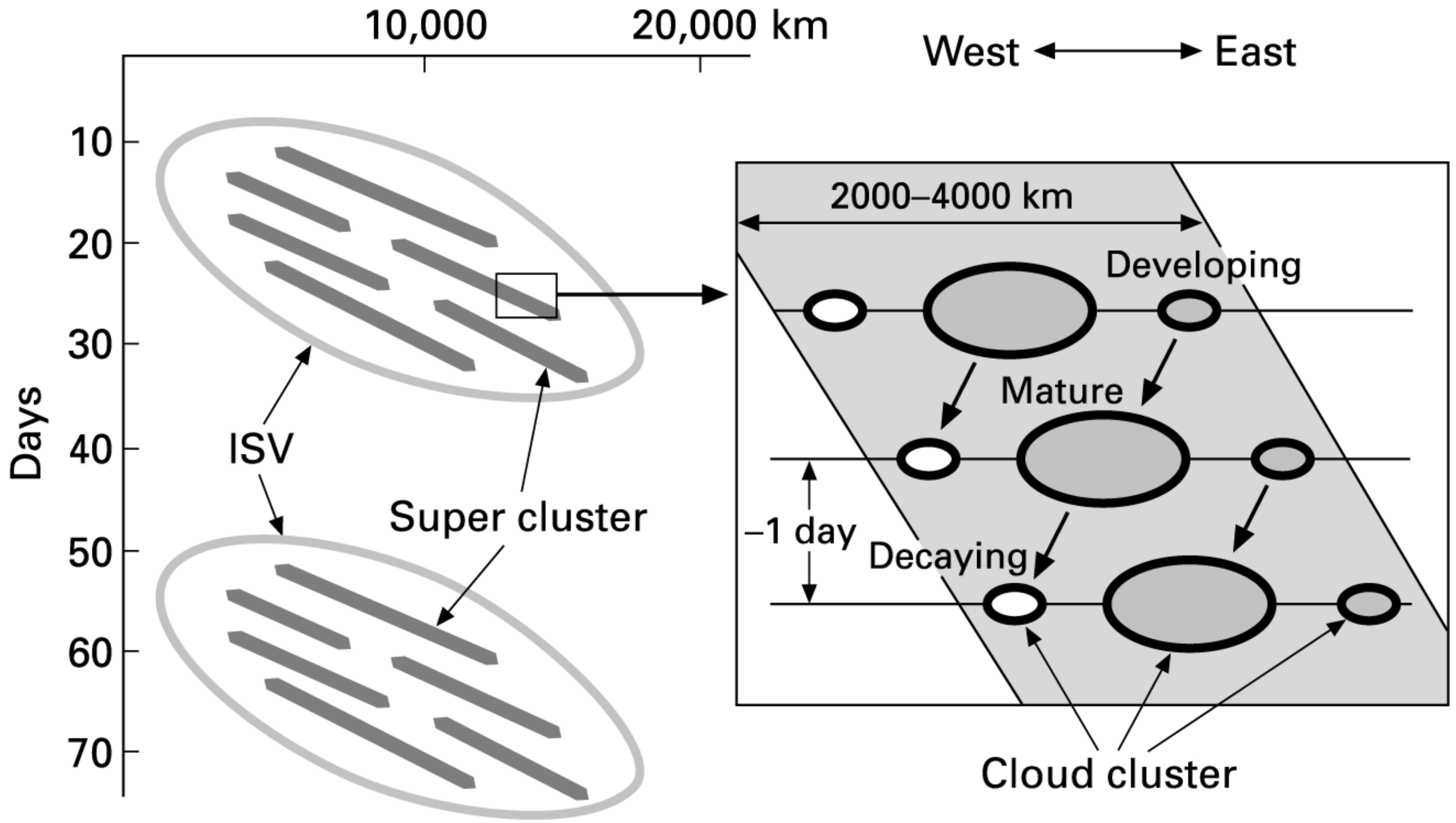
The MJO is not a Single Convective System



A large-scale ensemble of higher-frequency smaller-scale convective systems moving in multiple directions

Chen et al., *J. Atmos. Sci.* 1996

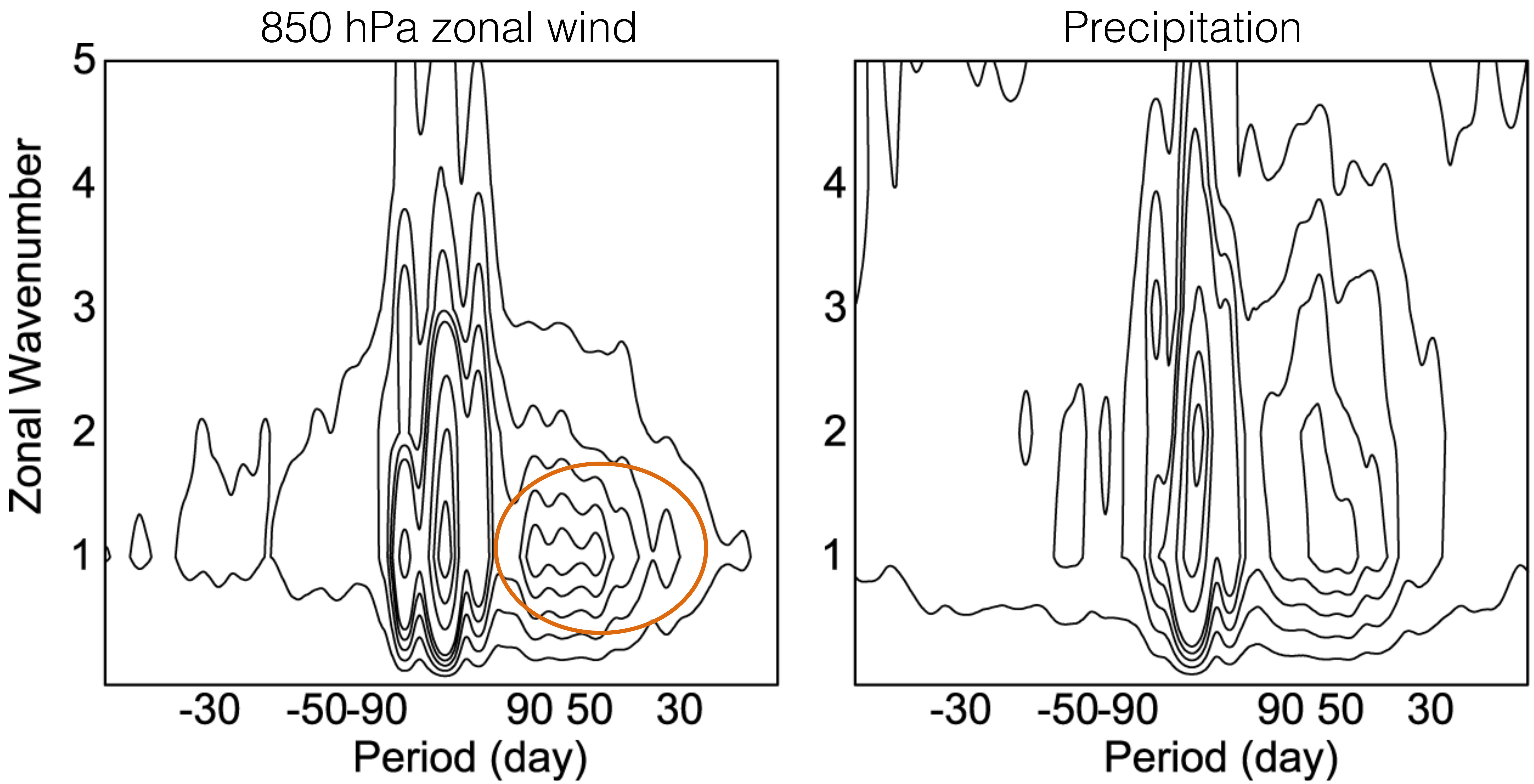
The MJO is not a Single Convective System



Nakazawa, *J. Meteorol. Soc. Japan* 1989

Large-Scale Structure of the MJO

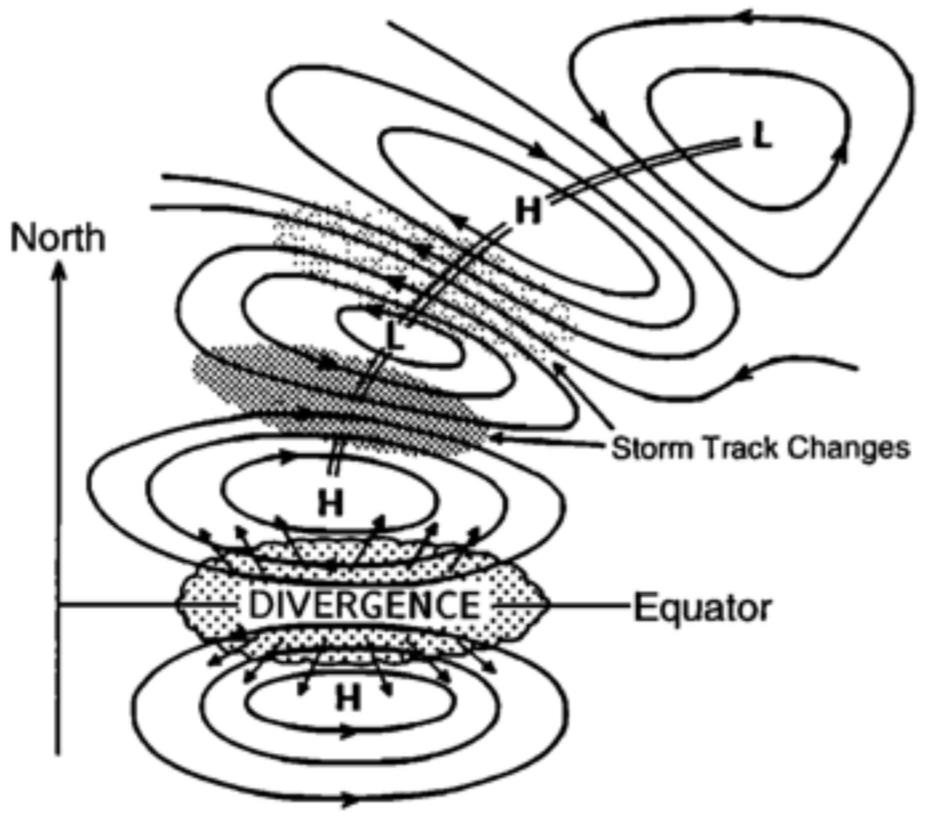
The MJO propagates eastward, with only one fully-formed MJO event in the tropics at any given time



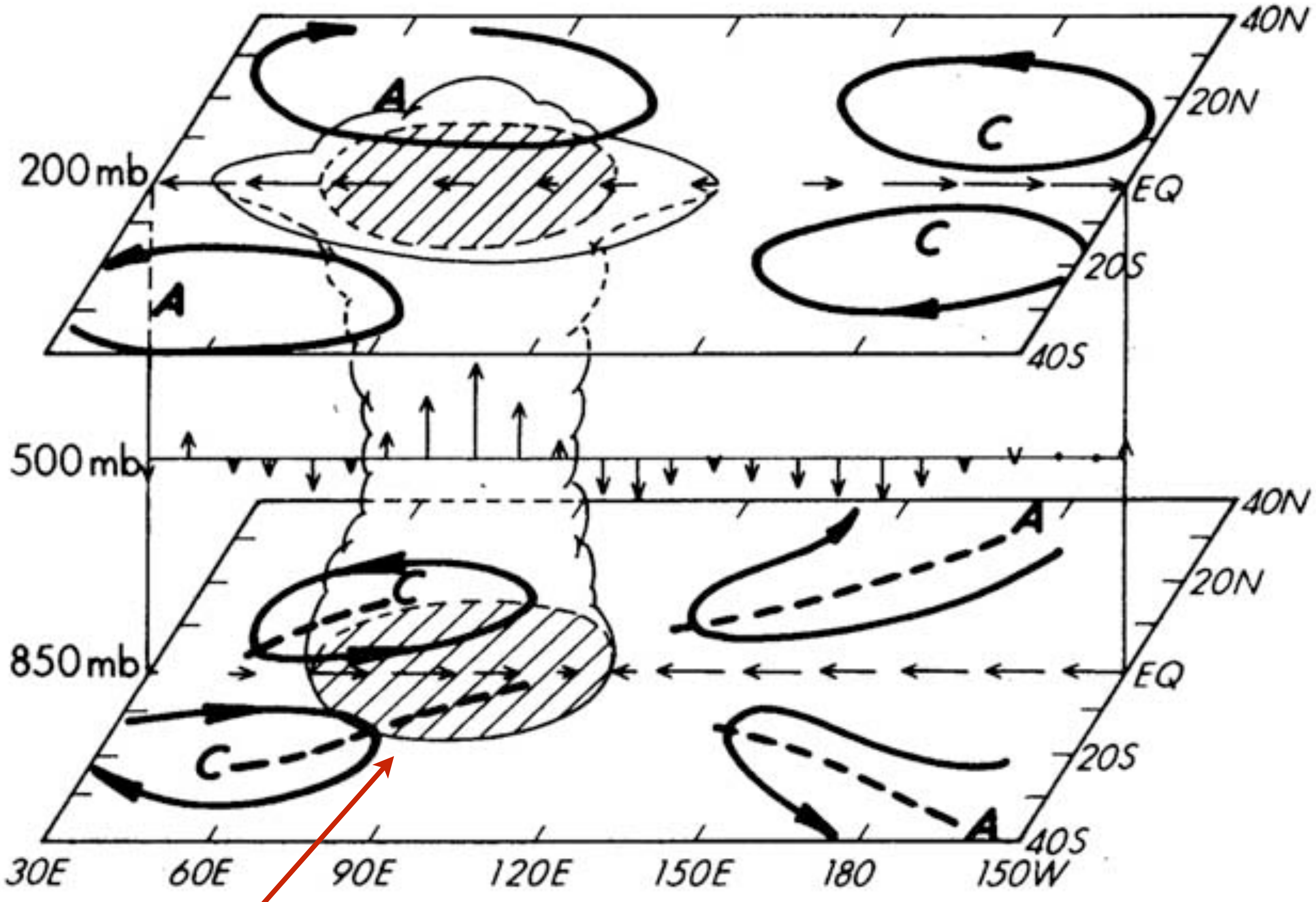
Zhang, *Rev. Geophys.* 2005

Large-Scale Structure of the MJO

Circulation patterns and the associated diabatic heating can affect weather in remote locations



Rossby wave
Upper-level easterlies
& low-level westerlies



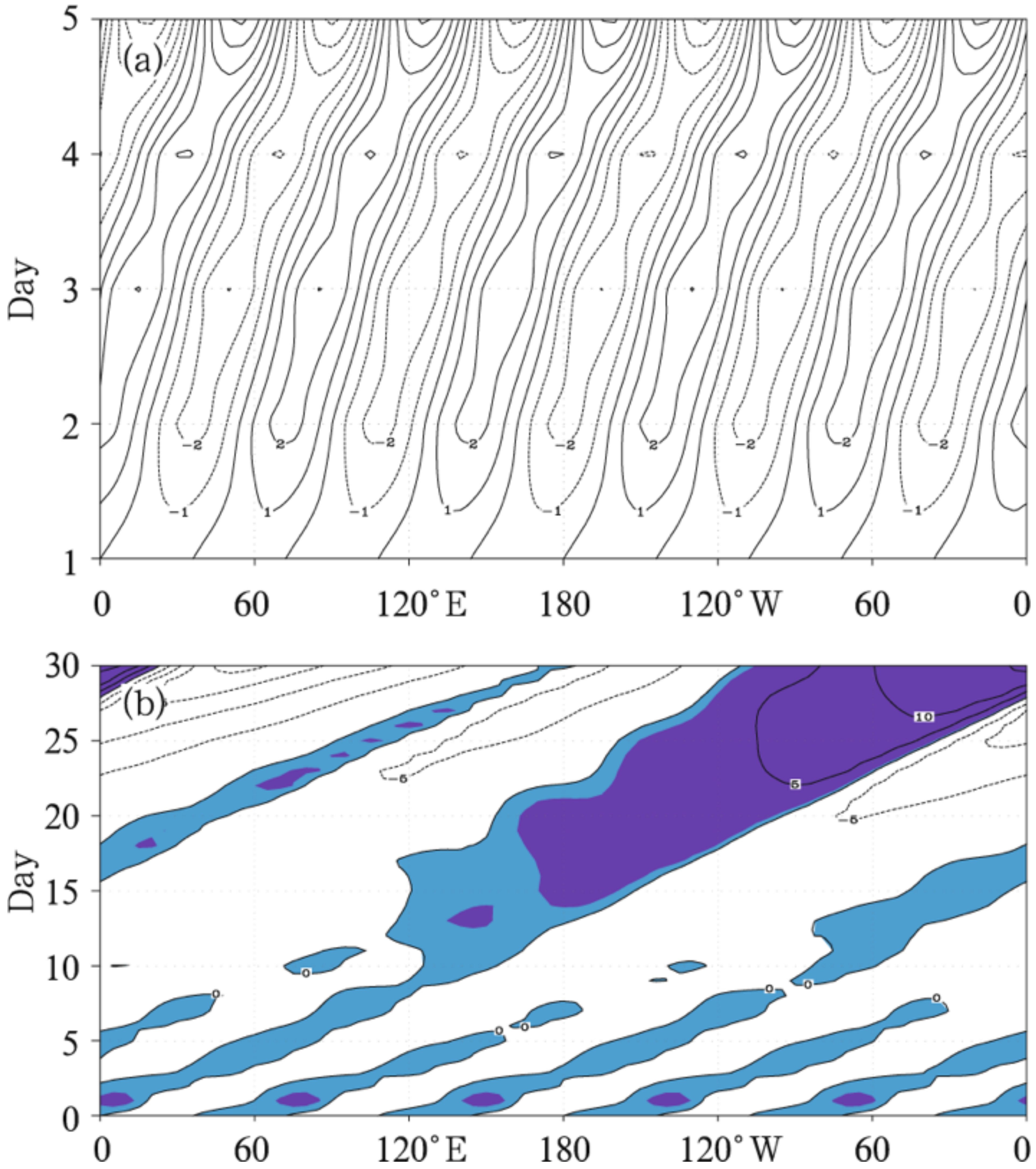
Kelvin wave
Upper-level westerlies
& low-level easterlies

MJO active phase

Rui and Wang, *J. Atmos. Sci.* 1990

Large-Scale Structure of the MJO

The planetary scale of the MJO can be understood as a large-scale response to localized heating



Assume MJO-related heating proportional to vertically-integrated moisture convergence via a constant δ

Linearized heating (δ=1 for both convergence and divergence)

- Initialize wavenumber *n*, wavenumber *n* grows exponentially
- Moist and dry Kelvin waves have same propagation speed

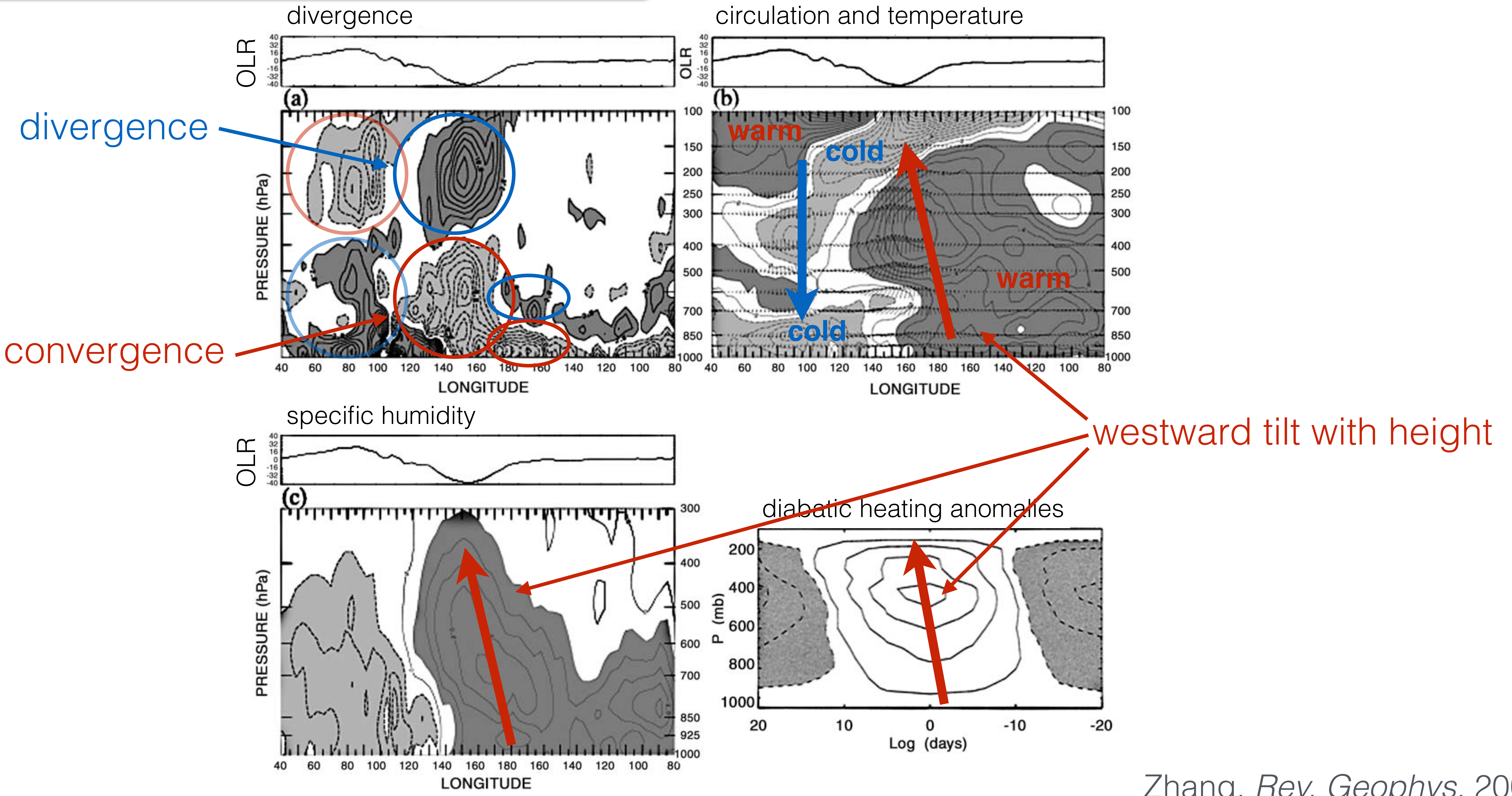
Nonlinear heating (δ=1 for convergence and 0 for divergence)

- Initialize wavenumber *n*, transitions to wavenumber 1
- Dry Kelvin waves have faster propagation speed
- Dry Kelvin waves 'catch up' and suppress moist waves within some critical distance
- Critical distance depends on phase speed of dry wave (~50 m s–1) divided by damping coefficient: ~160° in longitude

Li and Zhou, *J. Atmos. Sci.* 2009

Large-Scale Structure of the MJO

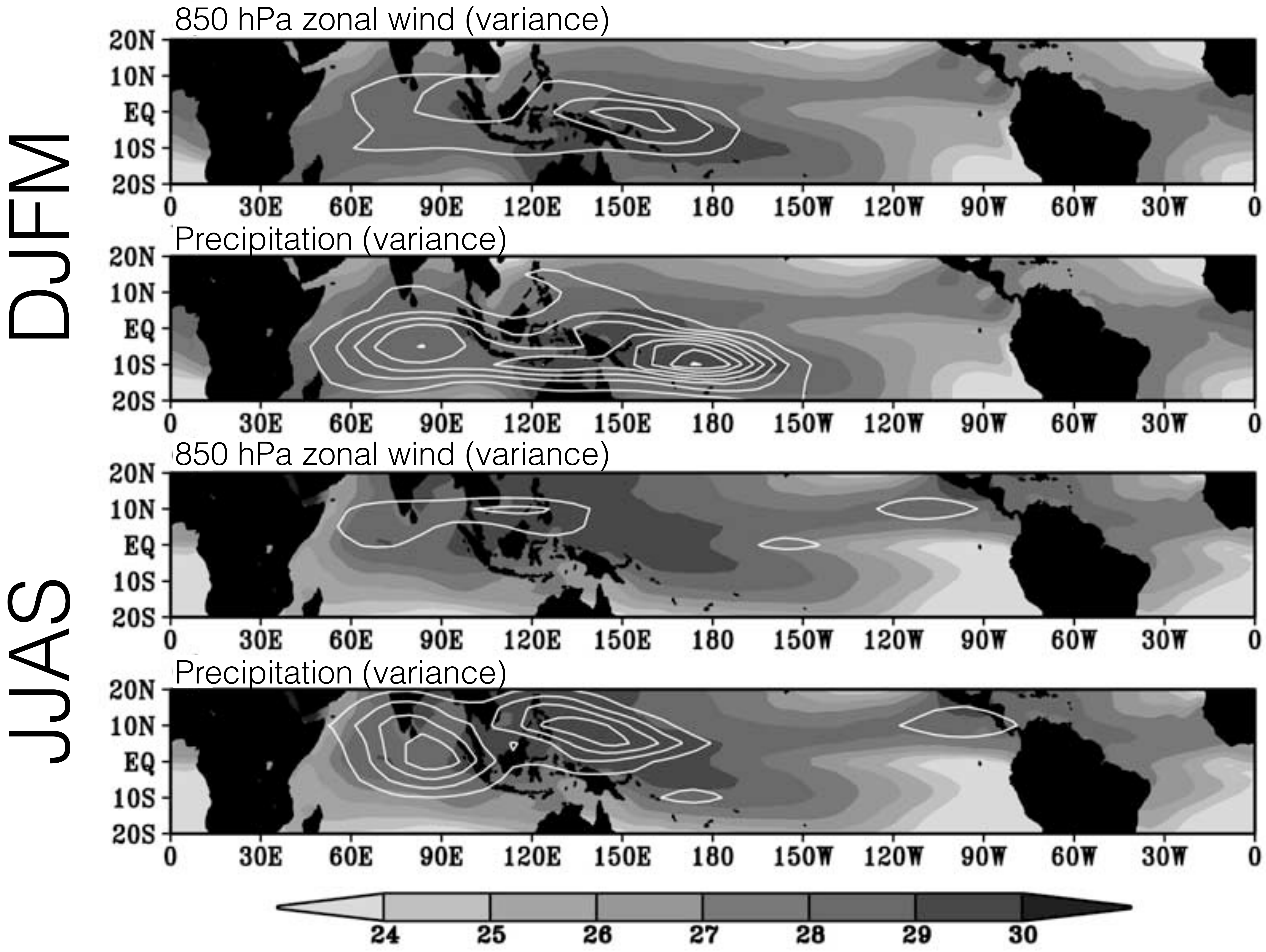
shallow convection leads, followed by deep convection and stratiform precipitation



Zhang, *Rev. Geophys.* 2005

Seasonality of the MJO

MJO is most active in the summer hemisphere, and is stronger during austral summer than during boreal summer



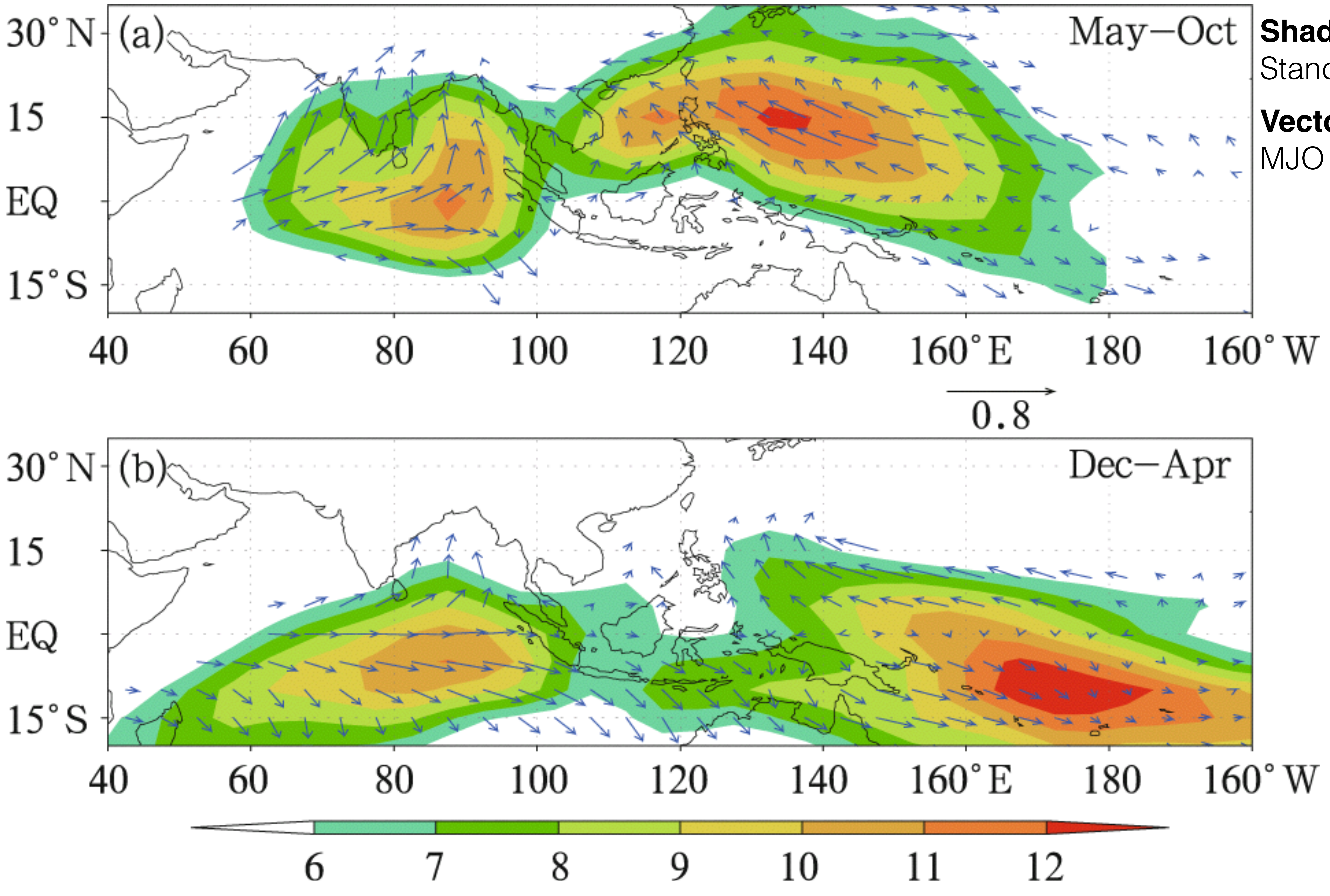
Shading:
Mean SST

The main part of MJO variability is confined to the Indian Ocean and Western Pacific during all seasons, but the seasonality is largest in the Western Pacific

Zhang, *Rev. Geophys.* 2005

Seasonality of the MJO

The propagation of the MJO differs substantially between boreal winter and boreal summer



Shading
Standard deviation of filtered precipitation

Vectors:
MJO propagation

MJO mainly propagates eastward along the equator during boreal winter, but northward over the Indian Ocean and northwestward over the Western Pacific during boreal summer.

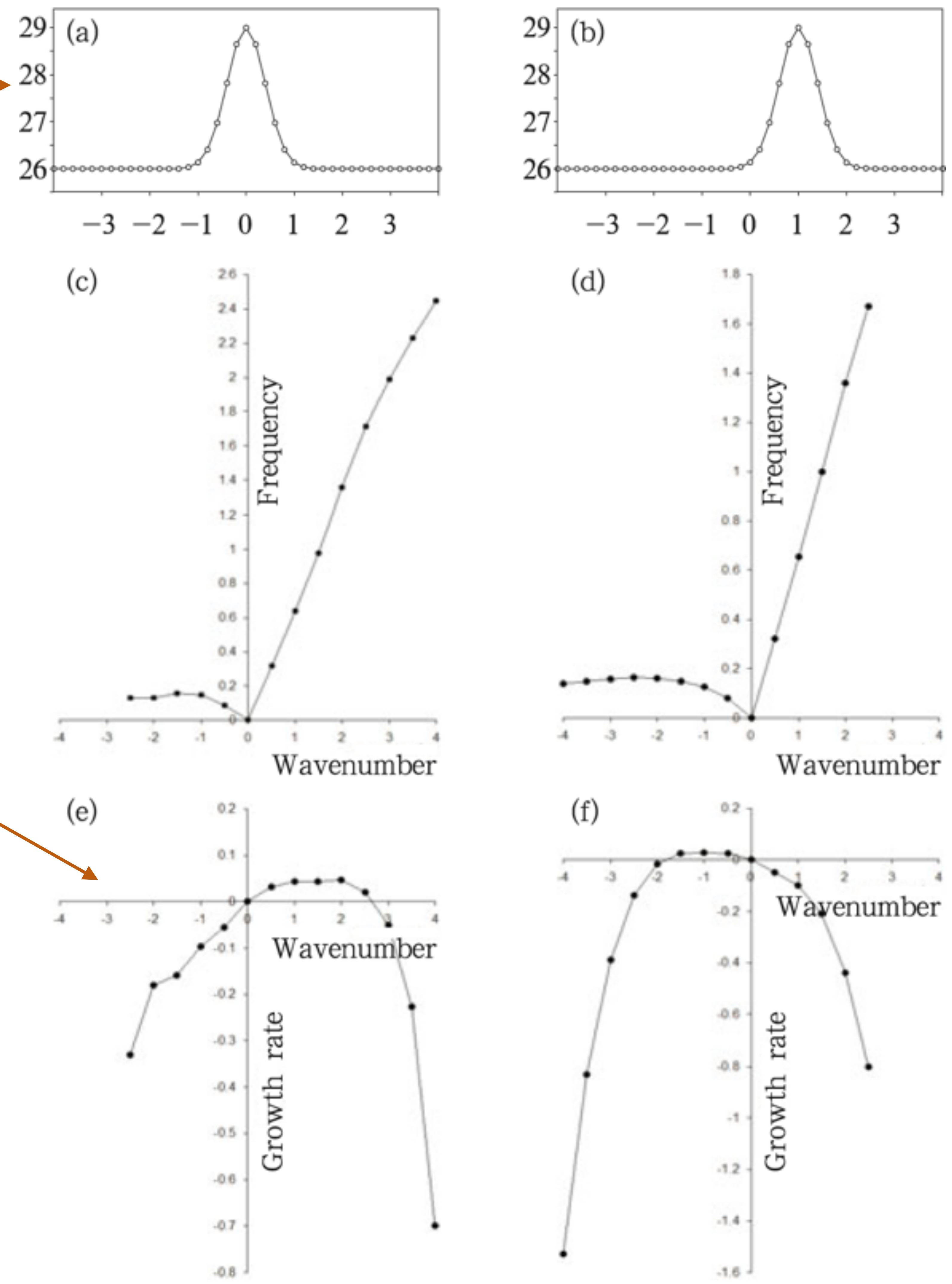
Li, *J. Meteorol. Res.* 2014

Seasonality of the MJO

These differences in propagation can be understood in terms of the dynamical (wave) response to convective heating anomalies

Peak SSTs are located near the equator (less than one Rossby deformation radius away) during boreal winter, but well north of the equator (more than one Rossby deformation radius away) during boreal summer.

This distribution of SST means that the Kelvin wave response grows and the Rossby wave response decays during boreal winter, while the Rossby wave response grows and the Kelvin wave response decays during boreal summer. Kelvin waves propagate in the zonal direction (east along the equator), while Rossby waves propagate in the meridional direction (north away from the equator)



Top panels:
Idealized SST distributions

Center panels:
Non-dimensional frequencies of the waves generated by convective heating

Lower panels:
Non-dimensional growth rates of the waves generated by convective heating

Li, *J. Meteorol. Res.* 2014

Seasonality of the MJO

The seasonality of the MJO in the Indian Ocean and Western Pacific is coherent with the seasonality of a variety of meteorological variables

(white contours = MJO strength)

sea surface temperatures

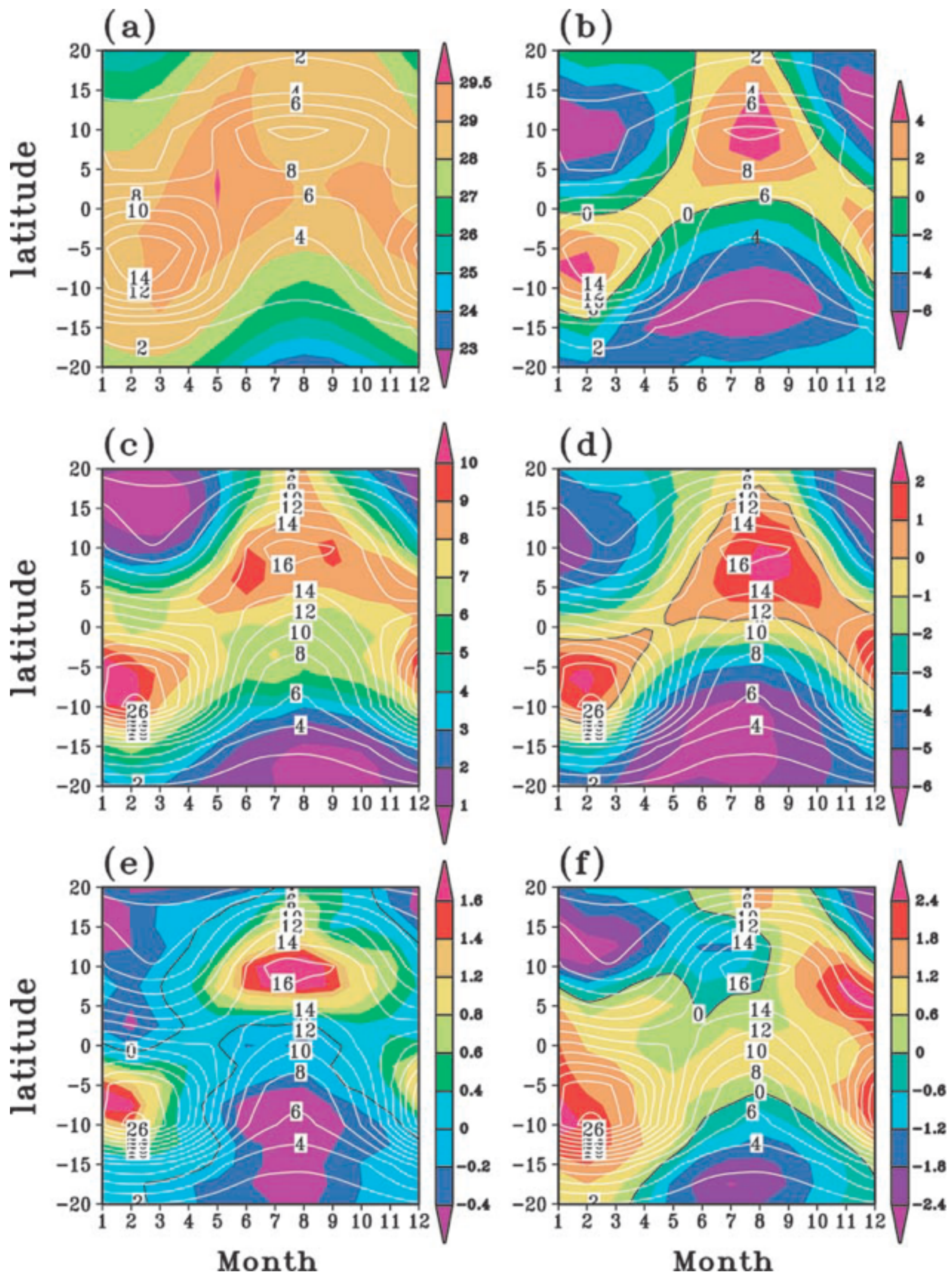
850 hPa zonal winds

precipitation

surface zonal winds

850 hPa moisture convergence

925 hPa moisture convergence



Zhang & Dong, *J. Climate* 2004

Describing the MJO: EOF Analysis

- a mathematical tool that describes the modes of spatial variability in a time series
- the leading "modes" contain the largest amount of information about the variability of the system
- does not necessarily provide physically meaningful modes of variability, and requires careful interpretation
- EOF modes do not cause variability — they are descriptions of variability
- for the MJO, we can use the coherence among OLR and tropospheric winds (i.e., convection and circulation anomalies) to create a multivariate EOF-based description of the state of the MJO

Wheeler & Hendon, *Mon. Wea. Rev.* 2004

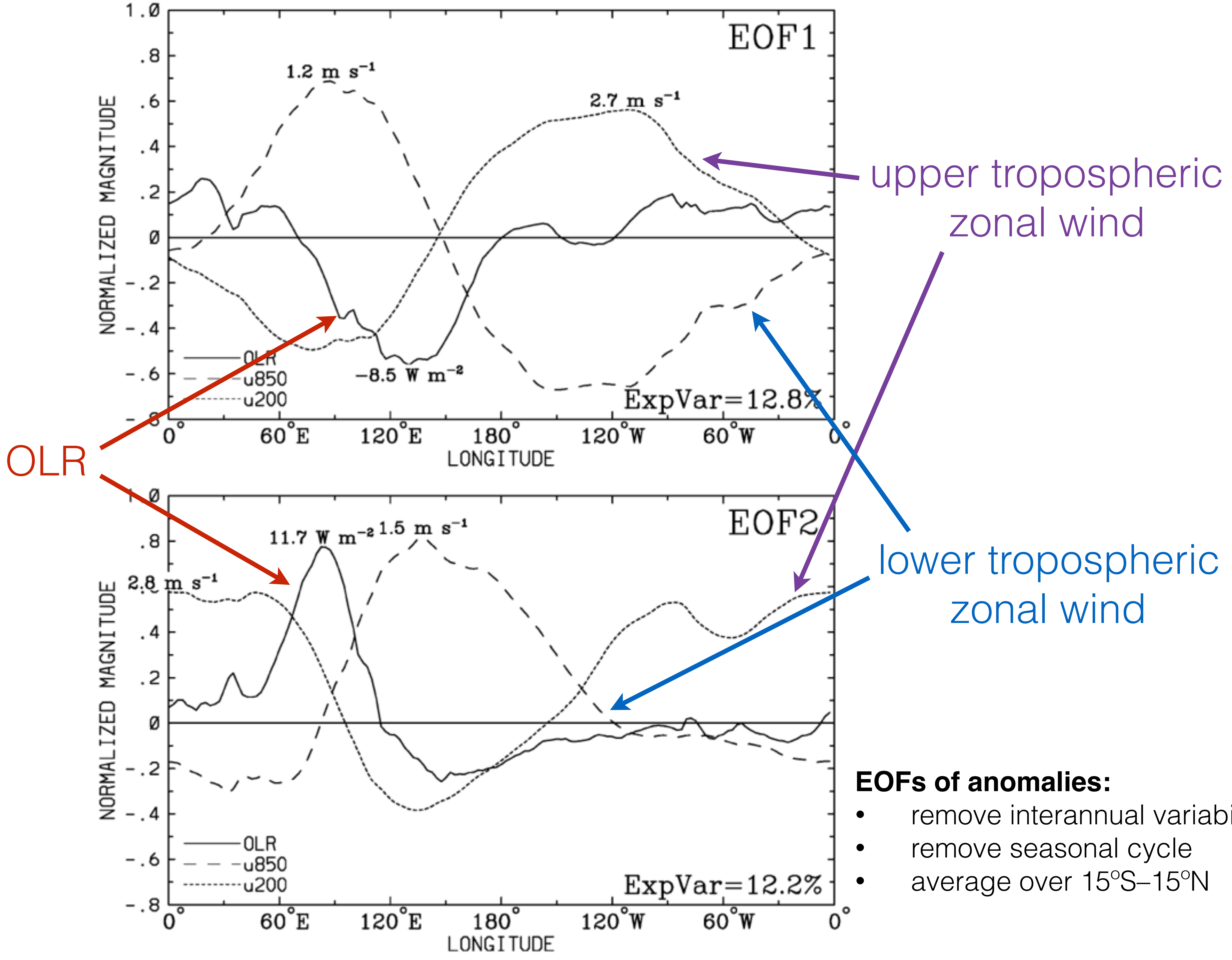
Describing the MJO: EOF Analysis

- **Realtime Multivariate MJO Index (RMM)**: Based on the first two EOFs of combined fields of near-equatorially-averaged 850 hPa zonal wind, 200 hPa zonal wind, and satellite-observed OLR data. Projection of daily data onto these multiple-variable EOFs (with the annual cycle and ENSO-related variability removed) yields principal component (PC) time series that vary mainly on the intraseasonal MJO time scale. This projection serves as an effective filter for the MJO without the need for time filtering, making the PC time series an effective index for real time use.
- **OLR MJO Index (OMI)**: projection of 20-96 day filtered OLR onto the daily spatial EOF patterns of 30-96 day eastward filtered OLR (not latitudinally averaged)
- **Filtered-OLR MJO Index (FMO)**: univariate EOF of normalized 20-96 day filtered OLR averaged from 15S-15N, using the same spatial EOF pattern for the entire year
- **Velocity Potential MJO Index (VPM)**: calculated in the same way as RMM, but using 200 hPa velocity potential (which indicates upper tropospheric divergence) instead of OLR in the combined EOF

Wheeler & Hendon, *Mon. Wea. Rev.* 2004

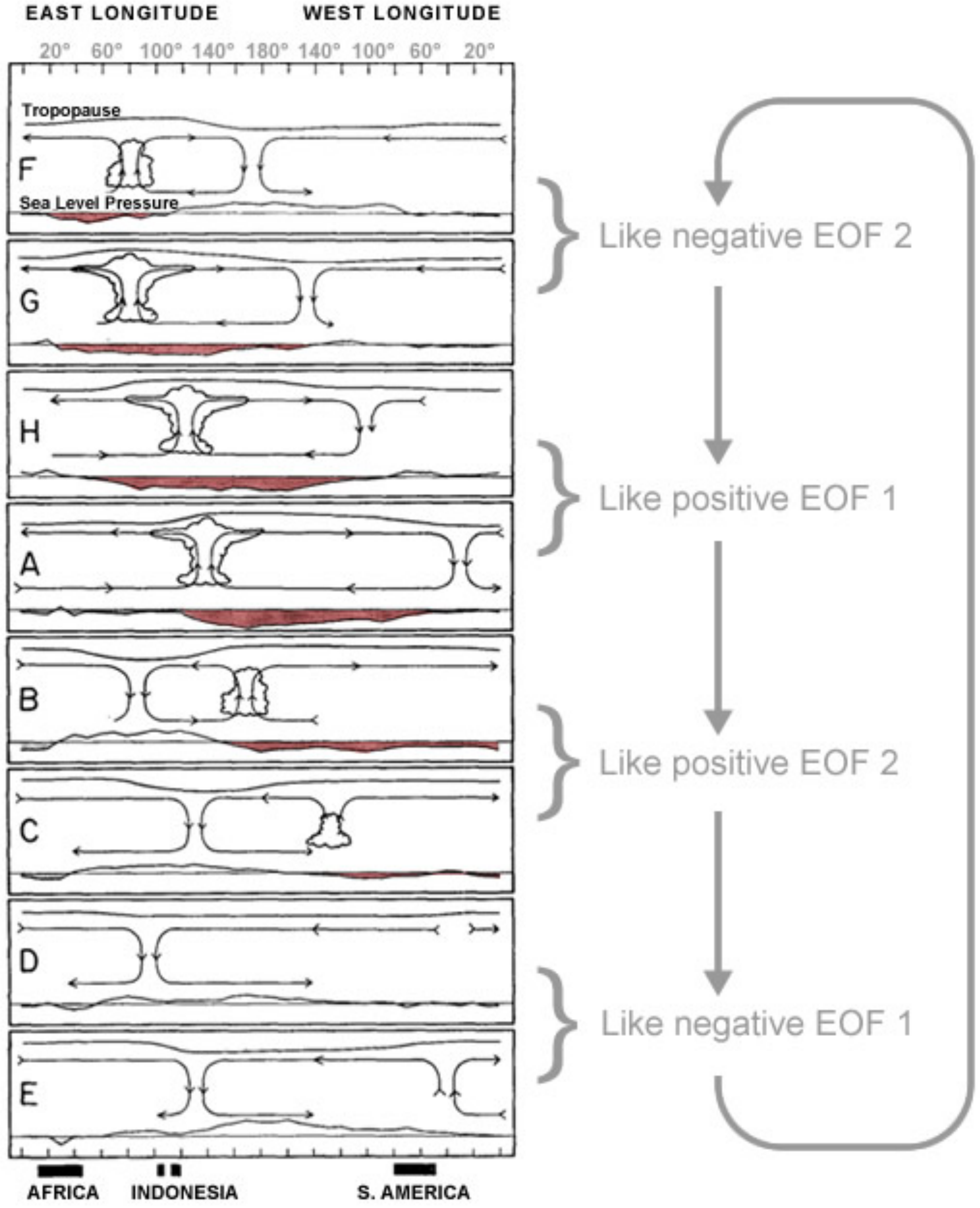
Describing the MJO: EOF Analysis

use coherence of OLR and winds to create a multivariate EOF-based description of the state of the MJO



EOFs of anomalies:

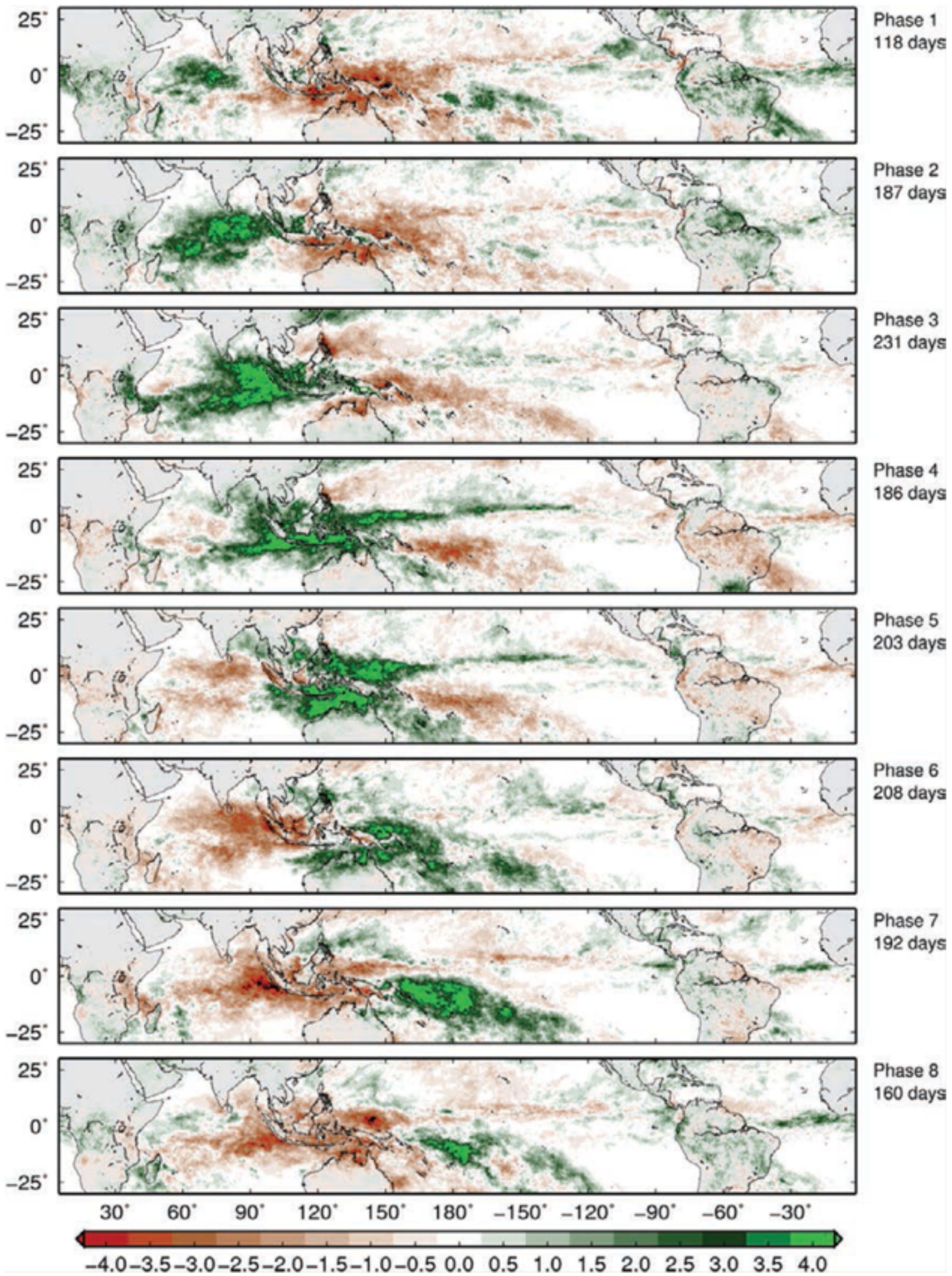
- remove interannual variability
- remove seasonal cycle
- average over 15ºS–15ºN



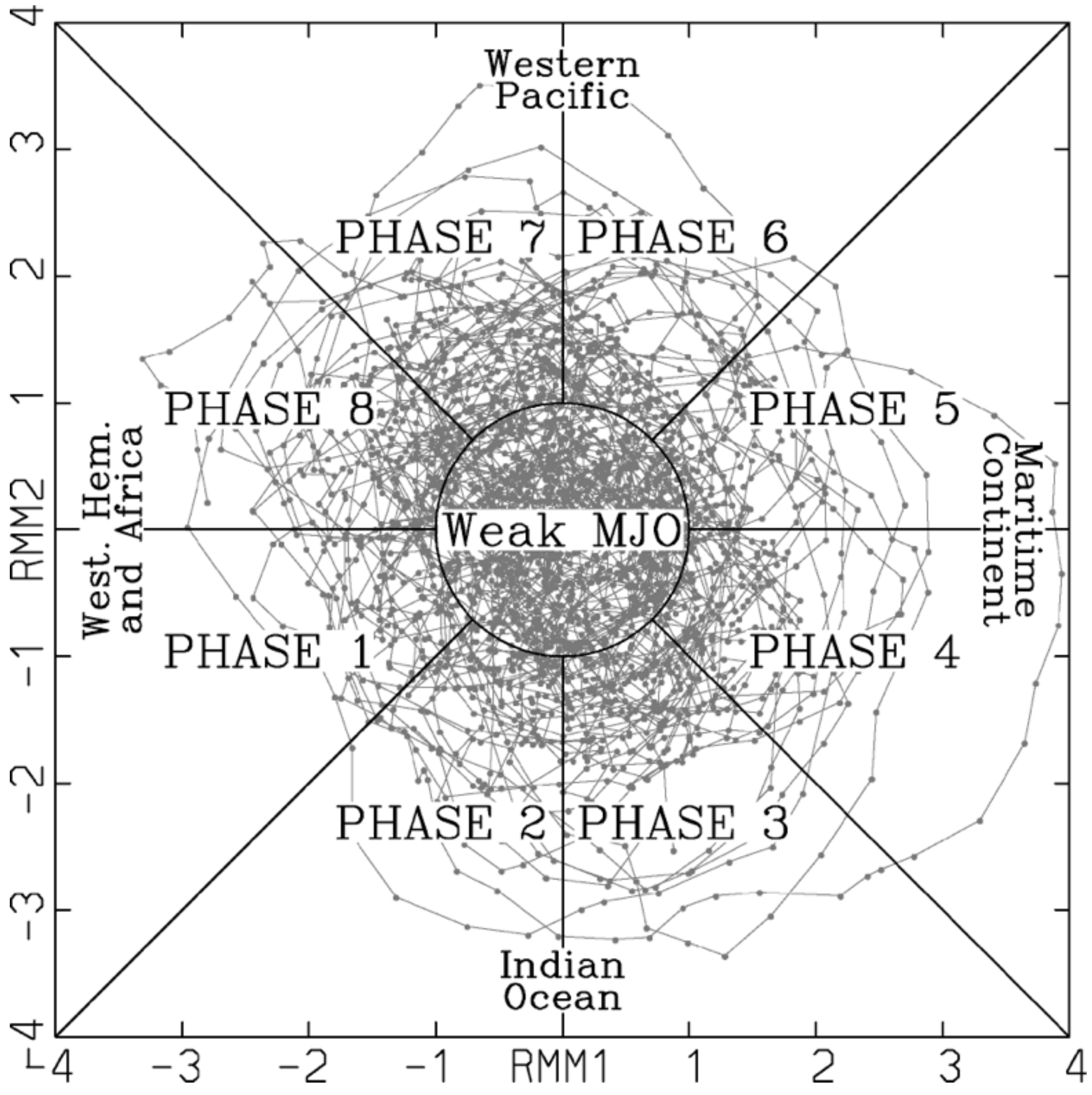
Wheeler & Hendon, *Mon. Wea. Rev.* 2004

Describing the MJO: EOF Analysis

anomalies of OLR and lower tropospheric winds associated with the phases of the MJO



TRMM precipitation anomalies by phase



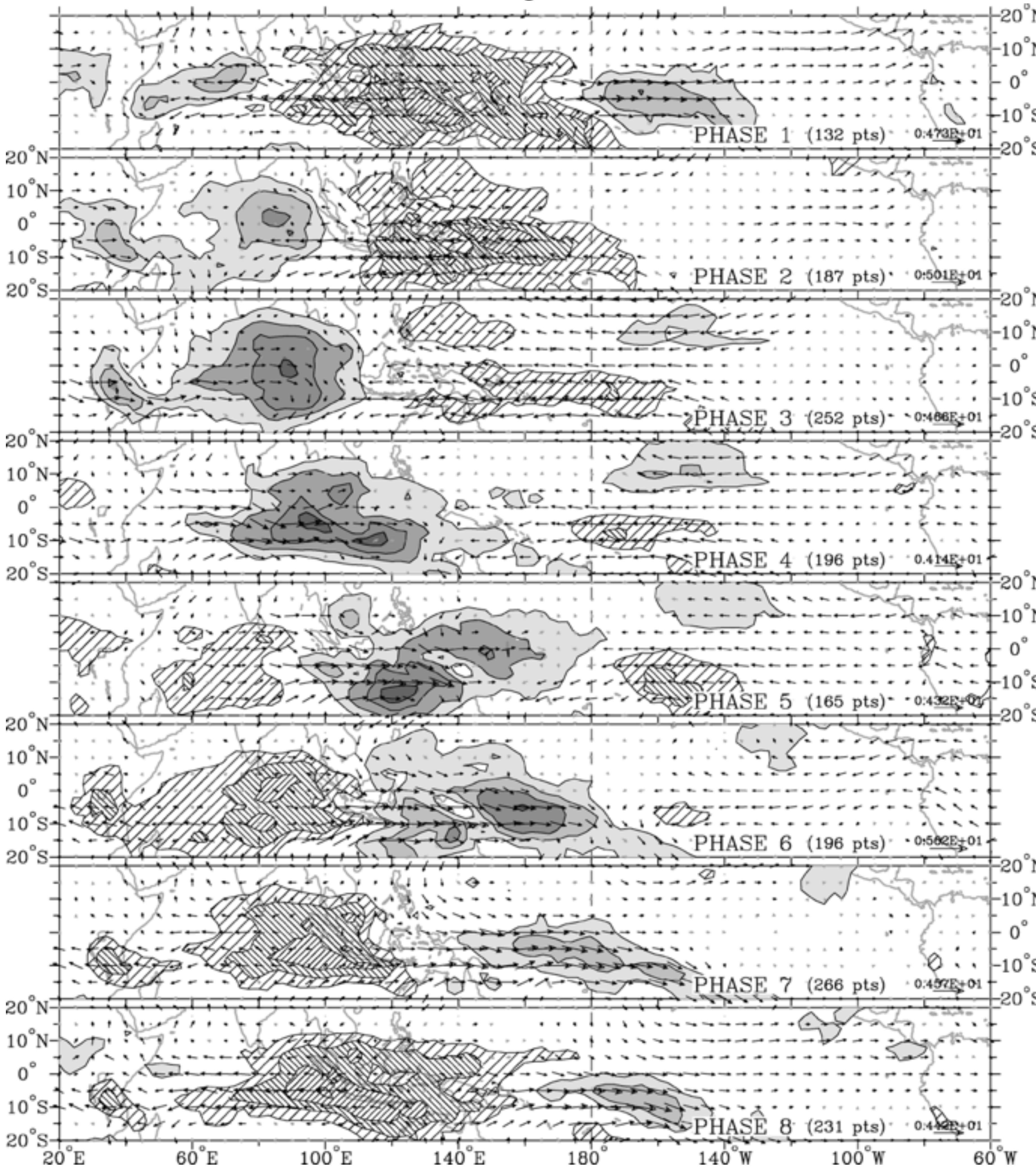
Zhang, *Bull. Am. Meteorol. Soc.* 2013

Describing the MJO: EOF Analysis

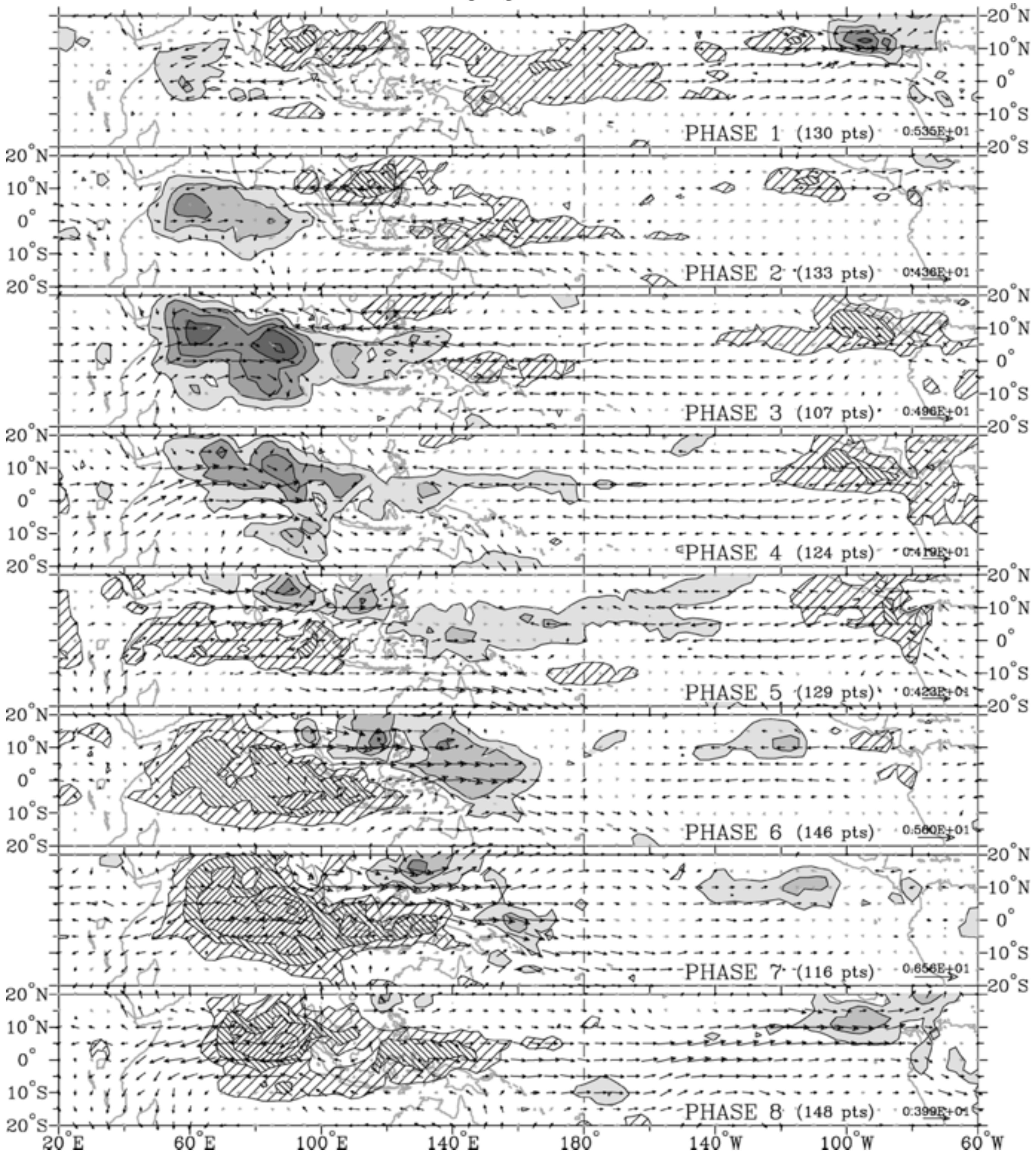
anomalies of OLR and lower tropospheric winds associated with the phases of the MJO

DJF

Phase 1
Phase 2
Phase 3
Phase 4
Phase 5
Phase 6
Phase 7
Phase 8



JJA

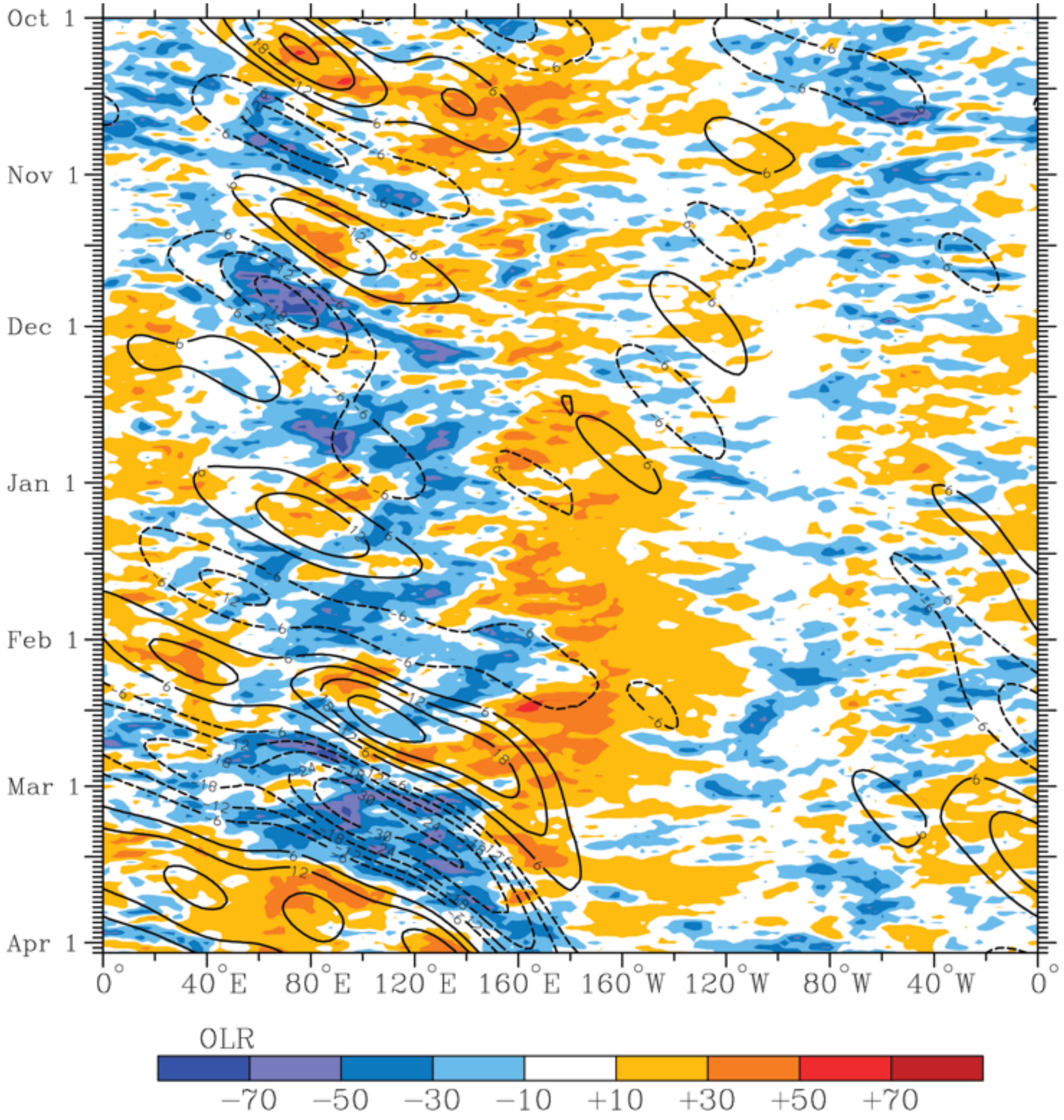


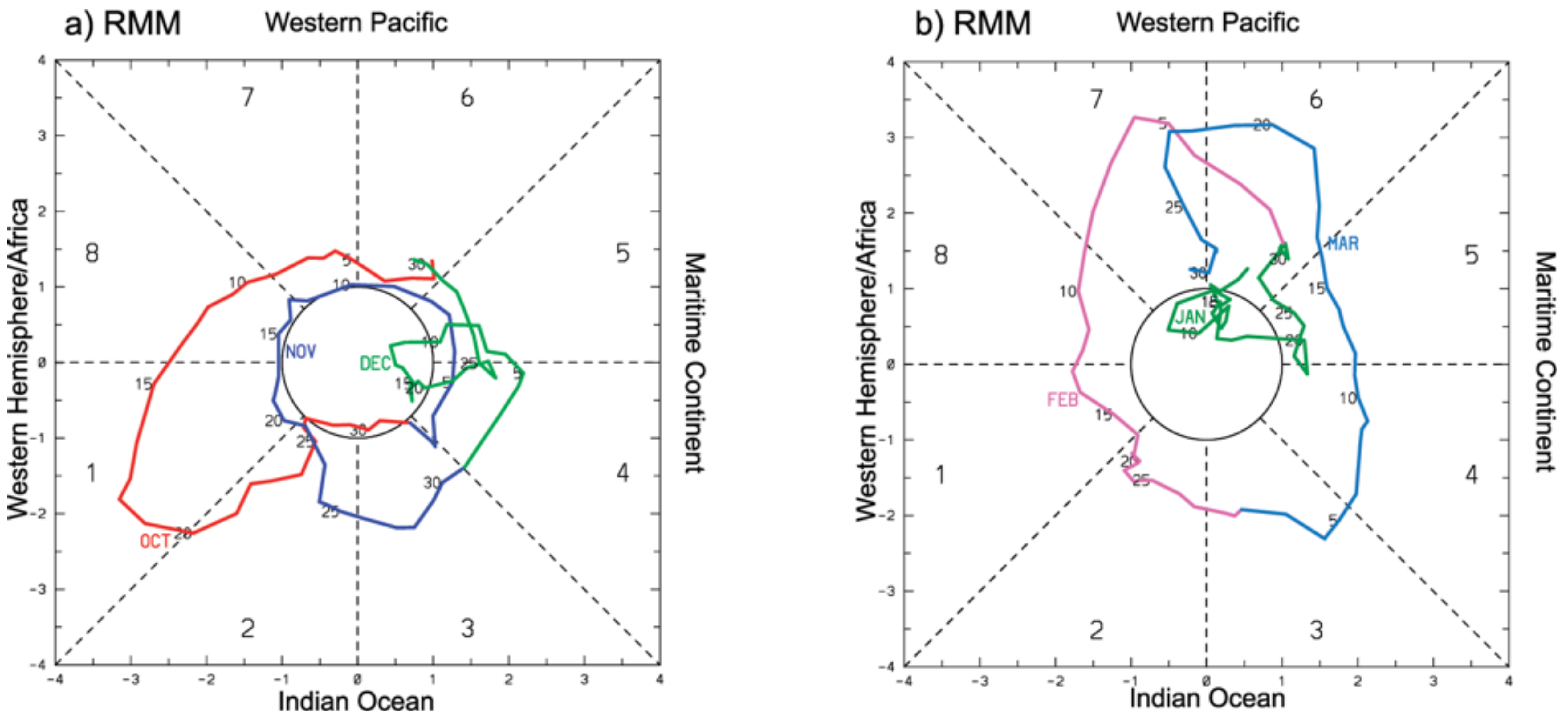
Phase 1
Phase 2
Phase 3
Phase 4
Phase 5
Phase 6
Phase 7
Phase 8

Wheeler & Hendon, *Mon. Wea. Rev.* 2004

Describing the MJO: EOF Analysis

anomalies of OLR and lower tropospheric winds associated with the phases of the MJO



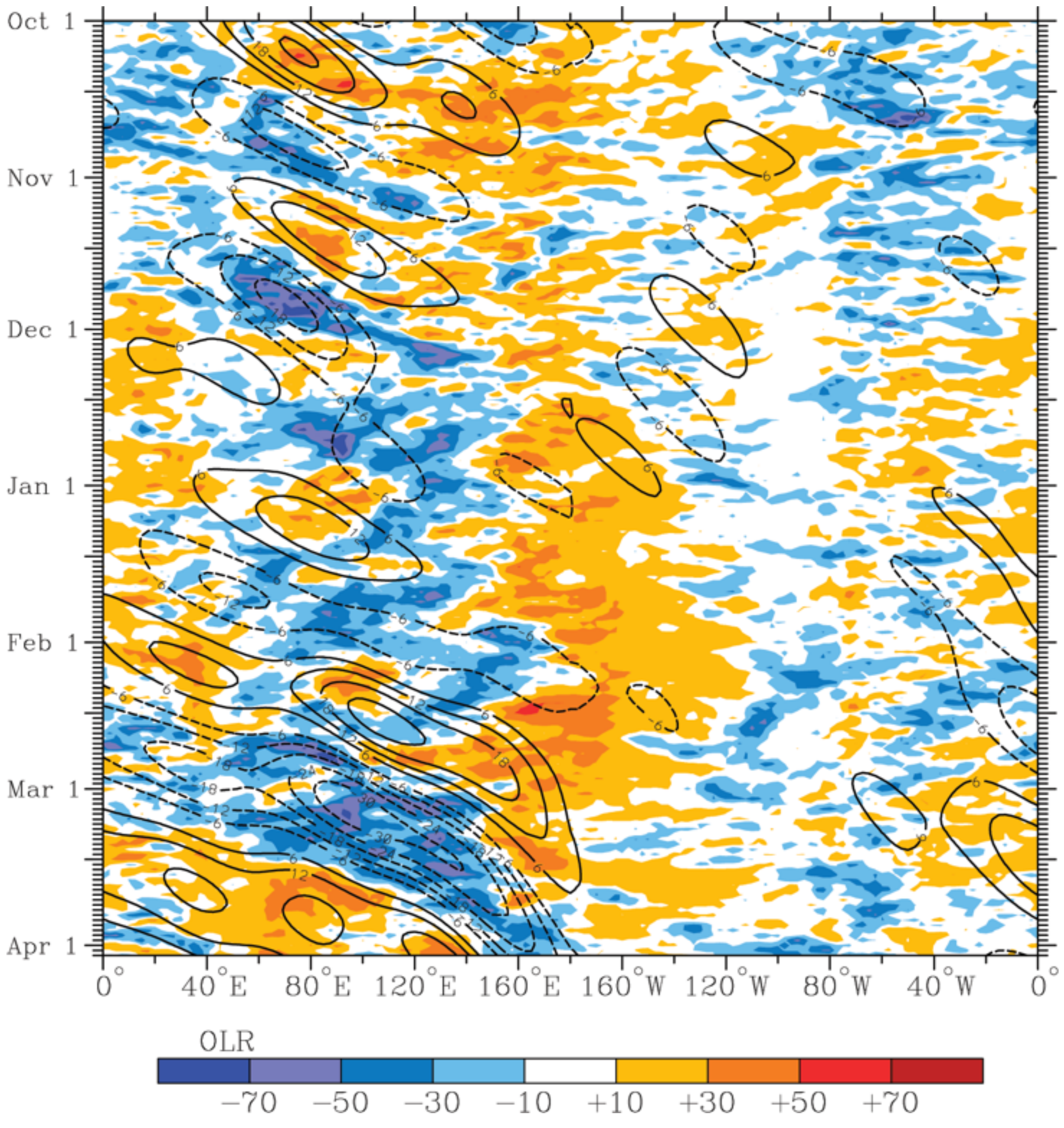


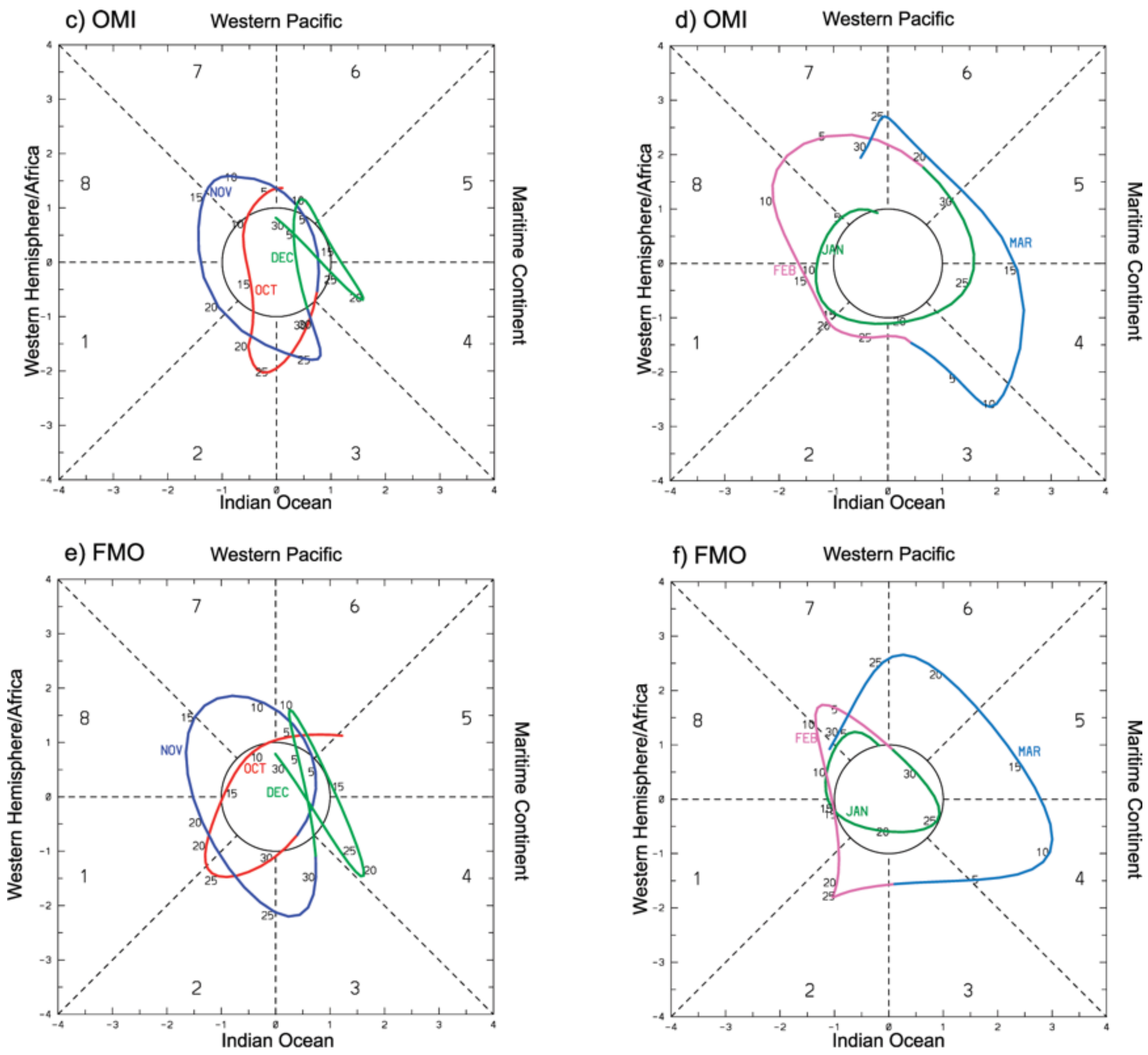
- OLR anomalies and RMM evolution during the DYNAMO campaign (October 2011–April 2012)
- RMM indicates almost constant MJO activity throughout the campaign
- What about other MJO indices?

Kiladis et al., *Mon. Wea. Rev.* 2014

Describing the MJO: EOF Analysis

other MJO indices differ from RMM regarding the strength and even existence of MJO activity during DYNAMO

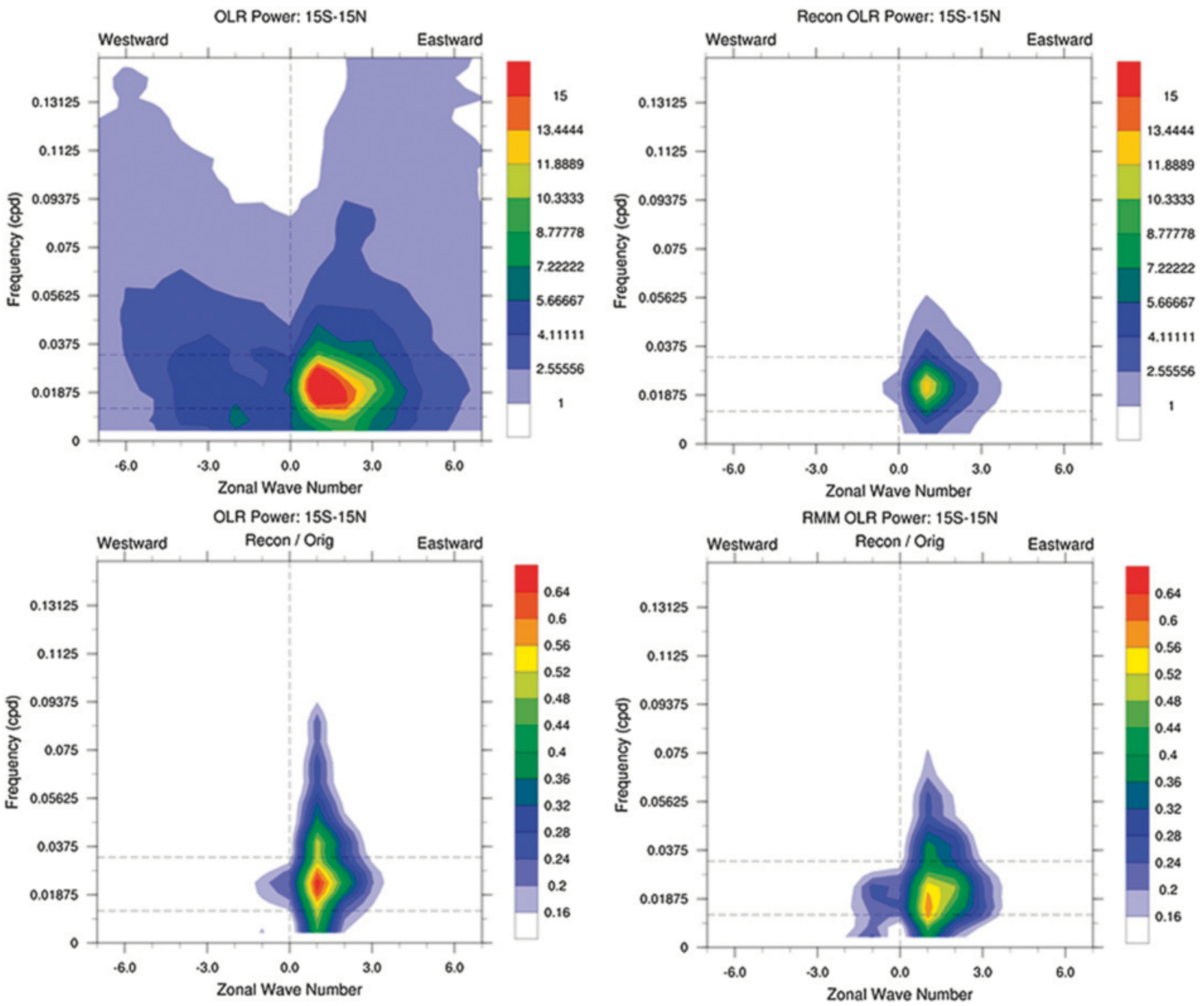




Kiladis et al., *Mon. Wea. Rev.* 2014

Describing the MJO: EOF Analysis

Replacing OLR with velocity potential (which measures divergence) in the EOFs improves MJO identification



Advantages:

- Better discriminates MJO signal during boreal summer
- Tracks the global evolution of the MJO (RMM mainly captures MJO in the eastern hemisphere)
- Better captures the relationship between MJO and Atlantic tropical cyclone activity

Disadvantages:

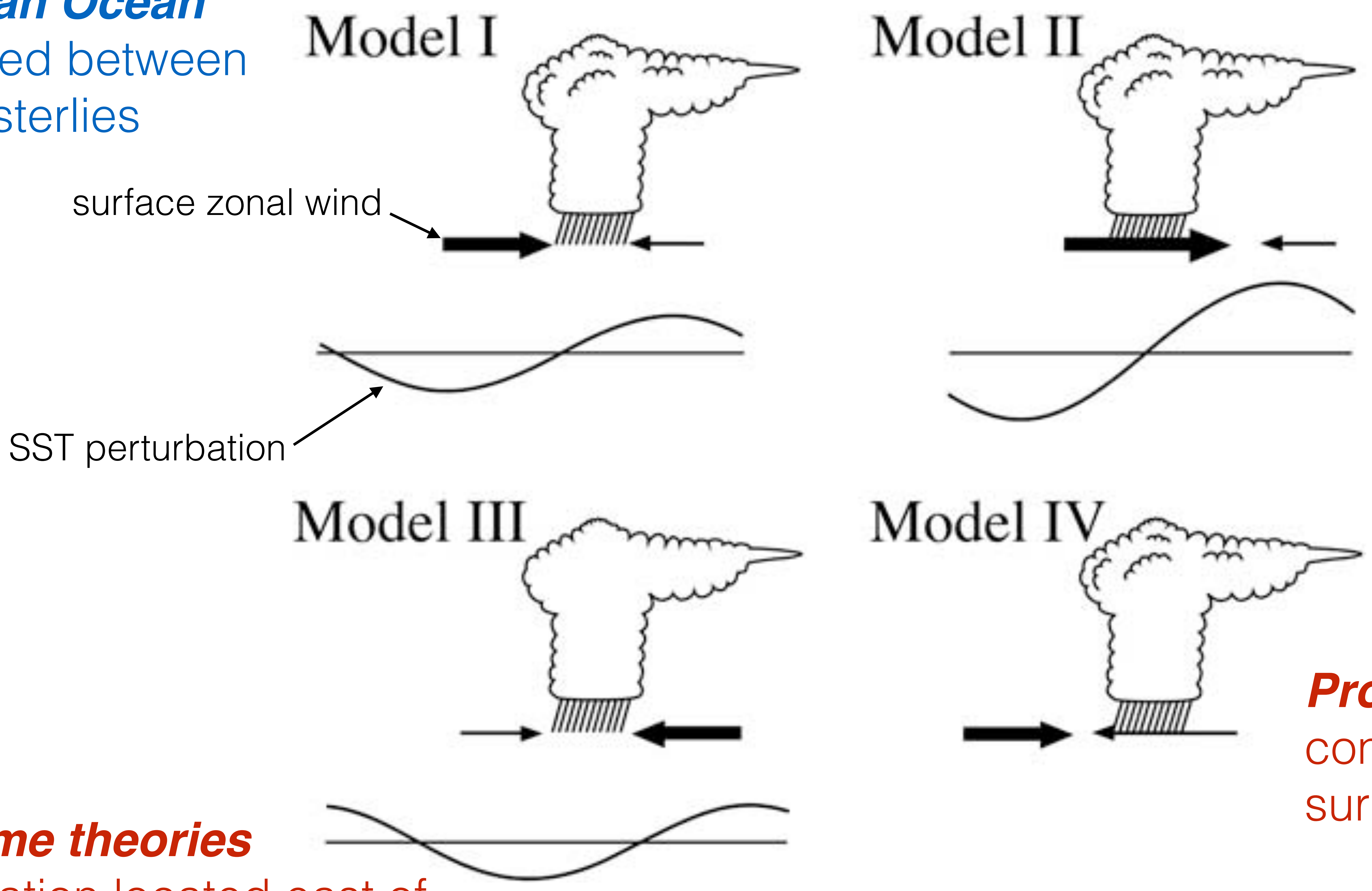
- Reduced sensitivity to MJO activity in Indian/Pacific Oceans, where the MJO is most unique
- Velocity potential is a reanalysis (model) product, rather than an observable

Ventrice et al., *Mon. Wea. Rev.* 2013

Structure of the MJO

Observed in Indian Ocean
convection centered between easterlies and westerlies

Observed in western Pacific
convection located in region of surface westerlies



Predicted by some theories
maximum evaporation located east of convective center (not observed)

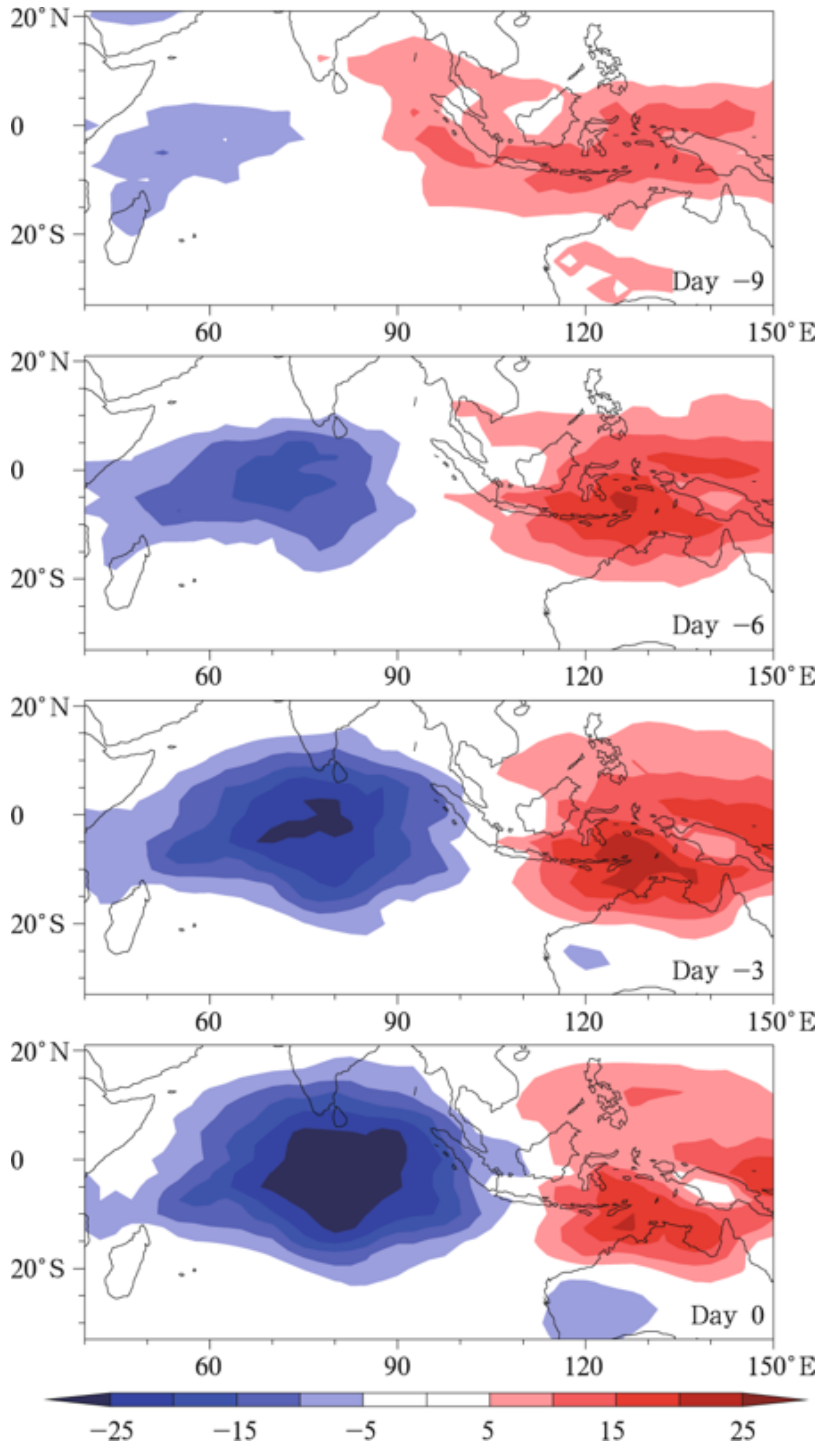
Produced by some GCMs
convection located in region of surface easterlies (not observed)

Zhang & Anderson, *J. Atmos. Sci.* 2003

What initiates an MJO event?

MJO events are initiated over the equatorial Indian Ocean

Filtered OLR anomaly



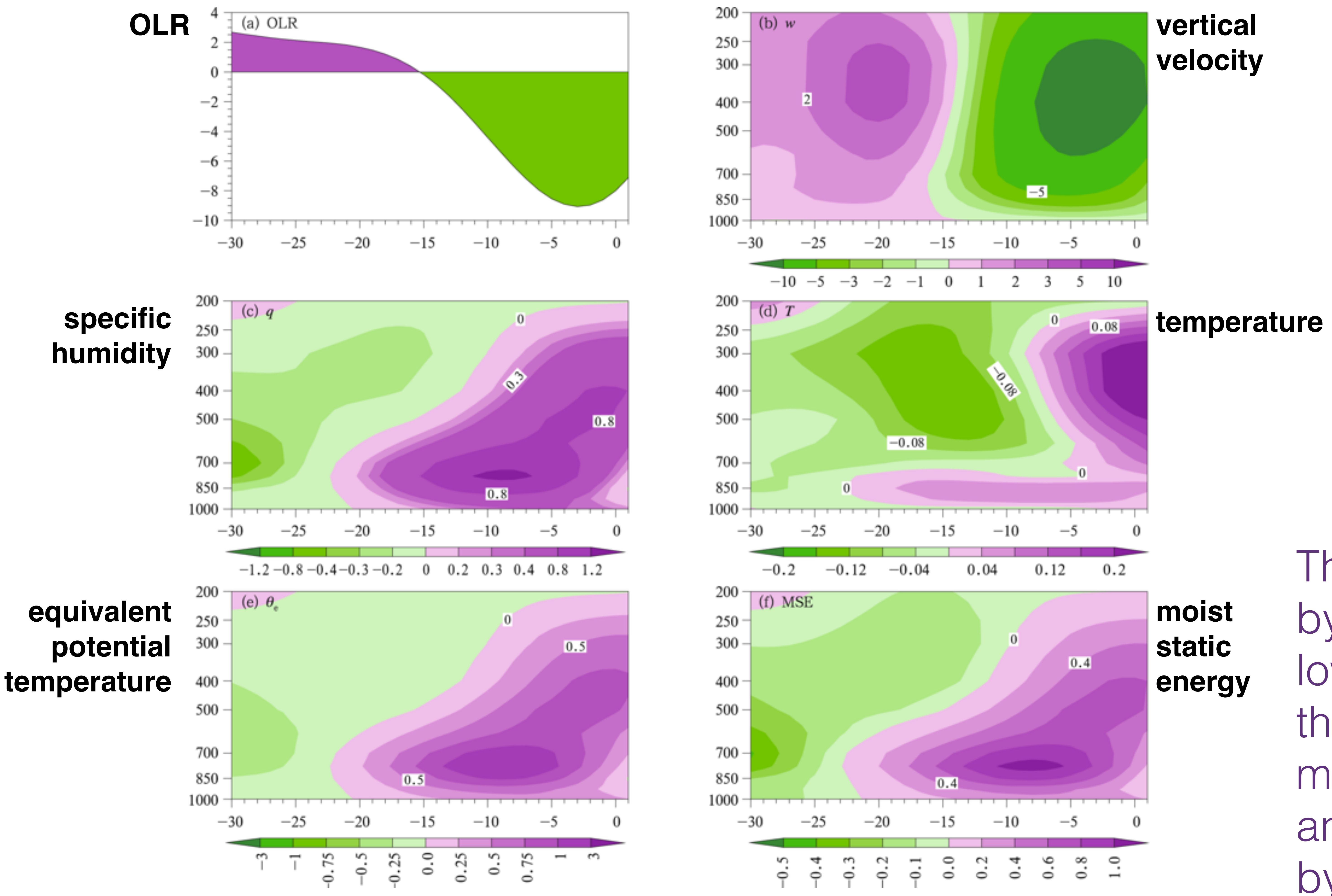
Initiation of the MJO has traditionally been assumed to arise from the return of a previous MJO event that has circumnavigated the globe — but careful analysis of the data does not support this hypothesis

The OLR anomaly starts growing in the western equatorial Indian Ocean, to the west of an MJO inactive phase

Zhao et al., *J. Climate* 2013

What initiates an MJO event?

The OLR anomaly over the initiation region becomes negative about 15 days before MJO appears

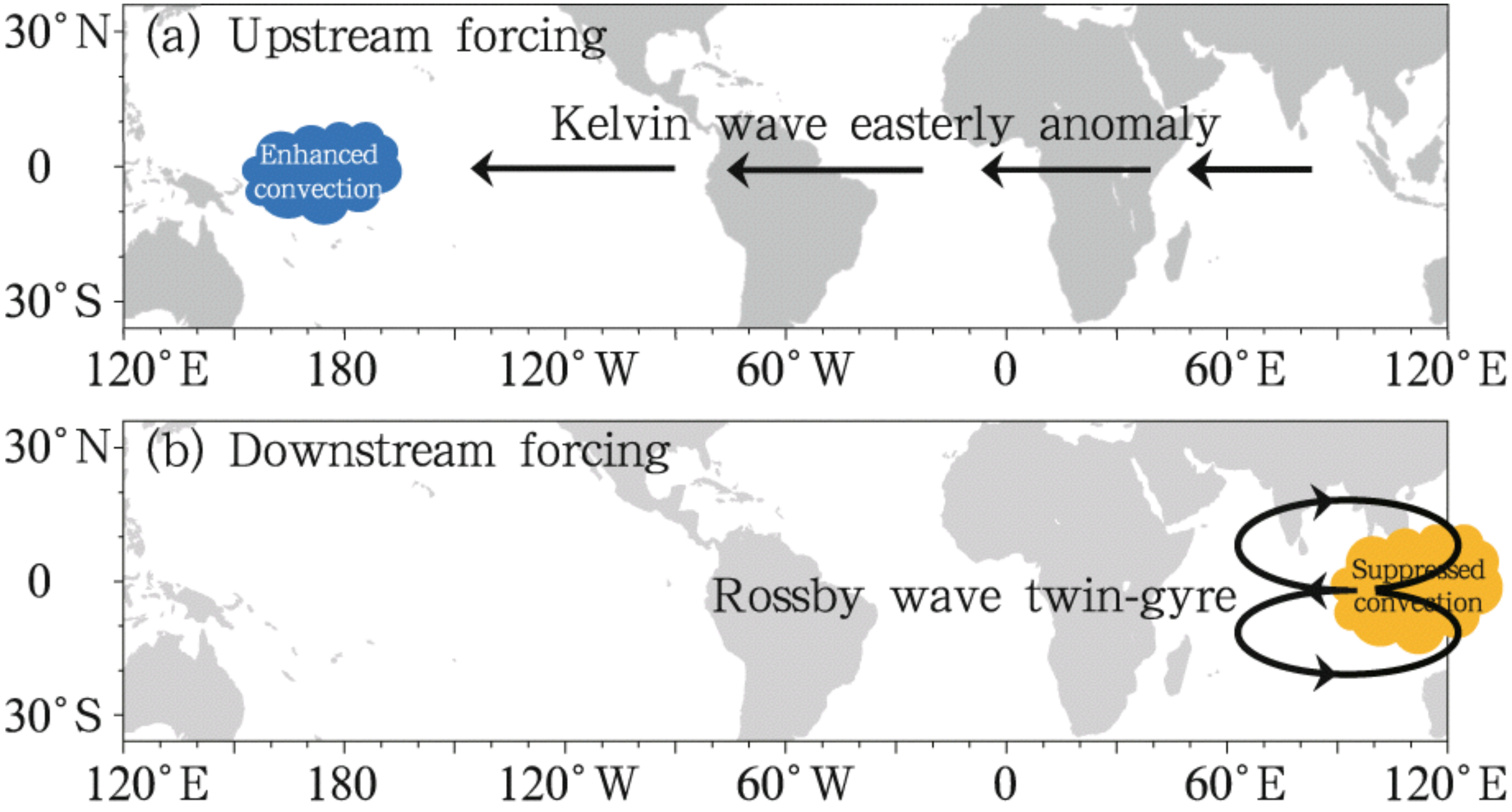


The growth of the OLR anomaly is preceded by moistening and warming in the PBL and lower troposphere. The dominant terms in the moisture budget are advection of mean moisture by the MJO (intraseasonal) flow and advection of MJO moisture anomalies by the mean flow.

Zhao et al., *J. Climate* 2013

What initiates an MJO event?

Moisture convergence in the western equatorial Indian Ocean could result from existing MJO activity in two ways



Kelvin wave response to MJO active phase in the western Pacific

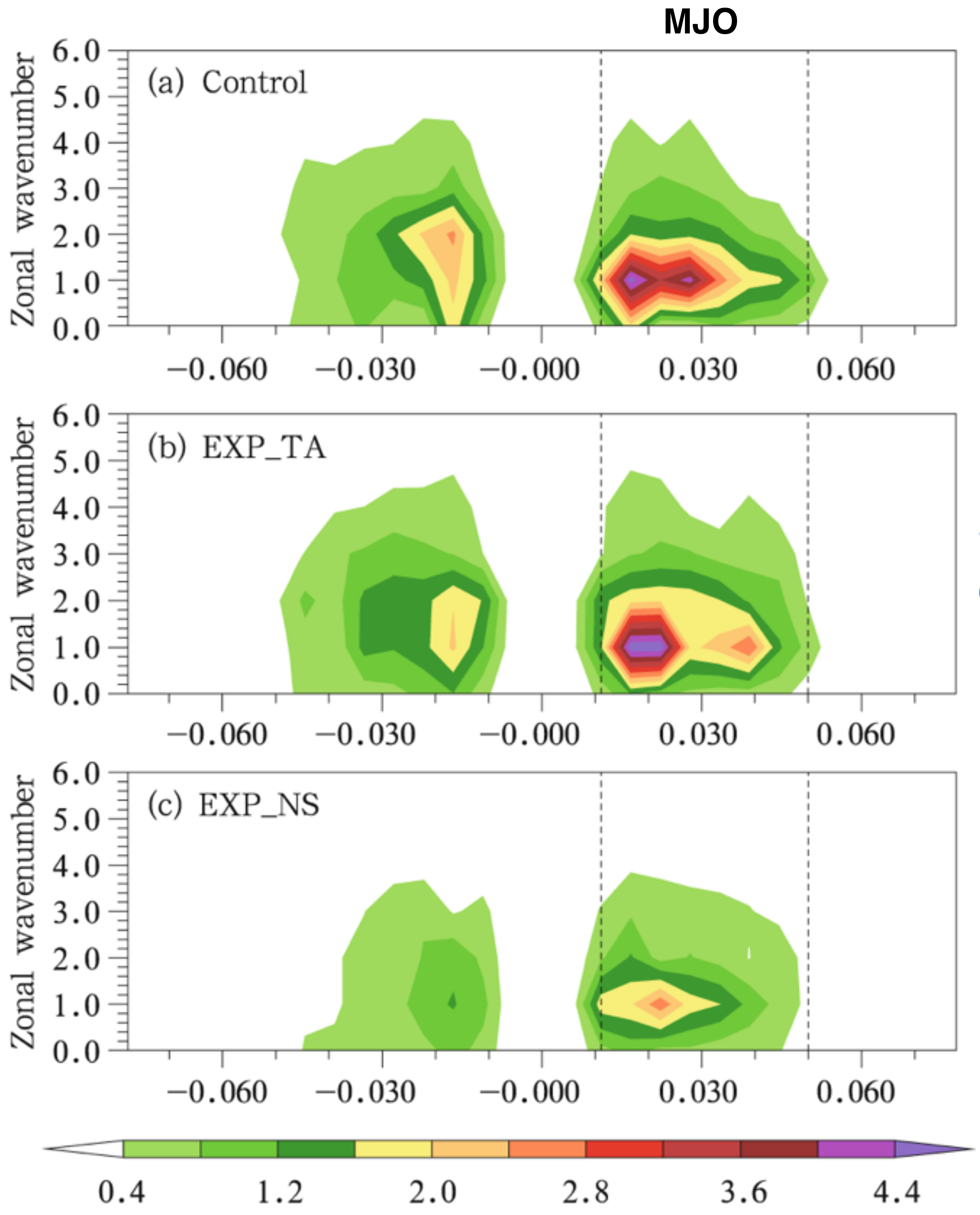
Rossby wave response to MJO inactive phase over the maritime continent

This one is more important

Zhao et al., *J. Climate* 2013

What initiates an MJO event?

Convergence of wave energy entering the tropics from Southern Hemisphere mid-latitudes also plays a role



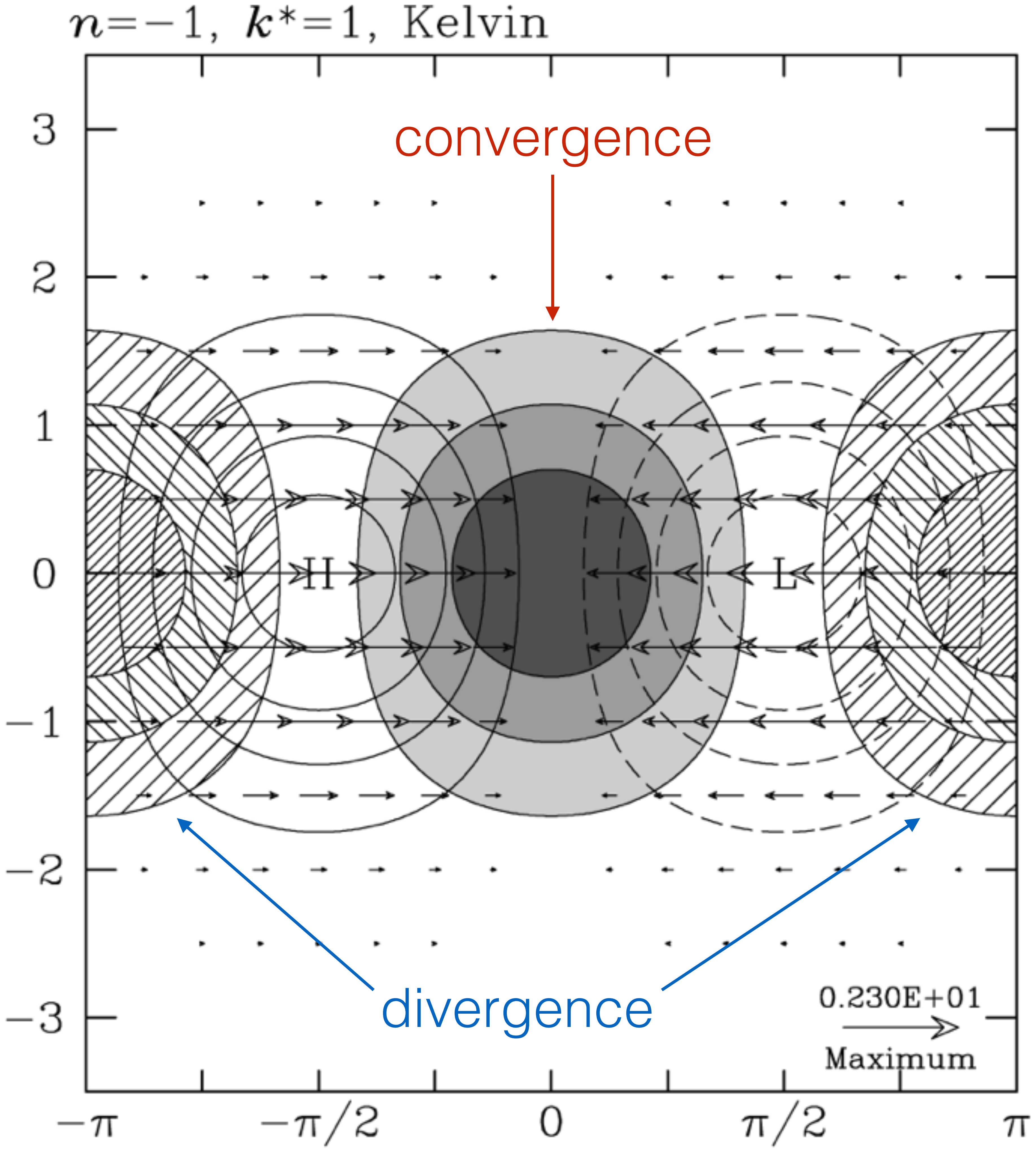
Suppressing circumnavigating MJO events has little impact on the MJO variability

Breaking the connection between tropics and mid-latitudes reduces MJO variability by almost 50%

Li, *J. Meteorol. Res.* 2014

What controls MJO propagation?

Kelvin waves are the only eastward propagating equatorial wave, and hence the basis of most MJO theories…



…but Kelvin waves propagate eastward too fast!

Key questions:

1. What mechanisms distinguish the MJO from convectively coupled Kelvin waves?
2. What processes supply the MJO with energy against dissipation?

Kiladis et al., *Rev. Geophys.* 2009

Internal vs. external forcing

Internal: the MJO is driven by its own energy source

- A local source of instability tied to deep, moist convection supports MJO growth: possibly evaporation from the underlying ocean or advection
- Kelvin waves that support growth on the MJO (rather than Kelvin wave) scale
- Largest growth of instability at smaller scales than the MJO
- Evidence supporting these theories is inconclusive

External: the MJO is driven by something outside the MJO

- A non-local source of instability drives deep, moist convection and grows the MJO: monsoon processes, stochastic processes associated with convection, forcing by mid-latitude eddies
- Again, evidence supporting these theories is inconclusive

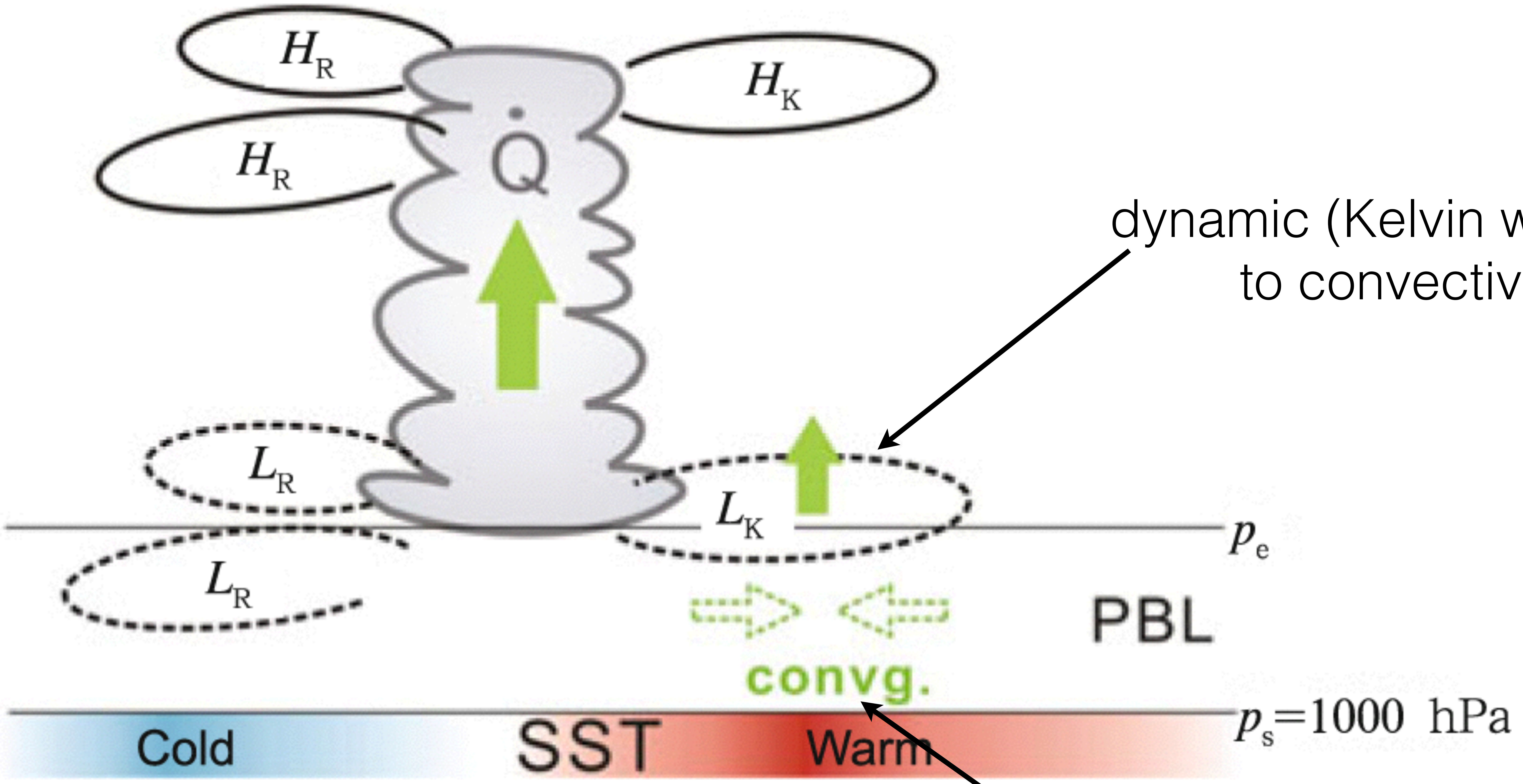
Is the MJO a moisture mode?

- growth of Kelvin wave anomalies is governed by interactions between buoyancy and pressure gradients
- growth of moisture mode anomalies is governed by feedbacks that increase moisture anomalies
- depend on feedbacks between MJO activity and the sources and sinks of moist static energy, such as turbulent surface fluxes and radiative cooling
- many observations are consistent with the hypothesis that the MJO depends on these sources and sinks, and that moisture contains most of the atmospheric “memory” at time scales longer than a few days
- simple linear models based on moisture modes produce westward-propagating disturbances — unlike the MJO, which propagates weakly eastward
- inclusion of non-linearity produces eastward-propagating disturbances, but with unrealistic moisture gradients
- if sources of moist static energy upstream of the MJO are stronger than the (negative) wind–evaporation feedback associated with anomalous easterlies, then the simple linear model can produce disturbances with weak eastward propagation

Sobel and Maloney, *J. Atmos. Sci.* 2012 & 2013

Is the MJO a moisture mode?

Moisture convergence ahead of the MJO drives eastward propagation — but what drives moisture convergence?

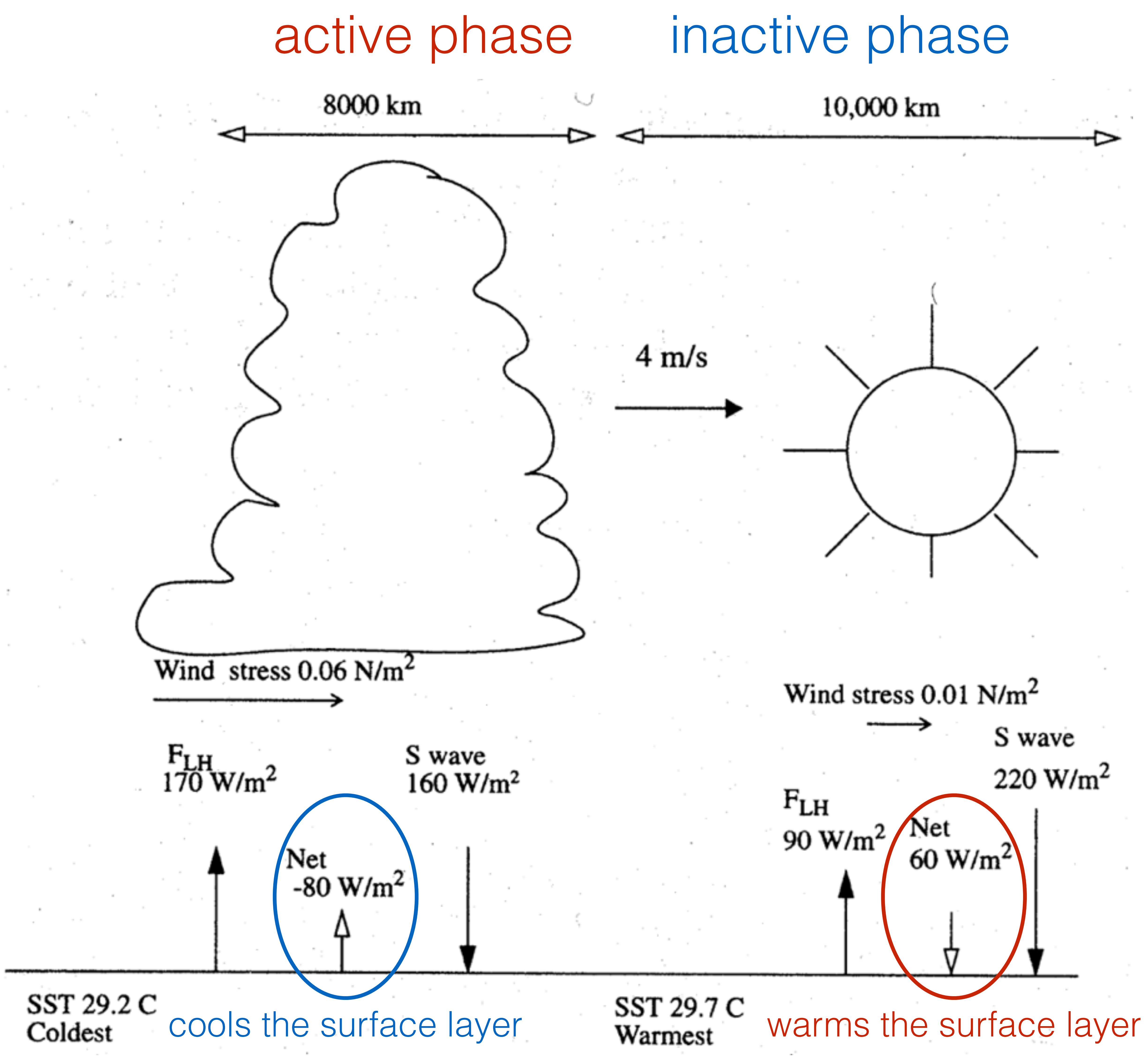


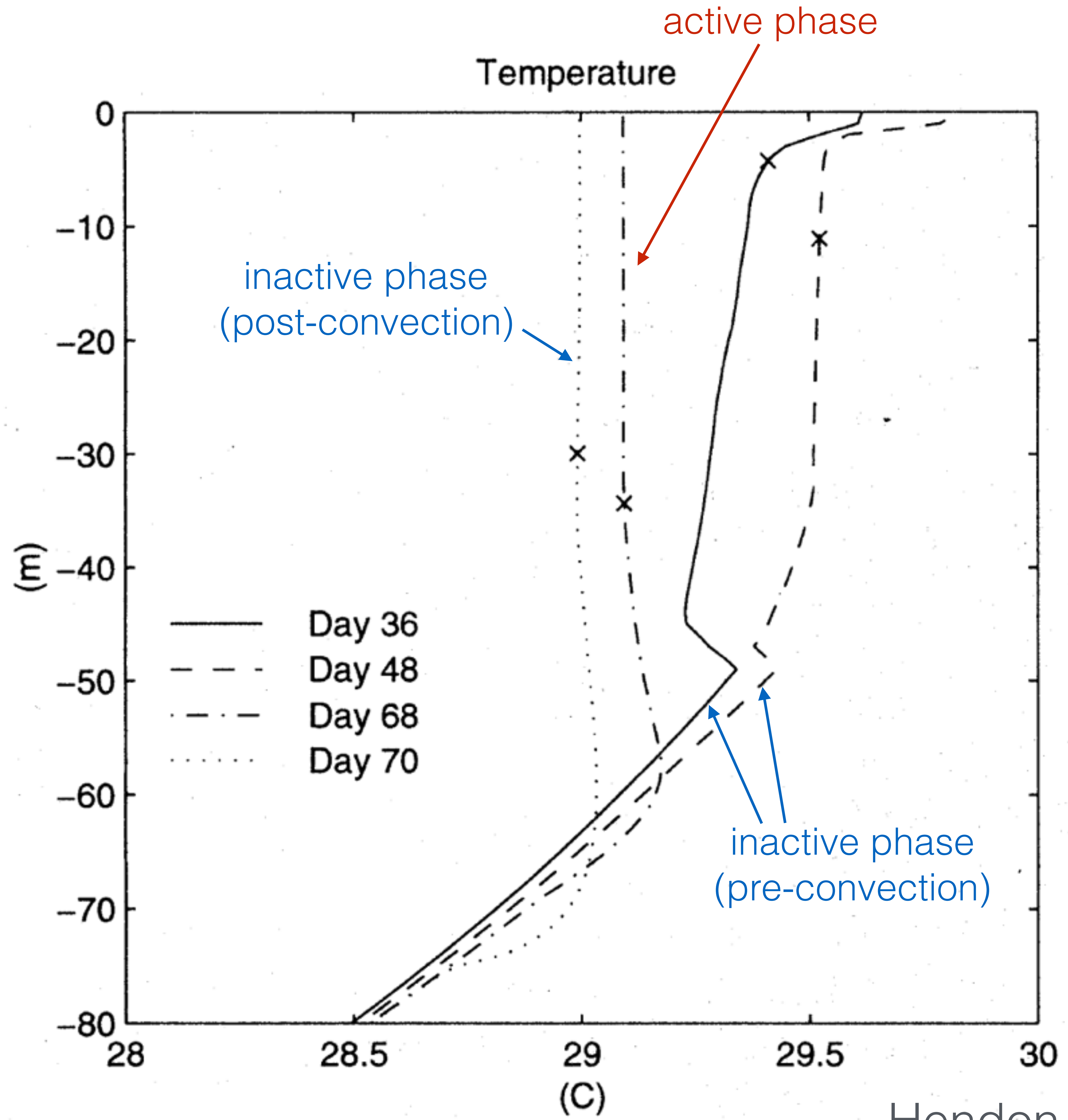
dynamic (Kelvin wave) response to convective heating

hydrostatic response to warm SST anomaly ahead of convection

Hsu and Li, *J. Climate* 2012

Air–Sea Interaction and the MJO

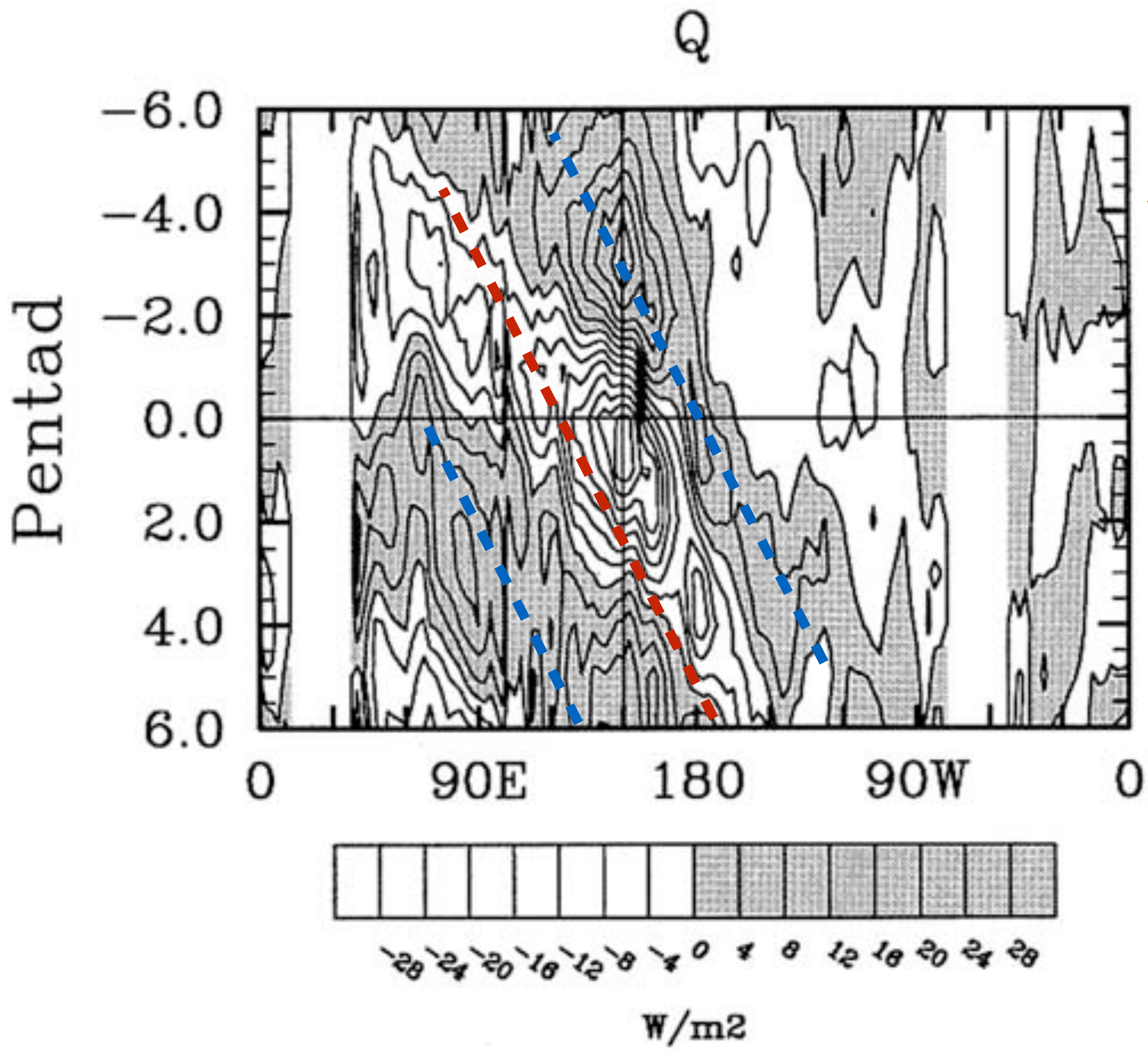




Hendon, 2005

Air–Sea Interaction and the MJO

Although the MJO is fundamentally a coupled mode of variability, the ocean mainly responds to the atmosphere

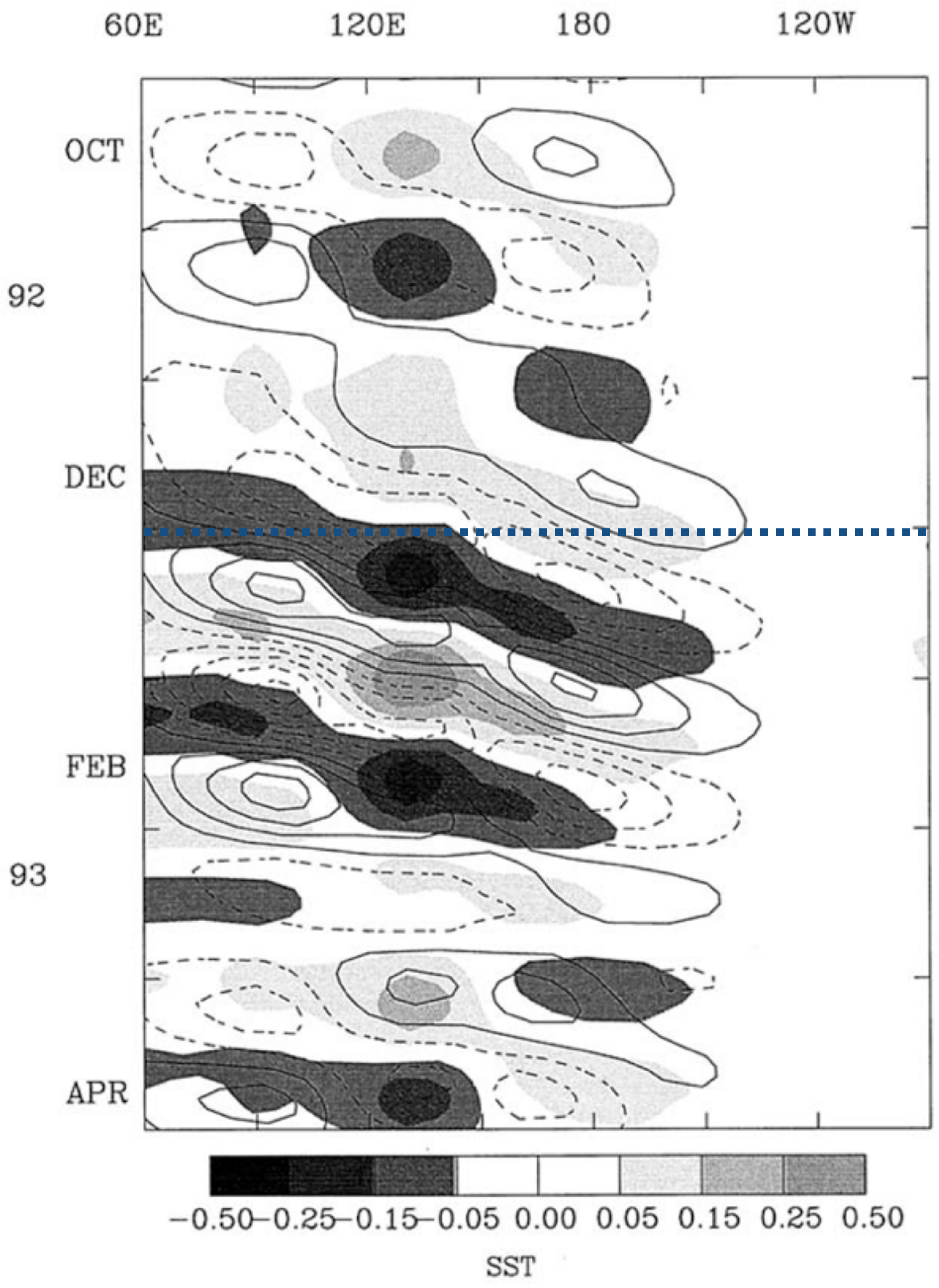


MJO composite downward surface heat flux

Model simulations indicate that air–sea interactions improve the simulation of the MJO, but they are not essential to its existence

Zhang, *Rev. Geophys.* 2005

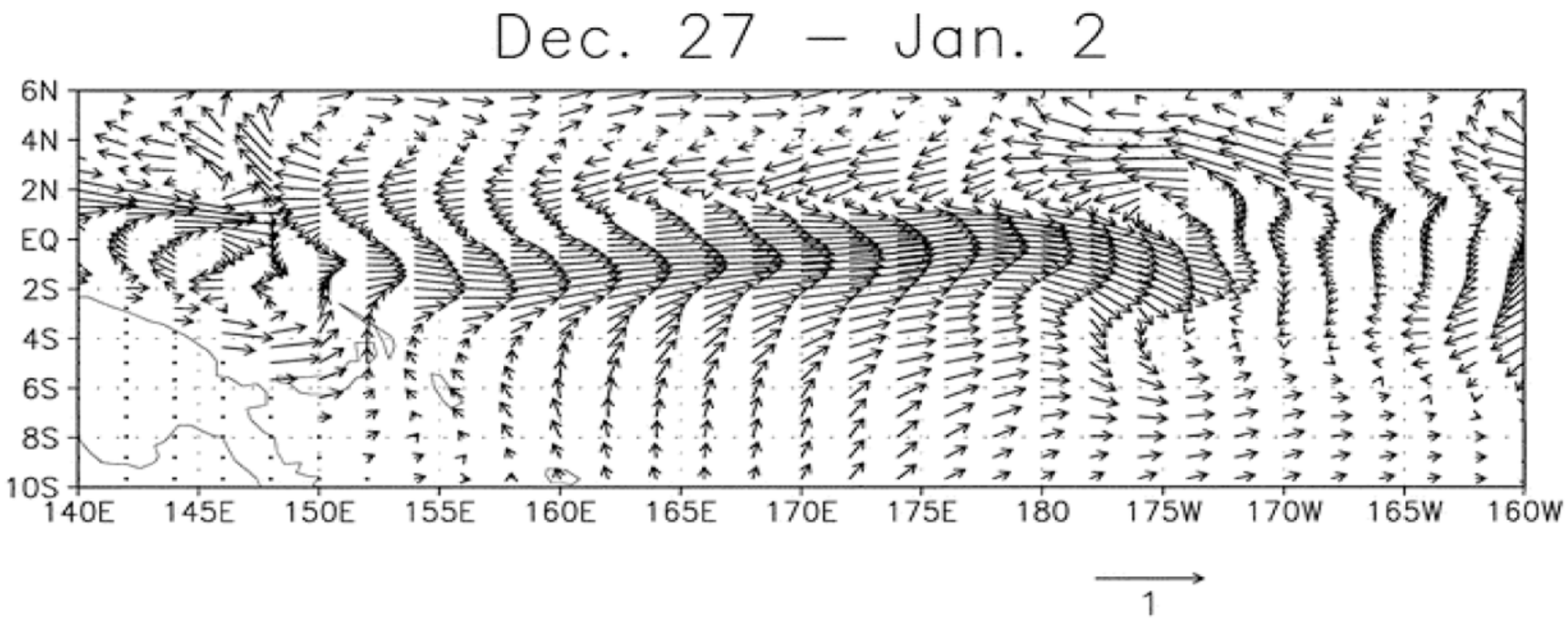
Air–Sea Interaction and the MJO



contours: OLR

shading: SST

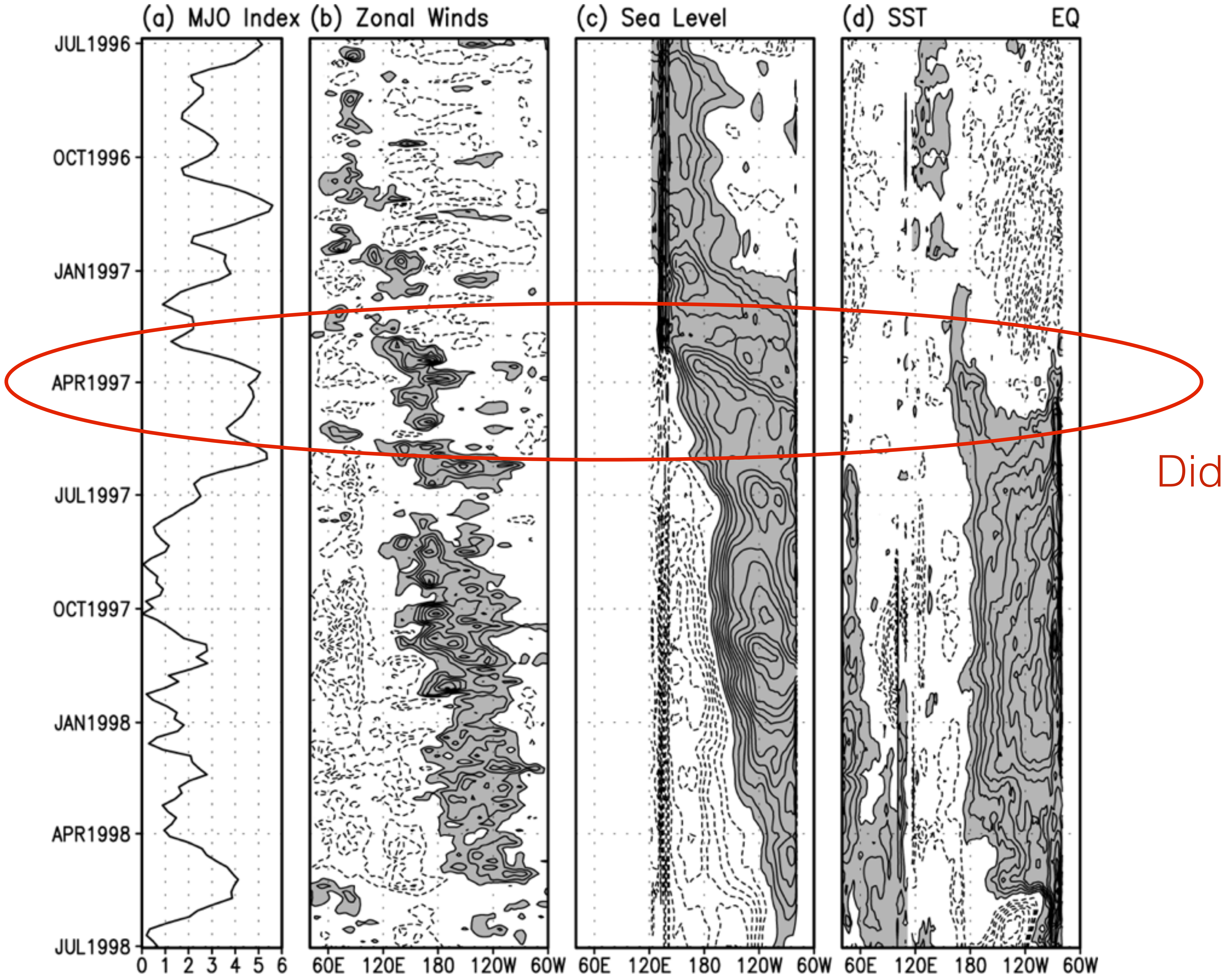
The response of surface ocean currents to an MJO event (OLR/SST shown at left)



Hendon, 2005

The MJO and ENSO

Westerly wind anomalies in the tropical Pacific are associated with both the positive phase of the MJO and the development of El Niño

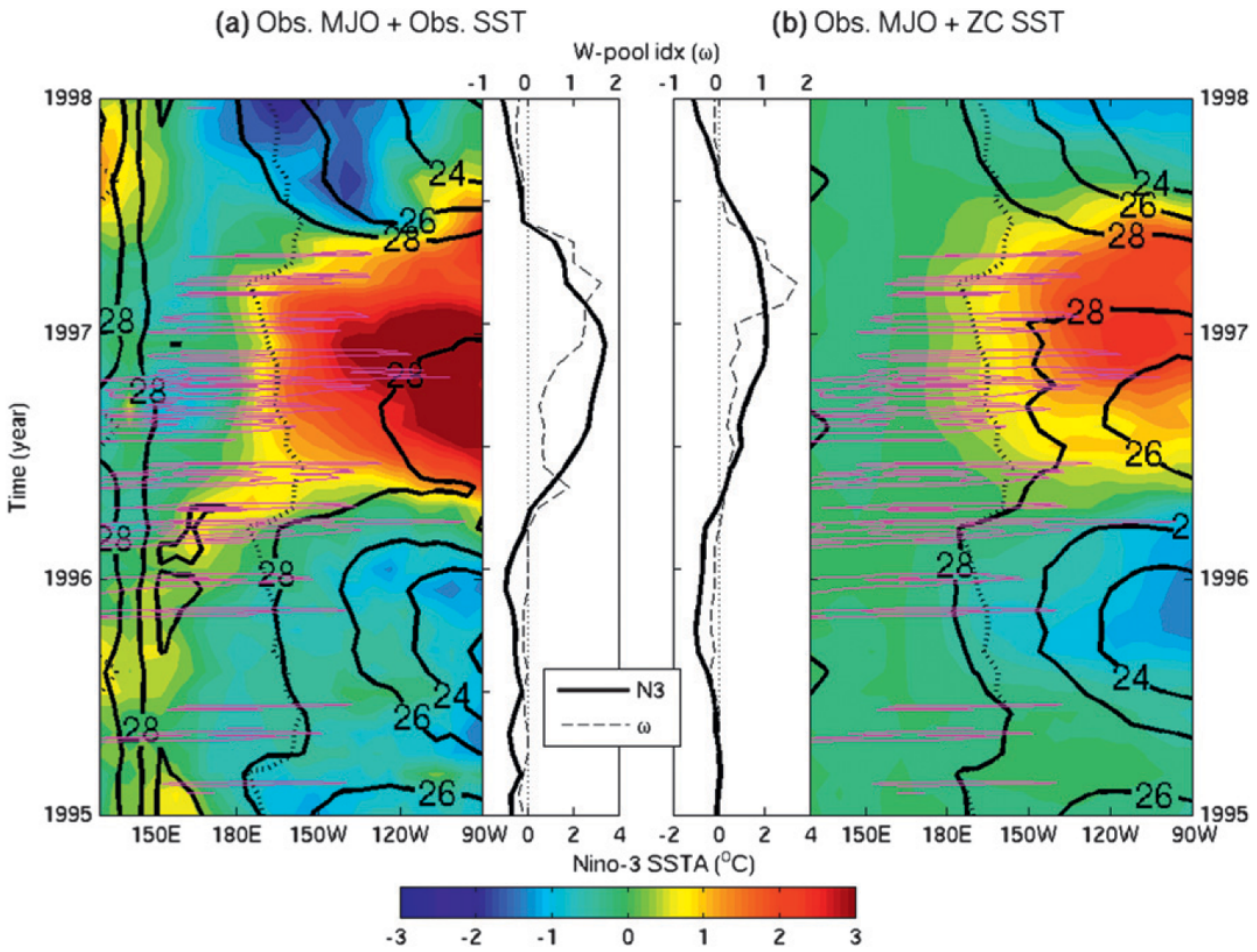


Did MJO activity trigger the 1997–1998 El Niño?

Lau, 2005

The MJO and ENSO

Westerly wind anomalies in the tropical Pacific are associated with both the positive phase of the MJO and the development of El Niño



Coupled model simulation with MJO wind anomalies imposed reproduces 1997–98 El Niño and 1998–99 La Niña

Kapur and Zhang, *J. Climate* 2012

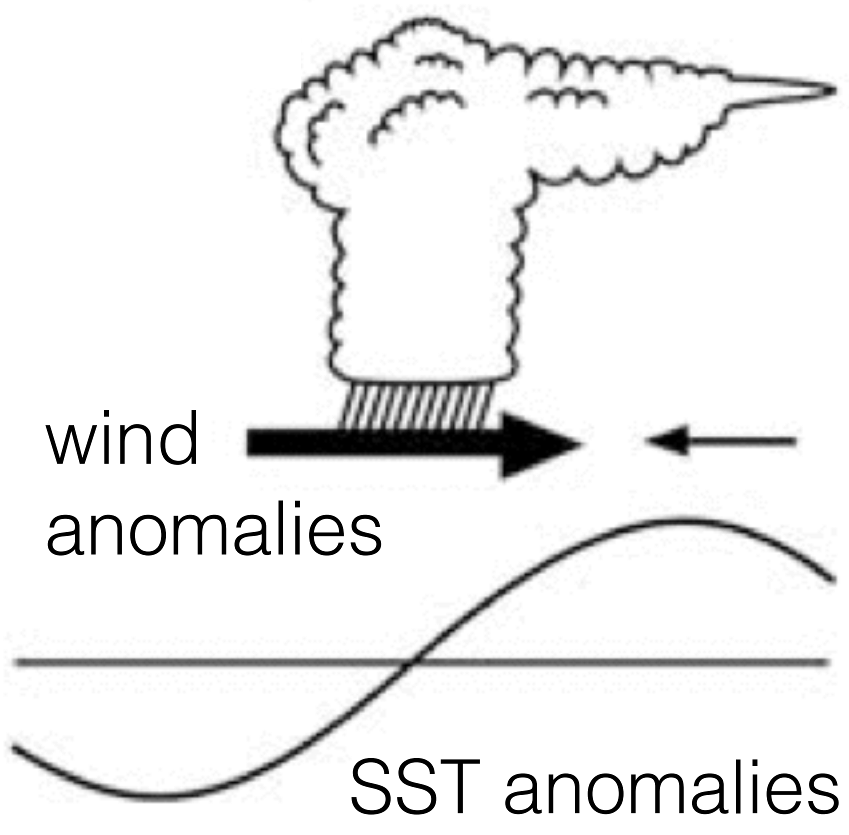
What is ENSO?

1. An unstable nonlinear oscillator?
   - Delayed oscillator: changes in the thermocline depth grow out of phase with changes in wind stress
   - Recharge oscillator: a warm event (El Niño) leaves the equatorial thermocline shallower with a colder than normal sea surface (La Niña). The reservoir of warm water is then refilled over time.
   - Western Pacific oscillator: off-equatorial response provides a negative feedback
   - Advective–reflective oscillator: wave-driven currents push the warm pool back
2. A stable system with non-normality?
   - Stochastic disturbances grow and decay through atmosphere–ocean coupling perturbing the system from a neutral or cold (La Niña) state

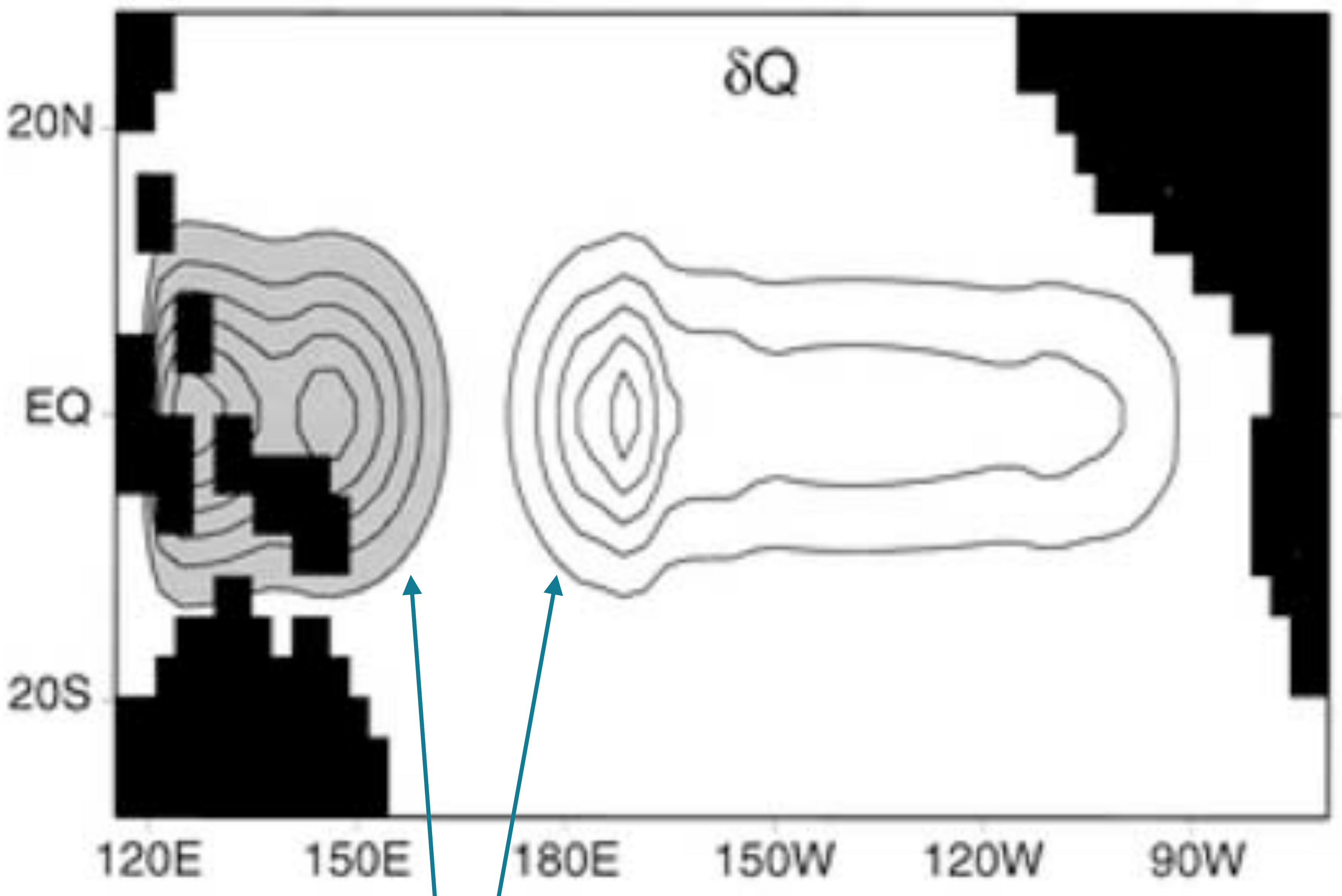
The MJO and ENSO

Zonal wind anomalies associated with the MJO can act as a stochastic forcing in the western and central tropical Pacific

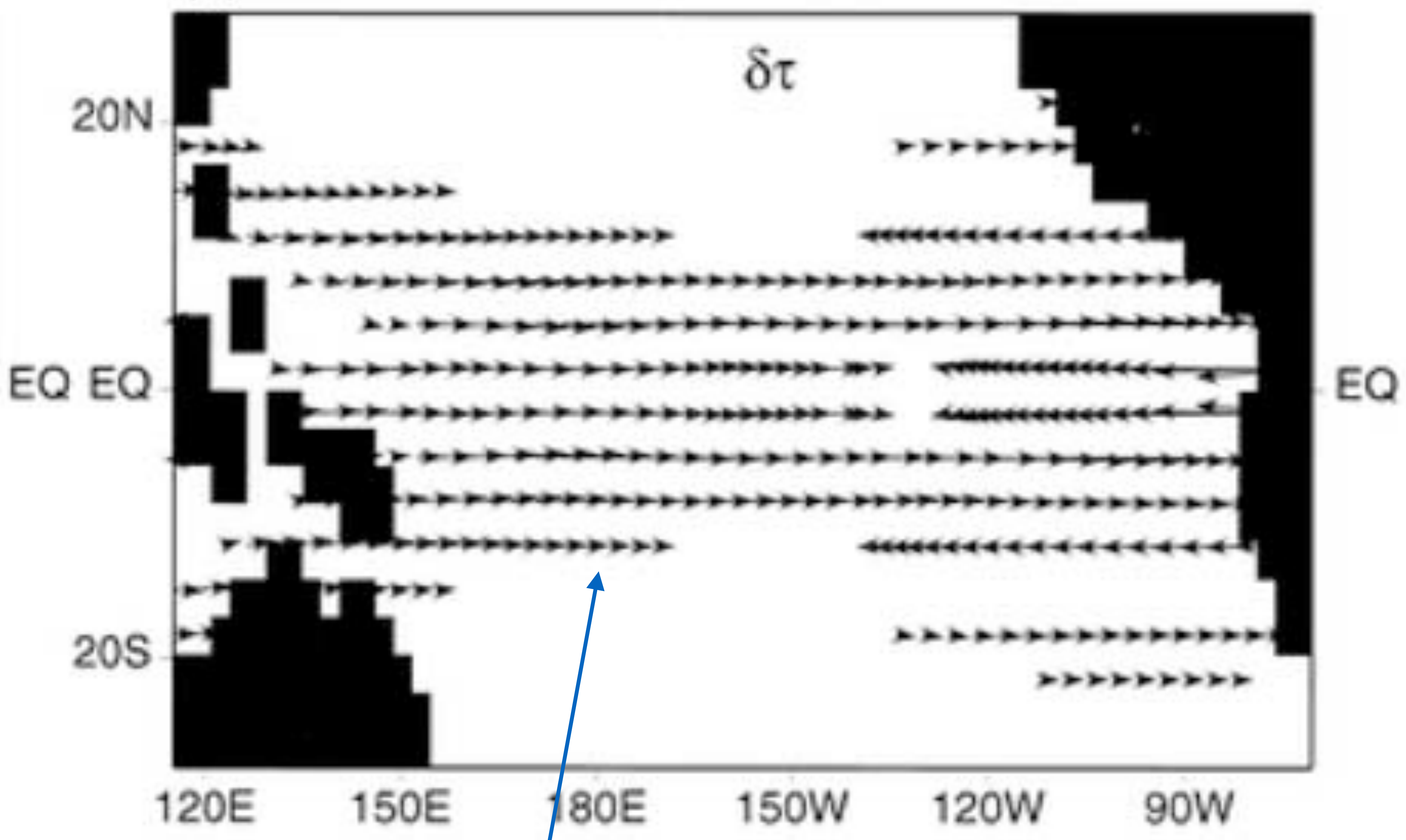
MJO in the western Pacific



Idealized surface heat flux



Idealized surface wind stress



surface heat flux dipole

westerly wind anomalies in the western and central Pacific

Kelvin waves send warm water east

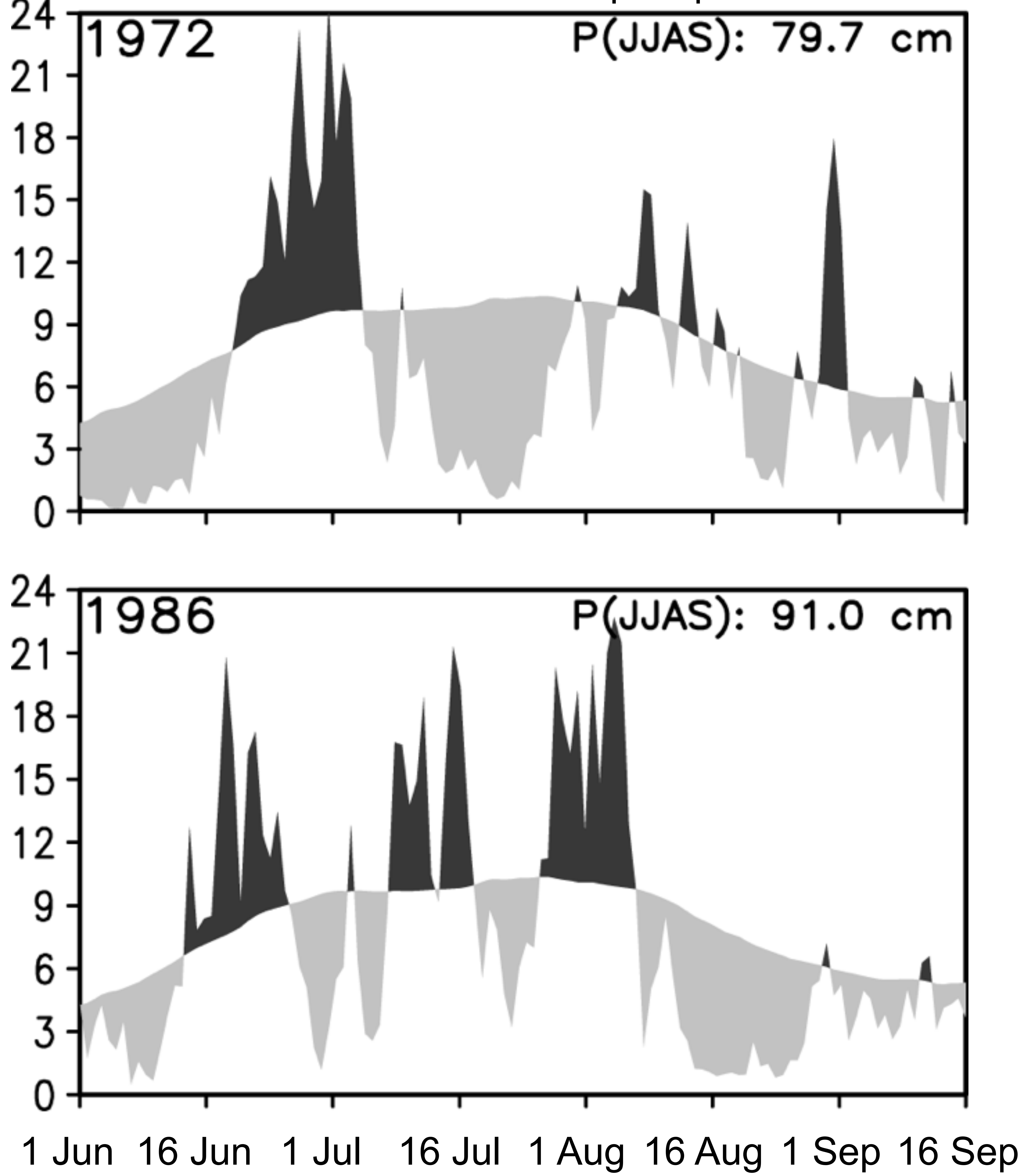
Significant correlations between MJO-driven Kelvin wave activity and ENSO indices suggest that the MJO may play a role in enhancing warming during the early stages of El Niño

Moore & Kleeman, *J. Climate* 1999

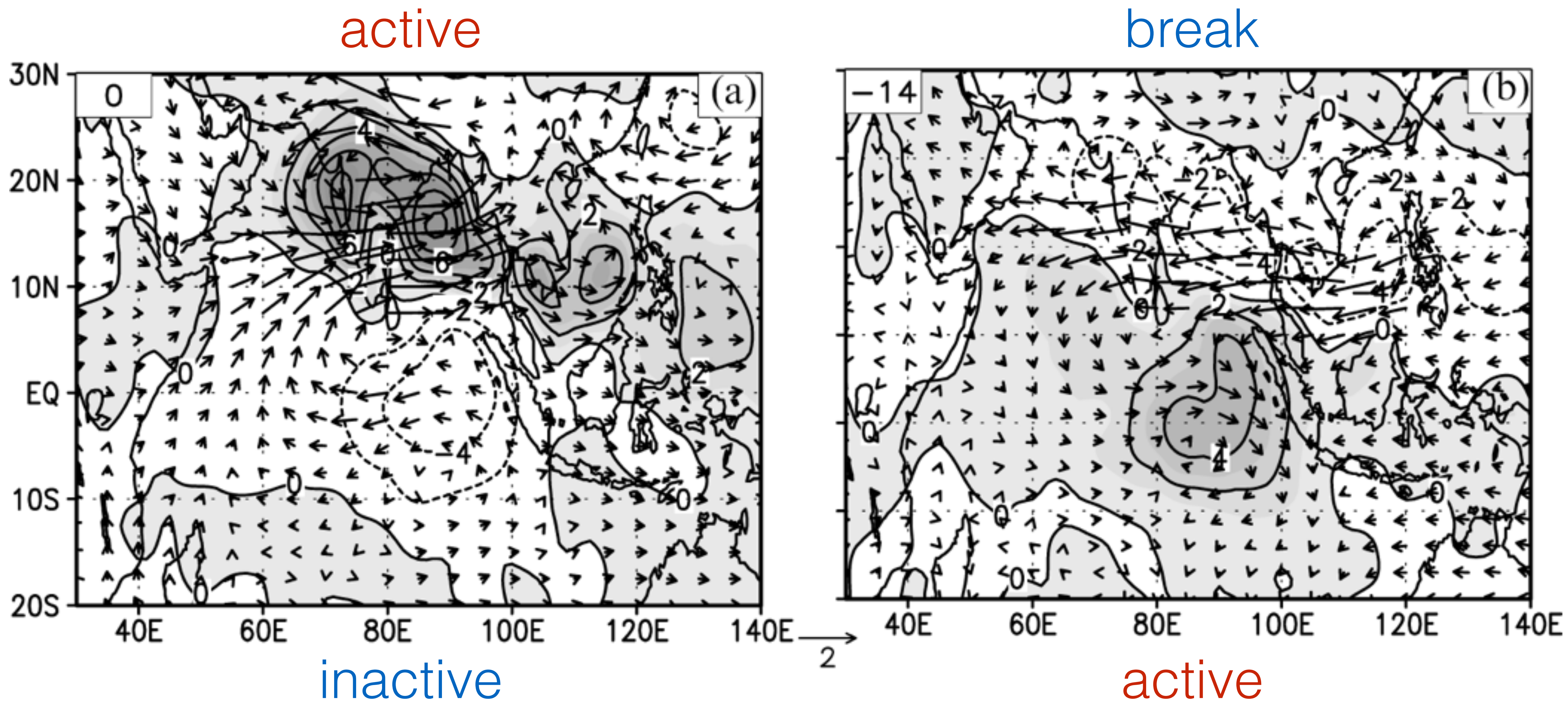
The MJO and Monsoons

All monsoons experience active and break phases (intraseasonal oscillations) during the monsoon season

South Asian monsoon precipitation



monsoon



MJO

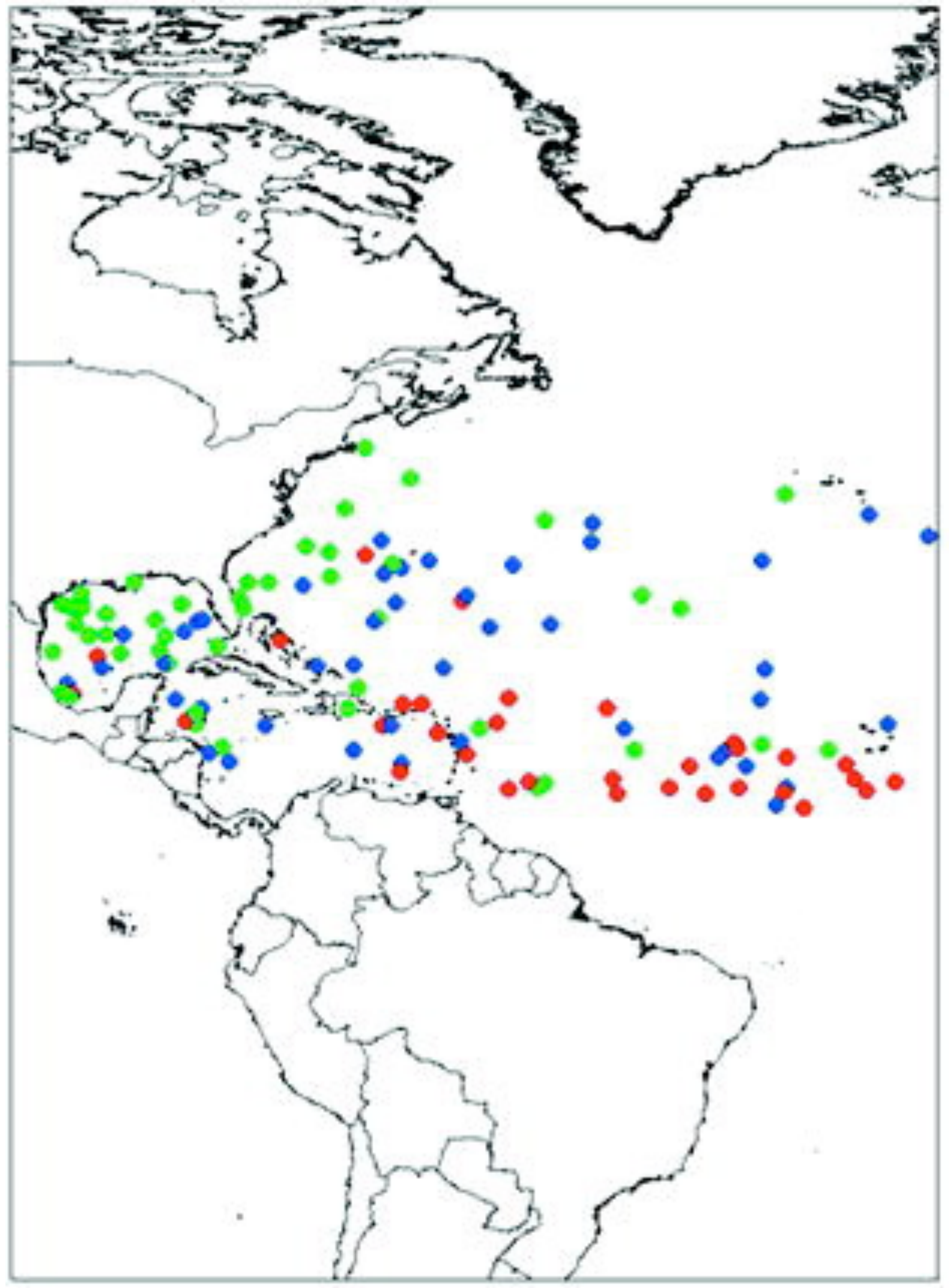
Active and break phases in the South Asian monsoon appear to be related to the MJO — we will discuss this more next week

Goswami, 2005

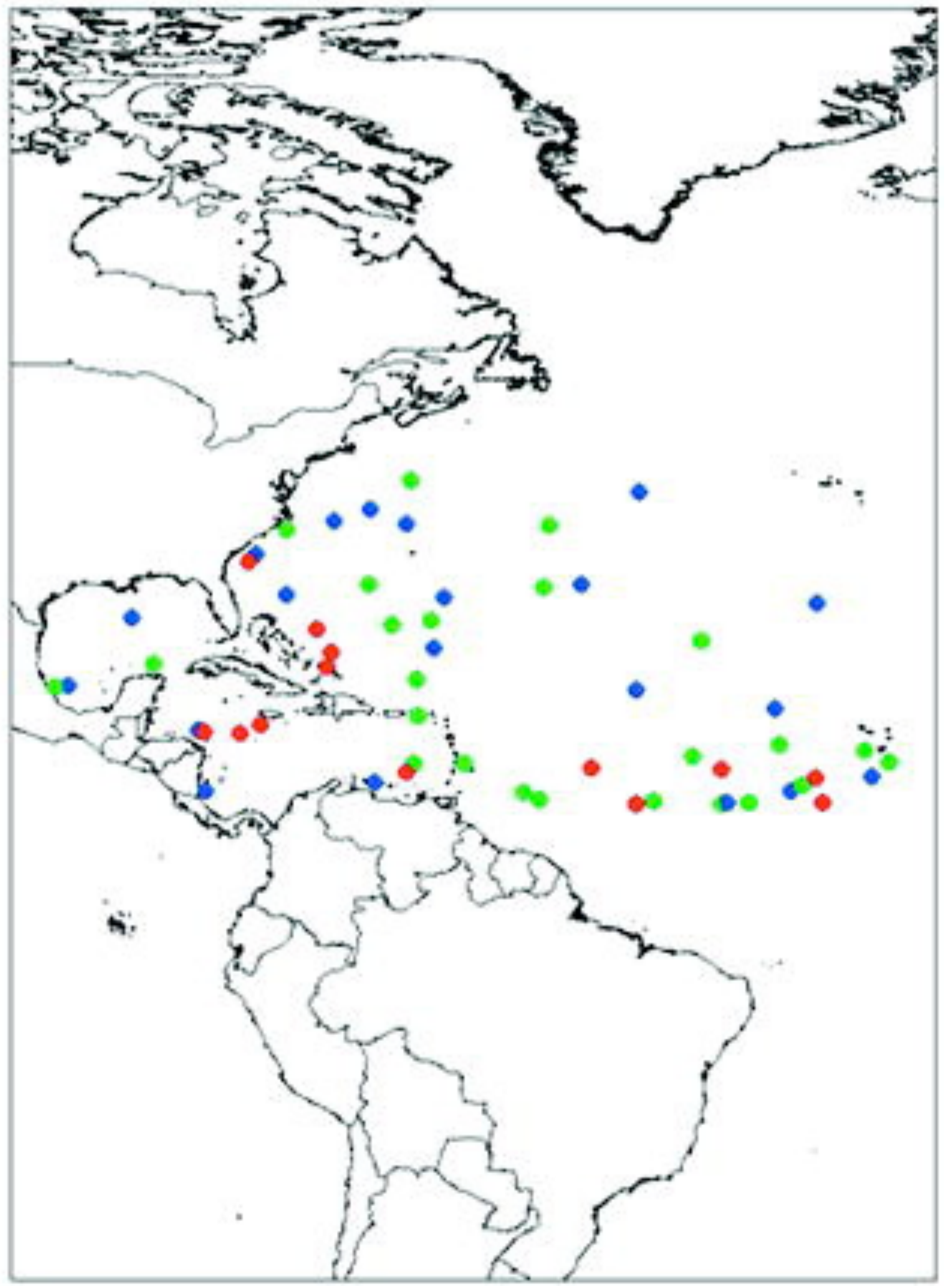
The MJO and Tropical Cyclones

The phase of the MJO appears to strongly affect tropical cyclone activity in the north Atlantic

genesis locations for weak, moderate, and strong TCs in the Atlantic basin

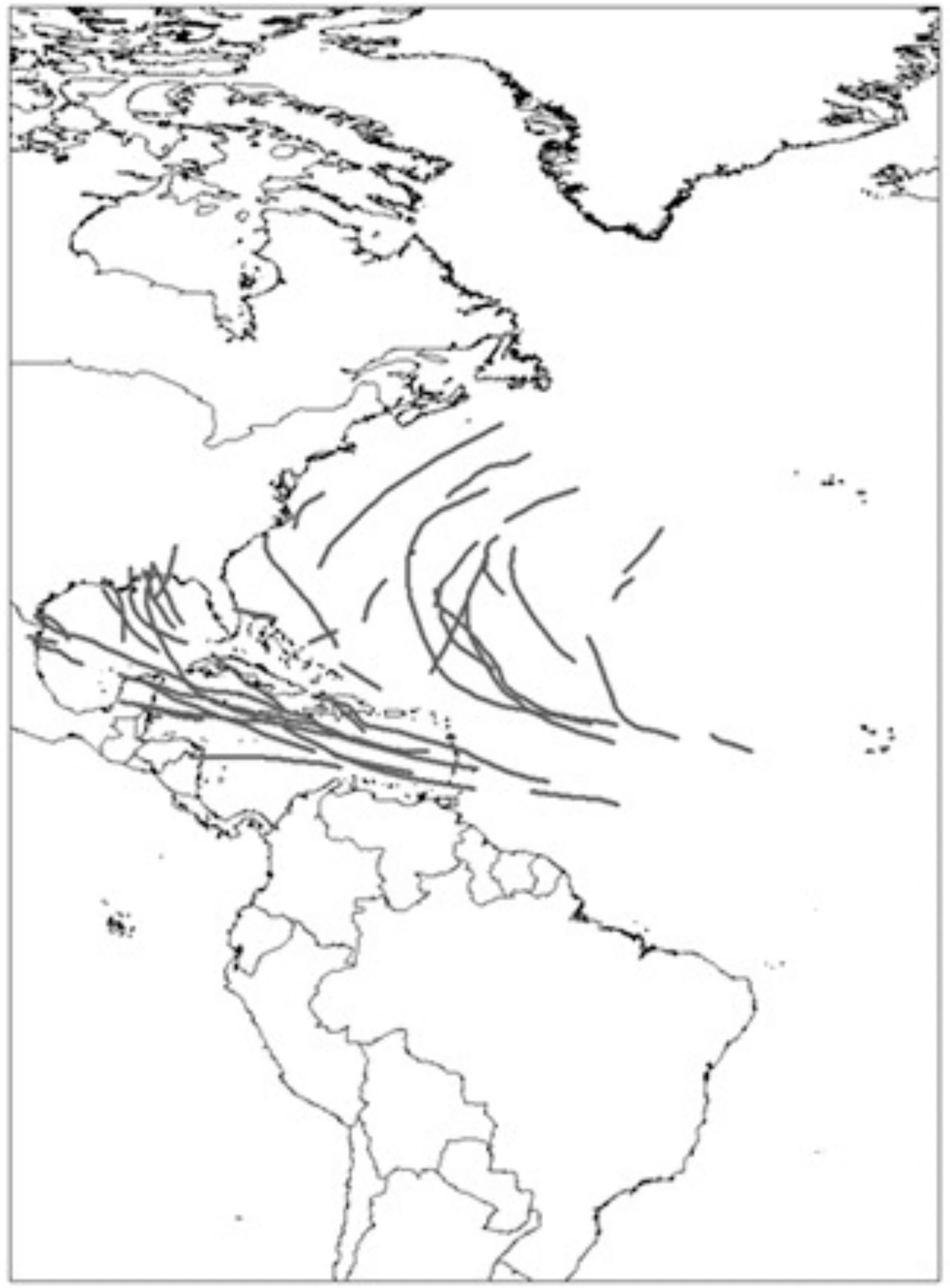


MJO active in Indian Ocean



MJO active in tropical Pacific

tracks of TCs at major hurricane strength



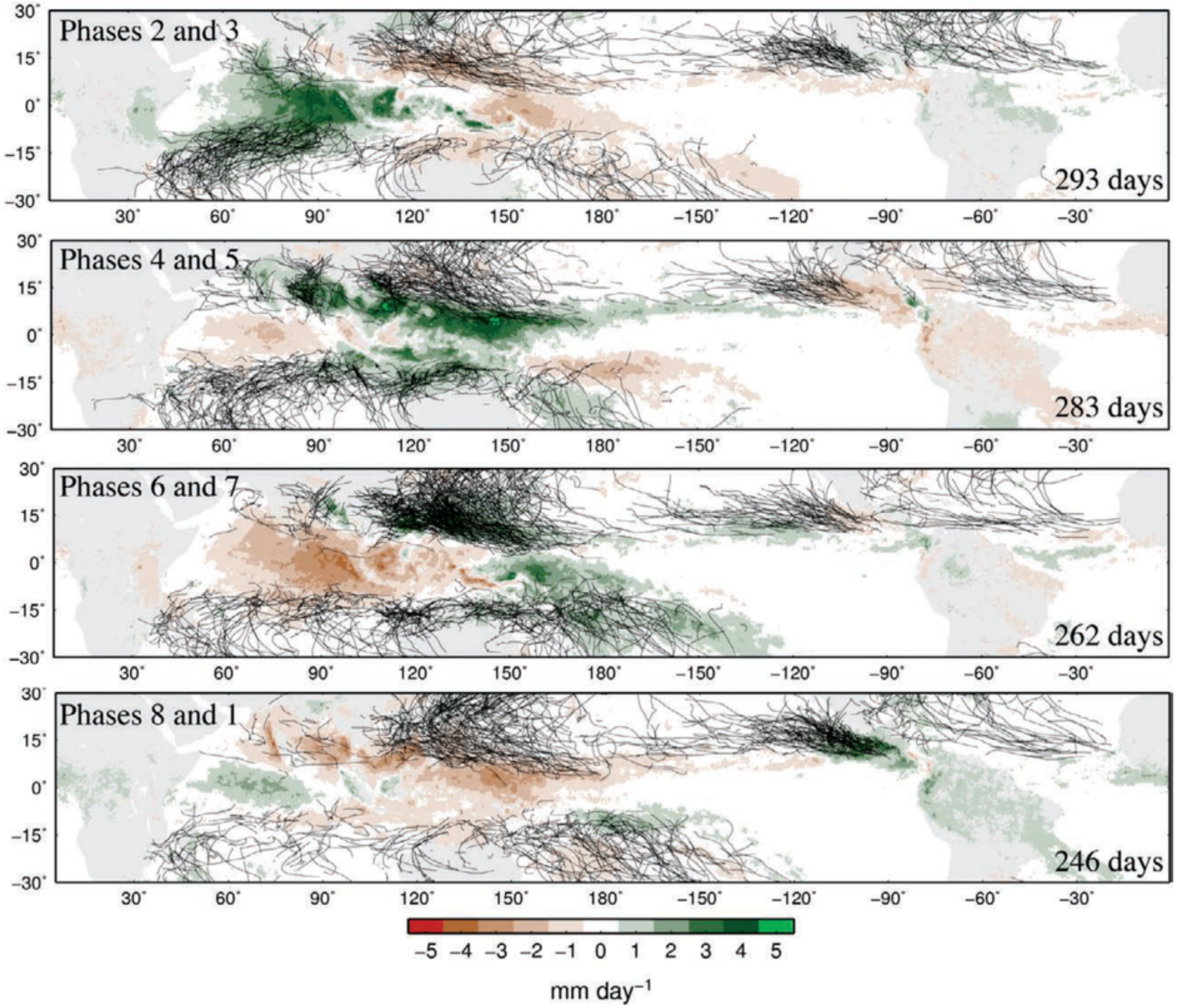
MJO active in Indian Ocean

MJO active in tropical Pacific

Klotzbach, *J. Climate* 2010

The MJO and Tropical Cyclones

In fact, MJO propagation affects tropical cyclone development globally



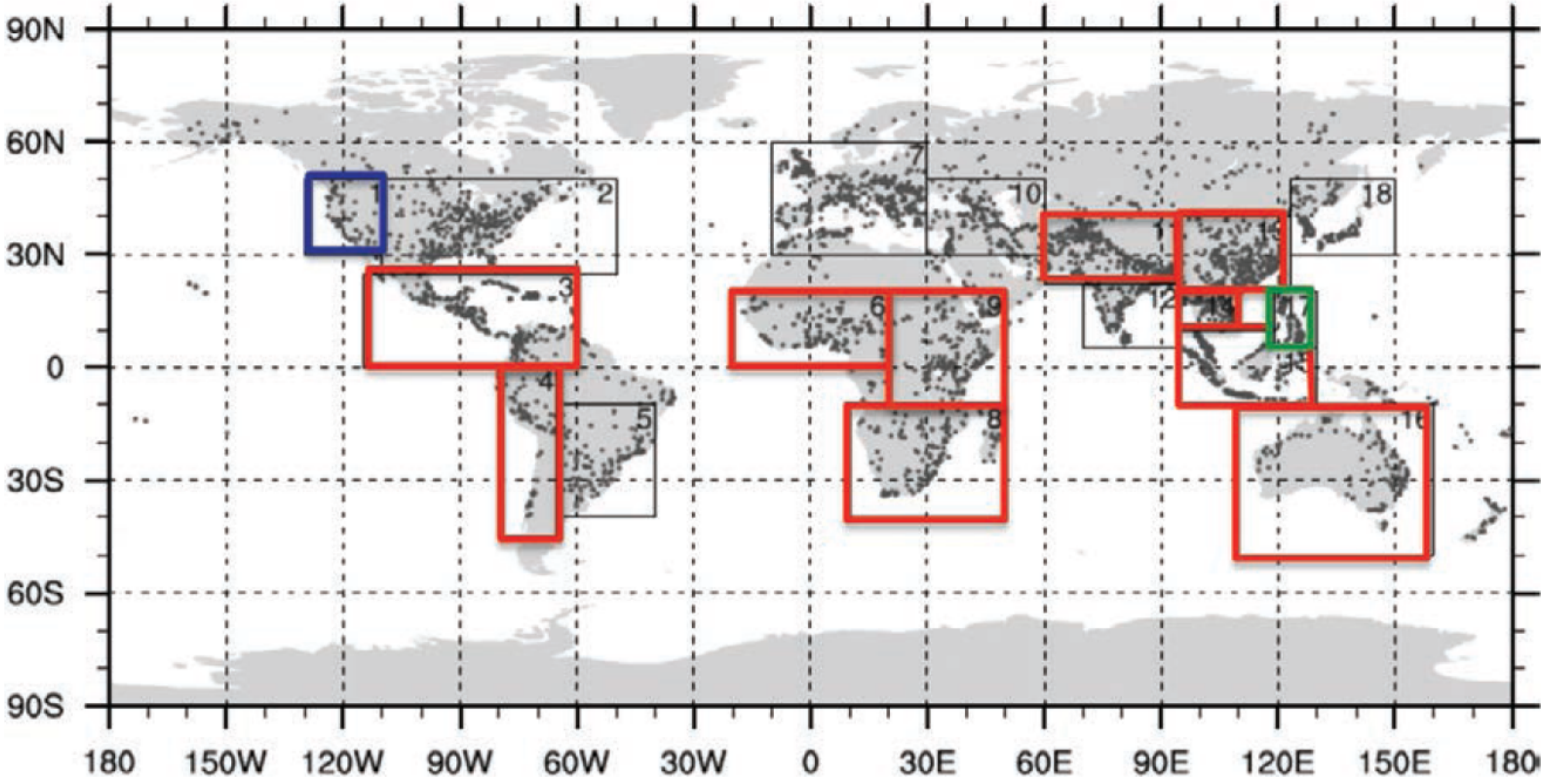
shading:
TRMM precipitation anomalies

lines:
IBTrACS tropical cyclone tracks

Zhang, *Bull. Am. Meteorol. Soc.* 2013

Global Effects of the MJO

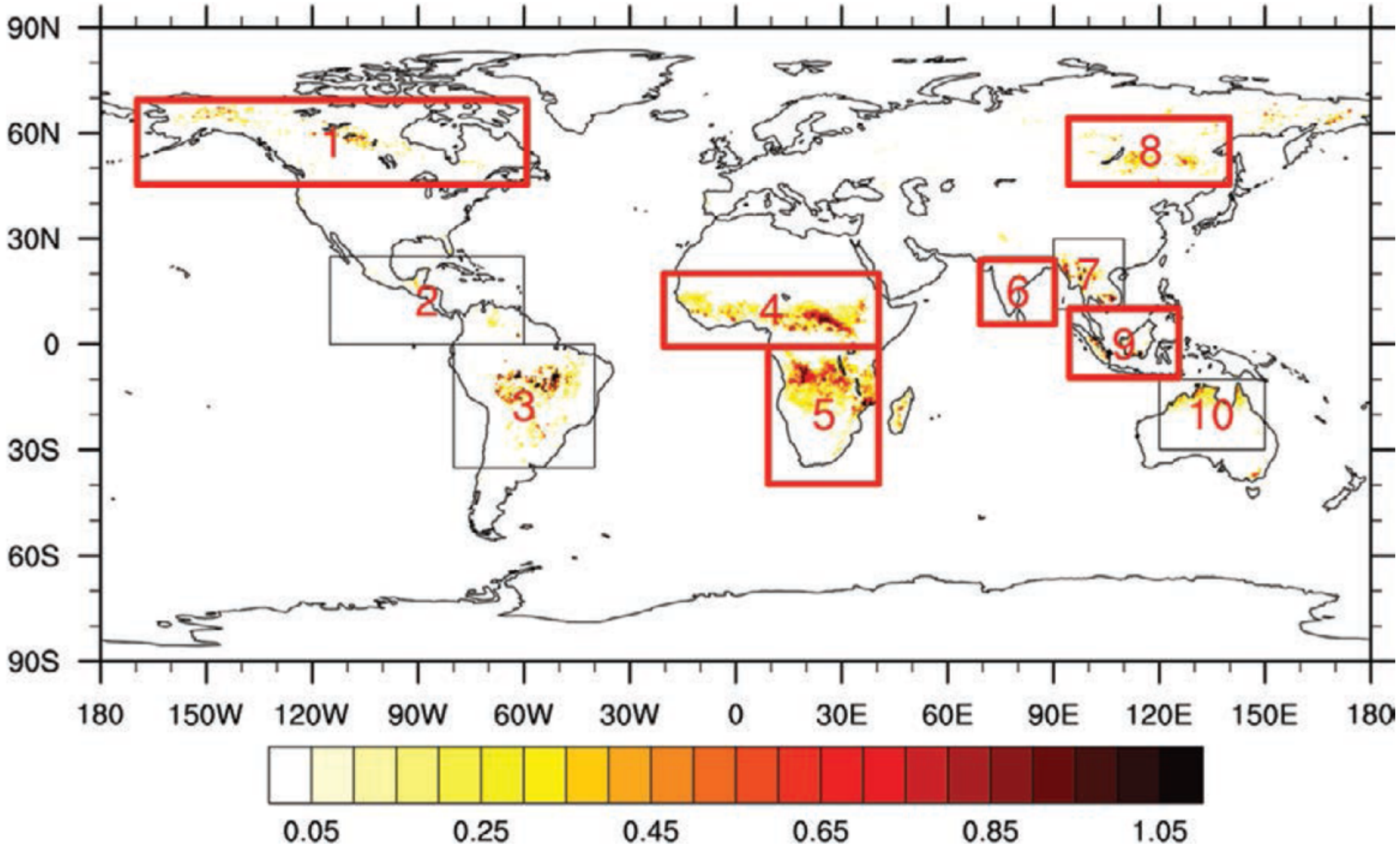
The MJO is strongly correlated with the occurrence of heavy precipitation and severe flooding in many regions around the world



Zhang, *Bull. Am. Meteorol. Soc.* 2013

Global Effects of the MJO

The MJO is also strongly correlated with fire occurrence and emissions, presumably via its impacts on precipitation likelihood and persistence



Zhang, *Bull. Am. Meteorol. Soc.* 2013

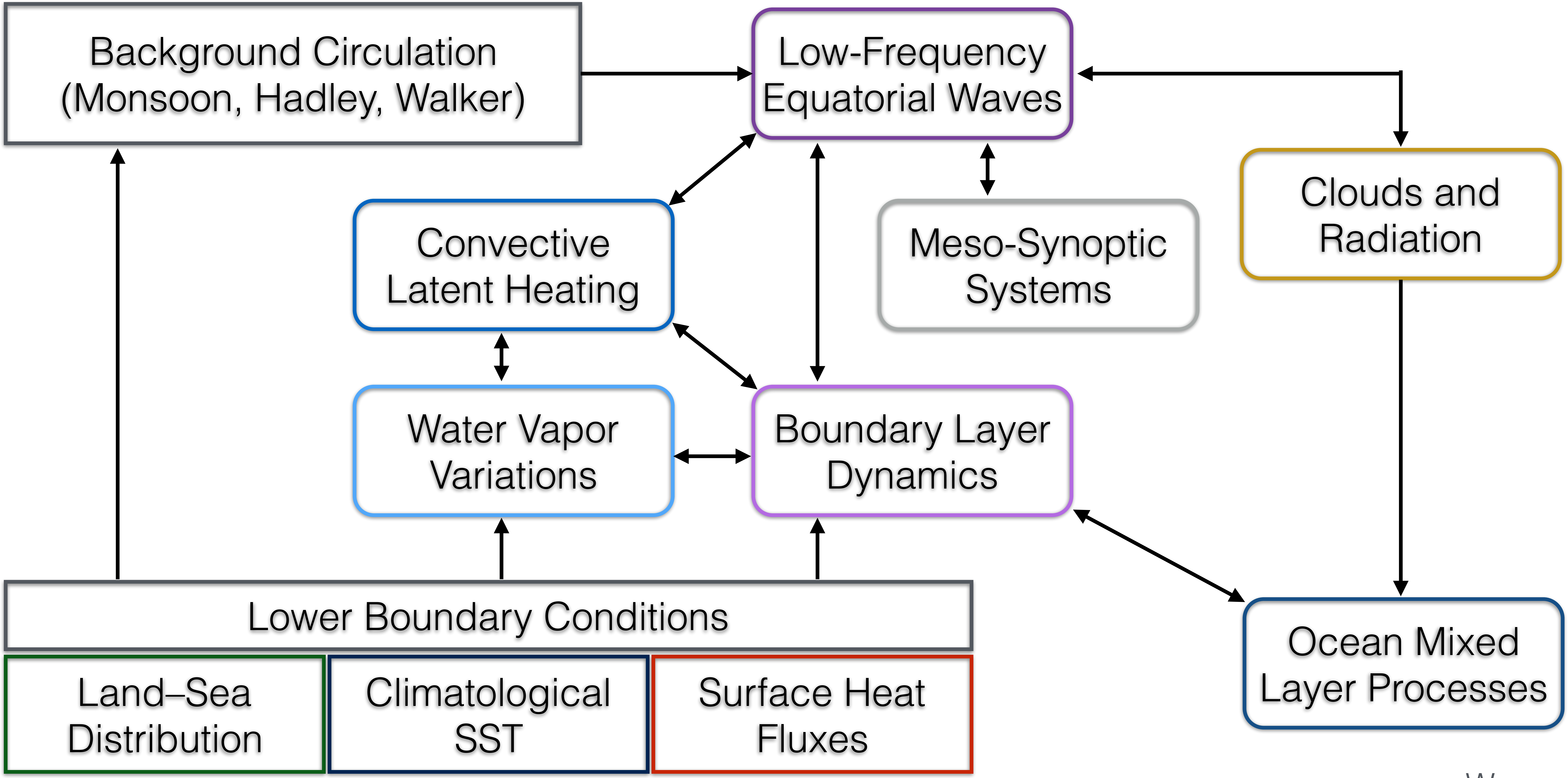
Global Effects of the MJO

- The MJO is related to intraseasonal variability in monsoon precipitation over Australia, South America, North America and Africa
- The MJO also affects the likelihood of extreme non-monsoon rainfall, especially during NH winter
- The MJO is connected to many of the important extratropical climate modes, including the North Atlantic Oscillation (NAO), the Northern and Southern Annular Modes (NAM & SAM), and the Pacific–North America (PNA) pattern
- The MJO affects upper tropospheric and tropopause temperatures, with implications for cirrus cloud distributions and the amount of water vapor entering the stratosphere
- The MJO affects atmospheric chemistry and the composition of aerosols
- The MJO has strong impacts on upper-ocean temperature, salinity, and productivity
- The MJO modulates equatorial currents in the Indian and western Pacific Oceans, with important effects on the rate of water exchange between the Indian and western Pacific Oceans
- The MJO affects global lightning activity and even the global angular momentum (i.e., the length of the day)

Zhang, *Bull. Am. Meteorol. Soc.* 2013

Modeling the MJO

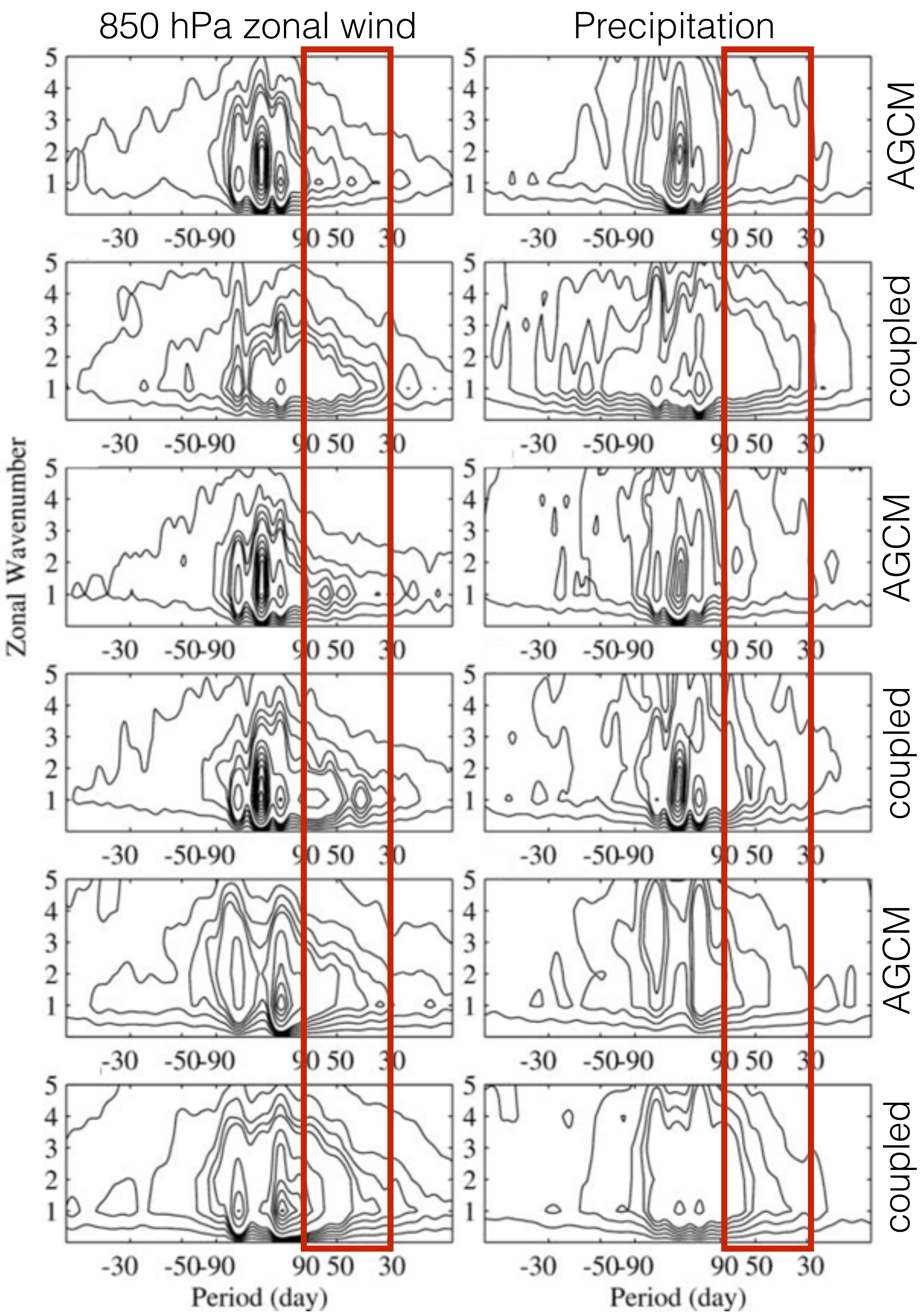
In order to successfully represent the MJO, a model must account for all of the coupled processes that are important to MJO variability

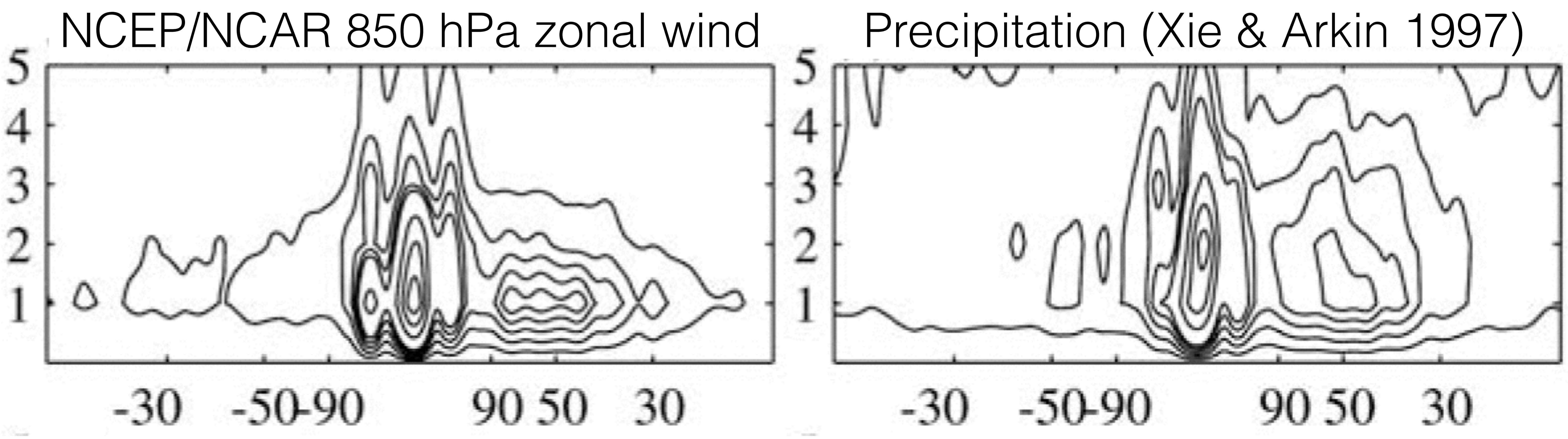


Wang, 2005

Modeling the MJO

Can climate models capture observed MJO variability?





Short answer: not very well, even for coupled models

Evaluation procedure:

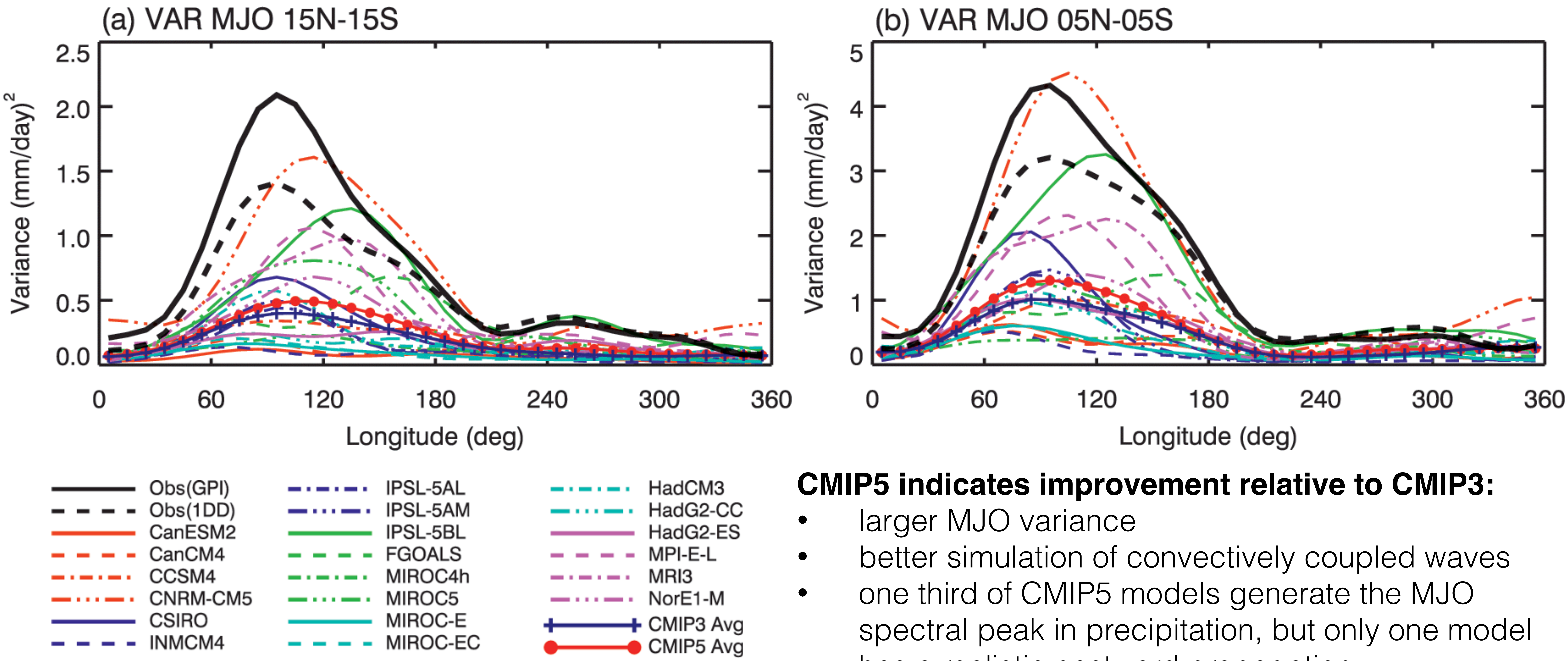
1. Examine the time–space power spectra
2. Objectively extract the MJO signals using data processing methods
3. Reconstruct the MJO from the leading modes and examine the main features
4. Check the spatial distribution and seasonal cycle of the model MJO

Getting the spectrum right is not necessarily enough!

Zhang, *Rev. Geophys.* 2005

Modeling the MJO

Can climate models capture observed MJO variability?



CMIP5 indicates improvement relative to CMIP3:

- larger MJO variance
- better simulation of convectively coupled waves
- one third of CMIP5 models generate the MJO spectral peak in precipitation, but only one model has a realistic eastward propagation

Hung et al., *J. Climate* 2013

Modeling the MJO

"It is intriguing that the MJO can be produced by theoretical and idealized models tuned to represent specific but simplified mechanisms, but not by many GCMs with more sophisticated treatment of physical processes. **It is not obvious what is in the idealized models but missing in the GCMs that would make the MJO present in the former and absent in the latter**. A successful theory of the MJO should not be judged solely by whether it produces and MJO. It must be able to quantitatively explain the difficulty of simulating the MJO by GCMs as well as the selection of the scales and phase speed of the MJO."

Zhang, *Rev. Geophys.* 2005

Summary

1. The MJO is the main mode of intraseasonal variability in the tropical climate system
2. The MJO signal travels around the globe, but MJO variability is strongest in the Indian Ocean and western Pacific
3. The mechanisms behind the MJO are still uncertain, but tropical wave dynamics and moisture convergence both play prominent roles
4. Climate models are largely unable to capture the MJO, although their representations of the MJO are generally improving
5. The MJO also has a north–south component during NH summer, which causes active and break phases in the South Asian monsoon
6. Recent studies suggest that the MJO may also modify ENSO variability, tropical cyclone activity, and many other components of global climate and weather