Intraseasonal Oscillation and Its Impacts

Part I:
Characteristics of ISO, Mechanism, and Understanding its predictability

Part II:
Impact on Monsoons and Extreme Events

APCC Subseasonal to Seasonal (S2S)
2016 Training Program
Busan, Korea

Boreal Winter (November-April) ISO:
Madden-Julian Oscillation (MJO)

Boreal Summer (May-October) ISO:
BSISO (Summer ISO)

Data:
- Global reanalysis products (winds, geopotential height, etc.)
- Satellites (rainfall, OLR, etc.)
- Ground stations (rainfall, temperature)

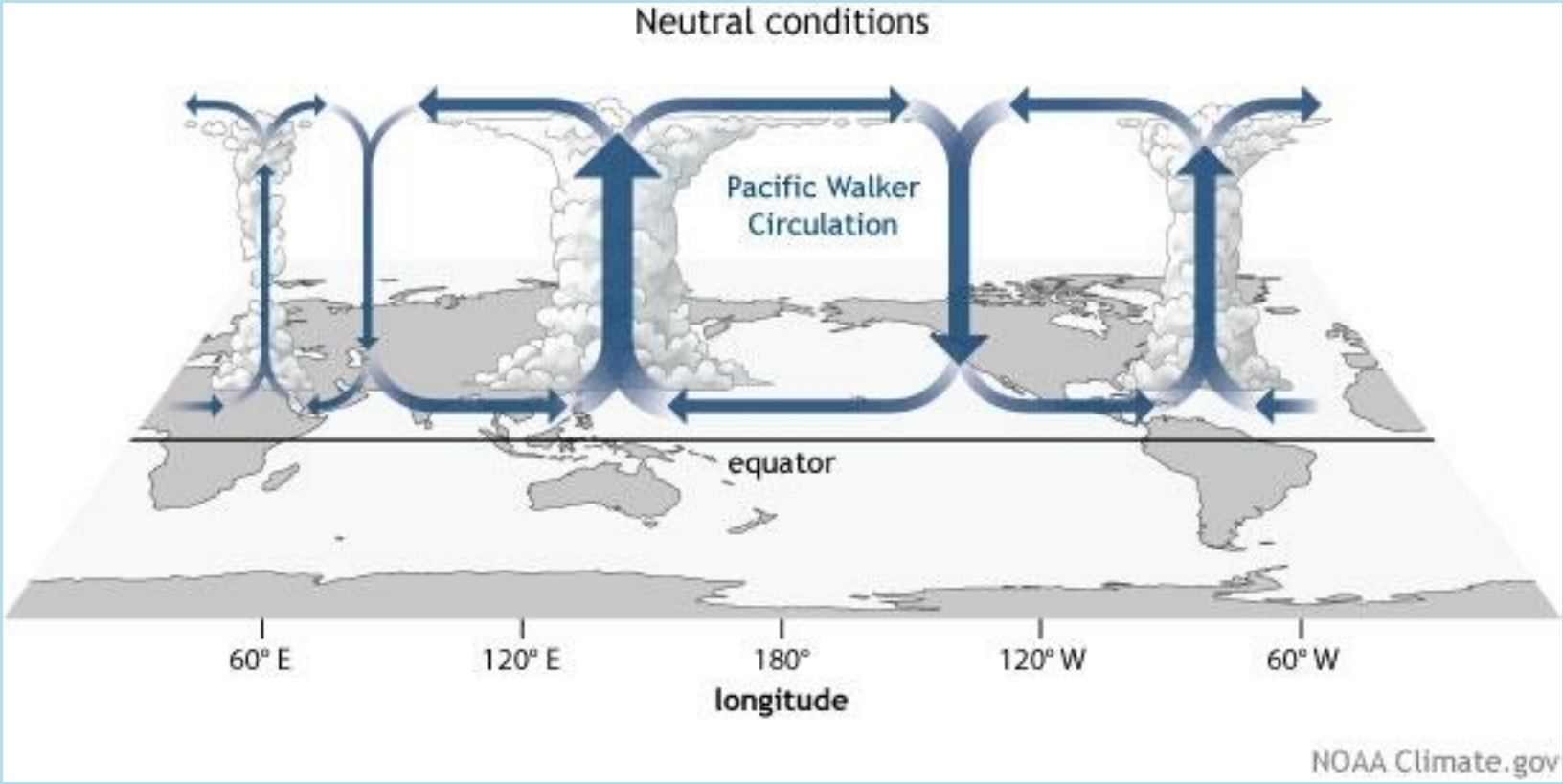
Analysis Tools:
- MJO/BSISO indices (e.g., RMM)
- Composites (selected averages)
- Regression
- Probability distribution function (PDF)
- Case studies
- Conceptual sketches

Source of Information: Journal articles, websites, lectures

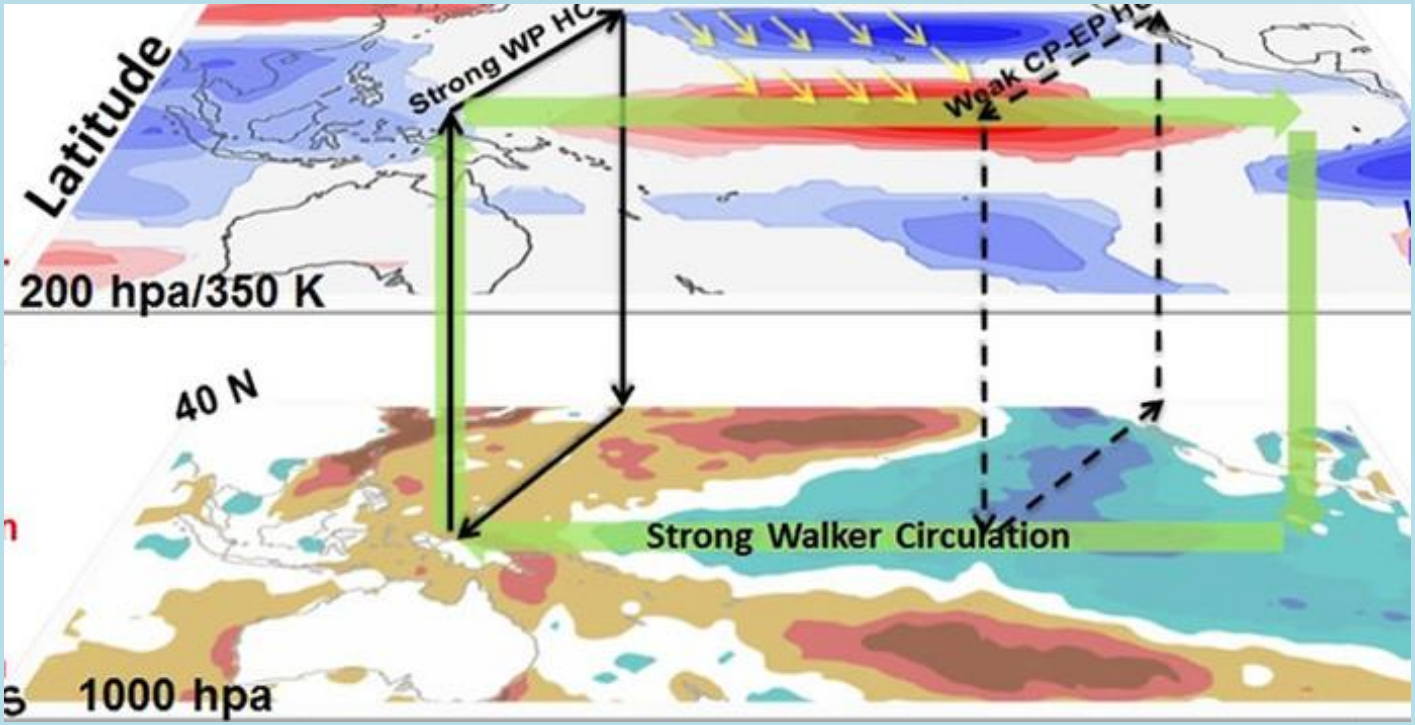
Repeat, repeat, repeat.

Ask, ask, ask.

Background Mean State:
The Seasonal Cycle and Asian Monsoons



Background Mean State:
The Seasonal Cycle and Asian Monsoons

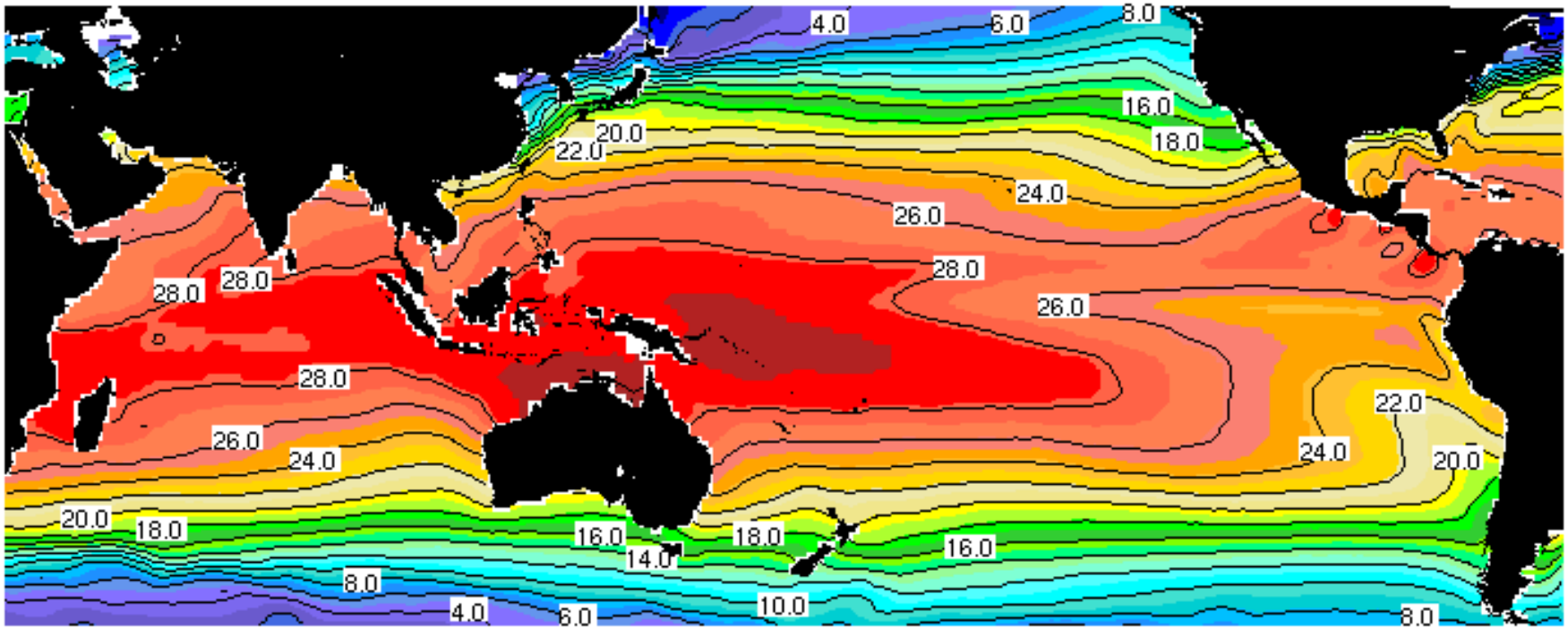


Nath et al (2016)

http://www.nature.com/articles/srep21370

Jan

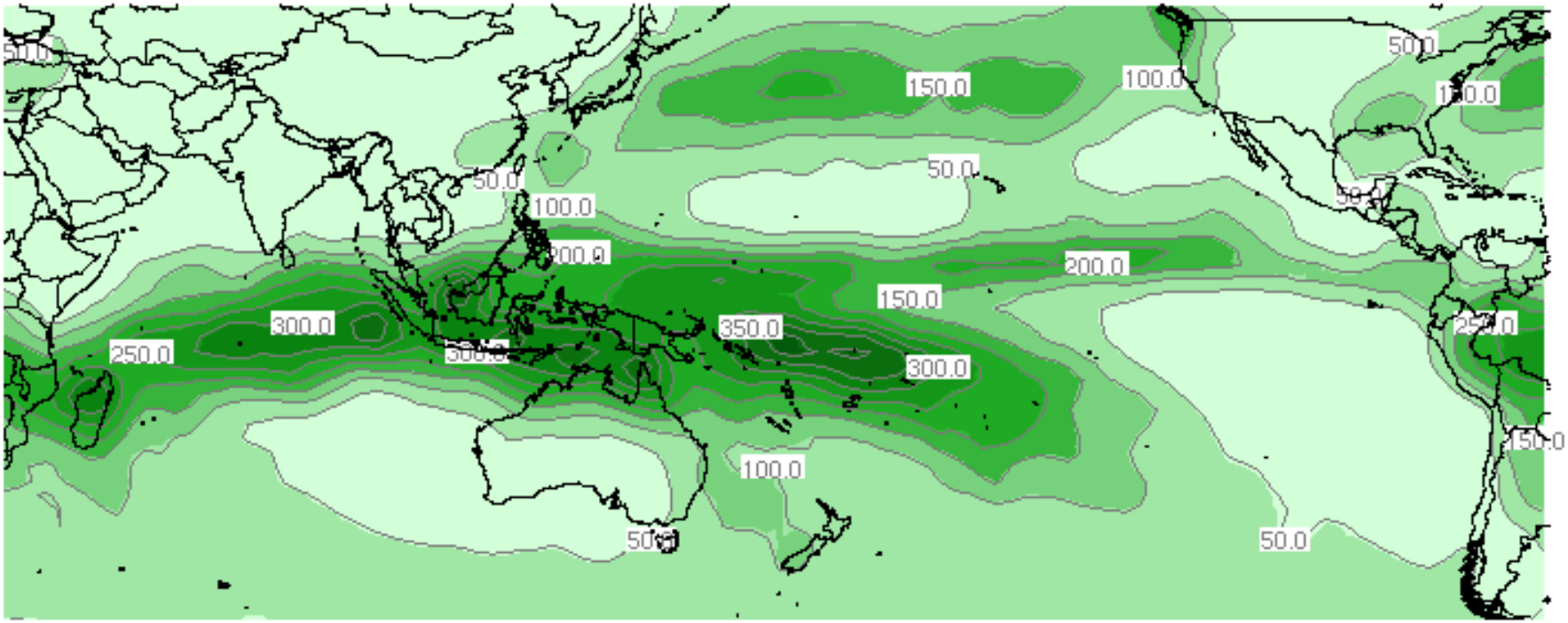
Sea Surface Temperature (SST)



https://iridl.ldeo.columbia.edu/maproom/Global/Climatologies/SST_Loop.html?bbox=bb%3A31.46%3A-55.26%3A299.63%3A51.33%3Abb

Jan

Precipitation



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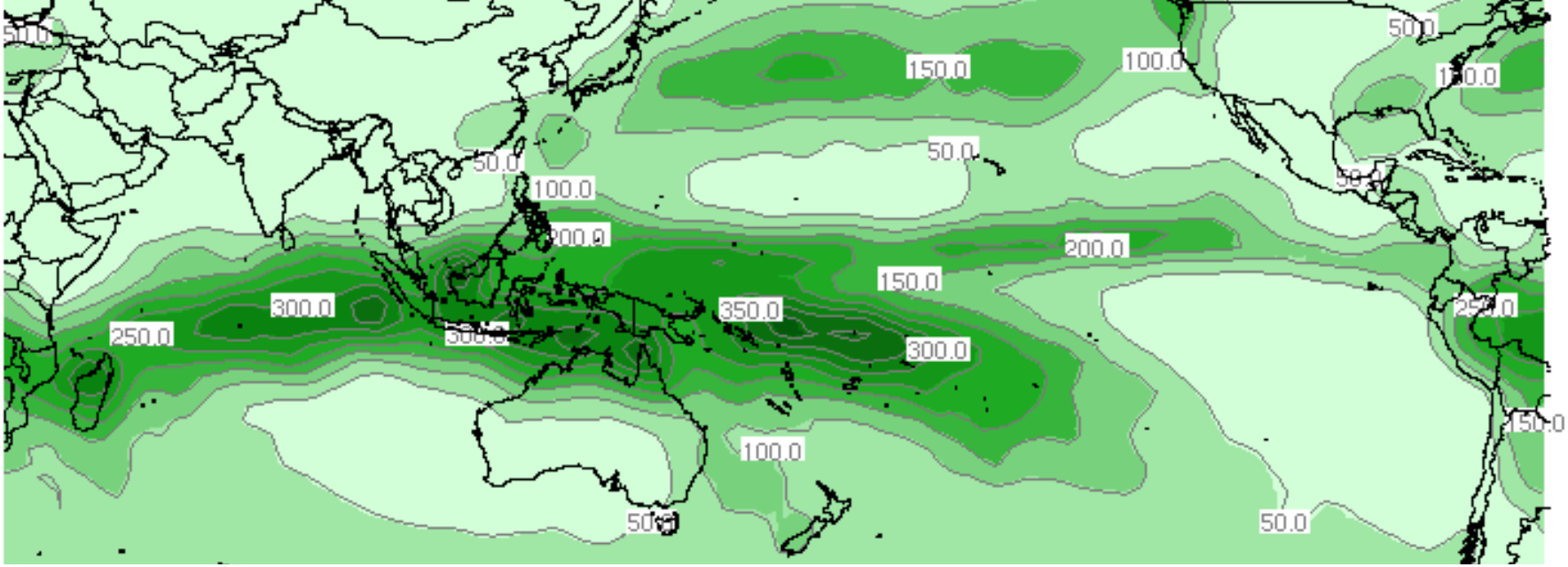
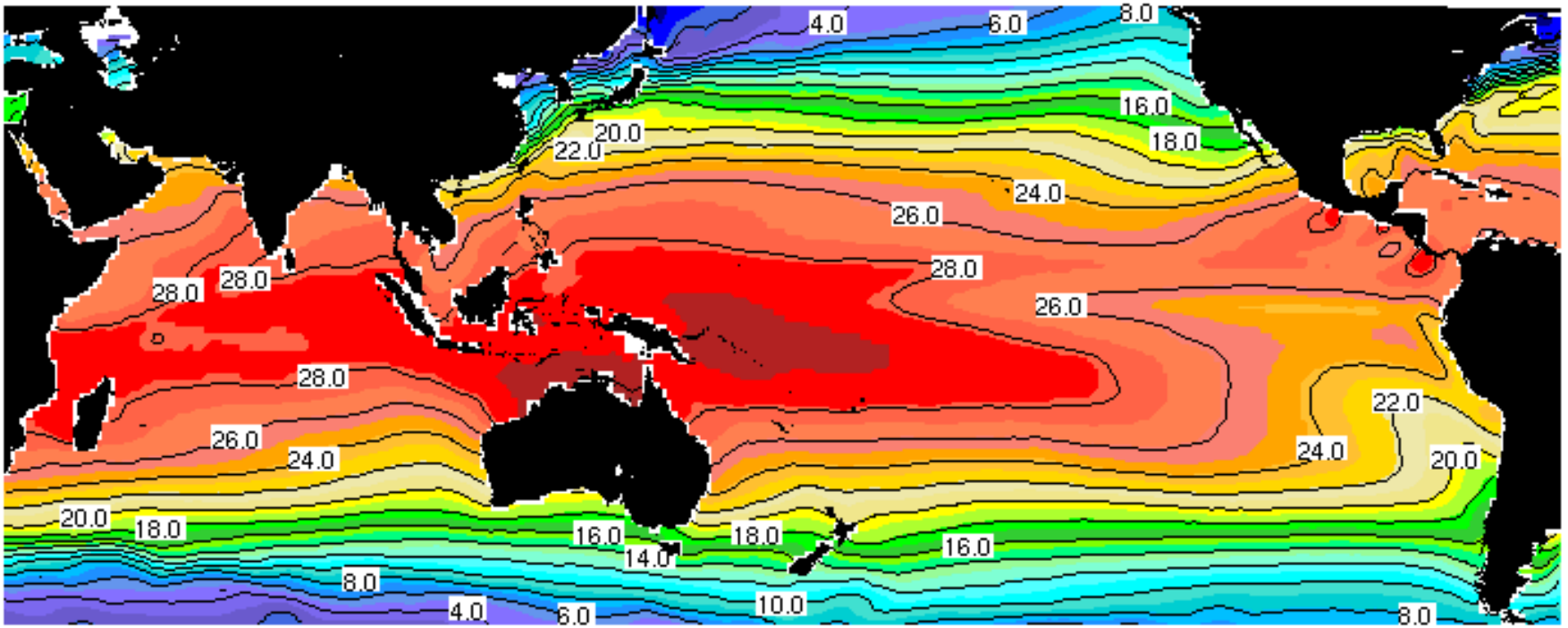
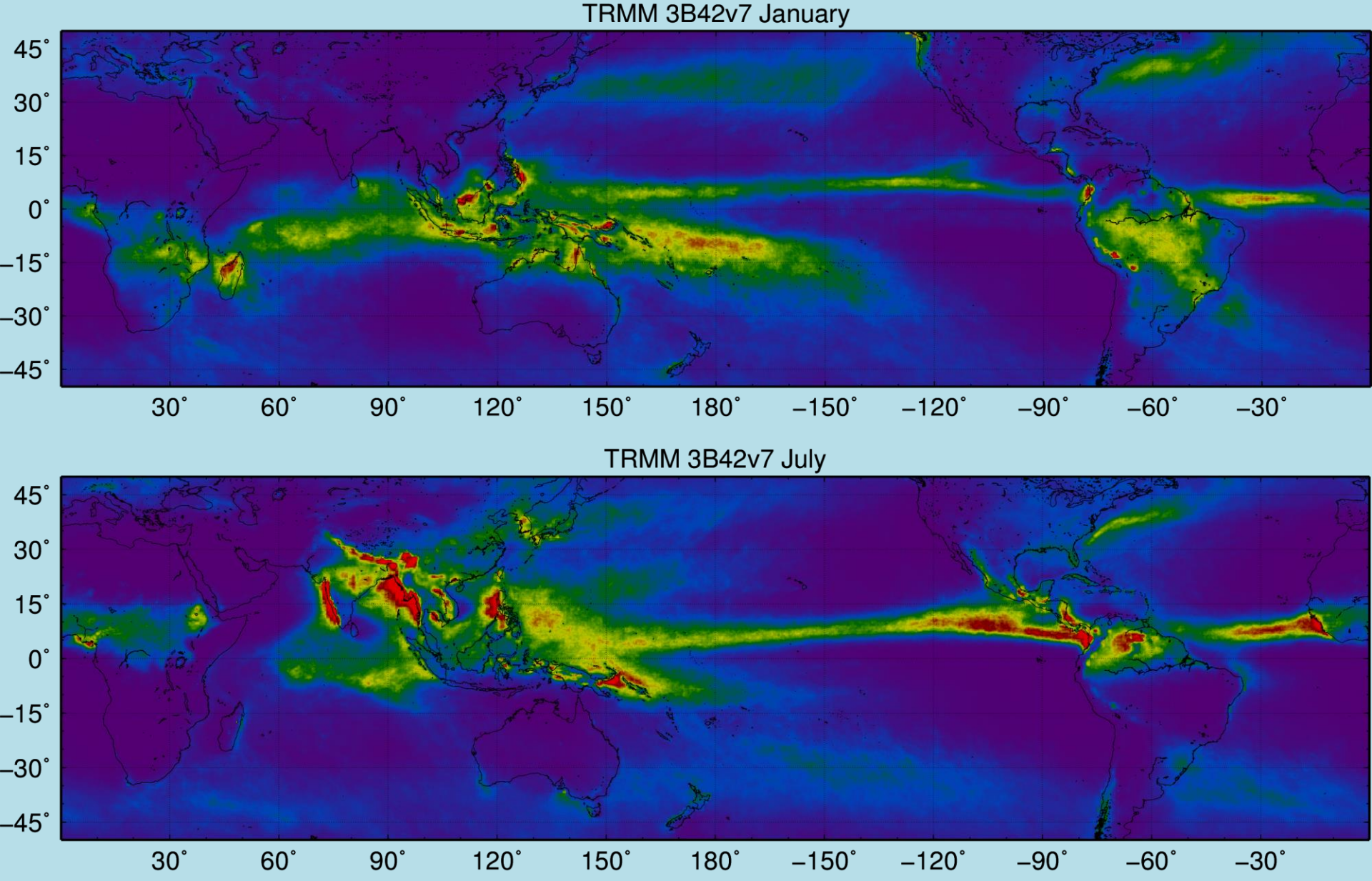
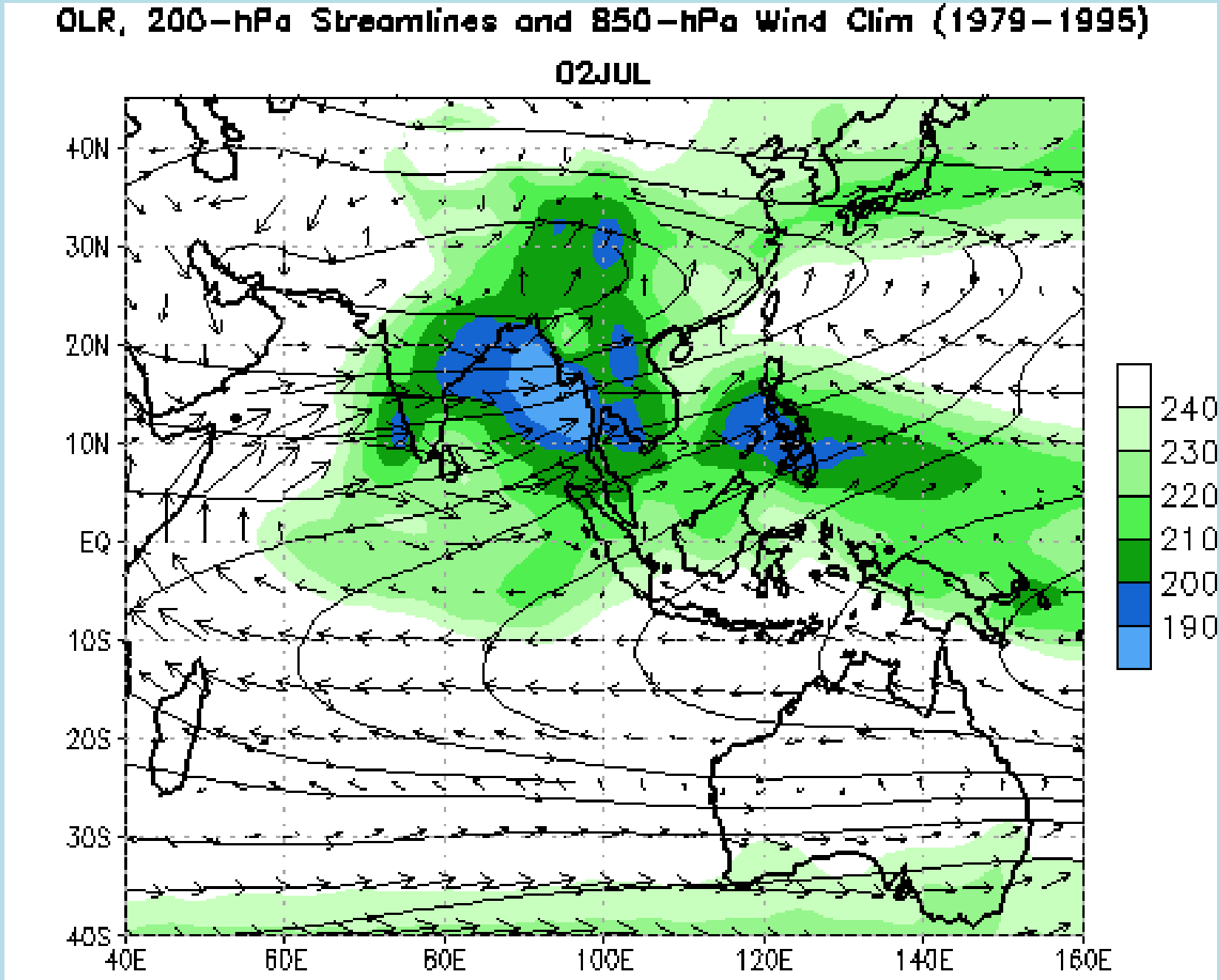

50.0
150.0
100.0
50.0
50.0
100.0
200.0
200.0
150.0
300.0
350.0
250.0
300.0
100.0
50.0
50.0
150.0

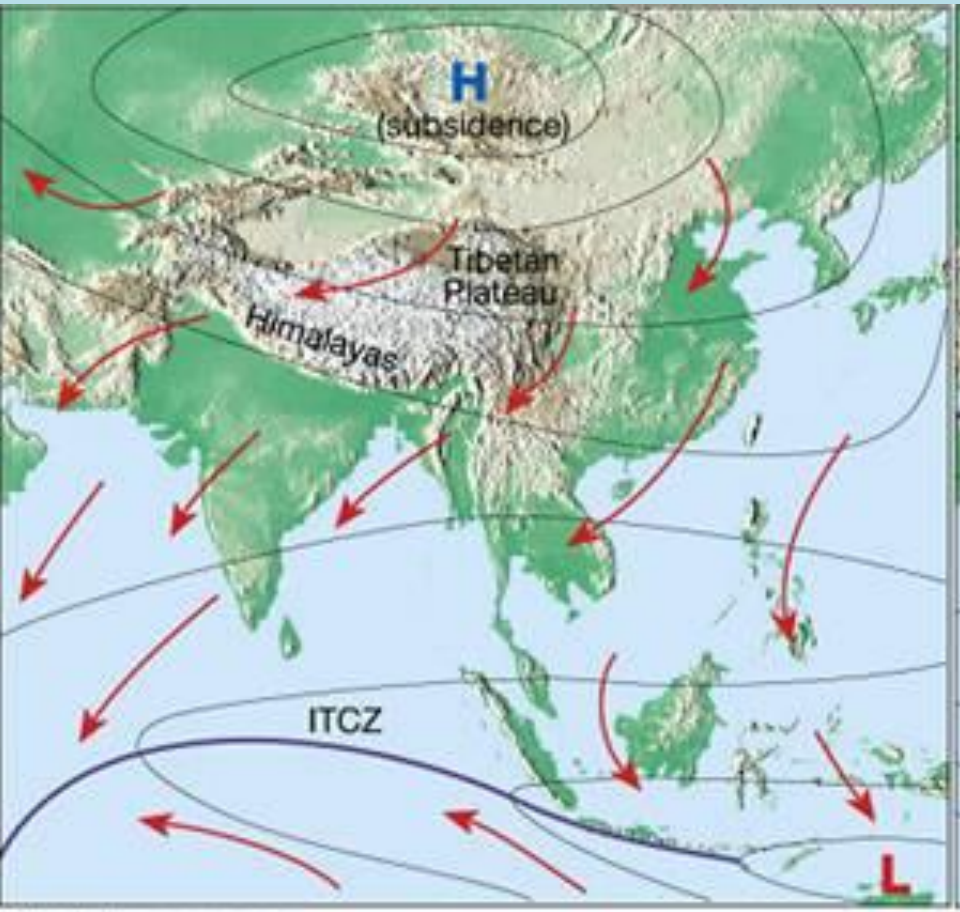
Jan


4.0
6.0
8.0
16.0
18.0
20.0
22.0
24.0
26.0
28.0
28.0
28.0
26.0
28.0
22.0
26.0
24.0
24.0
20.0
20.0
18.0
16.0
14.0
18.0
16.0
8.0
4.0
6.0
10.0
8.0

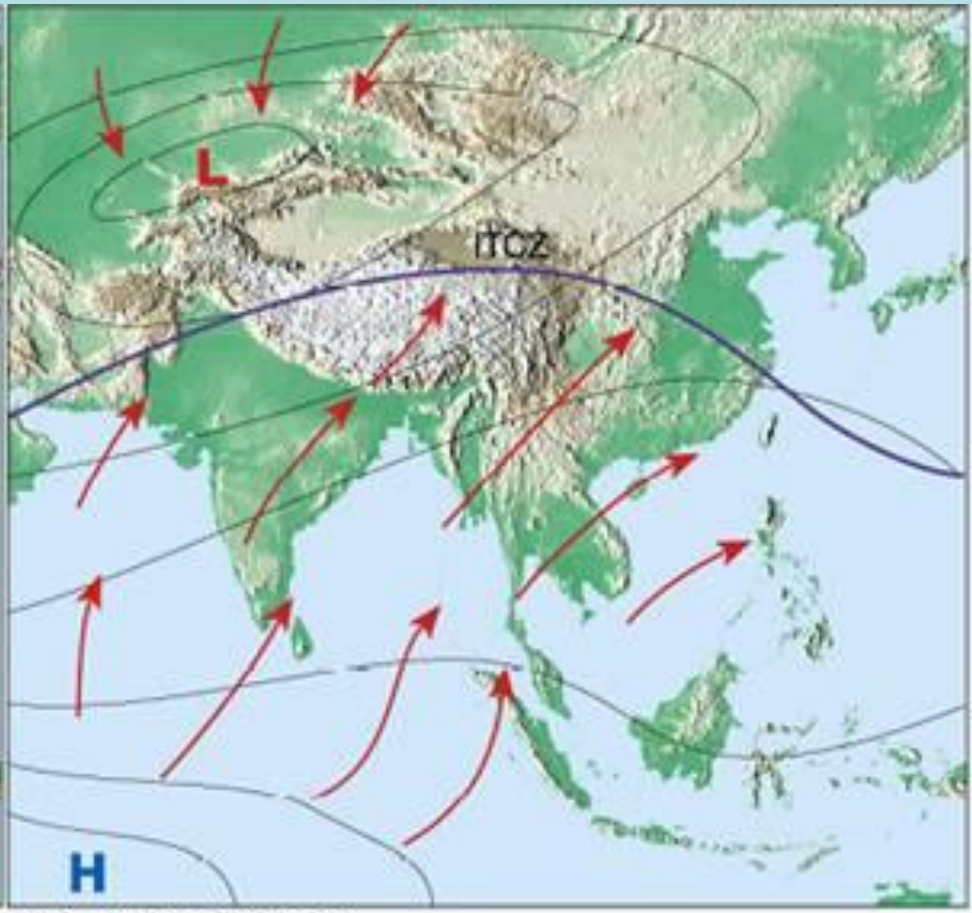

TRMM 3B42v7 January
45˚
30˚
15˚
0˚
−15˚
−30˚
−45˚
30˚
60˚
90˚
120˚
150˚
180˚
−150˚
−120˚
−90˚
−60˚
−30˚
TRMM 3B42v7 July
45˚
30˚
15˚
0˚
−15˚
−30˚
−45˚
30˚
60˚
90˚
120˚
150˚
180˚
−150˚
−120˚
−90˚
−60˚
−30˚



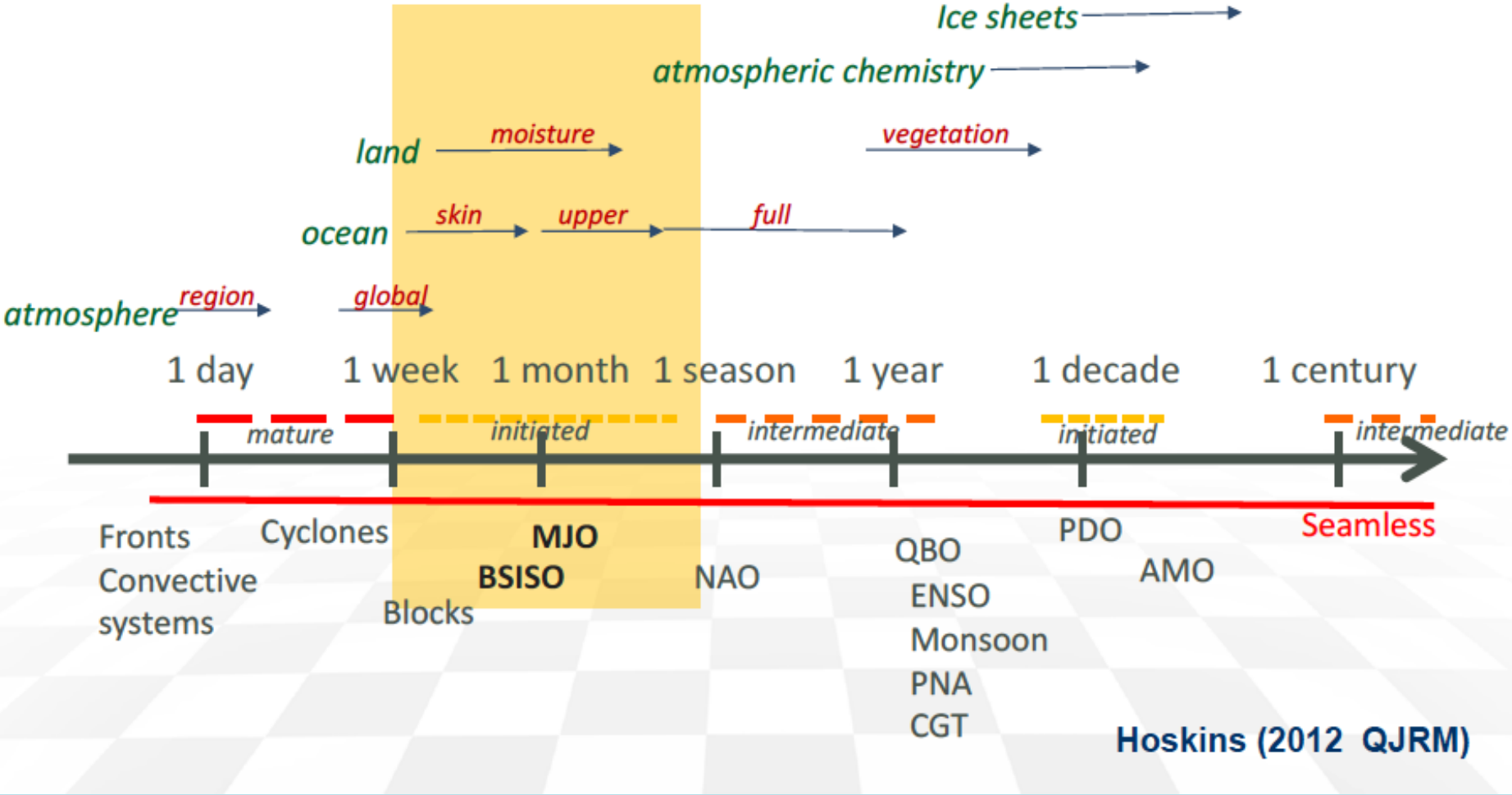
Data Sources: OLR - NESDIS/ORA, Winds - NCEP CDAS/ Reanalysis



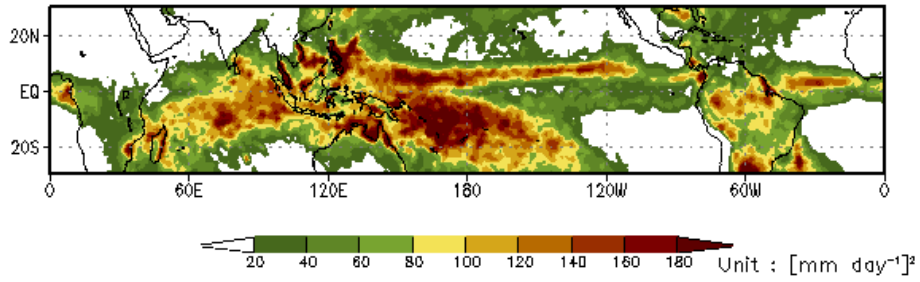
(a) Winter monsoon



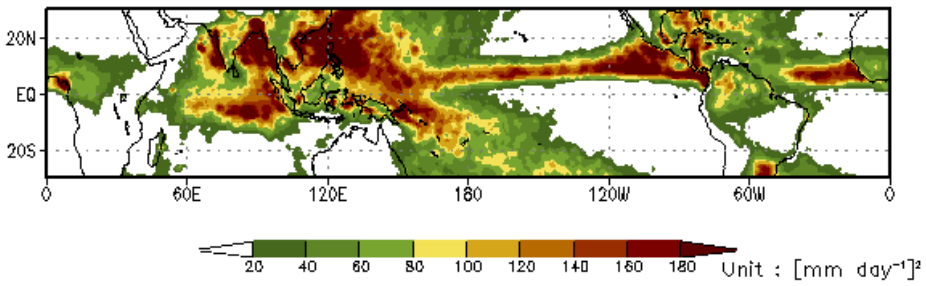
(b) Summer monsoon


Ice sheets
atmospheric chemistry
land
moisture
vegetation
ocean
skin
upper
full
atmosphere
region
global
1 day
1 week
1 month
1 season
1 year
1 decade
1 century
mature
initiated
intermediate
initiated
intermediate
Fronts
Convective systems
Cyclones
Blocks
MJO
BSISO
NAO
QBO
ENSO
Monsoon
PNA
CGT
PDO
AMO
Seamless
Hoskins (2012 QJRM)

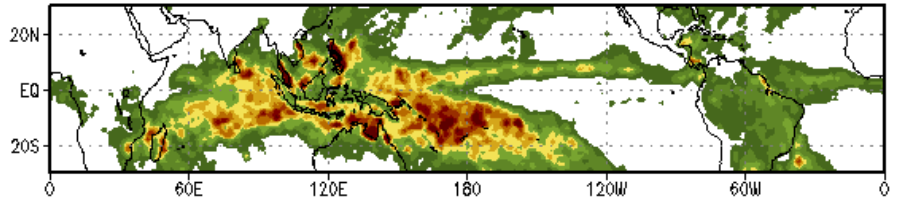
(a) Unfiltered variance, PRCP, TRMM, Winter



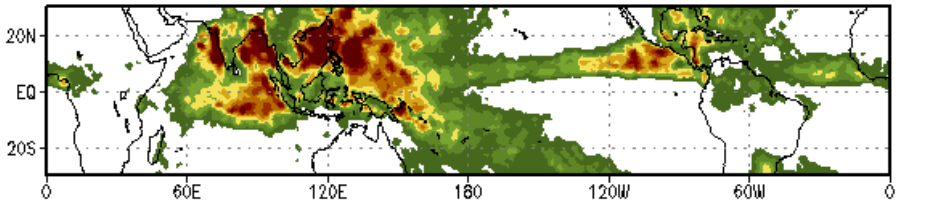
(a) Unfiltered variance, PRCP, TRMM, Summer



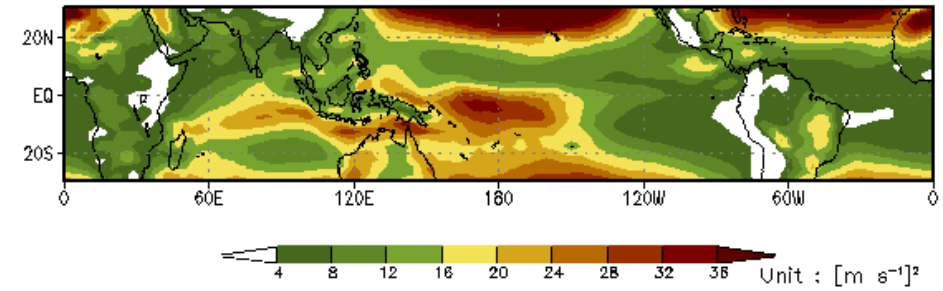
(b) 20–100 day variance, PRCP, TRMM, Winter



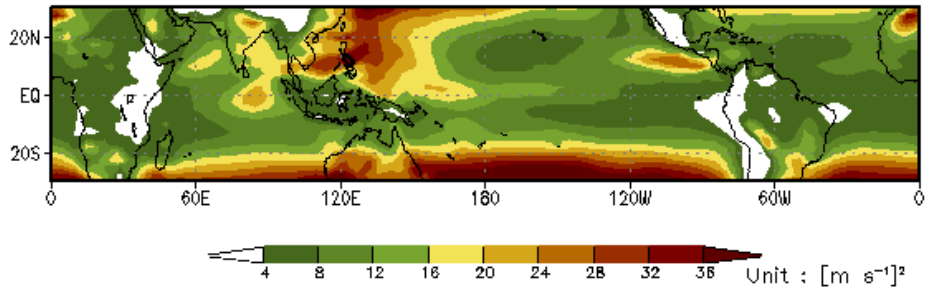
(b) 20–100 day variance, PRCP, TRMM, Summer



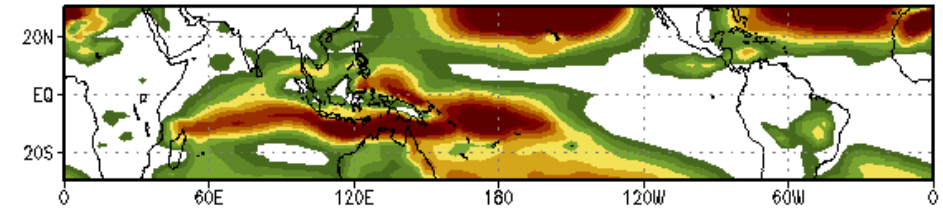
(a) Unfiltered variance, U850, ERA40, Winter



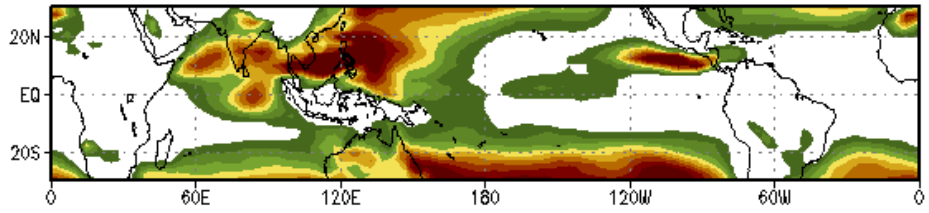
(a) Unfiltered variance, U850, ERA40, Summer



(b) 20–100 day variance, U850, ERA40, Winter

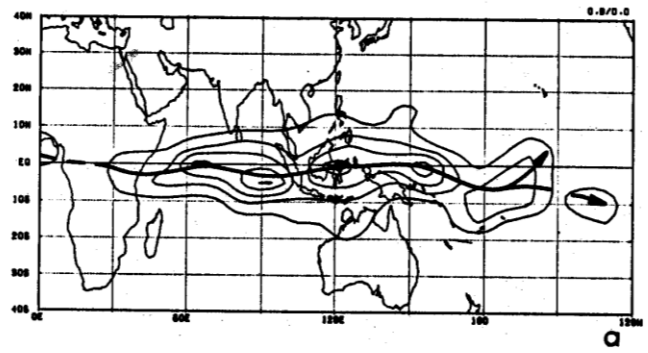


(b) 20–100 day variance, U850, ERA40, Summer

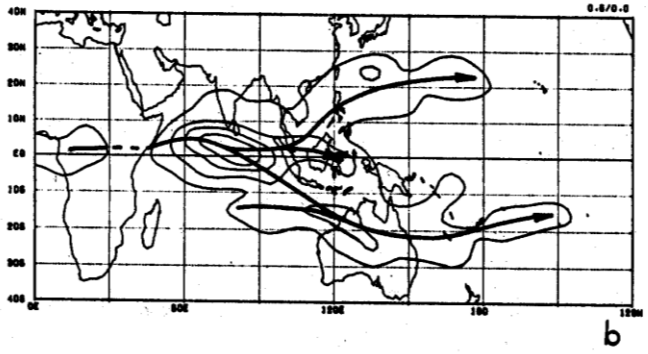


Dominant Tropical Intraseasonal Variability: Propagation

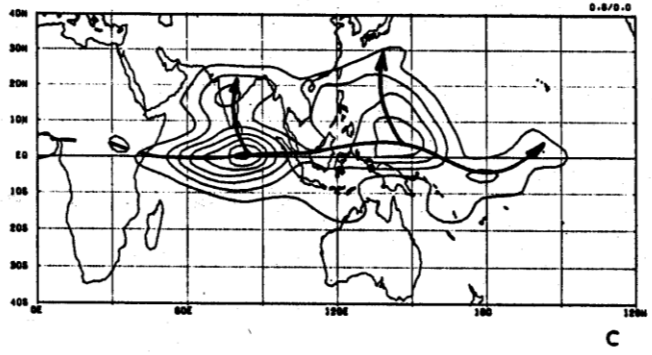
MJO: Eastward
BSISO: Eastward and Northward



MJO



MJO



BSISO

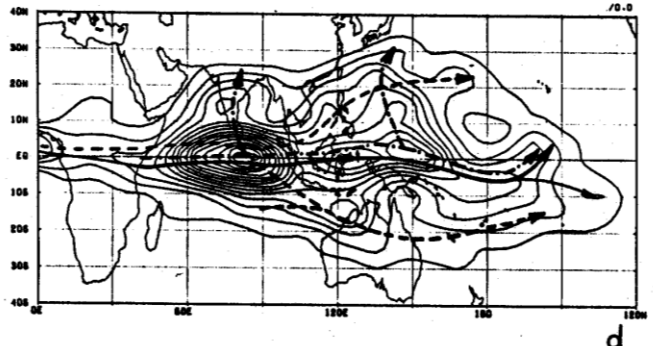


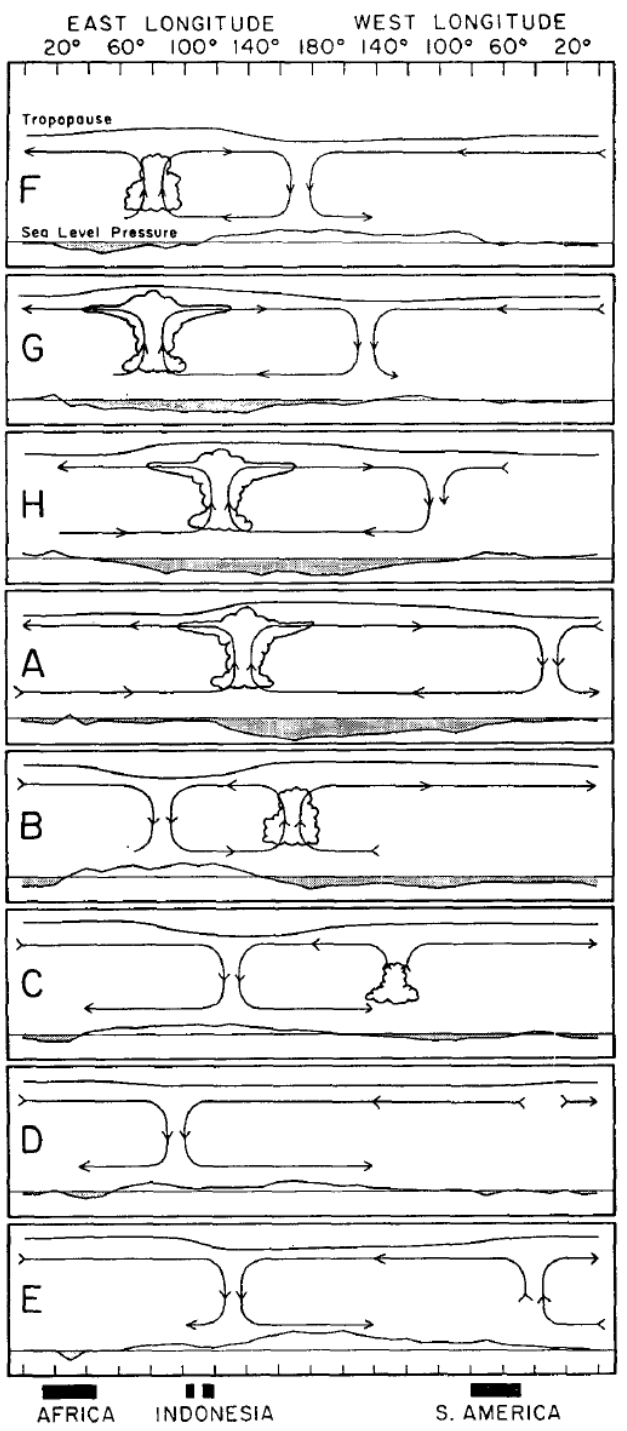
Fig. 5. Contour plot of total number of occurrence of centers for (a) EE mode; (b) N(S)E mode; (c) EN mode; and (d) all eastward propagating modes (the sum of (a), (b), and (c)) in each 2° × 2° box for a ten-year period (1975–1985). The contour interval is 0.8 except in (b) which is 0.6. The thick solid, dashed, and dark dotted lines with arrows in (d) indicate the central paths for EE, N(S)E, and EN modes, respectively. For an explanation of EE, N(S)E, and EN modes, refer to the text

Wang and Rui (1990)

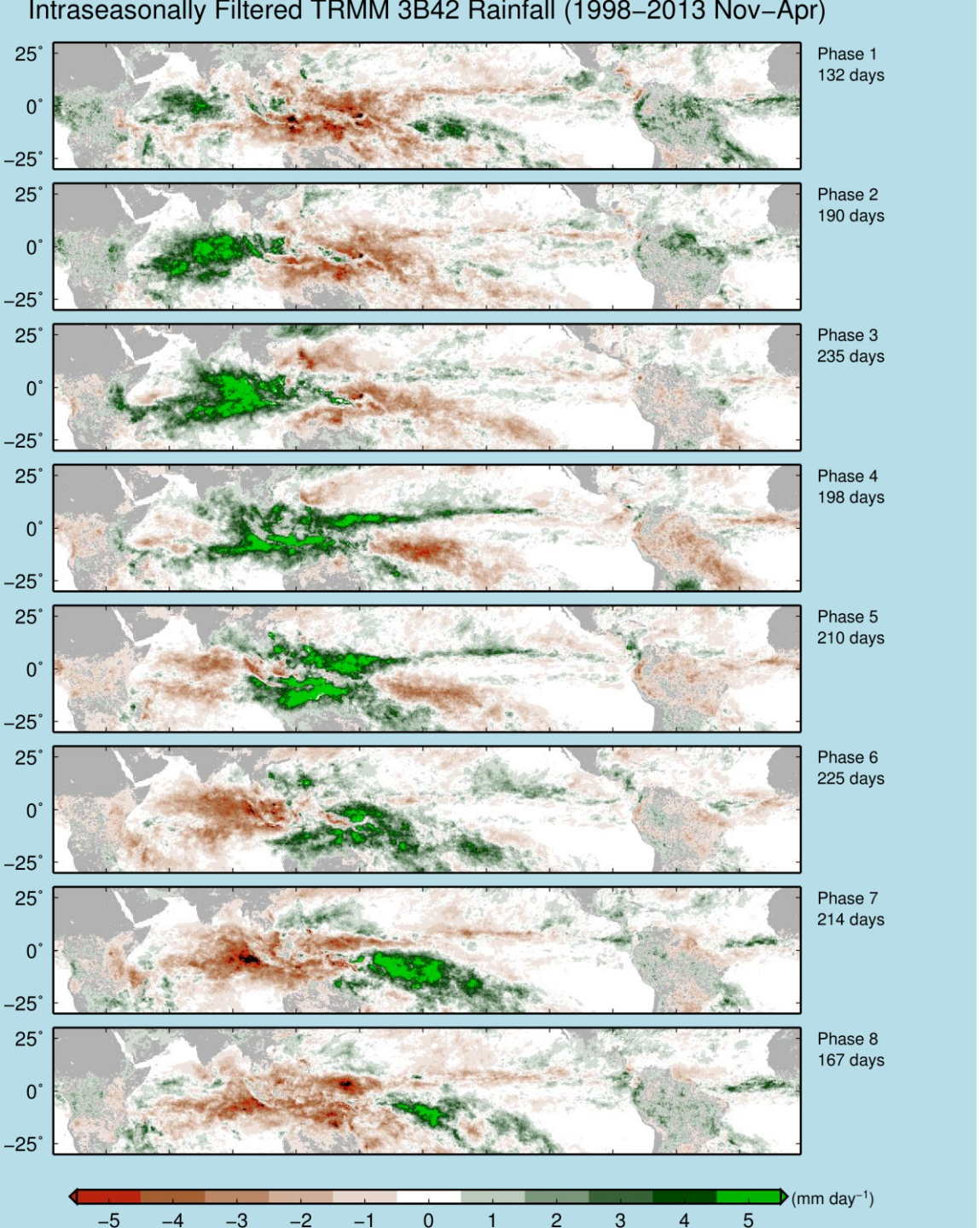
Madden-Julian Oscillation

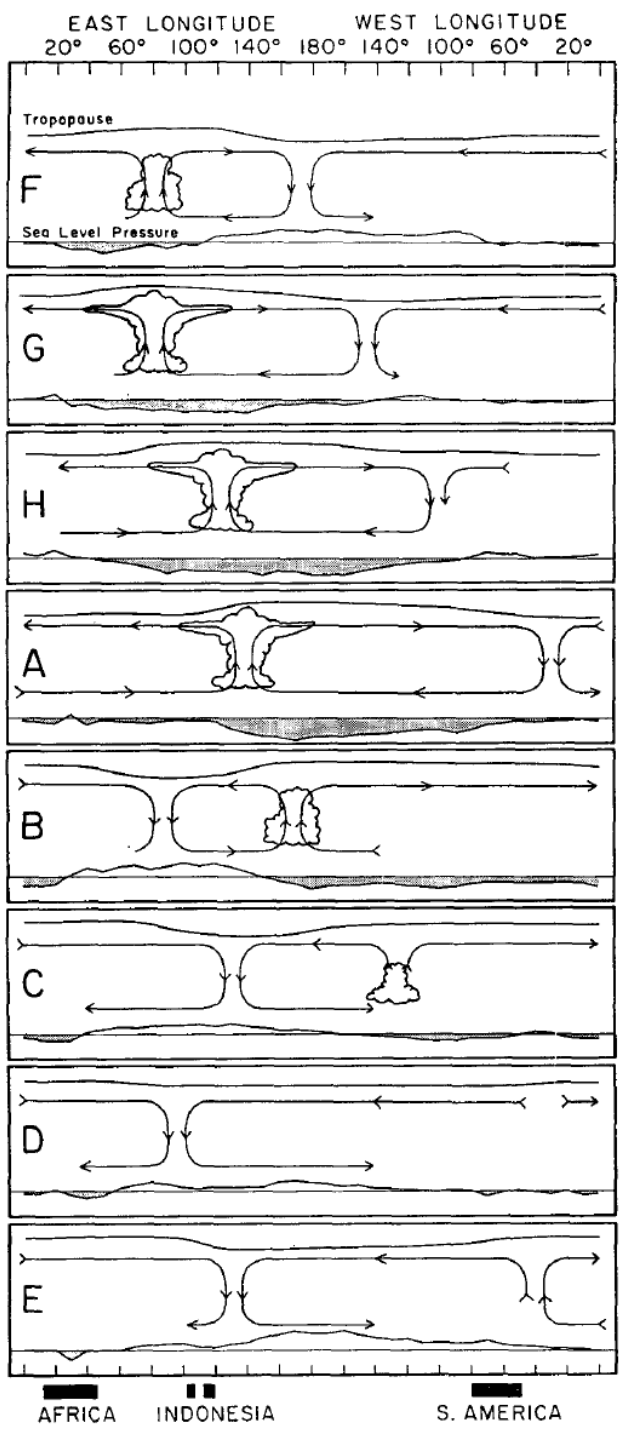
Basic observed features (or definition):

- intraseasonal timescale (20 – 90 days)
- planetary zonal scale (k = 1 – 3)
- slow eastward propagation ($c \approx 5\ ms^{-1}$) in tropical deep convection and zonal winds

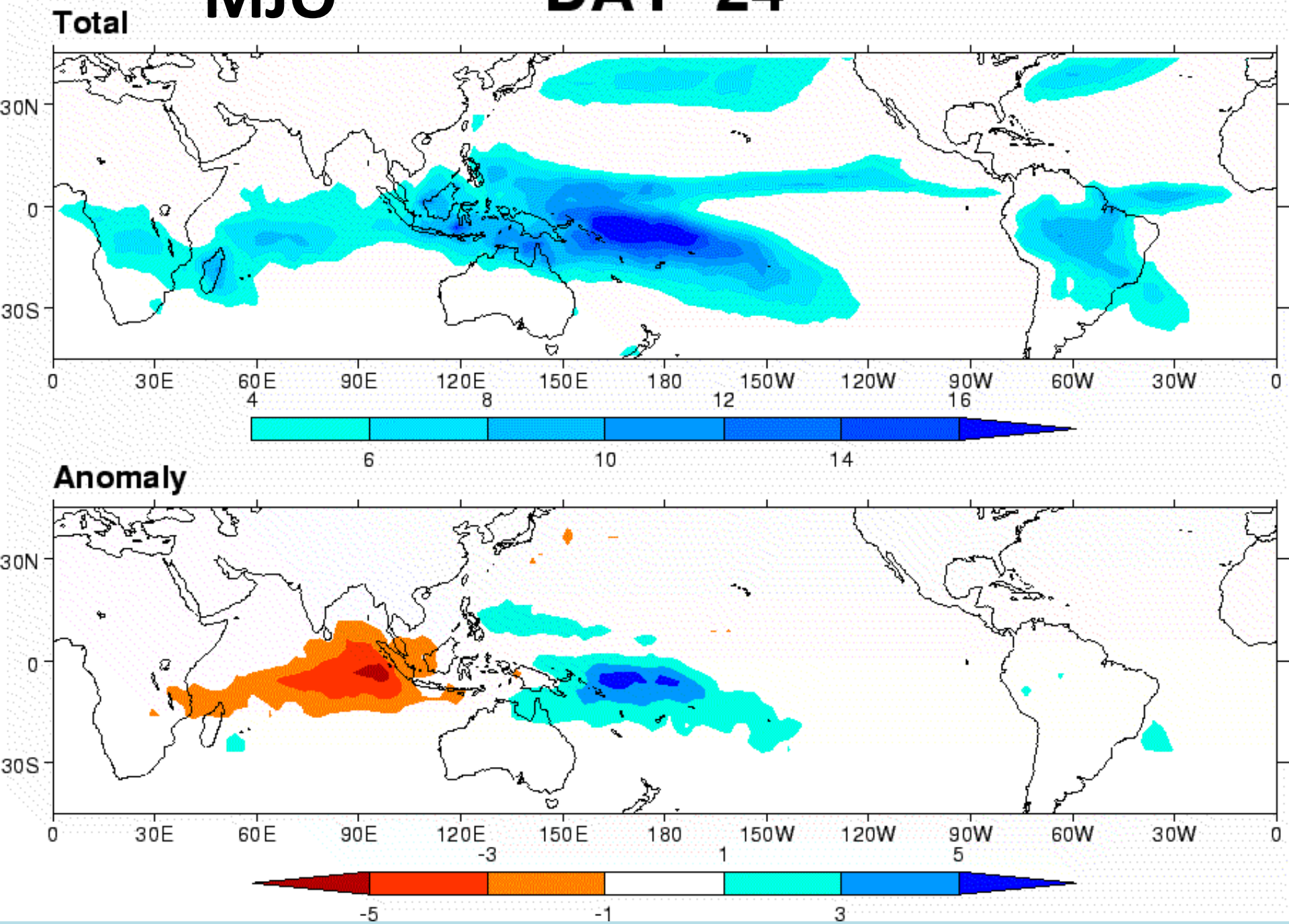


Madden and Julian (1972)


Intraseasonally Filtered TRMM 3B42 Rainfall (1998–2013 Nov–Apr)
Phase 1
132 days
Phase 2
190 days
Phase 3
235 days
Phase 4
198 days
Phase 5
210 days
Phase 6
225 days
Phase 7
214 days
Phase 8
167 days
25°
0°
–25°
–5 –4 –3 –2 –1 0 1 2 3 4 5
(mm day⁻¹)

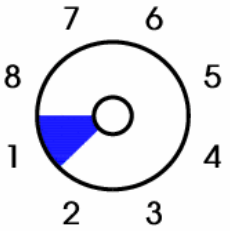

EAST LONGITUDE
WEST LONGITUDE
20° 60° 100° 140° 180° 140° 100° 60° 20°
Tropopause
Sea Level Pressure
F
G
H
A
B
C
D
E
AFRICA
INDONESIA
S. AMERICA

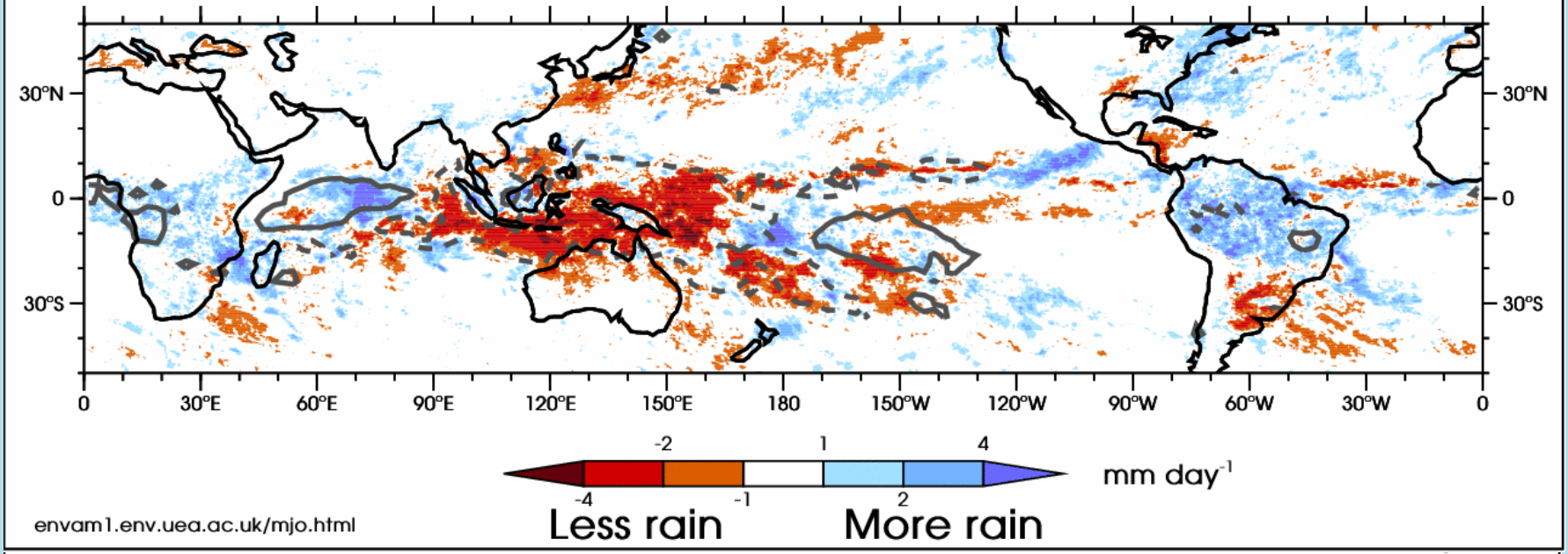
MJO DAY -24


Total
30N
0
30S
0
30E
60E
90E
120E
150E
180
150W
120W
90W
60W
30W
0
4
8
12
16
6
10
14
Anomaly
30N
0
30S
0
30E
60E
90E
120E
150E
180
150W
120W
90W
60W
30W
0
-3
1
5
-5
-1
3

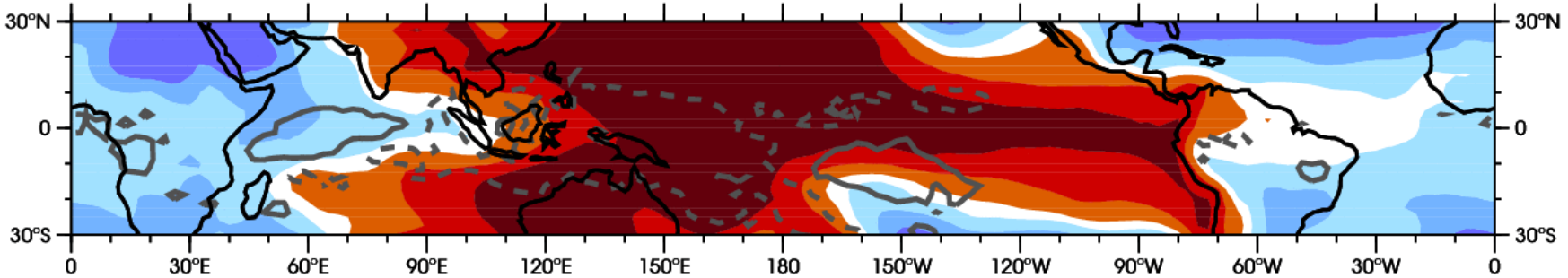
MJO CYCLE
Precipitation rate (TRMM)

RMM Phase 1 of 8
Day 0 of 48





envam1.env.uea.ac.uk/mjo.html

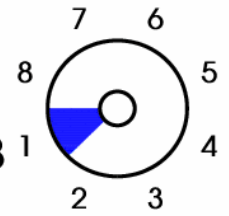


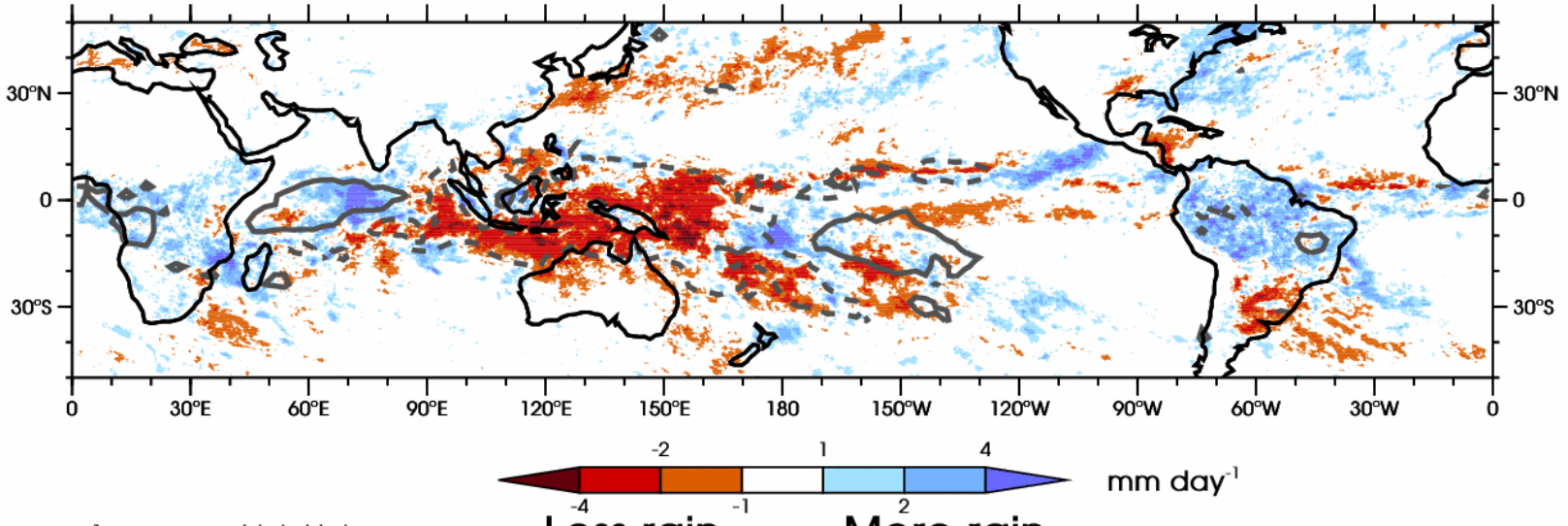
envam1.env.uea.ac.uk/mjo.html

Surface Pressure

MJO CYCLE
Precipitation rate (TRMM)

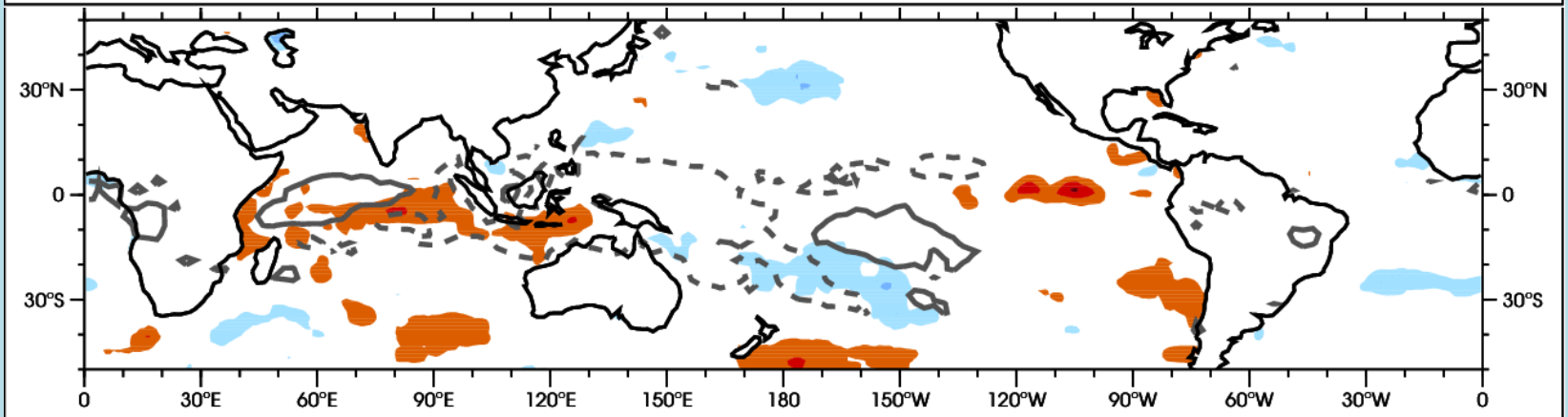
RMM Phase 1 of 8
Day 0 of 48

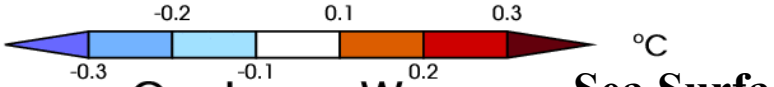




Less rain More rain

envam1.env.uea.ac.uk/mjo.html

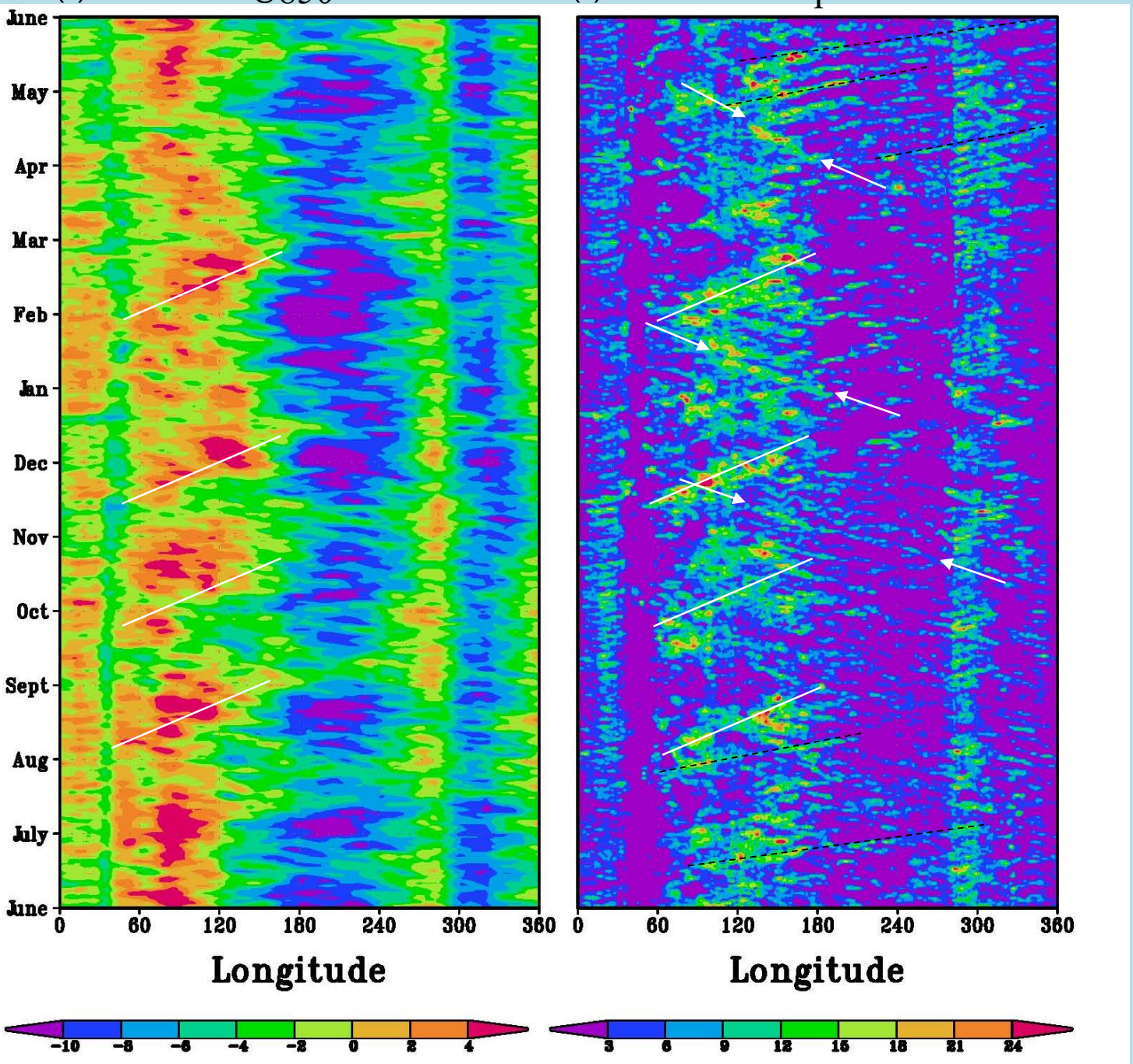




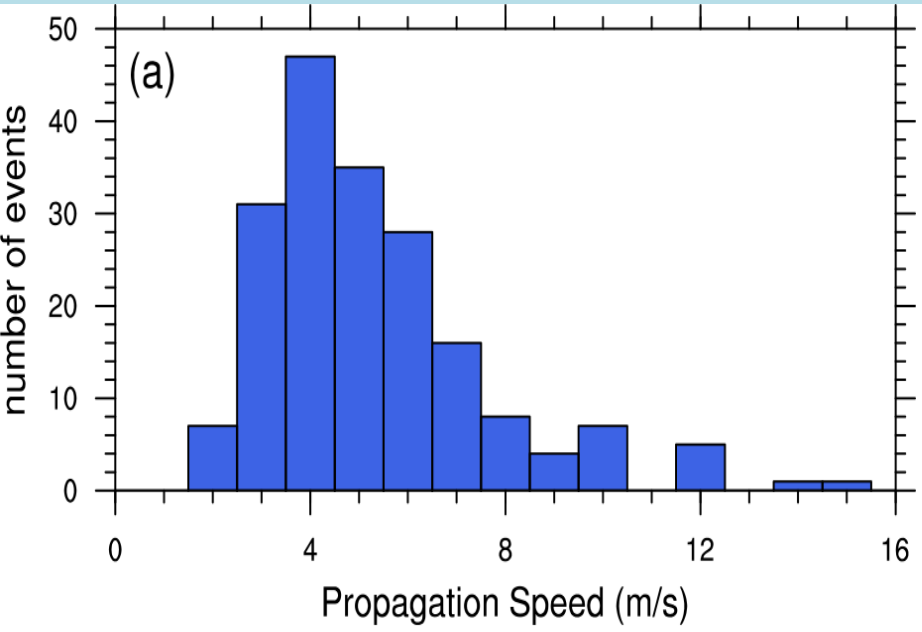
Cool Warm

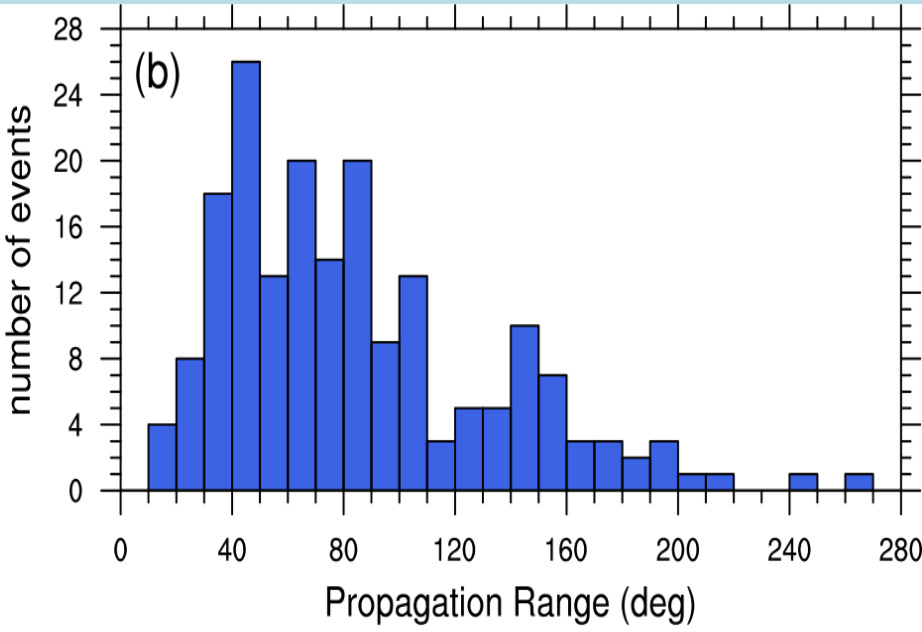
envam1.env.uea.ac.uk/mjo.html

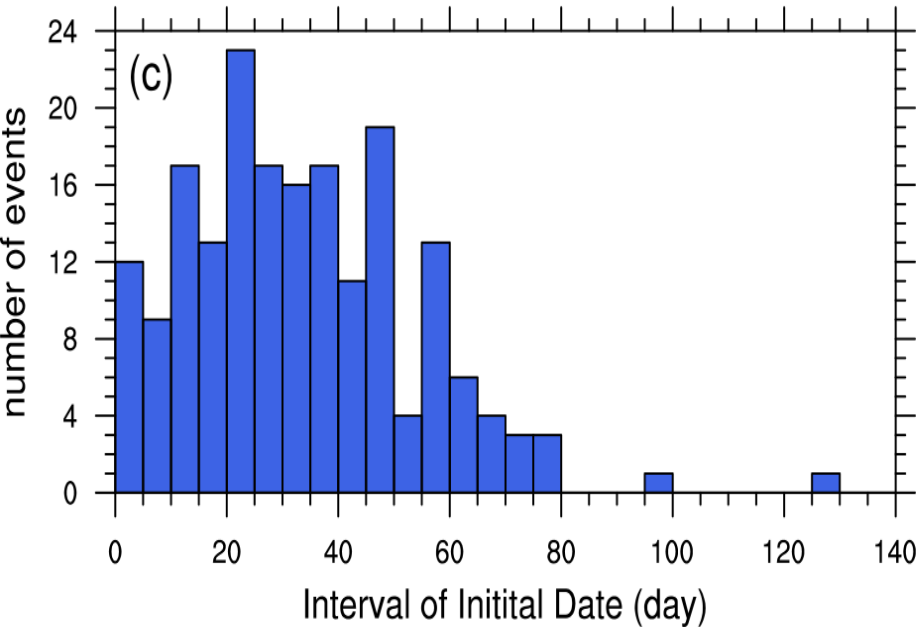
Sea Surface Temperature

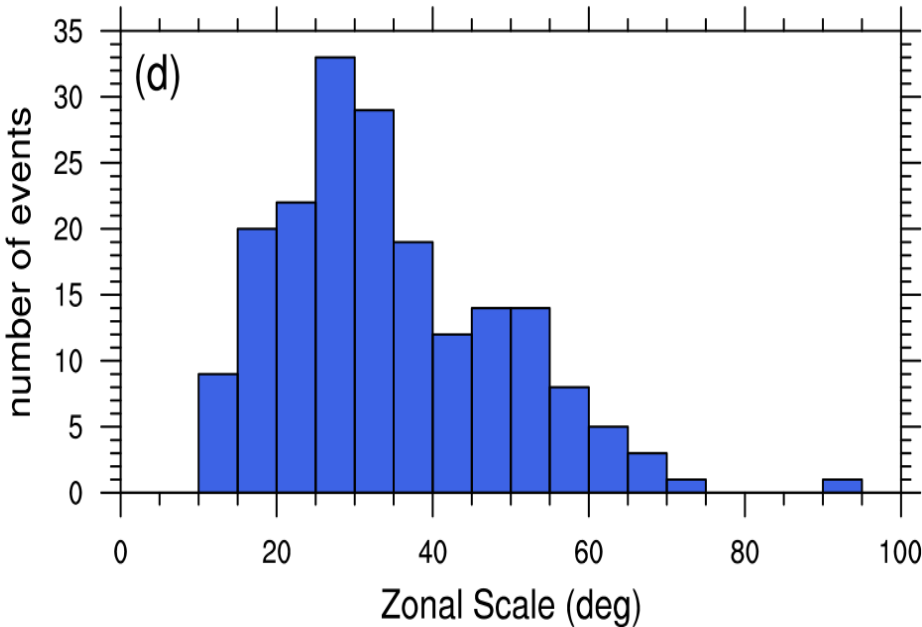

(a)
U850
(b)
Precipitation
June
May
Apr
Mar
Feb
Jan
Dec
Nov
Oct
Sept
Aug
July
June
0
60
120
180
240
300
360
Longitude
0
60
120
180
240
300
360
Longitude
-10
-8
-6
-4
-2
0
2
4
3
6
9
12
15
18
21
24

Basic Statistics of the MJO



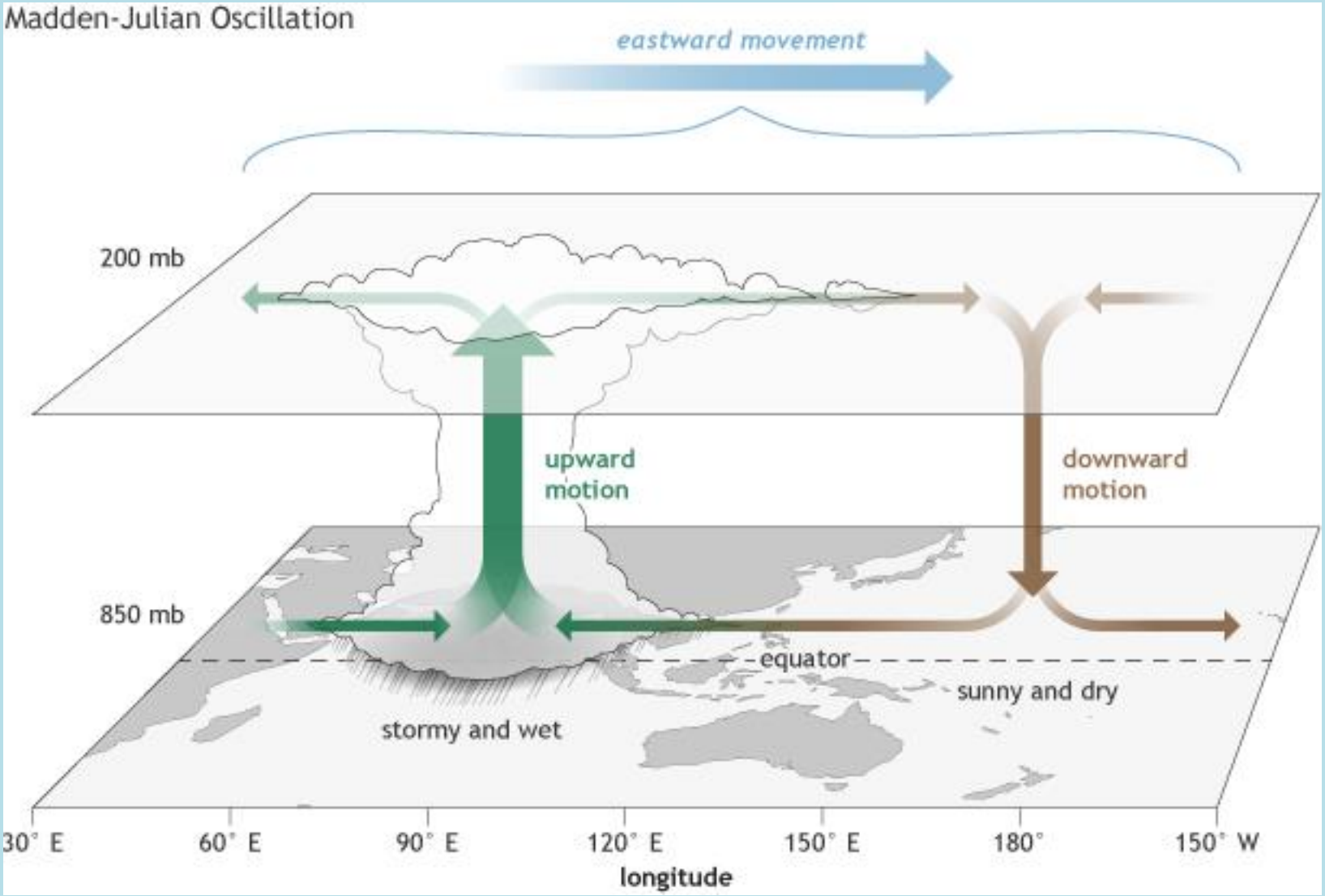




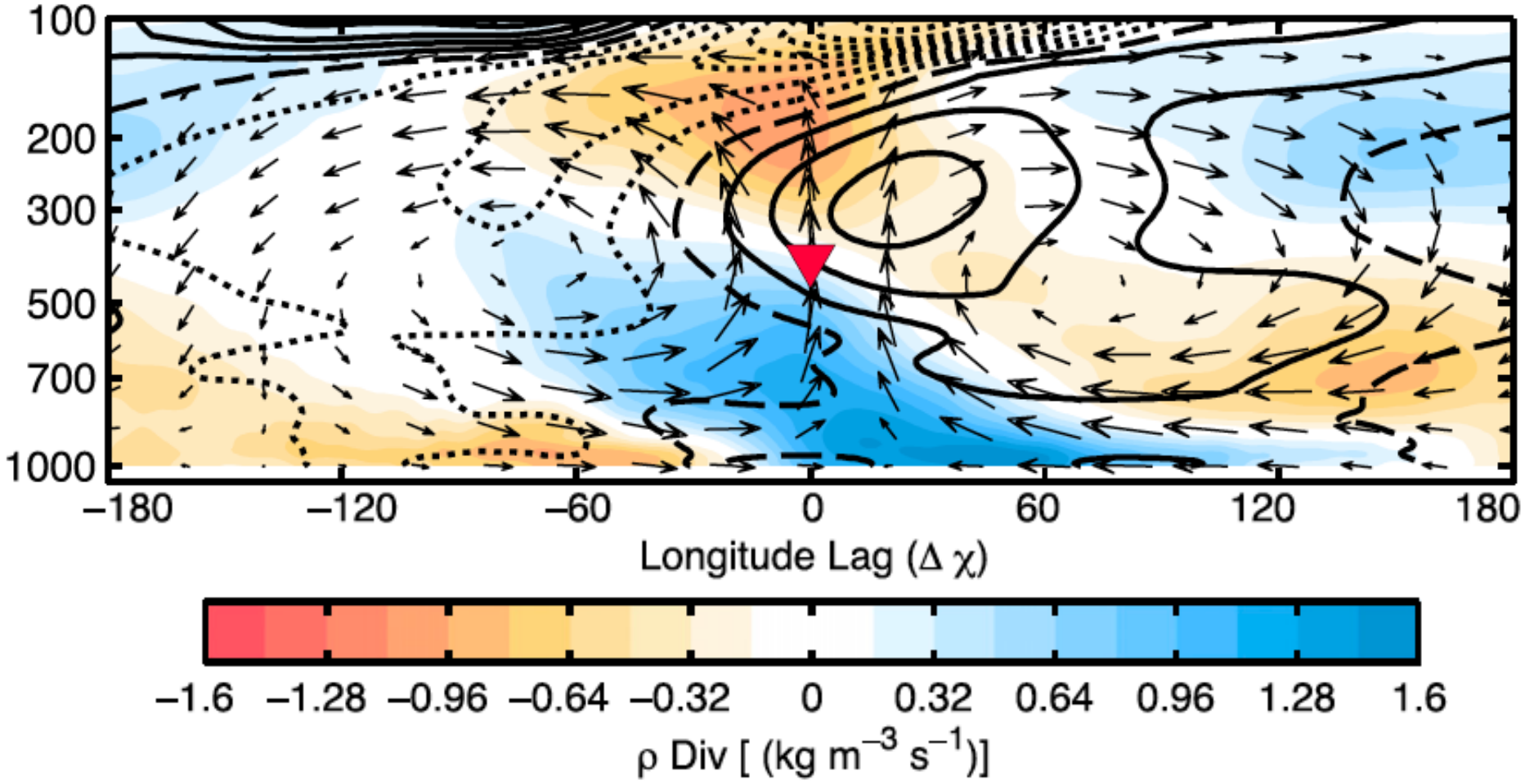


Main Structure of the MJO

Structure

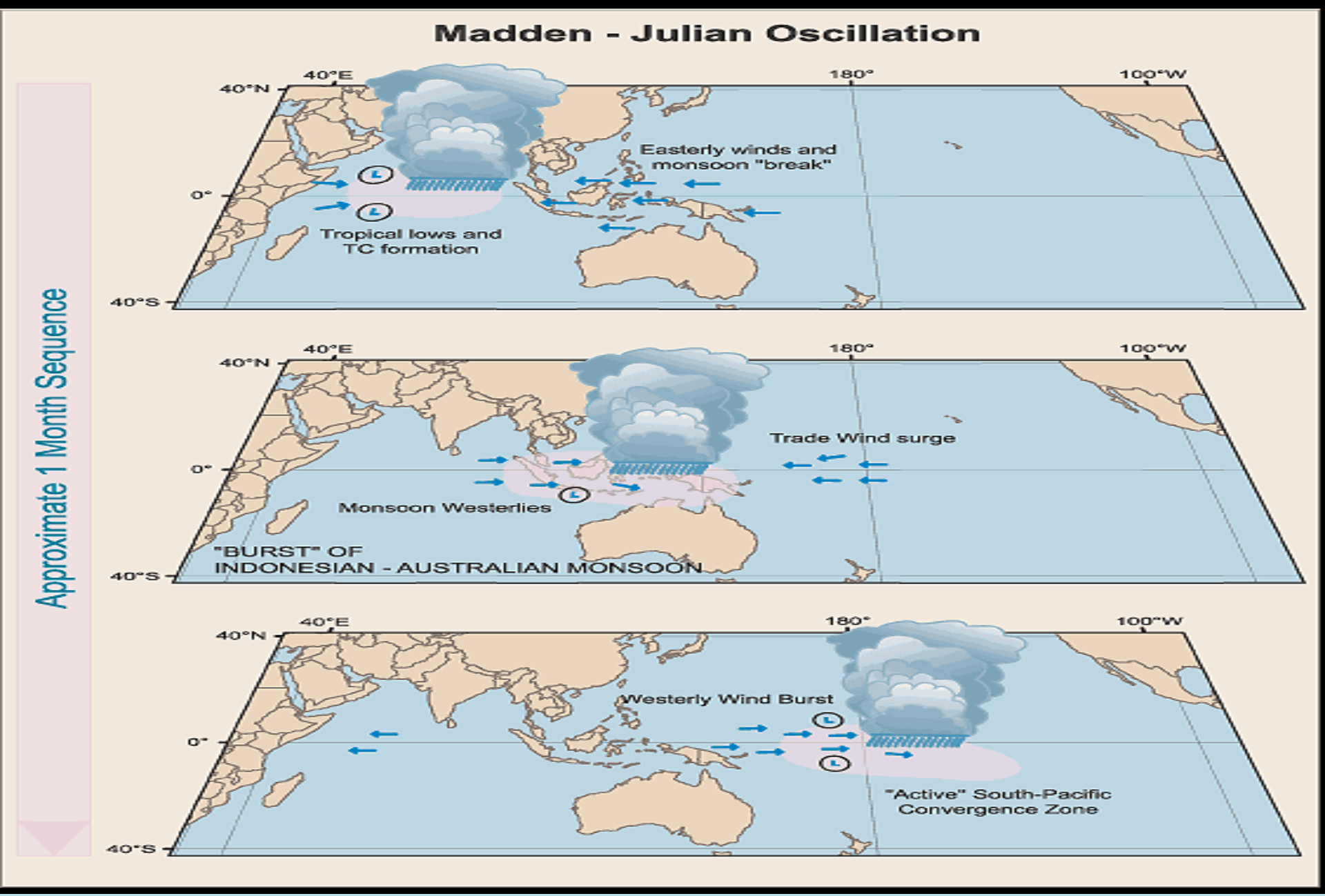


Climate.gov

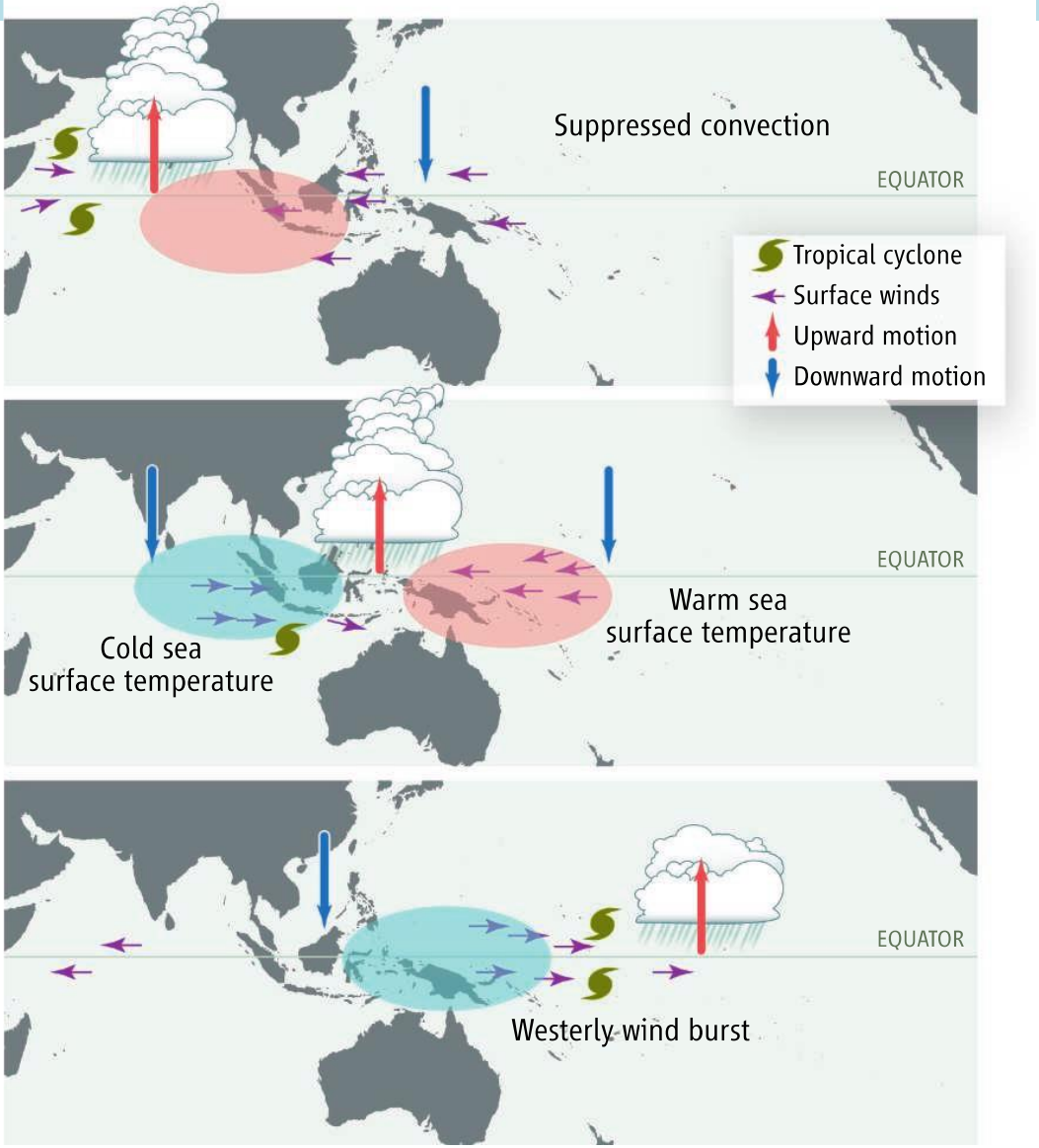


Adames and Wallace (2014)

Temperature (contours)
(u, ω) vectors
mass divergence ρ x Div (colors)

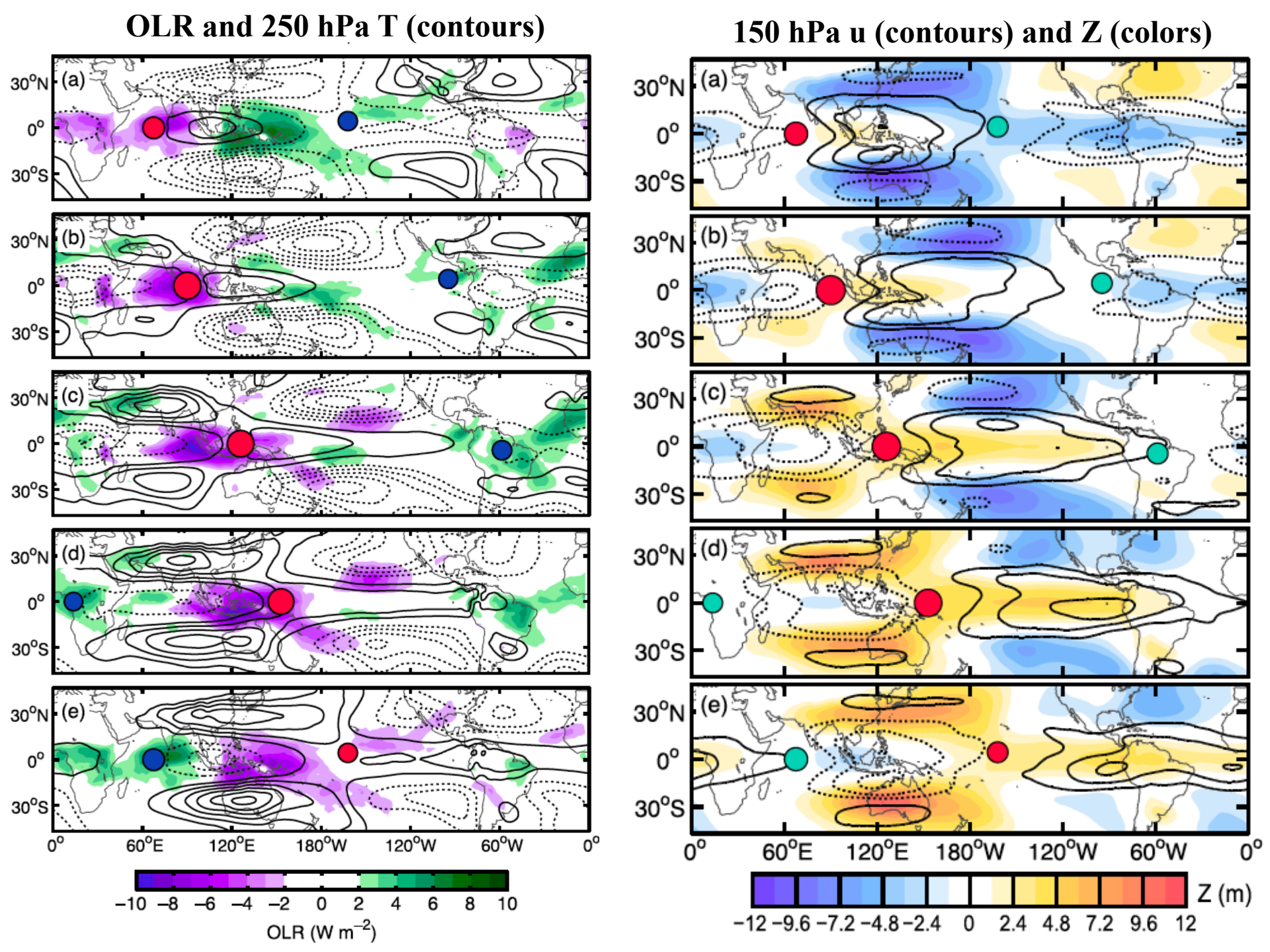


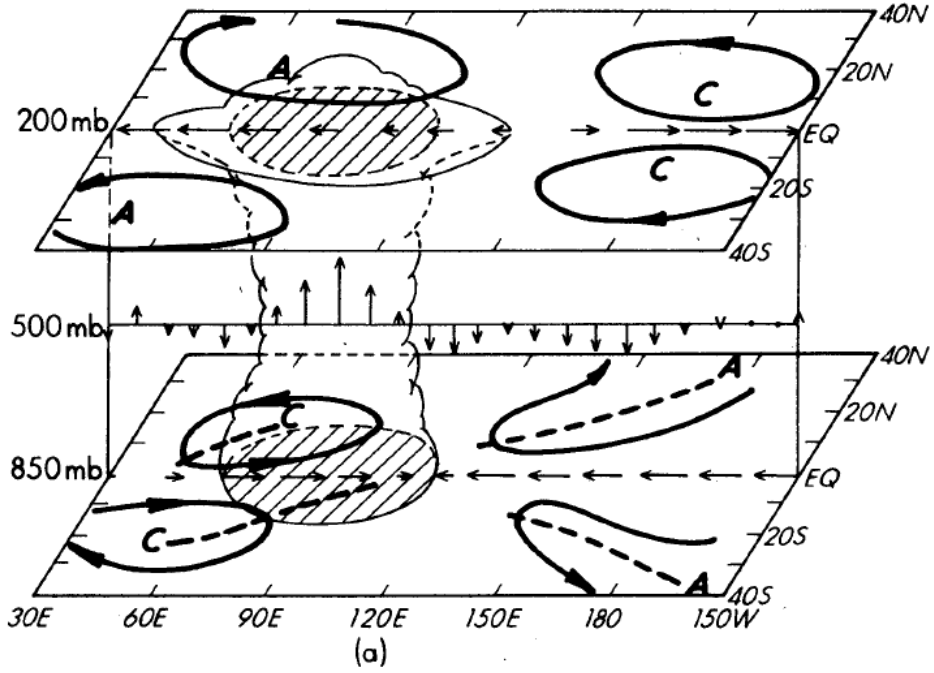
From International Science Roundtable for the Media. "Madden-Julian Oscillation." 17 April 2007. <http://www.igbp.net/prepcom4/wheeler_image.gif>



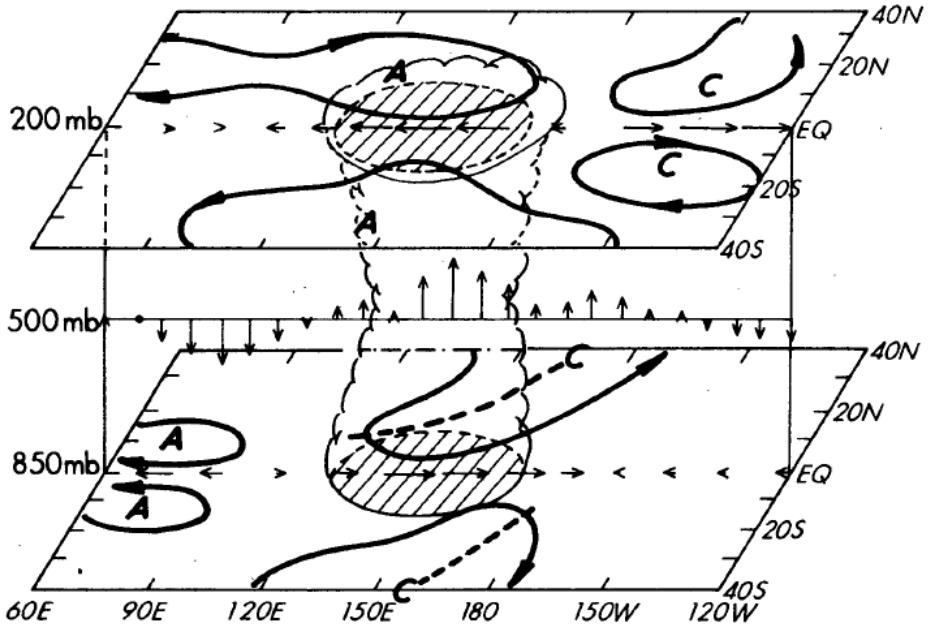
The Madden-Julian Oscillation. Precipitation first develops in the Indian Ocean and moves eastward with a speed of about 5 m s^{-1}. Surface winds converge under the convection, and a burst of eastward surface winds follows the passage of the heaviest rainfall. This burst is an important driver for ocean dynamics. Each panel is separated by ~15 days.

Hartmann and Hendon 2007


OLR and 250 hPa T (contours)
150 hPa u (contours) and Z (colors)
(a)
(b)
(c)
(d)
(e)
30°N
0°
30°S
0°
60°E
120°E
180°W
120°W
60°W
0°
−10 −8 −6 −4 −2 0 2 4 6 8 10
OLR (W m−2)
−12 −9.6 −7.2 −4.8 −2.4 0 2.4 4.8 7.2 9.6 12
Z (m)



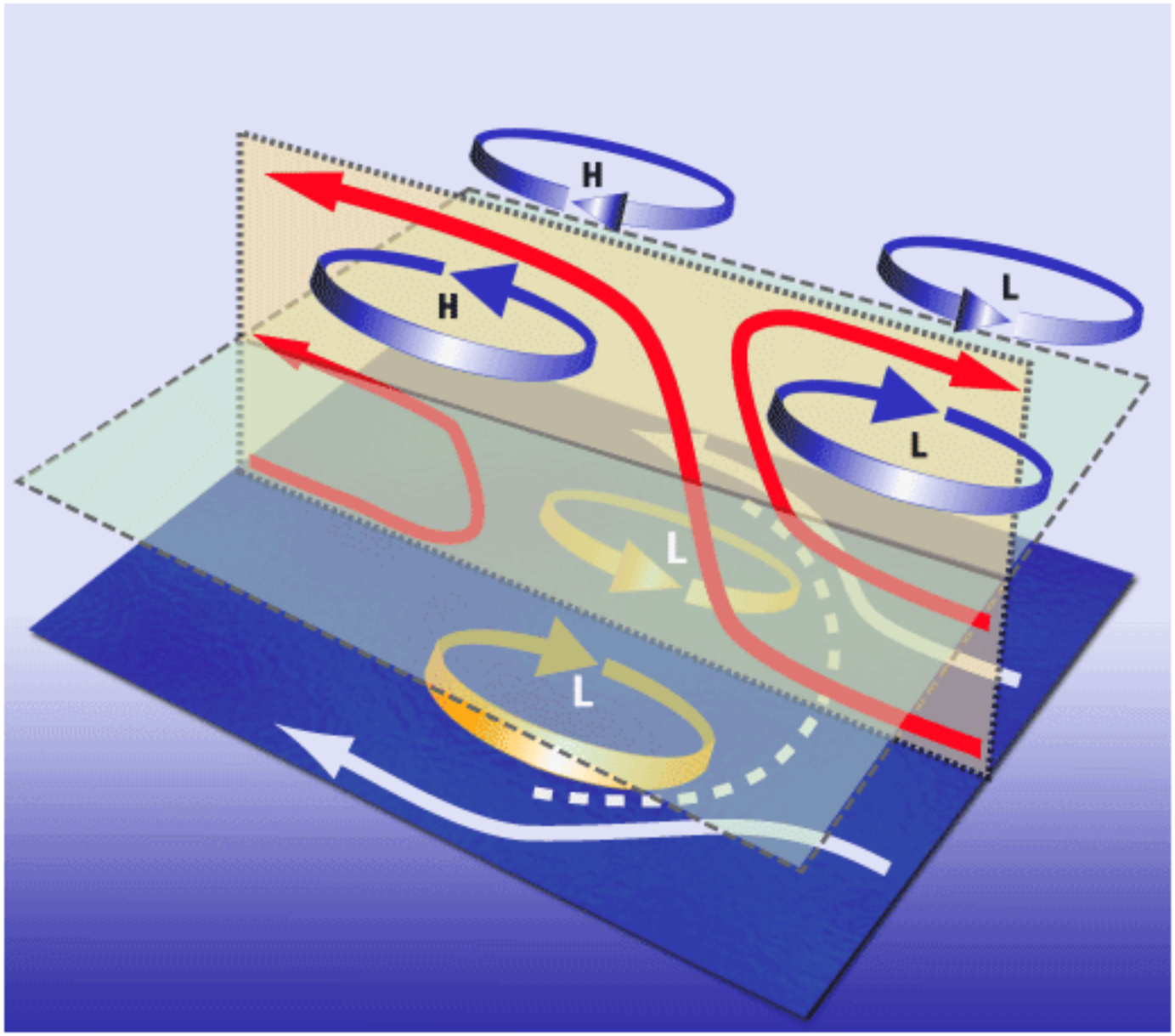
(a)

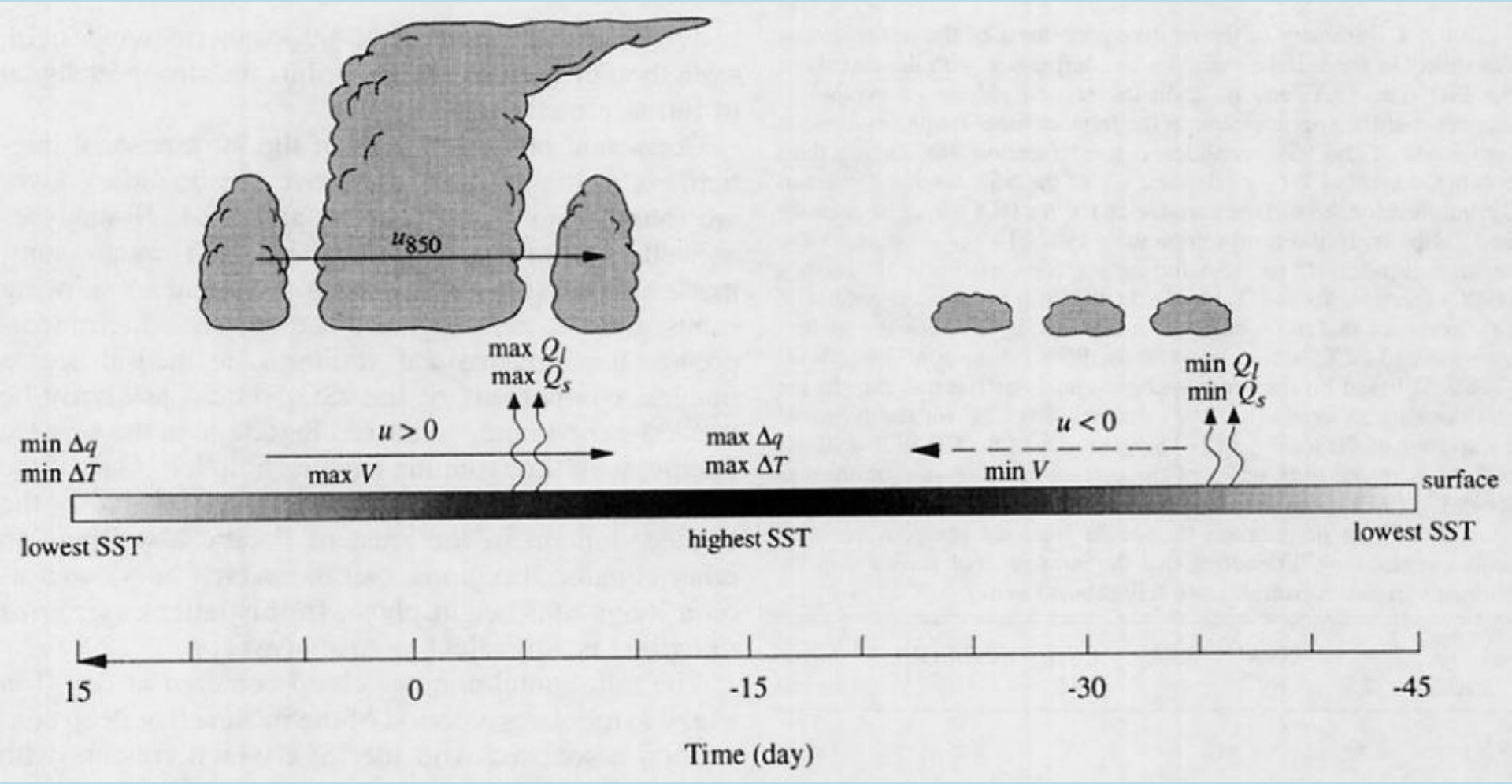


(b)

Rui and Wang (1990)

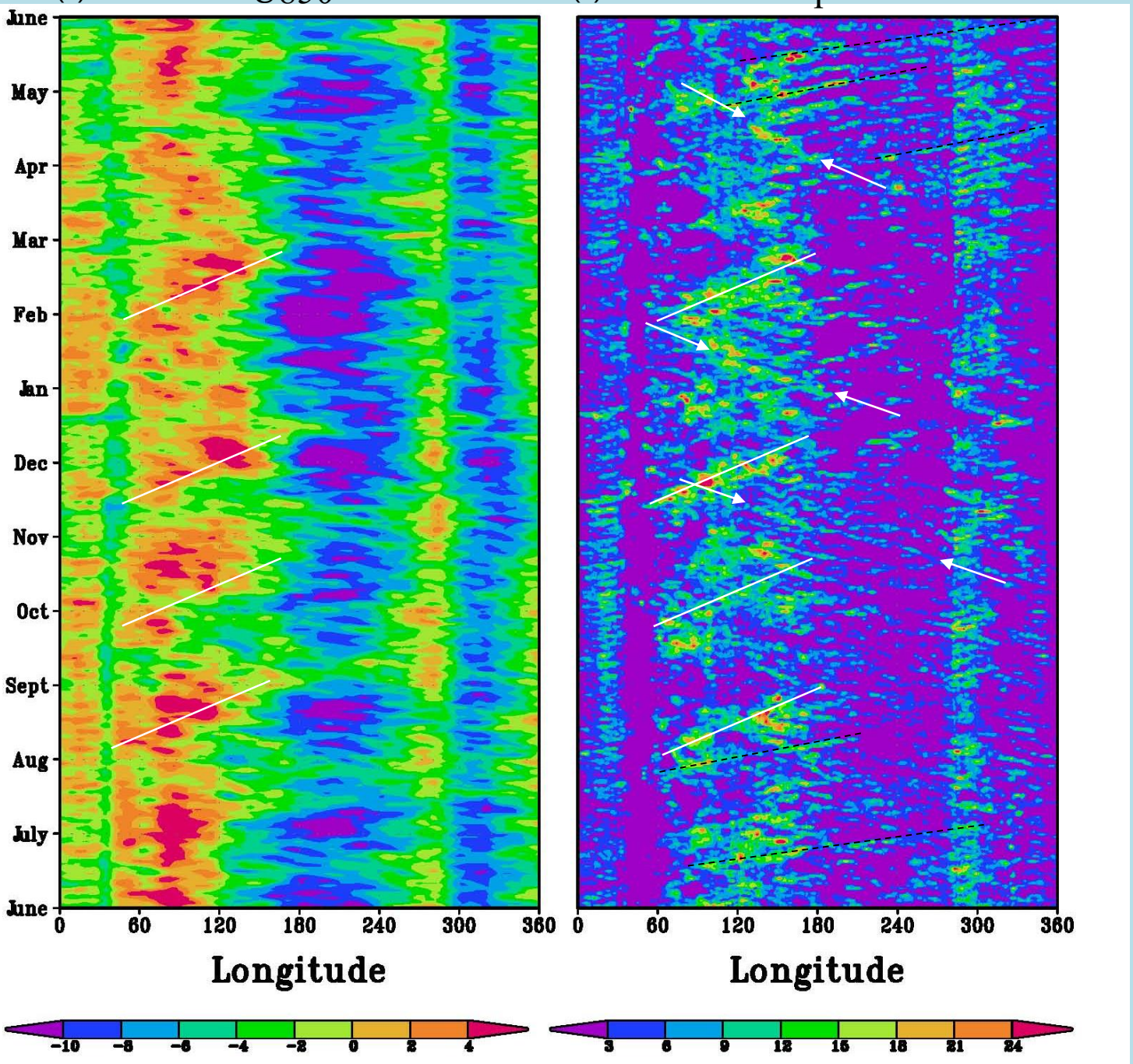
MJO-mature



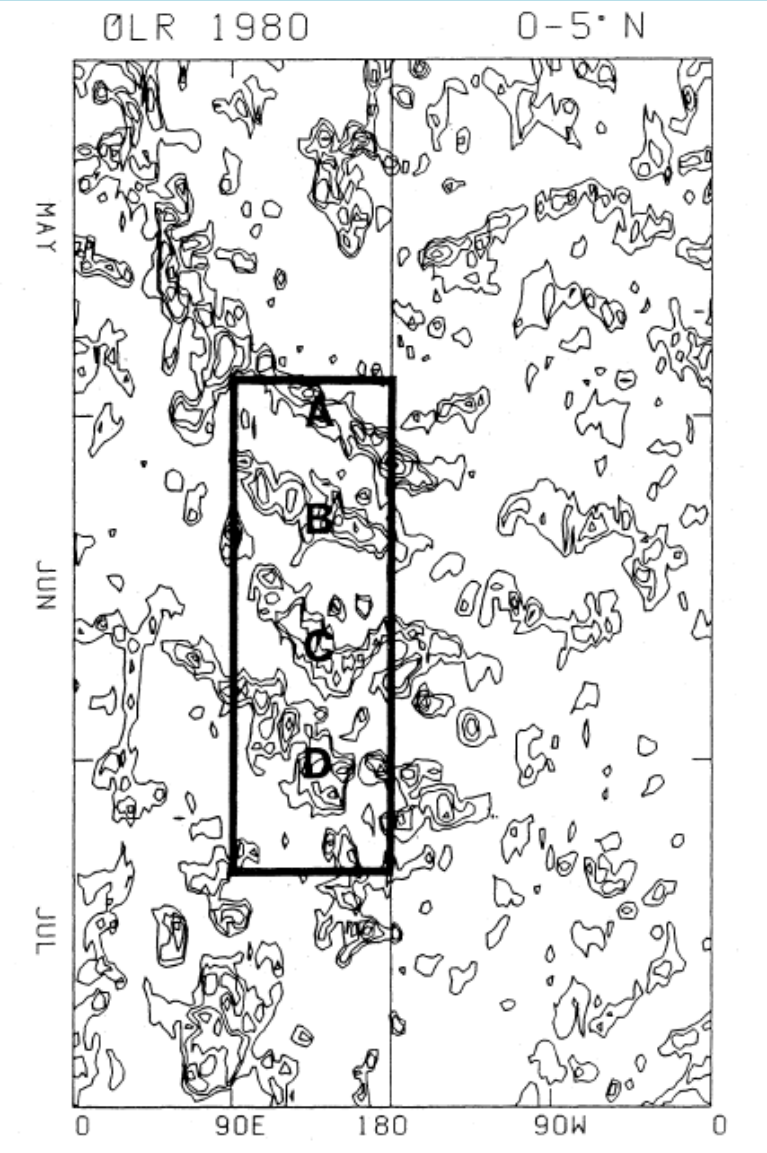

u_{850}
max Q_l
max Q_s
min Q_l
min Q_s
min Δq
min ΔT
$u > 0$
max V
max Δq
max ΔT
$u < 0$
min V
surface
lowest SST
highest SST
lowest SST
15
0
-15
-30
-45
Time (day)

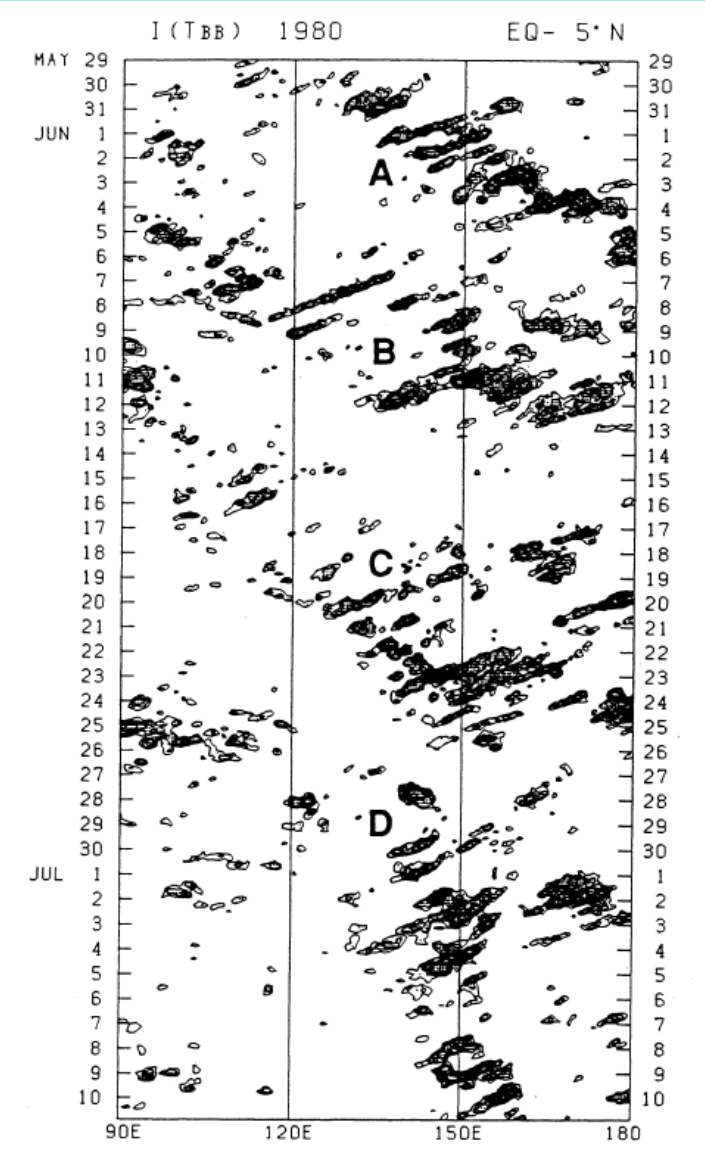
Zhang (1996)

Multi-Scale Structure of the MJO

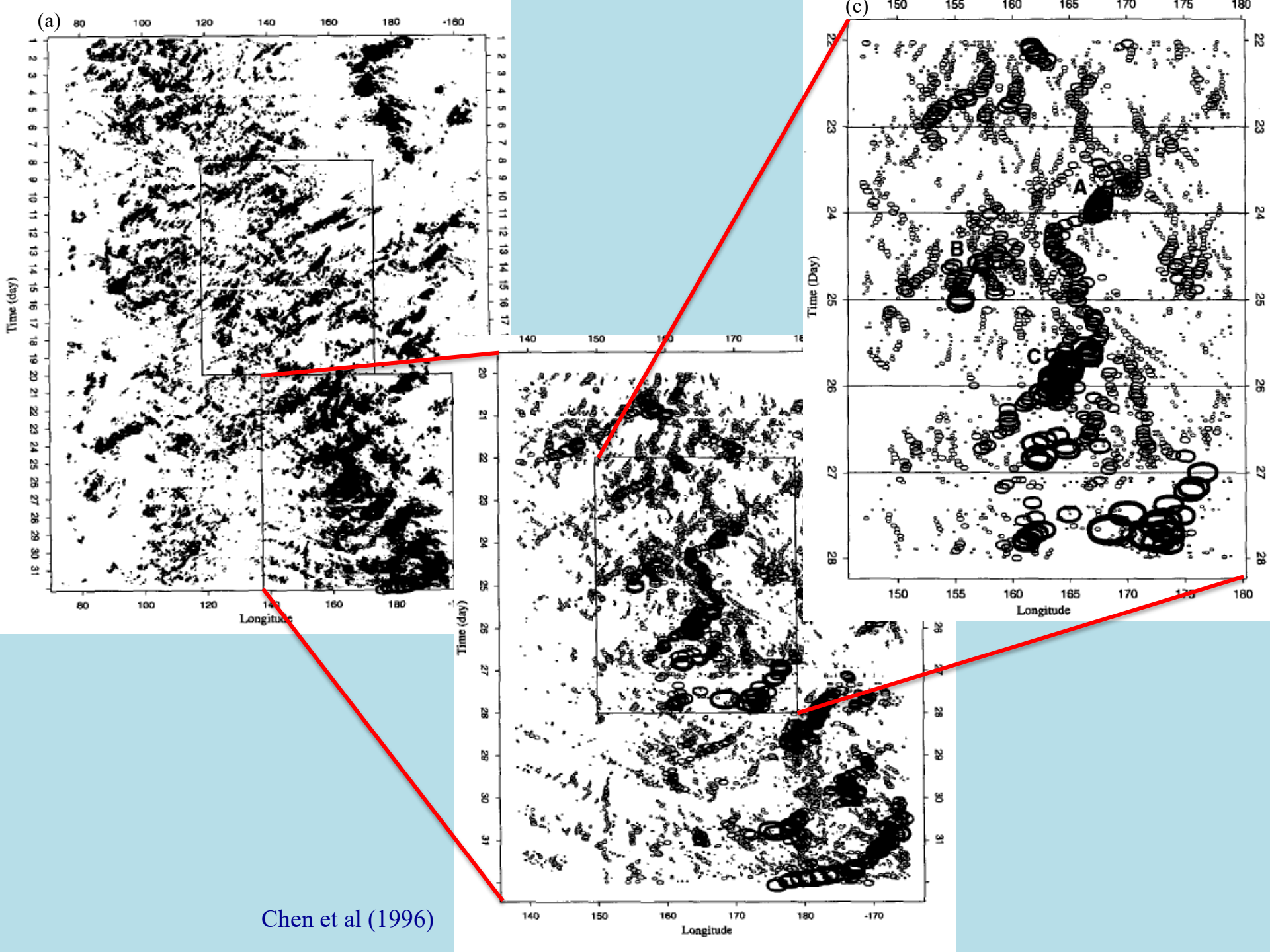

(a)
U850
(b)
Precipitation
June
May
Apr
Mar
Feb
Jan
Dec
Nov
Oct
Sept
Aug
July
June
0
60
120
180
240
300
360
Longitude
0
60
120
180
240
300
360
Longitude
-10
-8
-6
-4
-2
0
2
4
3
6
9
12
15
18
21
24

Multiscale Structure of the MJO





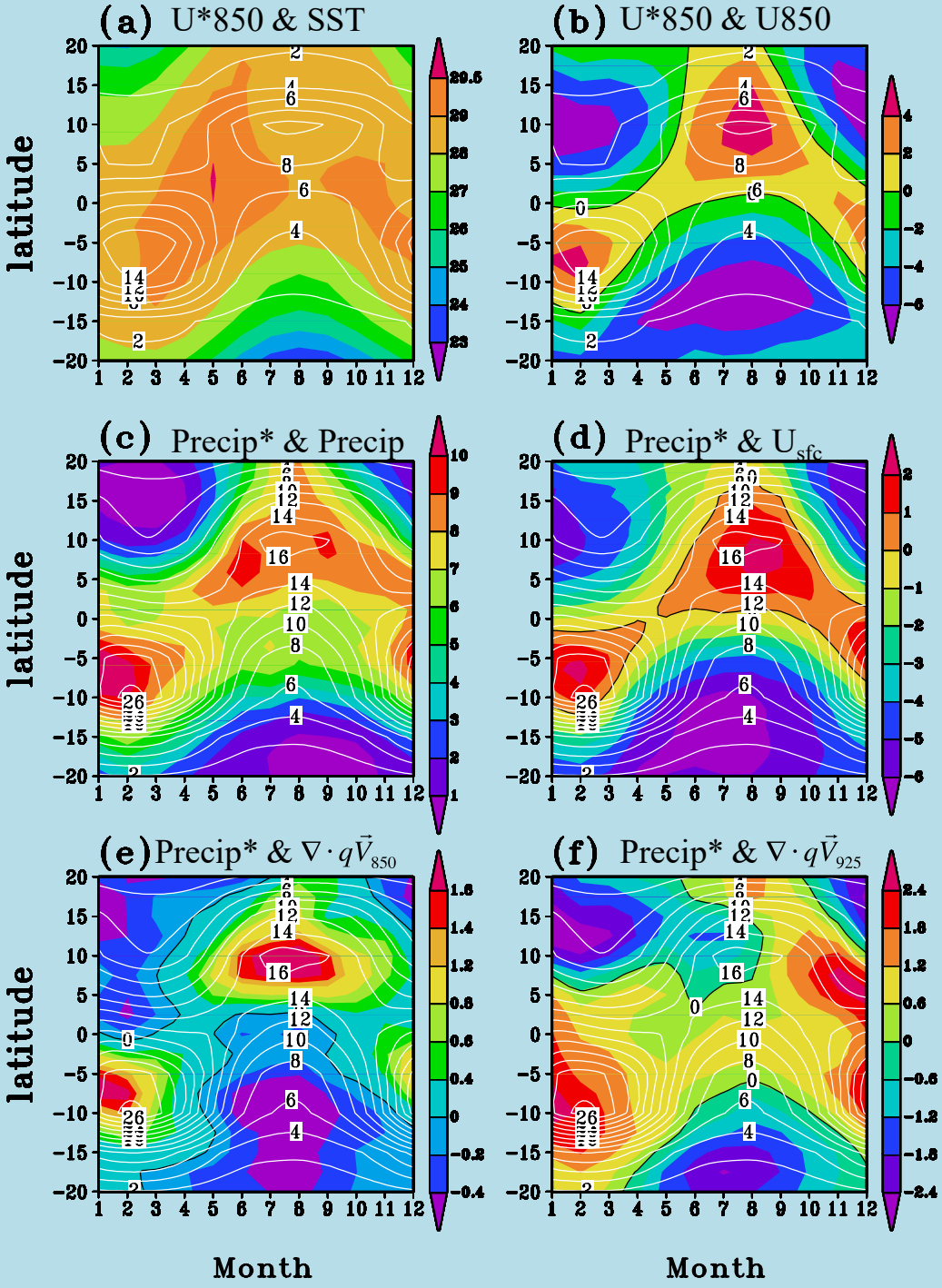
Nakazawa (1988)



Chen et al (1996)

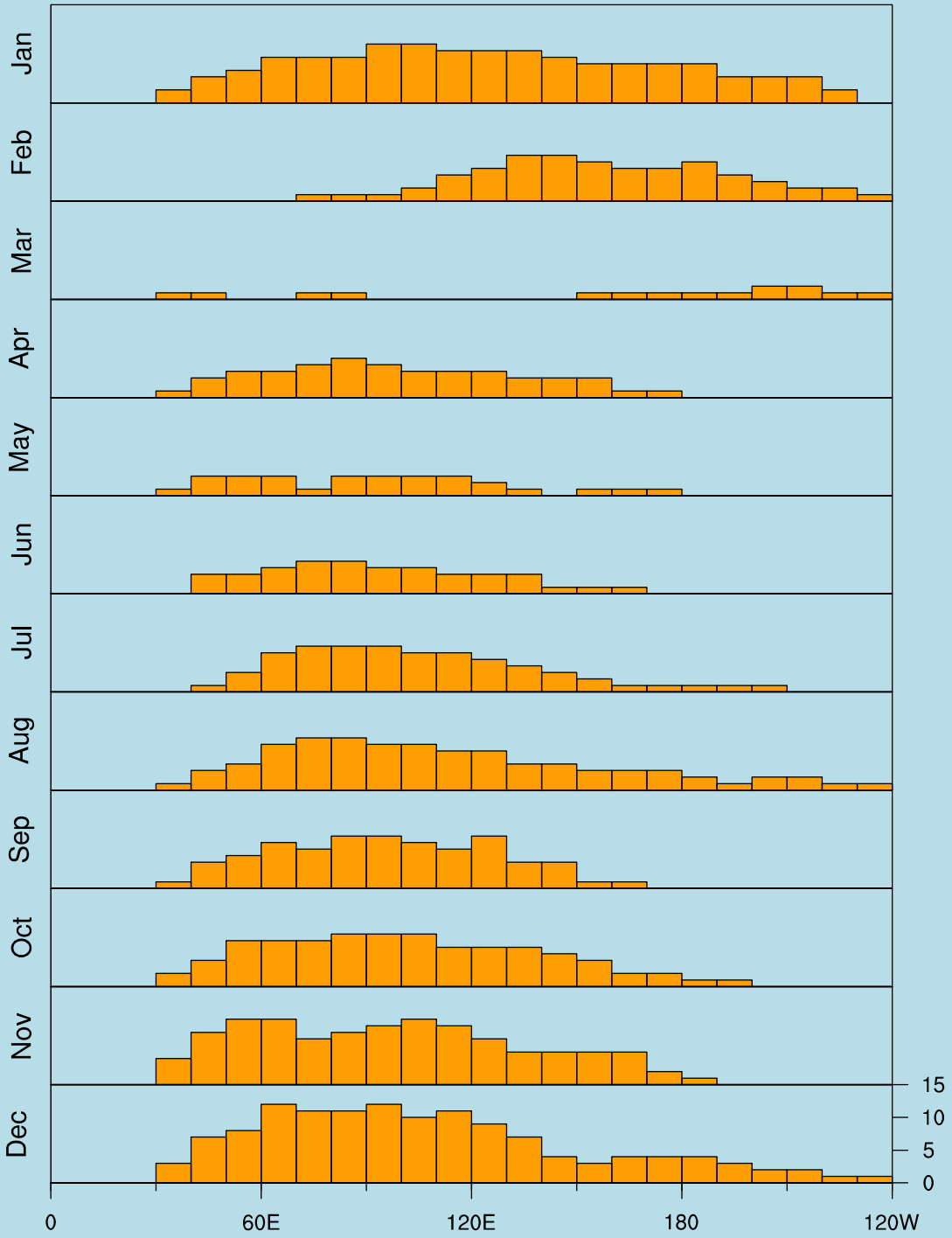
Seasonal and Interannual Variability of the MJO

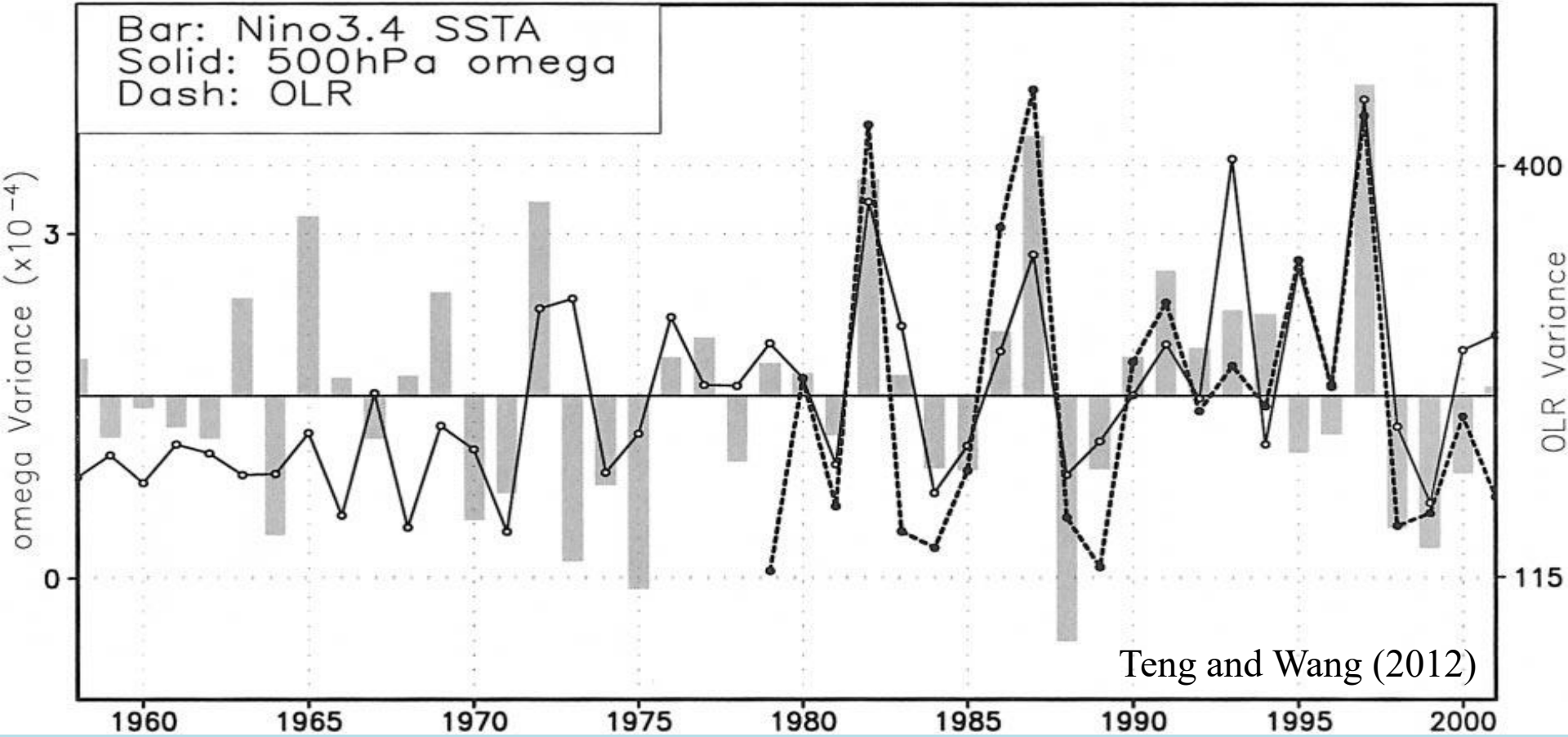
Seasonal Cycle



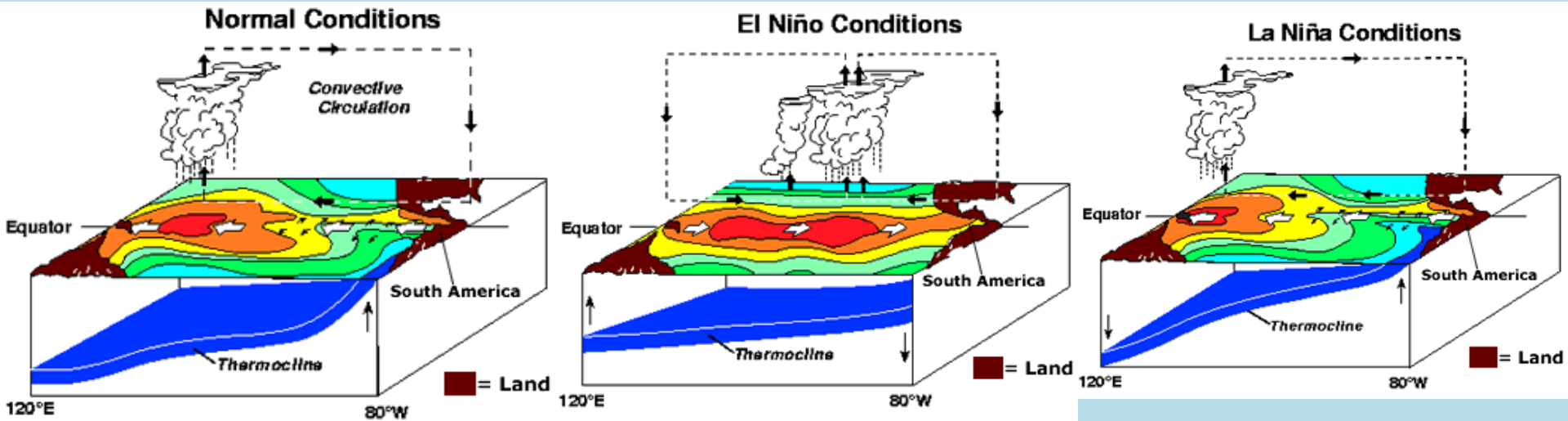
Zhang and Dong 2004

Seasonal Cycle

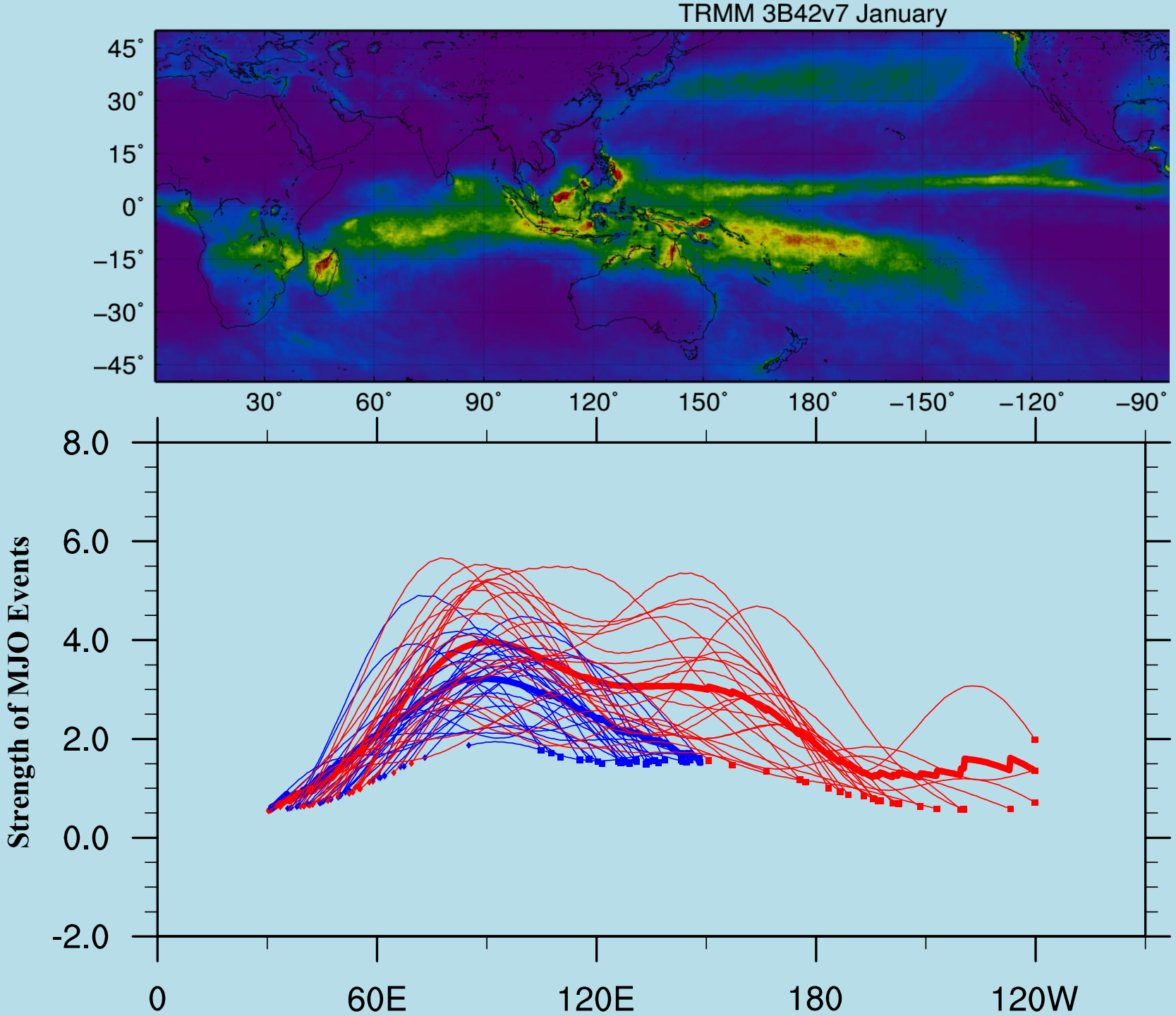


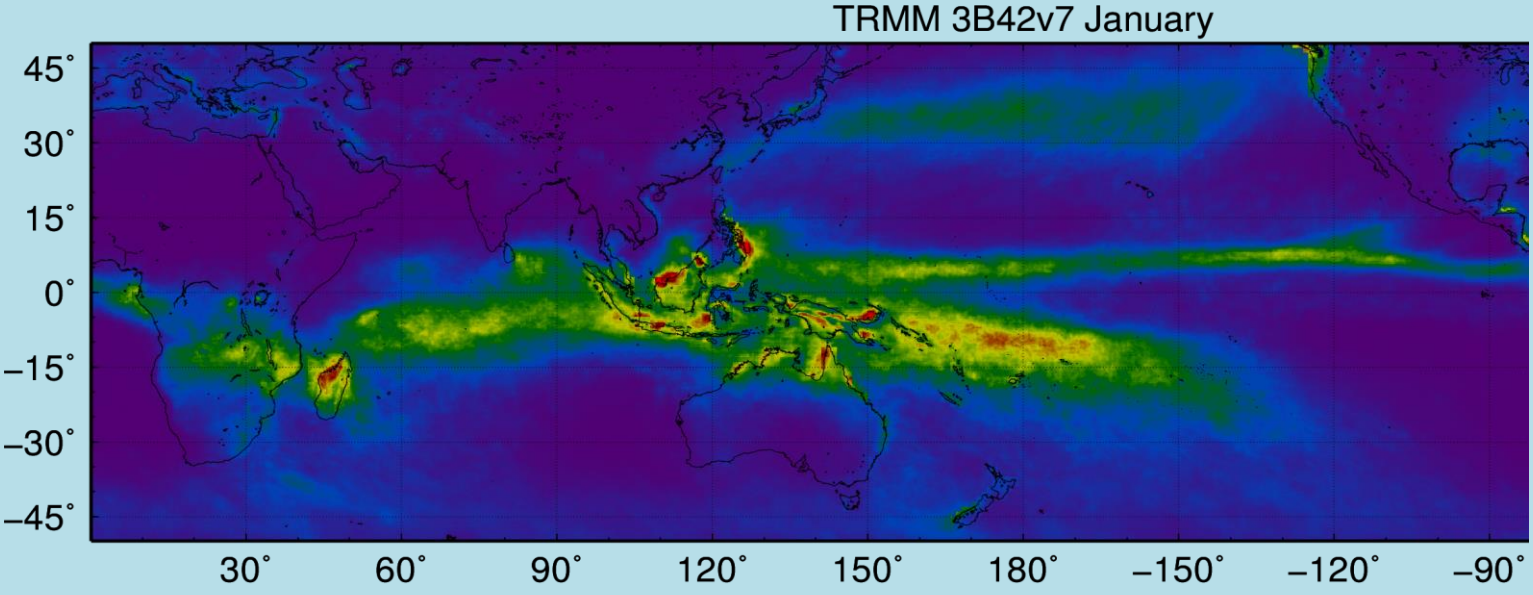


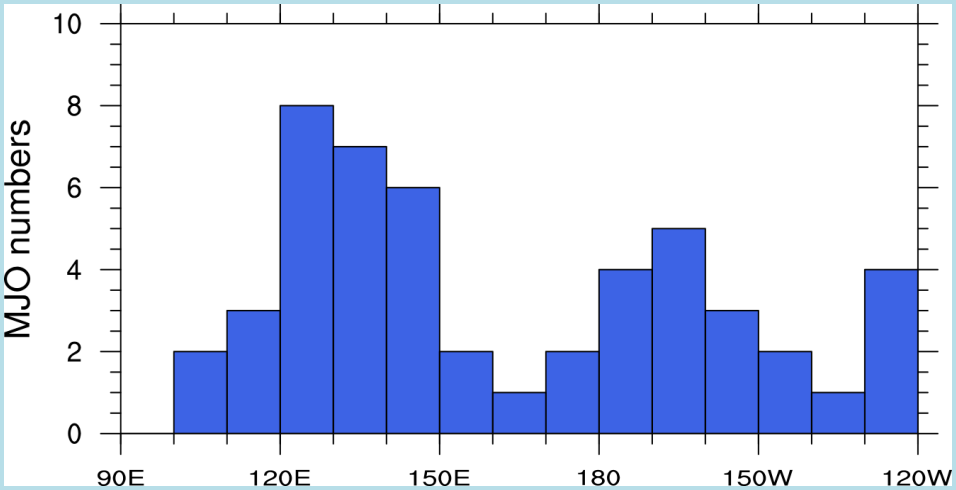
Teng and Wang (2012)



Barrier Effect of the Maritime Continent on the MJO


TRMM 3B42v7 January
45˚
30˚
15˚
0˚
–15˚
–30˚
–45˚
30˚
60˚
90˚
120˚
150˚
180˚
–150˚
–120˚
–90˚
Strength of MJO Events
8.0
6.0
4.0
2.0
0.0
-2.0
0
60E
120E
180
120W



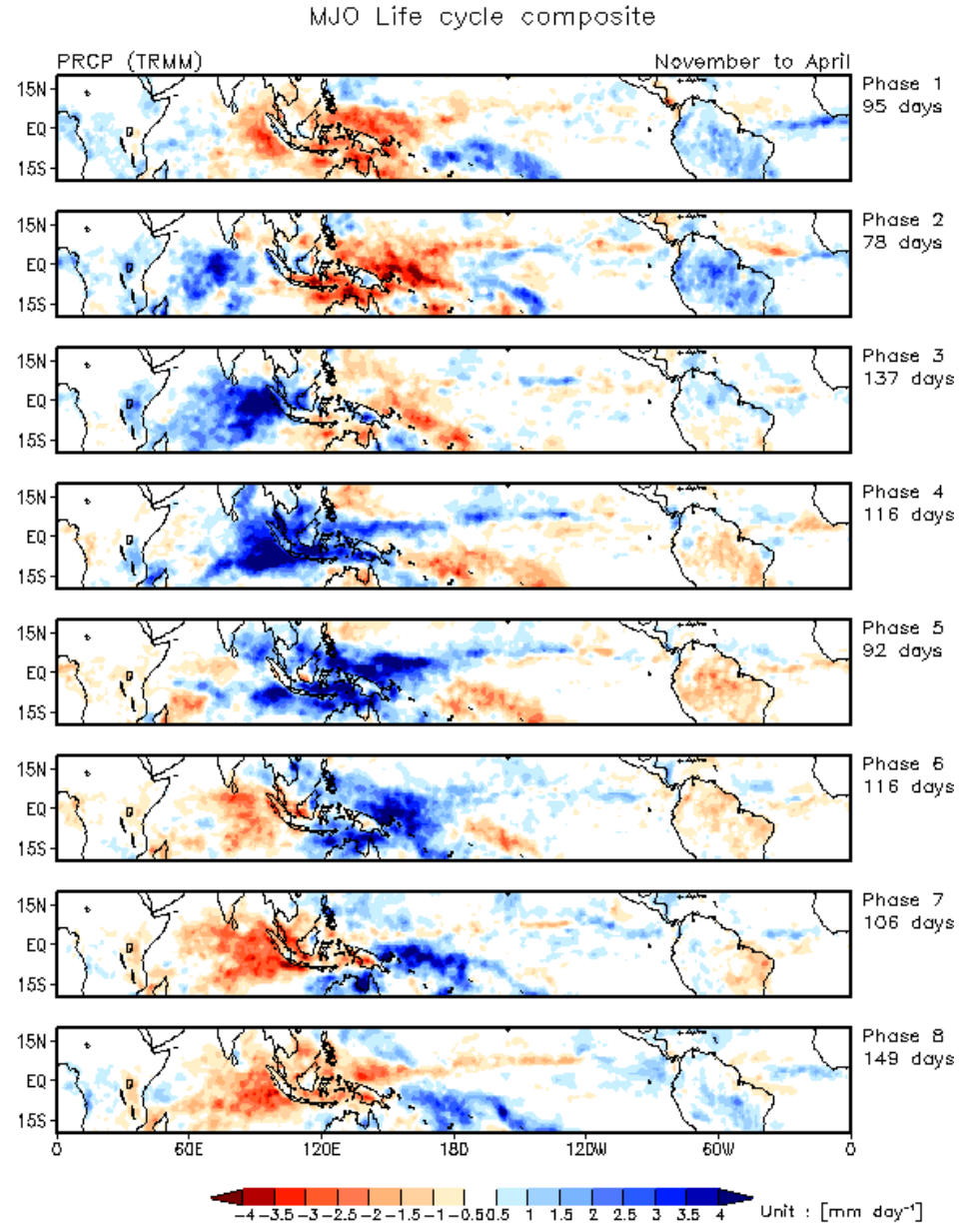


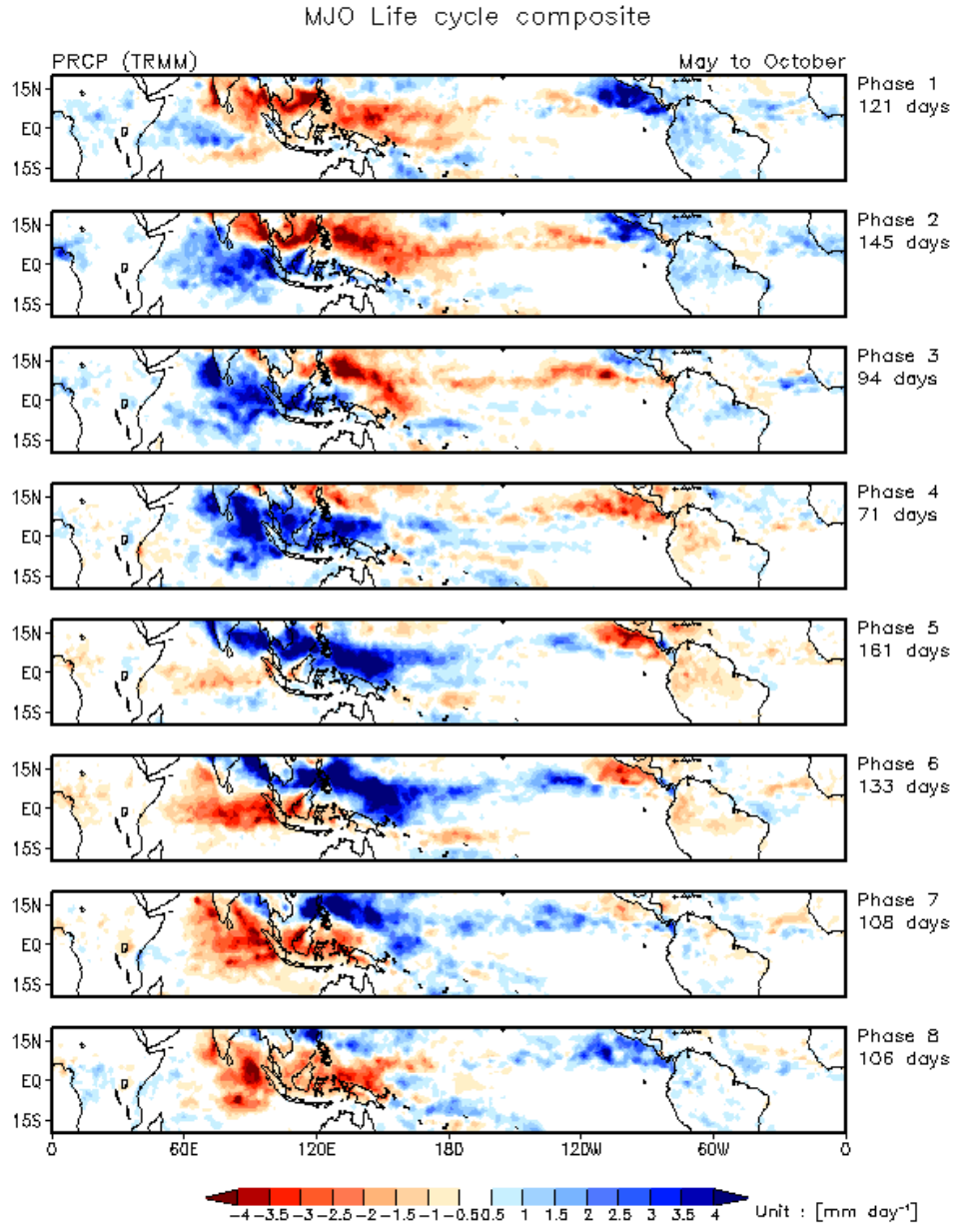
MJO Terminating Longitude

MJO vs. BSISO

Dec-Feb Composite

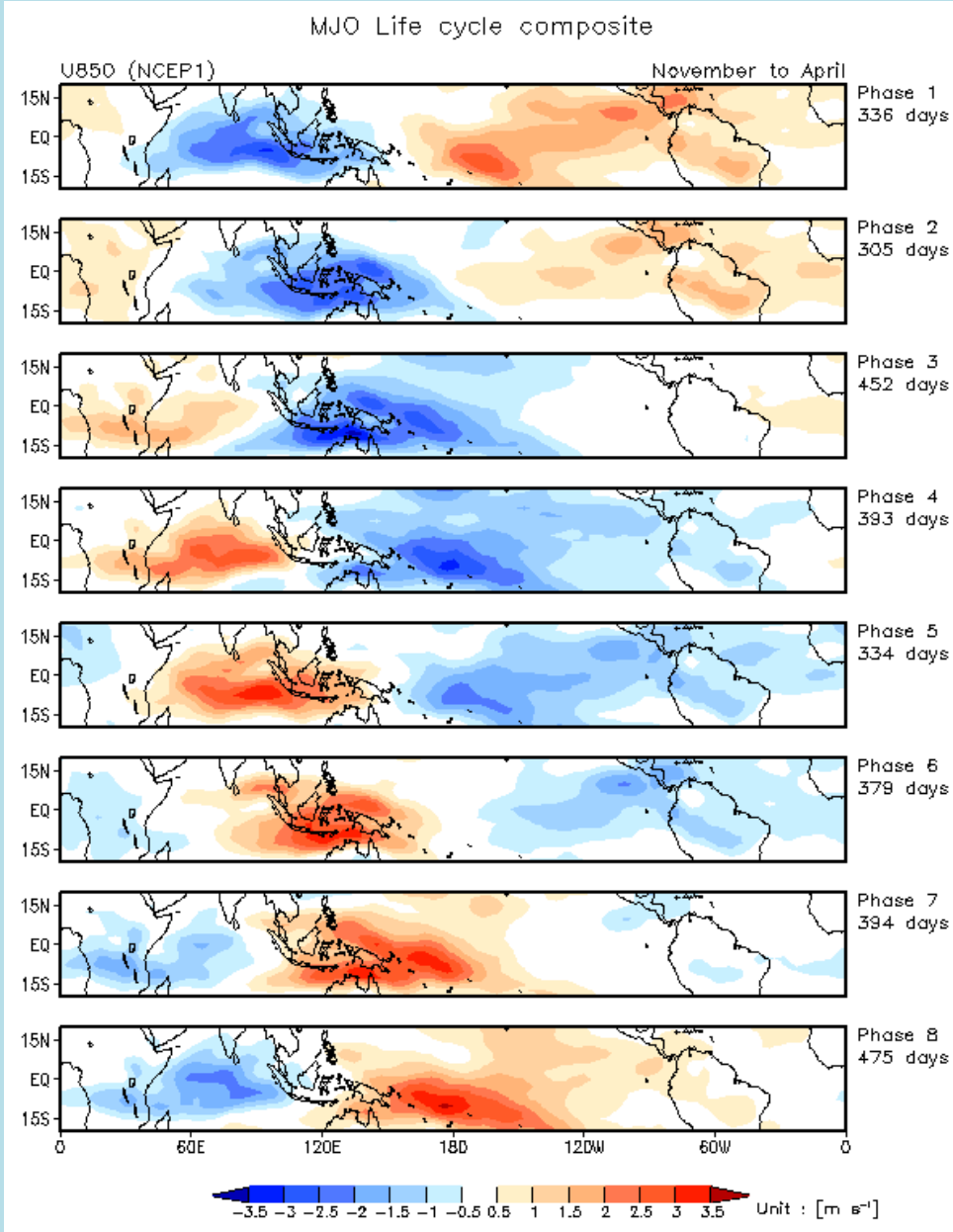
May-June Composite

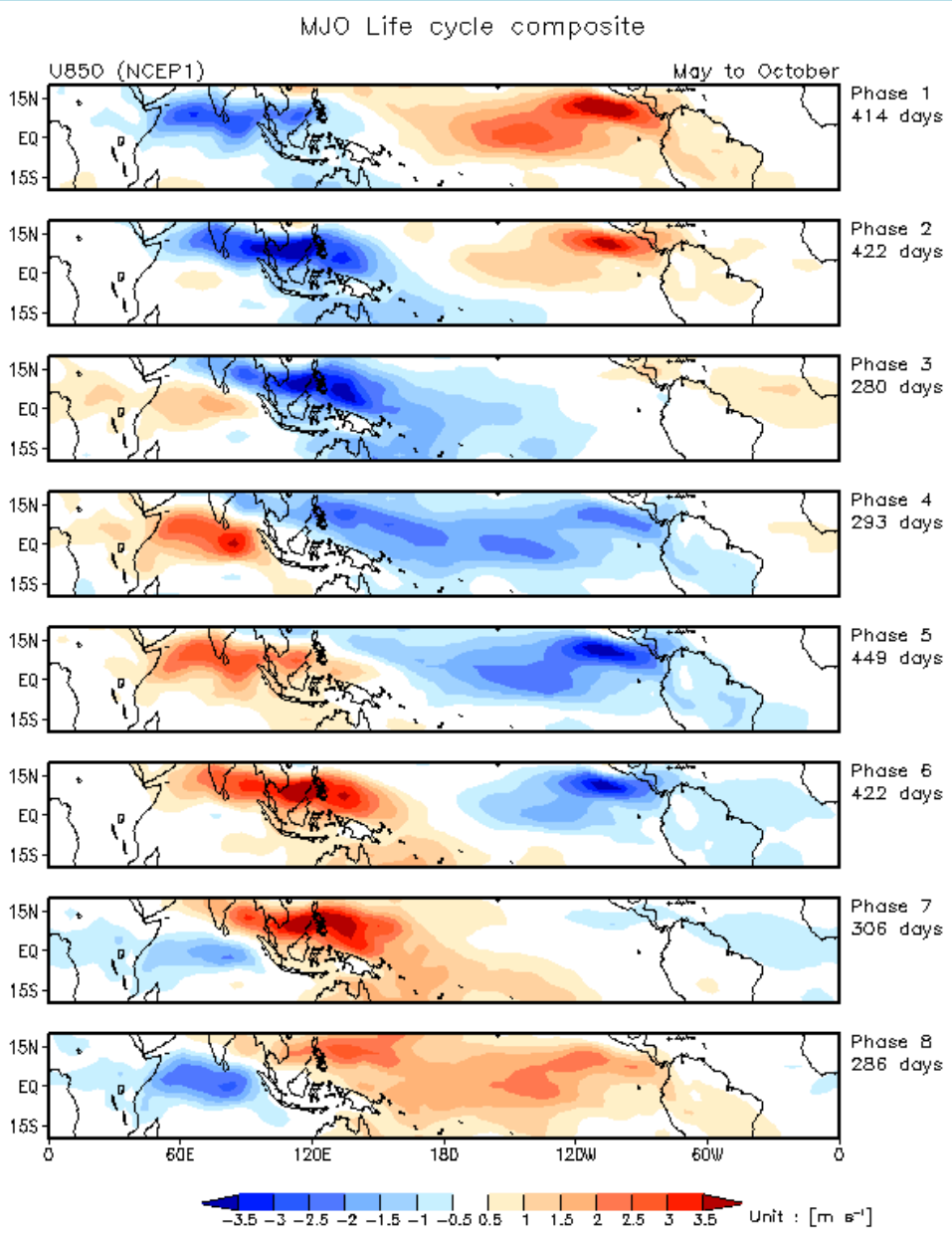


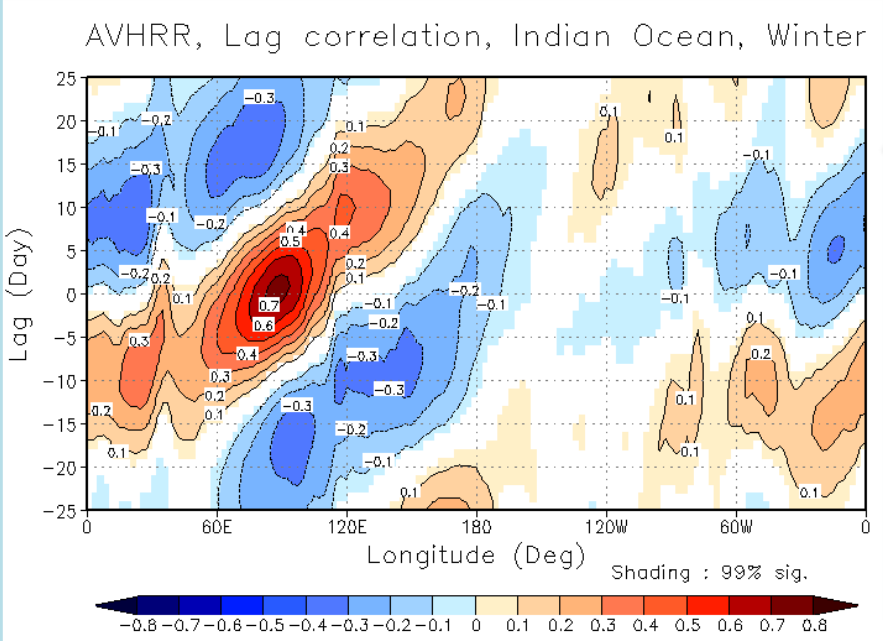


Dec-Feb Composite

May-June Composite

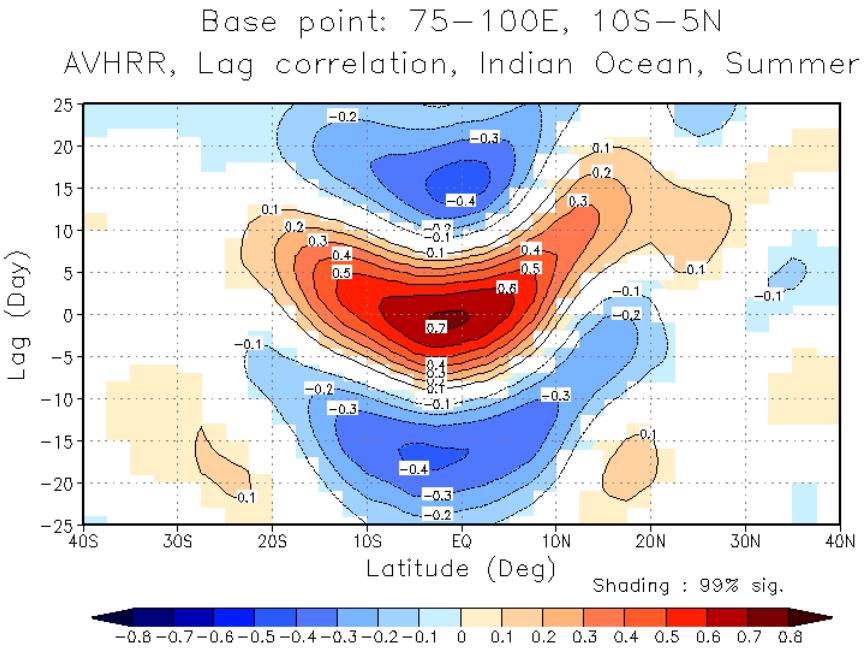


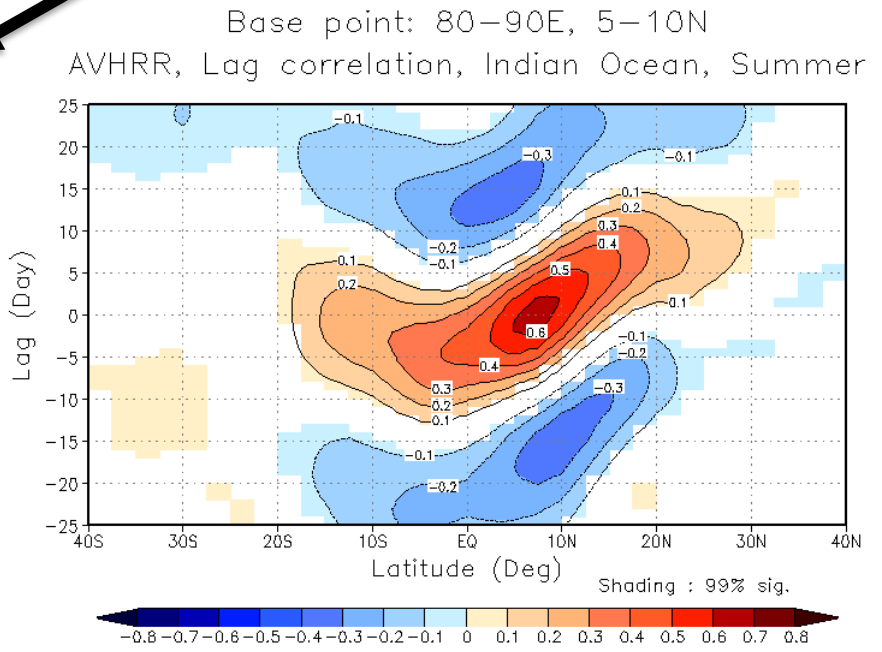




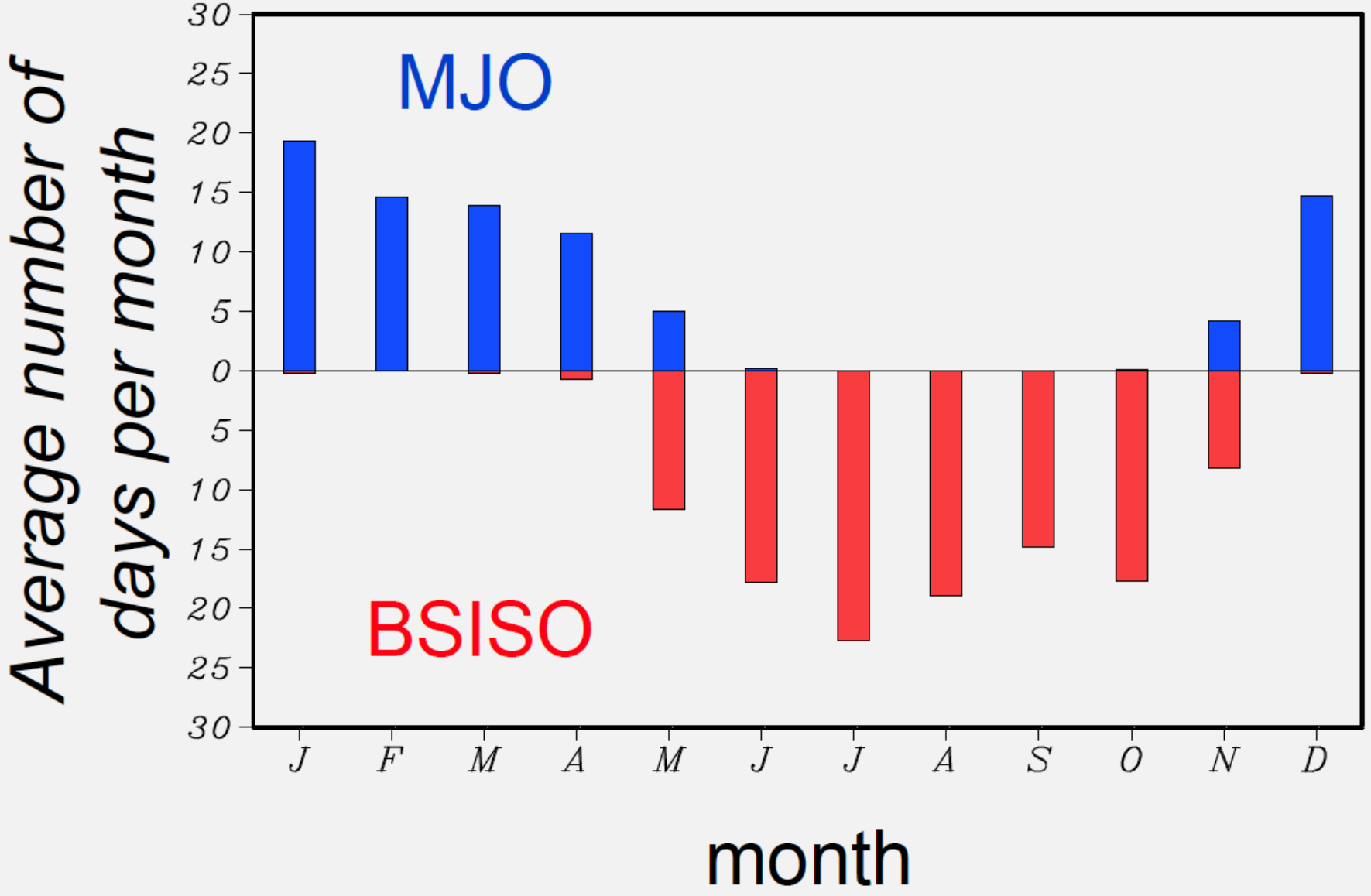
MJO

BSISO



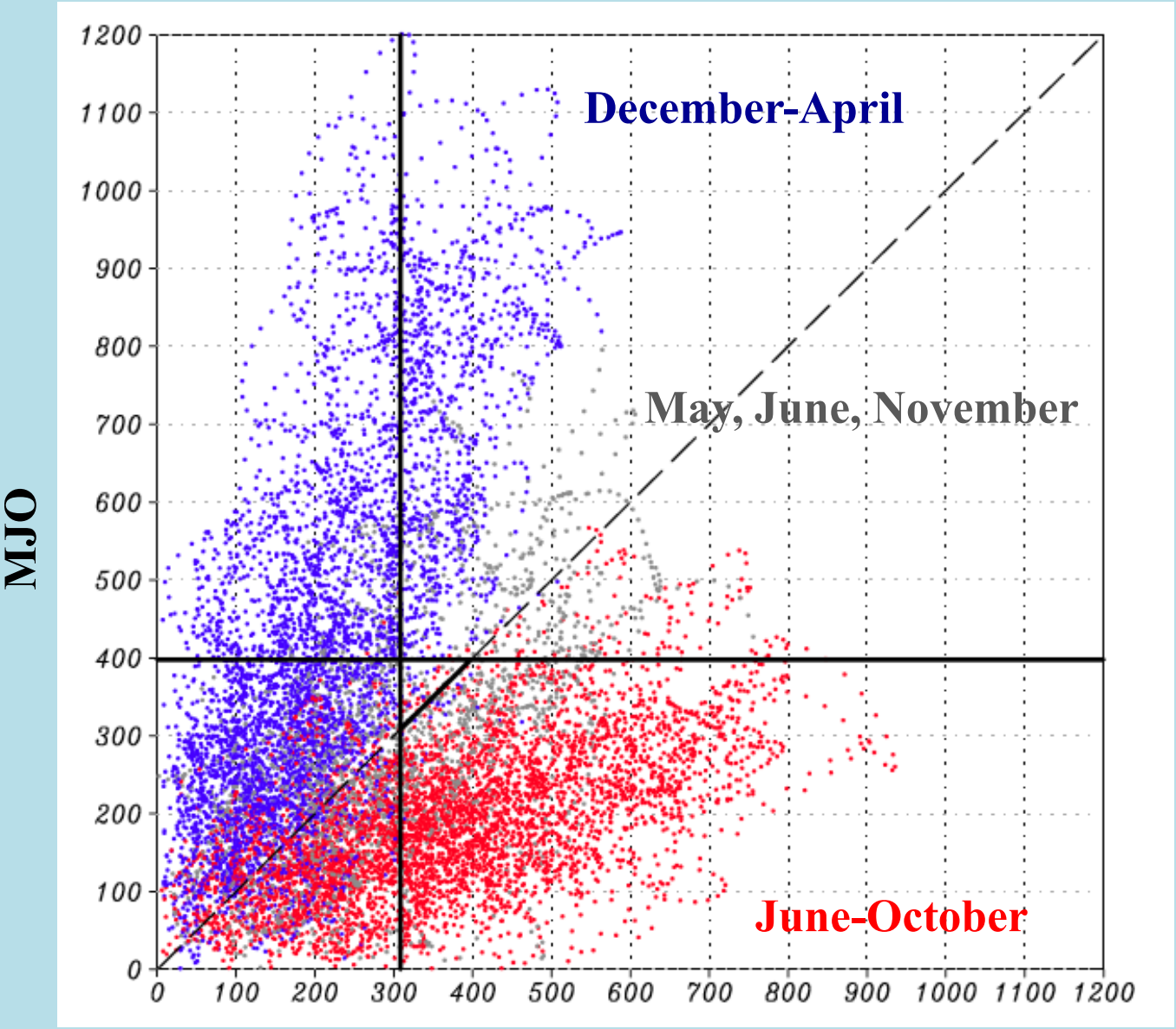


- 20-100day filtered, 80-100E averaged OLR is used

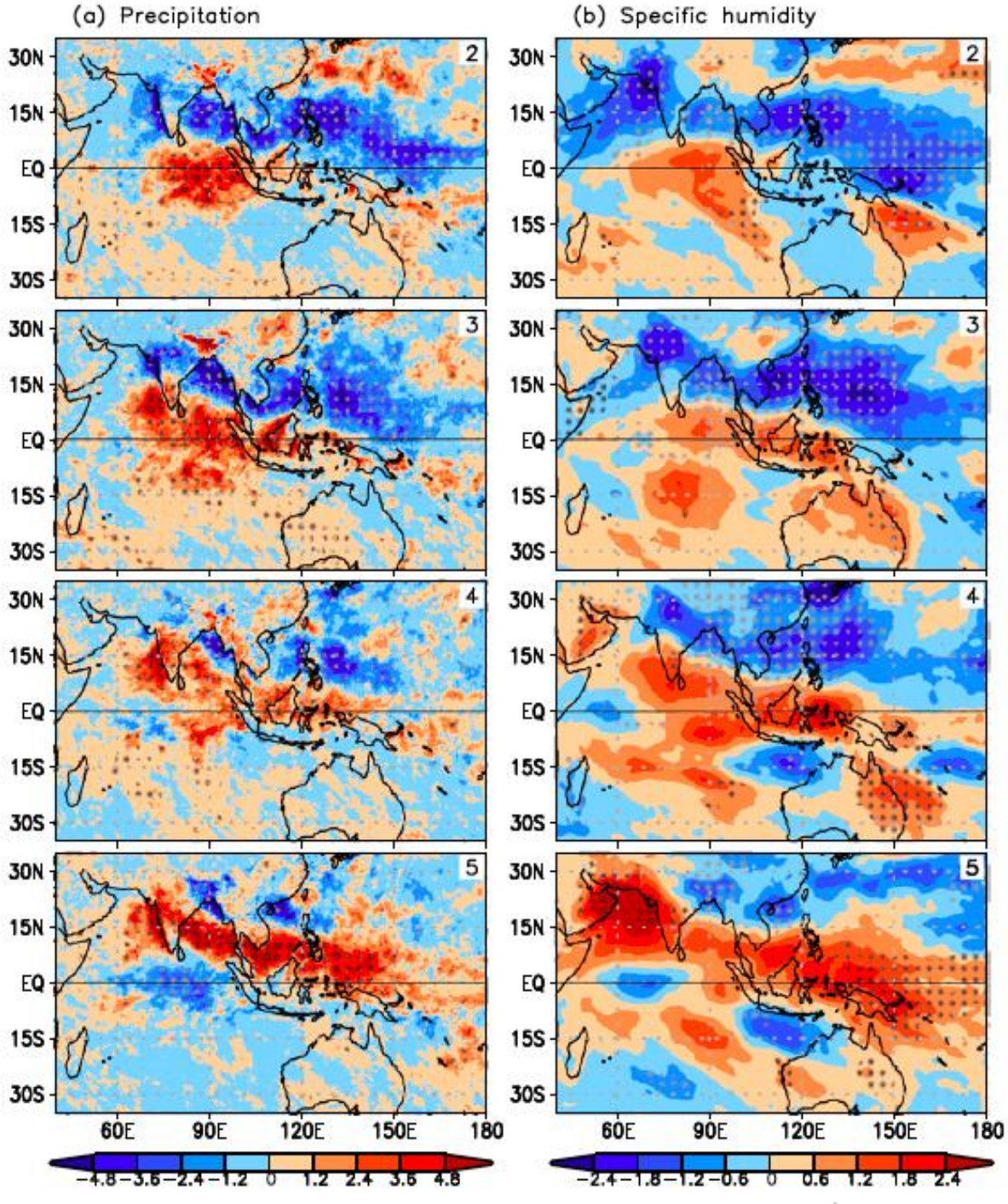


Kikuchi et al. (2012)

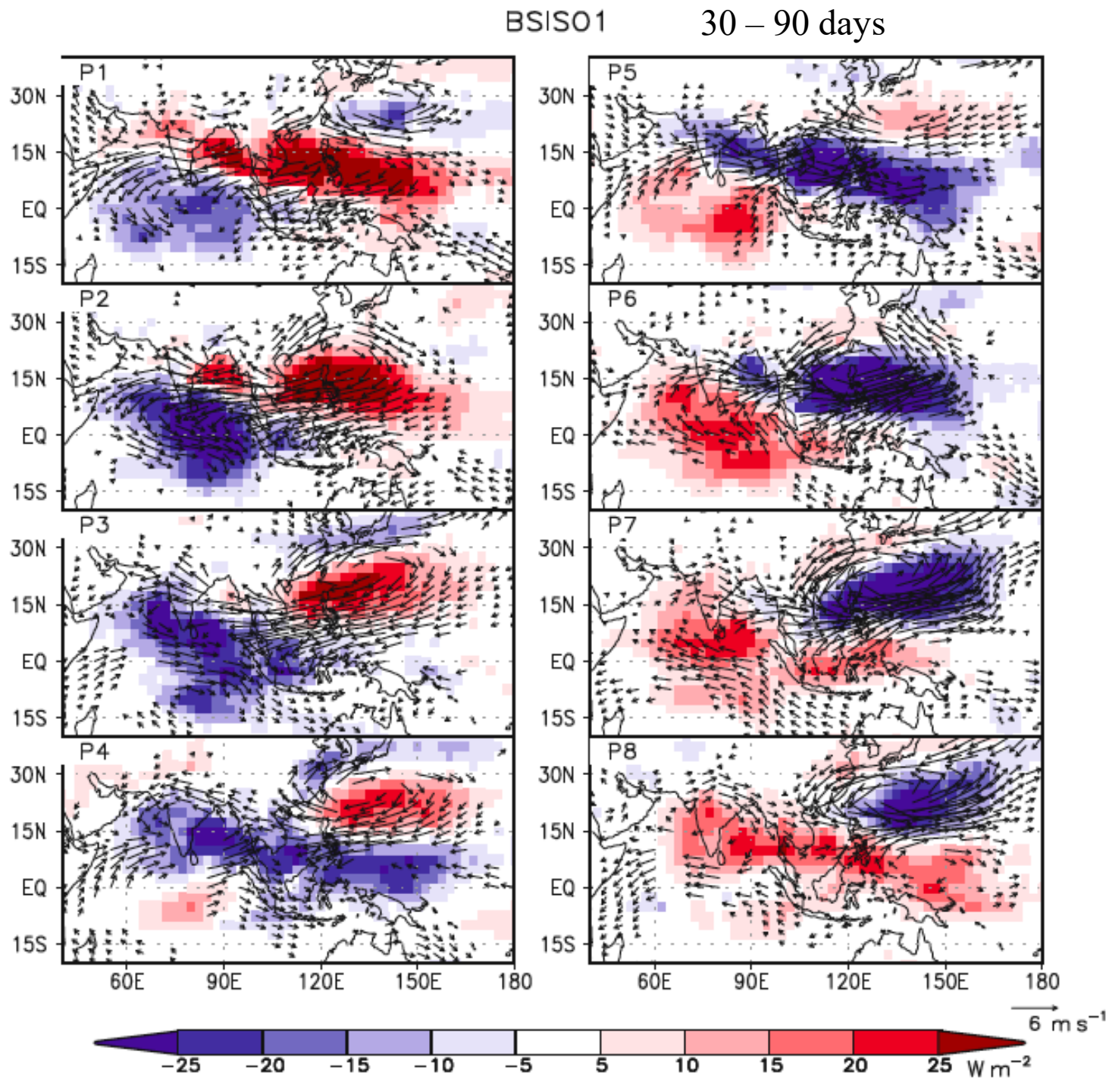
Amplitude of ISO



Kikuchi et al. (2012)

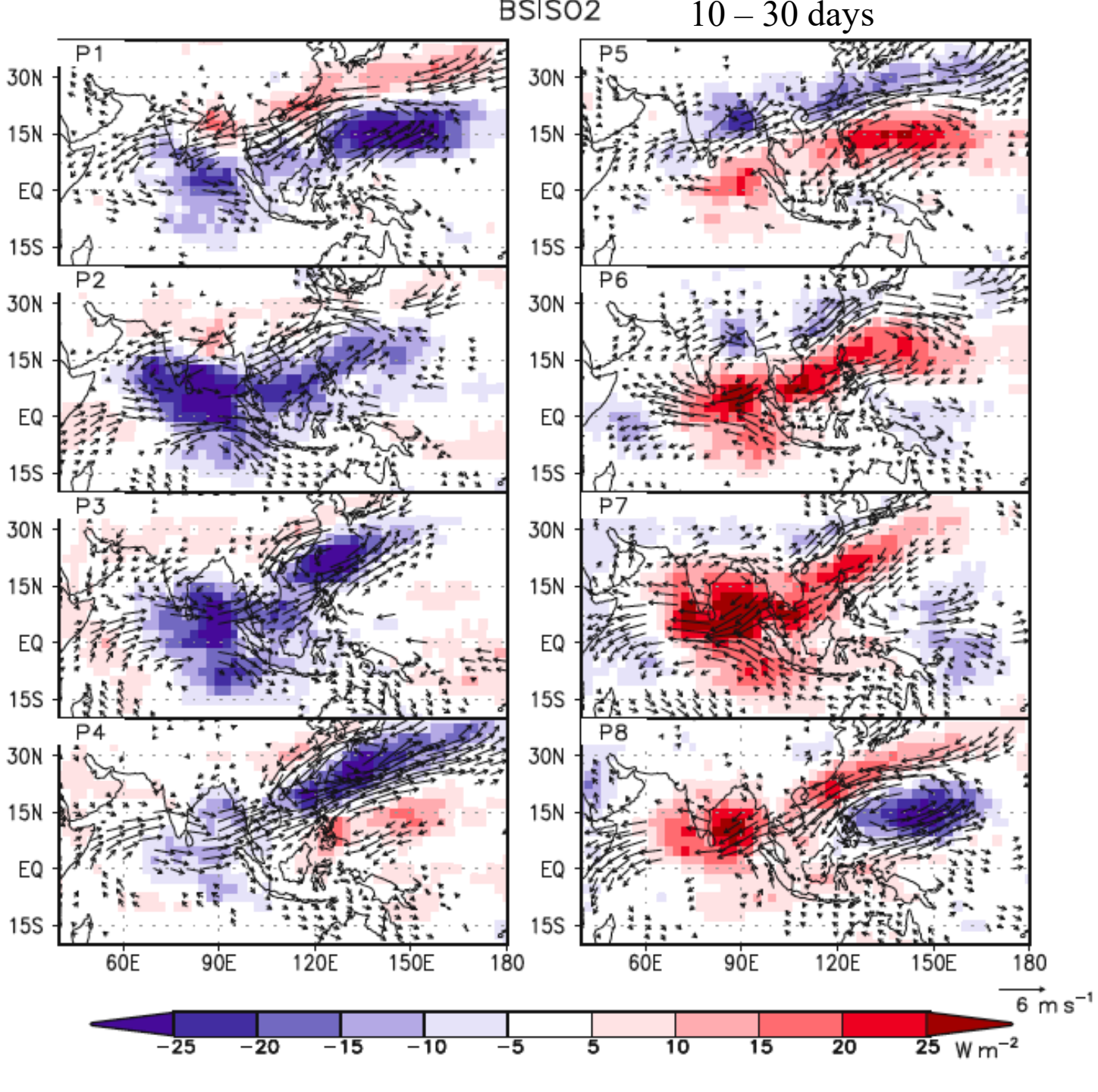


Hazra and Krishnamurthy (2015)



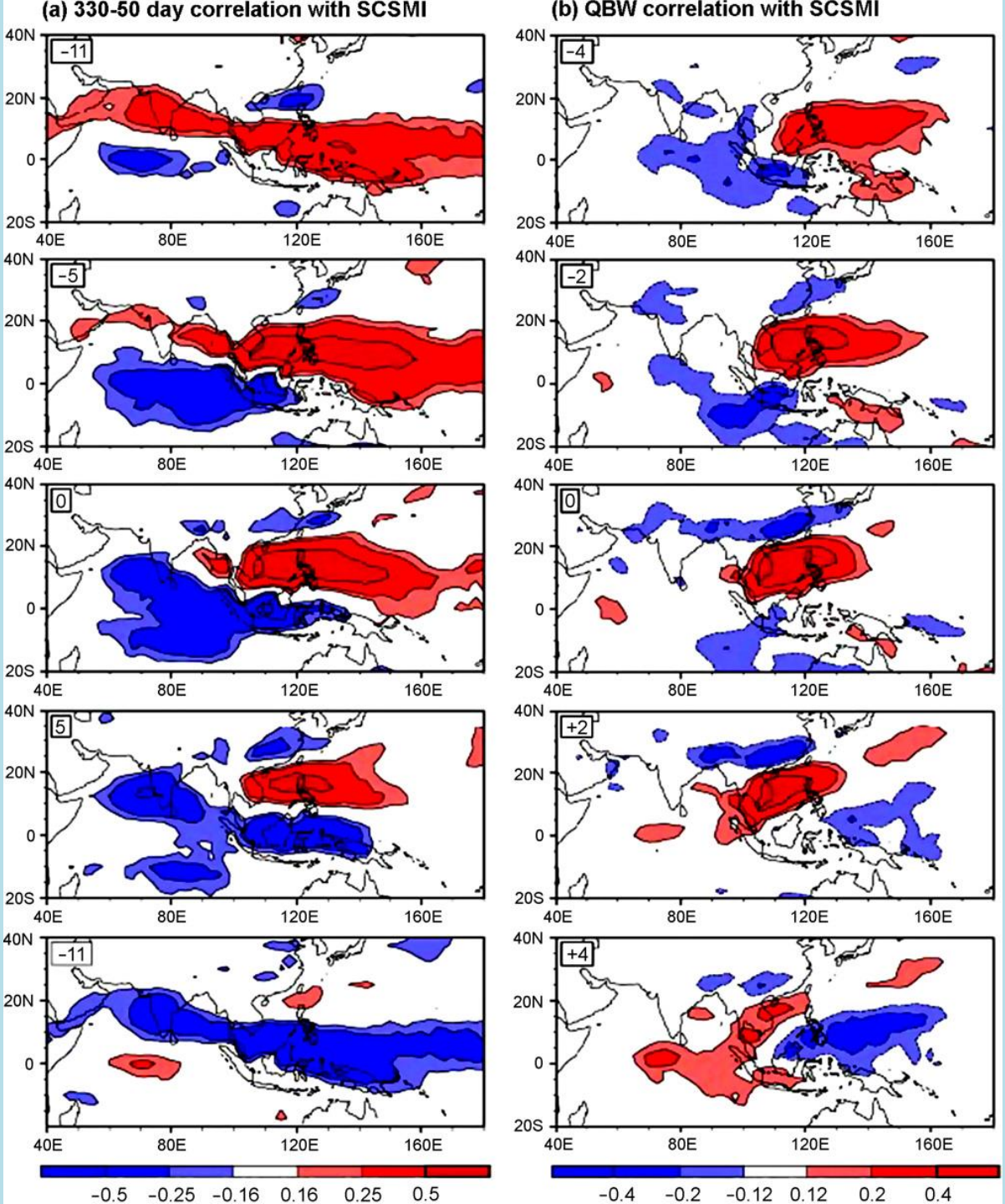
ORL (contours)
850-hPa Winds

Lee et al (2013)

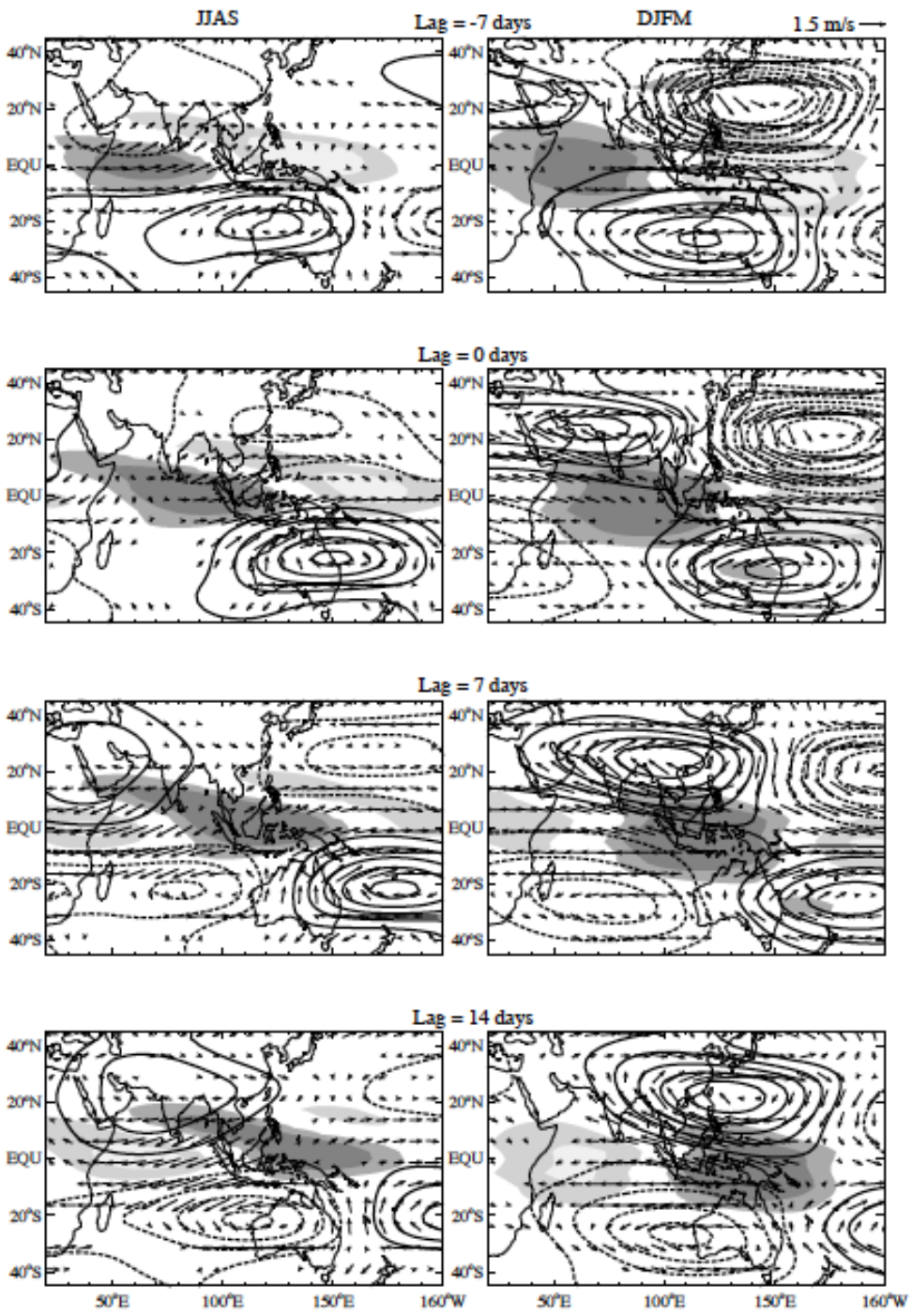


ORL (contours)
850-hPa Winds

Lee et al (2013)

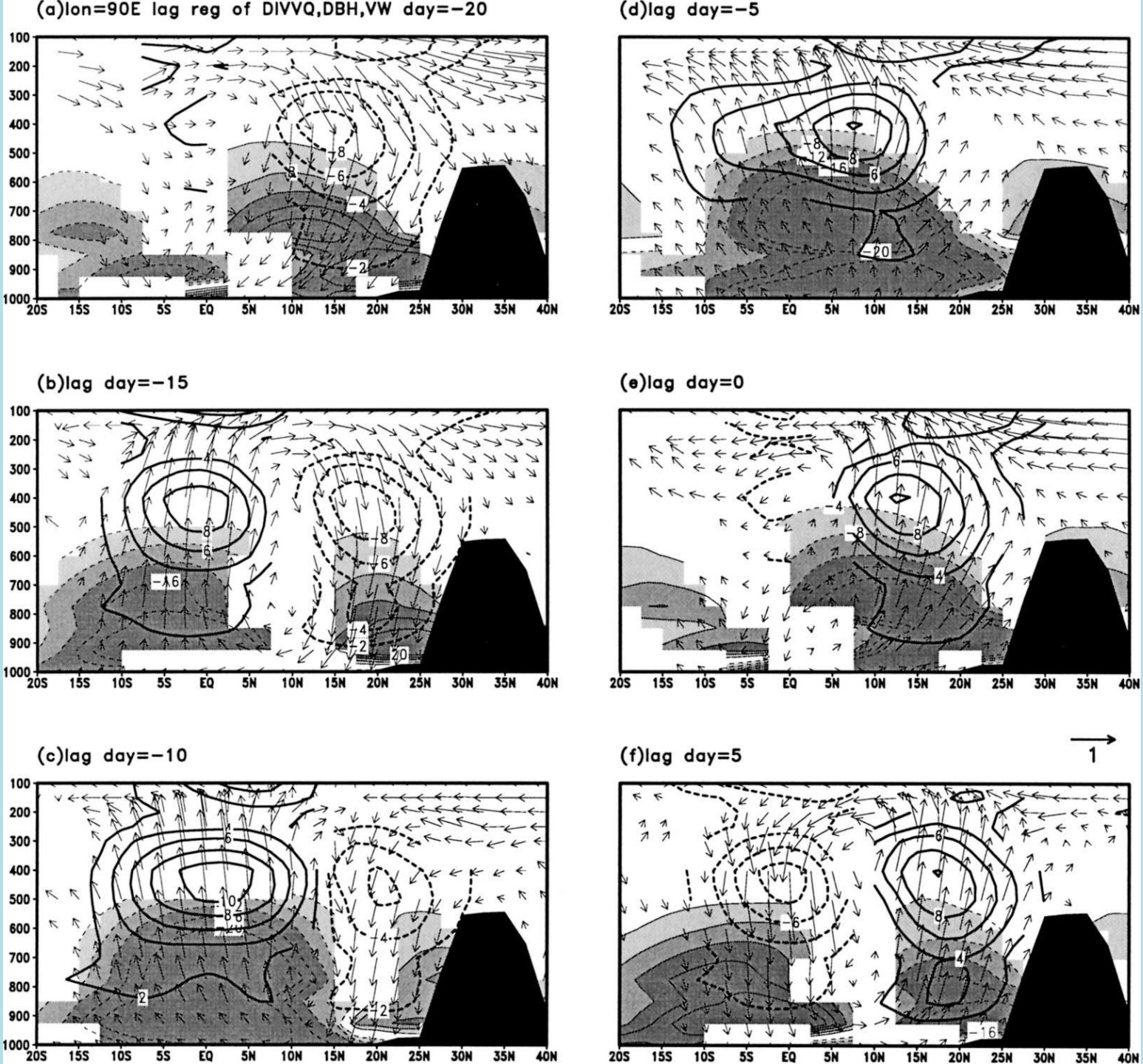


Wang et al (2004)



OLR (shaded)
200-hPa Wind vectors
200-mb streamfunction (contours)

Lawrence (2002)



Diabatic heating (contours)
Moisture divergence (shades)

Hsu et al (2004)

Summary

1. **Background state: Seasonal cycle – Monsoons**
2. **The most fundamental features of the MJO/BSISO:**

(a)

(b)

(c)

Summary

1. **Background state: Seasonal cycle – Monsoons**
2. **The most fundamental features of the MJO/BSISO:**

(a)

(b)

(c)

3. The basic structures of the MJO/BSISO:

(a)

(b)

(c)

Summary

1. **Background state: Seasonal cycle – Monsoons**
2. **The most fundamental features of the MJO/BSISO:**

(a)

(b)

(c)

3. The basic structures of the MJO/BSISO:

(a)

(b)

(c)

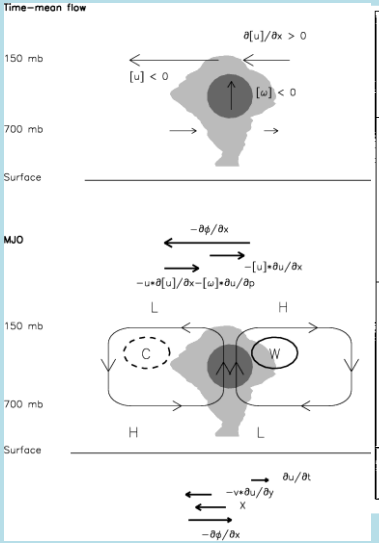
4. Others

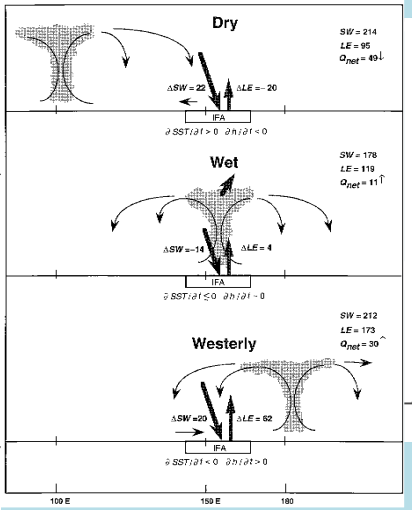
(a)

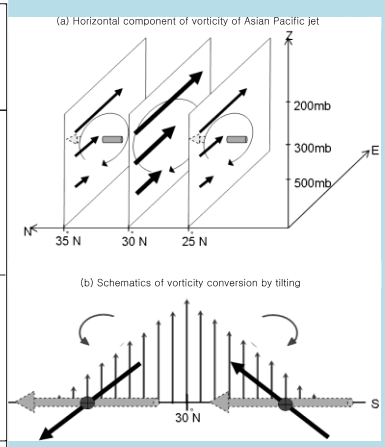
(b)

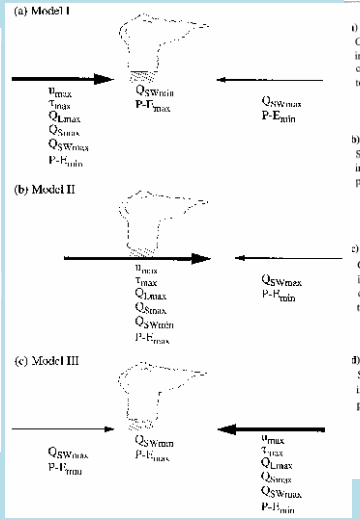
(c)

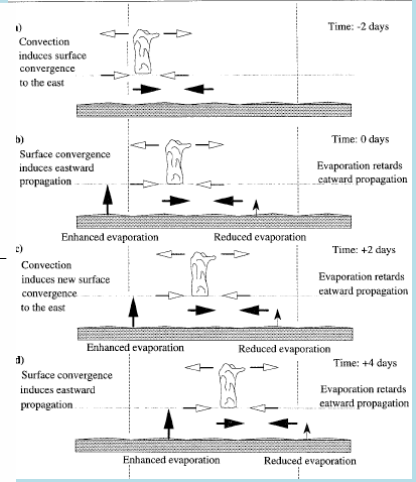
Mechanisms

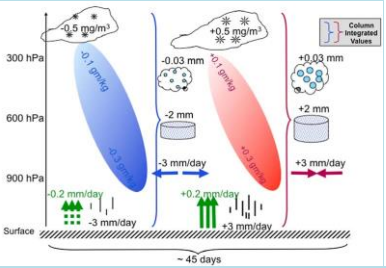


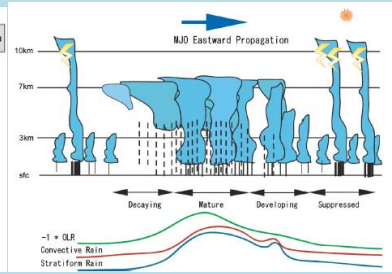


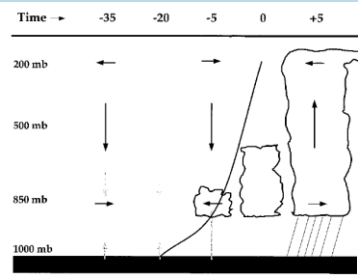


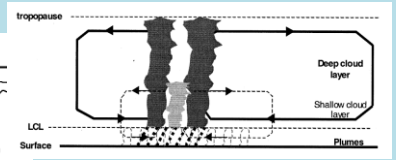


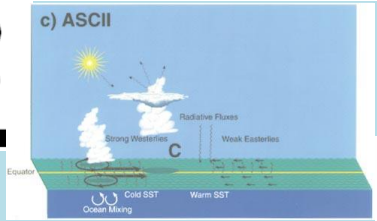


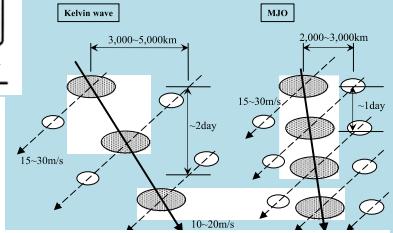


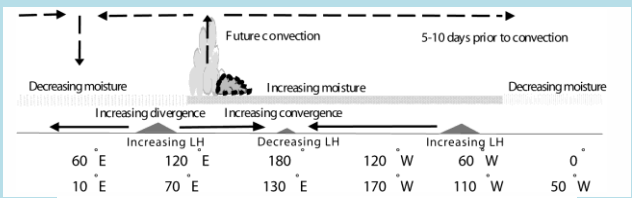


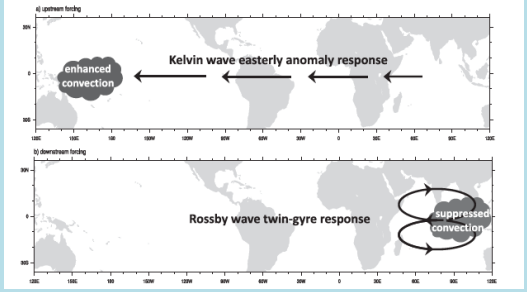


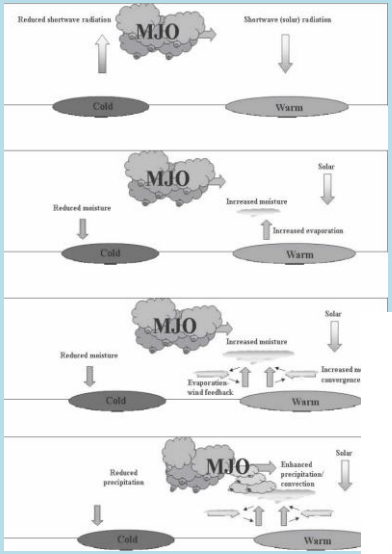


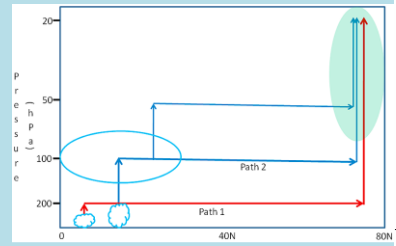


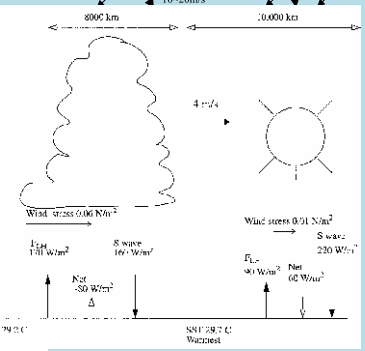


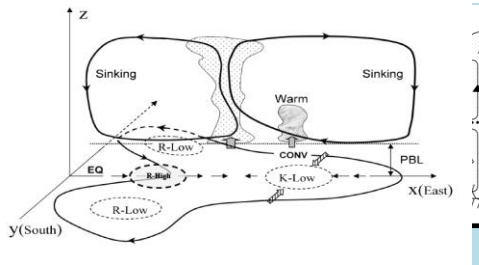


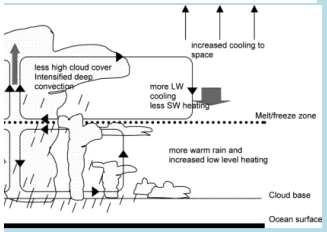




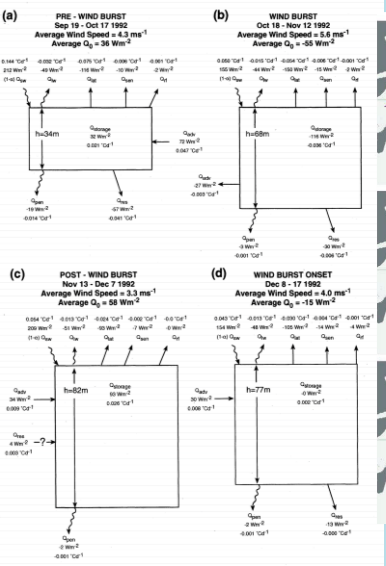


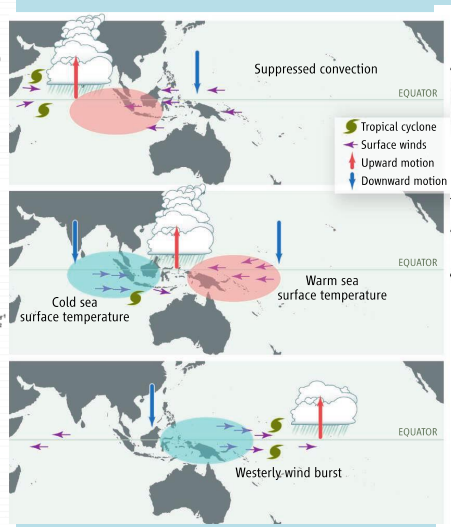


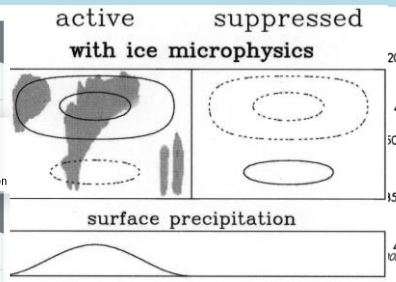


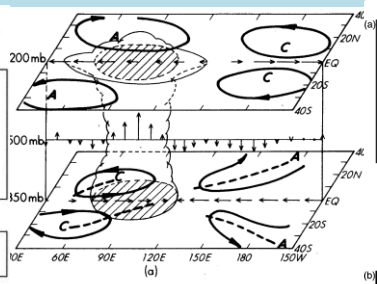


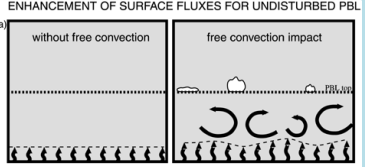
IG. 11. Schematic illustrating the impact of air–sea coupling on the dynamics of the
in BAM.

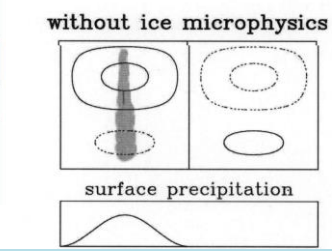


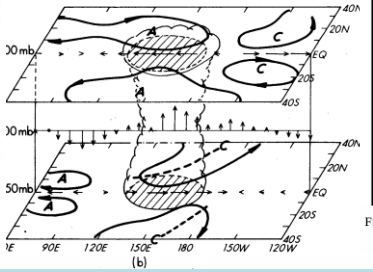












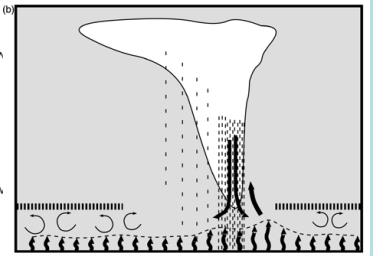
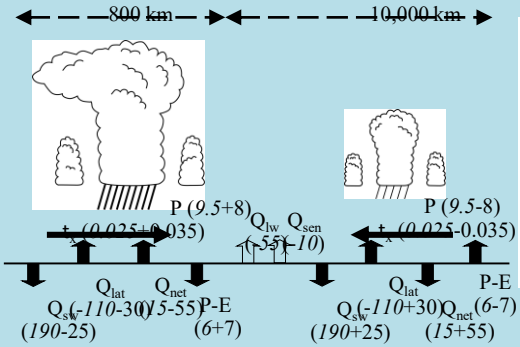
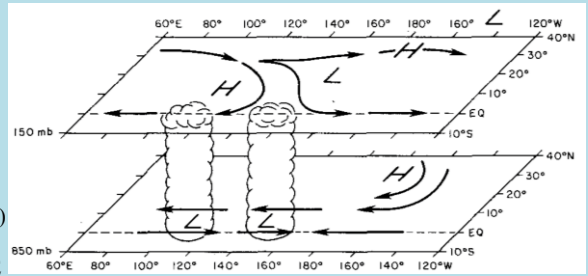
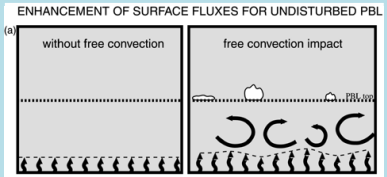
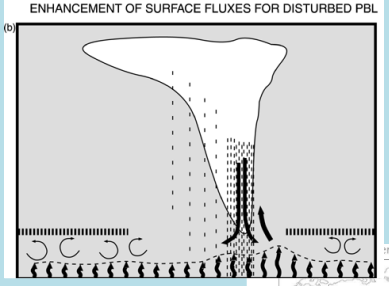


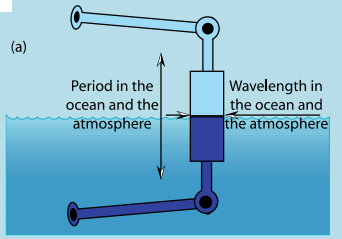
FIG. 1. Enhancement of surface fluxes for (a) undisturbed convective boundary layer and (b) disturbed boundary layer.

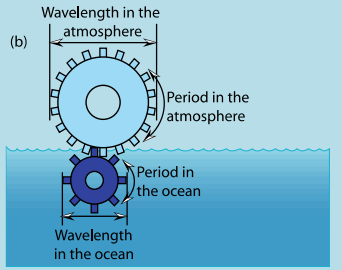


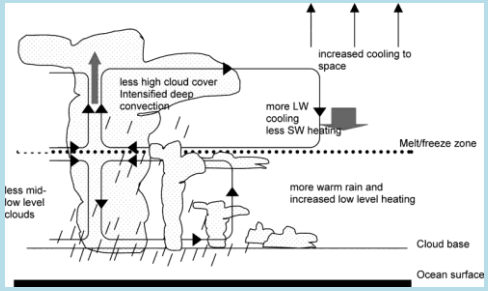


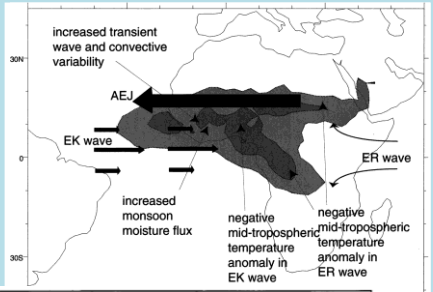


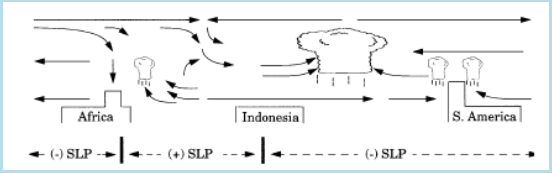


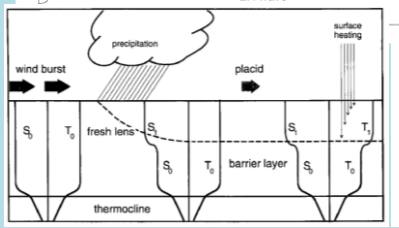


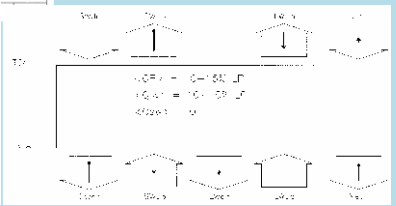


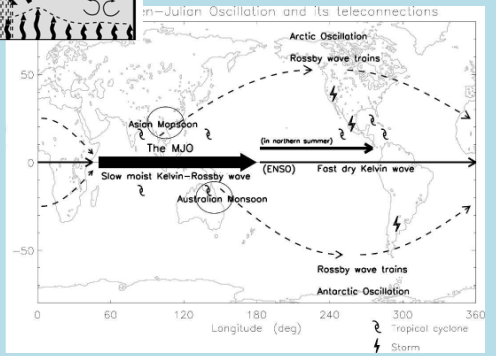


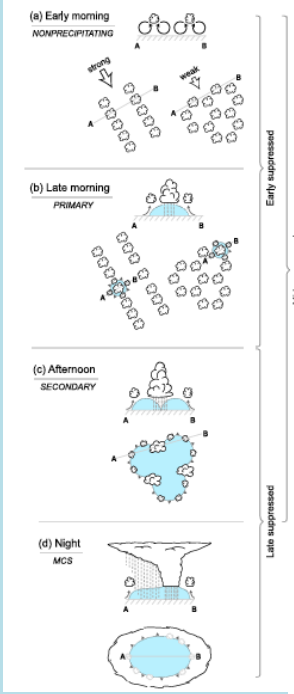


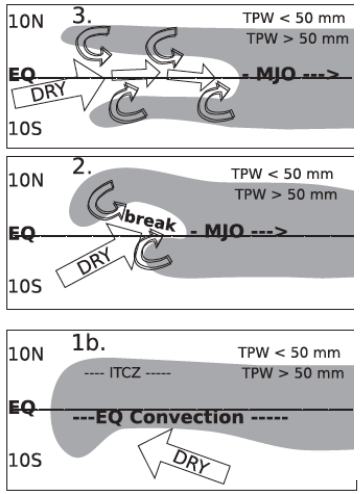


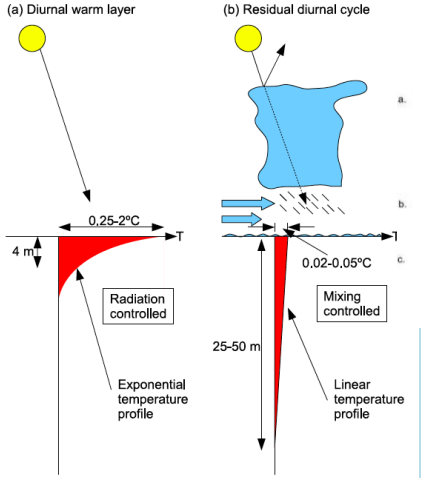


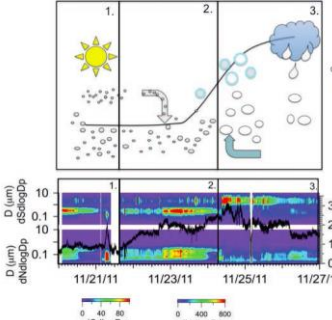


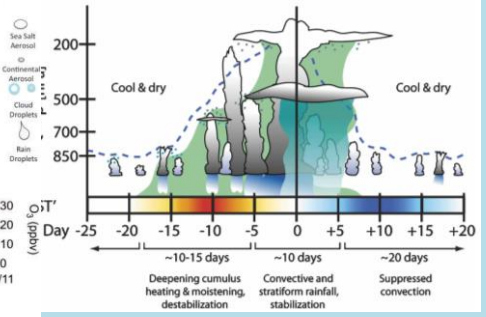


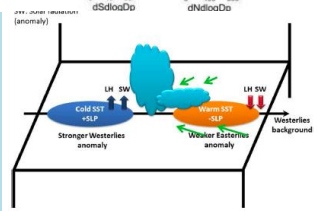

(a) Early morning
NONPRECIPITATING
(b) Late morning
PRIMARY
(c) Afternoon
SECONDARY
(d) Night
MCS
Early suppressed
Mid-suppressed
Late suppressed

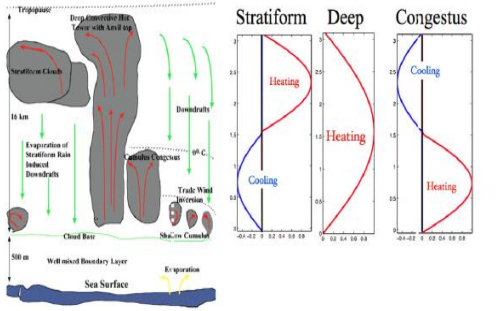

10N
3.
TPW < 50 mm
TPW > 50 mm
EQ
DRY
- MJO --->
10S
2.
break
1b.
---- ITCZ -----
---EQ Convection -----

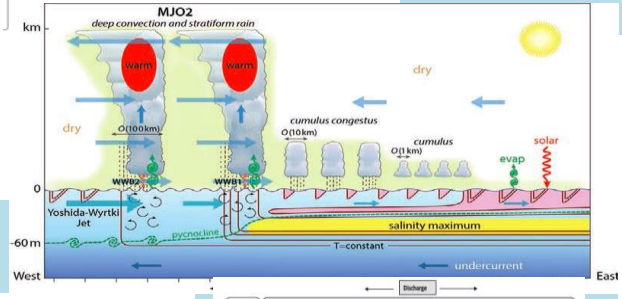

(a) Diurnal warm layer
0.25-2°C
4 m
Radiation controlled
Exponential temperature profile
(b) Residual diurnal cycle
0.02-0.05°C
Mixing controlled
25-50 m
Linear temperature profile

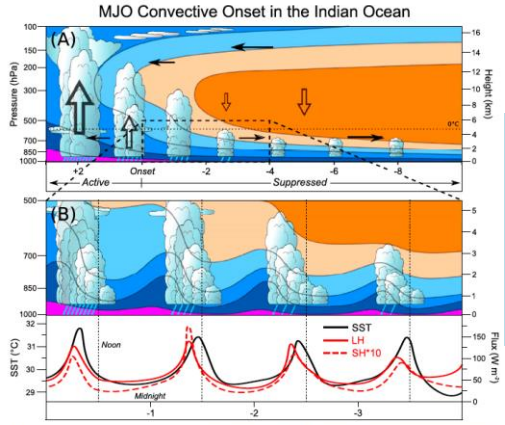

Sea Salt Aerosol
Continental Aerosol
Cloud Droplets
Rain Droplets
11/21/11
11/23/11
11/25/11
11/27/11

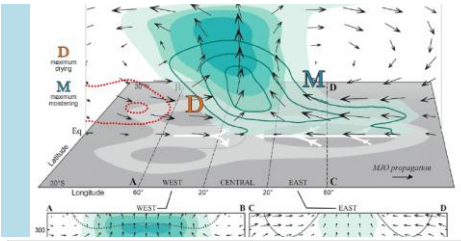

Cool & dry
Cool & dry
Day -25 -20 -15 -10 -5 0 +5 +10 +15 +20
~10-15 days
~10 days
~20 days
Deepening cumulus heating & moistening, destabilization
Convective and stratiform rainfall, stabilization
Suppressed convection

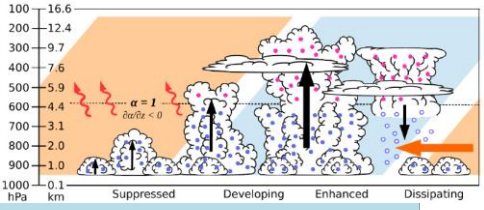

Cold SST +SLP
Warm SST -SLP
Stronger Westerlies anomaly
Weaker Easterlies anomaly
Westerlies background

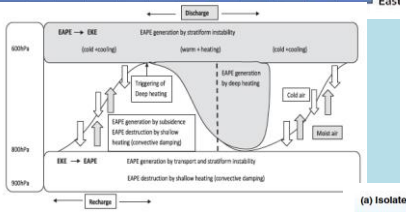

Stratiform
Deep
Congestus
Heating
Cooling
Sea Surface

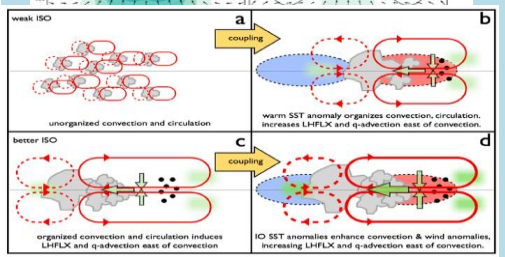

MJO2
deep convection and stratiform rain
warm
dry
cumulus congestus
cumulus
evap
solar
Yoshida-Wyrtki Jet
pycnocline
salinity maximum
T=constant
undercurrent
West
East

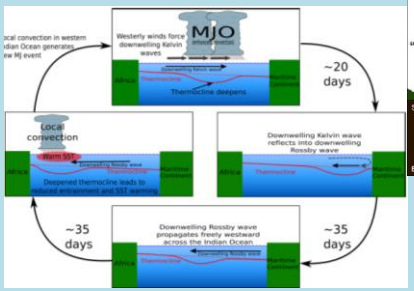

MJO Convective Onset in the Indian Ocean
(A)
(B)
Active
Onset
Suppressed
SST
LH
SH*10
Noon
Midnight

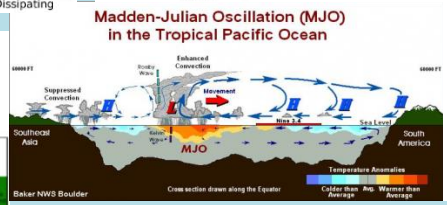

MJO propagation
WEST
CENTRAL
EAST

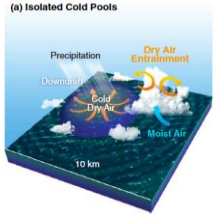

α = 1
Suppressed
Developing
Enhanced
Dissipating

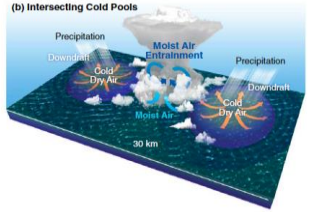

Discharge
Recharge
Triggering of Deep heating
Cold air
Moist air

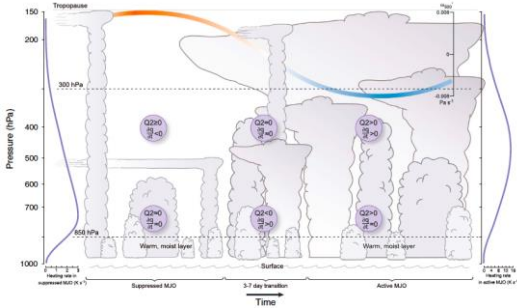

weak ISO
coupling
unorganized convection and circulation
warm SST anomaly organizes convection, circulation, increases LHFLX and q-advection east of convection.
better ISO
organized convection and circulation induces LHFLX and q-advection east of convection
IO SST anomalies enhance convection & wind anomalies, increasing LHFLX and q-advection east of convection.


MJO
~20 days
Local convection
~35 days
~35 days


Madden-Julian Oscillation (MJO)
in the Tropical Pacific Ocean
Suppressed Convection
Enhanced Convection
Movement
Southeast Asia
South America
MJO
Temperature Anomalies
Baker NWS Boulder

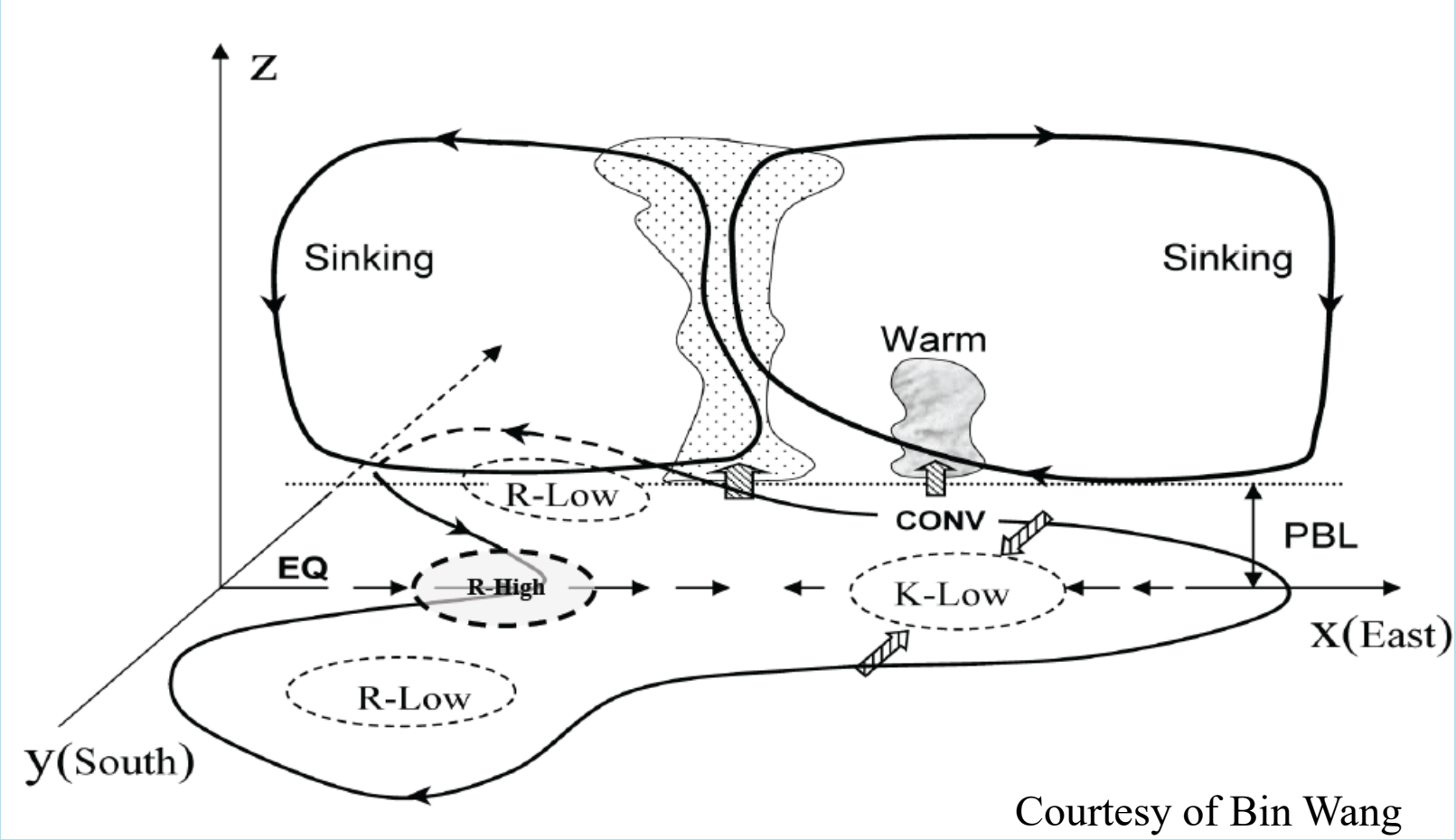

(a) Isolated Cold Pools
Precipitation
Dry Air Entrainment
Downdraft
Cold Dry Air
Moist Air
10 km


(b) Intersecting Cold Pools
Precipitation
Moist Air Entrainment
Downdraft
Cold Dry Air
Moist Air
30 km


Tropopause
300 hPa
850 hPa
Surface
Warm, moist layer
Suppressed MJO
3-7 day transition
Active MJO
Time

MJO as a Frictional Coupled Rossby-Kelvin Couplet

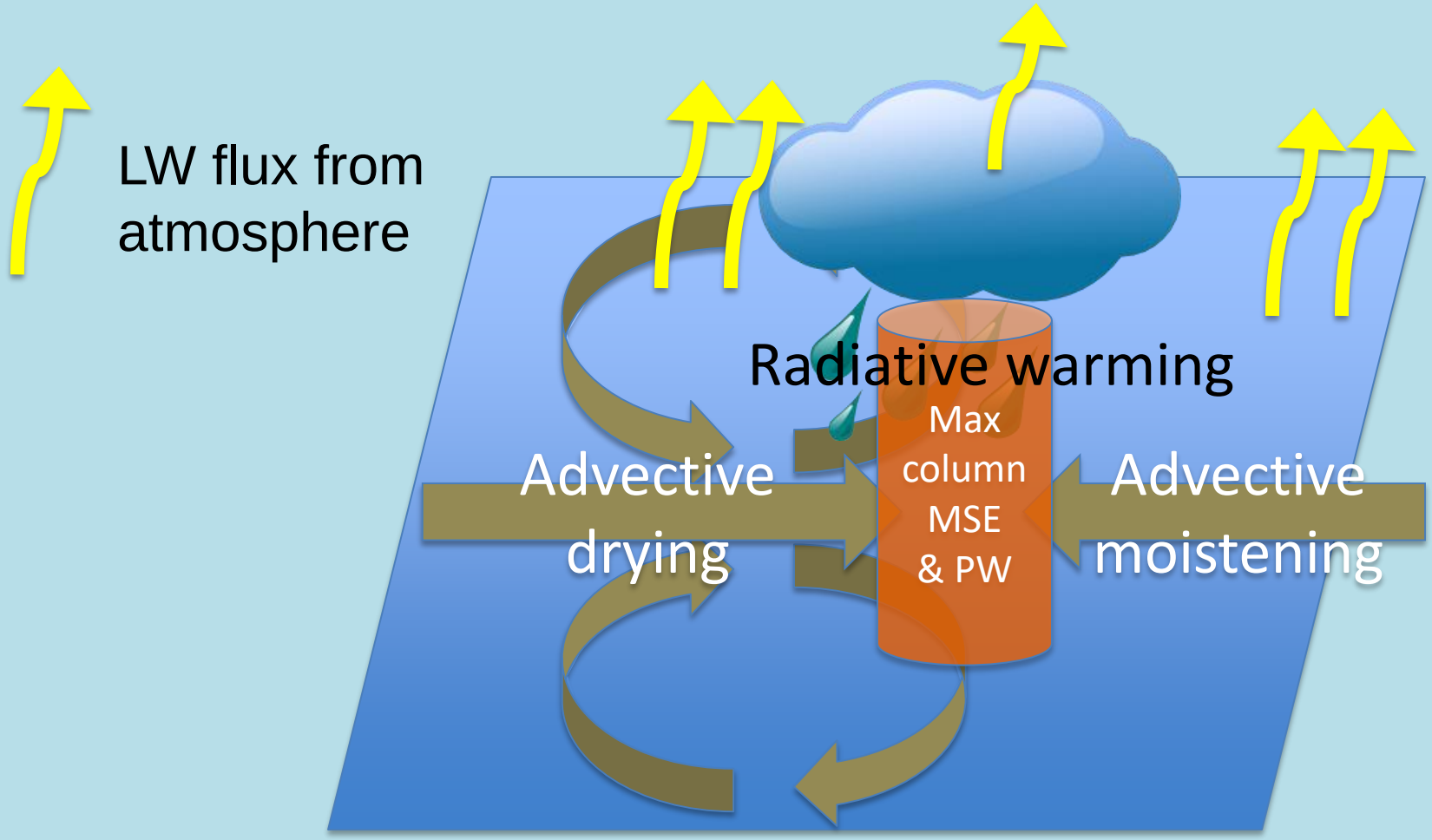
Wang (1987), Wang and Rui (1990), Wang and Li (1994)



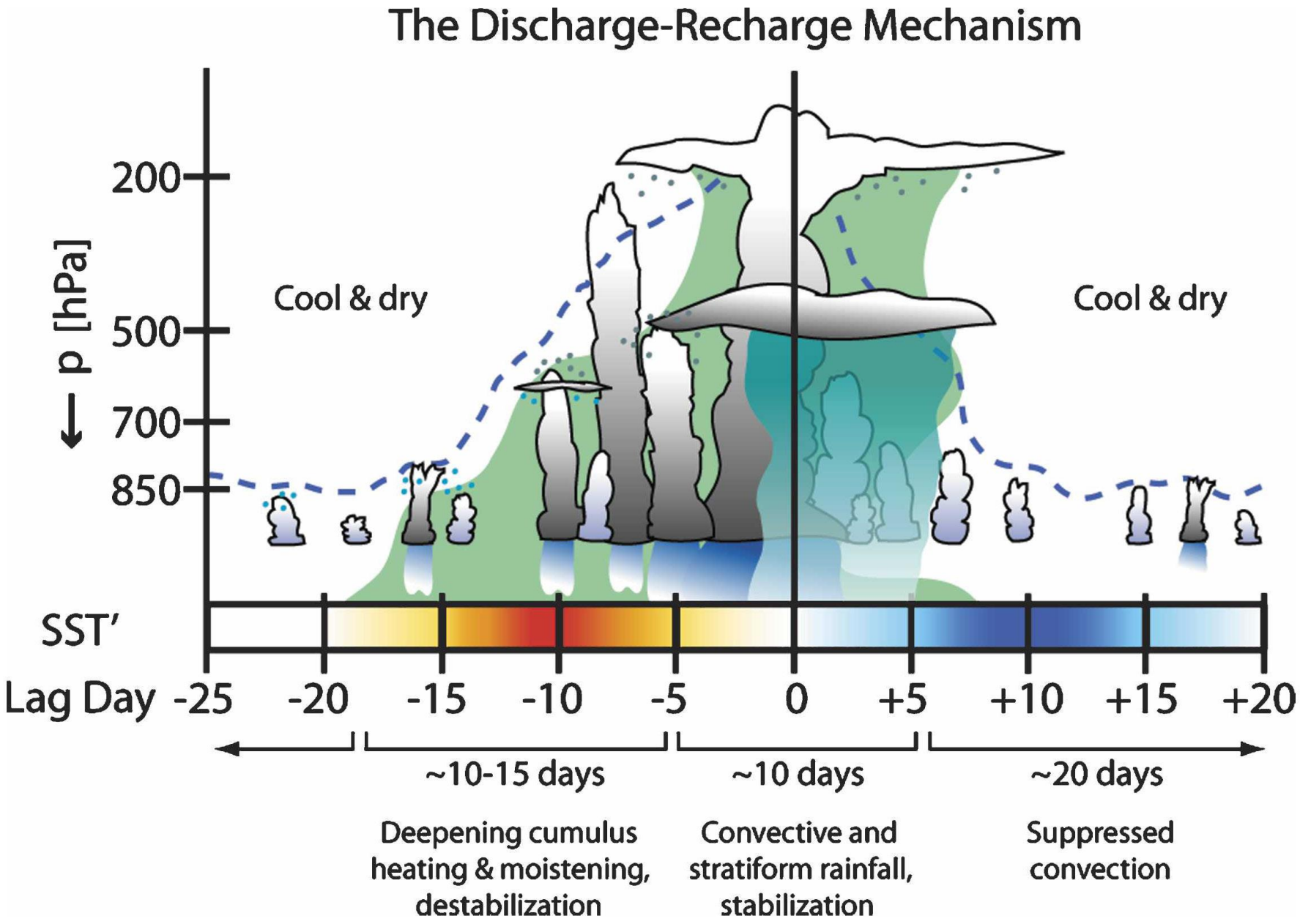
Courtesy of Bin Wang

"MJO as a moisture mode (convection-moisture coupling), driven by radiative-convective feedback and propagating due to horizontal moisture advection." – Adam Sobel

Raymond and Fuchs (2009), Sobel and Maloney (2012), Adames and Kim (2015)



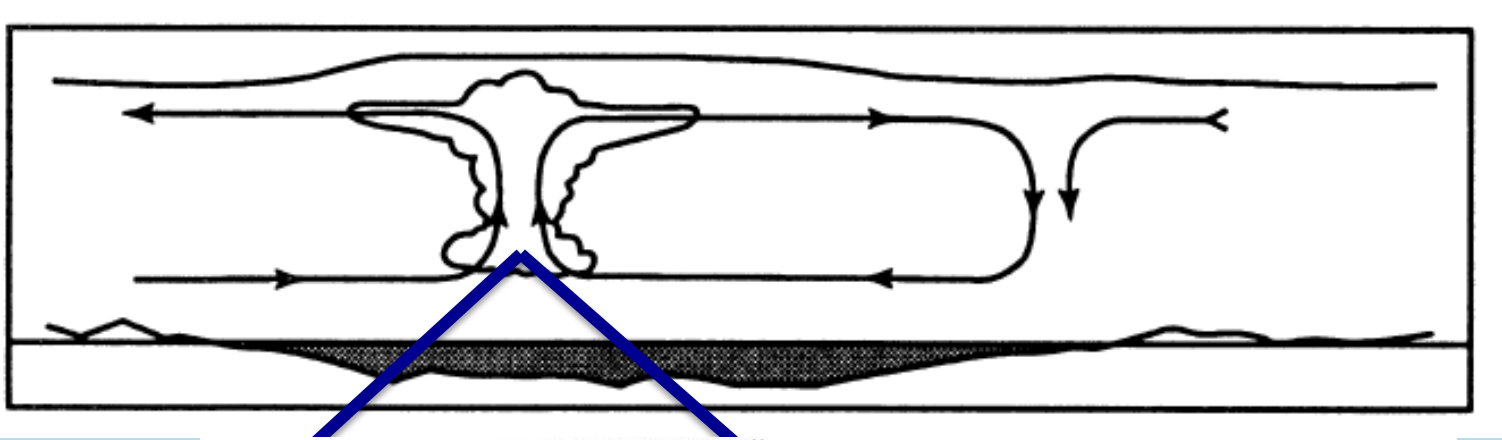
Courtesy of Adam Sobel

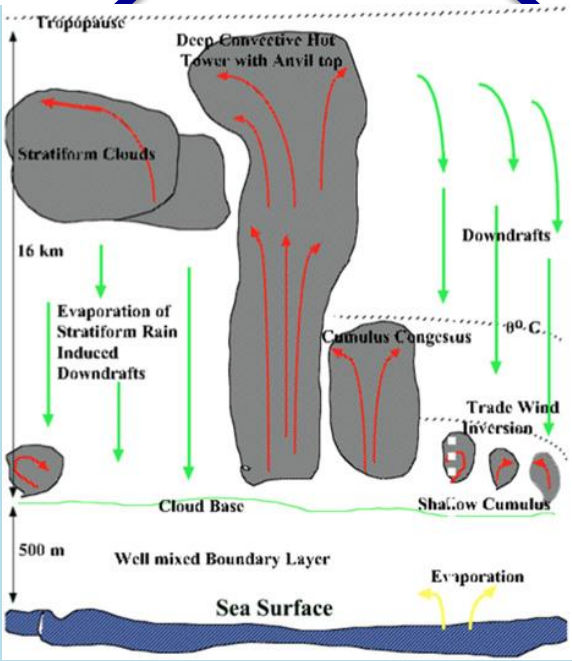


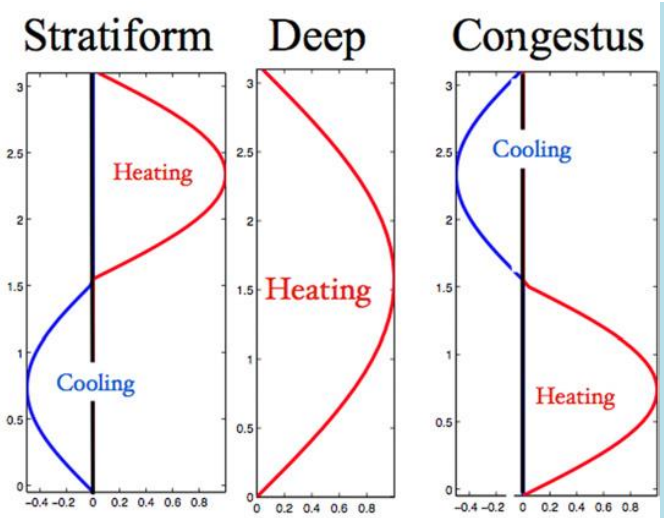
Benedict and Randall (2007)

Multicloud, Multiscale, Stochastic Model of the MJO

Biello and Majda (2005), Majda and Stetchmann (2009), Khouider at al. (2012)



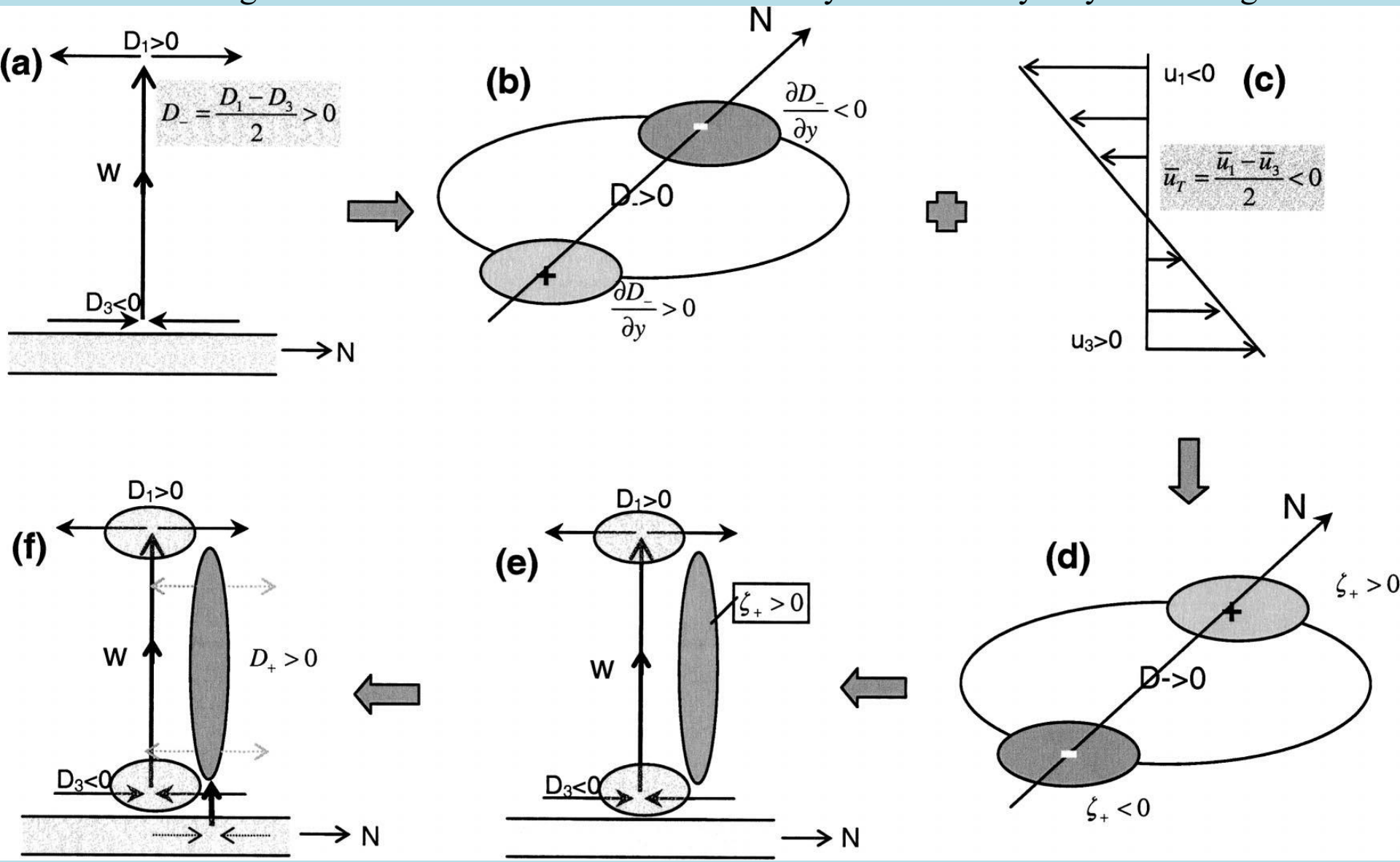




Khouider and Majda (2008)

A BSISO Theory:

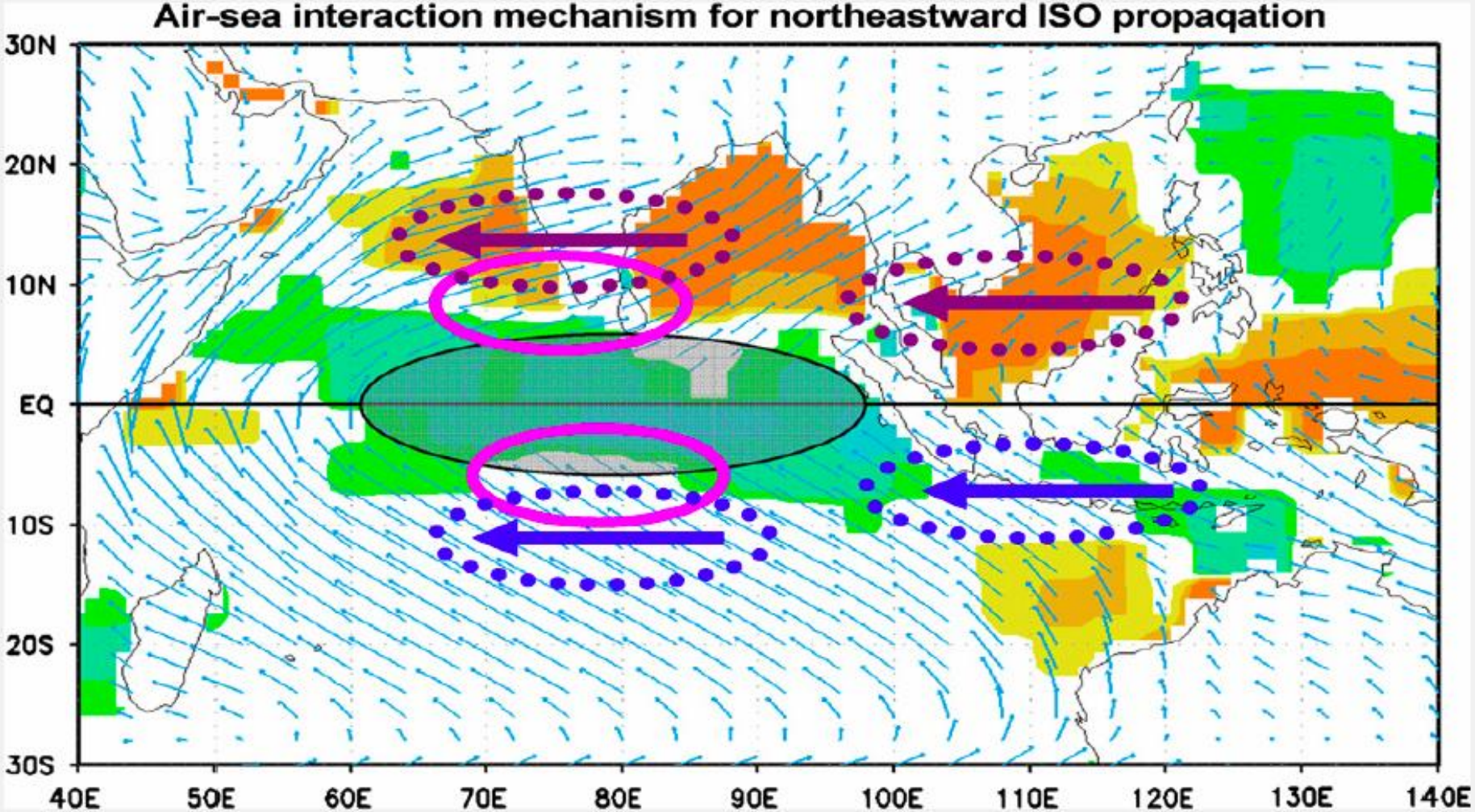
Convergence + **Vertical Wind Shear** => Vorticity => Boundary-Layer Convergence



D: divergence

Jiang et al. (2004)

Propagating Air-sea interaction mechanism



Fu et al. (2003), Wang et al. (2009)

Mechanism Summary

1. **Major factors for the MJO:**

(a) Moisture: vertical structure, interaction with clouds, supply

(b) Circulation: dynamic framework, moisture supply

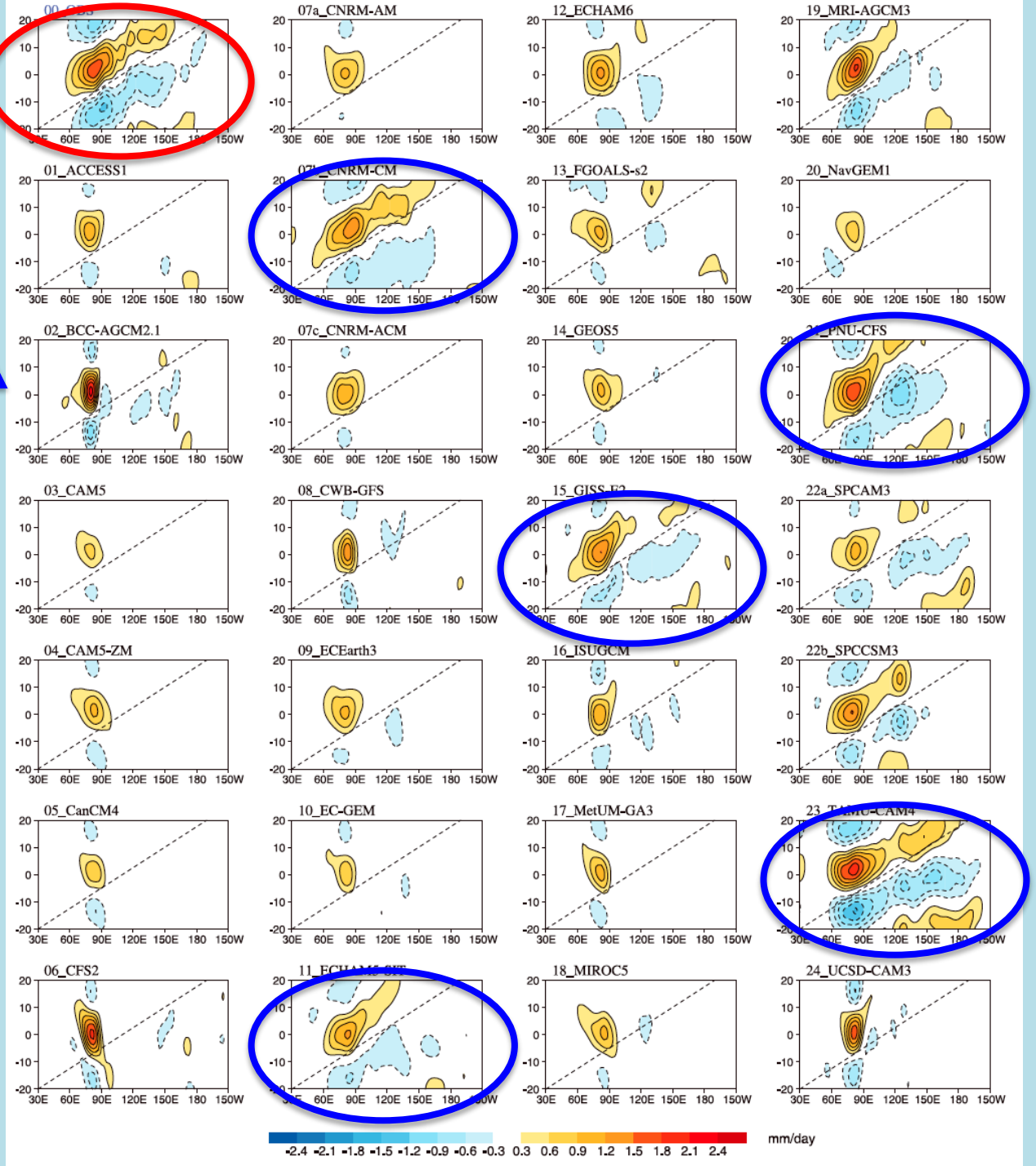
(c) Radiation: distabilization, interaction with clouds

(d) Clouds/Convection: latent heating, interaction with moisture and radiation

(e) Air-sea interaction: surface fluxes

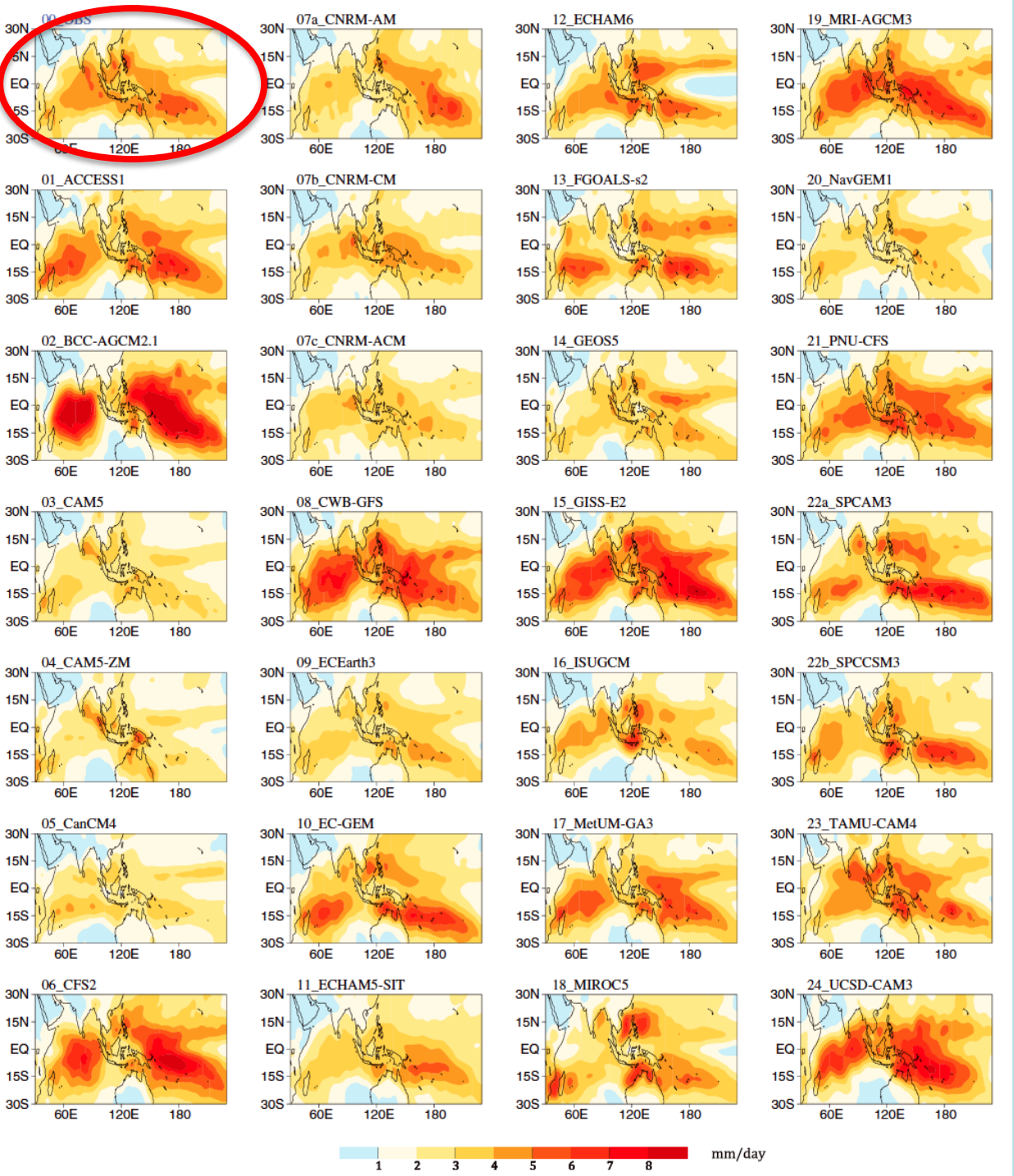
2. There are competing MJO/BSISO theories, each emphasize on different factors.

Prediction of the MJO/BSISO



"Good" MJO simulations by the "CMIP5 generation": **18%**

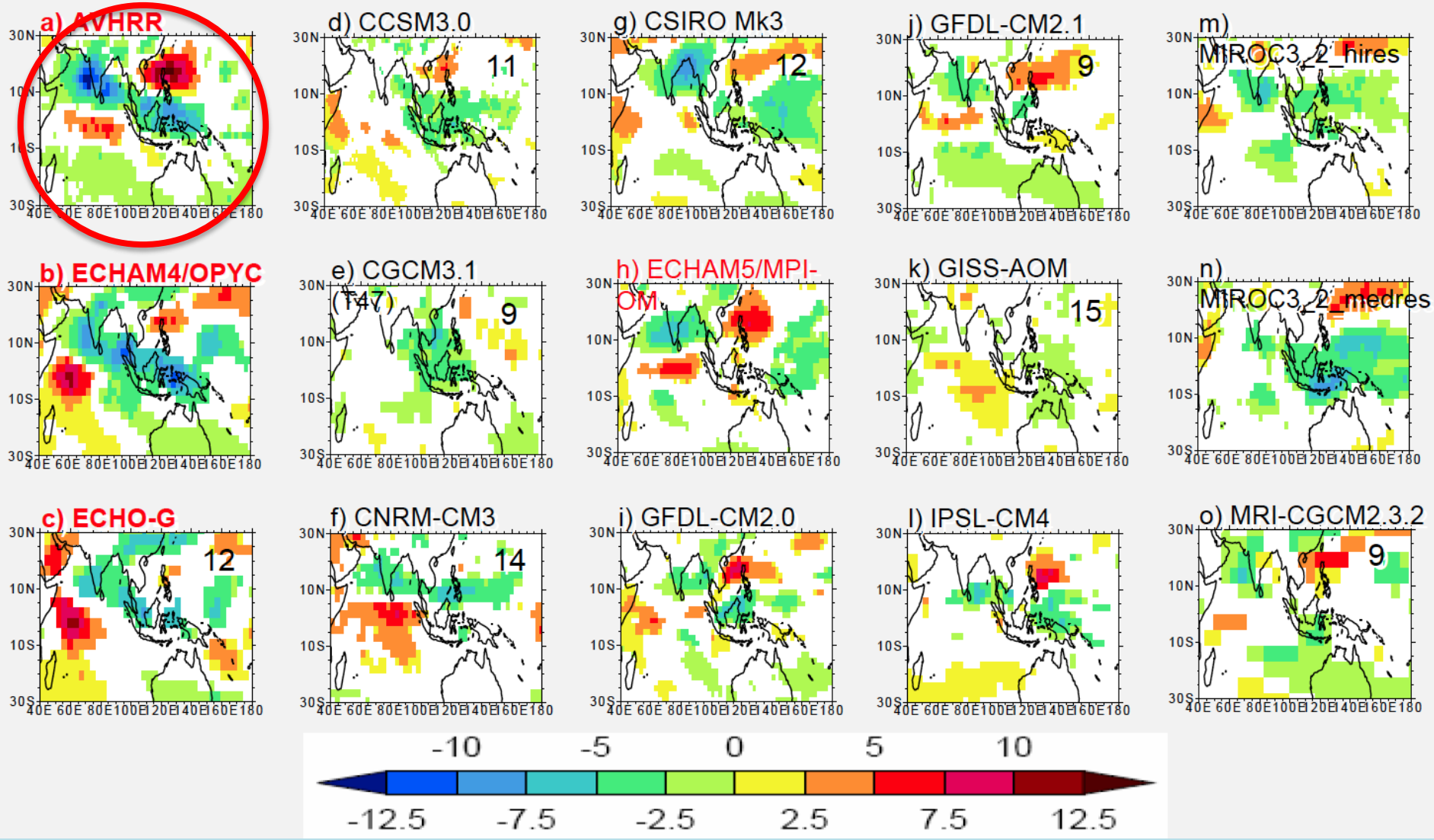
Jiang et al. (2015)



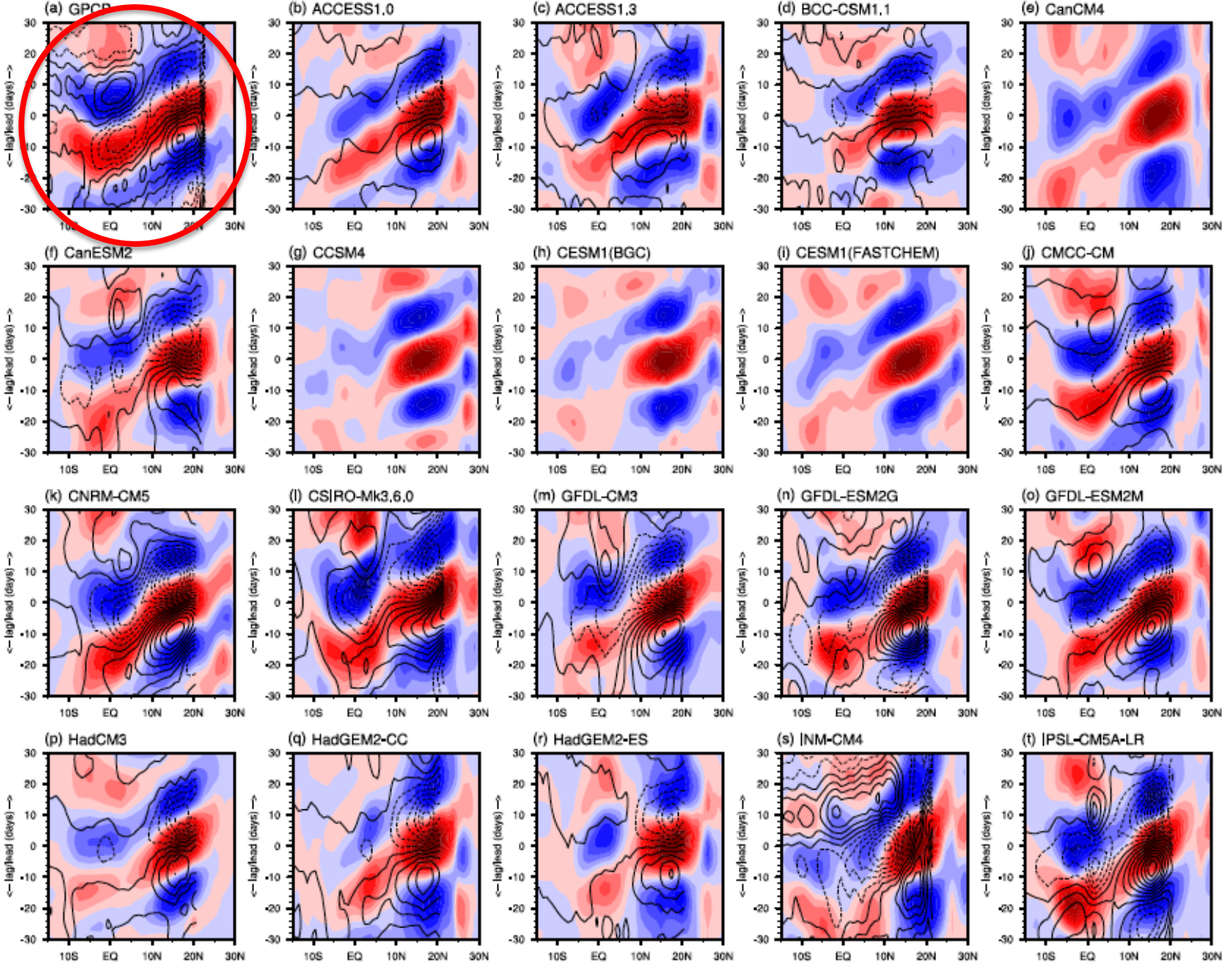
Boreal winter intraseasonal variability (standard deviation) in rainfall

Jiang et al. (2015)

Climate Model Simulations of the BSISO



Courtesy of Bin Wang



Sabeerali et al. (2013)

Prediction vs. Predictability

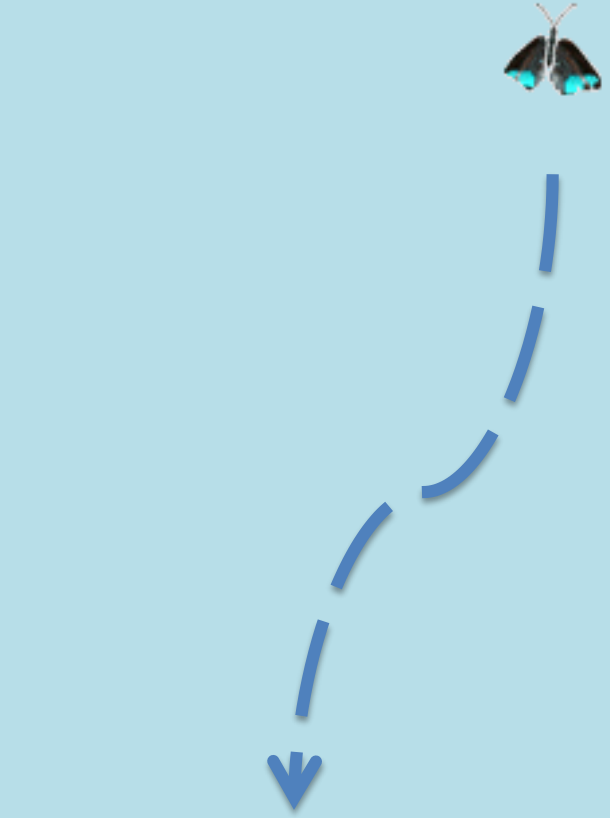
Prediction: Action of forecast

Prediction skill: Model (or human) capability of making forecast

Predictability: Characteristics of Nature – How fast two states of the system would departure from each other in time

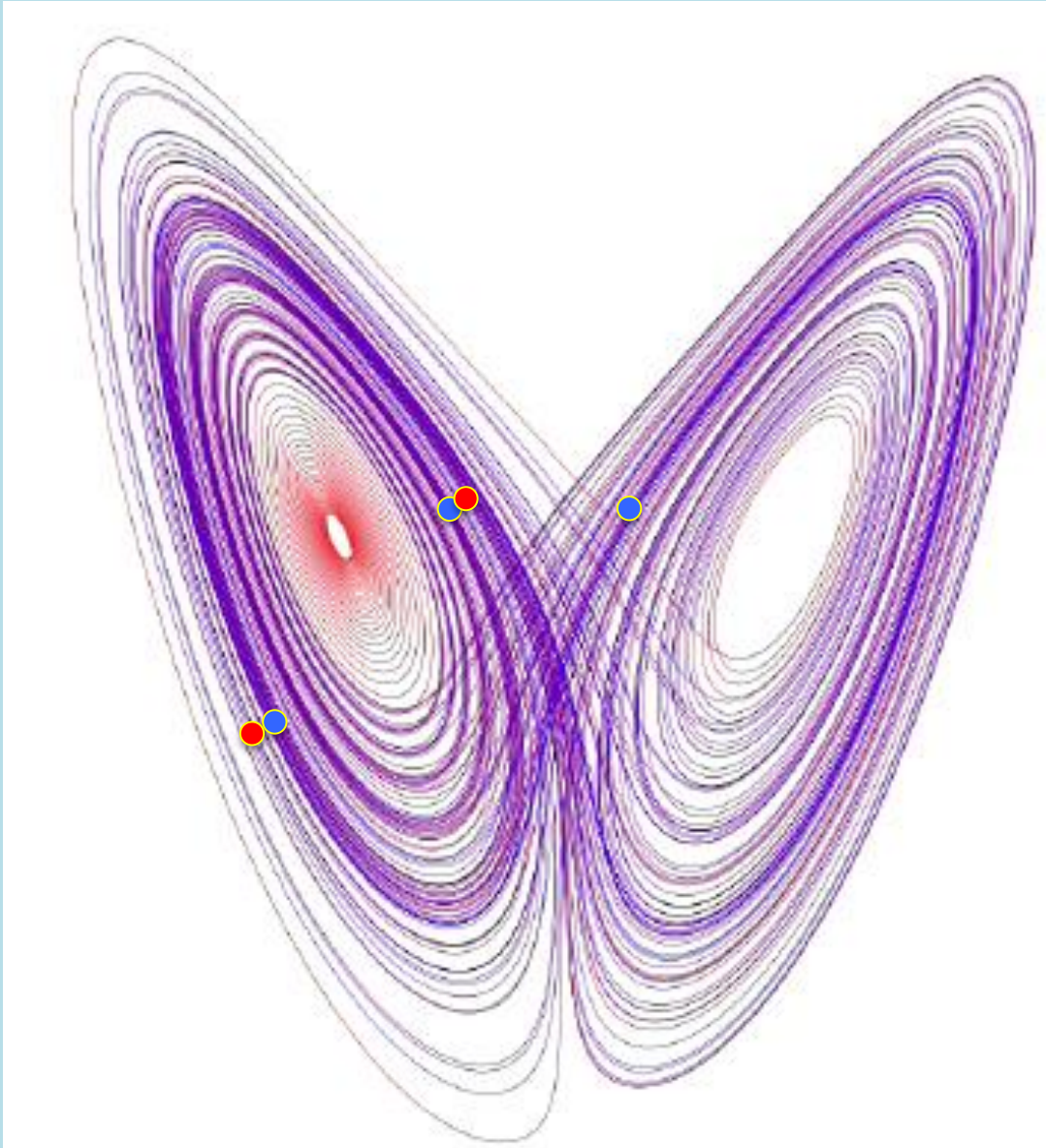
Estimate of Predictability: How a model may reproduce its own forecast or simulation of the system

Predictability:
- Butterfly Effect

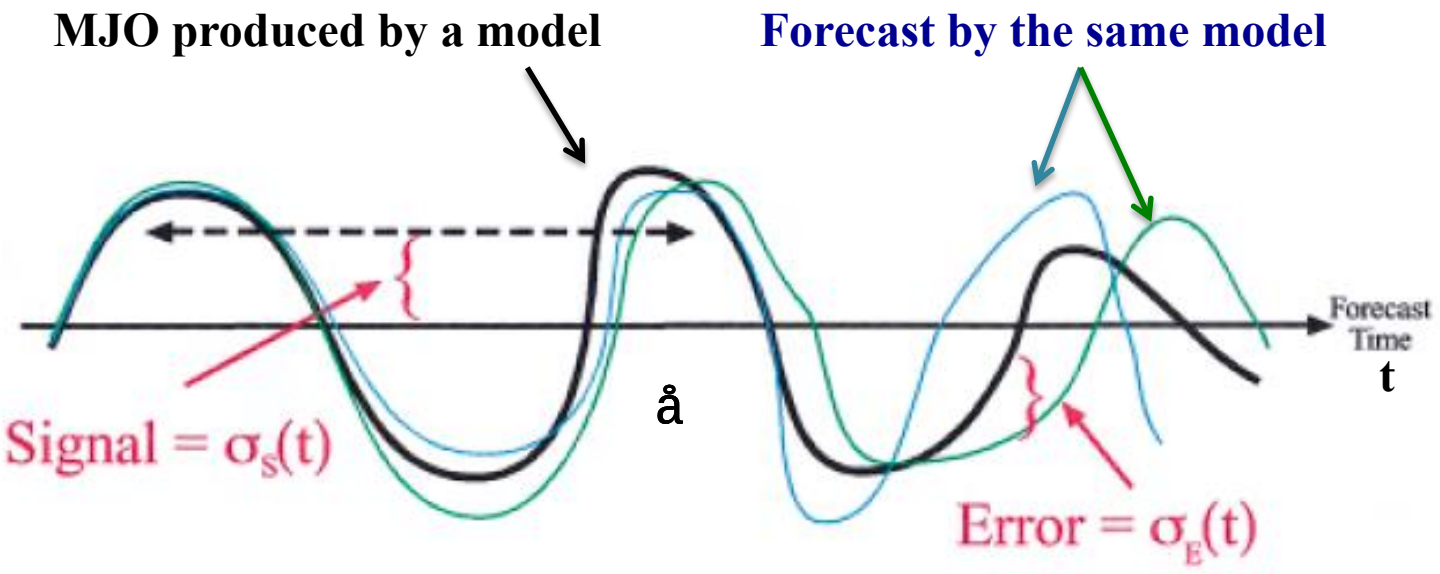


Predictability (Edward Lorenz):

- **Butterfly Effect**
- **Chaos Theory**



Estimating Predictability: Forecast a "perfect" simulation by the same model



Prediction skill: $\overline{\sigma_E^2}(t) < \overline{\sigma_S^2}(t)$

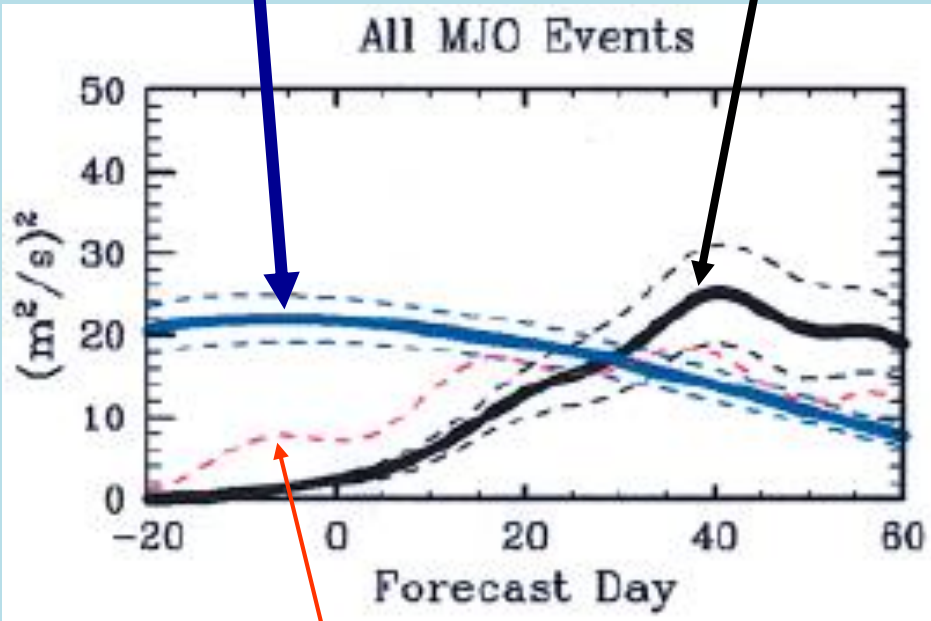
Predictability: $\overline{\sigma_E^2}(t_0) = \overline{\sigma_S^2}(t_0)$

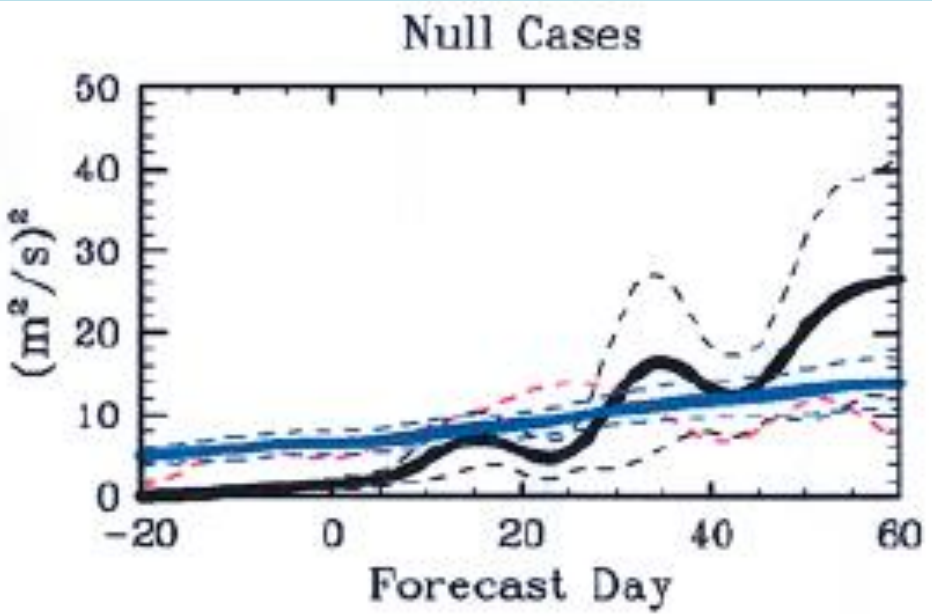
Waliser et al. (2003)

Estimating Predictability

MJO signal

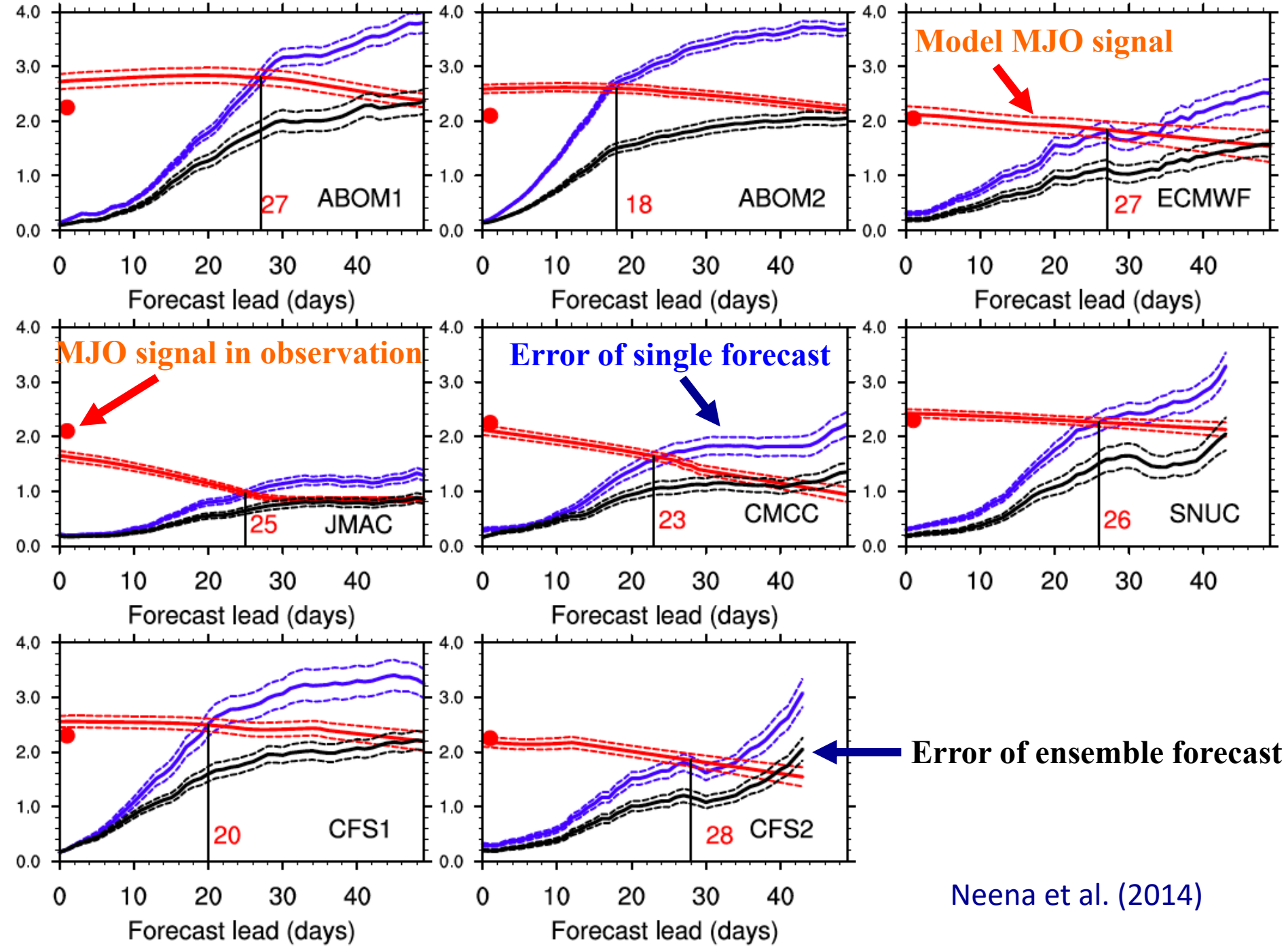
Mean forecast error





Persistent forecast error

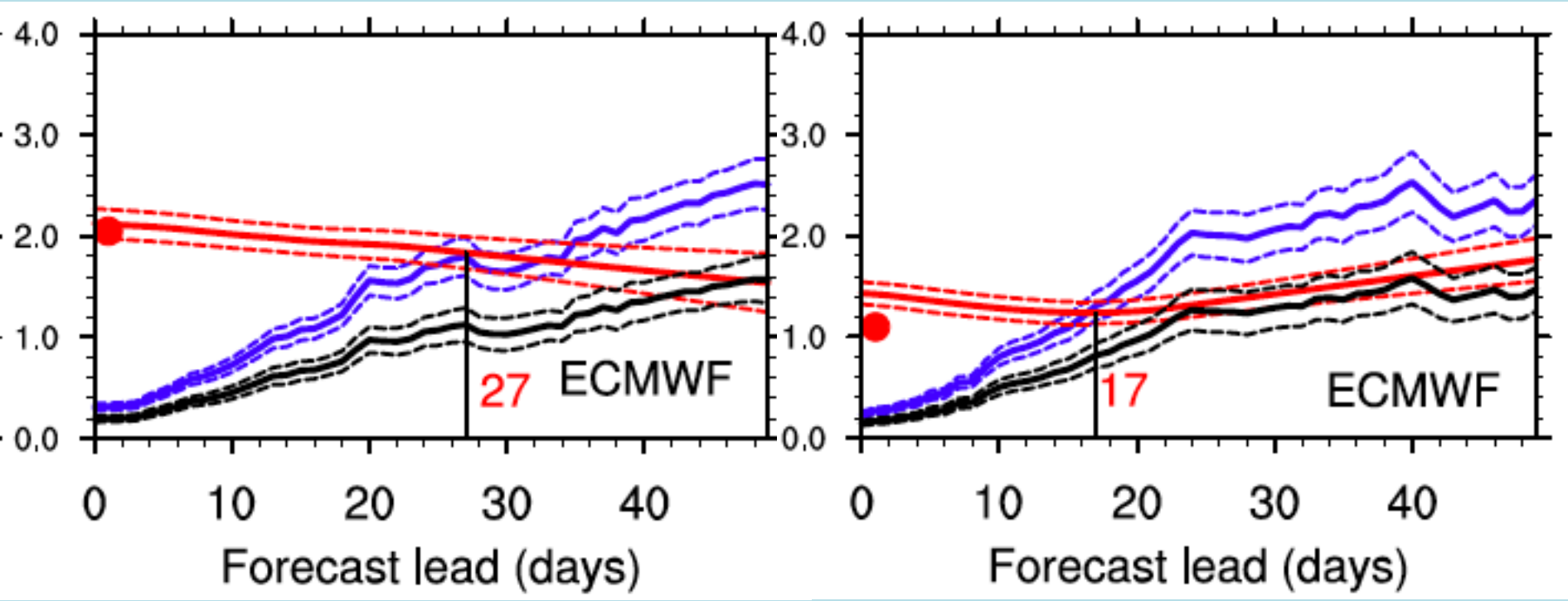
Waliser et al. (2003)



Neena et al. (2014)

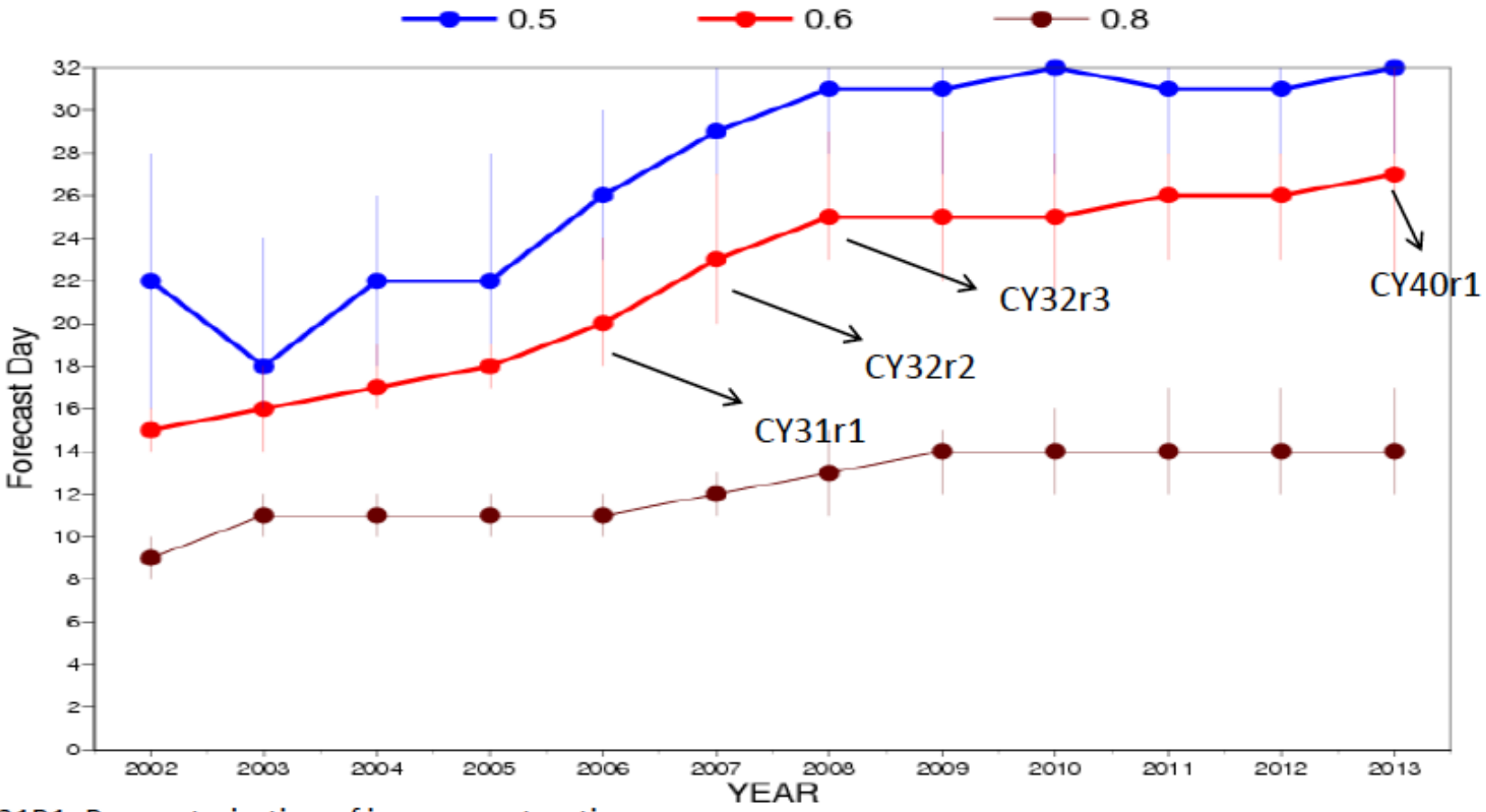
Strong MJO

Weak MJO



Neena et al. (2014)

MJO prediction skill: ECMWF

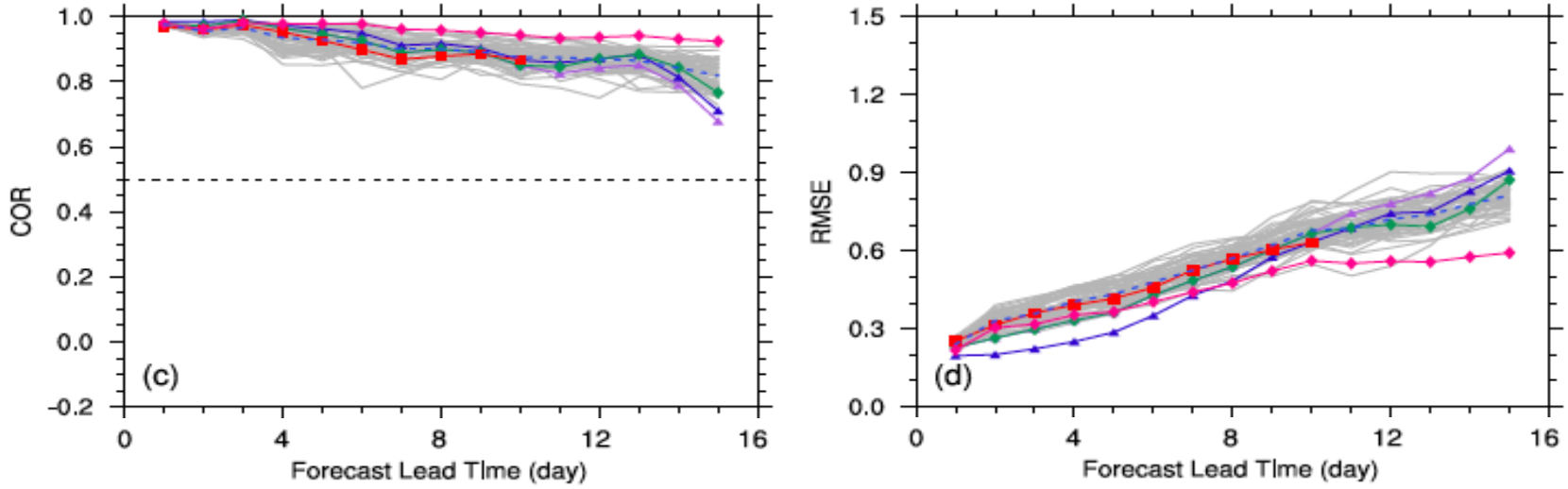


CY31R1: Parameterisation of ice supersaturation
CY32R2: McRAD (radiation scheme)
CY32R3: Changes in convective scheme (Bechtold at al. 2008)
CY40R1: Improved diurnal cycle of precipitation ...

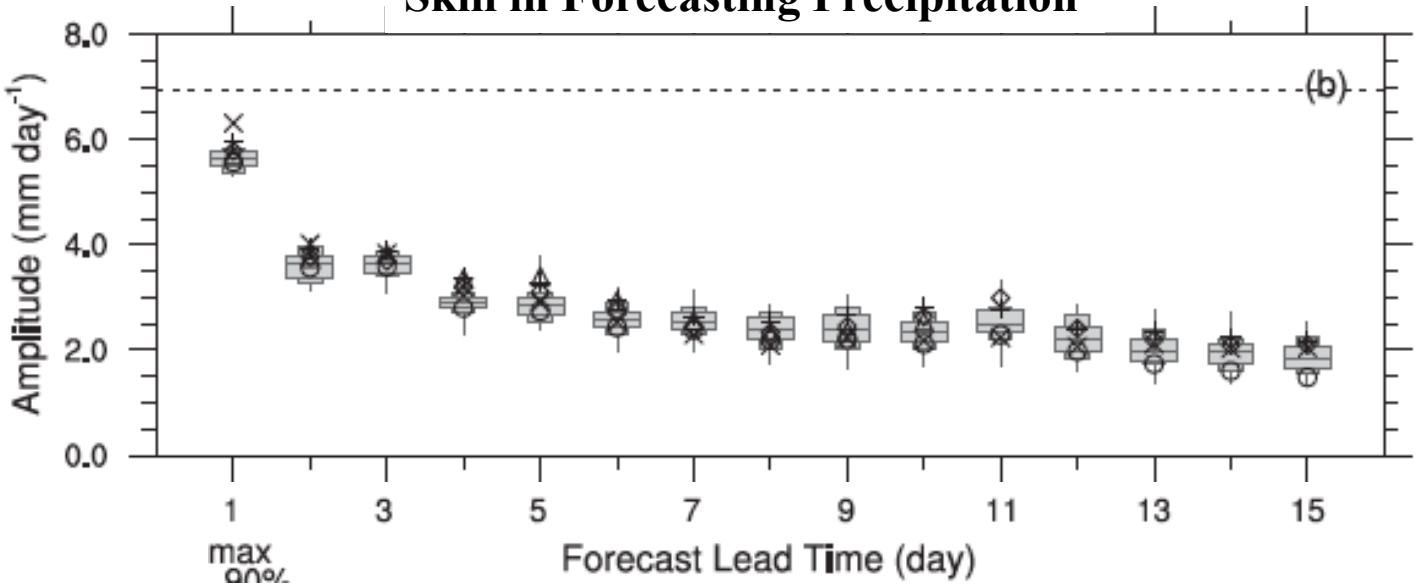
** Courtesy of F. Vitart and Hyemi Kim*

ECMWF Forecast of an MJO event over the Indian Ocean in November 2011

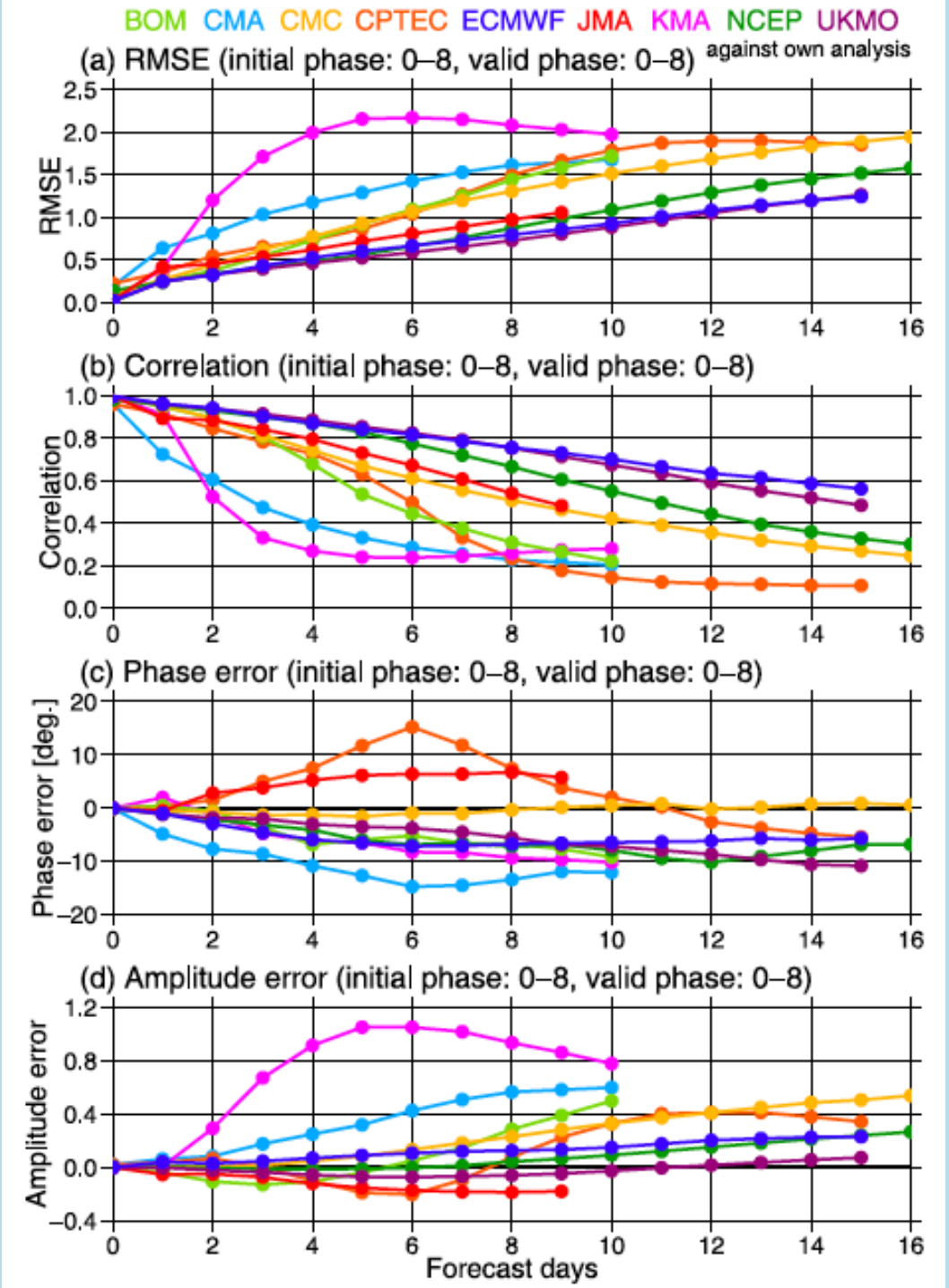
Skill in Forecasting Zonal Winds



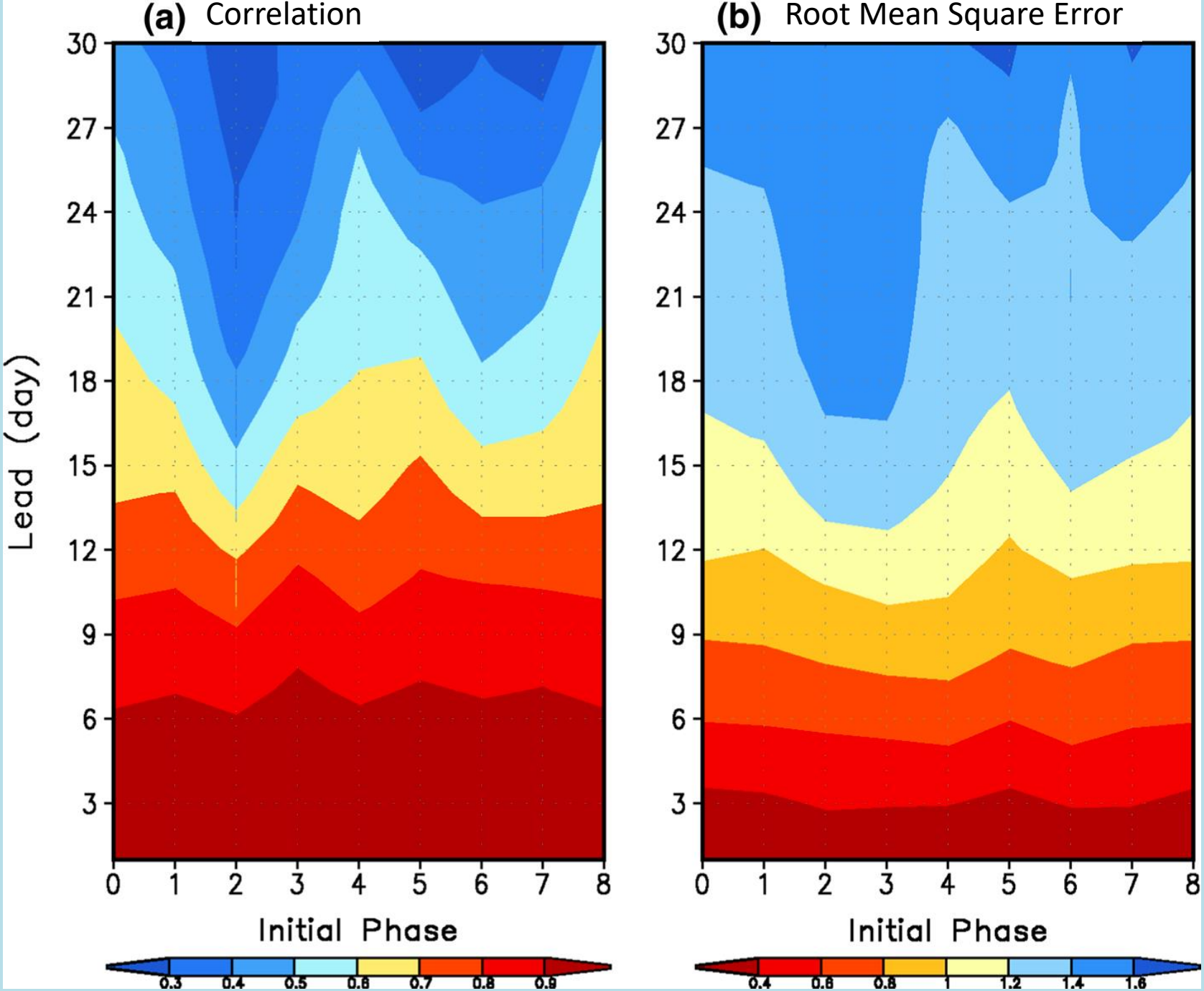
Skill in Forecasting Precipitation



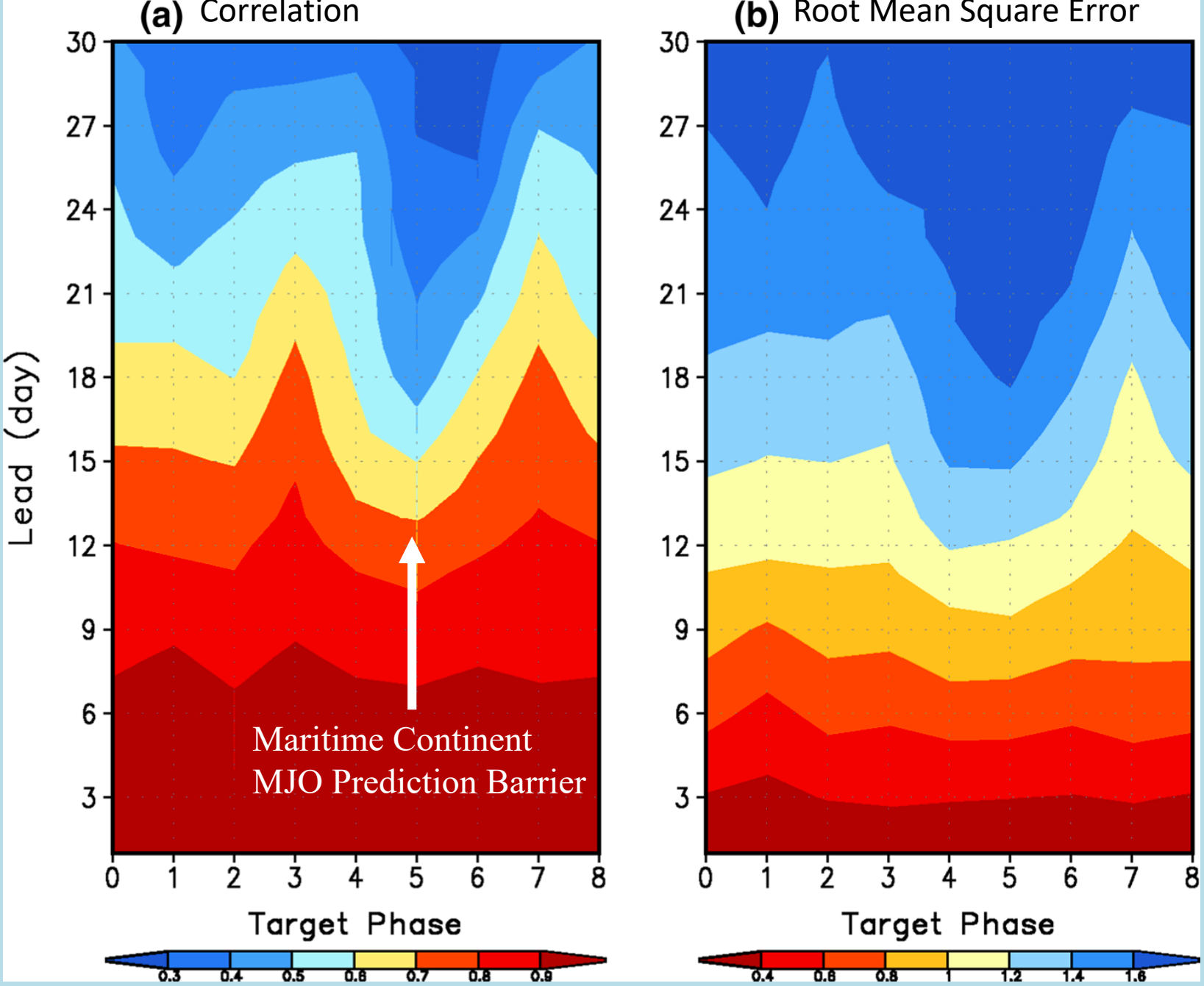
Ling et al. (2014)



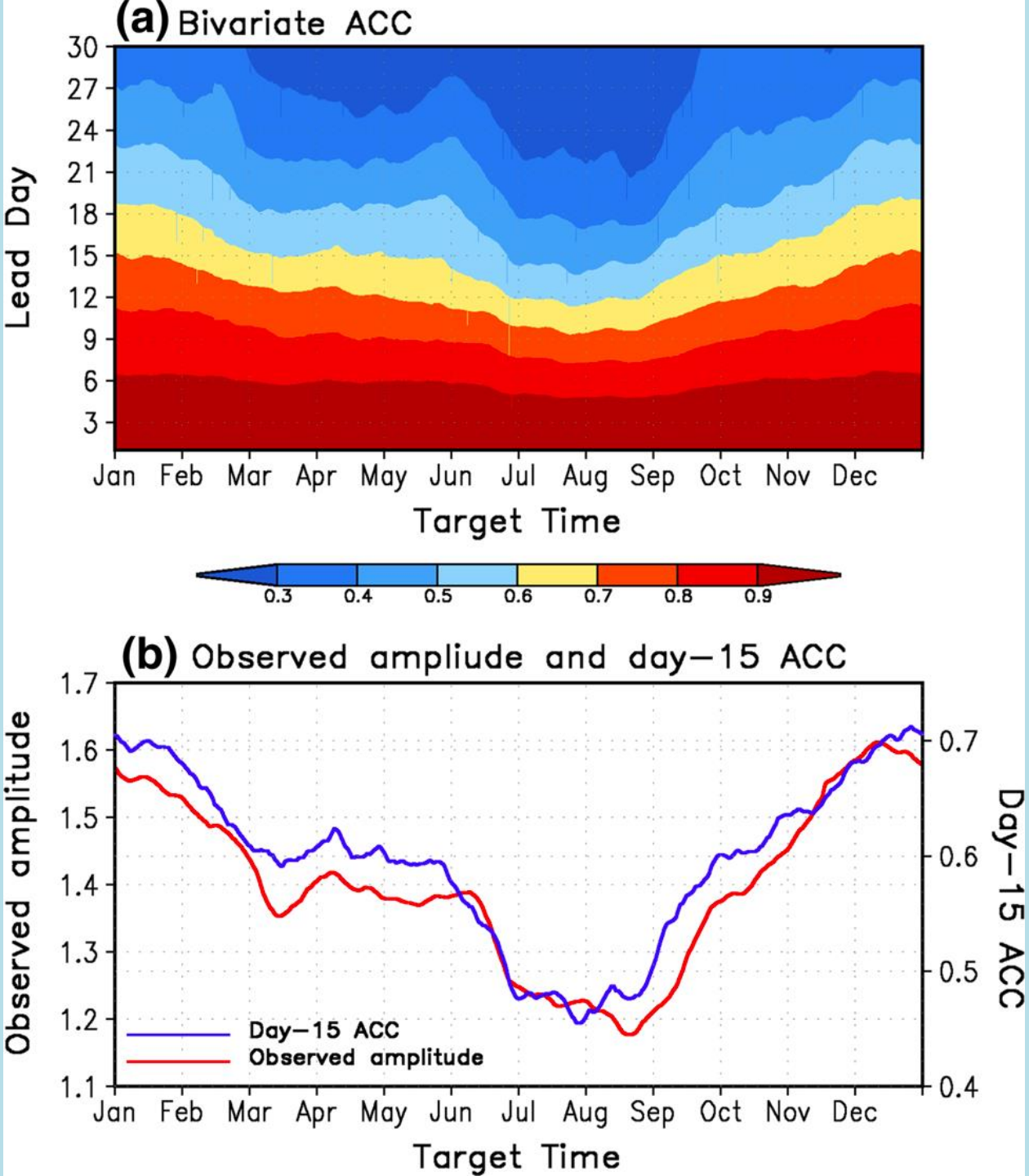
Matsueda and Endo (2011)



Wang et al. (2013)

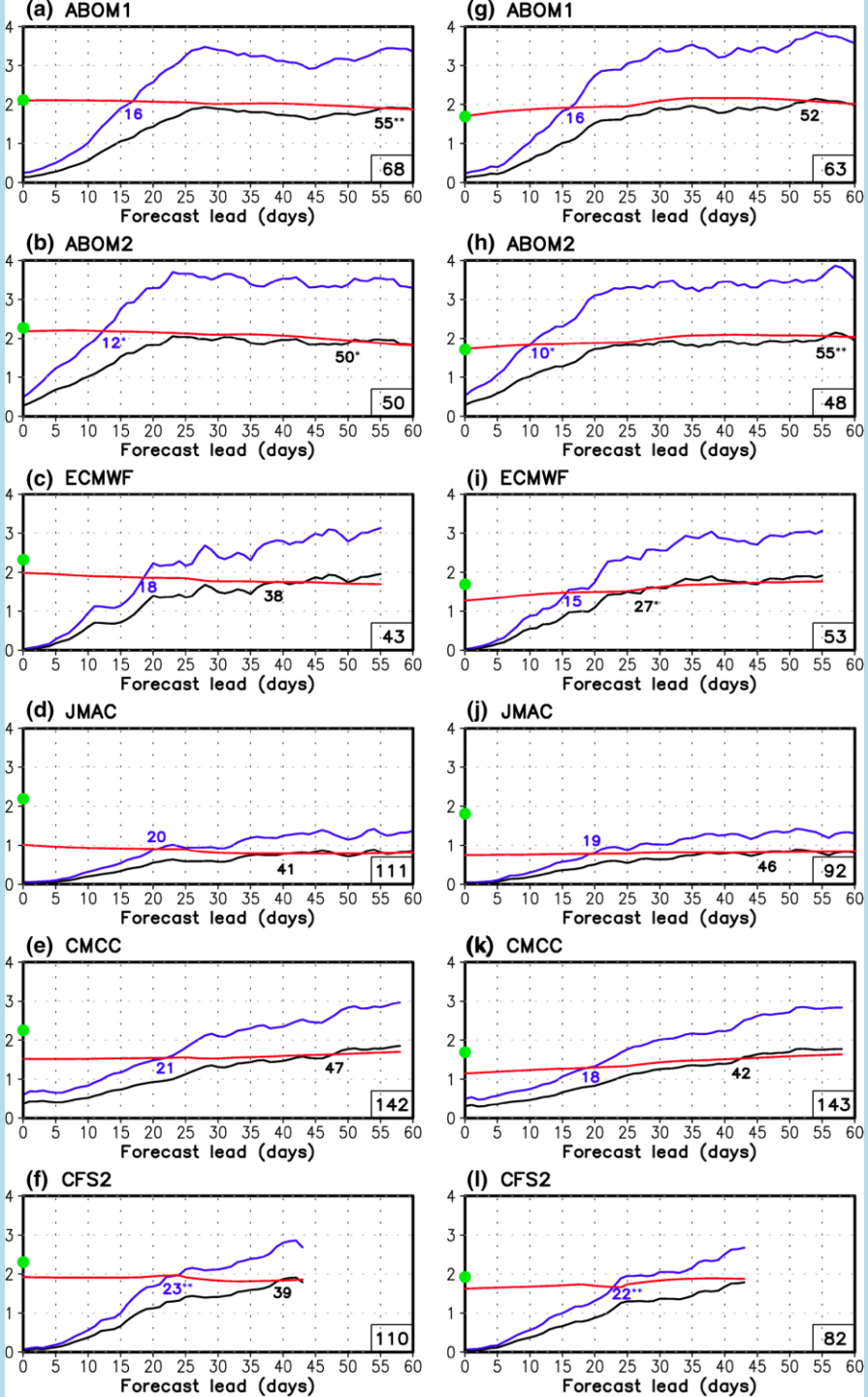


Wang et al. (2013)

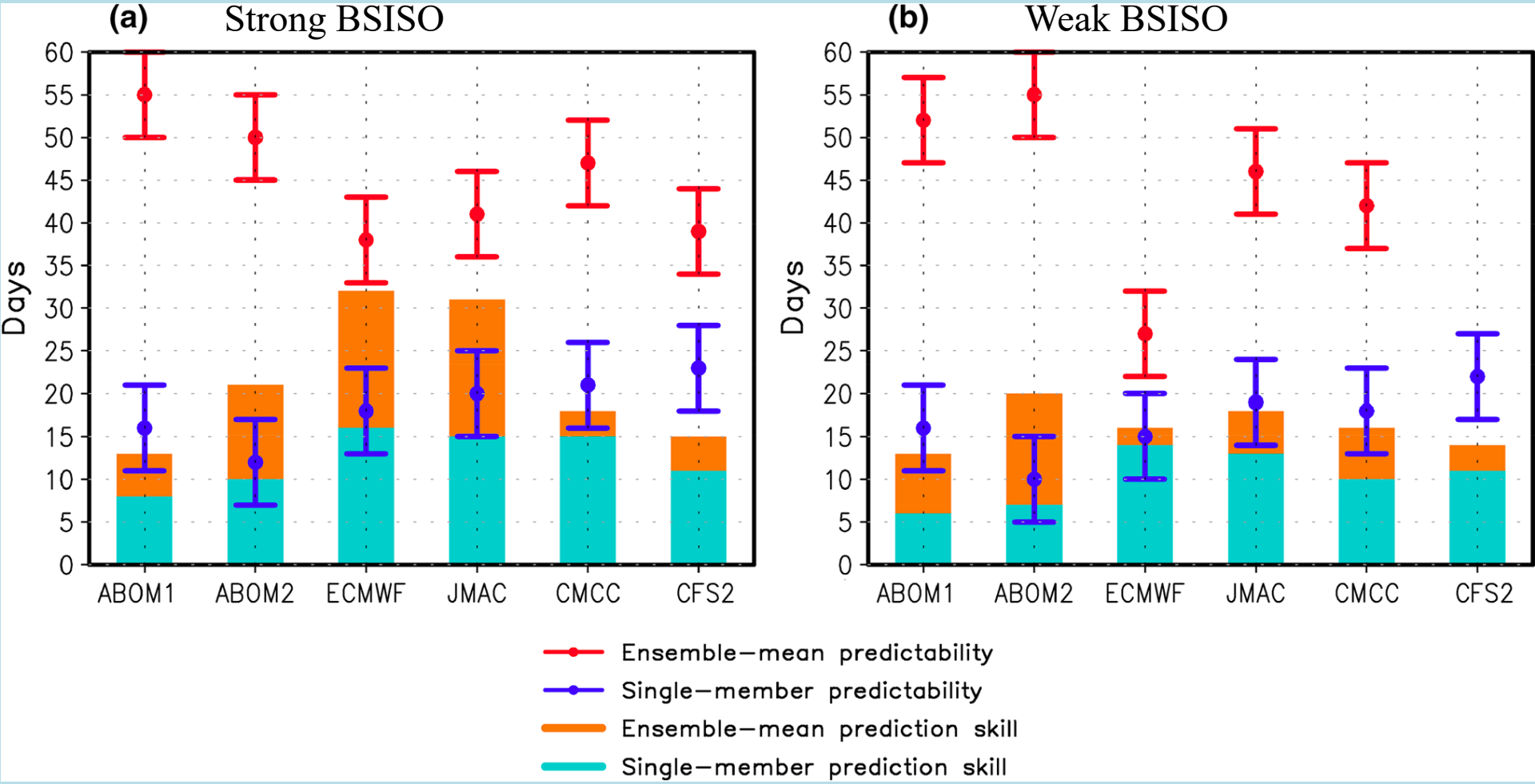


Wang et al. (2013)

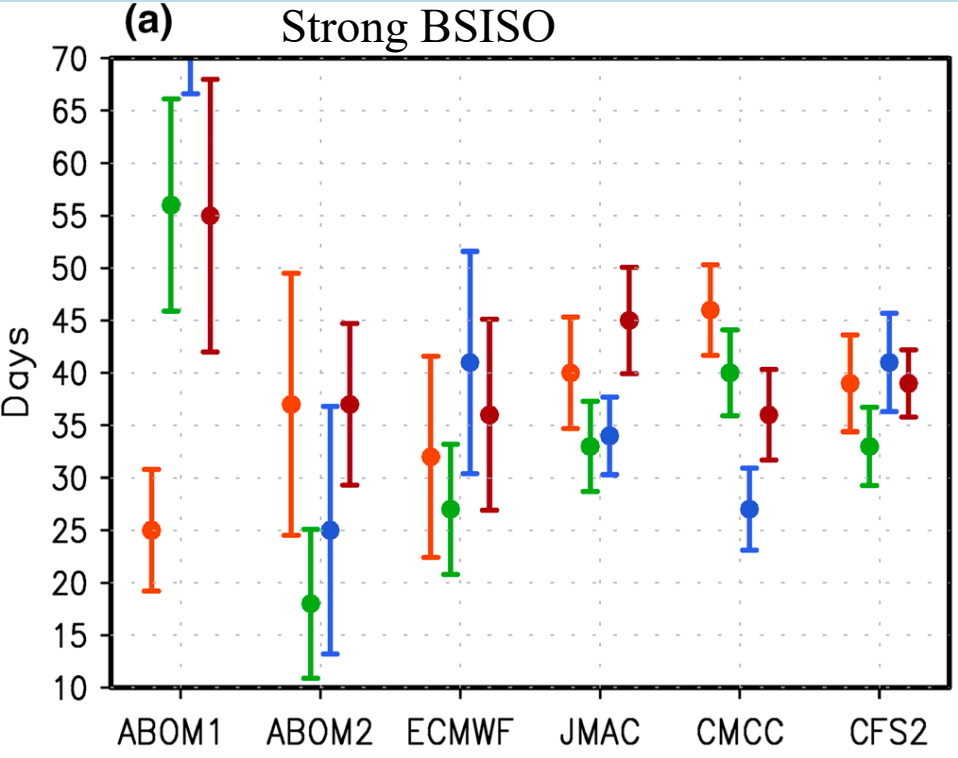
BSISO

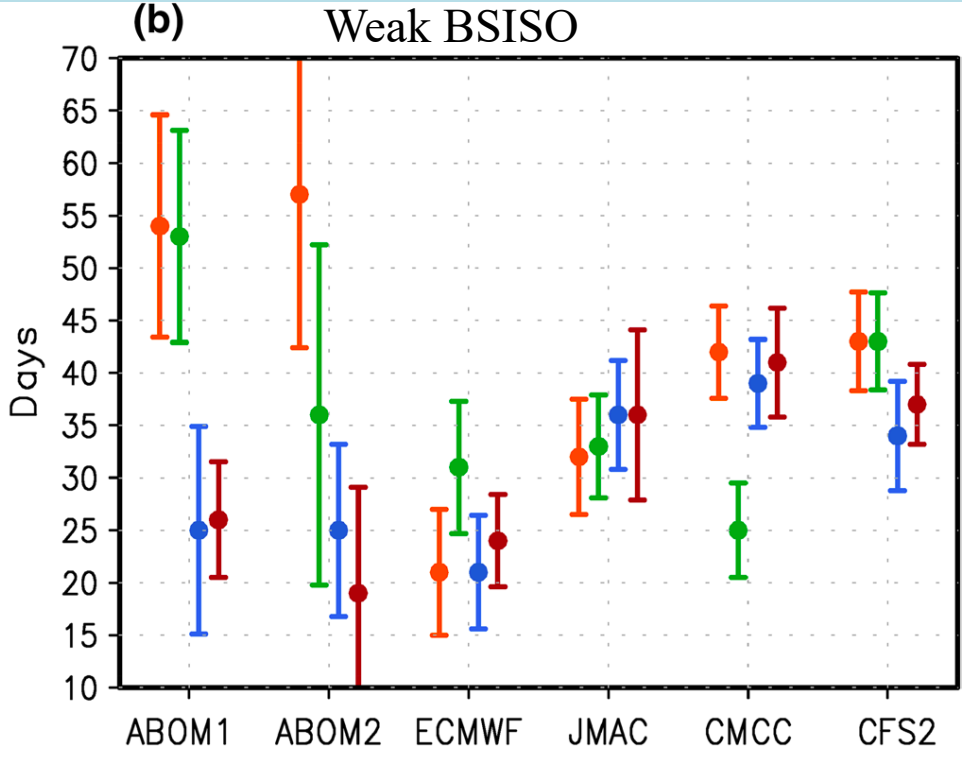


Lee et al. (2013)



Lee et al. (2013)





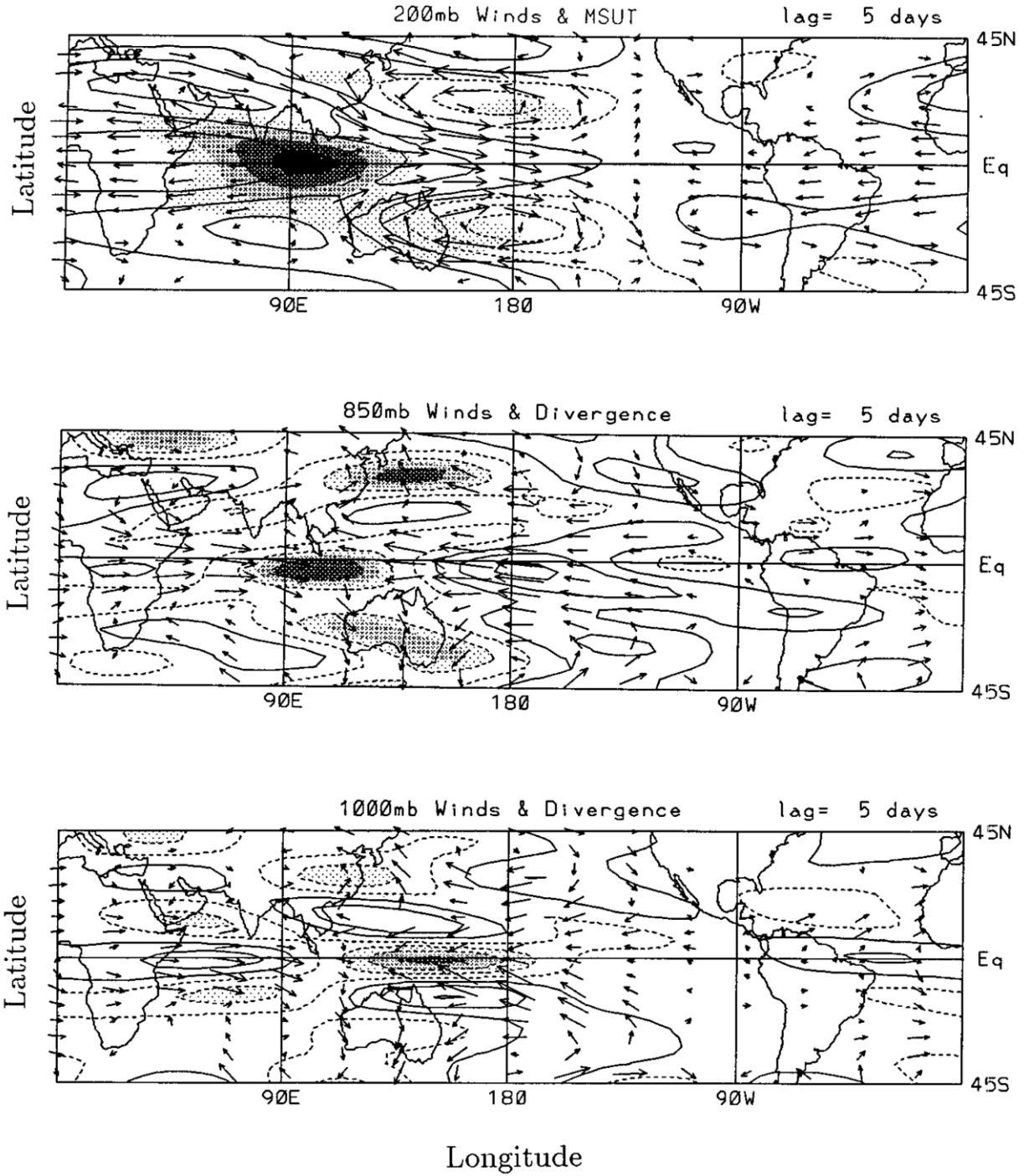
	P1&8	P2&3	P4&5	P6&7
ABOM1	17	26	16	9
ABOM2	14	19	9	8
ECMWF	11	14	9	9
JMAC	29	24	28	30
CMCC	36	33	38	35
CFS2	25	32	22	31

PHASE 1&8
PHASE 2&3
PHASE 4&5
PHASE 6&7

	P1&8	P2&3	P4&5	P6&7
ABOM1	16	18	17	12
ABOM2	14	12	13	9
ECMWF	13	15	14	11
JMAC	20	26	28	18
CMCC	38	33	42	30
CFS2	23	22	20	17

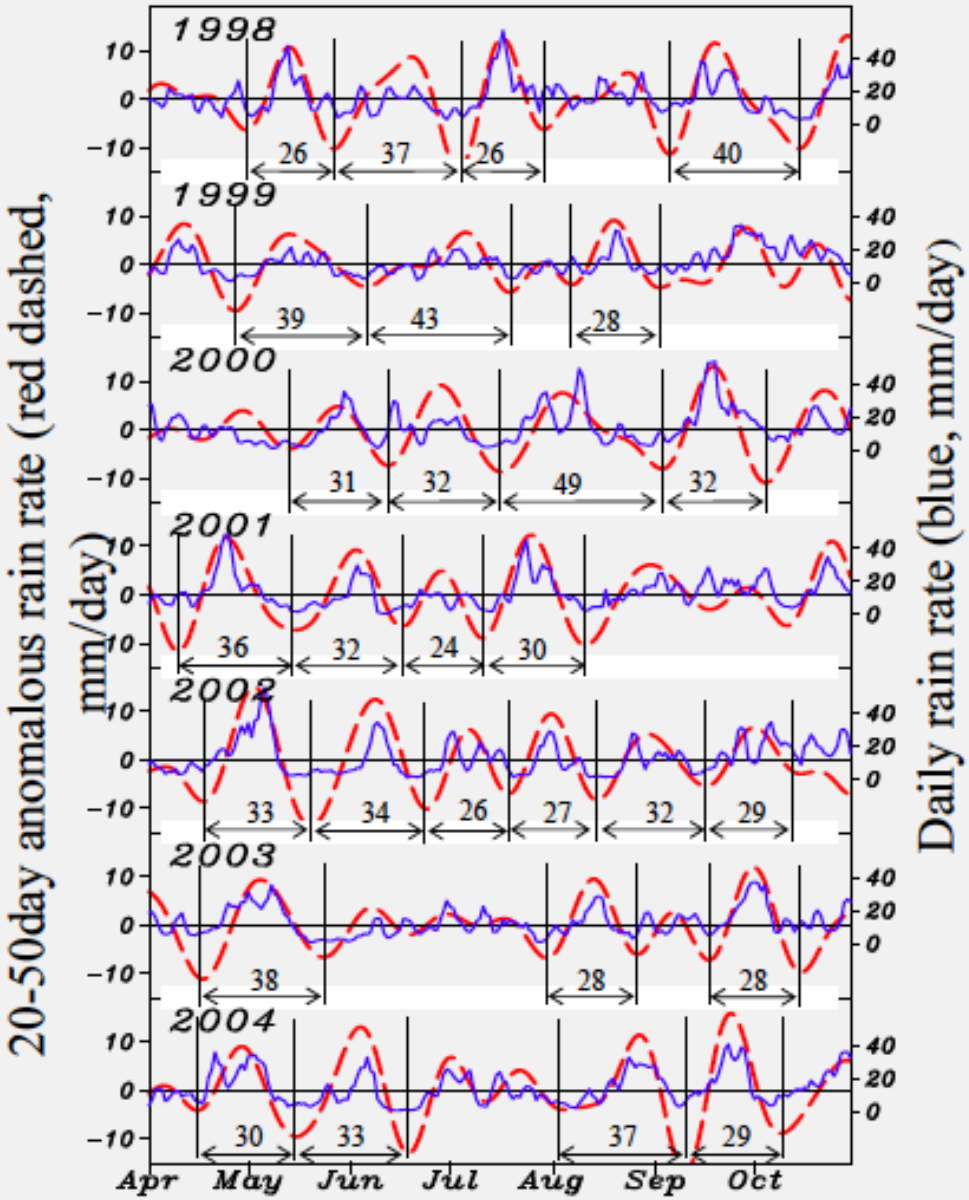
Prediction of the MJO/BSISO
Summary

1. **Predictability is a natural property, but its estimate depends on models.**
2. **Estimated predictability is higher for MJO (20-30 days) than BSISO (15-25 days).**
3. **Estimated prodictability and prediction skill depend on (a) metrics, (b) the season, and (c) MJO/BSISO conditions at the initial and target time; but the sensitivity varies among models.**
4. **Ensemble forecast skill is generally higher than single forecast.**
5. **Most global models cannot produce statistical signals of the MJO/BSIS**

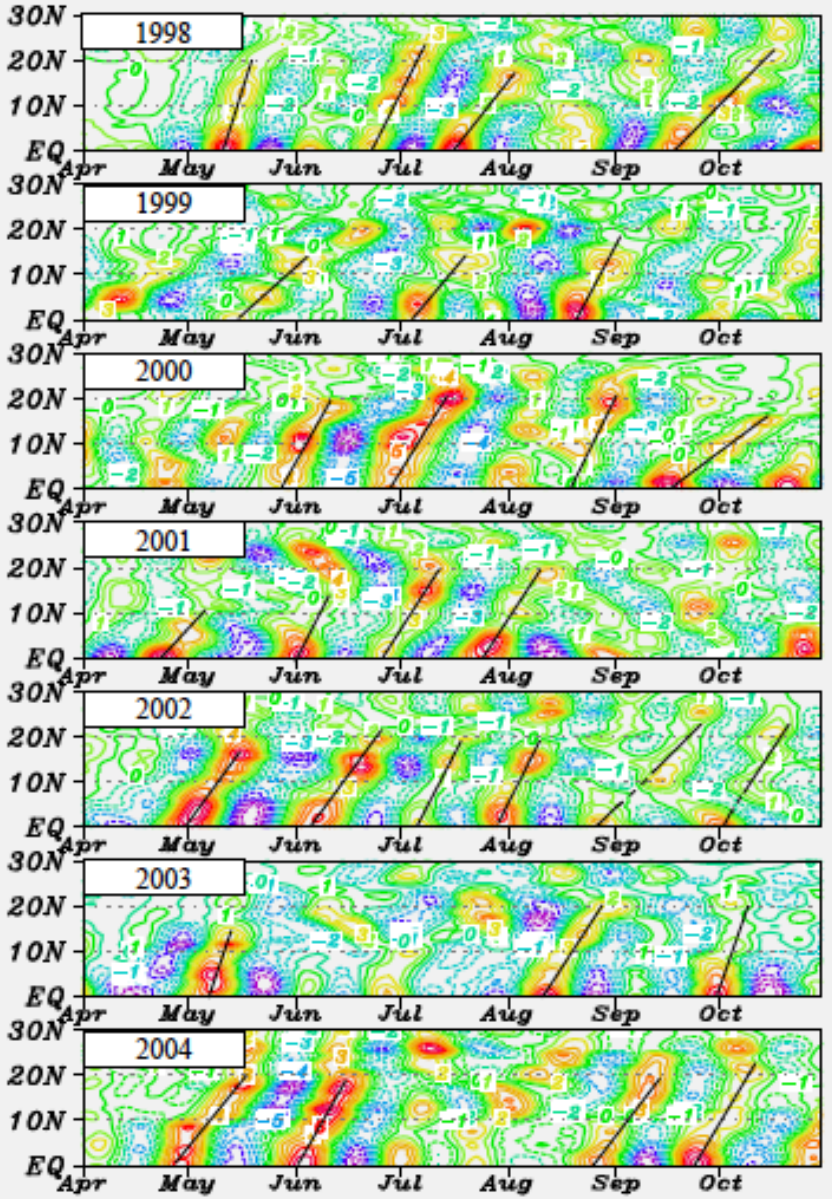


Hendon and Salby (1994)

Interannual Variability of BSISO



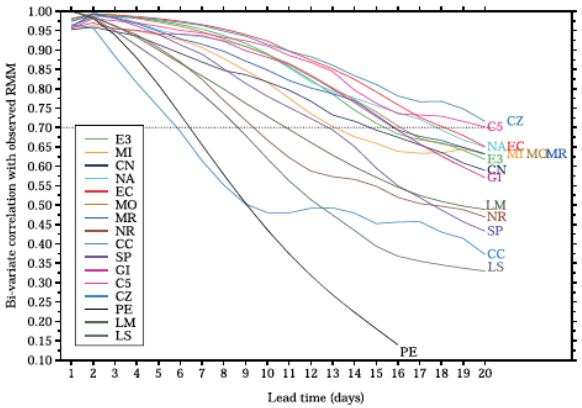
(a) TMI rain rate (75-100E,5S-5N)



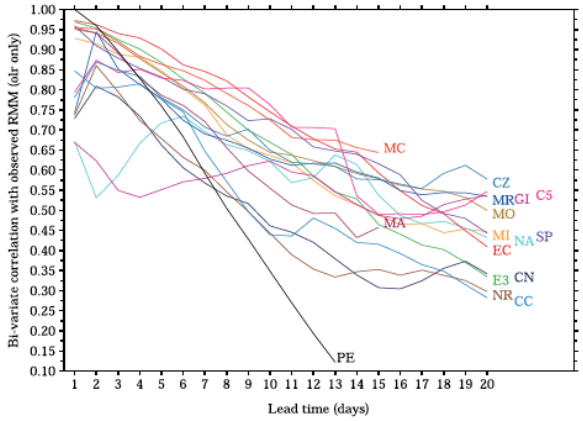
(b) 20-50day 3B42 rain rate (75-100E)

Wang et al. (2005)

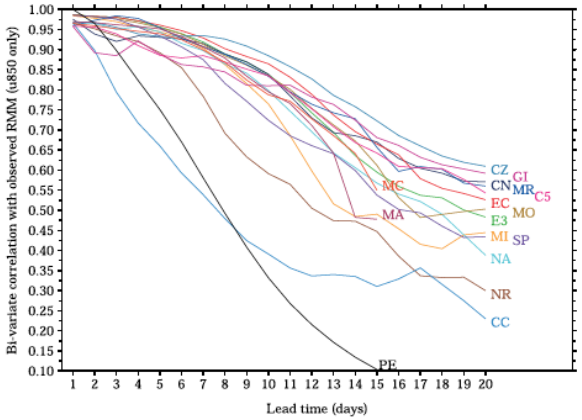
a. Bivariate correlation of total RMM1 and RMM2



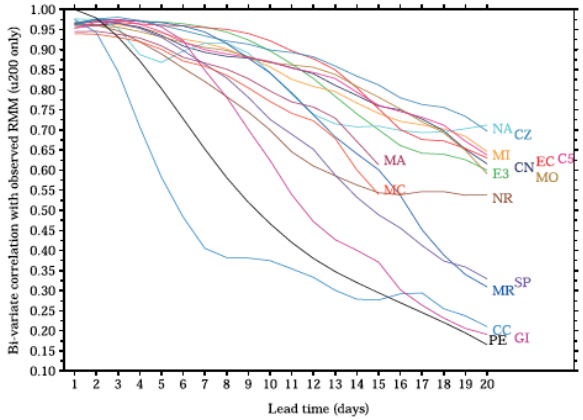
b. Bivariate correlation of OLR components only



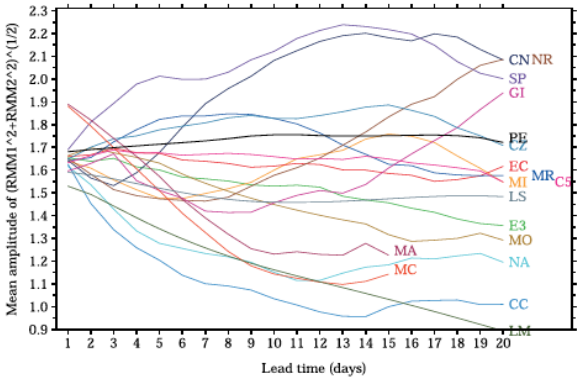
c. Bivariate correlation of U850 components only



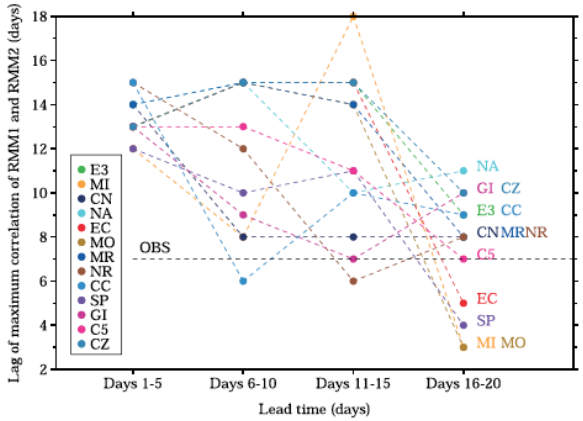
d. Bivariate correlation of U200 components only



e. RMM amplitude: $(RMM1^2 + RMM2^2)^{(\frac{1}{2})}$



f. Lag correlation of RMM1 and RMM2



Klingaman et al. (2015)