Coupled tropical-extratropical interactions, including globally unstable modes

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Acknowledgements: Jorgen Frederiksen

Advanced School and Workshop on Tropical-Extratropical Interactions on Intra-seasonal time scales

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Outlines

- Existing MJO models
- Three-dimensional instability theory of intraseasonal oscillations and convectively coupled equatorial waves
- Comparison of observations and theory

Historical Proposed Theoretical Models of the MJO

Mainly tropical signal

- Madden and Julian 1971 – “it cannot be a Kelvin wave”
- Parker 1973 – it’s a Kelvin wave
- Lindzen 1974; Lau & Peng 1987; Chang & Lim 1988 – a Kelvin wave sustained through wave-CISK
- Wang and Rui 1990; Salby et al. 1994 – a Kelvin-Rossby wave sustained through frictional wave-CISK
- Emanuel 1987; Neelin et al. 1987 – A Kelvin wave sustained through evaporation- wind feedback
- Ultraviolet catastrophe of these proposals
- Observations: Nishi 1989; Hsu 1996; Wheeler et al. 2000 – it’s not a Kelvin wave
- Theory: Frederiksen & Frederiksen 1993 – it’s not a Kelvin wave
- Skeleton model: Majda and Stechmann 2009 – multiscale interaction

Basis of Talk

- J.S. Frederiksen, 2002: Genesis of intraseasonal oscillations and equatorial waves. *J. Atmos. Sci.* **59**, 2761-2781.
- J.S. Frederiksen and H. Lin, 2013: Tropical-extratropical interactions of intraseasonal oscillations. *J. Atmos. Sci.* **70**, 3180-3197.

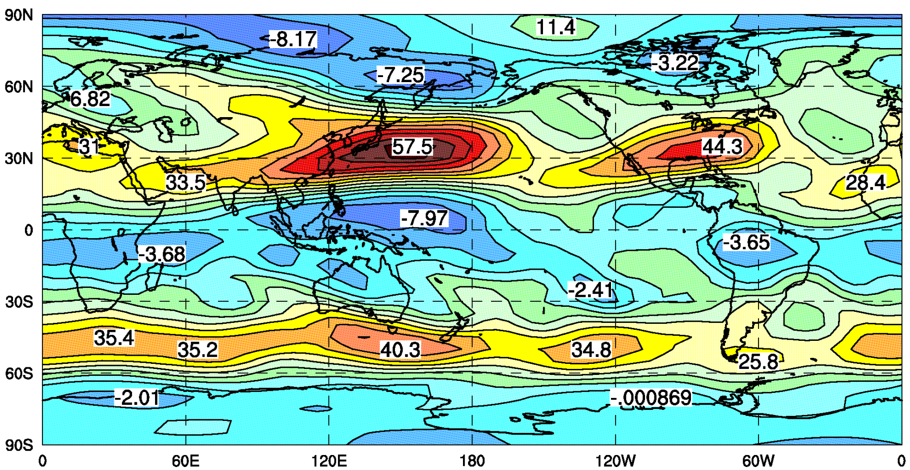
Theoretical Studies of Intraseasonal Oscillations

Frederiksen & Frederiksen 1993 JAS; 1997 CAP; Frederiksen 2002 JAS

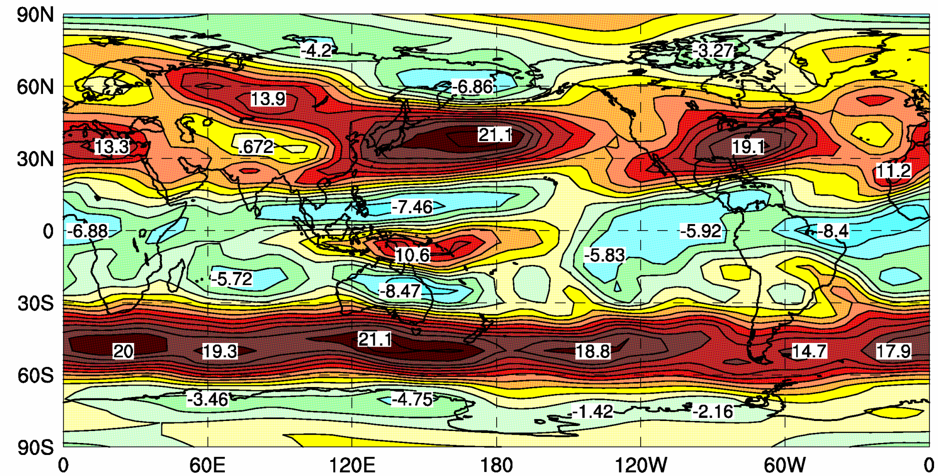
- Instability Theory of Intraseasonal Oscillations and Convectively Coupled Equatorial Waves
- Basic State for January 1979
- Instability Theory with Convection and Evaporation
- Frequency Spectra of Modes in Theory and Observations
- Properties of Theoretical ISOs broadly similar to Observed MJO
- It's a coupled tropical-extratropical mode sustained through moist baroclinic-barotropic instability
- Properties of Convectively Coupled Kelvin Waves, Equatorial Rossby Waves, Mixed Rossby Gravity Waves and Eastward Internal Gravity Waves similar to Observed Waves

January 1979 Basic State

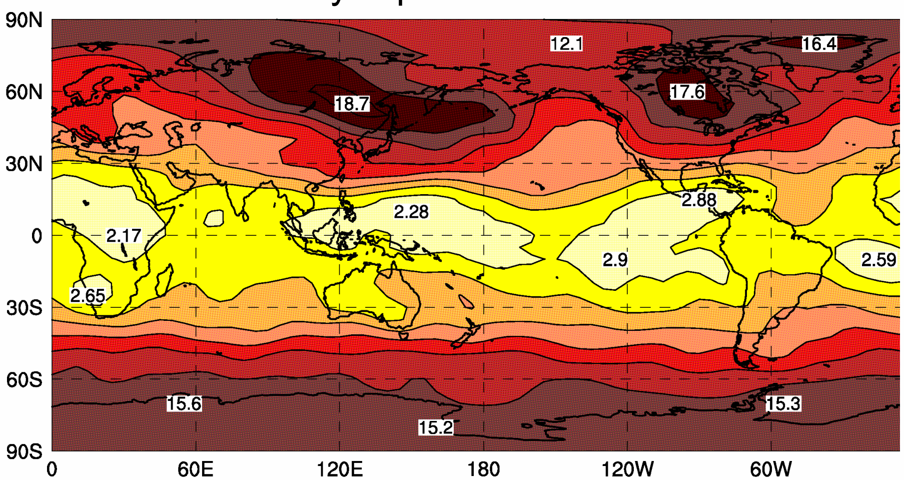
300 hPa zonal wind



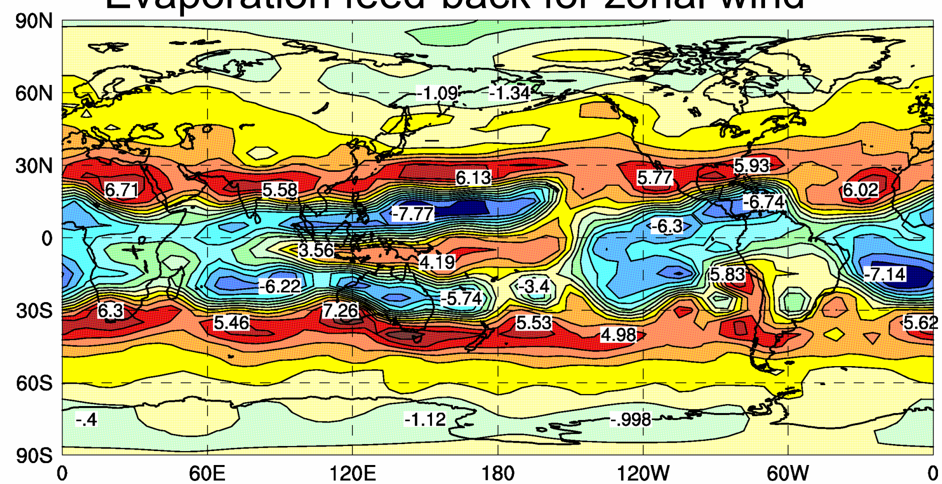
700 hPa zonal wind



Moist static stability is positive → stable to wave-cisk



Evaporation feed-back for zonal wind



Theoretical Studies of Intraseasonal Oscillations

Frederiksen & Frederiksen 1993 JAS; 1997 CAP; Frederiksen 2002 JAS

- Evaporation–wind feedback (EWF) parameterization in the primative equaiton
- Convection through a generalized Kuo-type parameterization
- Linearized about 1979 January monthly mean global fields
- Solve eigenvalue–eigenvector problem (with a 2480 × 2480 matrix) for 3D basic state

Theoretical Studies of Intraseasonal Oscillations

Frederiksen & Frederiksen 1993 JAS; 1997 CAP; Frederiksen 2002 JAS

		DISS				EVAP				MOISTA				DRY		
Class	$\lvert m^* \rvert = 1$	Mode	T_r^d (days)	τ_i^d (days)	A_c	Mode	T_r^d (days)	τ_i^d (days)	A_c	Mode	T_r^d (days)	τ_i^d (days)	A_c	Mode	T_r^d (days)	τ_i^d (days)
MJO	1	13	32.4	17.9	0.5082	66	34.4	8.18	0.6782	58	28.2	8.73	0.8531	46	28.2	11.7
									0.5669	91	48.3	15.2	0.5312	50	62.1	12.5
K	2	22	14.4	30.3	0.6044	97	14.2	12.9	0.3262	204	17.7	−27.0	0.2194	181	10.6	−24.0
EIG	4	29	2.84	87.5	0.9777	130	2.84	23.0	0.9414	243	2.87	−17.4	0.7769	208	2.13	−19.2
MRG	5	33	3.43	149	0.9404	142	3.42	31.8	0.8699	284	3.48	−14.6	0.7988	245	2.74	−16.5

Frequency Spectra for Equatorial Waves: Theory

Frederiksen 2002 J. Atmos. Sci.

Solid symbols for 3D basic state

Open Symbols for ZA basic state

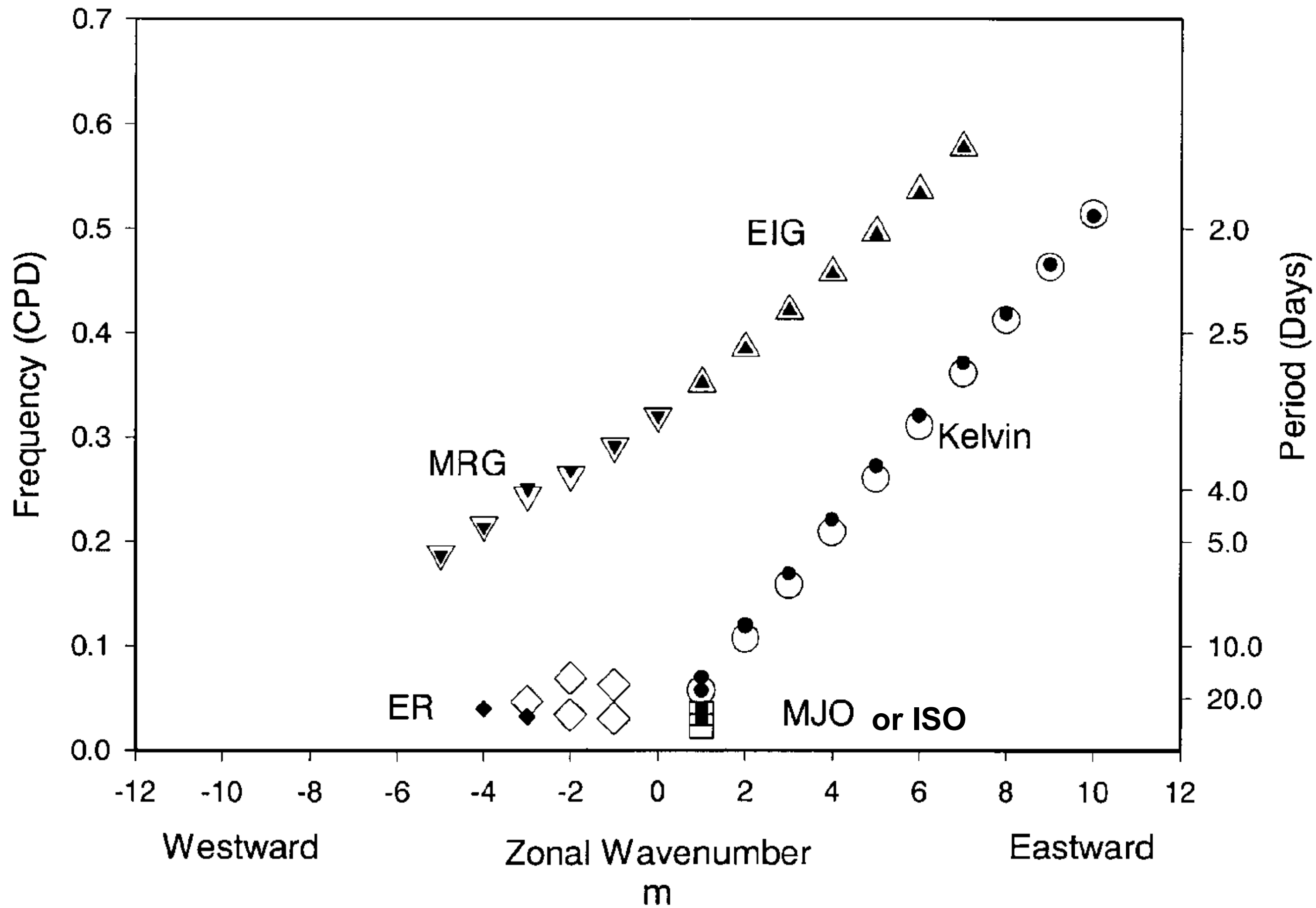
ISO/MJO is distinct from Kelvin waves even at zonal wavenumber 1

ISO/MJO has longer period than Kelvin waves

MJO is inconsistent with Kelvin wave (Hsu, 1996 J. Clim.; Wheeler, Kiladis & Webster 2000 JAS)

m for ZA and m* for 3D Basic States

m* is dominant wavenumber based on velocity potential

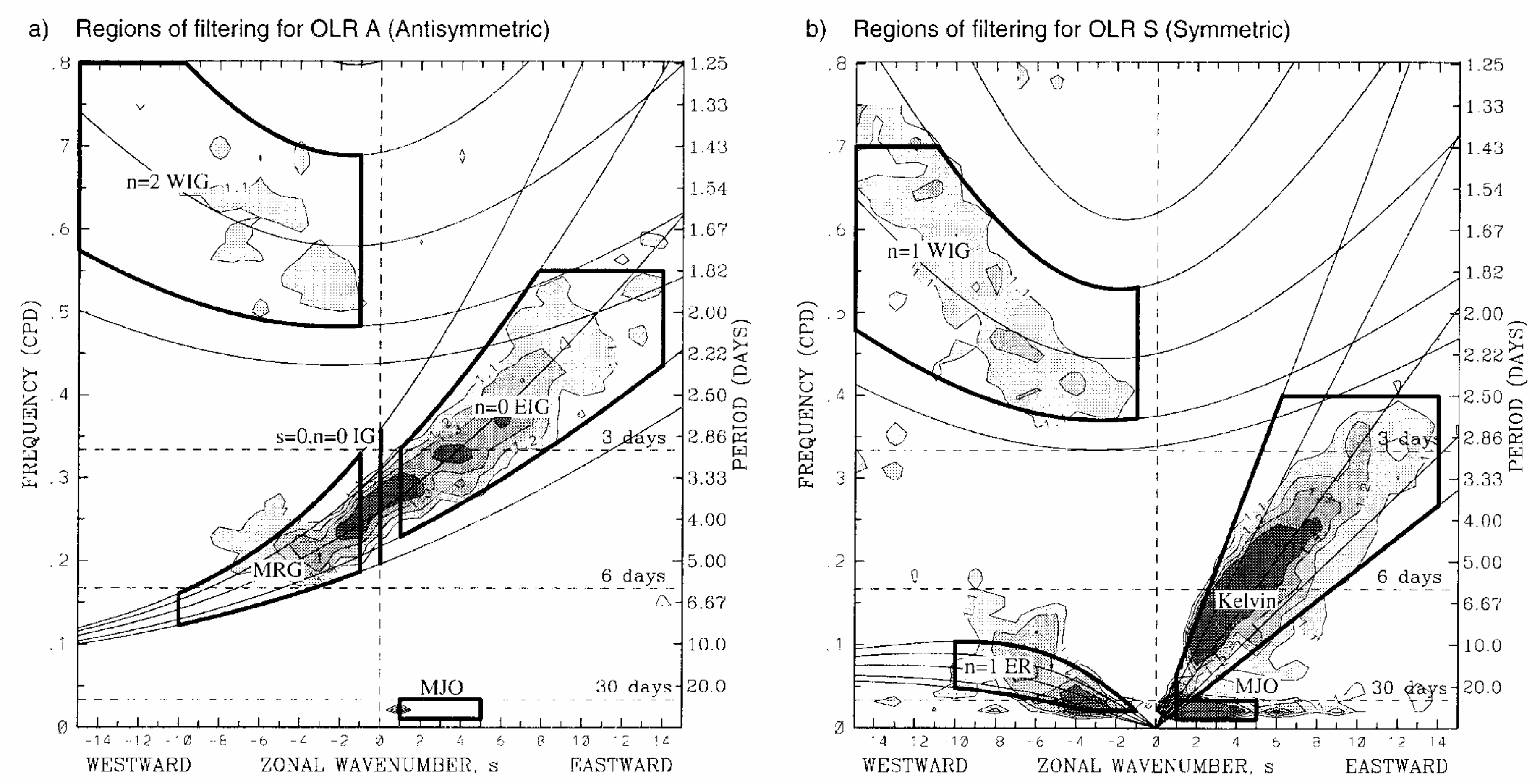


Frequency Power Spectra from Observations

Wheeler, Kiladis and Webster 2000 JAS:

MJO is distinct from Kelvin waves even at zonal wavenumber = 1

MJO has longer period than Kelvin waves

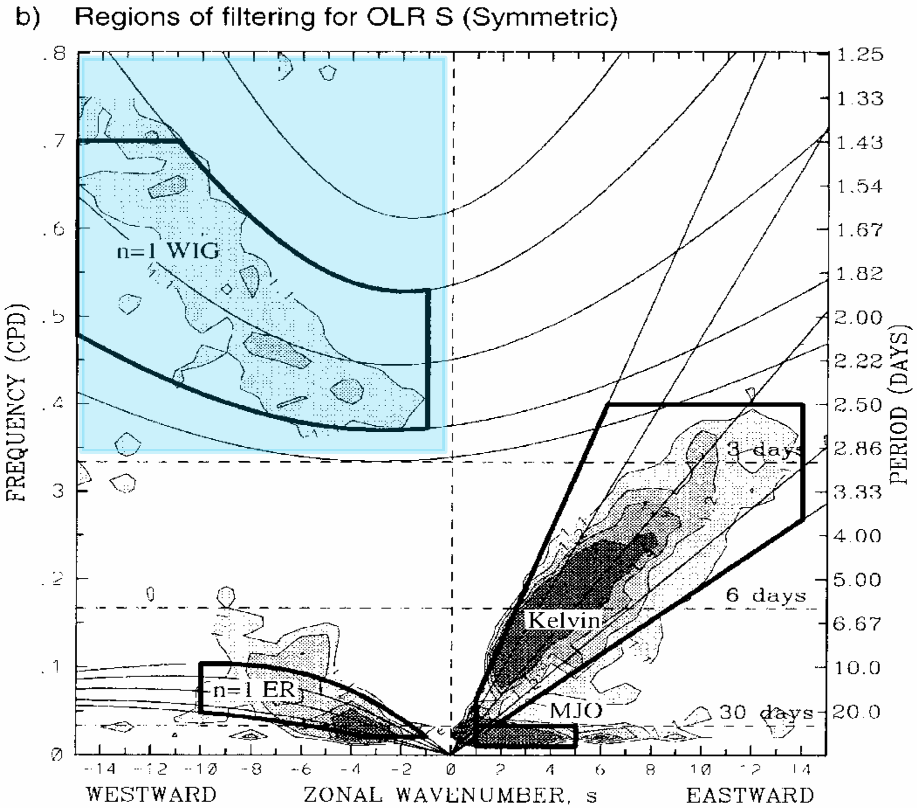


Frequency Spectra from Observations & Theory

MJO/ISO is distinct from Kelvin waves even at zonal wavenumber = 1

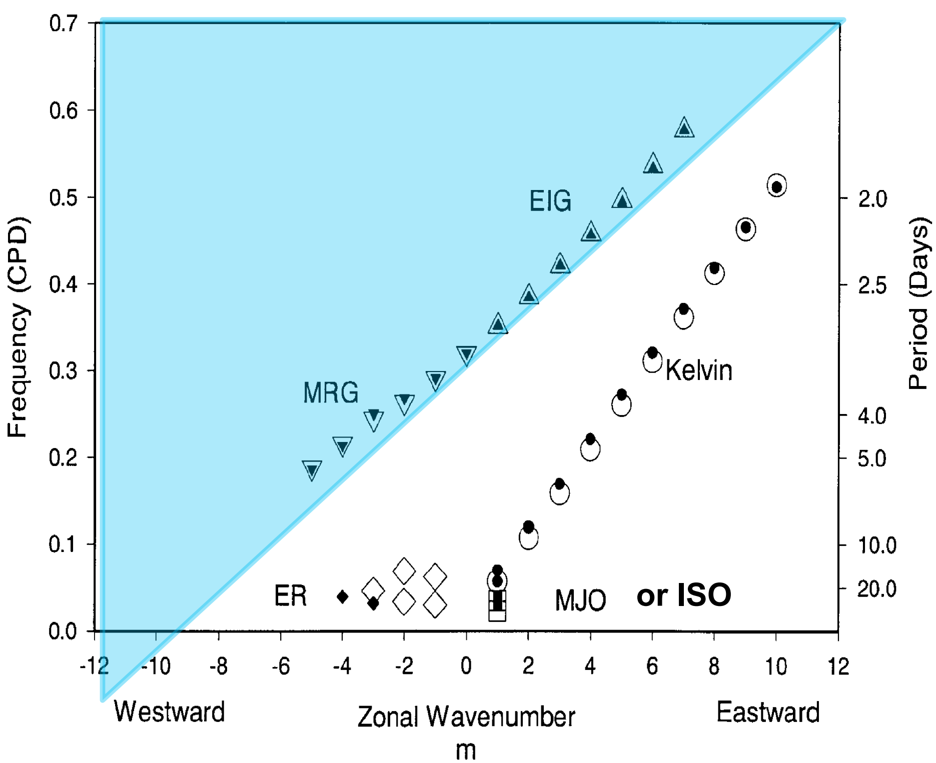
MJO/ISO has longer period than Kelvin waves

Spectra of Power



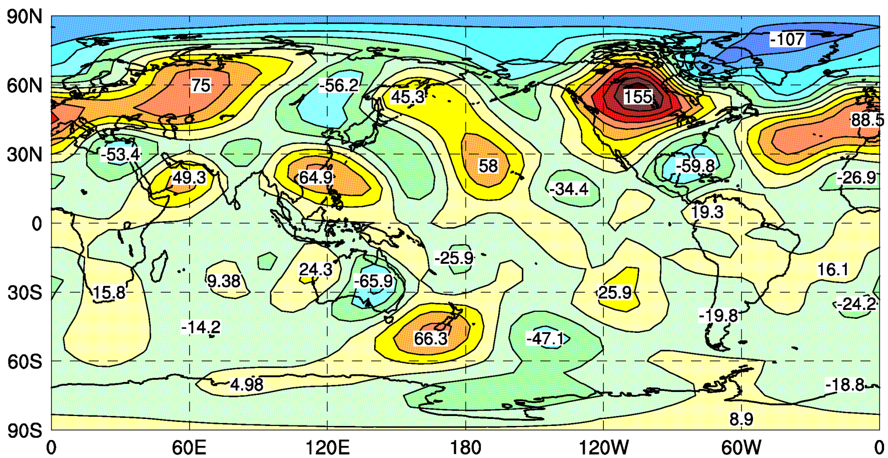
Spectra of Dominant Wavenumber

m for ZA and m* for 3D Basic States

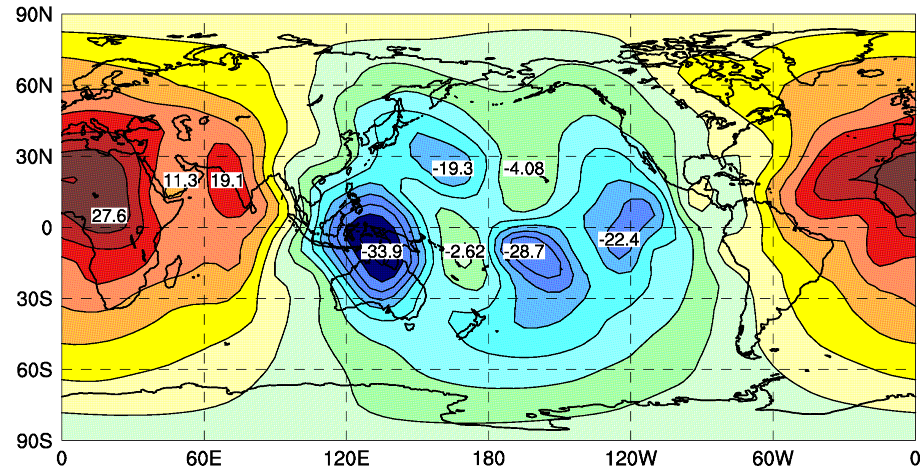


Leading Intraseasonal Oscillation: Theory

a



b



3D Basic State

(a): 500 hPa Streamfunction

(b): 300 hPa Velocity Potential

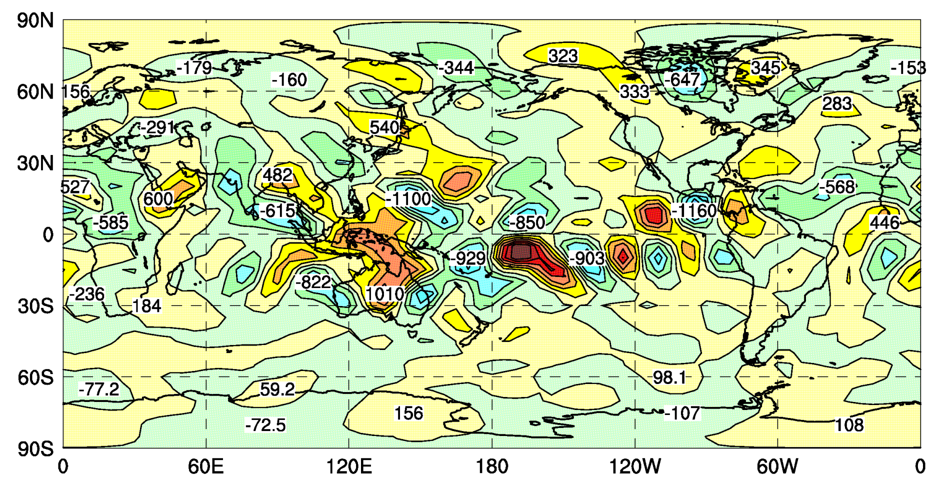
(d): 300 hPa Divergence

Theoretical ISO is FASTEST GROWING

|m*|=1 Mode for ALL Basic States

Period = 34.4 days

d



EVAP

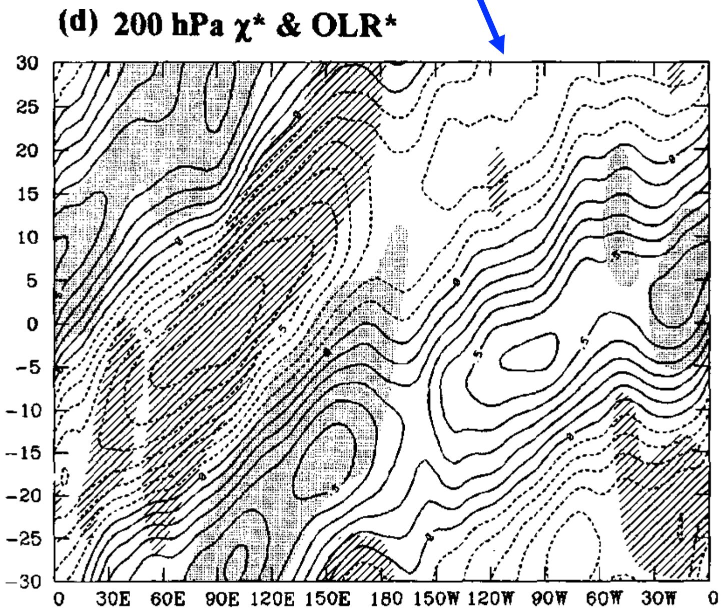
Non-dimensional as in Frederiksen 2002 JAS

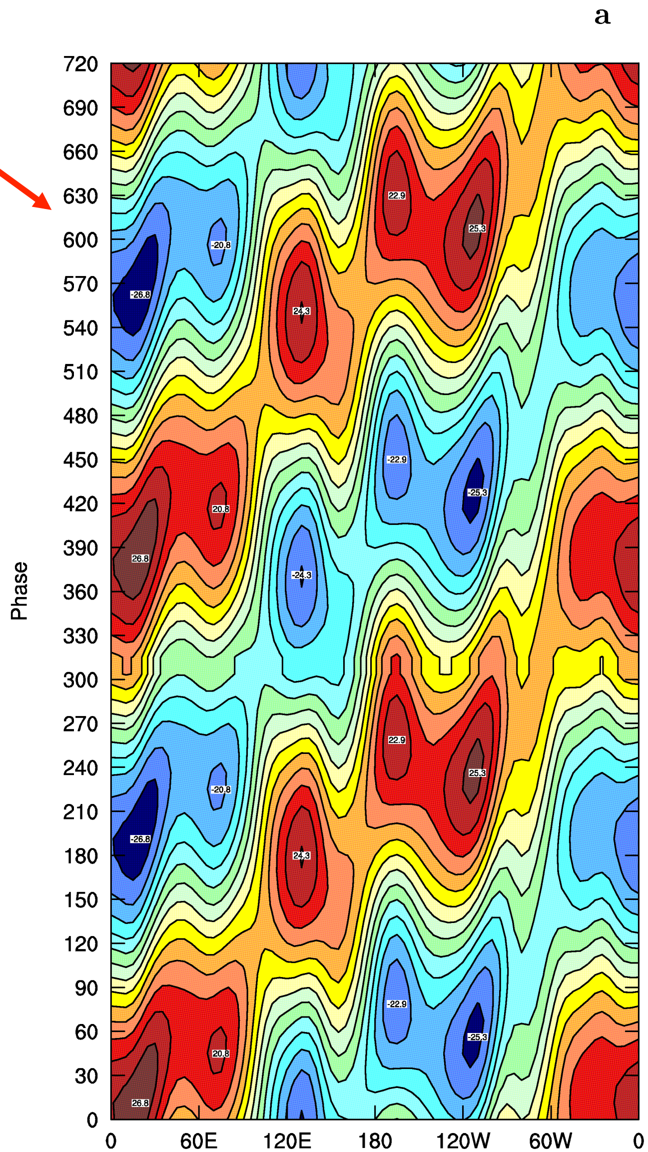
MJO Hovmøller Diagrams

Model MJO 300 hPa Velocity Potential (0 to 20N)

Observed MJO 200 hPa Velocity Potential (5S to 5N)

(contours) and OLR (shading) from HSU (1996).

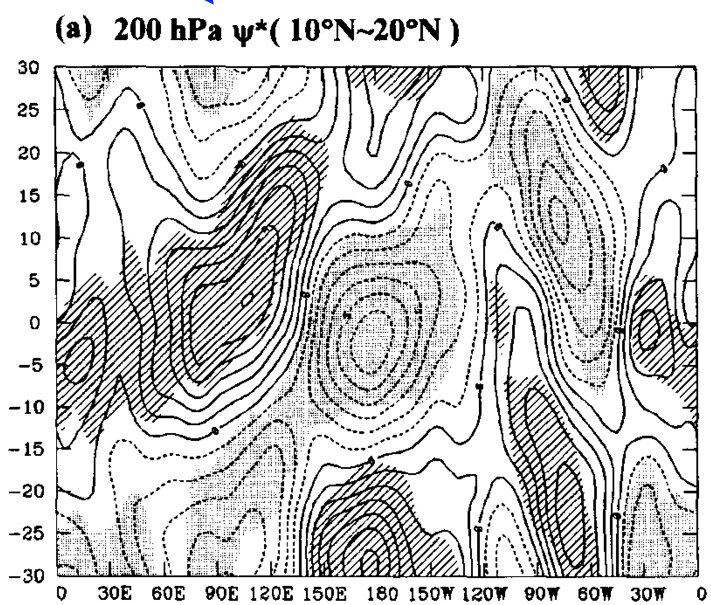


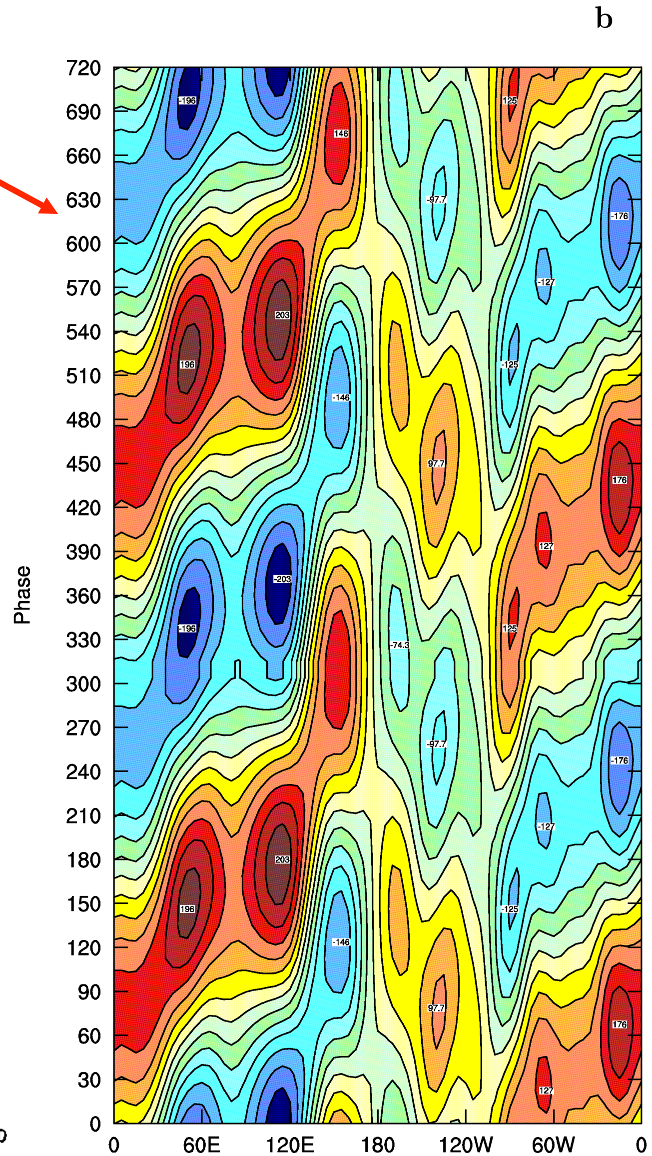


MJO Hovmøller Diagrams

Model MJO vertical shear zonal velocity (0 to 20N)

Observed MJO 200 hPa Streamfunction (10 to 20N) (contours) and 200 hPa zonal velocity (shading) from HSU (1996, J. Climate).





“Observational Analysis” of Theoretical ISO Modes

Frederiksen & Lin 2013 JAS

- Perform analyses similar to those of Lin et al, 2009, J. Clim.
- Regard the time series of the evolution of the theoretical ISO modes as an “observational” data set
- Examine the relationships between the phases of convection in the tropics and the development of the NAO/AO pattern in the NH
- Examine the extent to which Wave Fluxes associated with the Theoretical Modes are similar to the Observations

PHASES Wheeler & Hendon 2004 MWR

WH Index: Combined EOF analysis of OLR, 850 hPa and 200 hPa zonal winds (normalized)

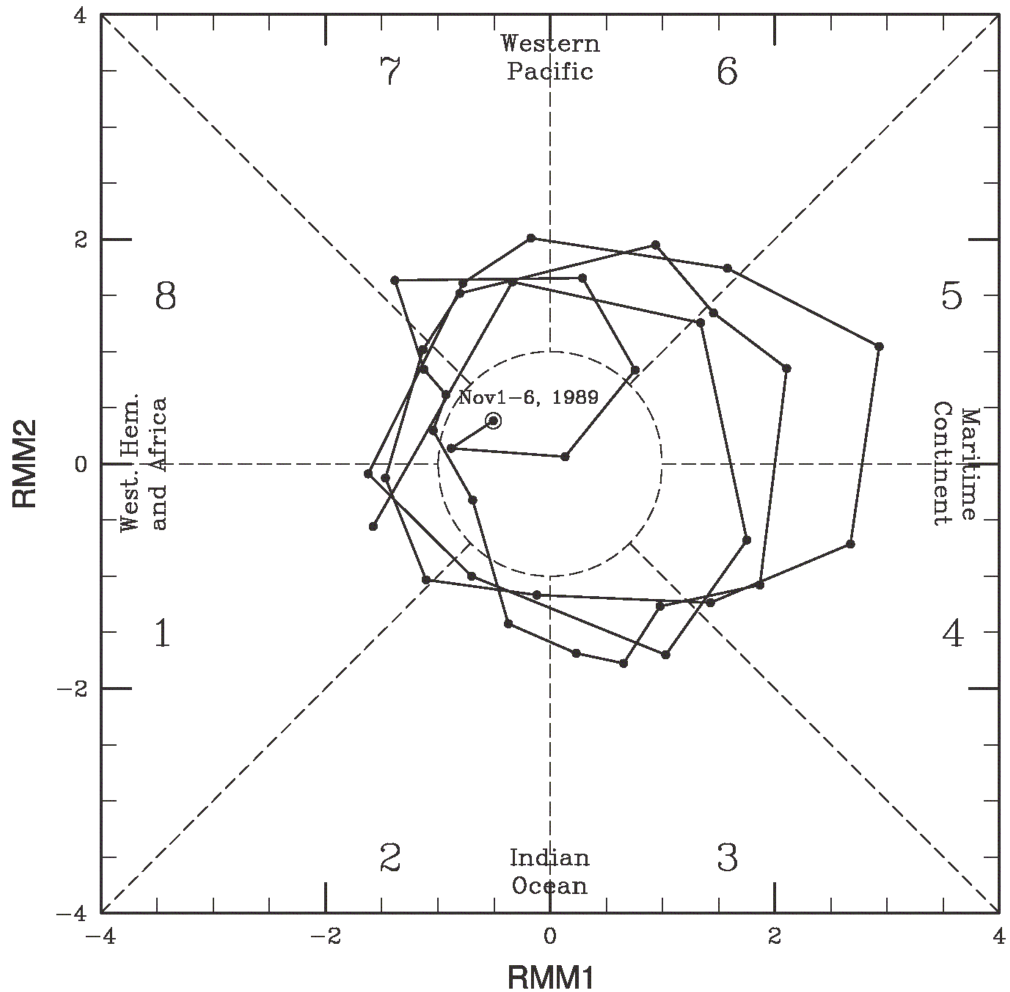


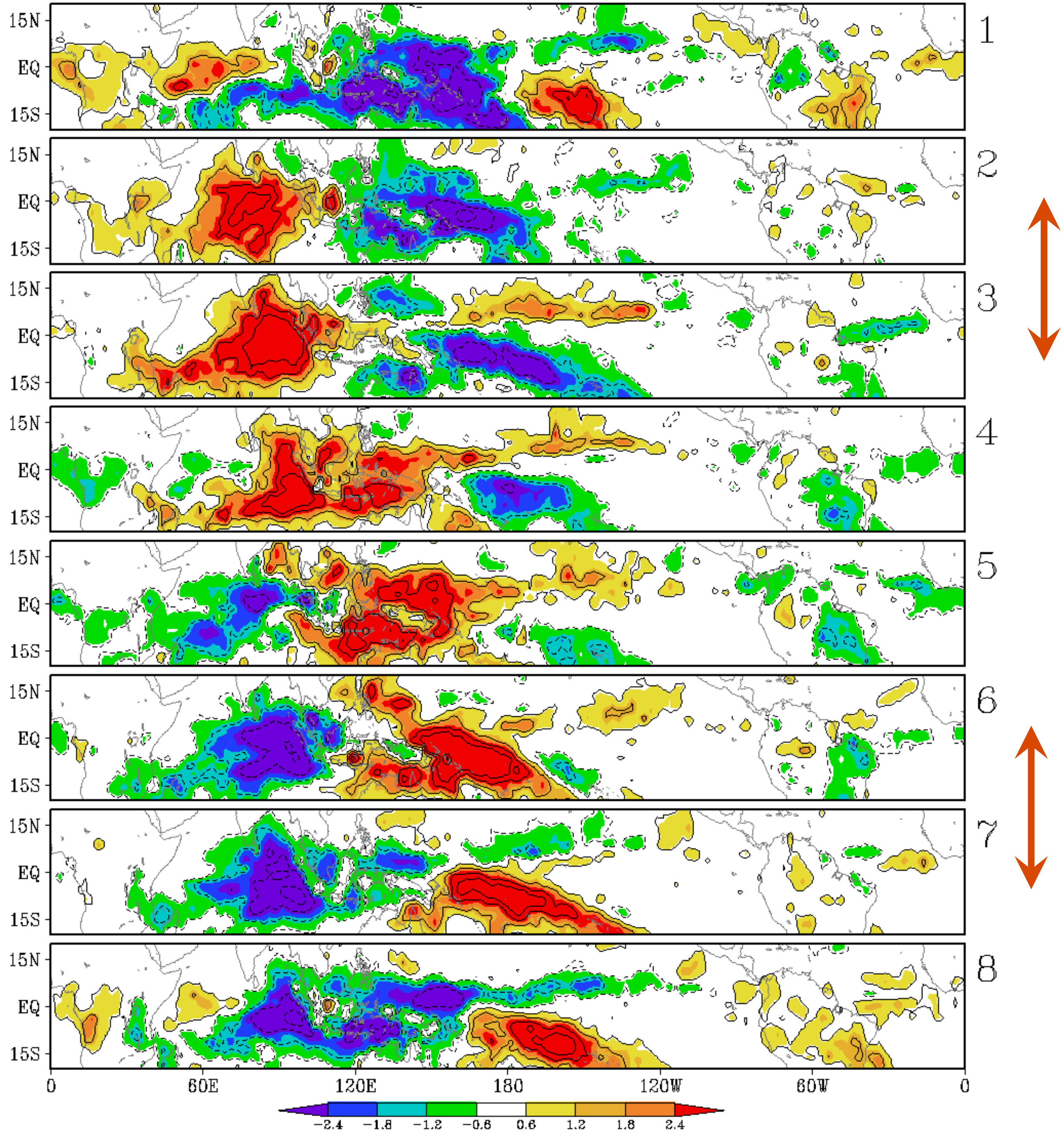
FIG. 2. Trajectory of the observed pentad MJO index in the RMM1–RMM2 phase space for all the pentads in the extended winter of 1989/90.

Lin et al. 2009 J. Climate

Composites of tropical

Precipitation rate for 8 MJO phases, according to Wheeler and Hendon index.

Xie and Arkin pentad data, 1979-2003



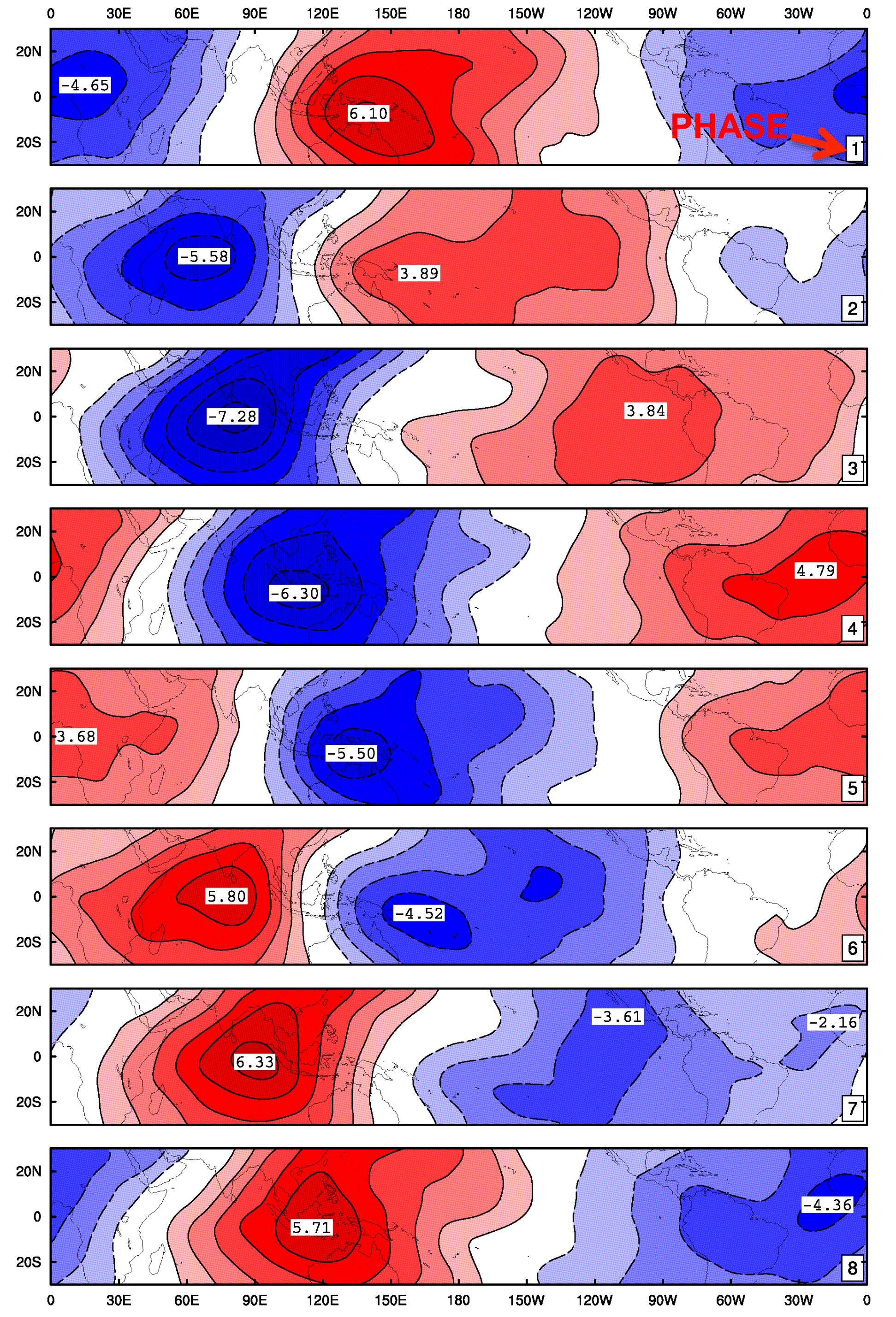
Observed Velocity Potential 8 PHASES

Frederiksen & Lin 2013 JAS

Composites of 200hPa velocity potential for 8 MJO phases

Winter pentad data are used, and MJO phases are defined using the Wheeler and Hendon index. Number of winters: 30 (1979/80 – 2008/09)

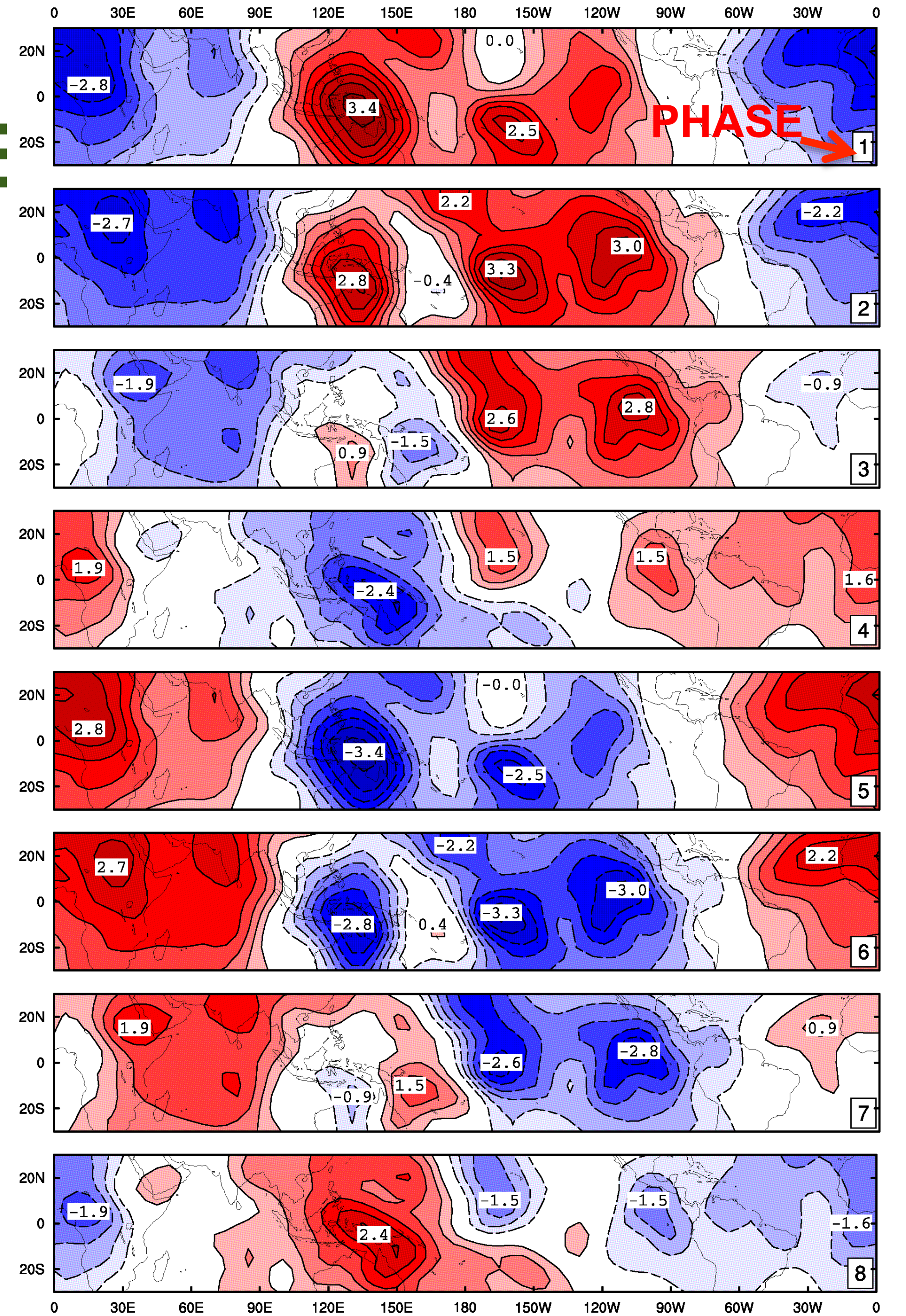
Contour interval: 1 $km^2 s^{-1}$



Theoretical Velocity Potential at 8 PHASE

Frederiksen & Lin 2013 JAS

Velocity potential of ISO at 300 hPa



EVAP case from Frederiksen 2002 J. Atmos. Sci.

Scaled down by 10 compared with F2002. Can be taken as in km^2/s

OBSERVATIONS 200 hPa

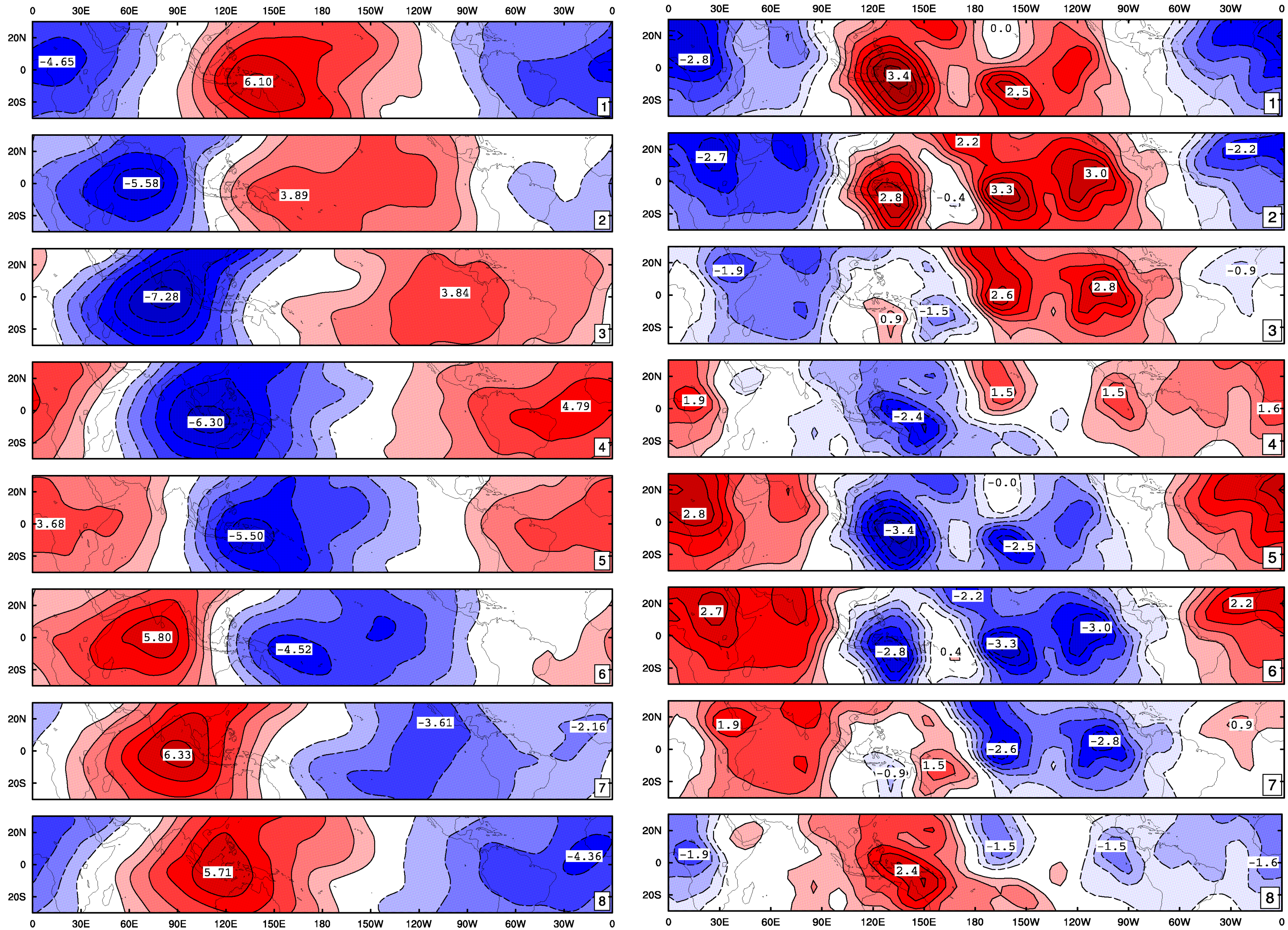
Average 30 winters 1979 - 2008

Velocity Potential - Convection

Frederiksen & Lin 2013 JAS

THEORY 300 hPa

January 1979



EOFs of OLR

Frederiksen & Lin, 2013, JAS

Correlation of PC1 and PC2 with WH index:

PC1 with RMM1: 0.62

PC2 with RMM2: 0.76

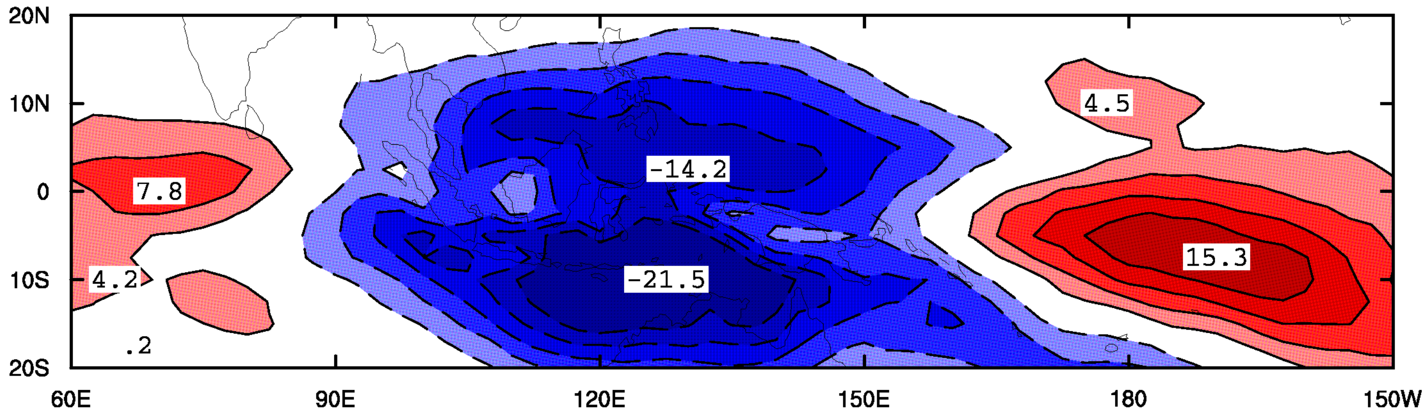
Number of winters: 30

1979/80 – 2008/09

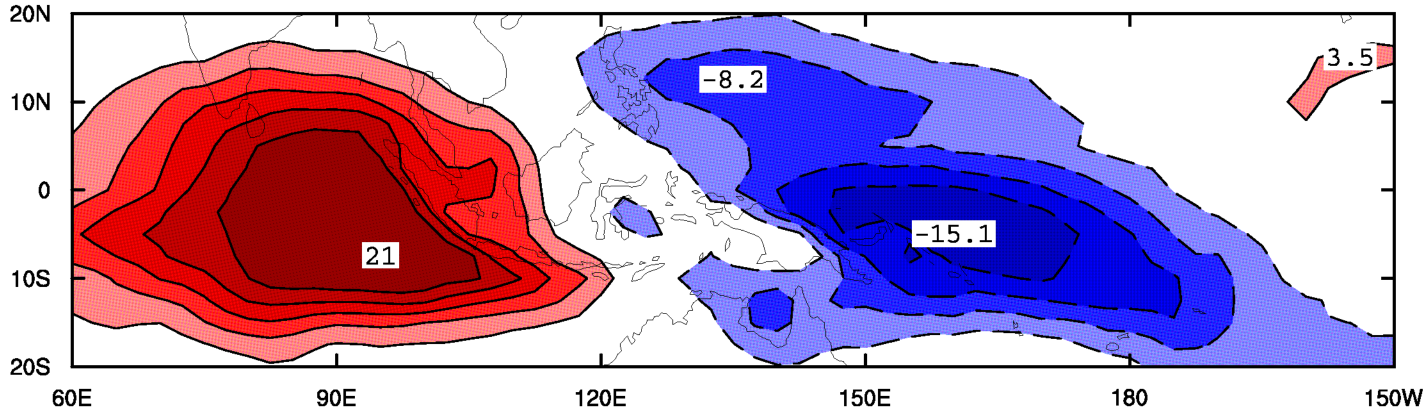
in Current Study

Calculated with pentad data & correlations with RMM also determined for pentad values

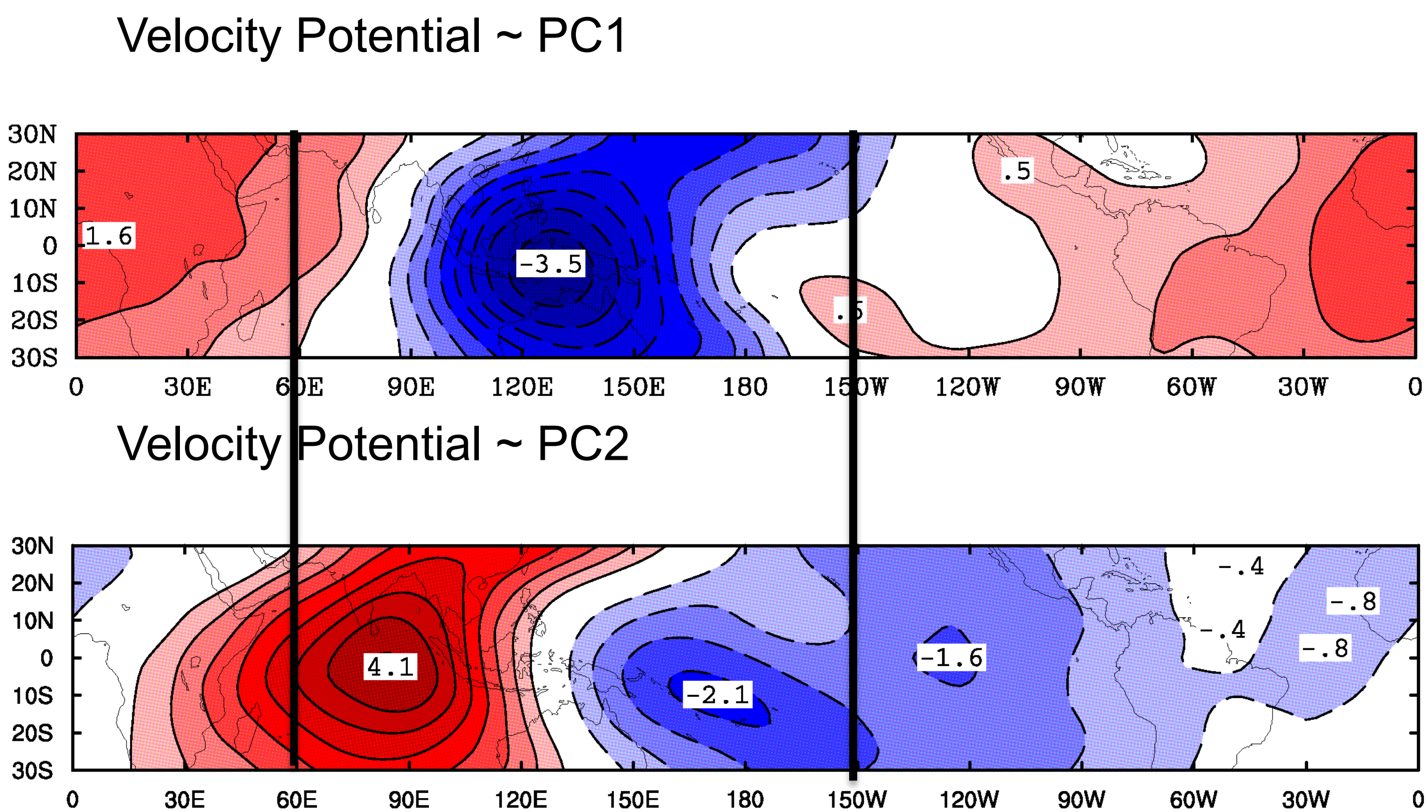
EOF1



EOF2

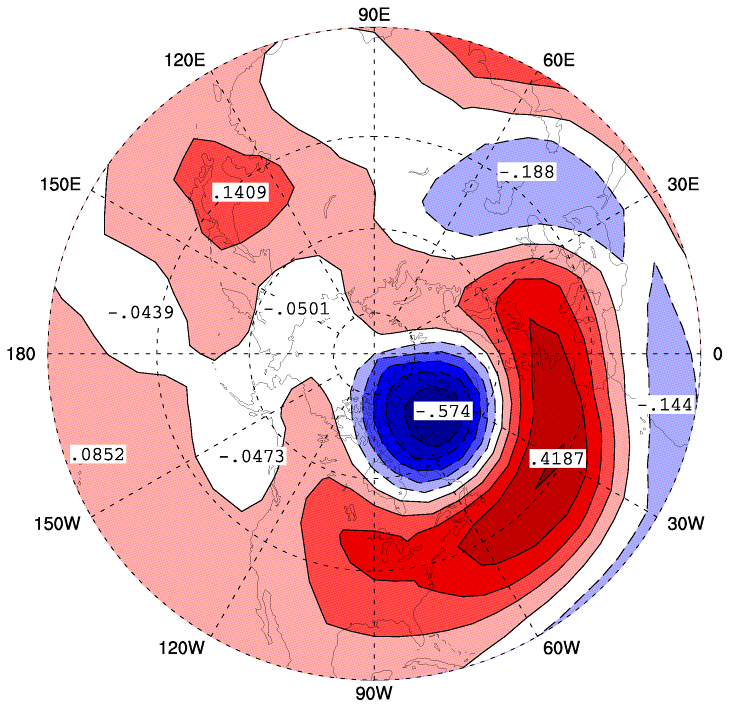


Velocity Potential patterns corresponding to OLR EOF1 and EOF2 (PC1 and PC2)



200-hPa velocity potential as regression to PC1 and PC2 of OLR. Magnitude corresponds to one standard deviation of the PC. Contour interval: 0.5×10^6 m^2 s^{-1}

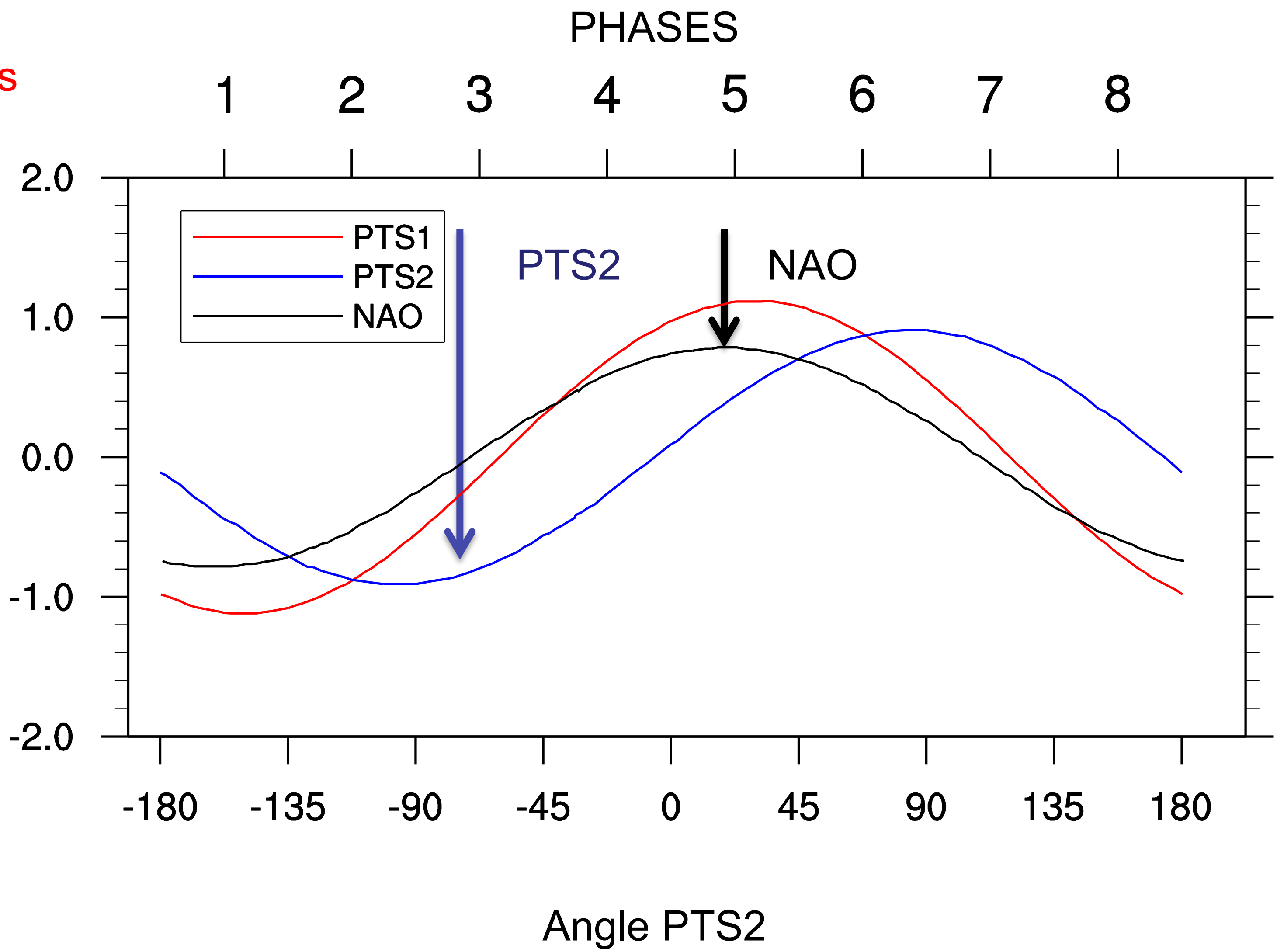
NAO pattern from rotated EOF



The NAO pattern used in this study, which is the second mode of a rotated EOF analysis of monthly mean 500-hPa geopotential height,

Theoretical Mode related To Velocity Potential Pattern Time Series (PTSs) and NAO Index

Same PHASE Relationships as in Observations Lin et al. 2009 Journal of Climate



Projections of velocity potential and NAO patterns onto theoretical intraseasonal mode

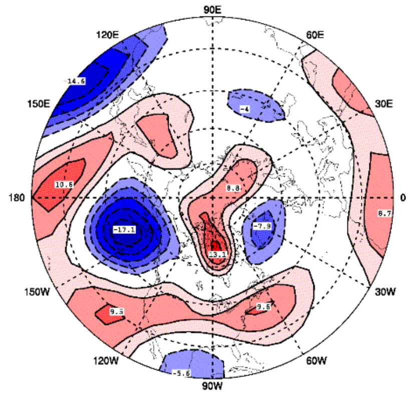
EVAP case from Frederiksen 2002 J. Atmos. Sci.

Evolution of 300 hPa Streamfunction

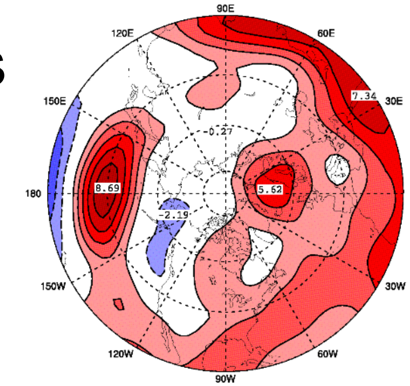
Frederiksen & Lin 2013 JAS

Theoretical Mode

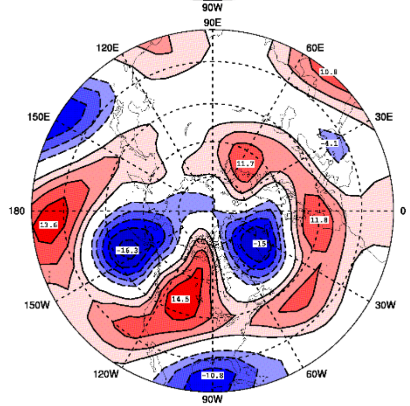
PHASE 3



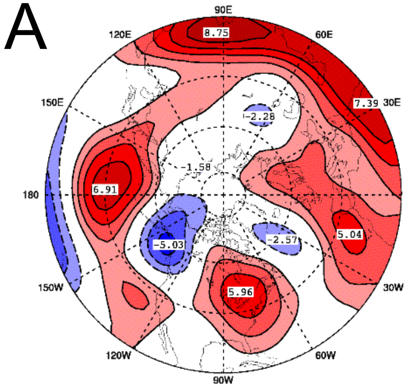
Observations Composite



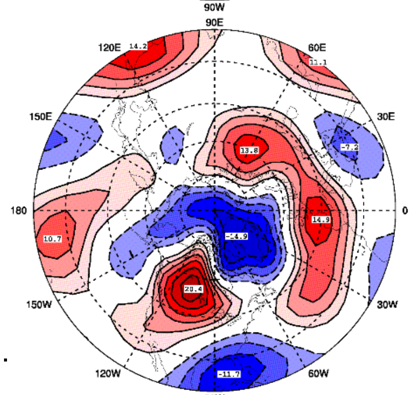
PHASE 4



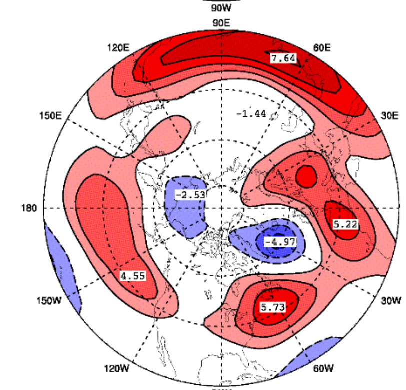
Negative PNA



PHASE 5



NAO/AO



PHASE 7 = - PHASE 3

Can be taken as in km^2/s
Scaled down by 10 compared with F2002.

In km^2/s

Waveflux - Theory

$$\mathbf{W} = \frac{1}{2|\mathbf{U}|}\begin{bmatrix} U(\psi_x^2 - \psi\psi_{xx}) + V(\psi_x\psi_y - \psi\psi_{xy}) \\ U(\psi_x\psi_y - \psi\psi_{xy}) + V(\psi_y^2 - \psi\psi_{yy}) \end{bmatrix}$$

Takaya and Nakamura 2001 GRL

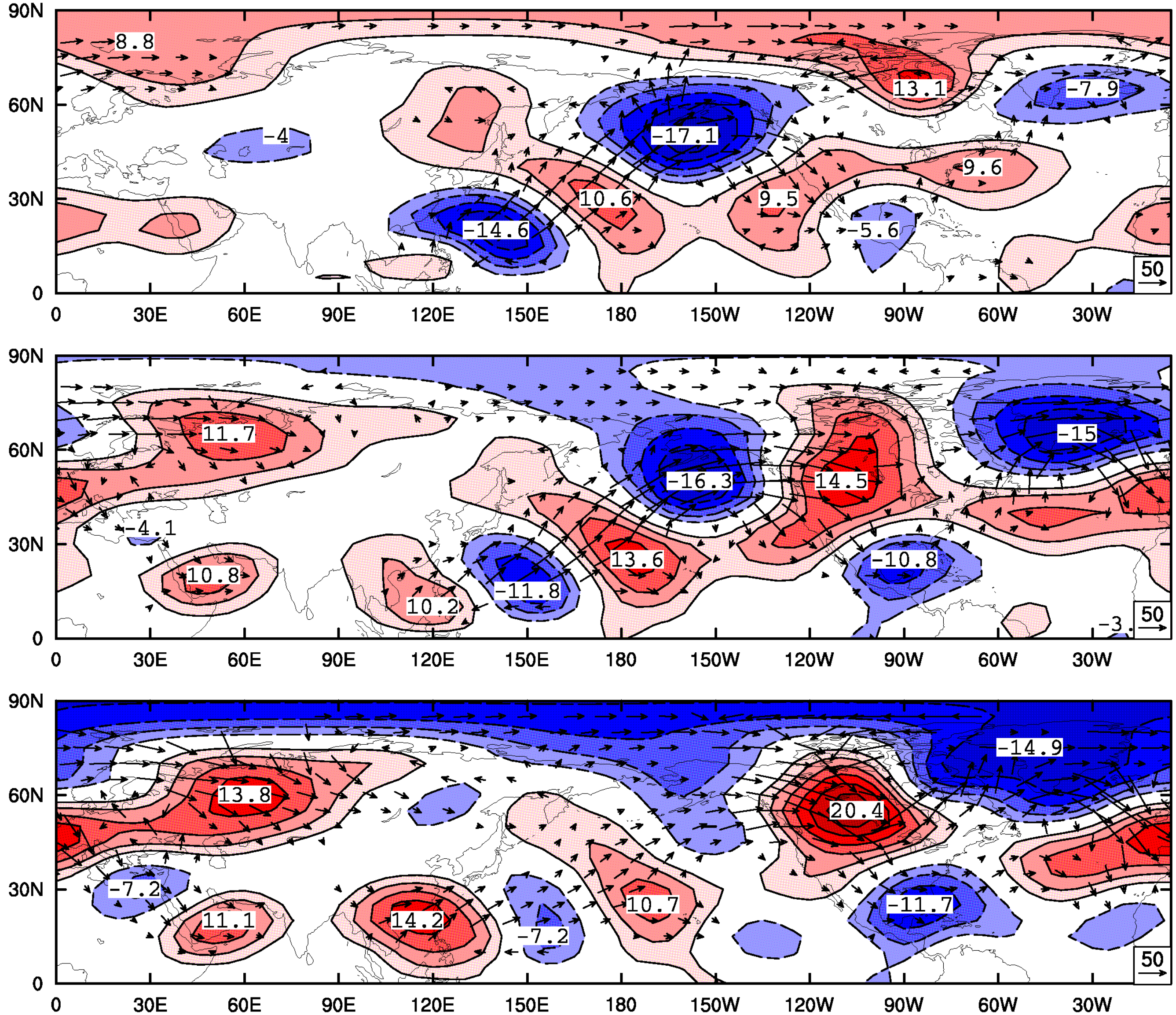
Wave fluxes for Theoretical Mode

300 hPa Streamfunction at PHASES 3, 4 and 5

PHASE 3

PHASE 4

PHASE 5



EVAP

Streamfunction can be taken as in km^2/s
Scaled down by 10 compared with F2002.

Wave Flux for Observational Composite

PHASE 3

PHASE 4

PHASE 5

Lin et al. 2009 J. Climate

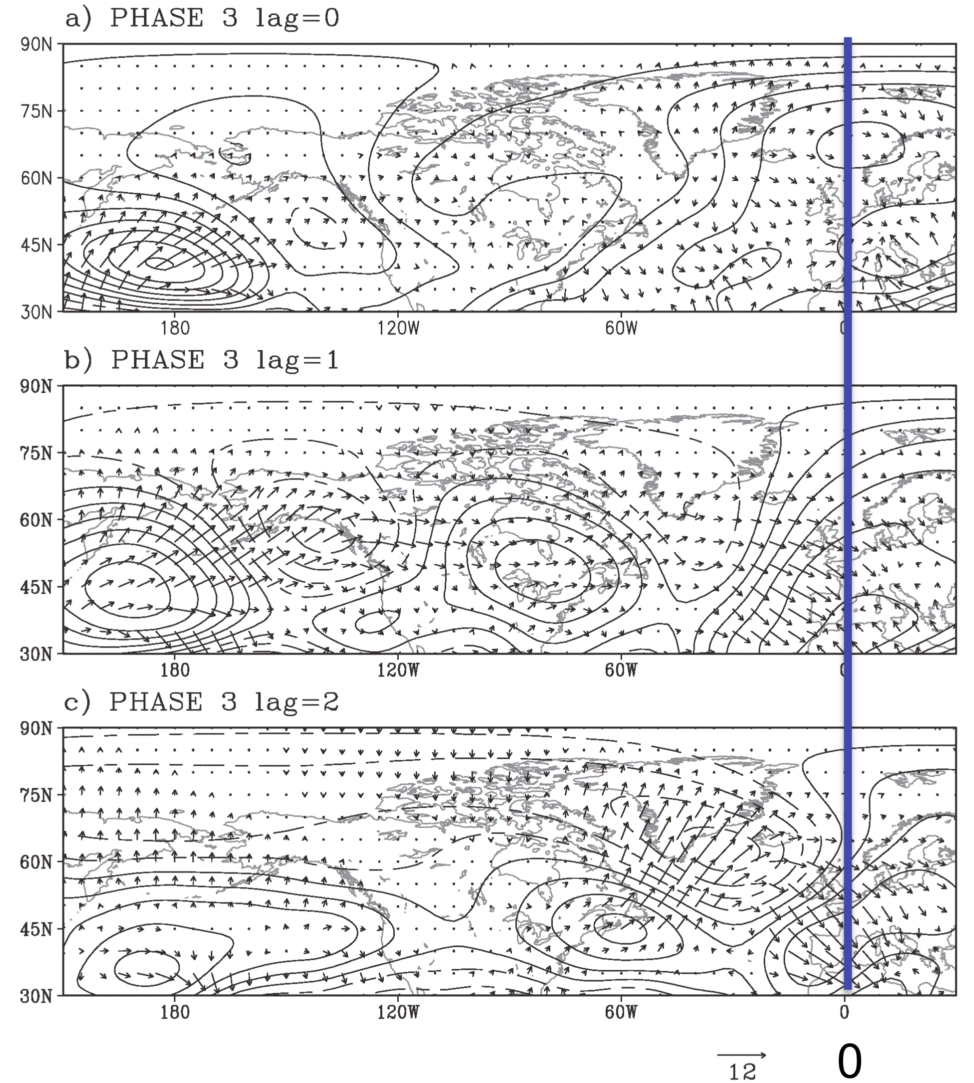
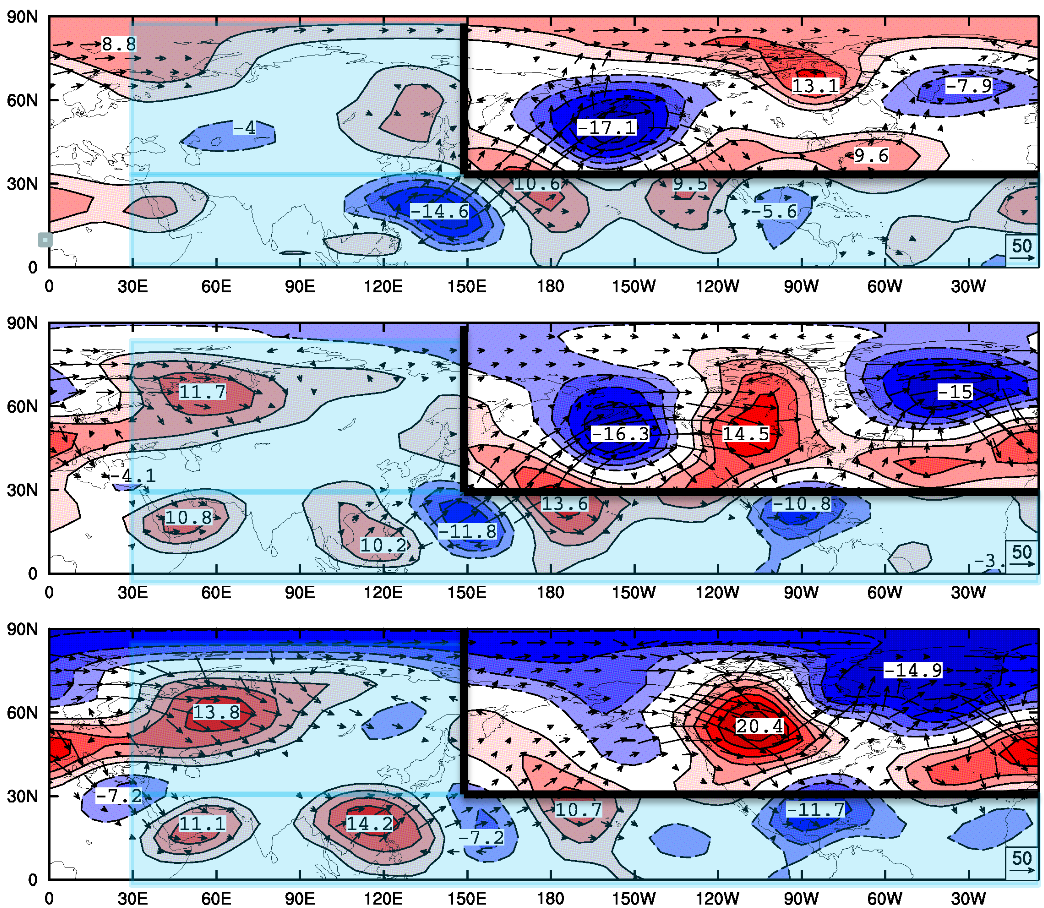


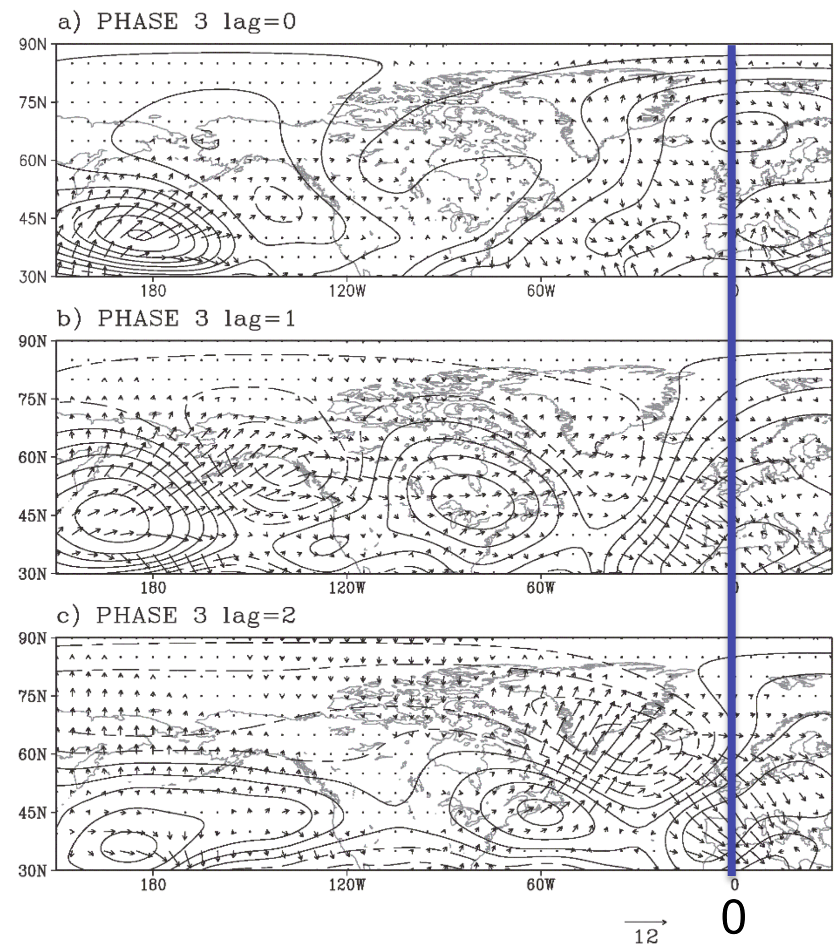
FIG. 5. 200-hPa wave activity flux with respect to MJO phase 3 for (a) lag 0, (b) lag 1, and (c) lag 2 pentads. The arrows are the horizonta (**W** vectors), and the contours the 200-hPa streamfunction anomalies. Contour interval is 1×10^6 m^2 s^{-1}. Contours with negative values ar dashed. Scaling for arrows is given below (c) (unit: m^2 s^{-2}). Wave activity flux with magnitude smaller than 0.5 m^2 s^{-2} is not plotted.

Wave Fluxes Theory & Observations

Theory

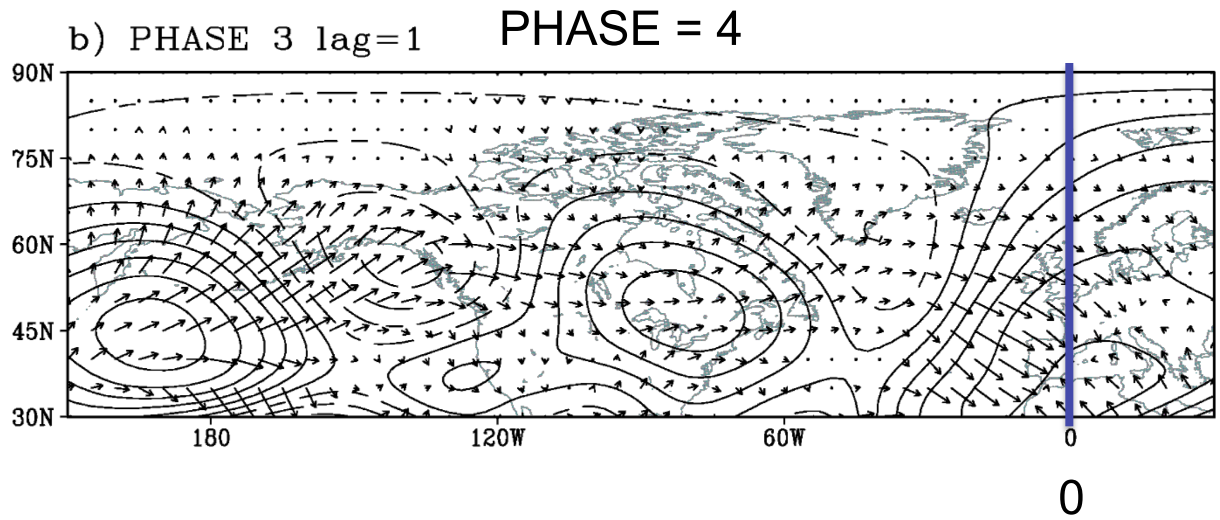


Observations

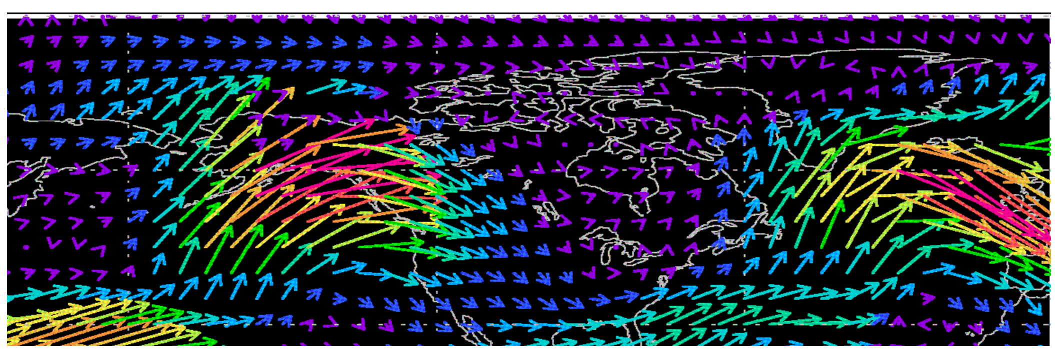


Wave Fluxes Theory and Observations

Lin et al. 2009



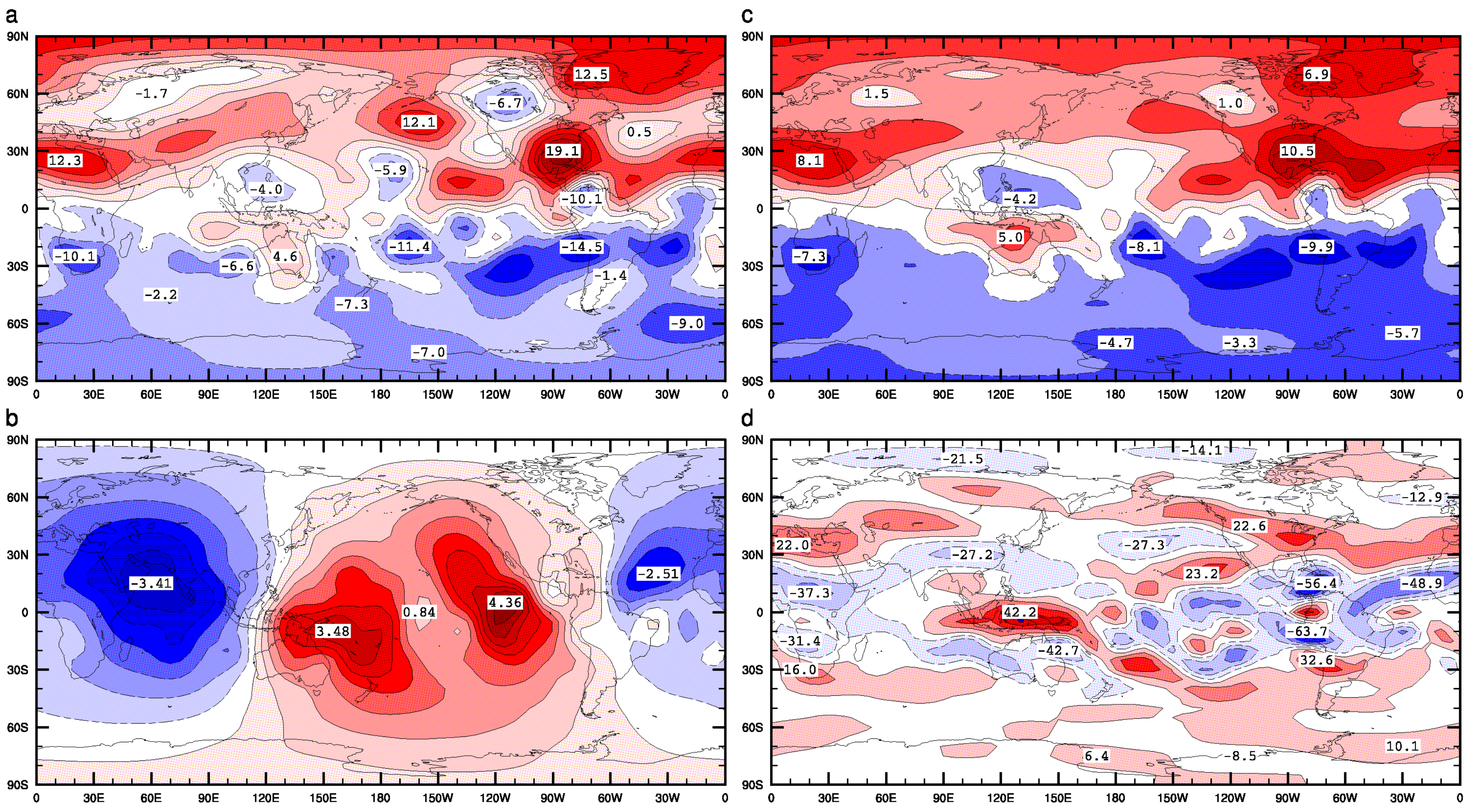
Frederiksen & Lin 2013



Second leading ISO for January 1979 EVAP
Period = 44.5 days. Frederiksen & Lin, 2013 JAS

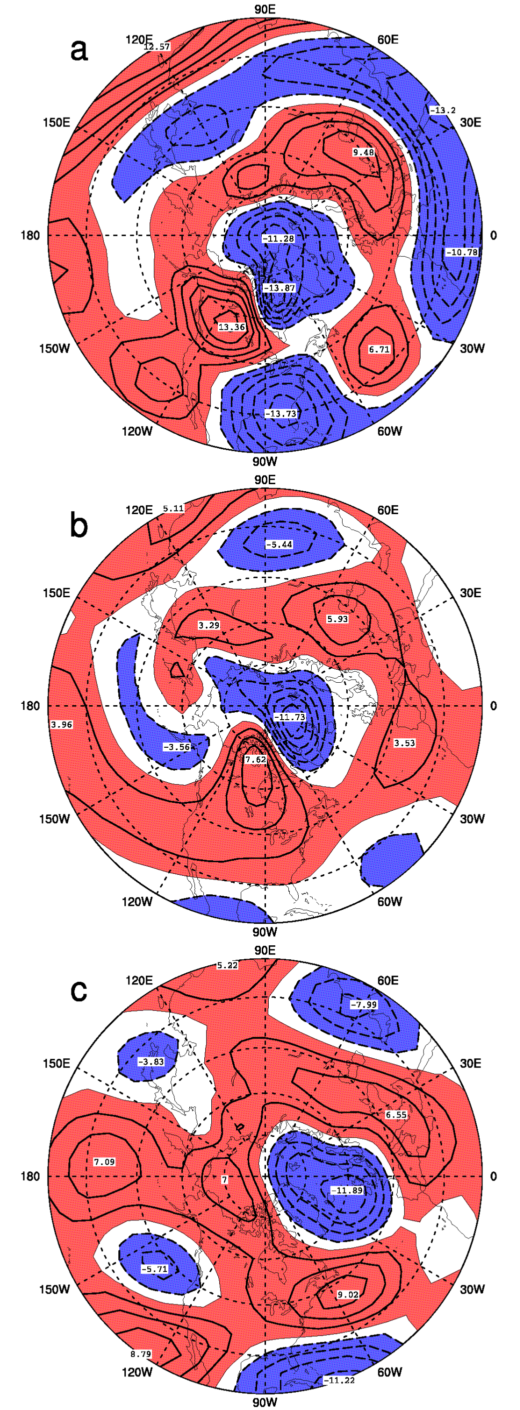
PHASE 3: Quadrupole structure, Extratropical wave trains

a: 300 hPa ψ, b: 300hPa χ, c: shear ψ, d: shear u



NAO/AO teleconnection patterns.
Jan 1979, 1988, 1980-2009

300 hPa ψ



(a) Second leading theoretical ISO mode for January 1979 lagged after PHASE 3 by 20 days. Period is 44.5 days, e-folding time is 10.2 days

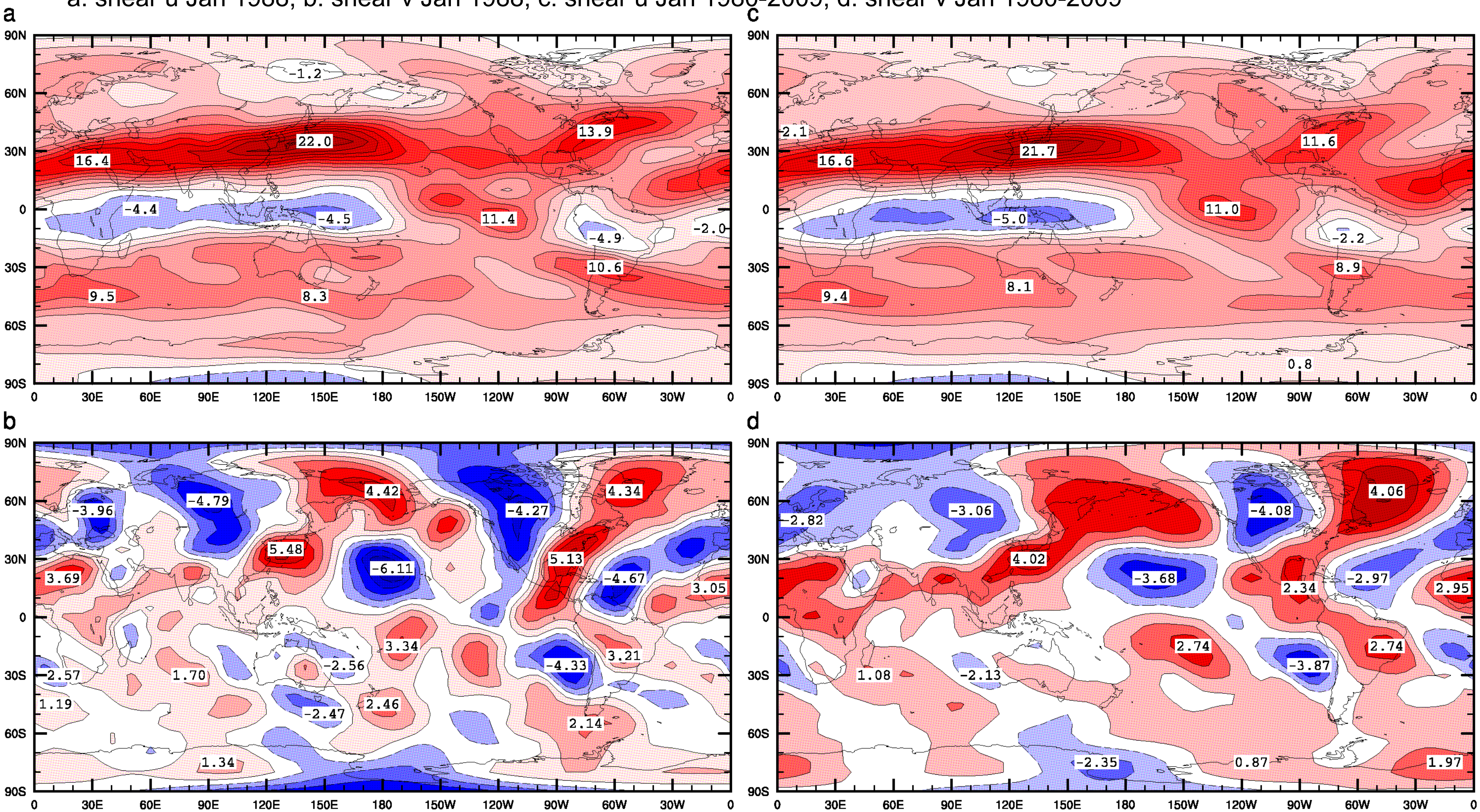
(b) Leading theoretical ISO mode for January 1988 lagged after PHASE 3 by 12 days. Period is 33.3 days, e-folding time is 8.0 days.

(c) Leading theoretical ISO mode for 30 year average January 1980-2009 lagged after PHASE 3 by 12 days. Period is 37.5 days, e-folding time is 13.2 days.

Baroclinic zonal and meridional winds for January 1988 (a, b) and January1980-2009 (c, d).

Causes of different ISO growth rates are baroclinicity and tropical-extratropical interactions

a: shear u Jan 1988, b: shear v Jan 1988, c: shear u Jan 1980-2009, d: shear v Jan 1980-2009



Conclusions – ISO/MJO

- The model ISOs have periods in the range ~30 to ~50 days with first internal mode tropical structure and equivalent barotropic extra-tropical structure.
- The theoretical ISOs capture the Complex Phase Relationships between MJO Convection and the NAO/AO and PNA.
- The tropical-extra-tropical interactions of the theoretical ISO seen in Wave Fluxes are very similar to those of observations (Lin et al. 2009, J. Climate)

Conclusions – ISO/MJO

- Second leading ISO mode for January 1979 has period of 44.5 days and distinct quadrupole structure straddling the equator
- Leading ISO mode for January 1988 is very similar to leading ISO mode for January 1979
- Leading ISO mode for 30 year average January 1980-2009 is slower growing
- Growth of ISO modes is increased with increasing baroclinicity of the zonal winds and increasing tropical-extratropical interactions seen in meridional winds