ISO-Mean Field Interaction

: Essential Dynamics for BSISO1

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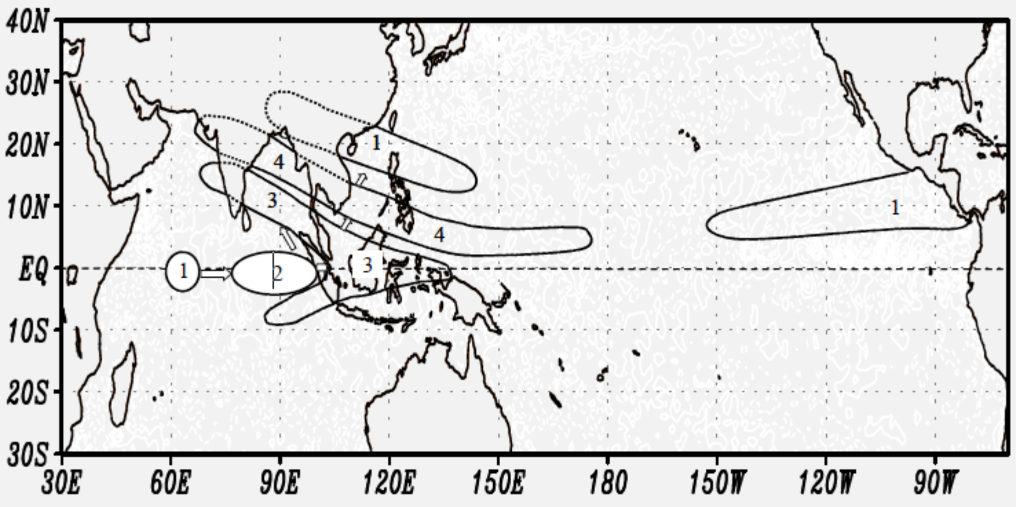
Content

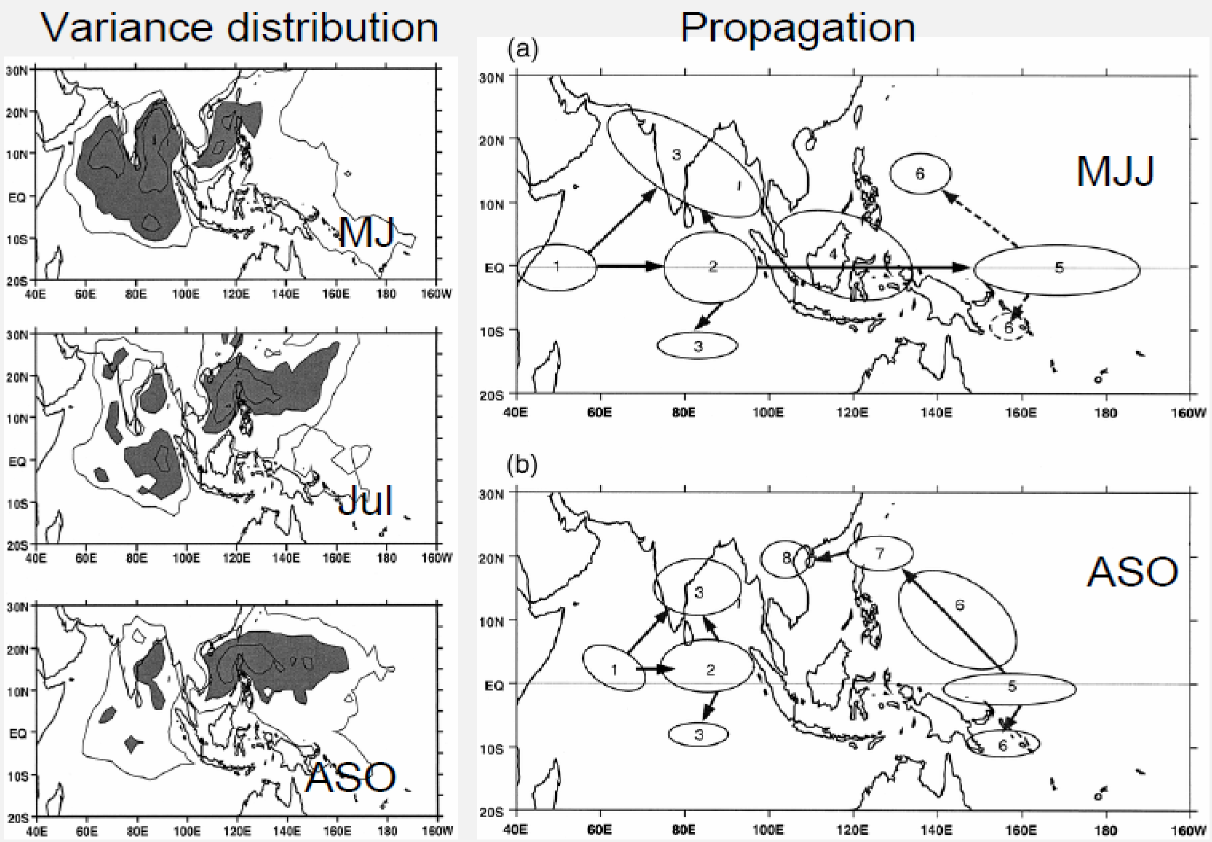
1. Introduction: Northward Propagation of BSISO

Schematic structure/movement of BSISO



Phase1: genesis in western EIO;
Phase 2: Intensification
Phase 3: Bifurcation, formation of tilted rain band
Phase 4:Northeastward propagation

Wang, Kikuchi and Webster 2005

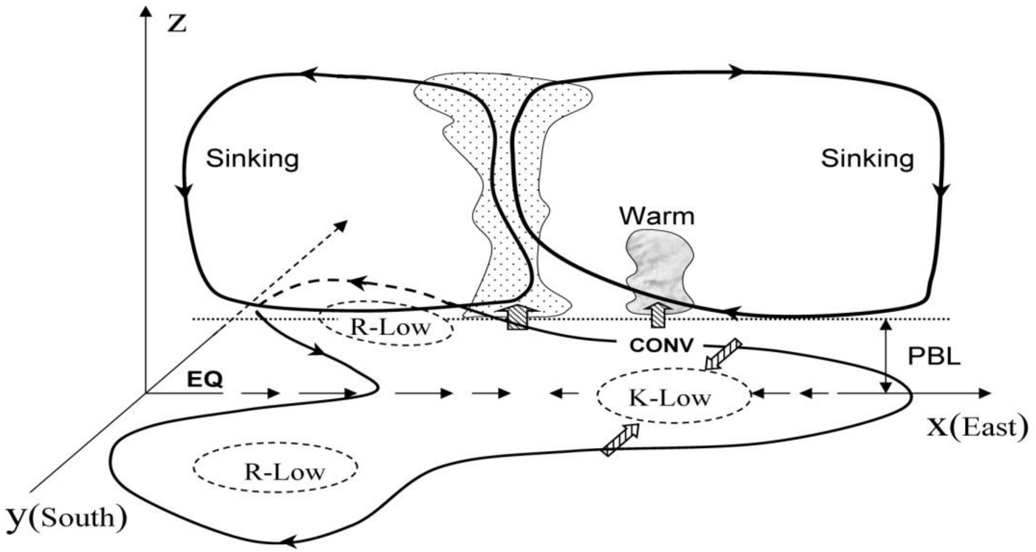


Camball-Cook and Wang 2001

- Life Cycle: The BSISO tends to initiate in the western Equatorial Indian Ocean (EIO) and propagate eastward to the eastern EIO where it bifurcates forming northwest-southeast tilted rain band and propagates northward.
- The ISV is larger over the Indian monsoon region during early summer but over the western North Pacific-East Asia (WNP-EA) monsoon region during late summer and fall.

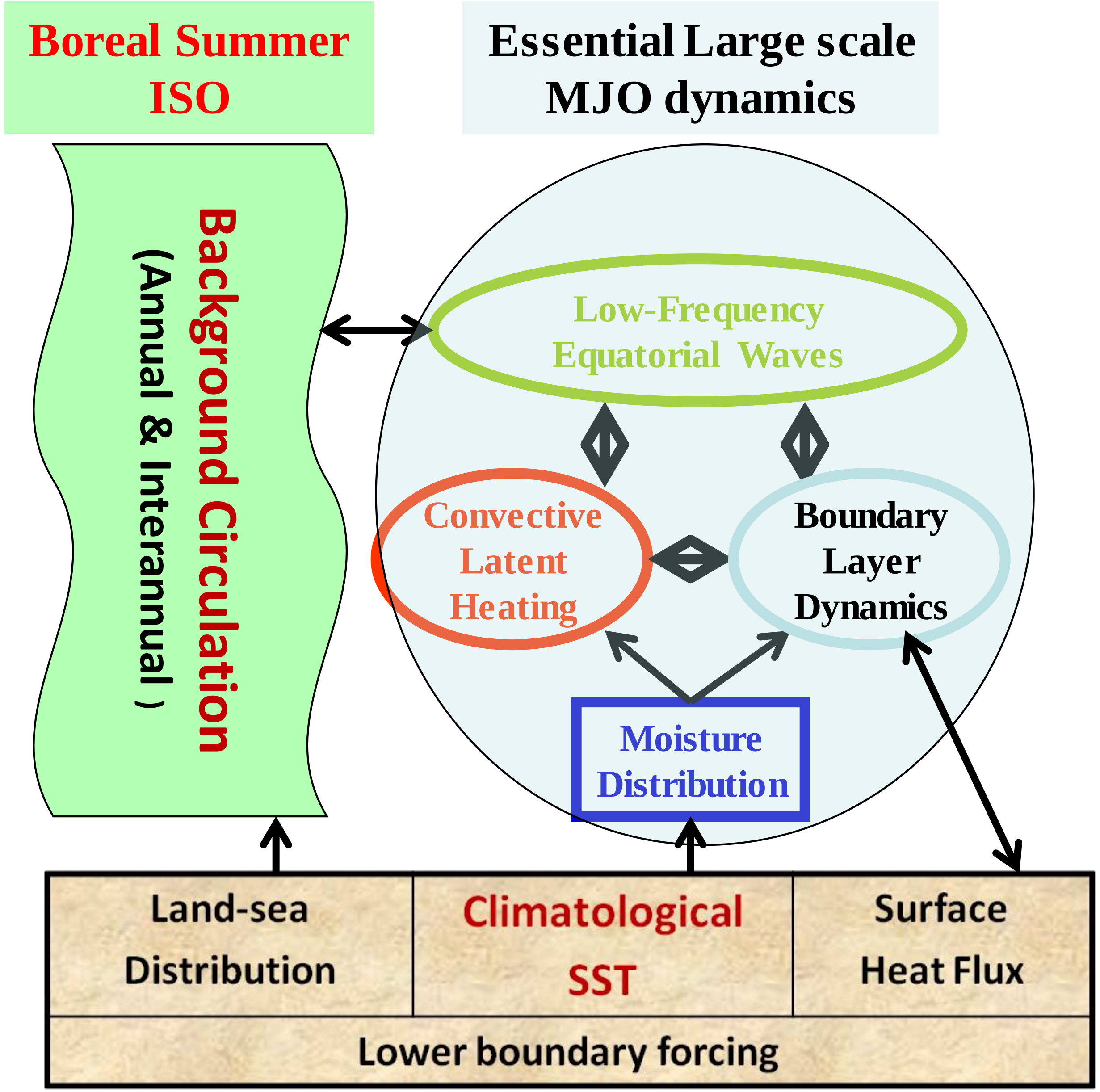
1. Introduction: Essential Physical Processes

BSISO1, the canonical northward propagating mode, is a modified MJO mode (the frictionally coupled moist Kelvin-Rossby wave) by boreal summer mean flows (Wang and Xie 1997; Wang 2005)



The frictionally coupled moist Kelvin-Rossby wave

Wang and Xie 1997; Wang et al. 2006



1. Introduction: Essential Physical Processes

- Monsoon **Easterly Vertical Shear** can **dramatically change horizontal and vertical structure of the moist Equatorial Rossby Wave**
- Rossby waves will be enhanced **in the vicinity of the latitudes where the vertical shear is strengthened**.

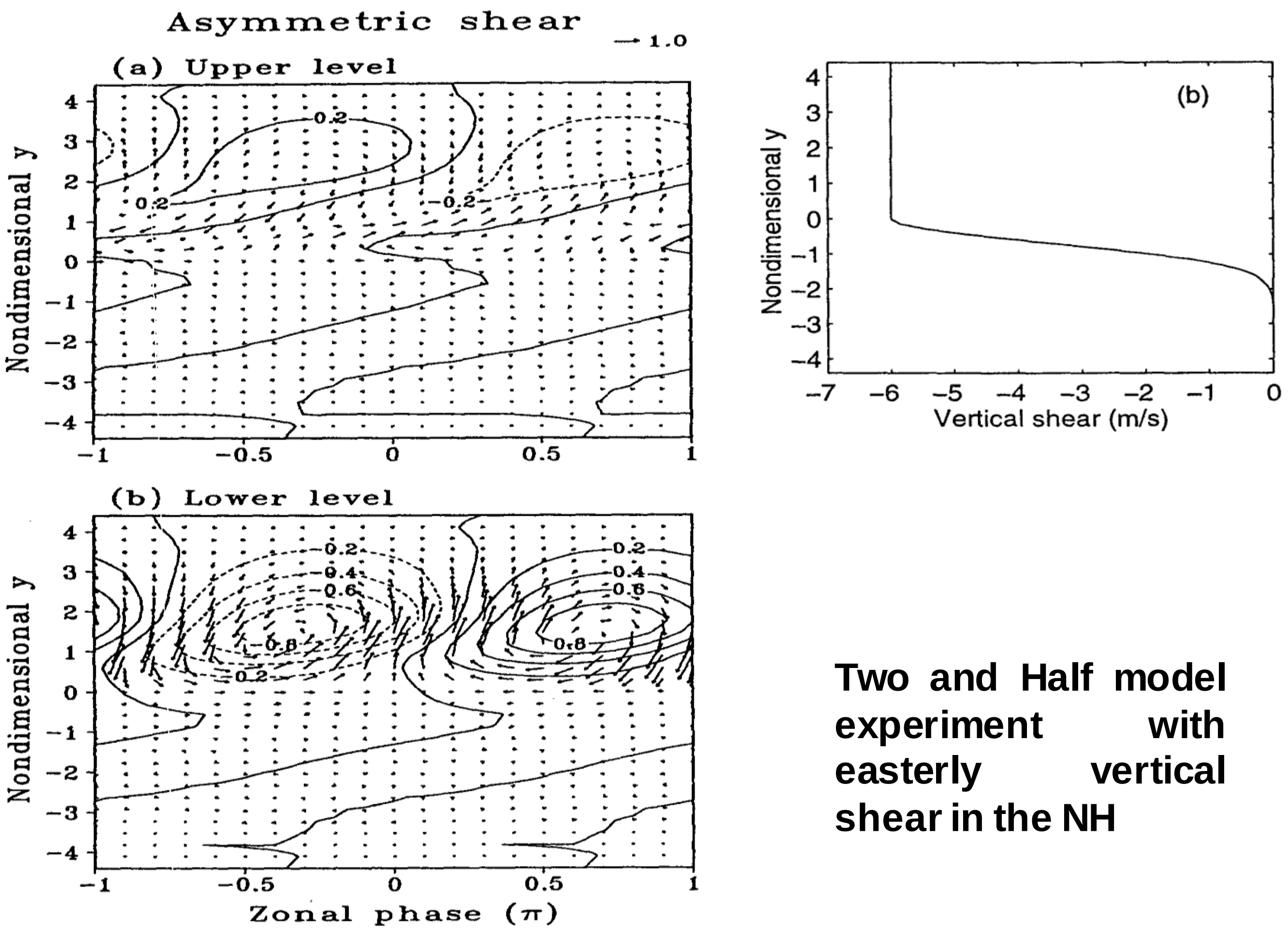


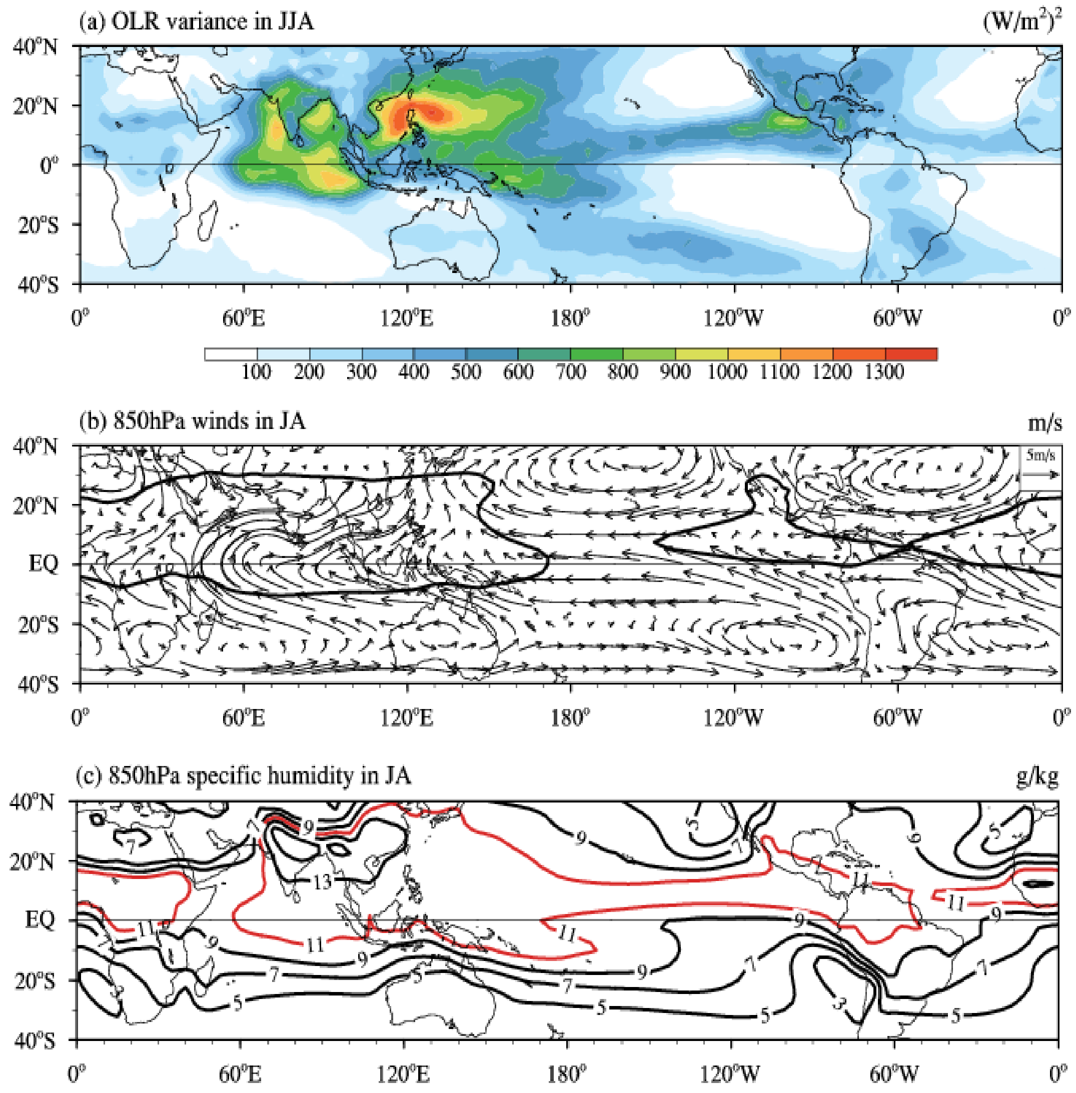
FIG. 12. (a) As in Fig. 2c, and (b) as in Fig. 2d, except for a shear of Fig. 8b.

Two and Half model experiment with easterly vertical shear in the NH

Wang and Xie 1997

1. Introduction: The Role of Summer Mean Background

- Monsoon **Easterly Vertical Shear** can **dramatically change horizontal and vertical structure of the moist Equatorial Rossby Wave**
- Rossby waves will be enhanced **in the vicinity of the latitudes where the vertical shear is strengthened**.
- The **BSISO activities are trapped** by boreal summer **Moist Static Energy (or SST)** distribution and **vertical wind shear**.



Wang and Xie 1997; Wang et al. 2006; Li 2014

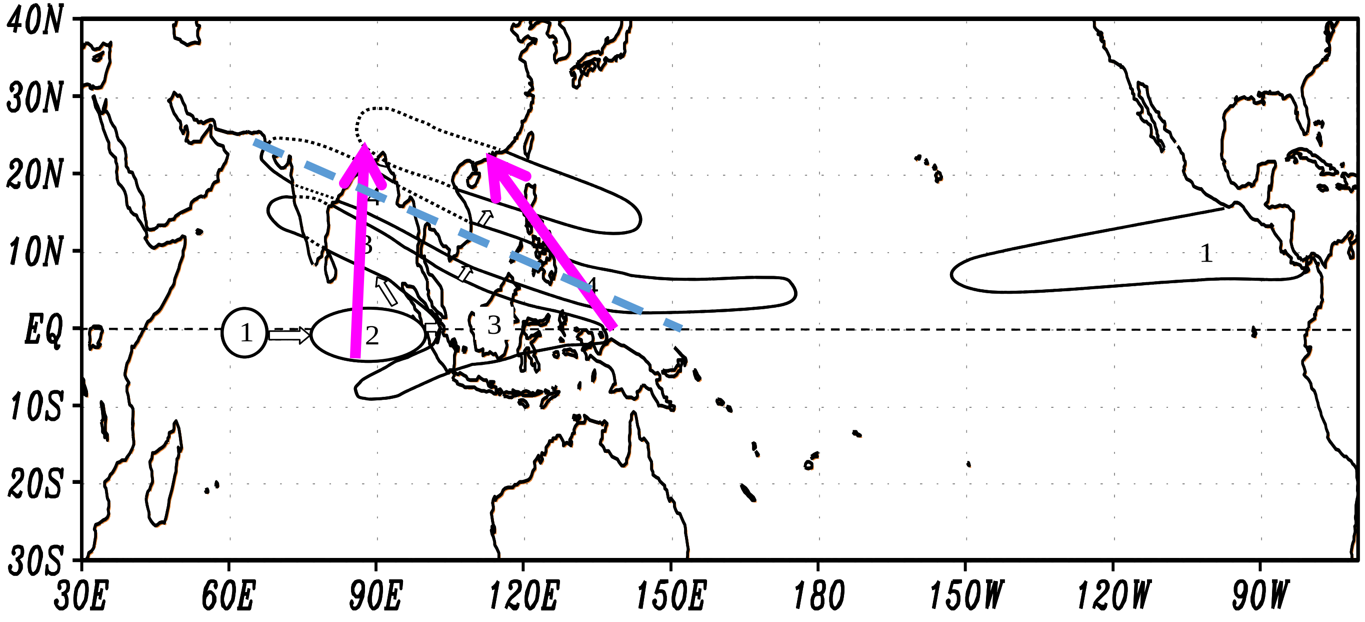
1. Introduction

Questions

(1) How are the active/break cycle of BSISO re-initiated and maintained?

(2) How the NW-SE tilted rain band form?

(3) What give rise to the northward propagation of BSISO over the summer monsoon regions?



Wang et al. 2006

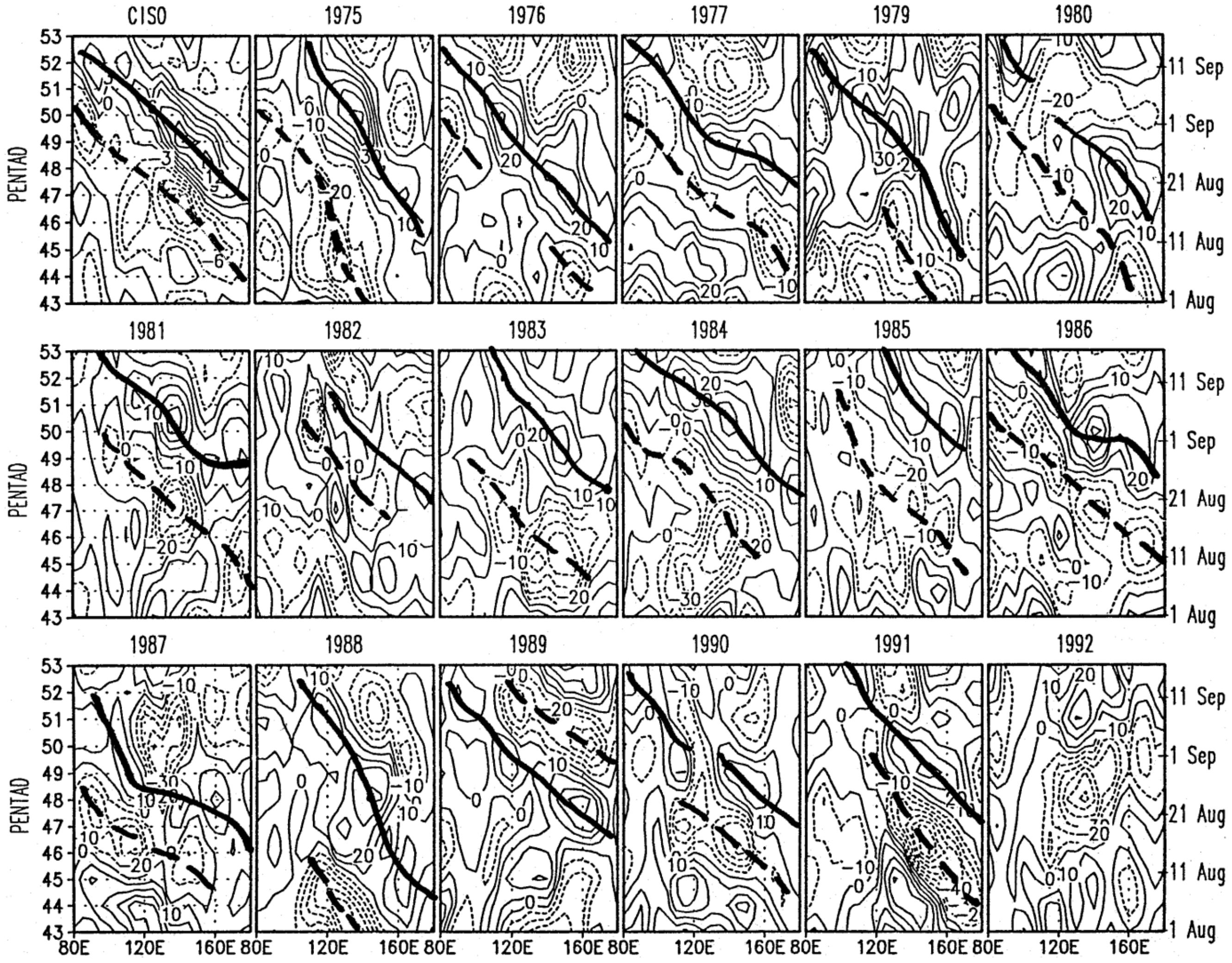
Content

2. Climatological IntraSeasonal Oscillation (CISO)

- The boreal summer monsoon displays statistically significant climatological intraseasonal oscillations (CISOs). The **extreme phases of CISO characterize monsoon singularities-monsoon events that occur on a fixed pentad with usual regularity**, whereas **the transitional phases of CISO represent the largest year-to-year monsoon variations.**

- The CISO results from **a phase-locking of transient ISO to annual cycle**. It exhibits a dynamically coherent structure between **enhanced convection and low-level convergent (upper-level divergent) cyclonic (anticyclonic) circulation**, that is the baroclinic Rossby wave structure.

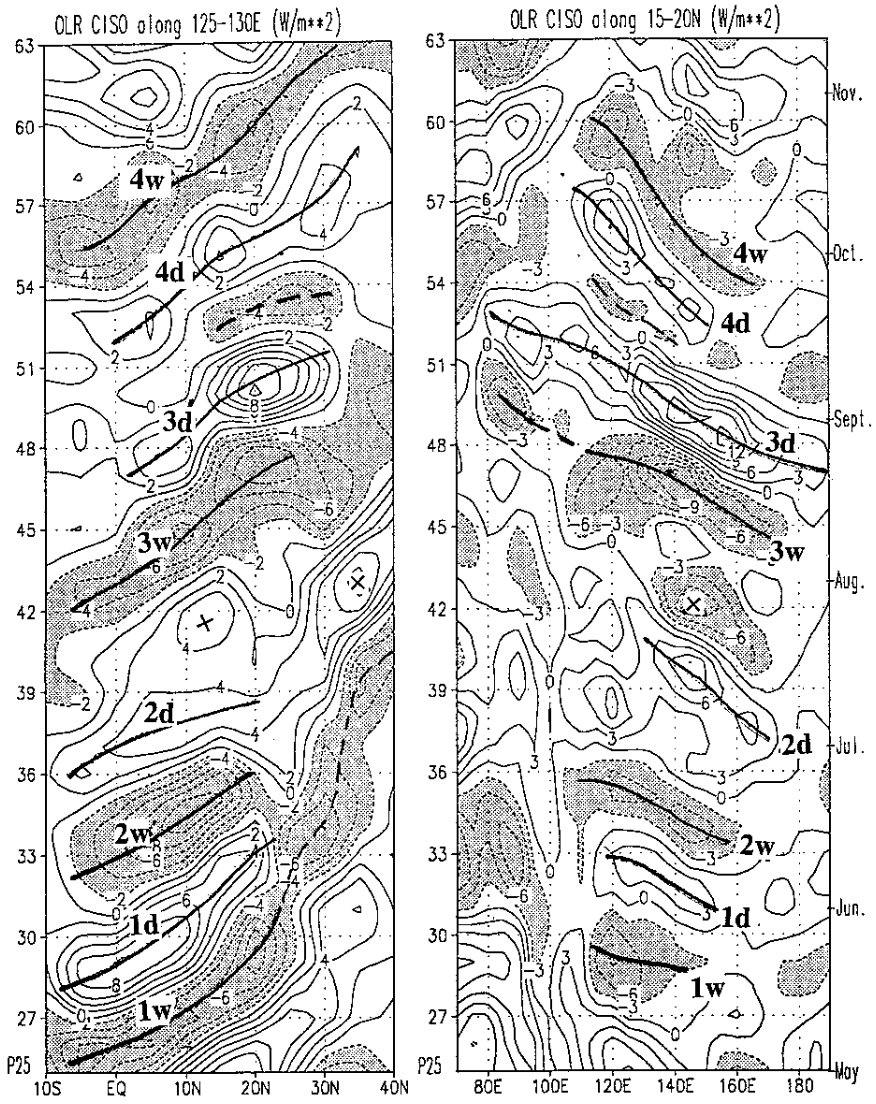
The time–longitude diagrams of 20–72-day OLR anomalies along 12.58–22.58N for the period of 1 August–15 September



Wang and Xu (1997 J Clim)

2. Climatological IntraSeasonal Oscillation (CISO)

- **Wet Phase I**: Monsoon onset over the South China Sea and Philippines in mid-May
- **Dry Phase I**: Premonsoon dry weather over the regions of WNPSM, Meiyu/Baiu, and Indian summer monsoon (ISM) in late May and early June
- **Wet Phase II**: The onsets of WNPSM, continental ISM, and Meiyu/Baiu in mid-June and onset of Changma in late-June.
- **Dry Phase II**: The first major breaks in WNPSM and ISM, and ends of the primary Meiyu/Baiu/Changma in mid-July.
- **Wet Phase III**: The peak of WNPSM and the secondary period of Meiyu/Baiu/Changma in mid-August
- **Dray Phase III**: The second breaks of WNPSM and ISM in early and mid September, respectively. Withdrawal of the second phase of Meiyu/Baiu/Changma
- **Wet Phase IV**: The last active WNPSM and withdrawal of ISM in mid-October.

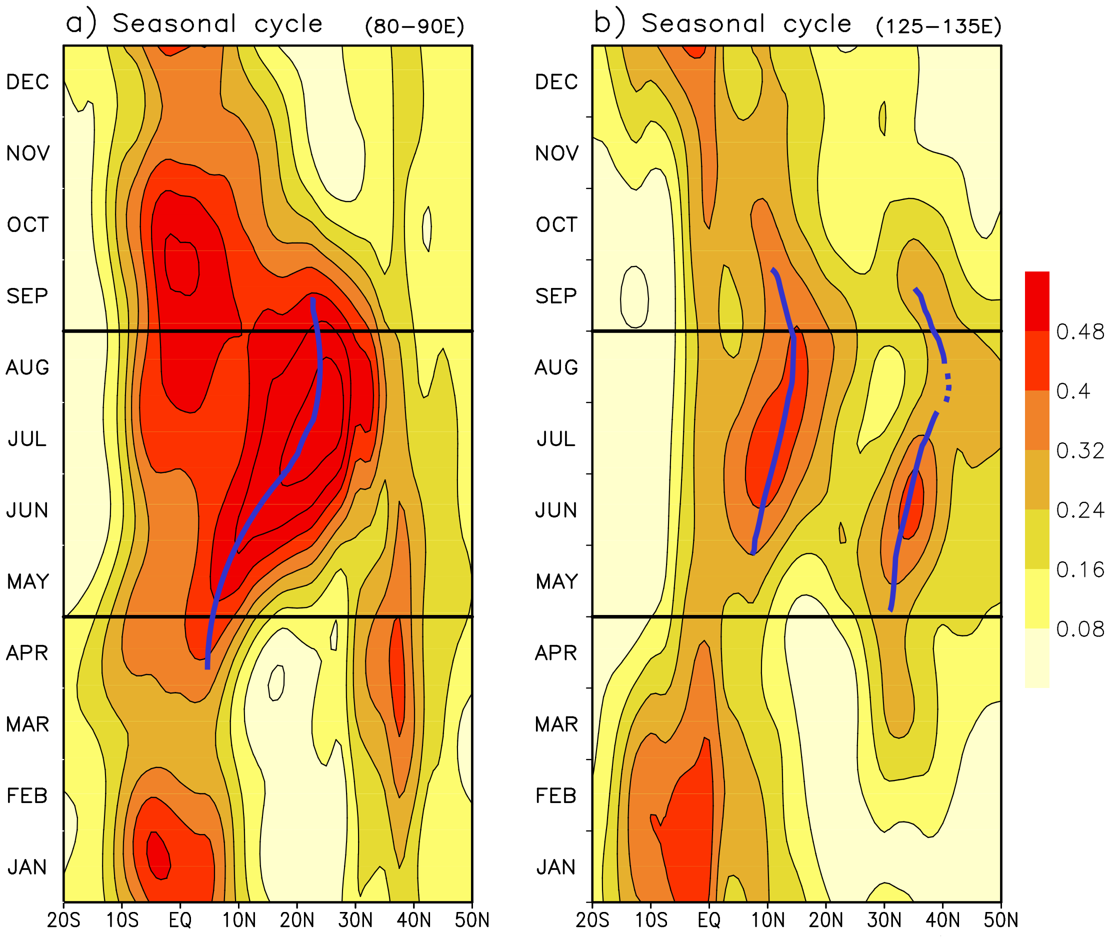


Wang and Xu (1997 J Clim)

2. Climatological IntraSeasonal Oscillation (CISO)

Slow Annual Cycle vs CSIO

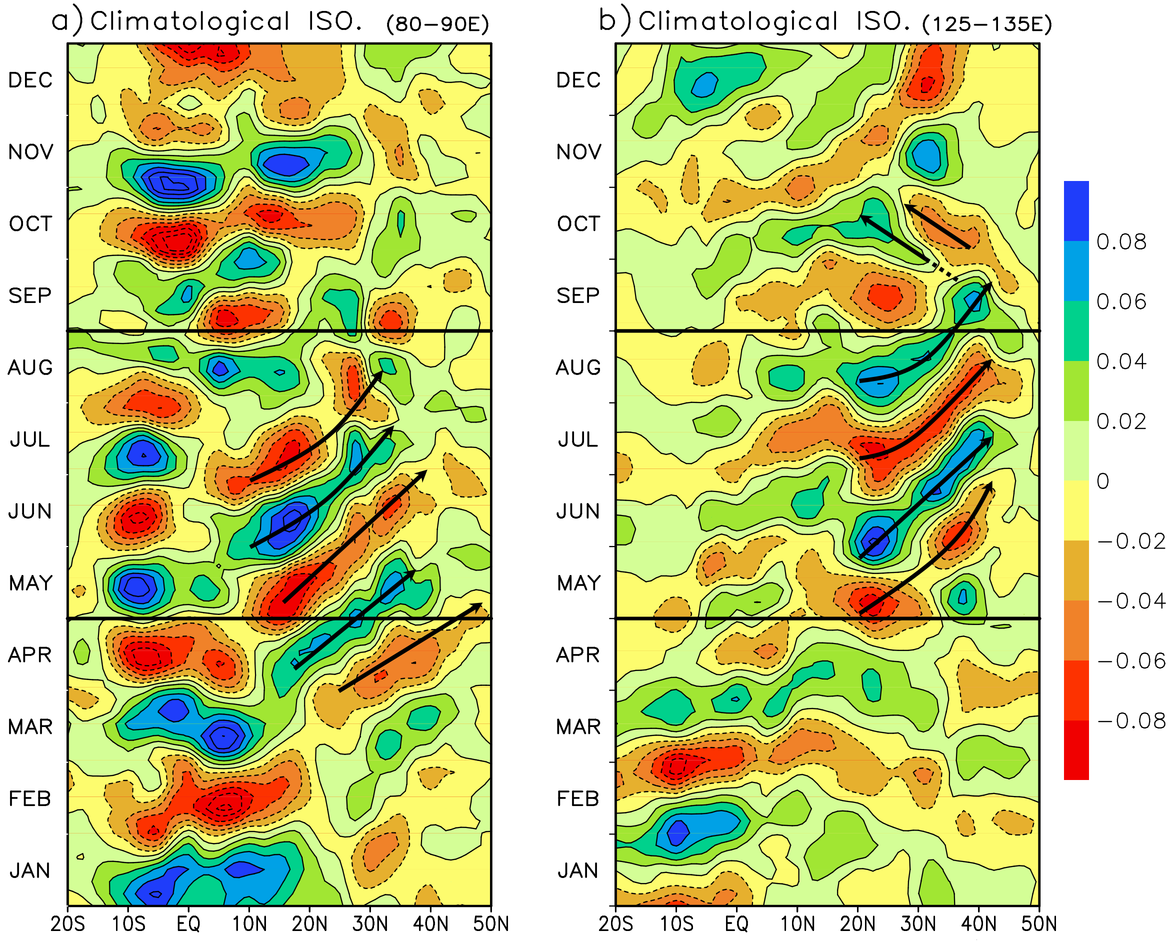
Slow Annual Cycle of High Cloud Fraction
(The first four harmonics of climatological seasonal cycle)



Indian Monsoon Region

WNP-EA Monsoon Region

Slow Annual Cycle of High Cloud Fraction
(Time scales less than 90 days)



Kang et al. (1999 Mon Wea Rev)

Content

3. Physical Mechanism of Oscillation

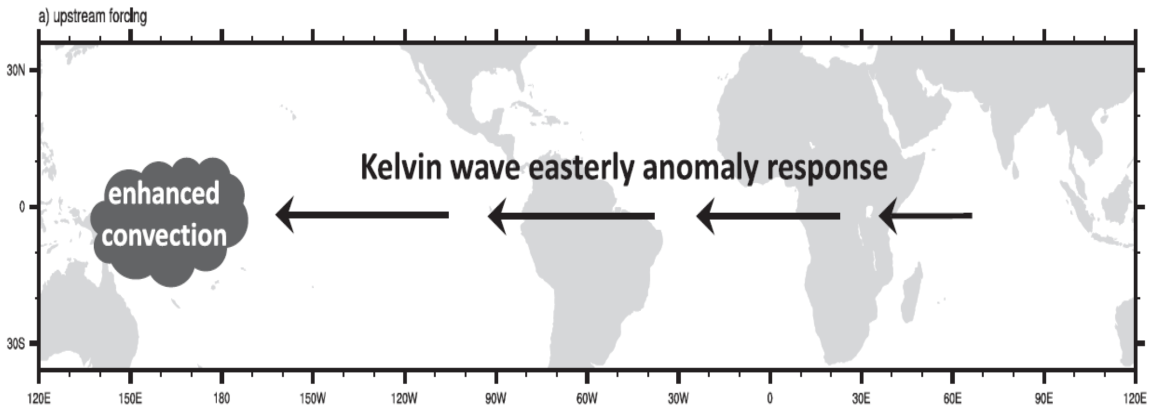
Question 1: How are the active/break cycle of BSISO re-initiated and maintained?

Hypotheses

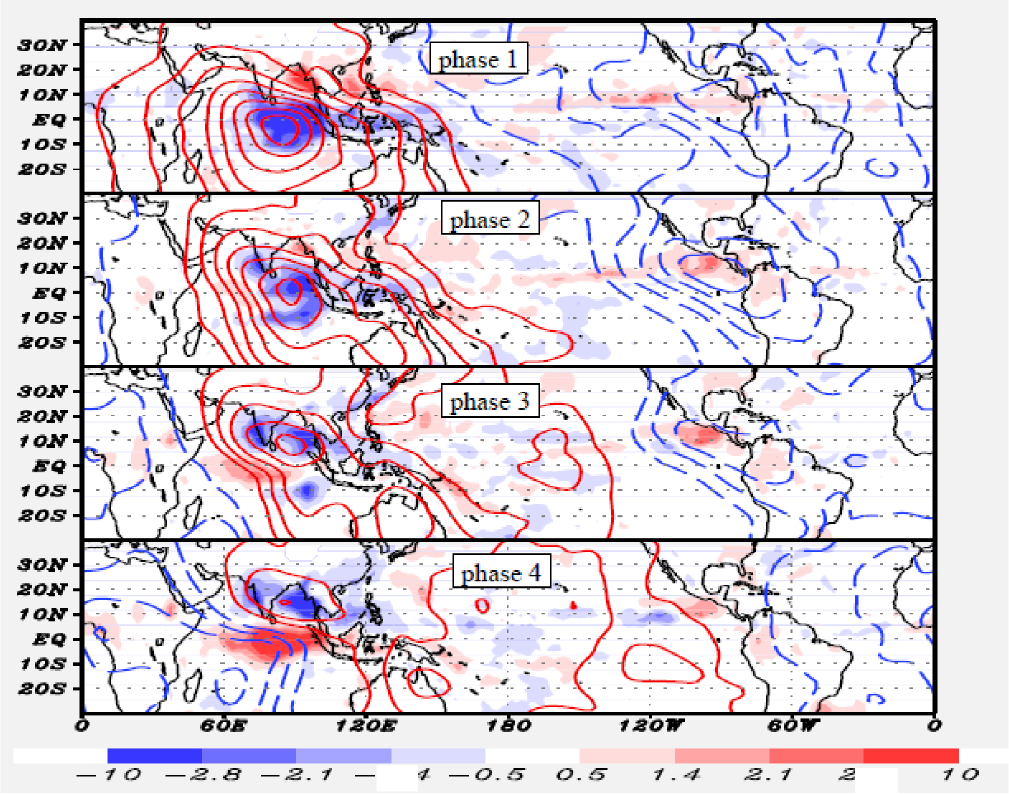
- **Circumglobal propagation** of the upper-level divergent wave of MJO (Julian and Madden 1981; Lau and Chang 1986; Hendon 1988 and many others)
- **Forcing from decaying off-equatorial Rossby waves** in Indian Monsoon region: re-initiation of equatorial convective anomalies by decaying off-equatorial Rossby waves (Wang and Xie 1997; Matthew 2000; Seo and Kim 2003)
- **Self-induction mechanism** (Wang et al. 2005)
- **Feedback between hydrological processes** in the atmosphere and radiation processes (Hu and Randal 1994; Stephen et al. 2004)
- **Midlatitude forcing**: Forced by midlatitude Rossby wave train (Hsu et al. 1990) or by injection of PV from Southern Hemisphere (Rodwell 1997)

3.1 Circum-Global Navigation of MJO

- New MJO convection can be generated over the western equatorial Indian Ocean by a **circumnavigating Kelvin wave** induced during the previous cycle of MJO convection (**upstream forcing scenario**)
- However, upper-level divergence waves may not be essential for re-initiation.



Systematic diagrams illustrating an upstream forcing scenario in which a positive MJO heating in the western Pacific may induce an anomalous easterly over the western Indian Ocean through Kelvin wave response



200-hPa velocity potential

Li (2014 JMR)

3.2 Downstream Rossby Wave Forcing

- **Rossby wave response to the suppressed convection** over **the eastern equatorial Indian Ocean** may re-initiate the convection.

Systematic diagrams illustrating a downstream forcing scenario in which a negative heating anomaly associated with suppressed-phase MJO may induce twin-gyre circulation in the tropical Indian Ocean through Rossby wave response.

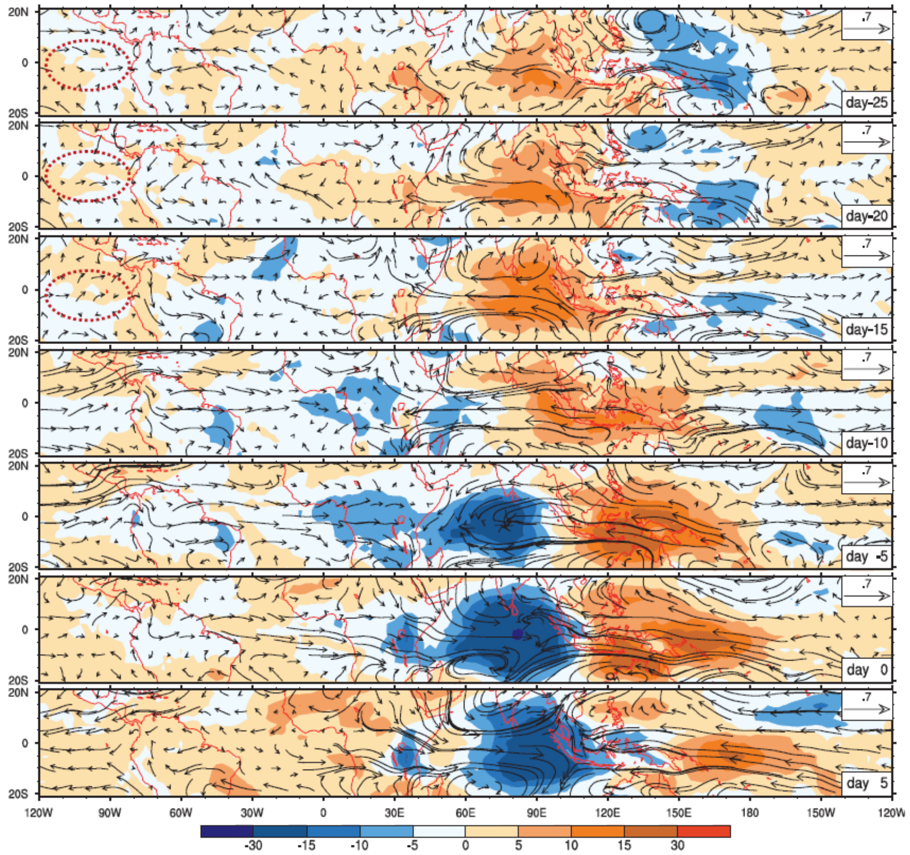
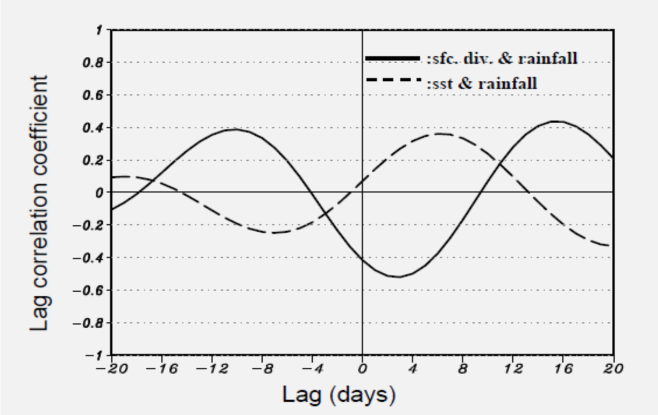


FIG. 11. Evolution of the composite OLR (color, W m^{-2}) and 850-hPa wind (vector, m s^{-1}) patterns from day −25 to day 5 at an interval of 5 days.

Li (2014 JMR)

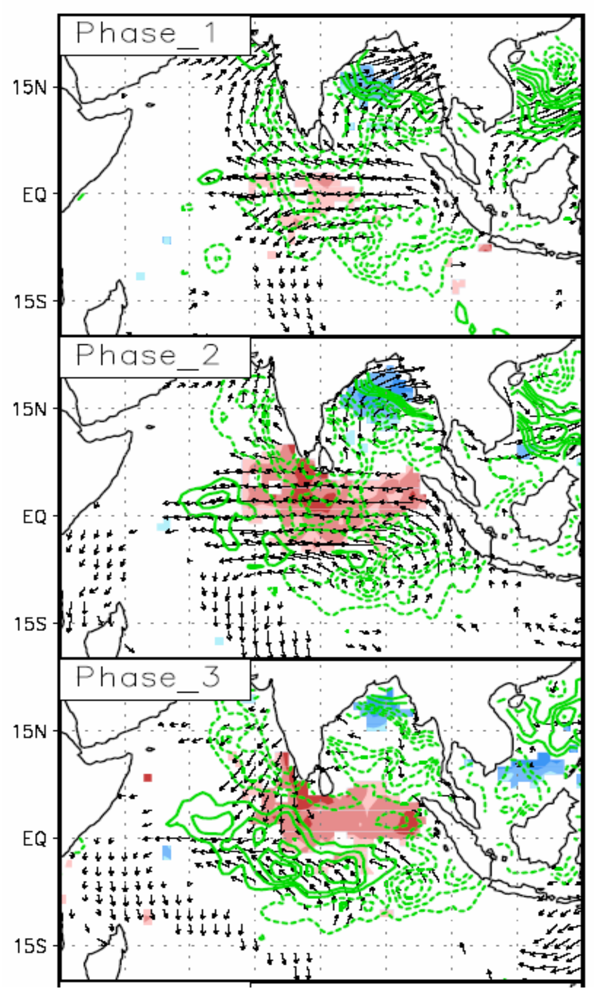
3.3 Self-Induction Mechanism

- The in situ **surface wind convergence and sea surface warming** that initiate new rainfall anomalies result from **the forcing of the previous active convection**, suggesting **a self-induction mechanism to sustain BSISO/MJO**.

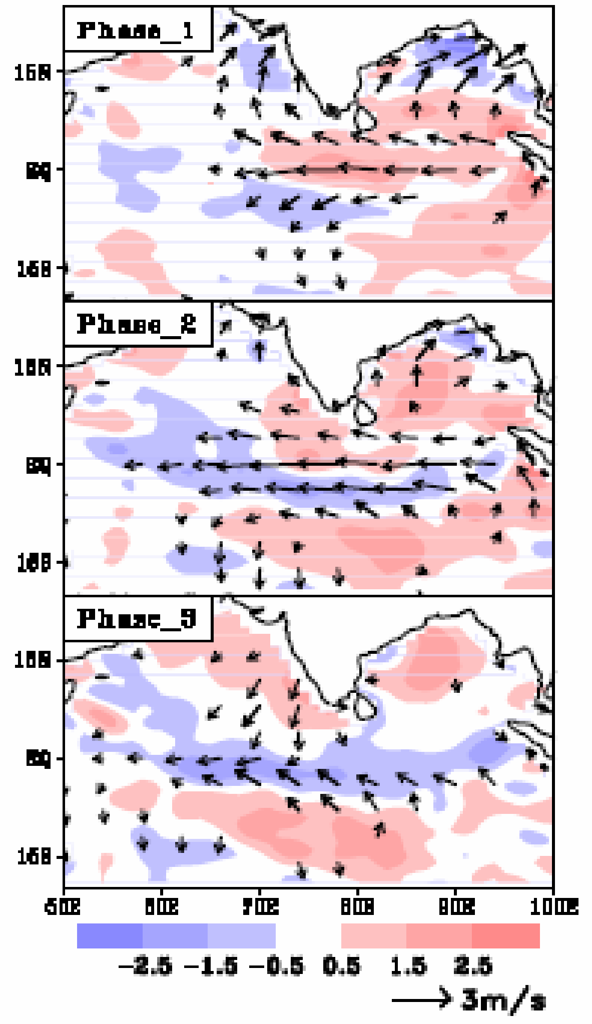


Surface convergence leads the genesis by 3-4 days and sea surface warming leads genesis by 6-7 days.

Rainfall (contours) and SST (color)



Surface winds and Divergence



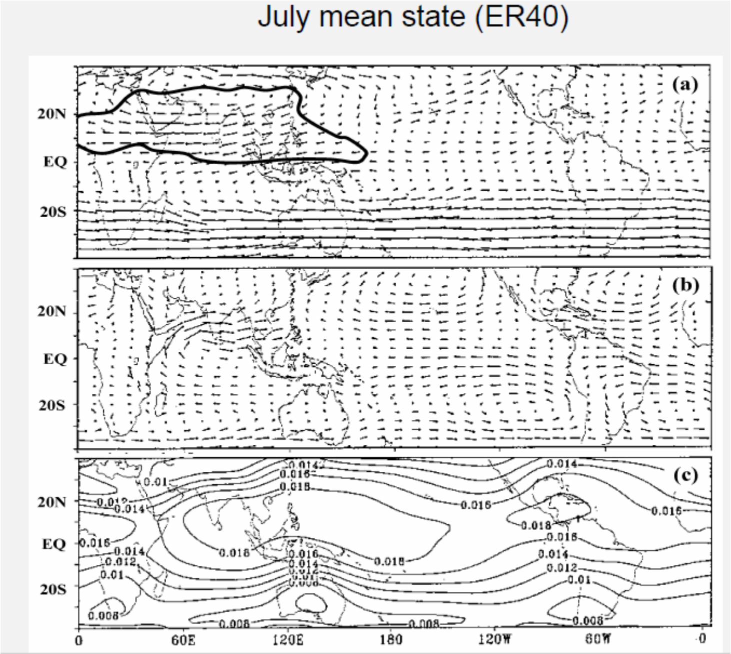
Wang et al. (2005)

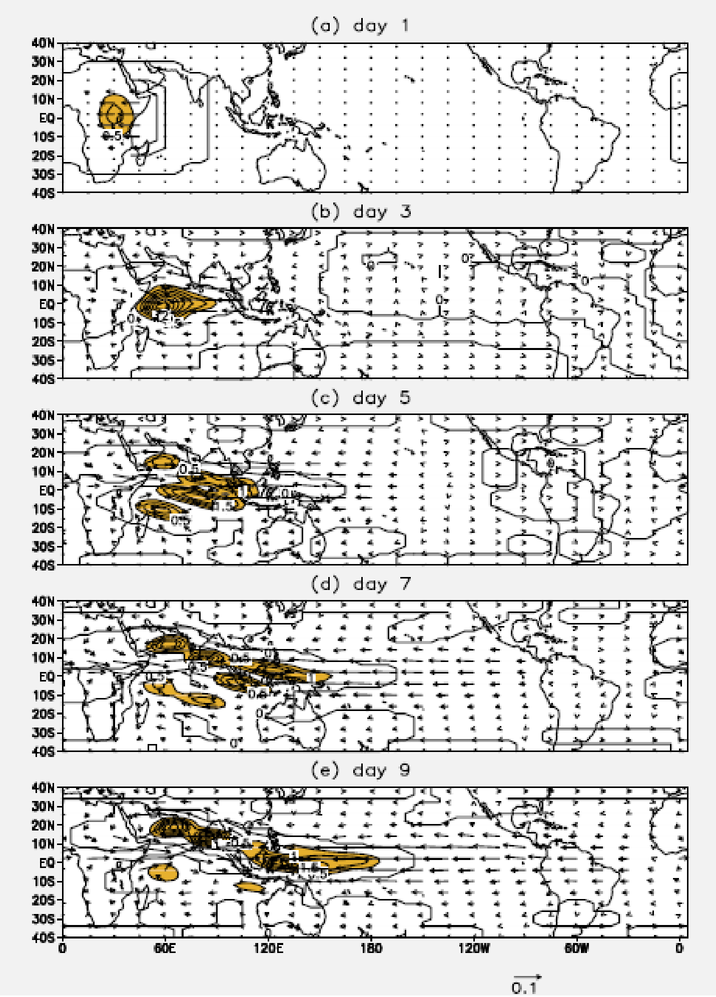
Content

4. Physical Mechanism for the NW-SE Tilted Rainband

Question 2: Why does the BSISO1 have a northwest-southeast (NW-SE) slanted structure?

- **Mean flows (easterly vertical wind shear) and SST distribution trap ISO in the Eastern Hemisphere.**
- The model experiment indicates that the **NW-SE slanted precipitation anomalies** in the monsoon regions forms due to **emanation of the moist Rossby waves** from **the equatorial rainfall anomalies over the maritime continent.**





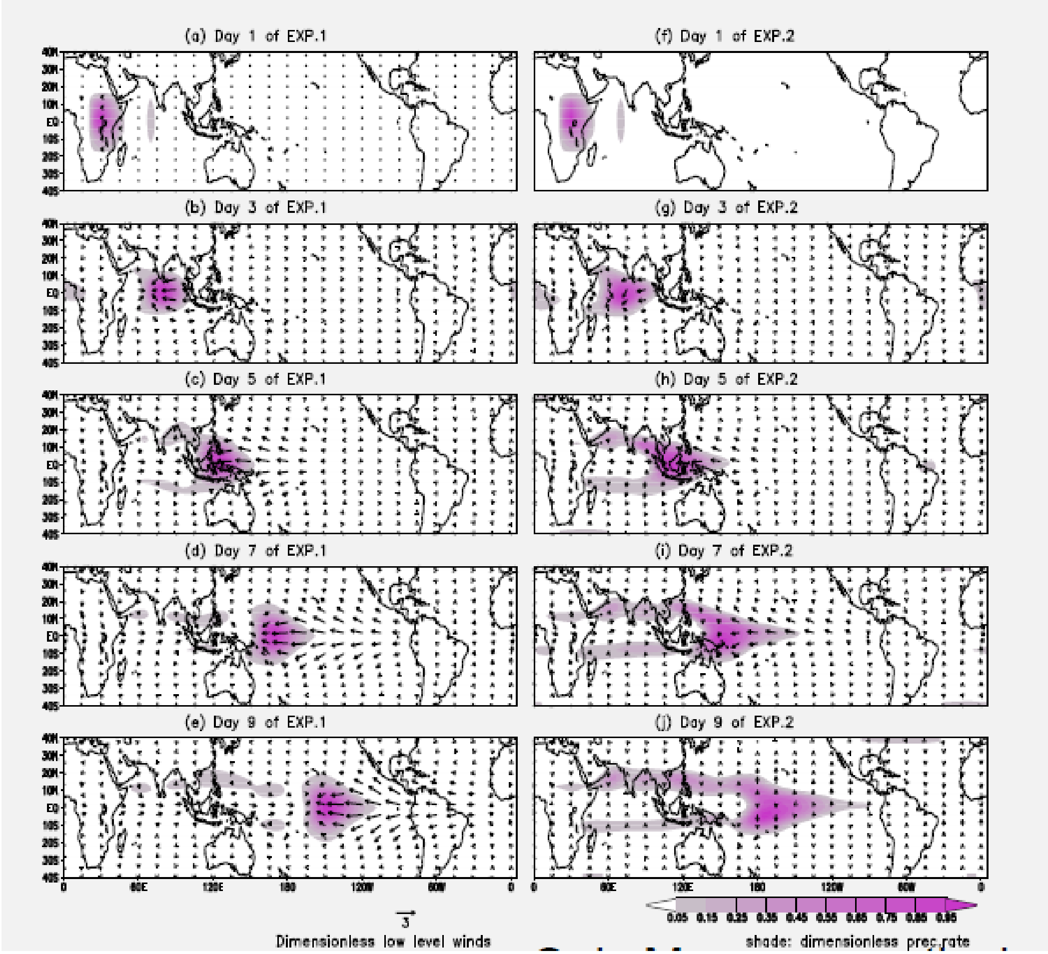
Model Result with Realistic SST and Vertical Wind Shear

Drbohlav and Wang 2005

4. Physical Mechanism for the NW-SE Tilted Rainband

Question 2: Why does the BSISO1 have a northwest-southeast (NW-SE) slanted structure?

- **Mean flows (easterly vertical wind shear) and SST distribution trap ISO in the Eastern Hemisphere.**
- The model experiment indicates that the **NW-SE slanted precipitation anomalies** in the monsoon regions forms due to **emanation of the moist Rossby waves** from **the equatorial rainfall anomalies over the maritime continent**.
- **Interaction** between **moist Rossby wave** and the **vertical shear** of the mean monsoon provides a **mechanism for the formation of the slanted ISO rain band**.



Mean Flow Removed Uniform SST

Only Monsoon Vertical Shear Included

Drbohlav and Wang 2005

Content

5. Physical Mechanism for Propagation of BSISO1

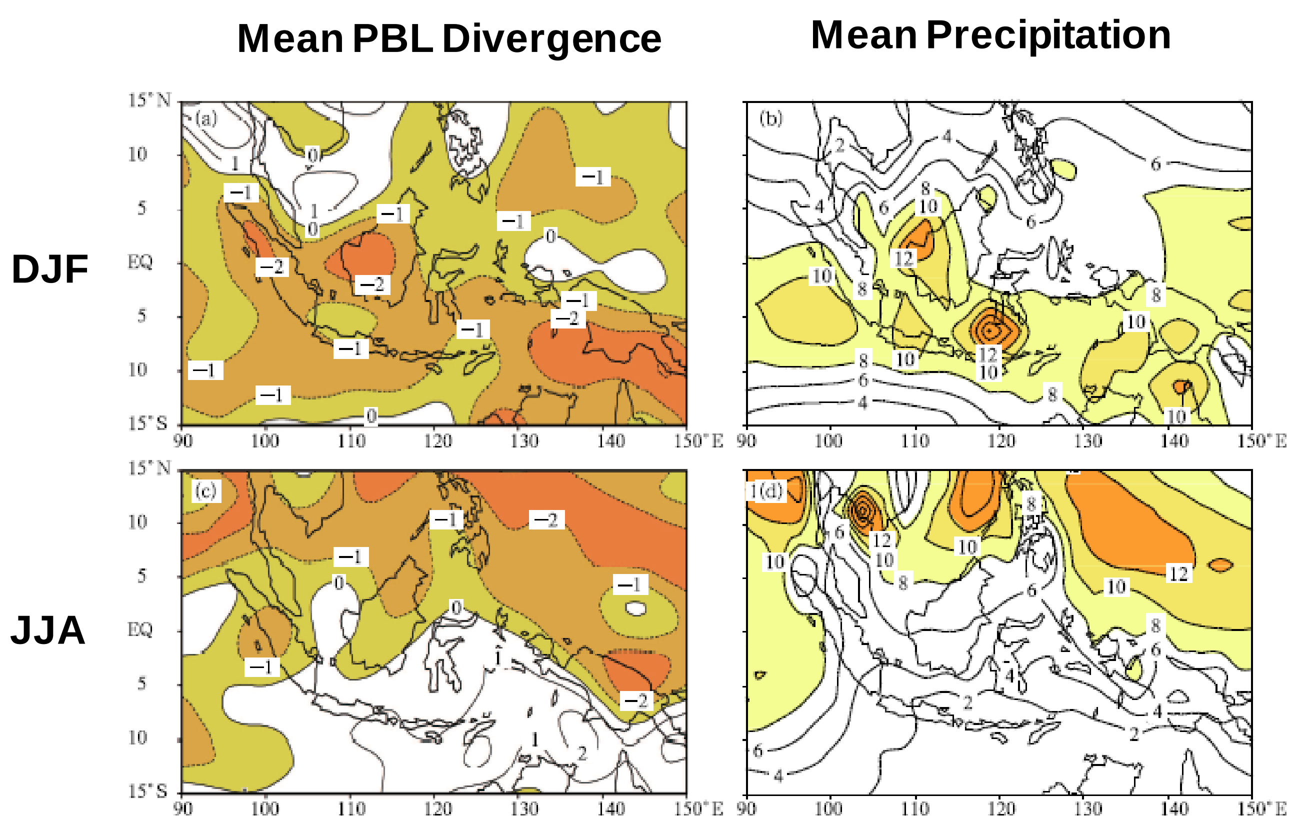
Question 3: Why move northward?

Hypotheses

- **Mean State Asymmetry:** The equatorial **Asymmetry of a thermal equator (SST distribution)** in boreal summer controls MJO propagation (Li 2014)
- **The Easterly Vertical Shear Mechanism (Interaction between vertical shear and convection)**: **Barotropic vorticity leads convective** anomalies in northward propagation (Jiang et al. 2004; Drbohlav and Wang 2005)
- **Moisture-convection feedback mechanism**: Moisture advection by the mean southerly in the PBL and by the BSISO wind due to the mean meridional specific humidity gradient contribute to the northward propagation (Jiang et al. 2004)
- **Air-Sea Interaction**: The Air-sea interaction enhances BSISO variability and intensifies the northward propagation due to both cloud radiation-SST and wind evaporation-SST feedbacks in boreal summer (Wang and Xie 1997; Waliser et al. 1999; Kemball-Cook and Wang 2001; Fu et al. 2003, 2006)

5.1 Mean State Asymmetry (SST control)

- **In boreal winter**, because maximum mean ascending motion and moisture are near the equator, atmospheric moist Kelvin waves are unstable and grow faster than Rossby waves => **Kelvin wave dominate** and MJO convection is confined near the equator.
- **In boreal summer**, because maximum mean ascending motion and moisture are located more than one Rossby radius of deformation away from the equator, **atmospheric moist Kelvin waves stabilize** due to the mean descending motion near the equator while **Rossby wave become unstable** => **Decoupling of Kelvin-Rossby wave** and **emanating the moist Rossby wave**.



Li (2014)

5.1 Mean State Asymmetry (SST control)

- **The equatorially asymmetric summer mean SST distribution** alone leads to the **decay of equatorial Kelvin waves** but **the growth of Rossby wave**
- In the presence of **realistic PBL moisture and divergence distribution** contributes to the growth of Rossby wave.
- **The background easterly shear and meridional moisture distribution** also contribute to the northward propagation.

Mean State Asymmetry plays an important role on the emanation of Rossby wave in JJA

- ➢ **Major Factor: SST distribution**
- ➢ **Contributing Factor: PBL moisture and divergence distribution, easterly vertical shear, meridional moisture distribution**

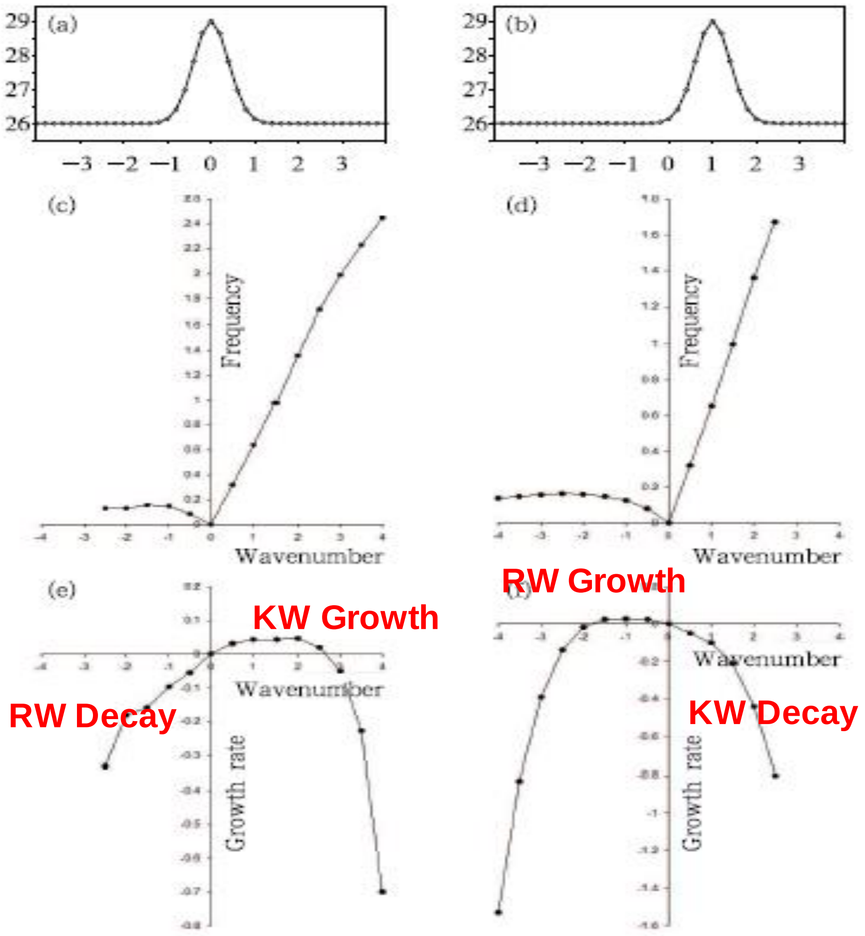
Experiment with Idealized Background meridional SST distribution

DJF | **JJA**

Meridional SST distribution

Non-Dimensional Frequency

Non-Dimensional Growth Rate

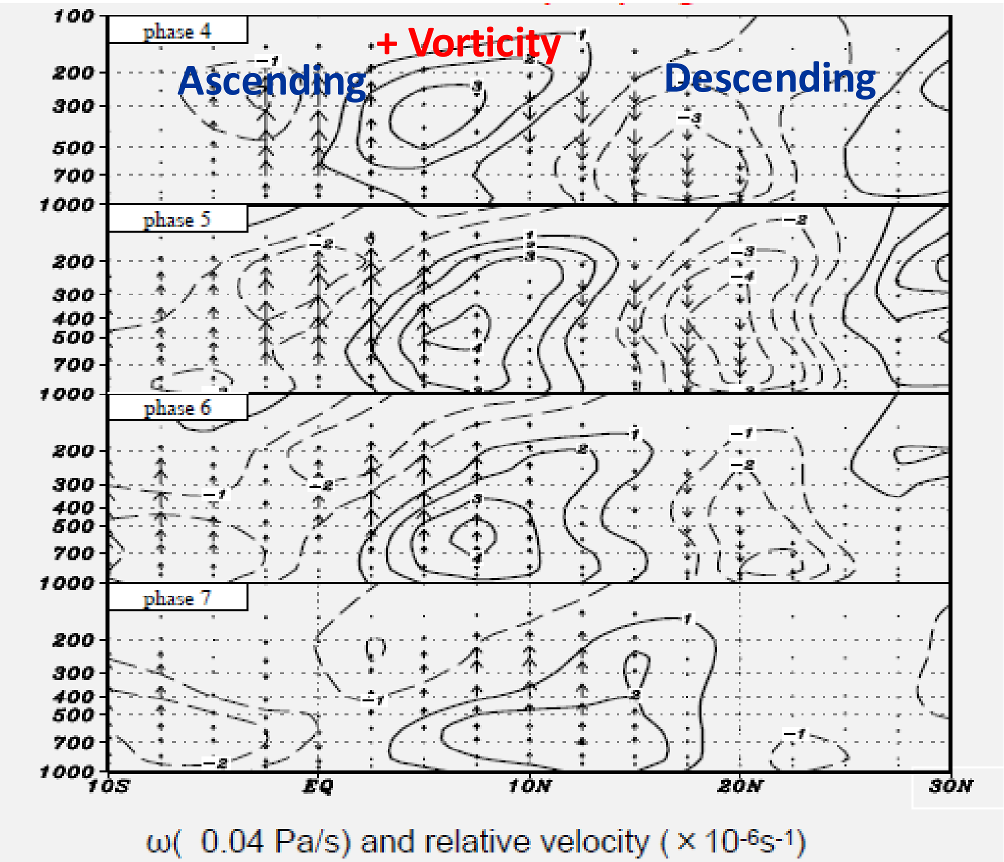


Li (2014)

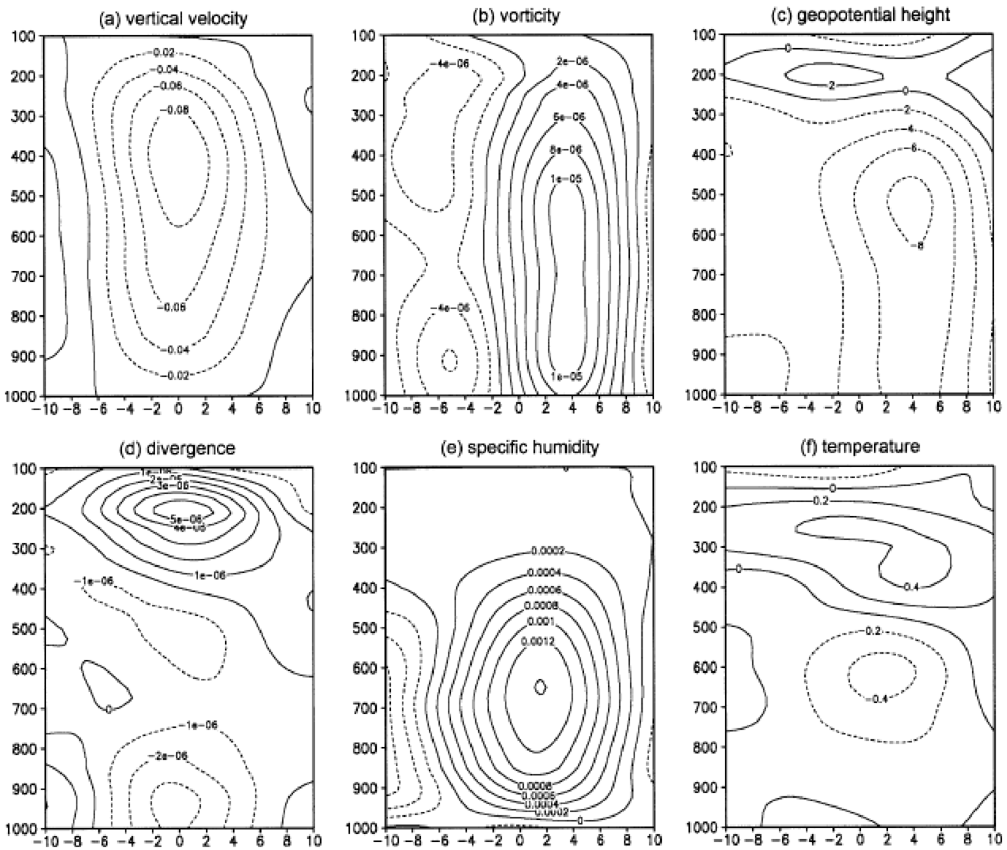
5.2 The Vertical Shear Mechanism

Major Point: Barotropic vorticity leads convective anomalies **in northward propagation.** Barotropic cyclonic vorticity induces boundary layer moisture convergence **that** leads to northward propagation of BSISO convection.

Observation



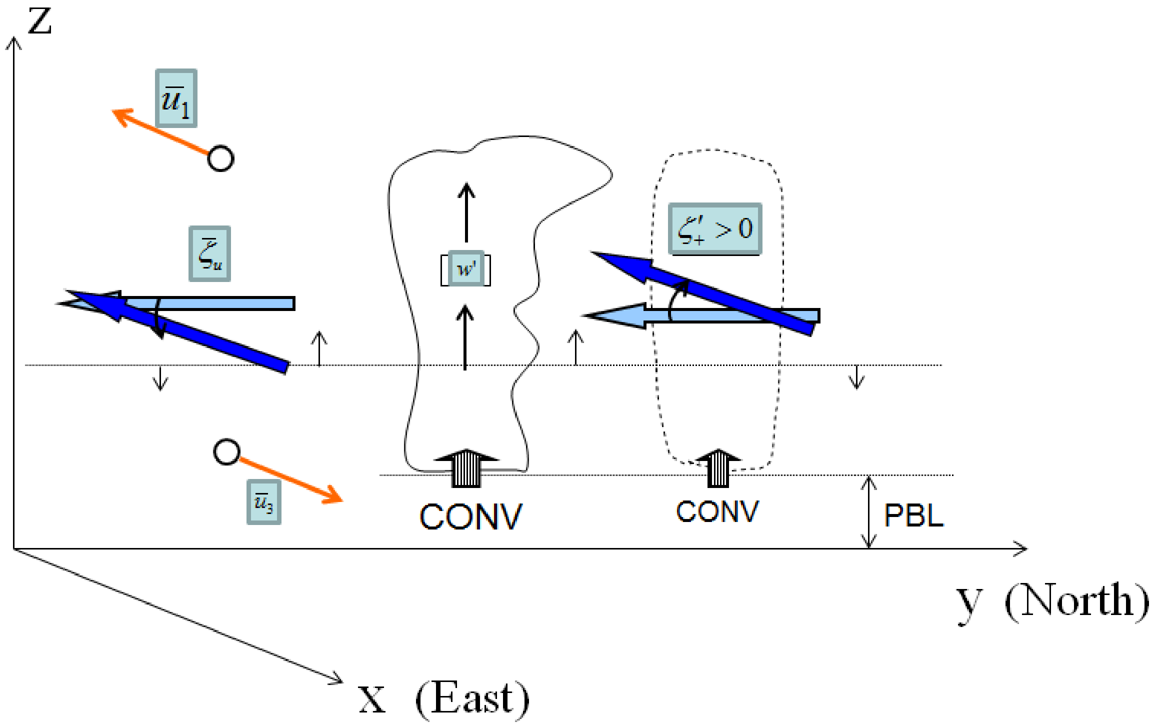
ECHAM Model



Jiang et al. (2004)

5.2 The Vertical Shear Mechanism

Atmospheric Internal Dynamic Mechanism: **Monsoon easterly vertical shear provides a vorticity source** => **Rossby wave-induced heating generates a perturbation vertical motion**, which twists mean flow horizontal vorticity => **positive vorticity is generated to the north of the convection region** => The **creating boundary layer moisture convergence favor northward movement of the enhanced rainfall**



Generation of Barotropic Vorticity

$$\frac{\partial \varsigma_+}{\partial t} = -\beta v_+ - U_T \left(\frac{\partial \omega}{\partial y} \right)$$

Wang and Xie (1996)

Jiang et al. (2004)

5.3 Moisture-Convection Feedback Mechanism

A. Moisture Advection by the Mean Southerly Flow in the PBL:

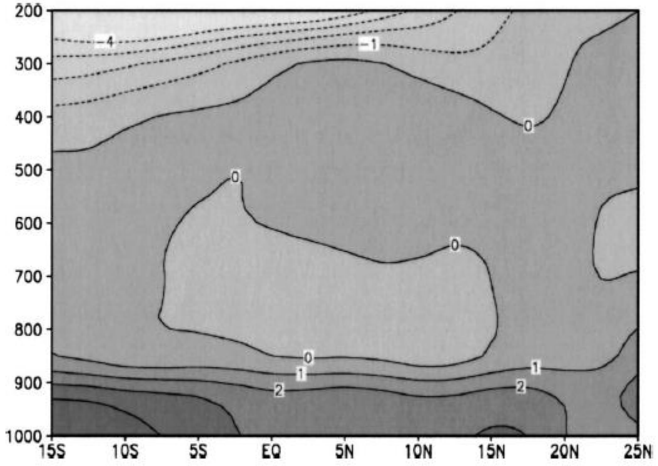


FIG. 11. Meridional–vertical profile of the north–south component of the summer mean flow (m s^{-1}) averaged between 70° and 95°E.

◀**The obs summer mean flow over the EIO sector shows a prevailing northward component in the PBL**

Hypothesis

$$\frac{\partial q}{\partial t} \propto -\overline{v_B}\frac{\partial q}{\partial y} \propto -w_B\frac{\partial \bar{q}}{\partial p}$$

▼ **Consider a strong ISO convection with convergence(divergence) at the sfc (upper) level.**

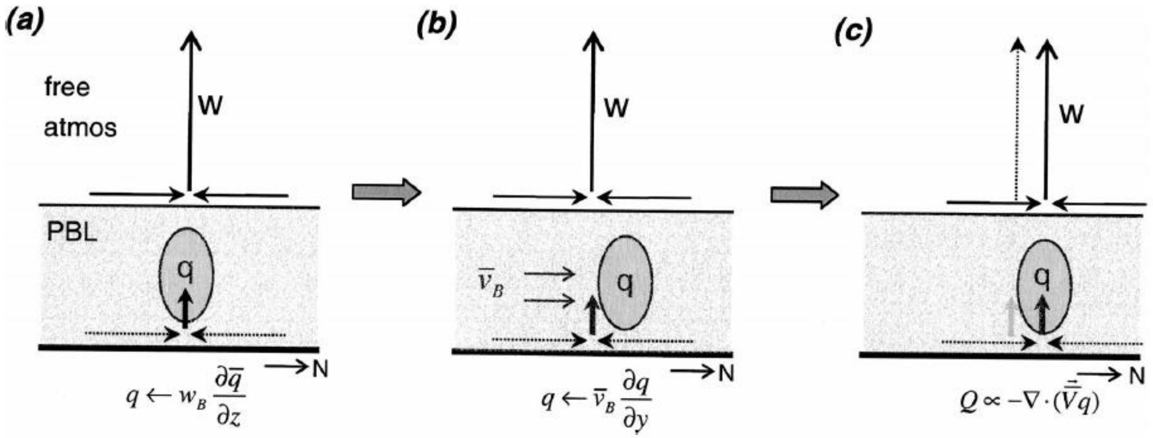


FIG. 12. Schematic diagram for the mechanism of moisture advection by mean flow. (a) The specific humidity perturbation caused by Ekman pumping is advected (b) by the mean northward meridional wind in the PBL, (c) which leads to the northward shift of moisture convergence and thus convective heating to the convection center.

(a) **Convergence** at sfc level -> **upward motion in the BL**.

(b) **Advection effect by the summer $\overline{v_B}$** in the PBL -> **shift the q center to the north of the convection**

(c) As the convective heating largely depends on the moisture convergence, the **shifted q center -> lead to the northward displacement of the convective heating** and thus the convection tends to move northward

Jiang et al. (2004)

5.3 Moisture-Convection Feedback Mechanism

B. Moisture Advection due to the mean meridional moisture gradient

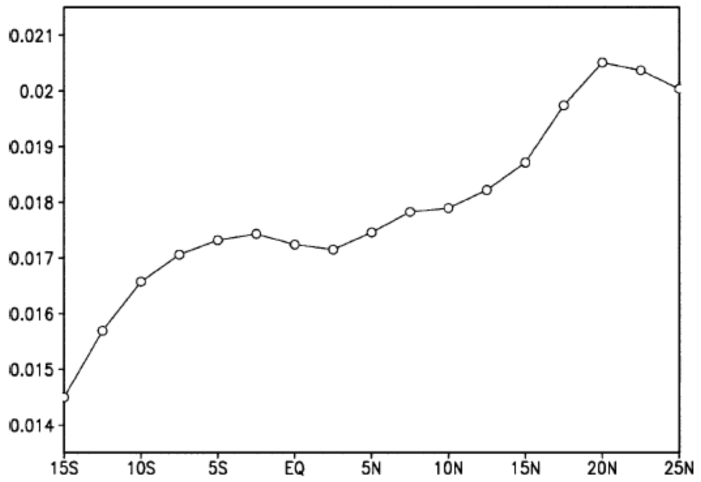


FIG. 13. Meridional profile of the summer mean specific humidity (kg kg^{-1}) at 1000 mb averaged between 70° and 95°E.

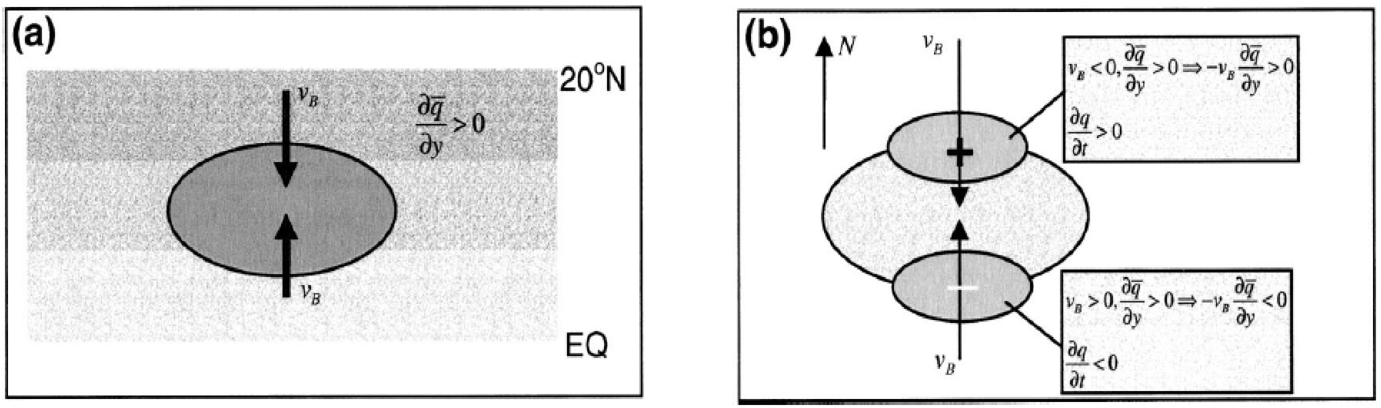


FIG. 14. Schematic diagram for the mechanism of moisture advection by the ISO wind in the presence of the mean specific humidity gradient. The meridional asymmetric mean specific humidity field is advected by convection-induced perturbation wind, (a) southward to the north of a convection center and northward to the south, which leads to a (b) positive moisture perturbation to the north and negative to the south of the convection center. As a result, the convection tends to move northward.

The meridional distribution of the JJA moisture maximum moisture : 20˚N over the northern IO

The **meridional asymmetric mean specific humidity field is advected** by convection-induced perturbation wind southward to the north of a convection center and northward to the south => **positive moisture perturbation to the north** and **negative to the south of the convection center** => As a result, **the convection tends to move northward**

Jiang et al. (2004)

5.4 Roles of Air-Sea Interaction

Findings

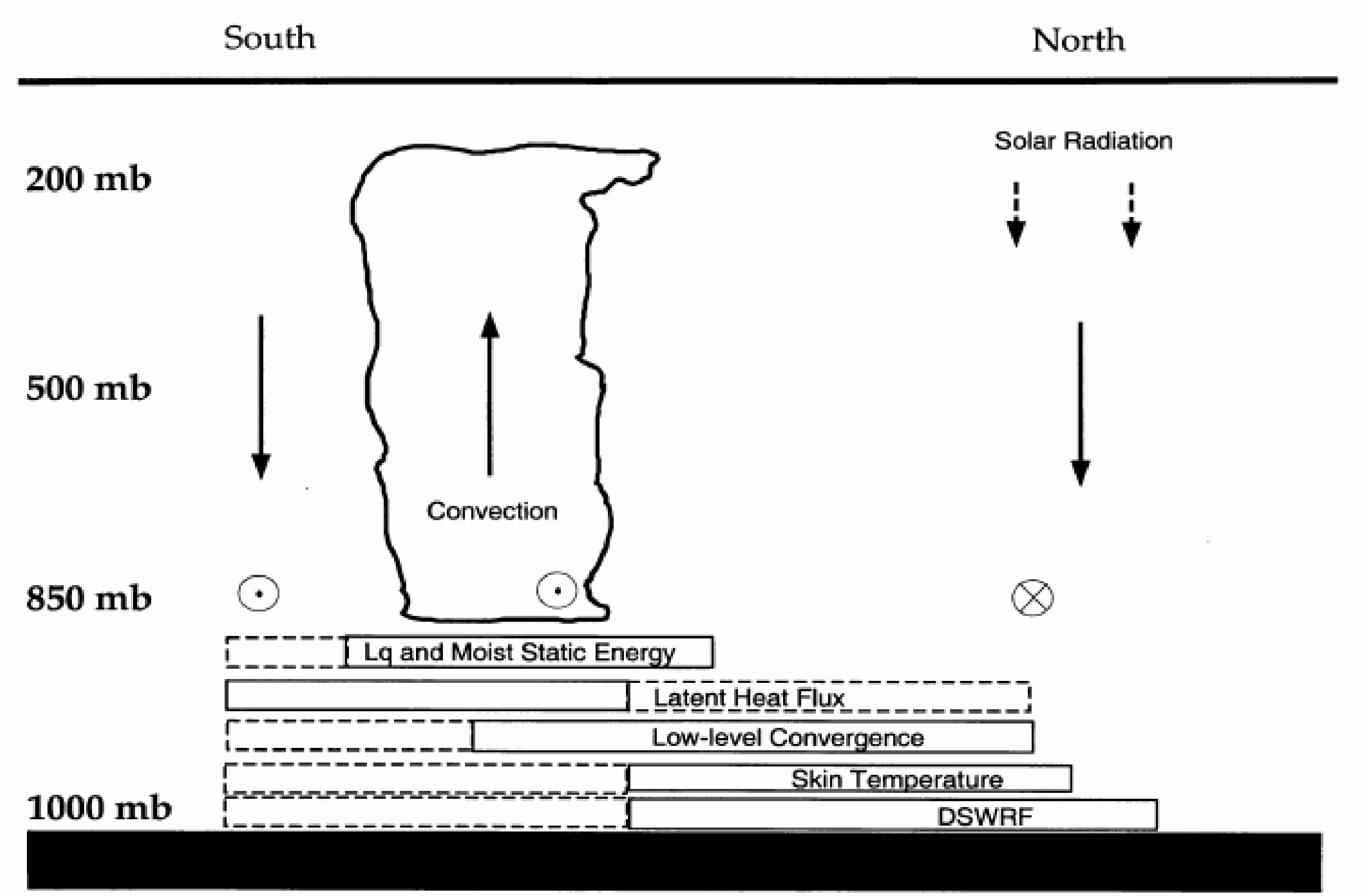
- Air-sea interaction **enhances ISO variability** (Flateu 1997; Wang and Xie 1998; Waliser et al. 1999 and many others)
- **AGCM (AMIP run) failed to simulate correct SST-Precipitation relationship**: in phase in the AGCM models but 90 degrees out of phase in reality (Wu et al. 2002)
- CGCM and AGCM alone yield fundamentally different ISO solution. **Air-sea coupling leads to realistic SST-precipitation relationship** (Fu et al. 2003)
- Air-Sea interaction **enhance predictability to BSISO** (Fu et al. 2006)

Questions

- How does the air-sea interaction enhance northward propagation of ISO?

5.4 Roles of Air-Sea Interaction

Observed Characteristics of Air-Sea Interaction in BSISO

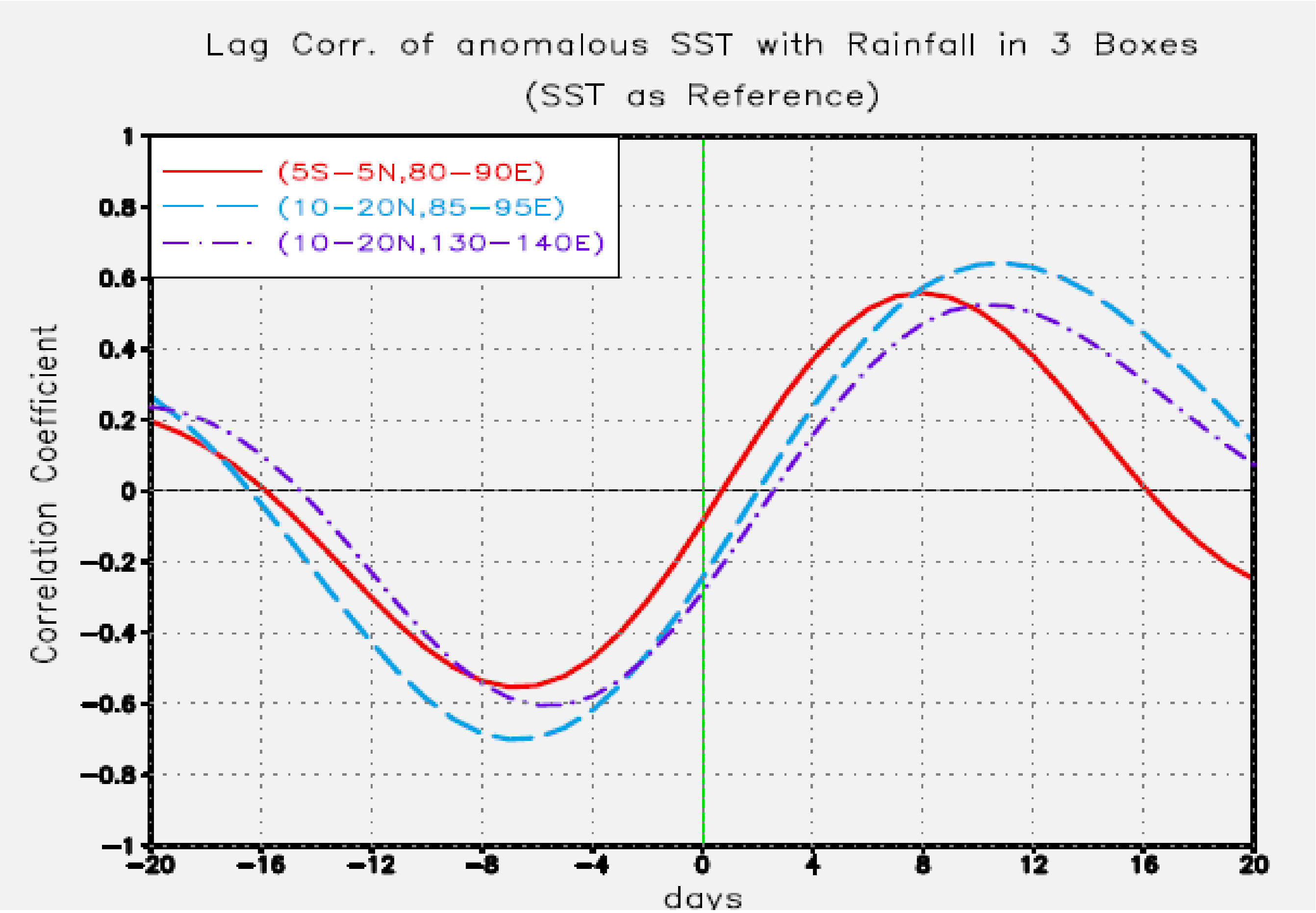


Cloud radiation-SST feedback and wind evaporation-SST feedback induce the northward propagation of ISO

Kemball-Cook and Wang (2001)

5.4 Roles of Air-Sea Interaction

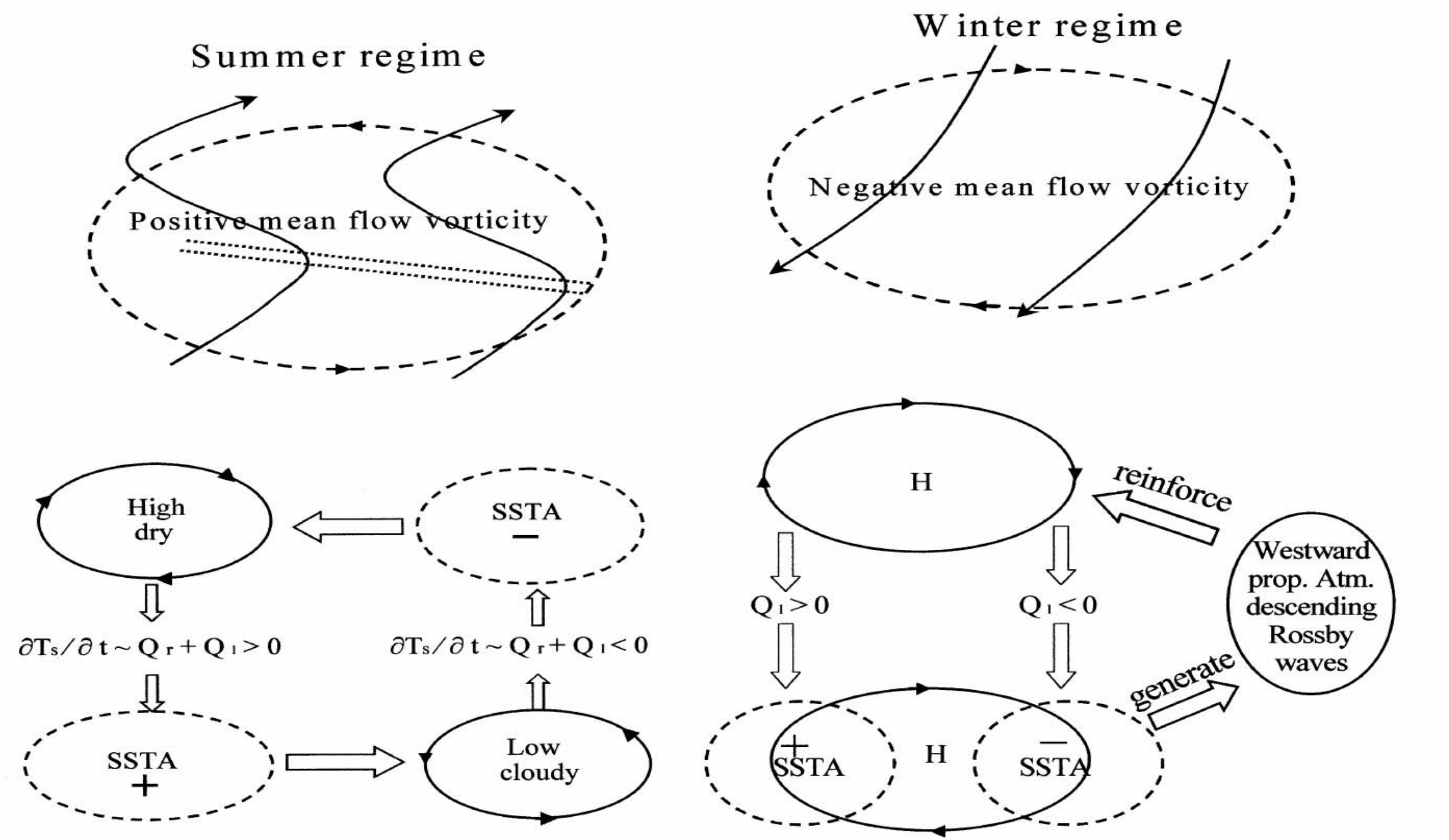
Observed Relationship between SST and Rainfall Anomalies



The local SST-rainfall phase relationship differs between the equatorial regions and off-equatorial monsoon region. In the off-equatorial region, SST leads convection by about 11 days.

Kemball-Cook and Wang (2001)

5.4 Roles of Air-Sea Interaction in the WNP



Both Cloud Radiation-SST and Wind Evaporation-SST Feedbacks in Summer Sustains ISO

Wind evaporation-SST Feedback in Winter Damps ISO and Persists the WNP Subtropical High

Content

6. Summery

BSISO1, the canonical northward propagating mode, is a modified MJO mode (the frictionally coupled moist Kelvin-Rossby wave) by boreal summer mean flows (Wang and Xie 1997; Wang 2005)

Essence of BSISO Dynamics

- **(a) The BSISO variability pattern is controlled by trapping effects of combined Easterly Vertical Shear and Moist Static Stability**
- **(b) The convective band forms due to emanation of the moist Rossby waves as equatorial Kelvin-Rossby Couplet weakens**
- **(c) Easterly Vertical Wind Shear plays a key role in formation of the BSISO rain band** destabilize the equatorial Rossby waves (most unstable wavelength of ~4,000 km) **and northward propagation of the BSISO**

References

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THANK YOU