中国科学院大气物理研究所
大气科学和地球流体力学数值模拟国家重点实验室

Impact of the Tibetan Plateau on East Asian Summer Monsoon: a Land–Air–Sea Interaction Perspective

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Targeted Trianing Activity

Content

1. Introduction

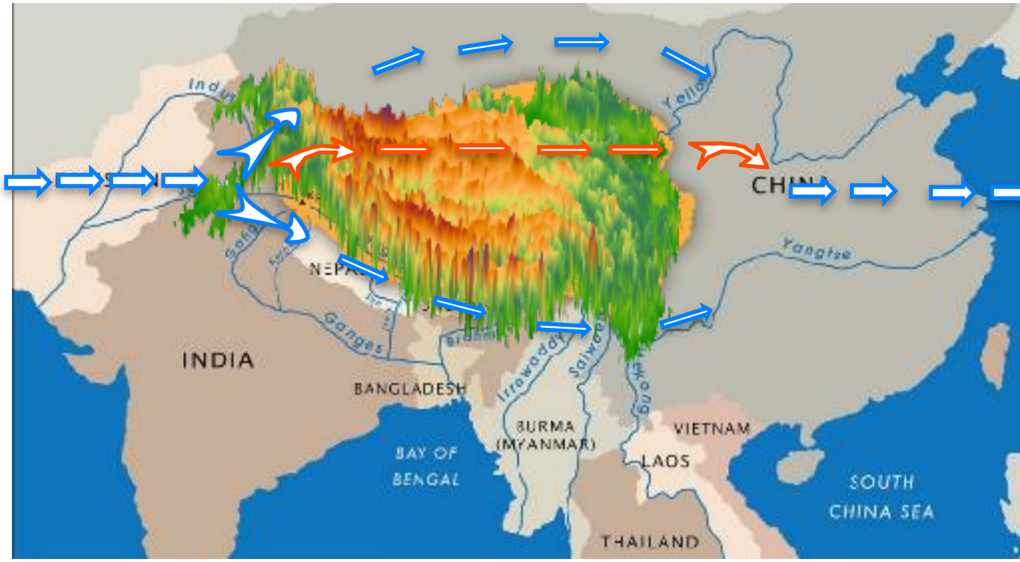
2. Relative contribution of the Tibetan Plateau heating and the IOBM

3. Oceanic Forcing on East Asian Summer Monsoon Altered by Tibetan Plateau Heating Effect

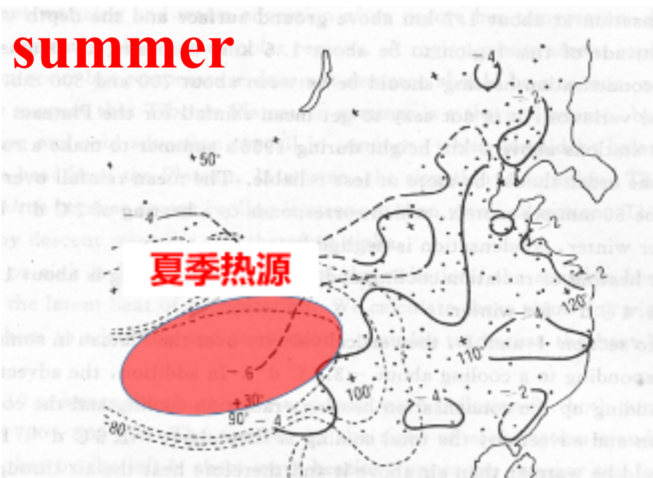
Importance of the Tibetan Plateau

Mechanical control in winter

(Yeh, 1950,Tellus)

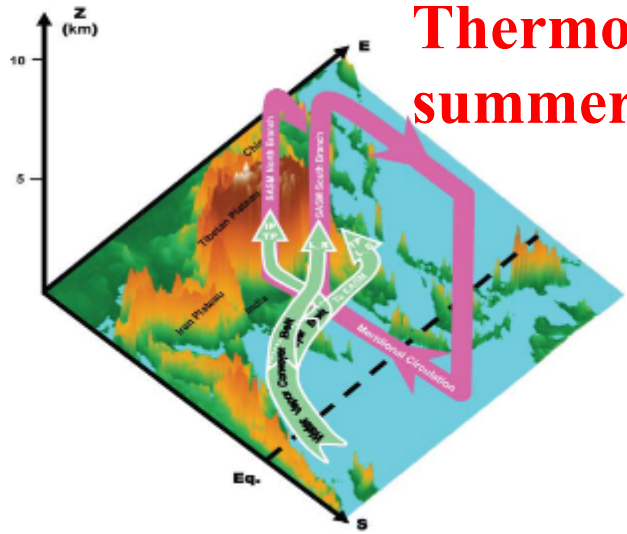


A strong heat source in summer



叶笃正，罗四维，朱抱真，1957：西藏高原及其附近的流场结构和对流层大气的热量平衡，气象学报，28（2），108-121.

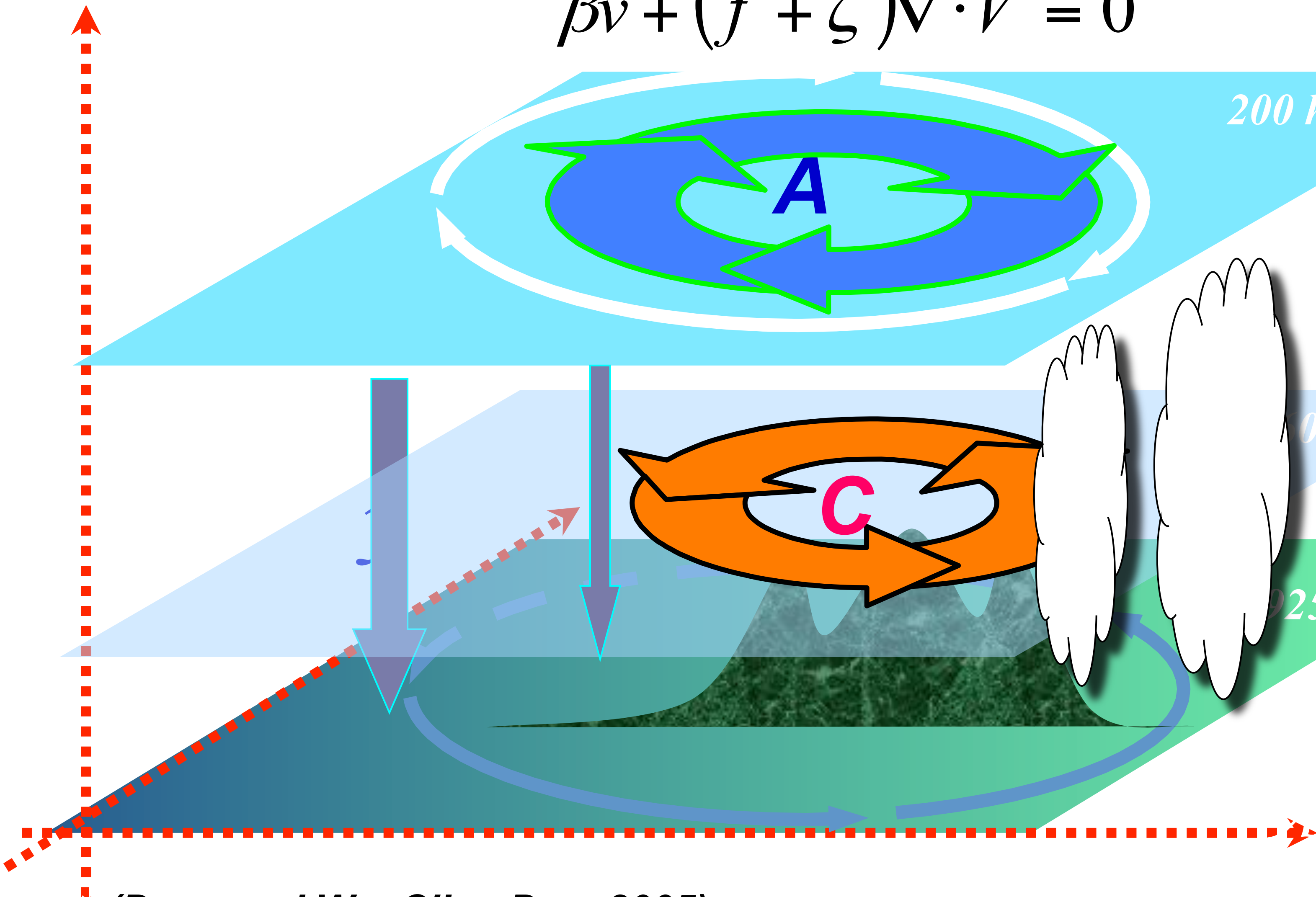
Thermol control in summer



(Wu et al., 2012, Sci Rep
An et al., 2015, Annu Rev Earth Palnet Sci)

Schematic diagram of the role of TP thermal forcing in the summer climate patterns

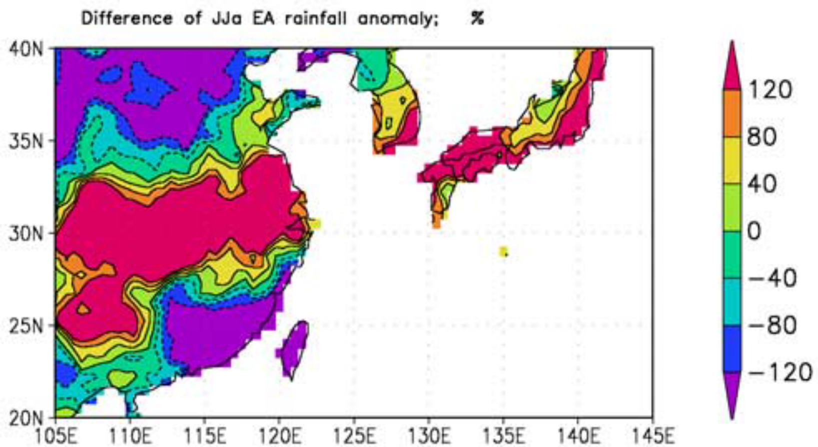
$$\beta v + \left(f + \zeta\right)\nabla \cdot \vec{V} = 0$$



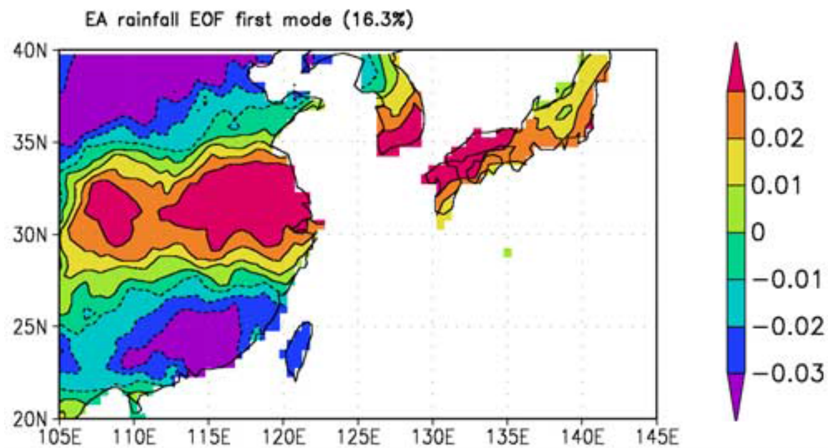
(Duan and Wu, Clim. Dyn. 2005)

Interannul variation of EASM precipitation and TP heating

Precipitation difference between strong and weak Tibetan Plateau heating years

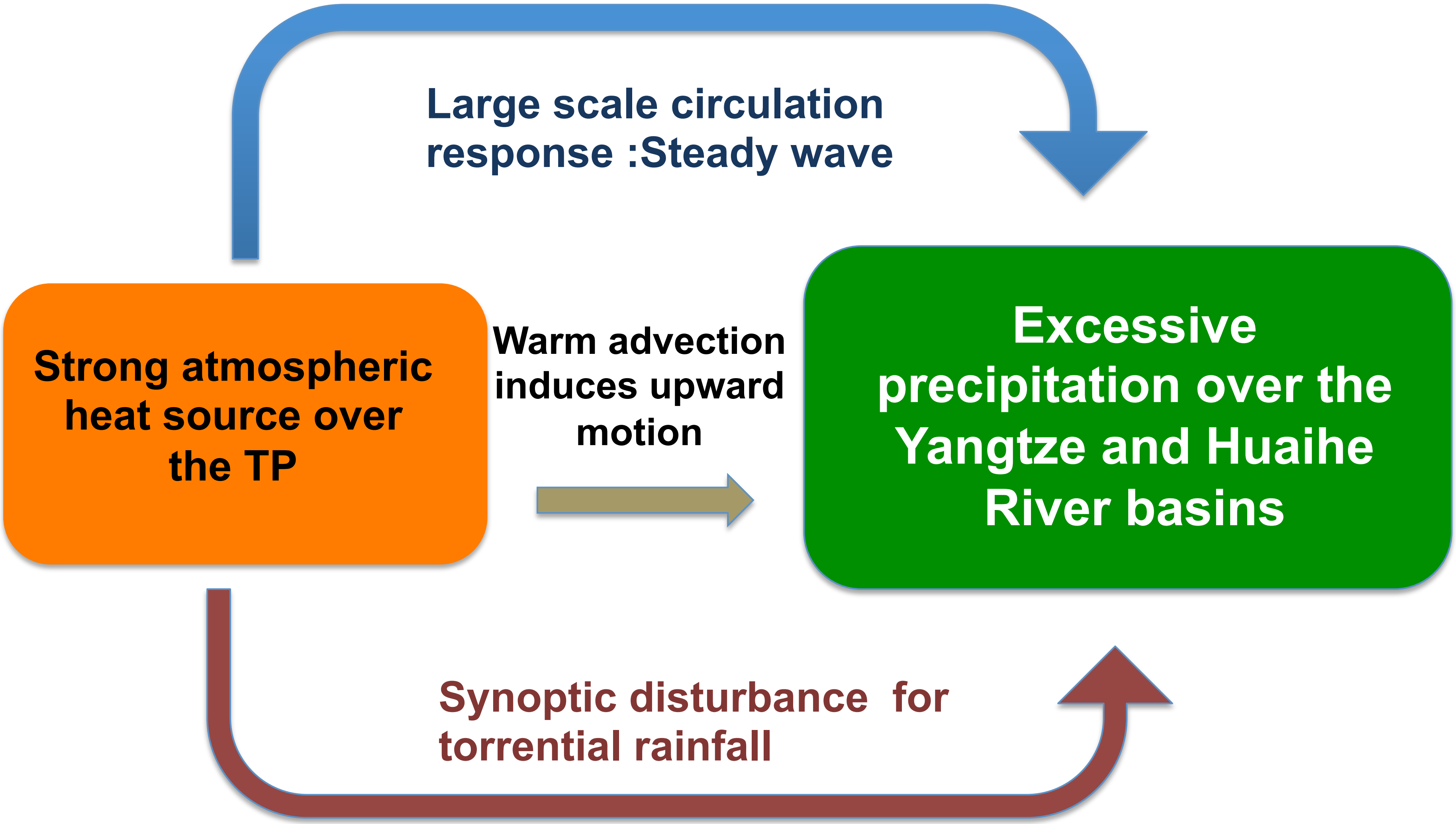


EOF1 of East Asian summer rainfall



(Hsu and Liu 2003)

Impact on summer rainfall anomaly in EASM

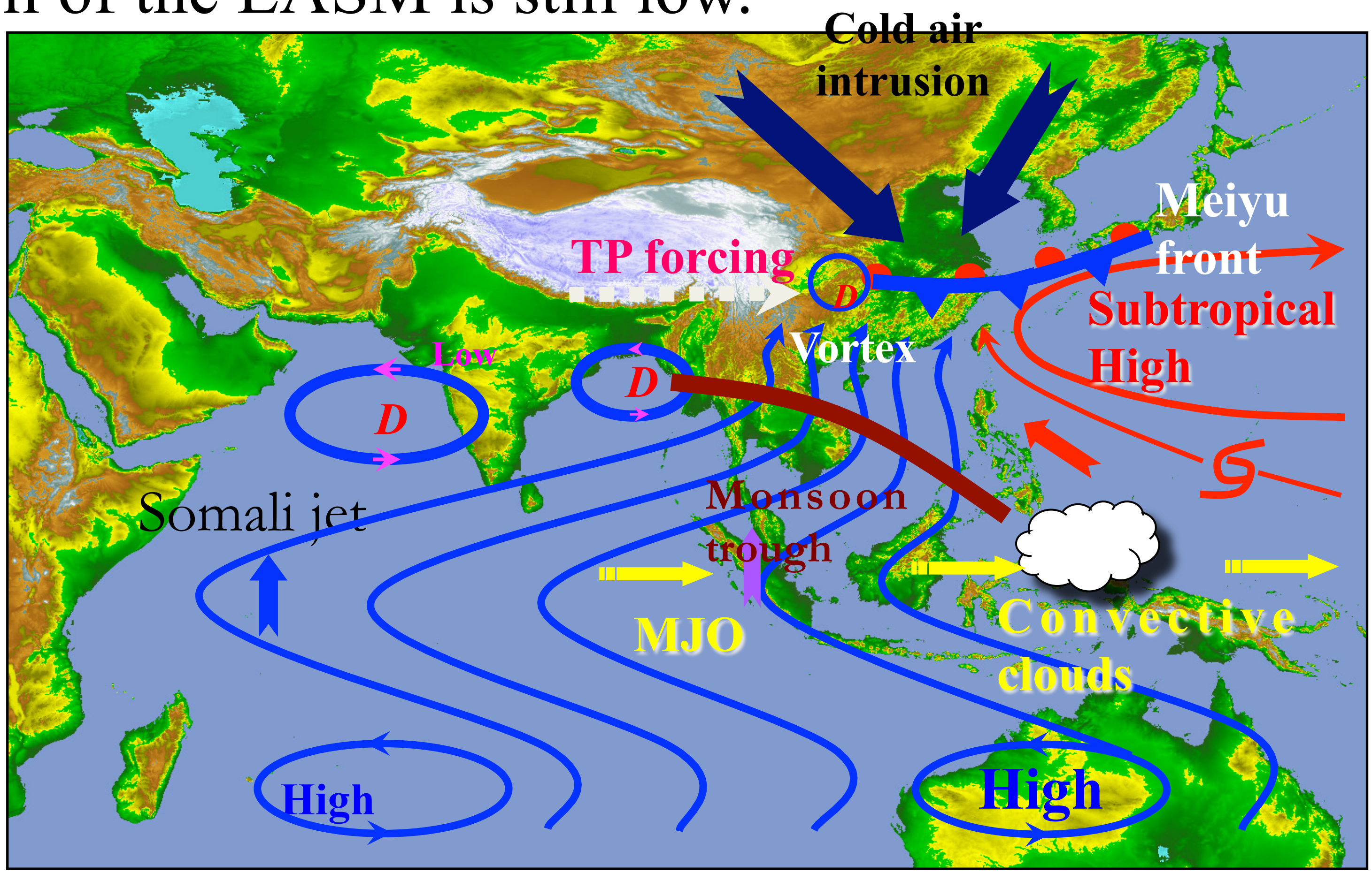


(Wang et al., 2014, Clim. Dyn. 2014)

Content

Motivation

- Many external factors are known to have impacts on the interannual variability of the EASM, but the prediction skill of the EASM is still low.

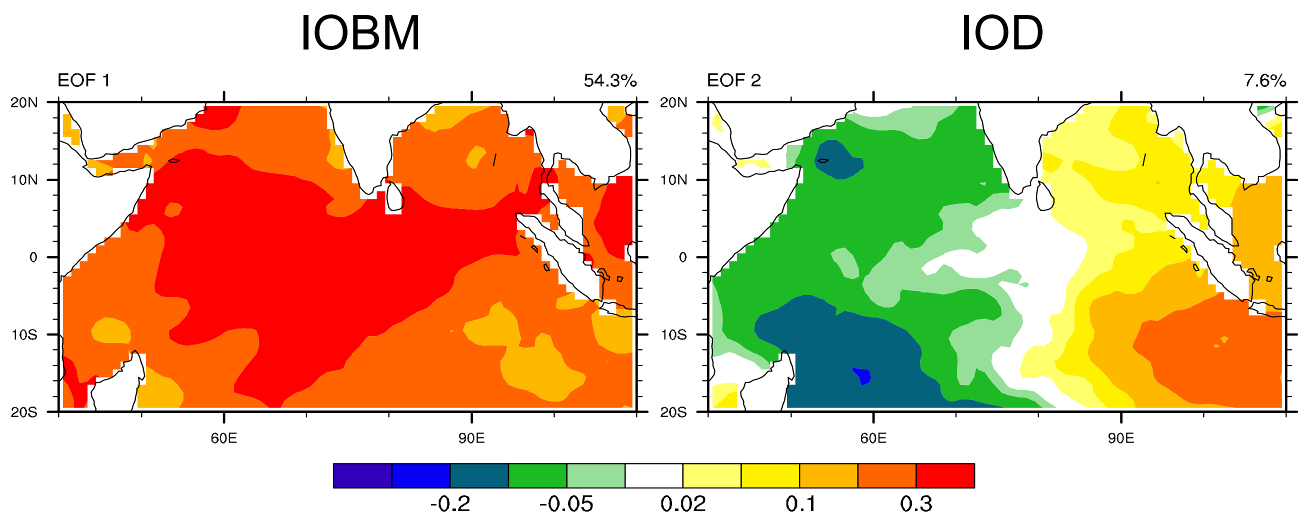


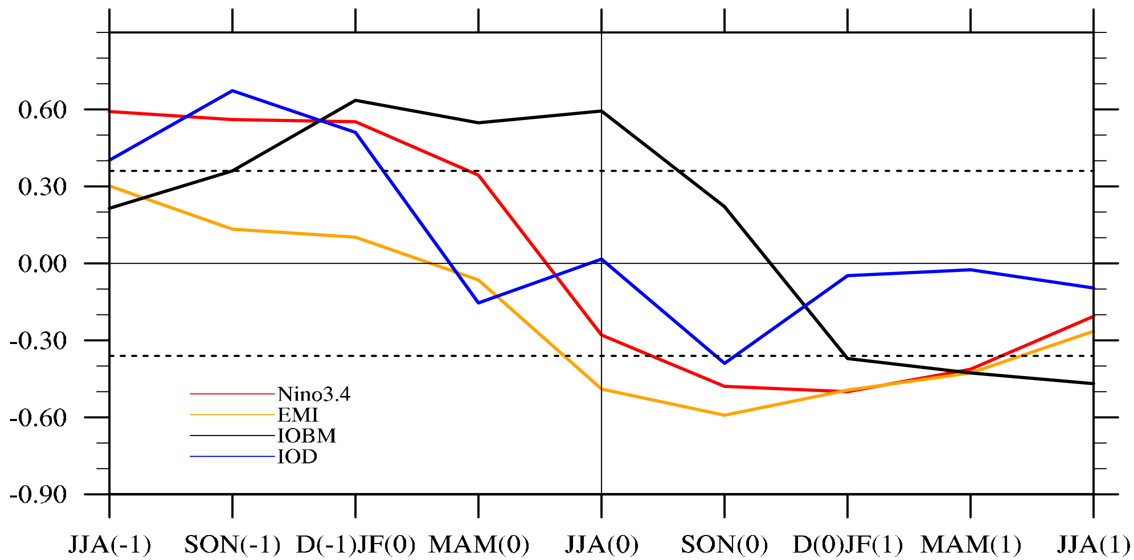
(Zhang and Tao 1998)

Motivation

- **Perhaps one reason is the lack of understanding of the relationships among different contributing factors.**
- **Some previous studies have attempted to discuss the relative contributions of different factors affecting the Asian monsoon (Yang and Lau 1998; Gong and Ji 1998a, b).**
- **Nevertheless, the relative contribution of land and ocean to the interannual variability of the EASM in terms of circulation and precipitation anomalies remains unclear.**

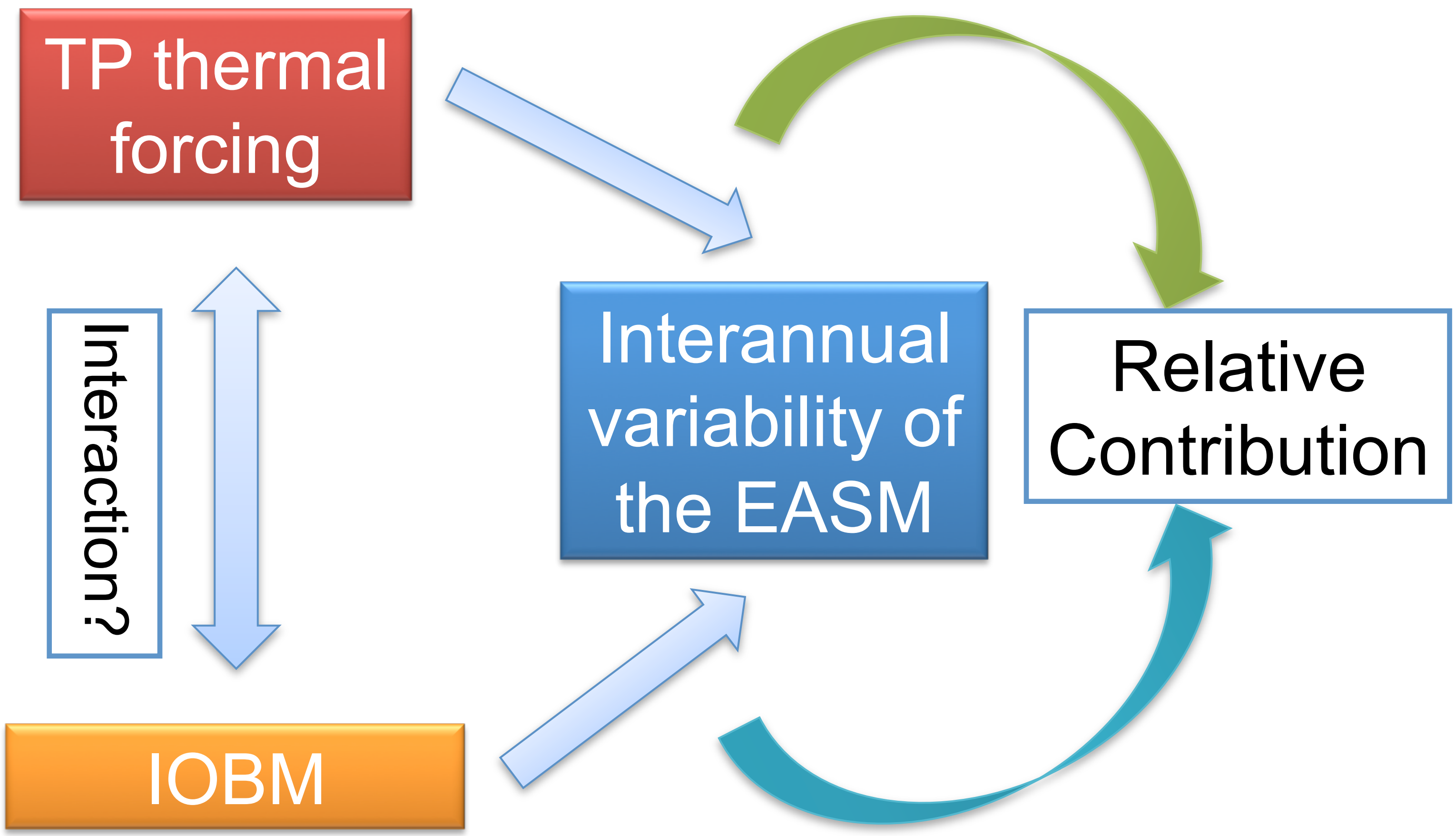
Impacts of the IOBM on the EASM





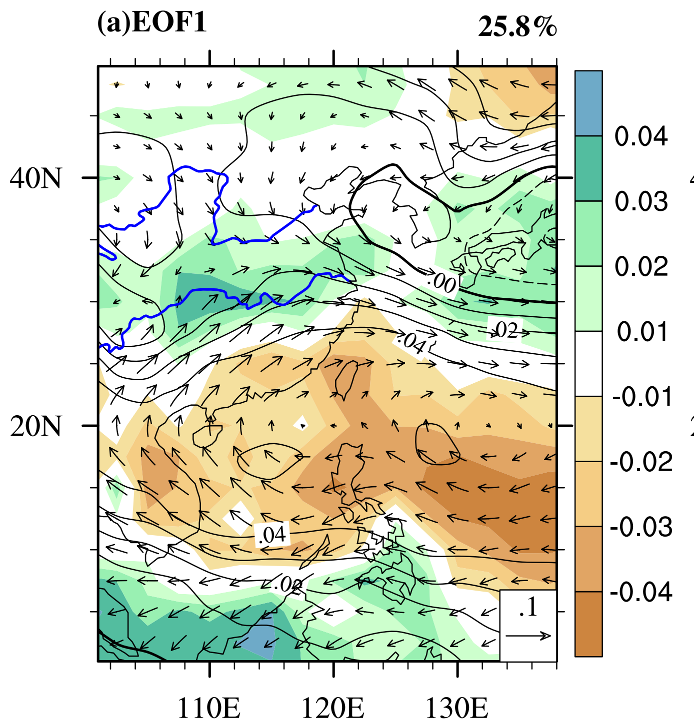
Lead–lag correlation between the EASM index (Wang et al. 2008b) and four main ocean indexes of different seasons.

Contents


TP thermal forcing
Interaction?
IOBM
Interannual variability of the EASM
Relative Contribution

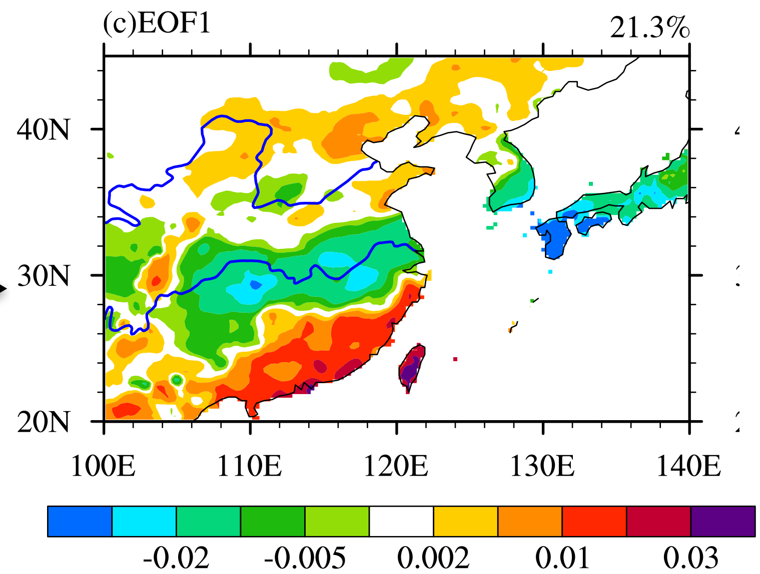
Definition of East Asian summer monsoon

The EASM index (Wang et al. 2008), is the simpler version of the PC1 of the interannual variability of the EASM obtained from the MV-EOF.
The PC1 of East Asian summer precipitation is also used as PR index.



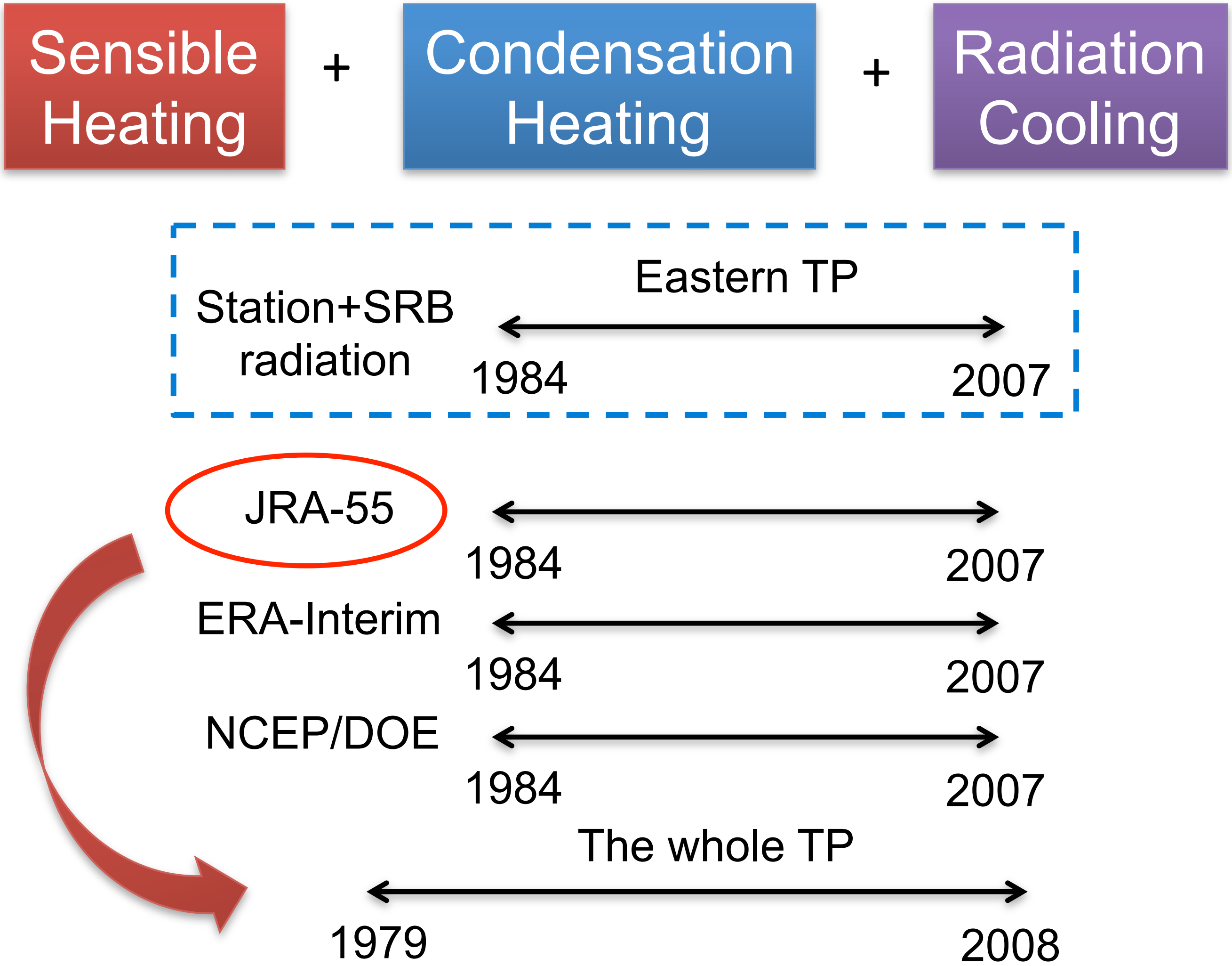
The leading mode of the MV-EOF of 850 hPa wind, precipitation (shaded) and sea level pressure (contour)

r=0.58



The leading mode of the EOF of East Asian summer precipitation based on APHRODITE

Atmospheric heat source over the Tibetan Plateau



Data analysis based on observations

	IOBM	TP thermal forcing
Correlation with the EASM index	0.615**	0.415*
Partial correlation with the EASM index	0.589**	0.361*
Correlation with the PR index	0.232	0.638**
Partial correlation with the PR index	0.120	0.618**
Standard regression coefficient on the EASM index	0.550**	0.292*
Standard regression coefficient on the PR index	0.094	0.618**

Partial correlation:

$$r_{12,3} = \frac{r_{12} - r_{13}r_{23}}{\sqrt{(1 - r_{13}^2)(1 - r_{23}^2)}}$$

Standard regression coefficient:

$$y = \hat{\beta}_1 x_1 + \hat{\beta}_2 x_2 + \hat{\beta}_0$$

$$b_i = \hat{\beta}_i s_{x_i} / s_y$$

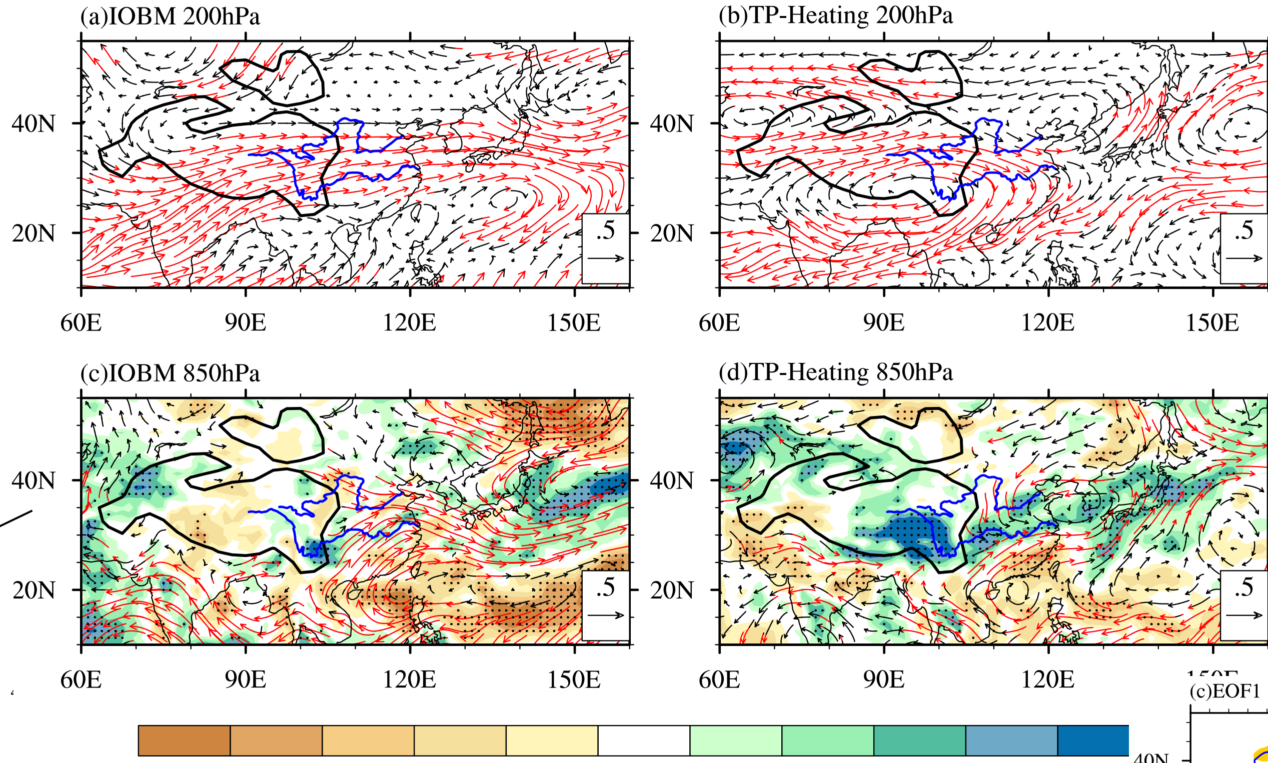
Data analysis based on Partial Correlations

IOBM/TP-Heating vs. Circulation/Precipiation

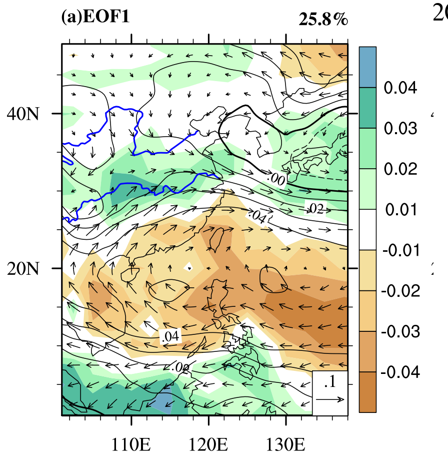
IOBM | TP-Heating

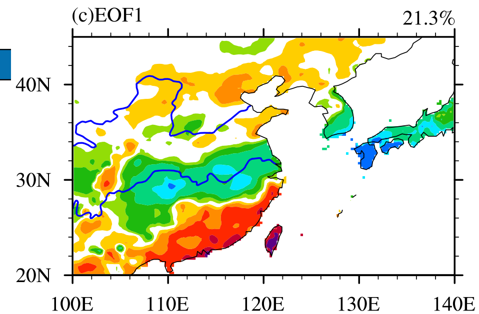
200hPa

850hPa



(shaded: precipitation; Black dots indicate 90% significance)



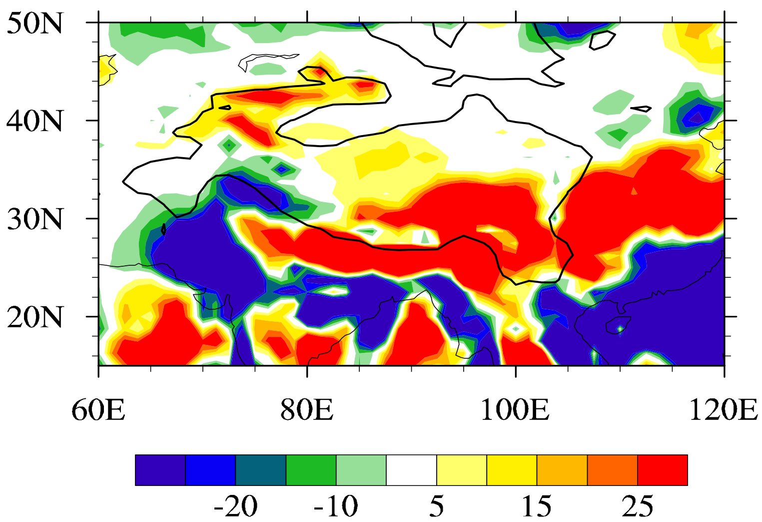


Experiment design

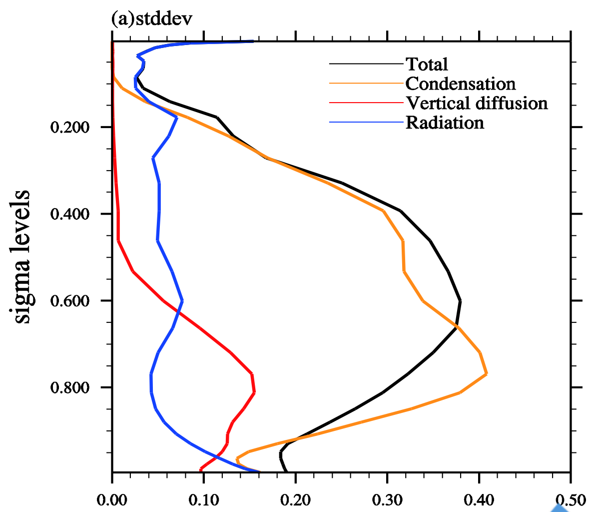
Model: FAMIL version of F/SAMIL, developed by LASG/IAP

Goal: Add 2.5σ of anomaly in both TP Heating and IOBM experiments

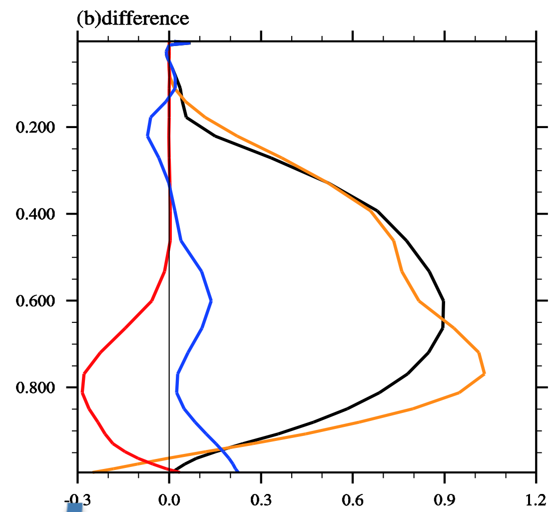
Difference of total diabatic heating between "strong years" and "weak years" of the TP thermal forcing



The vertical profile of the standard deviation of the diabatic heating over the eastern TP



The difference of the vertical profile of the diabatic heating between "strong years" and "weak years"



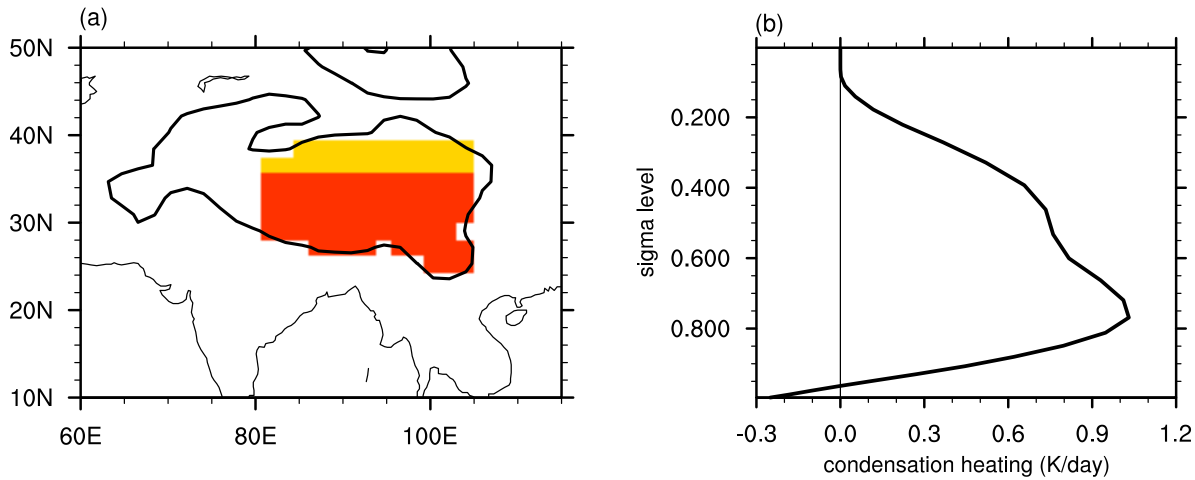
(K/day)

~2.5 times

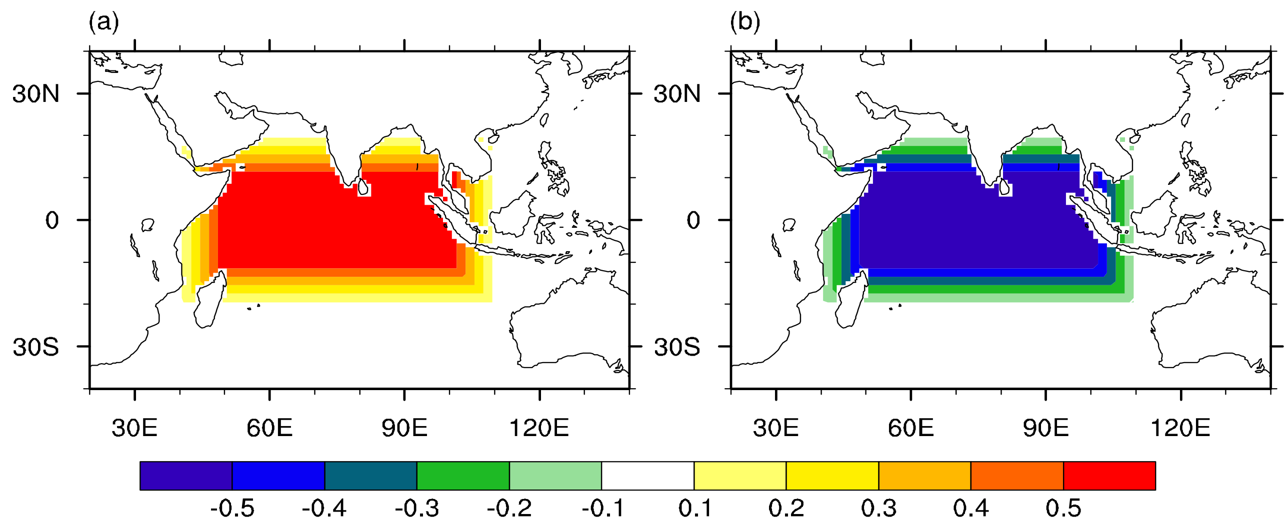
Experiment design

Distribution of the condensation heating added into TP HEATING experiments

Red: 1; Yellow: 1/4



SST anomalies added into the IOBM_TPctrl and IOBM_TPfree experiments



The standard deviation of the tropical Indian Ocean is 0.2K, so 2.5 times of that is 0.5K

Experiment design

CONTROL experiment runs for 20 years
The three sensitivity experiments comprise 20 ensembles with different initial conditions

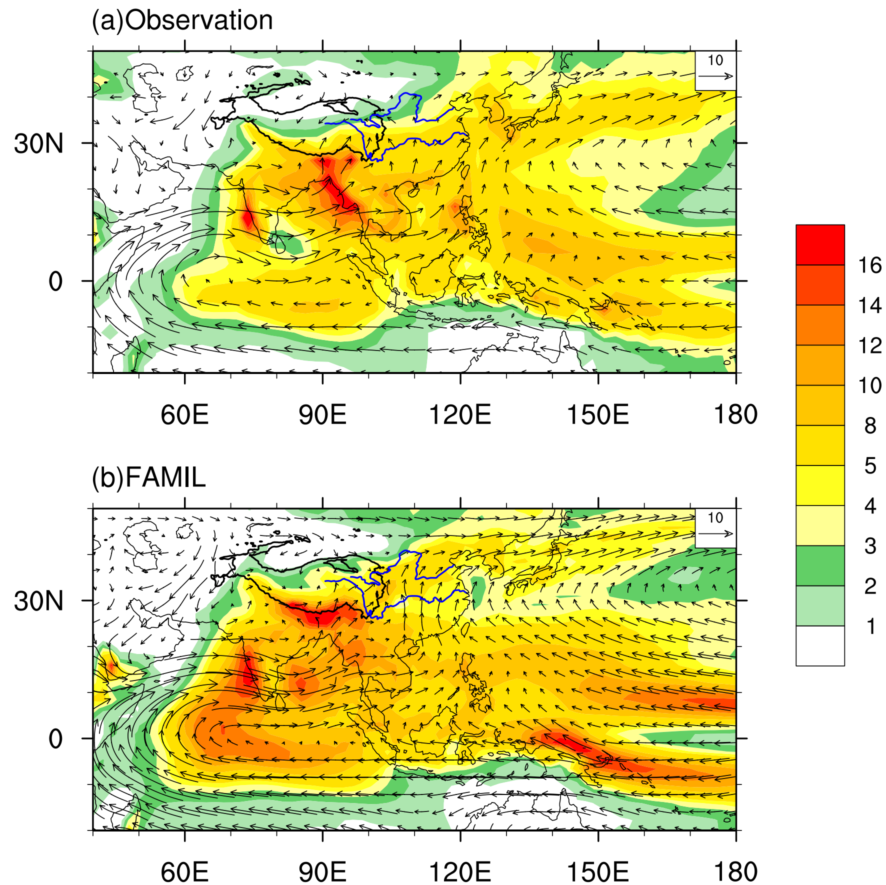
Experiment		Design
control		Prescribed global climatological SST/sea ice
TP heating	positive	Add 2.5 σ condensation heating profile in the central-eastern TP
	negative	Remove 2.5 σ condensation heating profile in the central-eastern TP
IOBM_TPctrl	positive	Add 0.5 K SST in the tropical Indian Ocean, with prescribed TP condensation heating in control
	negative	Remove 0.5 K SST in the tropical Indian Ocean, with prescribed TP condensation heating in control
IOBM_TPfree	positive	Add 0.5 K SST in the tropical Indian Ocean
	negative	Remove 0.5 K SST in the tropical Indian Ocean

Experiment results

JJA mean 850 hPa circulation and precipitation in FAMIL

Observation

FAMIL



850hPa wind and precipitation (shaded)

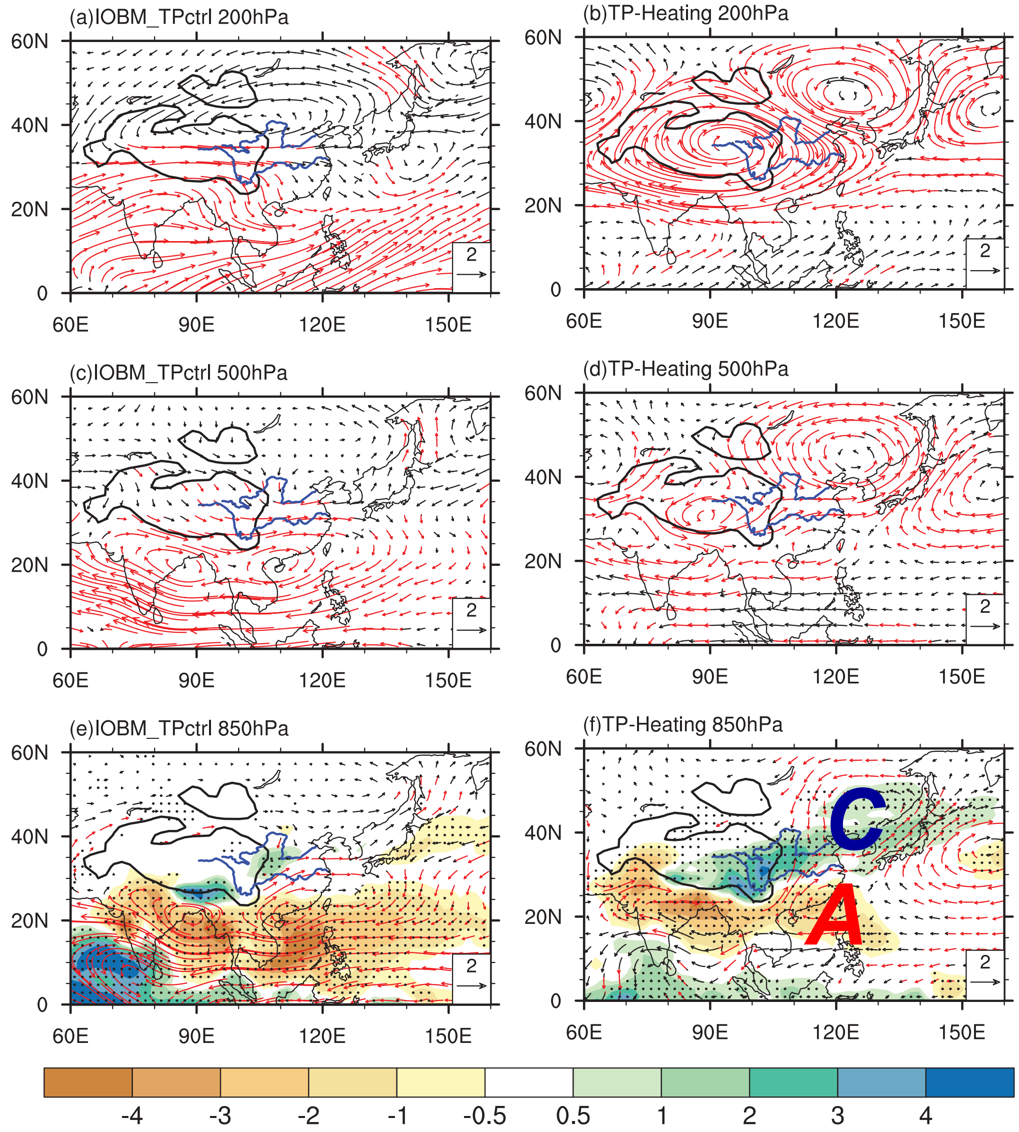
Experiment results

IOBM_TPctrl **TP-Heating**

200hPa

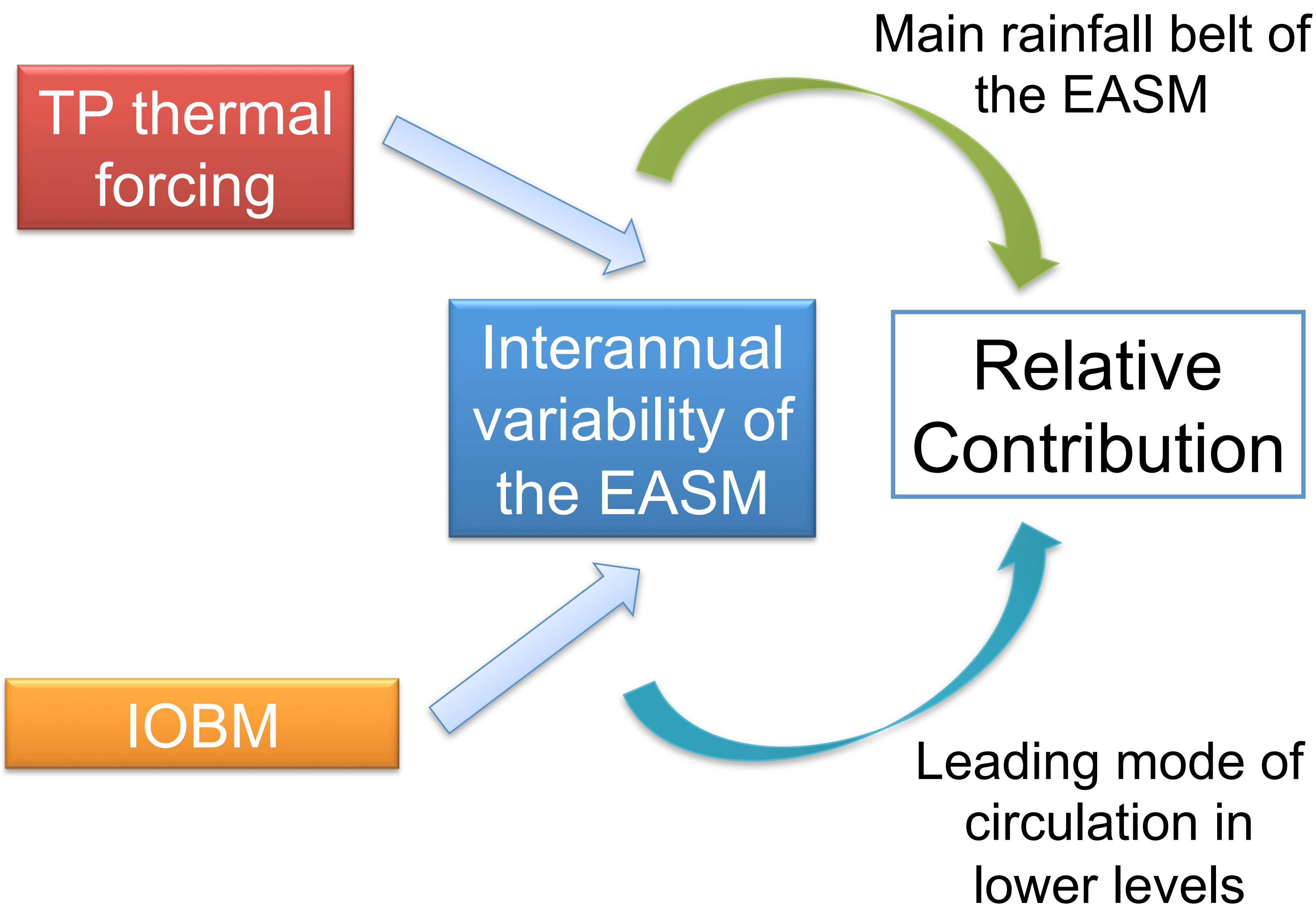
500hPa

850hPa



(shaded: precipitation; Black dots indicate 90% significance)

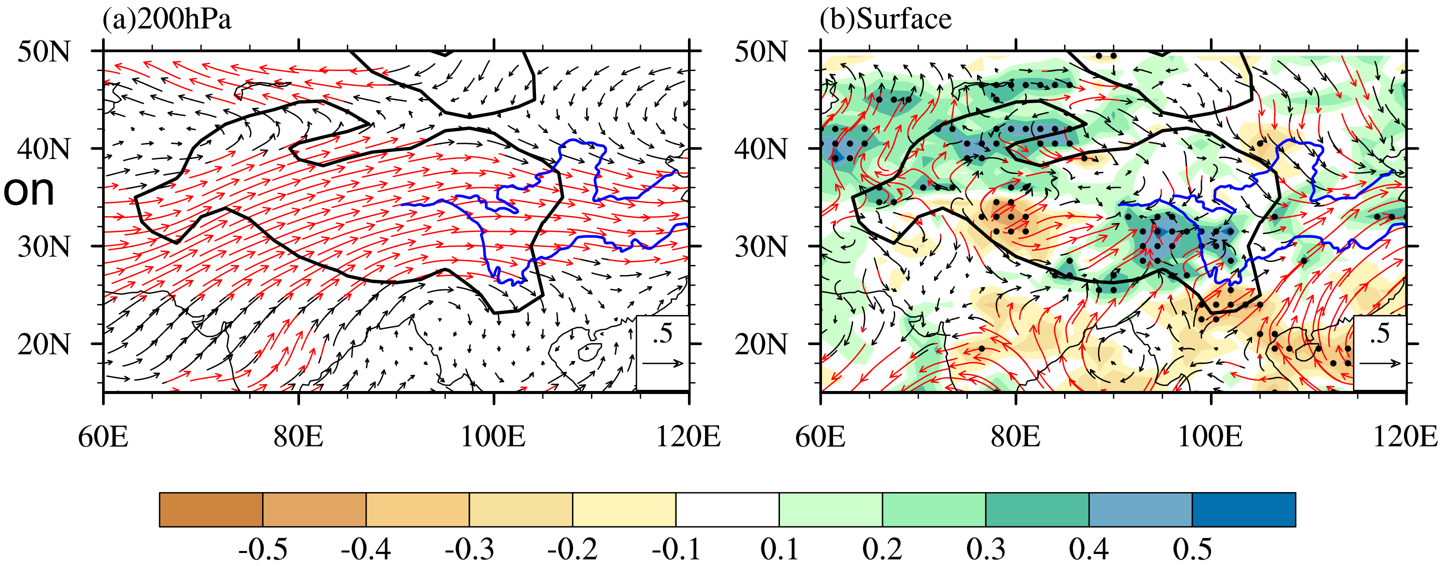
Relative importance between TP heating and IOBM



Impacts of the IOBM on the TP Heating

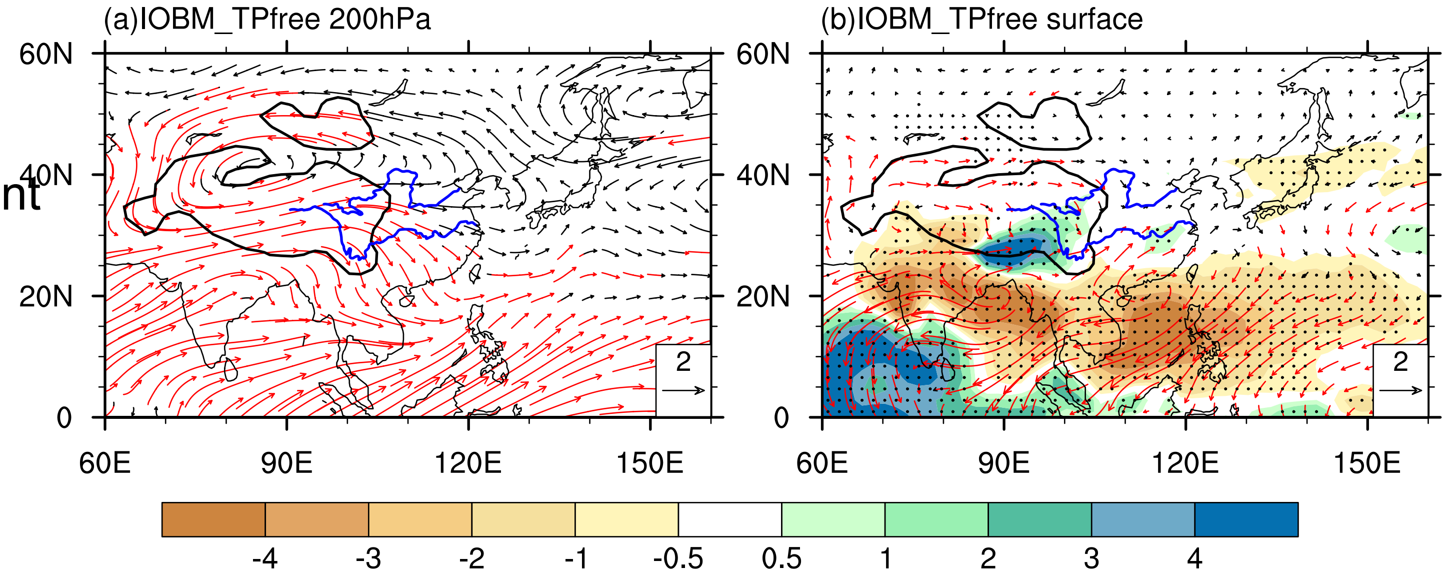
Correlation between IOBM and circulation/Prec.

Observation

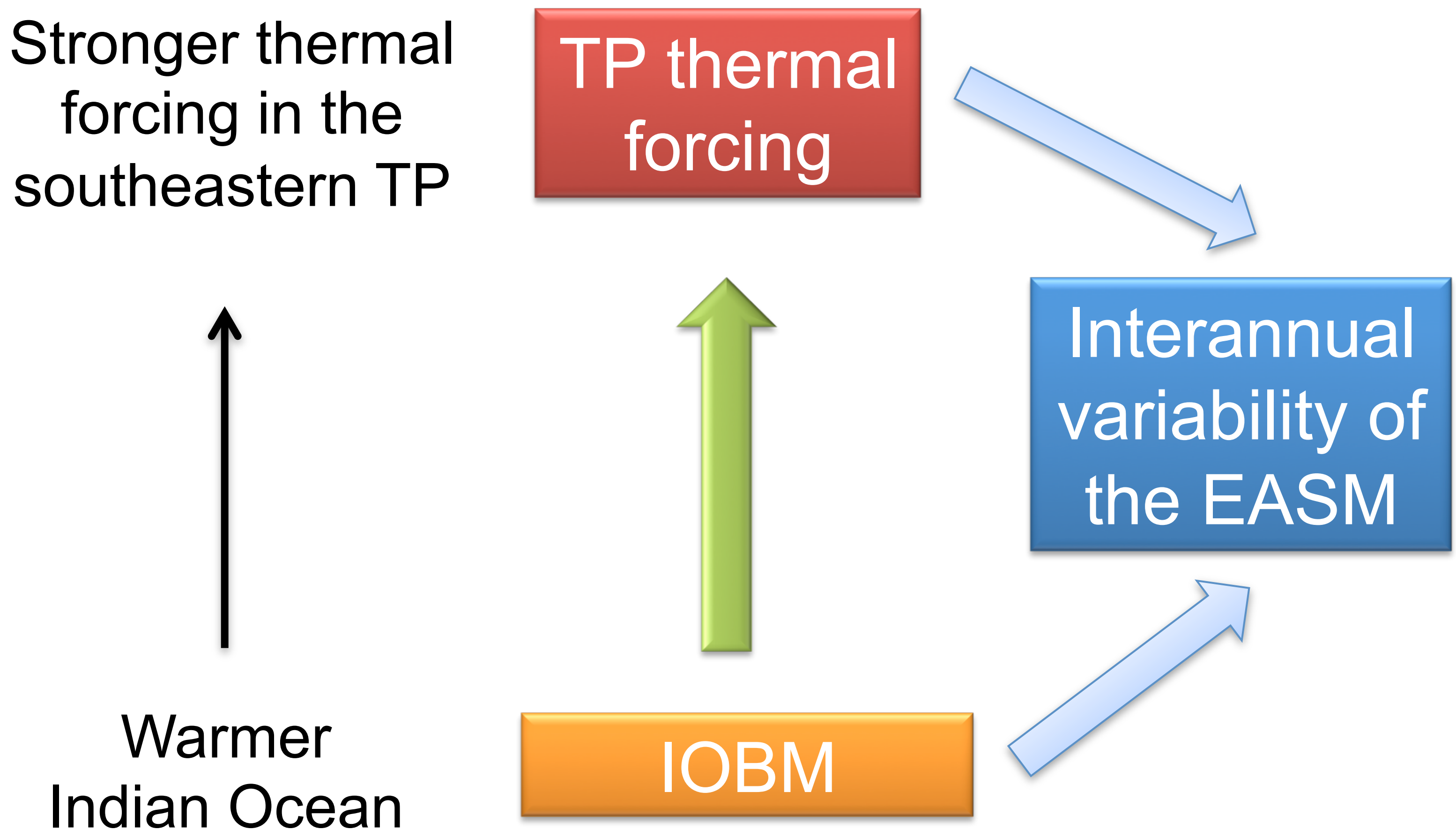


(Black dots indicate 90% significance)

Experiment Results



Impacts of the IOBM on the TP Heating



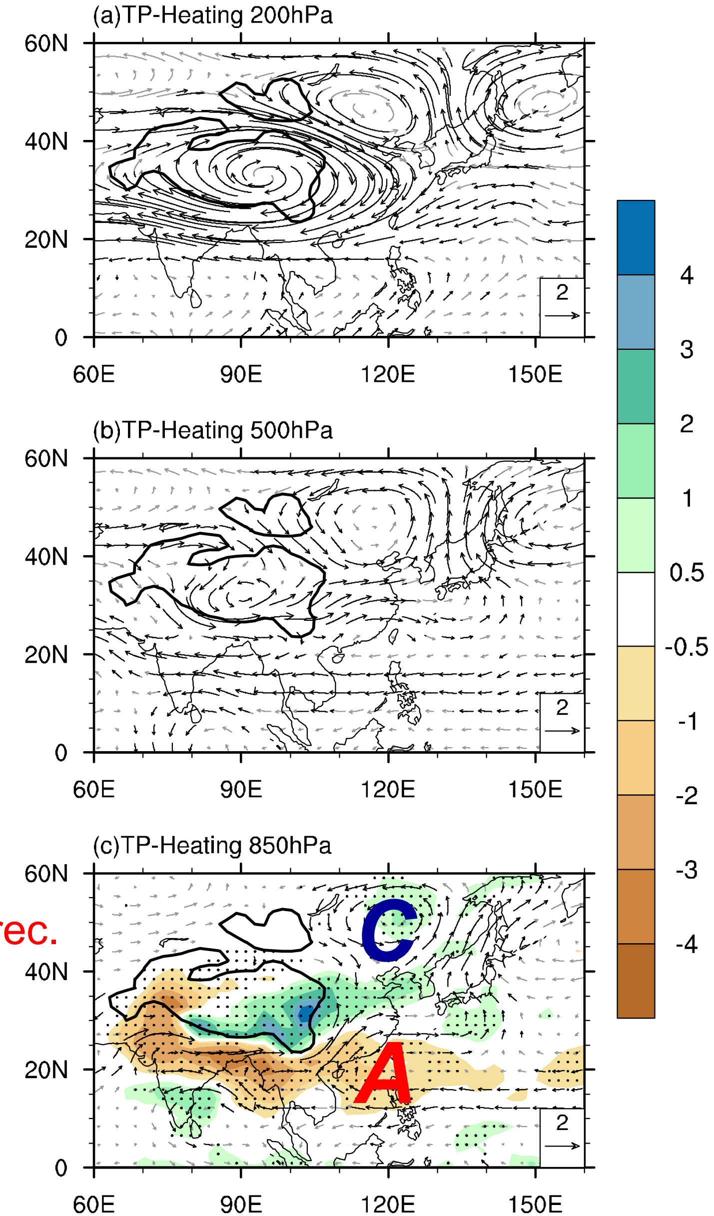
TP-Heating experiment based on FAMIL-OMLM

200hPa

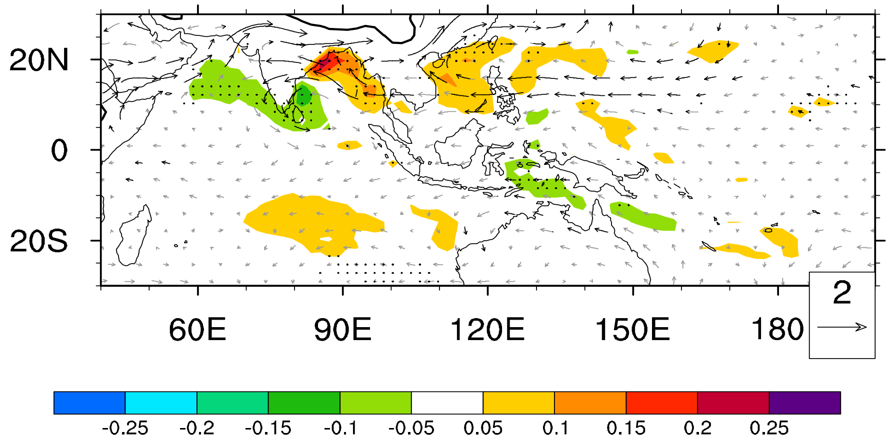
500hPa

shading：Prec.

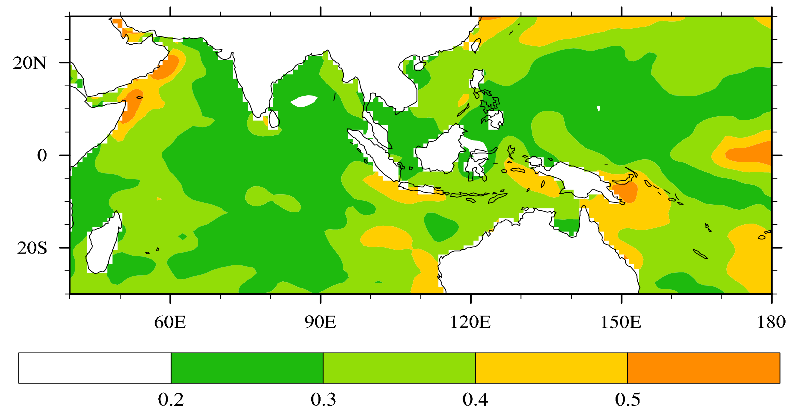
850hPa



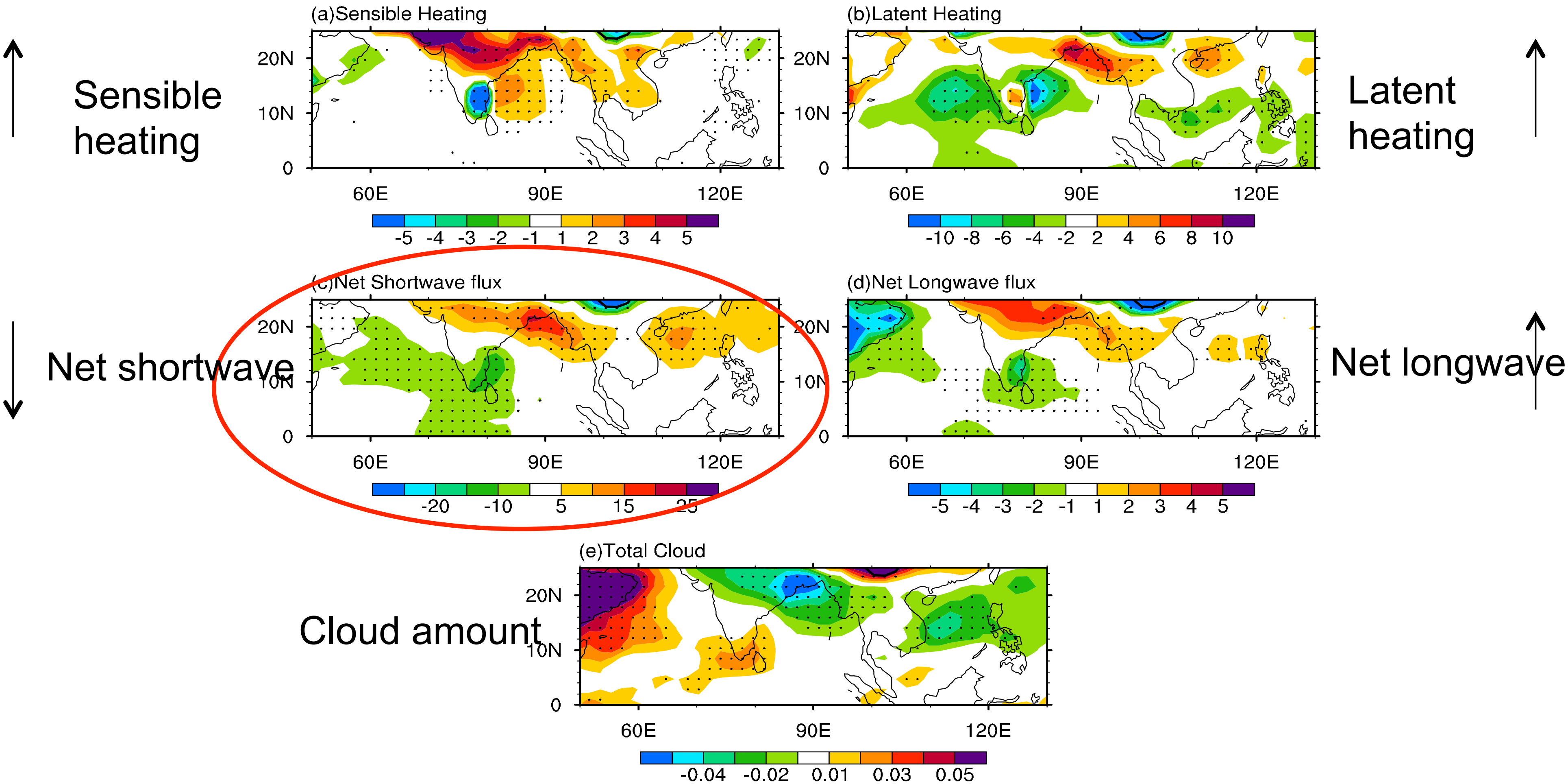
SST difference and 850 hPa circulation



JJA SST standard deviation

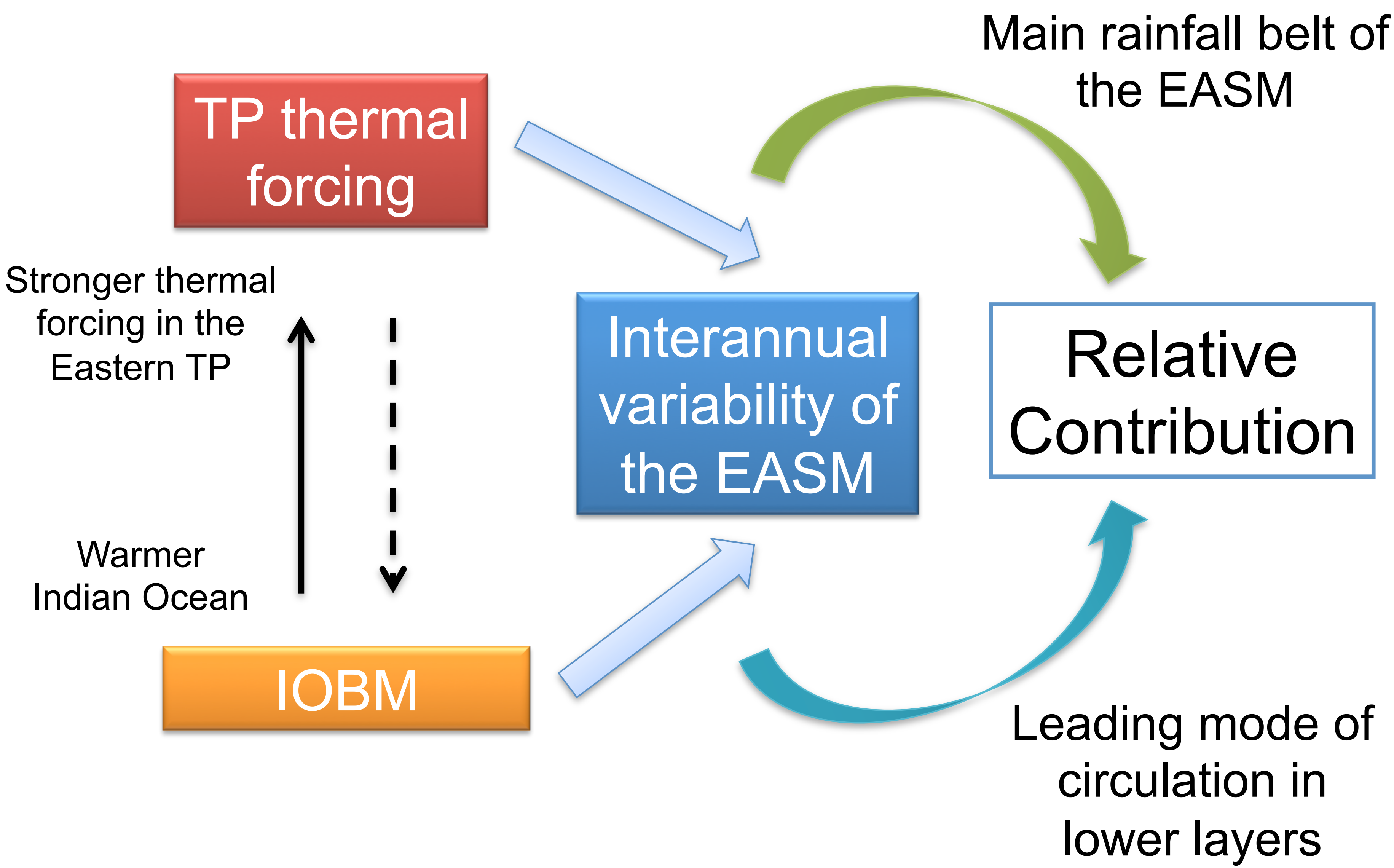


TP-Heating experiment: Surface heat fluxes



(dotting: 90% confidence level)

Conclusion


Main rainfall belt of the EASM
TP thermal forcing
Stronger thermal forcing in the Eastern TP
Interannual variability of the EASM
Relative Contribution
Warmer Indian Ocean
IOBM
Leading mode of circulation in lower layers

Discussion

- The relative contributions may change month by month in the summer.
- The other modes of IAV in EASM need a further study.
- The interaction between the TP thermal heating and the IOBM and the impacts of their interaction on the EASM should be investigated by using a fully air–sea coupled general circulation model.
- Factors impacting on the EASM in the leading seasons need to be considered. (ENSO, ENSO Modoki, IOD, Snow cover/ depth over the TP/Eurasia).
- The story might be different in other time scales.

Content

Background & motivation

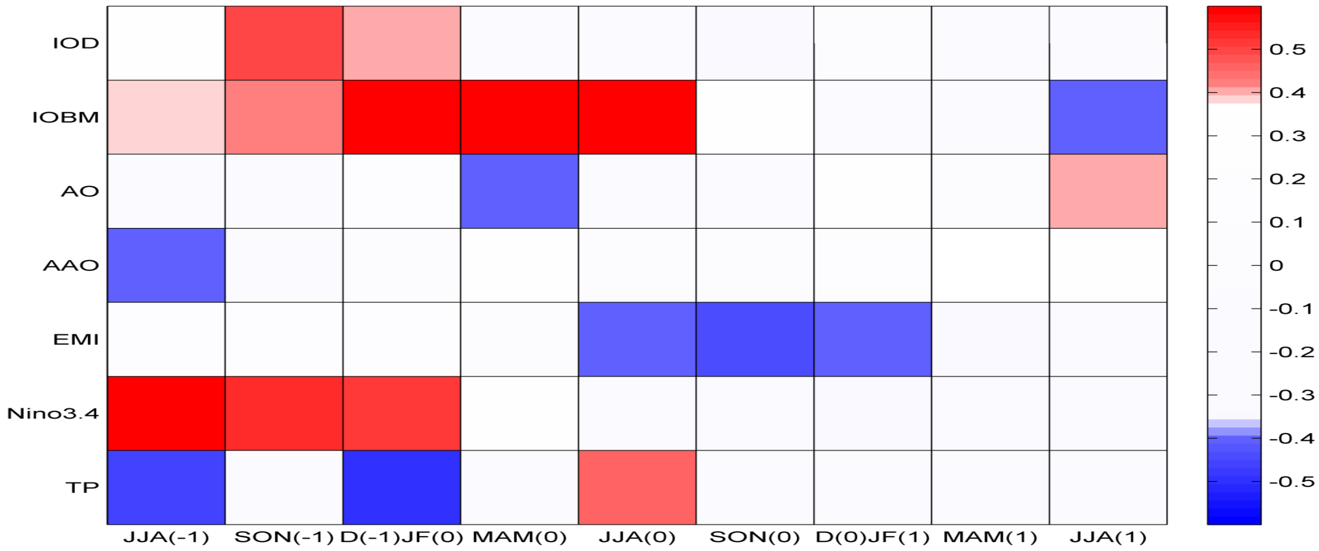
Background

- East Asian summer monsoon (EASM): strong interannual variability (IAV) (e.g. *Yang and Lau 2006; Zhou et al. 2010*).
- The IAV of EASM is determined by the combination effect of the Pacific and Indian Oceans (*Wang et al. 2000, 2006*), the thermal forcing over the Tibetan Plateau (TP) (*Zhao and Chen 2001; Duan et al. 2005; Wang et al. 2014*), as well as the mid-latitudes atmospheric internal dynamics (*He et al. 2016*).
- The leading mode of the gobal SSTA (quasi-quadrennial oscillation, QQO) has significant impacts on the East Asian climatic anomalies (*Liu and Duan 2017*).

Motivation

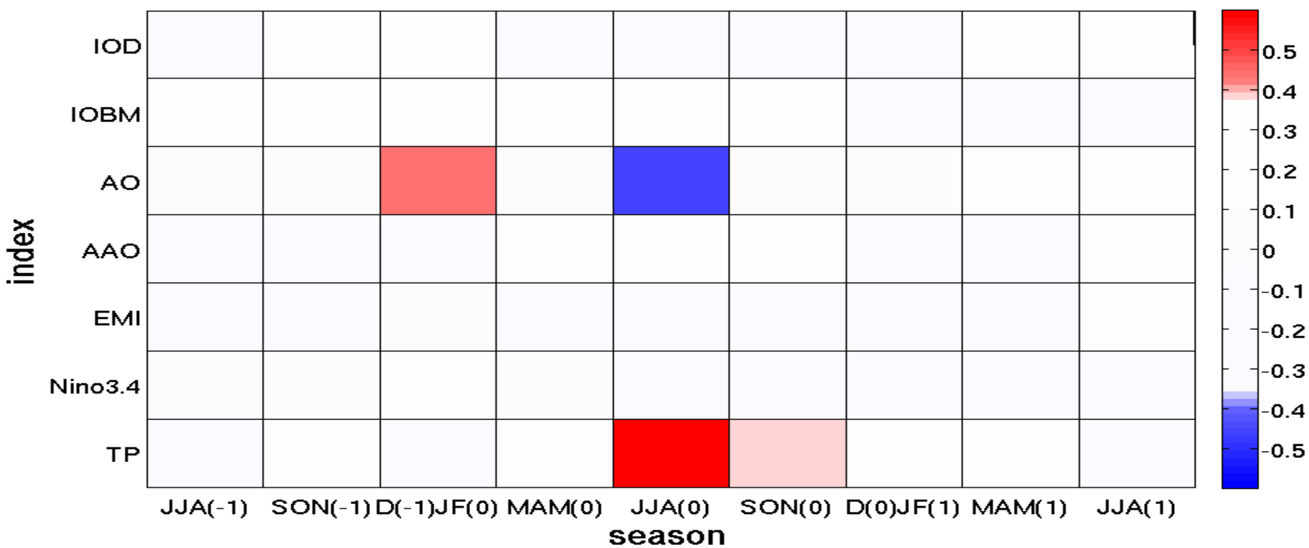
- Responses of EASM to the global SSTA in different phase of the QQO ?
- Relative contributions of the direct effects of the global SSTA and the thermal feedback of TP heating ?
- How the SSTA impact the anomalous TP heating ?

EASM and climate natural variability



Circulation

(Wang et al., 2008)



Precipitation

(EOF1 of Pr)

Data

- **Station observation**: 73 stations over the Tibetan Plateau
- **SST data**: HadISST1, 1°× 1° (*Rayner et al. 2003*)
- **Reanalysis datasets**: ERA-Interim, 1°× 1°, 37 pressure levels (Dee et al. 2011); JRA-55, 1.25° ×1.25°, 37 pressure levels (*Ebita et al. 2011*)
- **Precipitation data**: GPCP version 2.1, 2.5°× 2.5°(*Adler et al. 2003*)
- The temporal coverage is from 1979 to 2013 and the long-term linear trend is removed.

Methods: Principle Oscillation Pattern (POP) analysis of global SSTA

"Principal Oscillation Pattern (POP)" (Hasselmann 1988; Penland 1989; von Storch et al. 1995)

$$\mathbf{x}(t+1) = \mathbf{A} \cdot \mathbf{x}(t) + noise \quad (1)$$

$$\mathbf{A} = E\left[\mathbf{x}(t+1)\mathbf{x}^T(t)\right] \cdot \left[E\left[\mathbf{x}(t)\mathbf{x}^T(t)\right]\right]^{-1} \quad (2)$$

A pair of conjugate eigenvectors of Eq. (2), $\mathbf{p}_k = \mathbf{p}_k^r + i\mathbf{p}_k^i$ **and** $\mathbf{p}_k^* = \mathbf{p}_k^r + i\mathbf{p}_k^i$ **are called the principal oscillation patterns (POPs) or the normal modes of Eq. (1)**

In a cycle, the evolution of the POPs is

$$\cdots \rightarrow \mathbf{p}_k^i \rightarrow \mathbf{p}_k^r \rightarrow -\mathbf{p}_k^i \rightarrow -\mathbf{p}_k^r \rightarrow \mathbf{p}_k^i \rightarrow \cdots \quad (3)$$

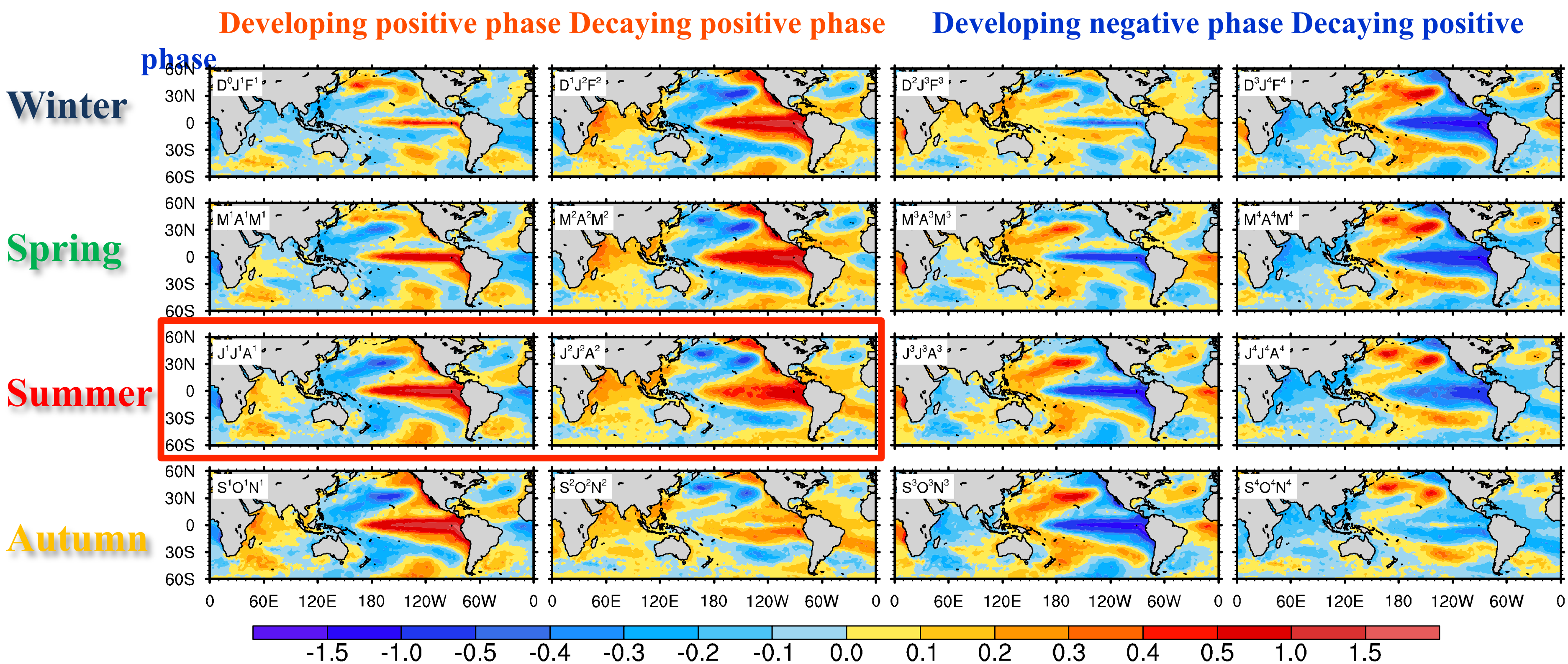
Evaluation indicators of the POPs of the global SSTA during 1979-2013

NO.	1	2	3	4	5	6	7	8
Period (month)	45.701	28.872	102.241	52.571	226.445	69.392	155.577	1648.545
Explained variance percentage	28.475	26.091	19.000	13.499	11.636	11.304	10.604	10.512
Biasing factor	0.534	0.511	0.436	0.367	0.341	0.336	0.326	0.324

Quasi-quadrennial Oscillation mode (QQOM) of global SSTA

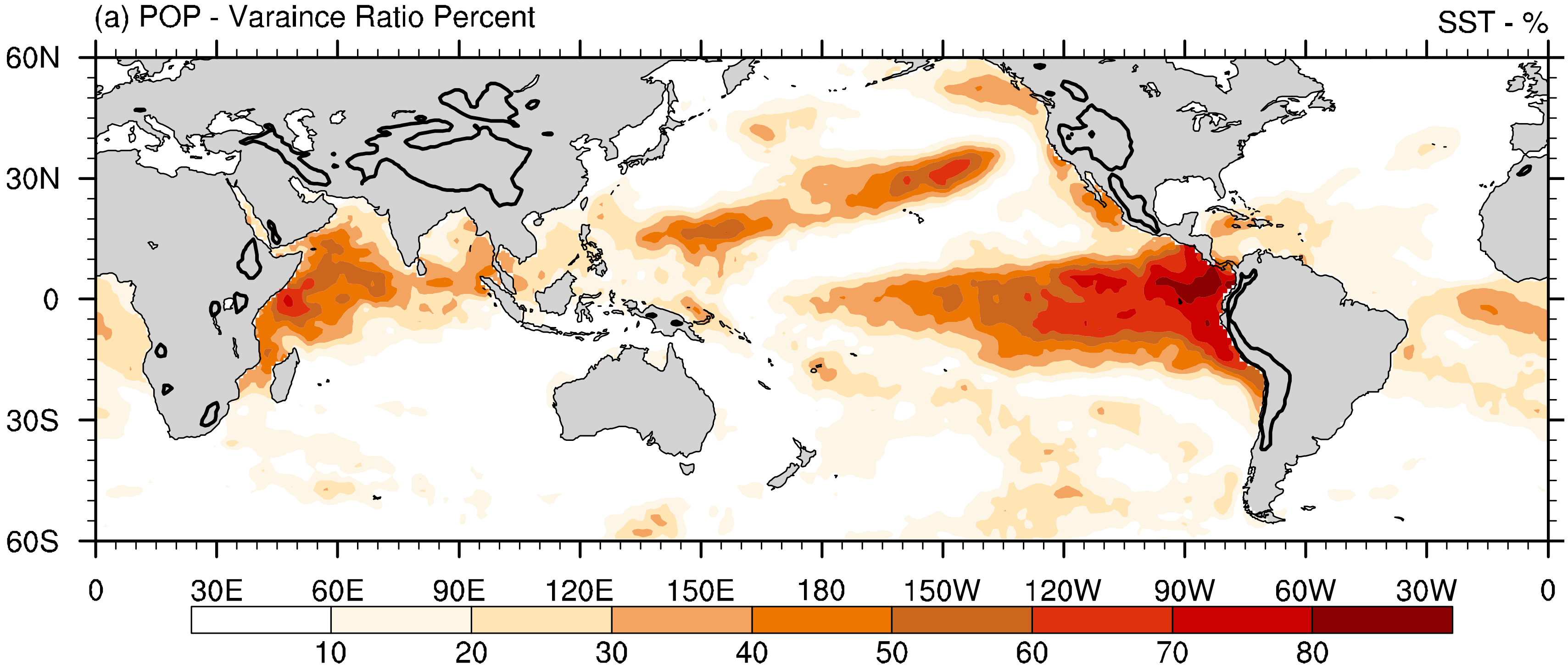
QQOM

- Developing phases： cold IOBM → IOD + developing El Niño
- Decaying phases： warm IOBM persist + decaying El Niño



The leading mode of the global SSTA: quasi-quadrennial oscillation (QQOM) (*Liu and Duan 2017 Clim. Dyn.*)

Explained variance of the QQOM



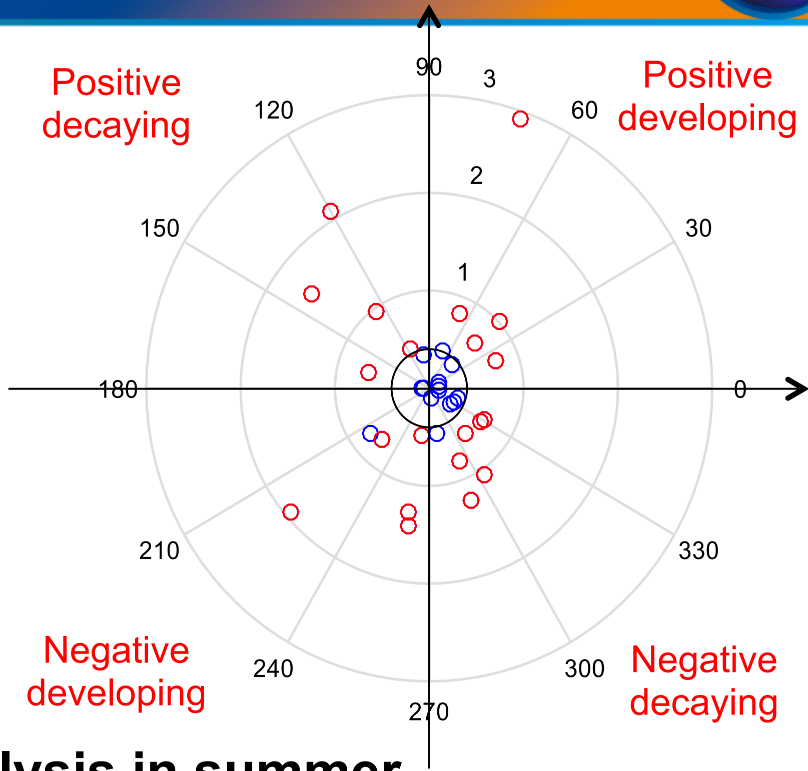
Methods: phase composite analysis

The reconstructed component can be written as

$$\hat{\mathbf{x}}(t) = z_r(t)\mathbf{p}_r + z_i(t)\mathbf{p}_i$$

The phase angle is $\theta = \arctan\left(z_r / z_i\right),\ \theta \in [-\pi, \pi)$

Criterion: both of the phase angles in spring and summer of the current year are within the current phase and the absolute value of the real part of POP time coefficient exceeds 0.4 standard deviations



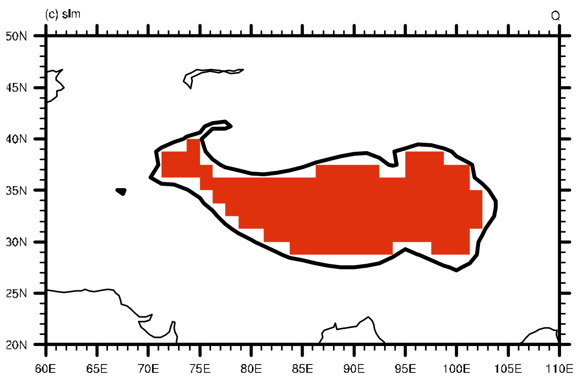
Years for phase composite analysis in summer

Phase	Year
Positive developing phase	1982, 1992, 1997, 2009, 2012
Positive decaying phase	1983, 1987, 1993, 1998, 2005
Negative developing phase	1984, 1988, 1999, 2001, 2007
Negative decaying phase	1981, 1985, 1989, 1996, 2000, 2011

Methods: AGCM numerical simulation

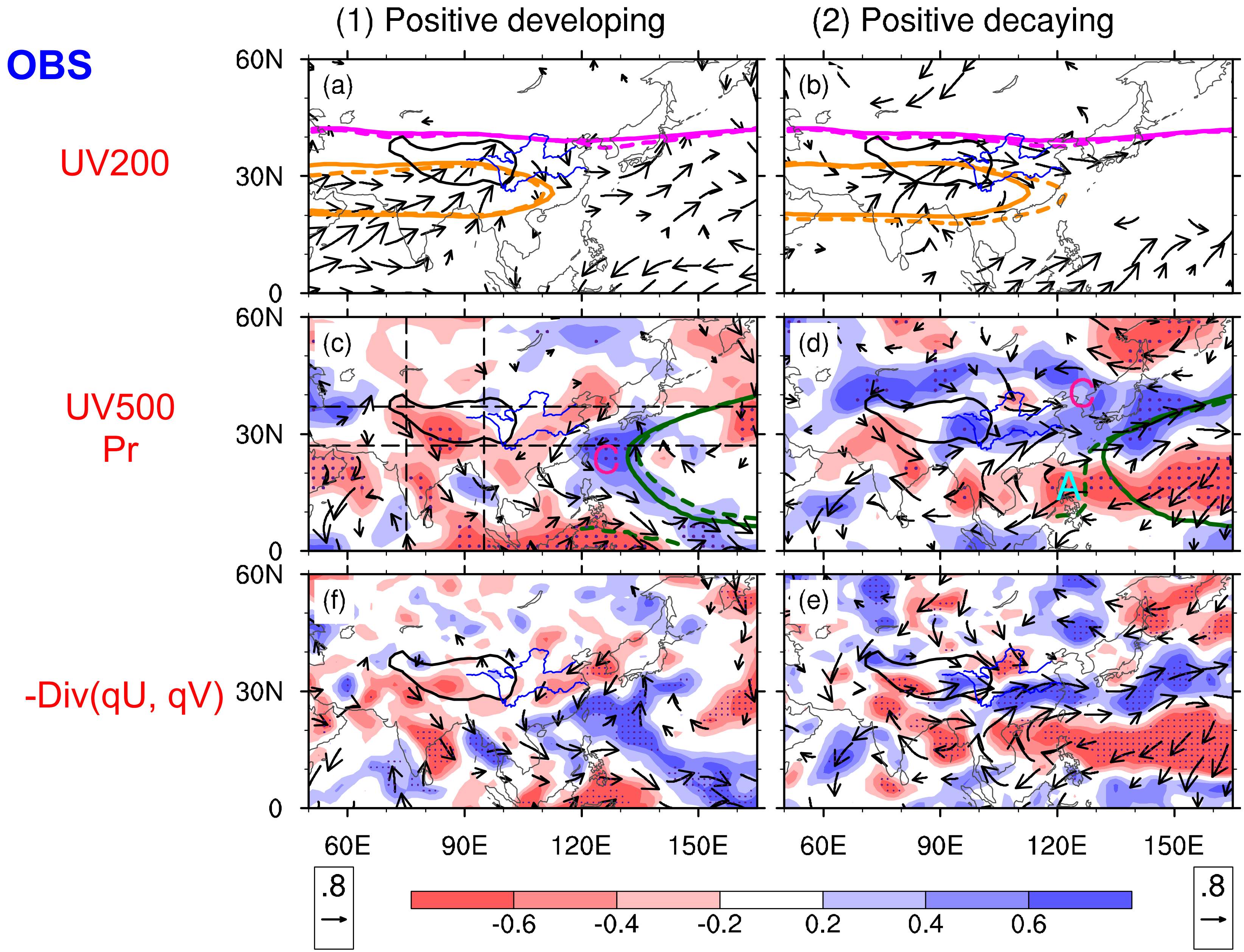
AGCM: FAMIL developed by LASG/IAP

Experiment	Design	Number of ensembles (Integration length for each)
AMIP2	Global SST/sea ice prescribed by AMIP2 from 1979 to 2009	1 (31 years)
CLIMA	Annual periodic climatological monthly SST/sea ice	1 (20 years)
TP_FREE	Addition of the ideal quadrennial POPs of the global SSTA with freeing the TP heating	4 (20 years)
TP_CTL	Addition of the ideal quadrennial POPs of the global SSTA with controlling the TP heating	4 (20 years)



The prescribed TP heating is derived from the climatological mean of the tendency of temperature in the modules of cloud microphysical processes, cumulus convection processes, and boundary layer processes in CLIMA experiment.

Response of EASM to the observed SSTA



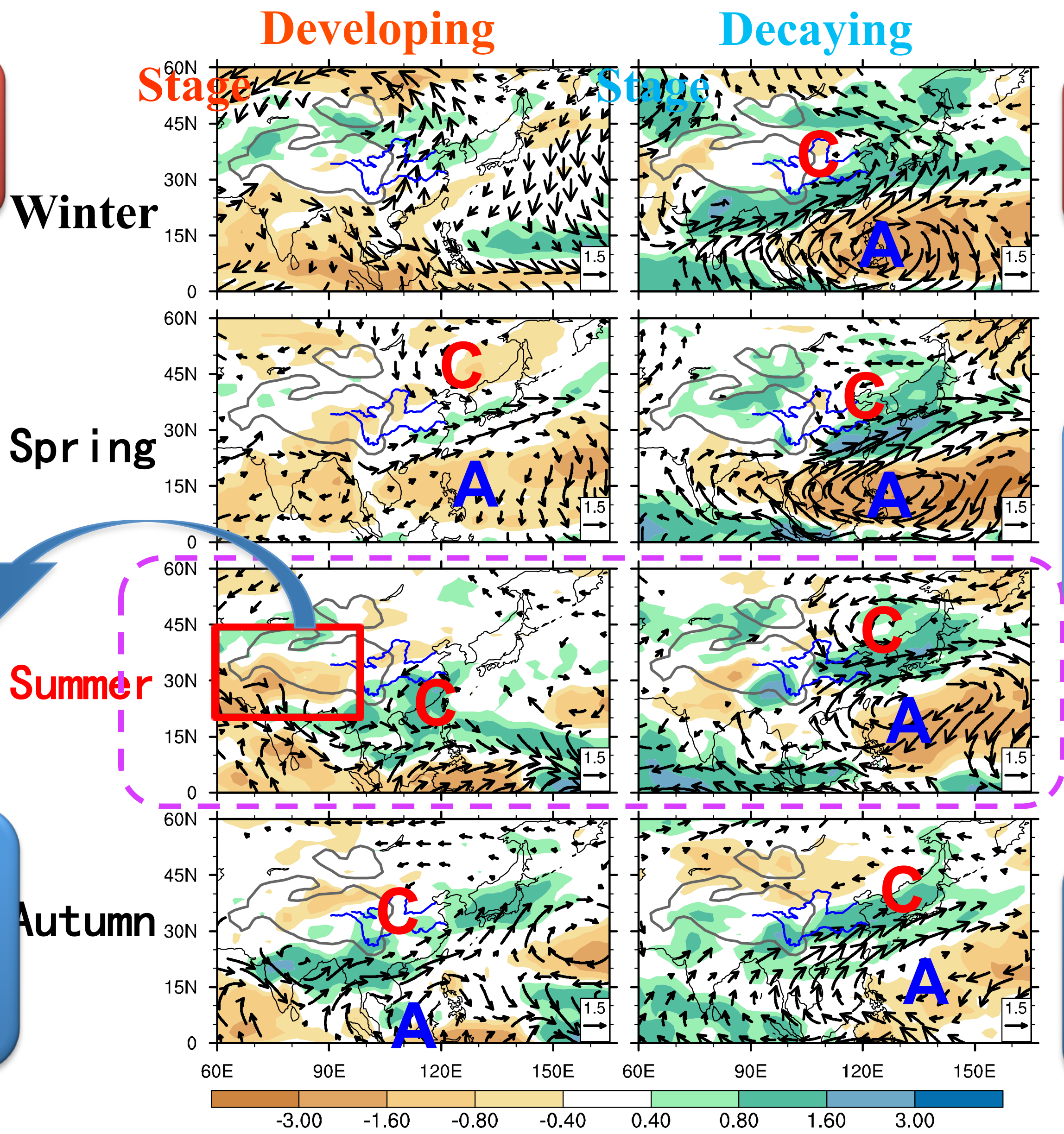
Response of EASM in AGCM (850 hPa circulation and Pr)

(Difference between positive and negative phases of QQOM)

IOD El Niño developing

Negative TP heating

Cyclonic anomaly over Phillipine Sea

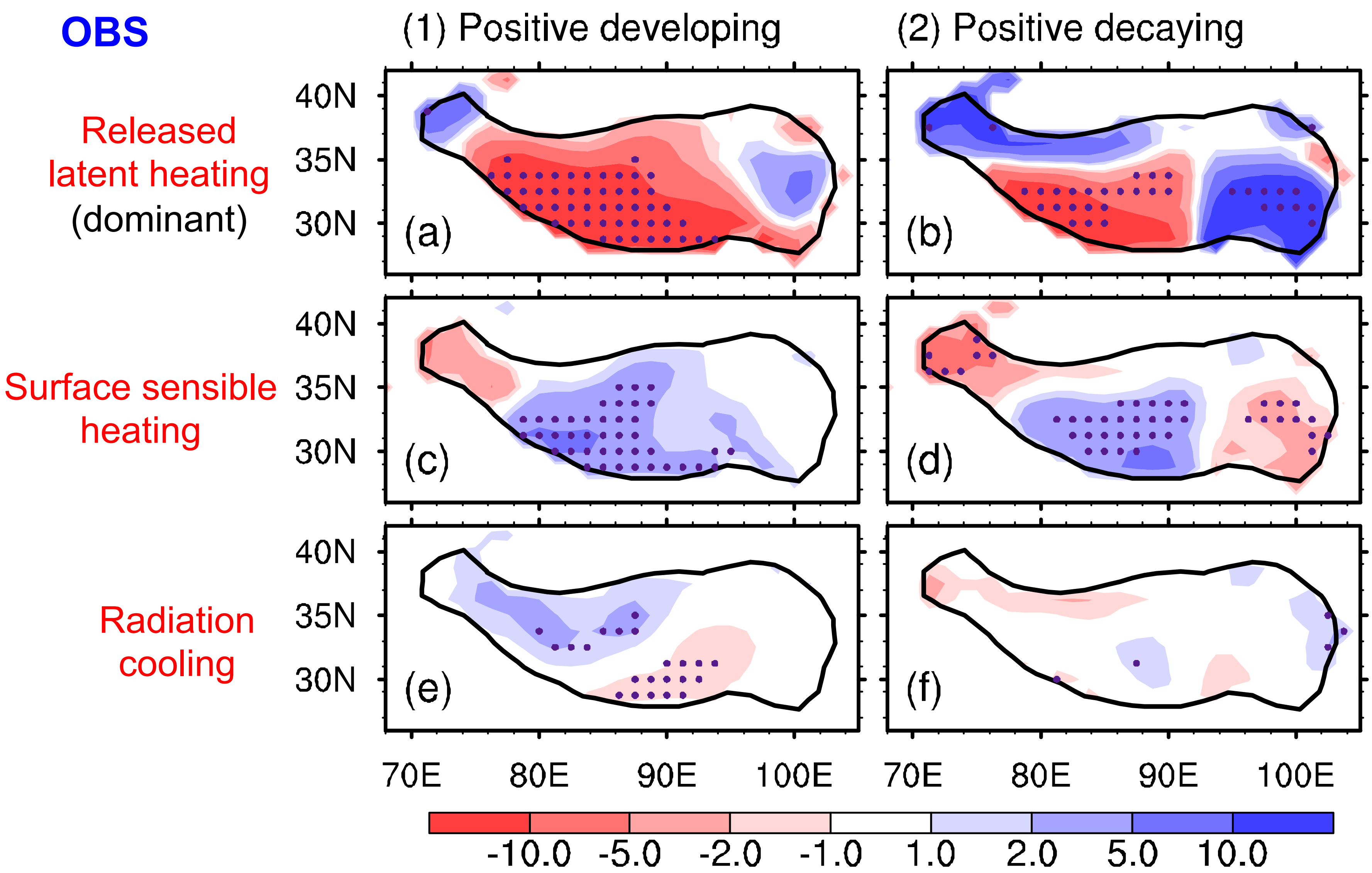


Warm IOBM decaying El Niño

Dipole pattern over East Asia

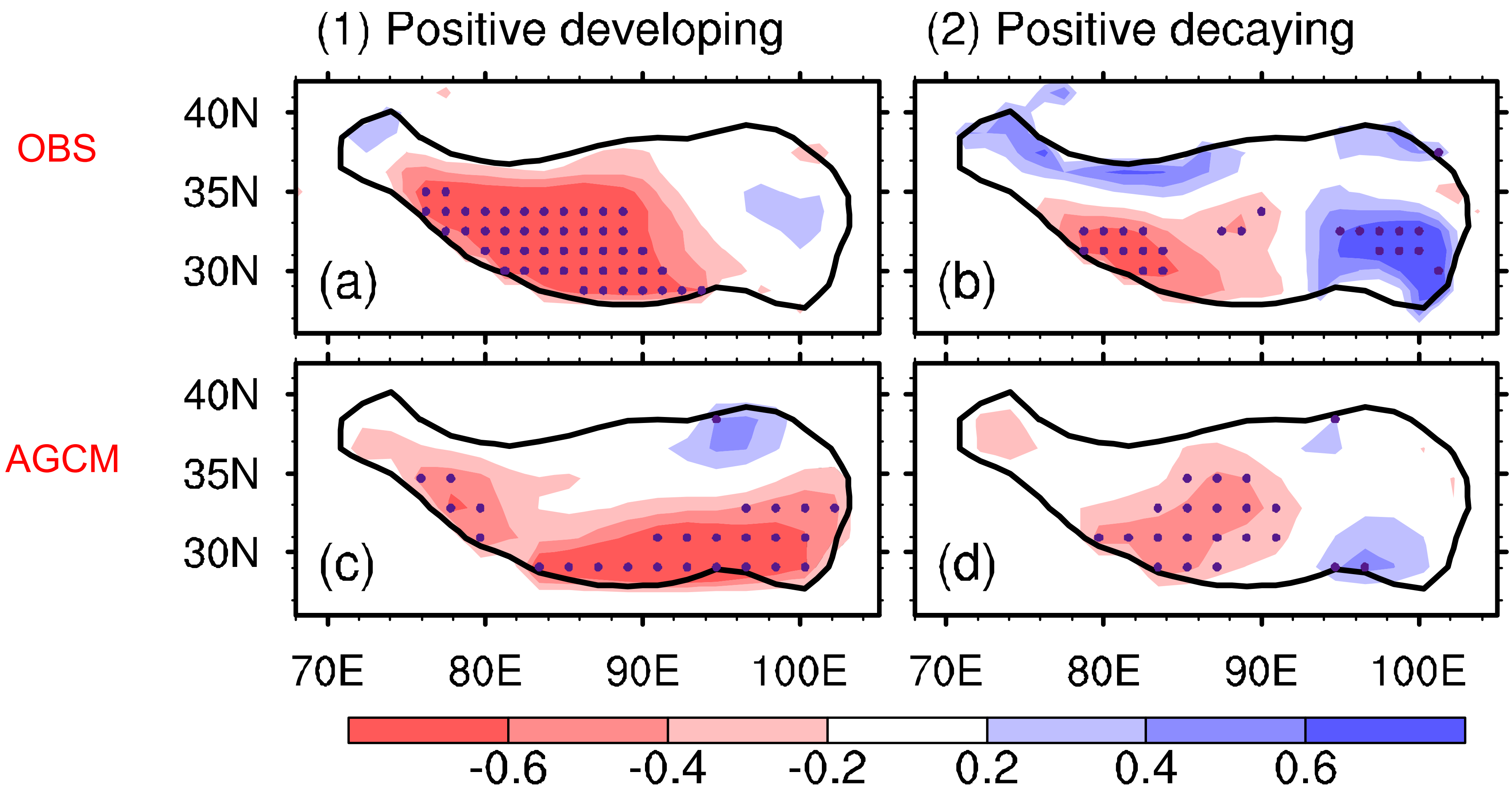
Enhanced main rainfall belt

Response of TP heating



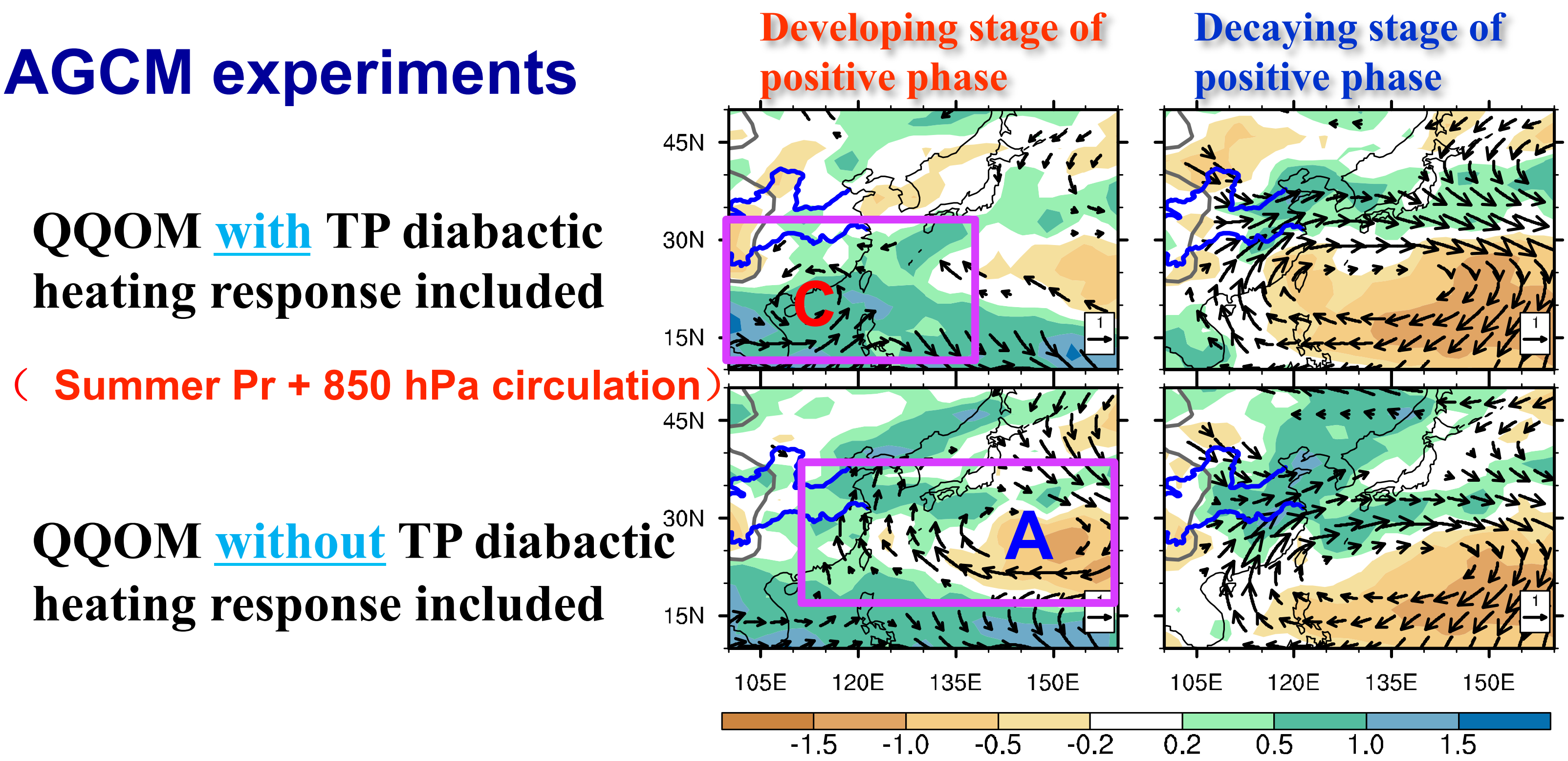
Response of TP heating

Released latent heating + Surface sensible heating



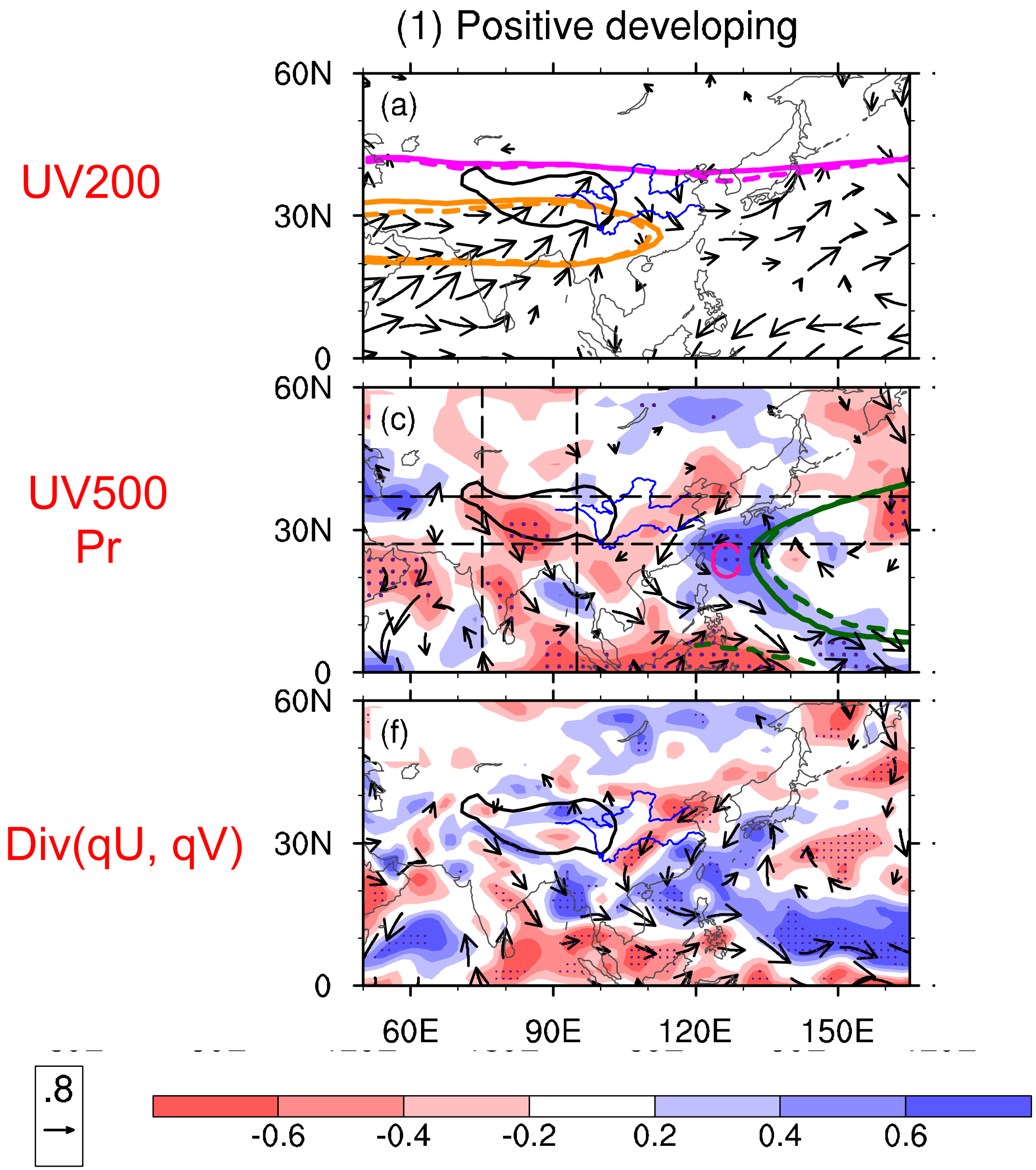
Diabatic heating effect of the Titetan Plateau

AGCM experiments



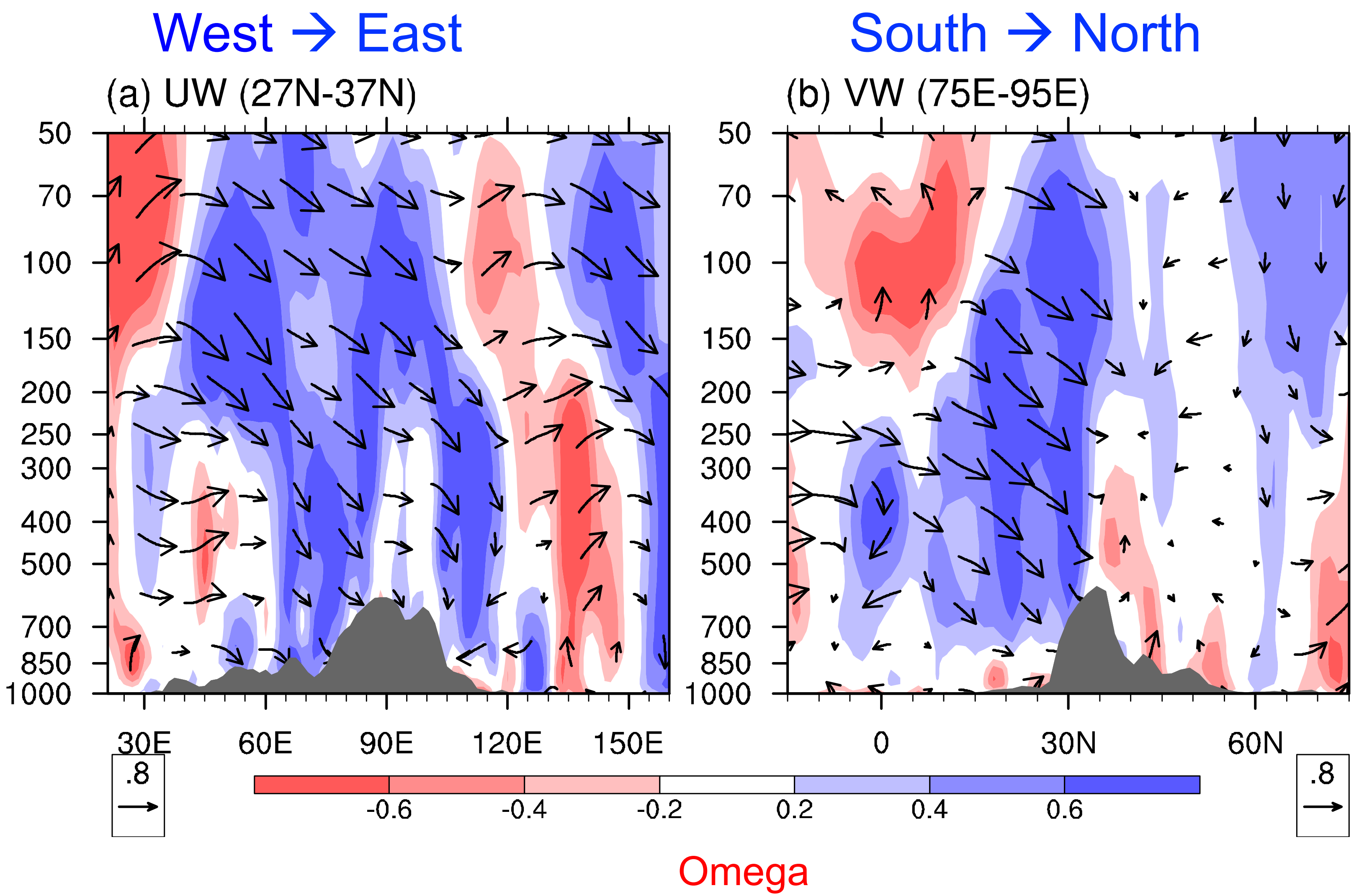
During the developing stage of the positive phase of QQOM, the significant negative anomaly of the diabatic heating over the TP will induce a cyclonic anomaly over the Phyllipine Sea.

Anomaly of TP heating

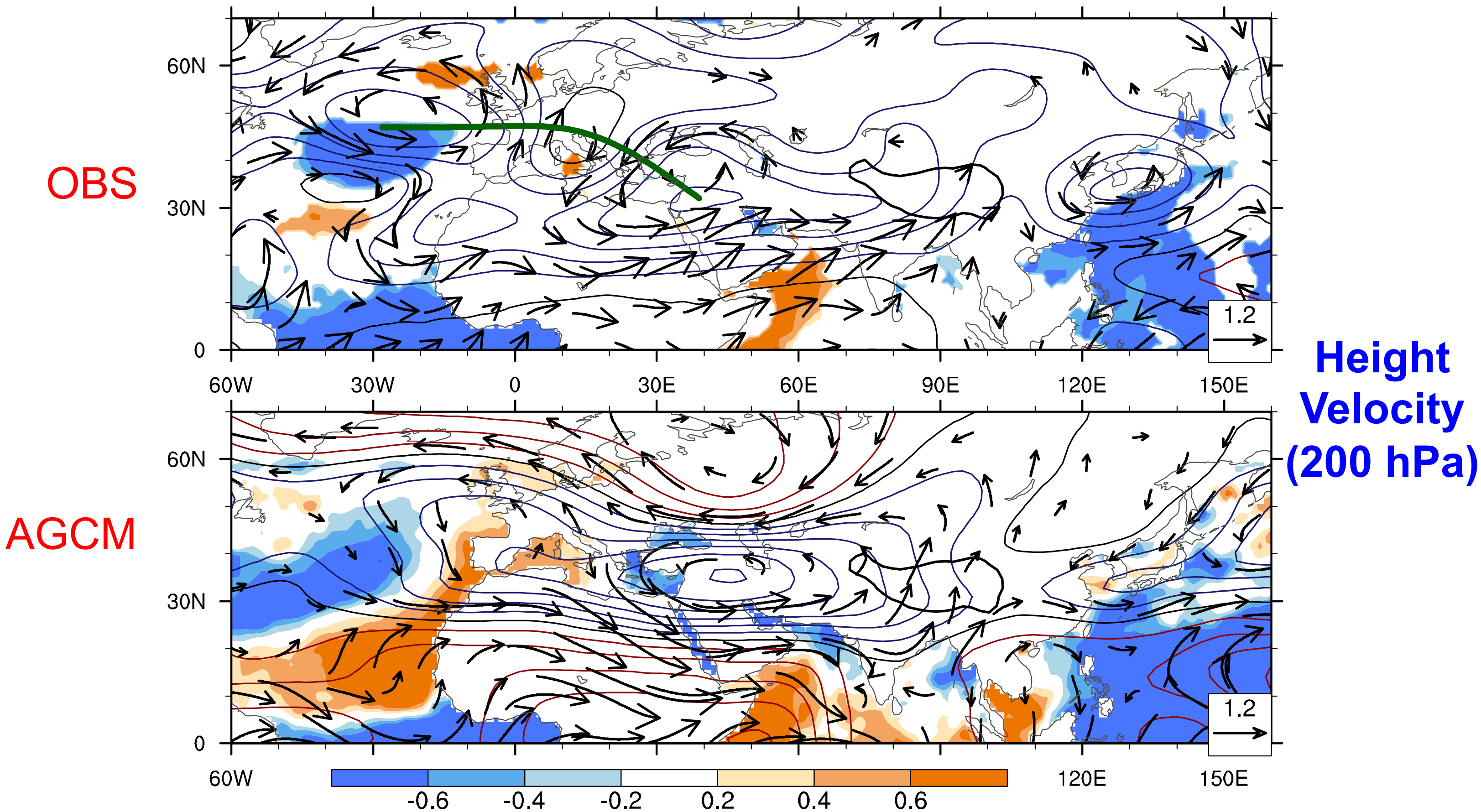


Why
the TP heating
weakens?

Response to the global SSTA POP: developing year summer



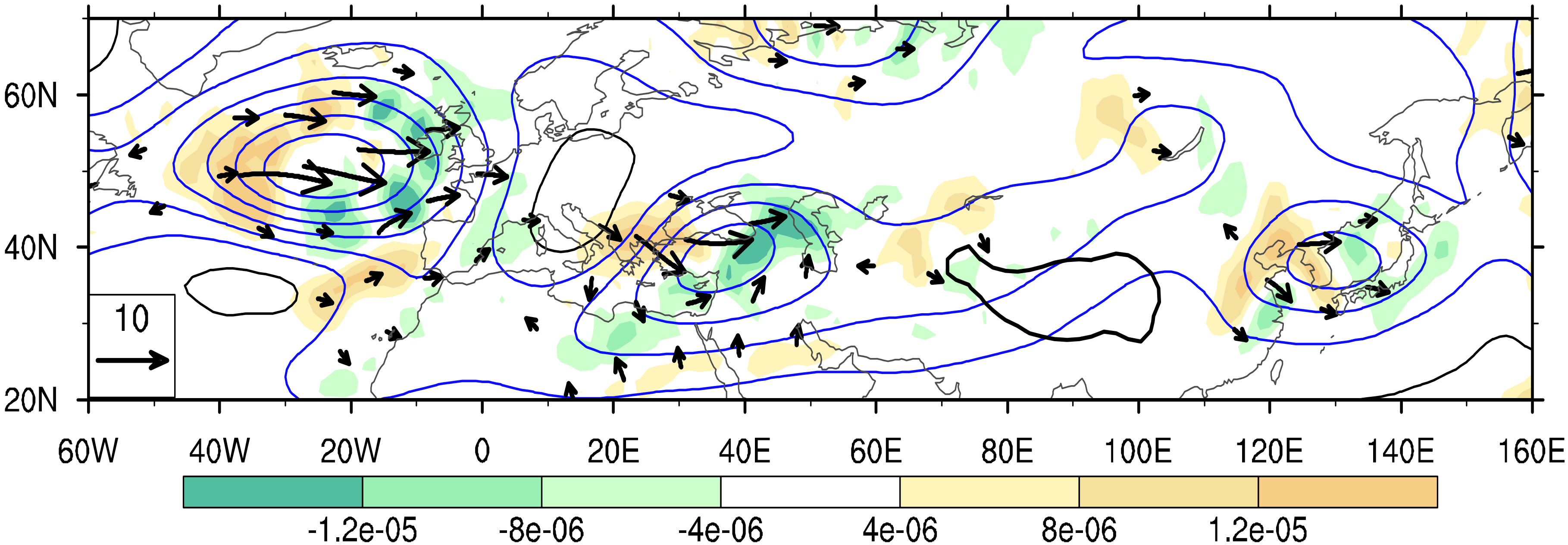
Response to the global SSTA POP: developing year summer



Normalized anomalies of circulations at 200 hPa and SSTAs in summer of the developing year during the QQO positive phase of the global SSTA. (a) composite analysis for the observational anomalies; (b) normalized difference in the numerical simulations between the sensitive experiment TP_FREE and the control experiment CLIM. Black vectors denote the horizontal wind, contours denote the geopotential height (red is positive; black is zero; blue is negative; interval is 0.3), and shading denotes the SSTA. The SSTA in (b) is prescribed in the experimental design.

Response to the global SSTA POP: developing year summer

Wave activity flux and its divergence at 200 hPa



Composite analysis for the observational wave activity in summer of the developing year during the QQOM positive phase of the global SSTA. Contours denote the geopotential height (units: gpm; red: positive; black: zero; blue: negative; interval: 10 gpm), black vectors and shading denote the horizontal components of wave activity flux (units: m^2s^{-2}) and their divergence (units: ms^{-2}).

Conclusions

- The remarkable precipitation anomaly of the EASM with the enhanced main rainfall belt occurs in the positive decaying years of the QQOM, corresponding to the enhanced and the westward-extended WPSH and the accelerated subtropical westerly jet in the upper troposphere.

- The significant response of the summer TP heating, featured by the suppressed in situ atmospheric heat source and deficient precipitation, can be detected only in the positive developing years of the QQOM. The weakened TP heating feedback rather than the direct SSTA effects plays a dominant role on the formation of the anomalous Philippine Sea cyclone.

- Both the wave trains from Atlantic and the upper-level southwesterly wind contributes the weaken TP heating in the positive developing years of QQOM.

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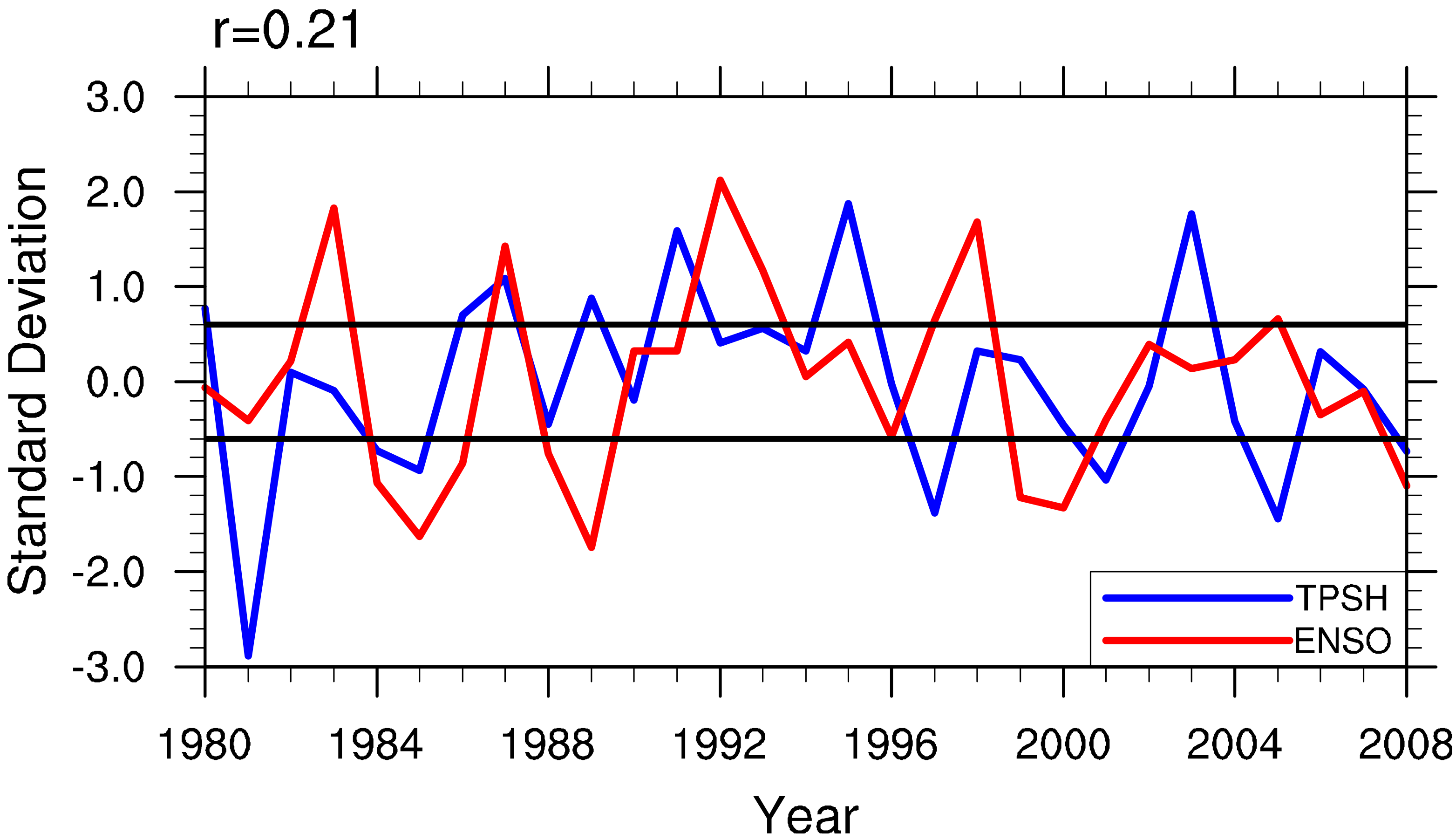
Thank you for your
attention !

Observed Data Analysis



A weak positive correlation exists between spring TPSH and ENSO, hence we use partial regression to separate their relative contributions.

Conclusions

① Above-normal spring SHTP induces a weak spring WPSH, but a strong summer WPSH, and vise versa. In particular, SHTP acts as an independent factor for the WPSH anomaly relative to ENSO events.

②