State Key Laboratory of Numerical Modelling for Atmospheric Sciences
and Geophysical Fluid Dynamics(LASG)
Institute of Atmospheric Physics Chinese Academy of Sciences

The ocean and decadal monsoon variability

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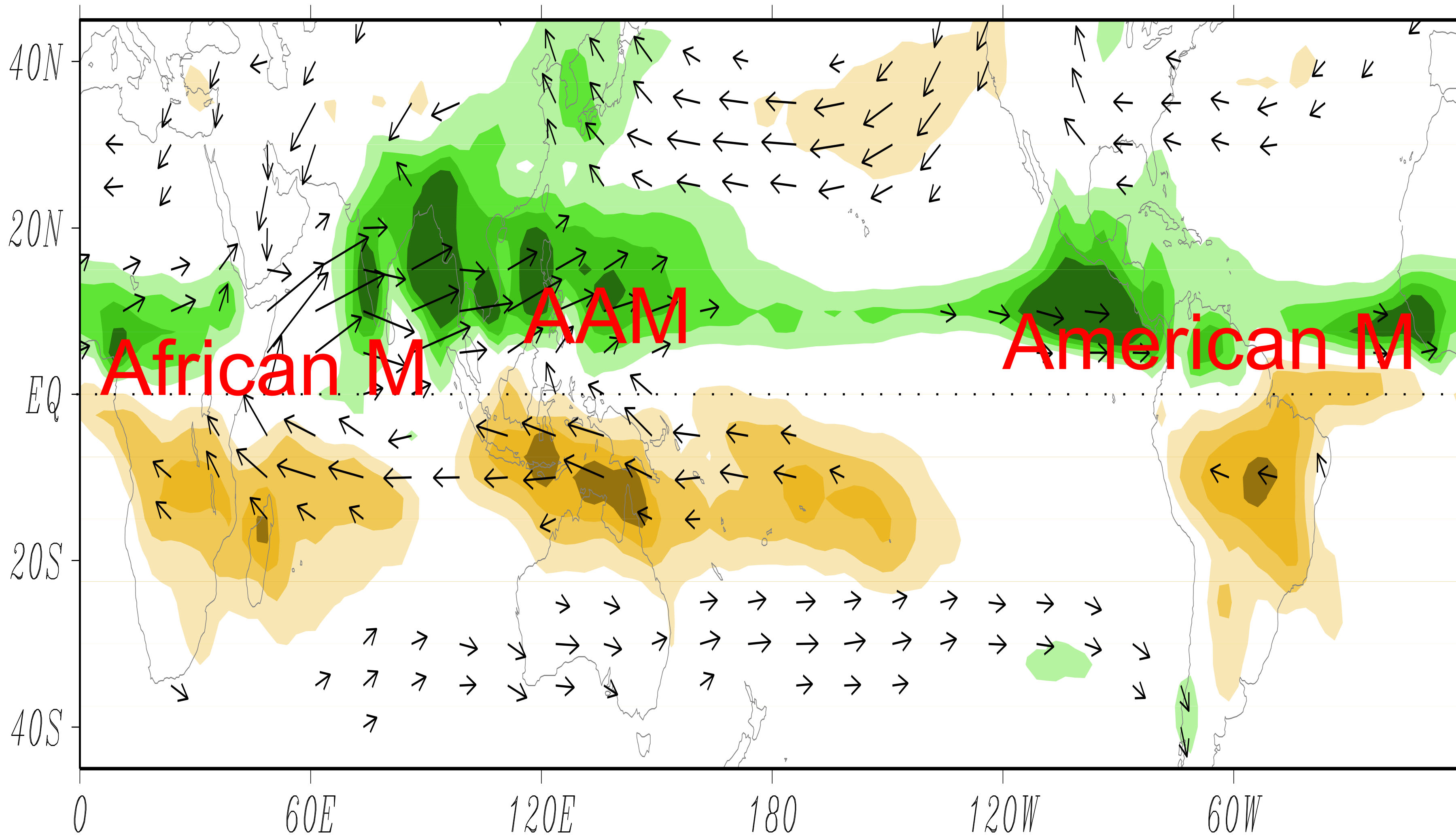
Targeted Training Activity (TTA) 2017: Monsoons in a Changing Climate

31 July - 4 August 2017, ICTP

Outline

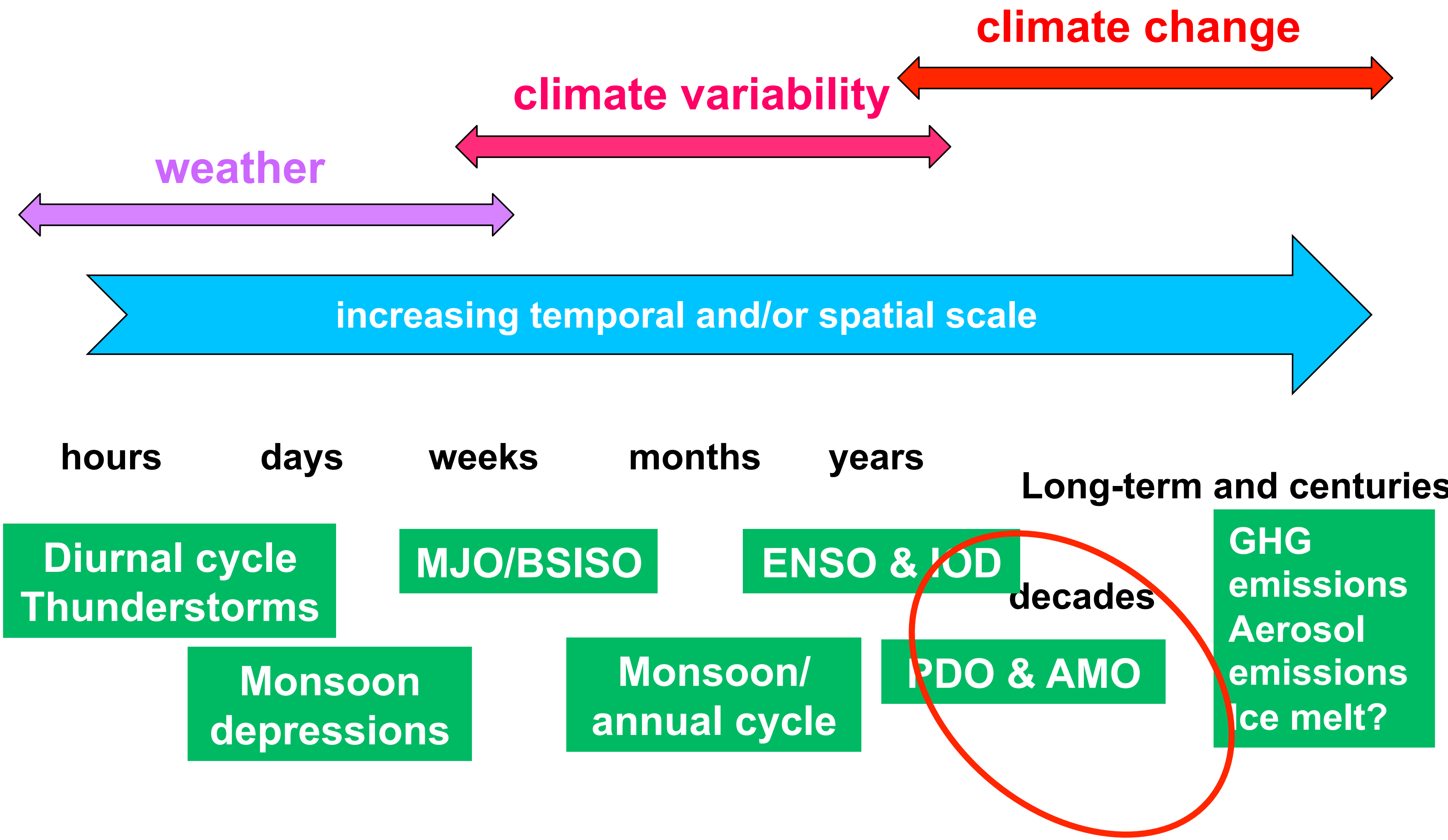
1. Background
2. GM and PDO
3. EASM and PDO
4. Indian Ocean warming
5. Concluding remarks

Global Monsoons



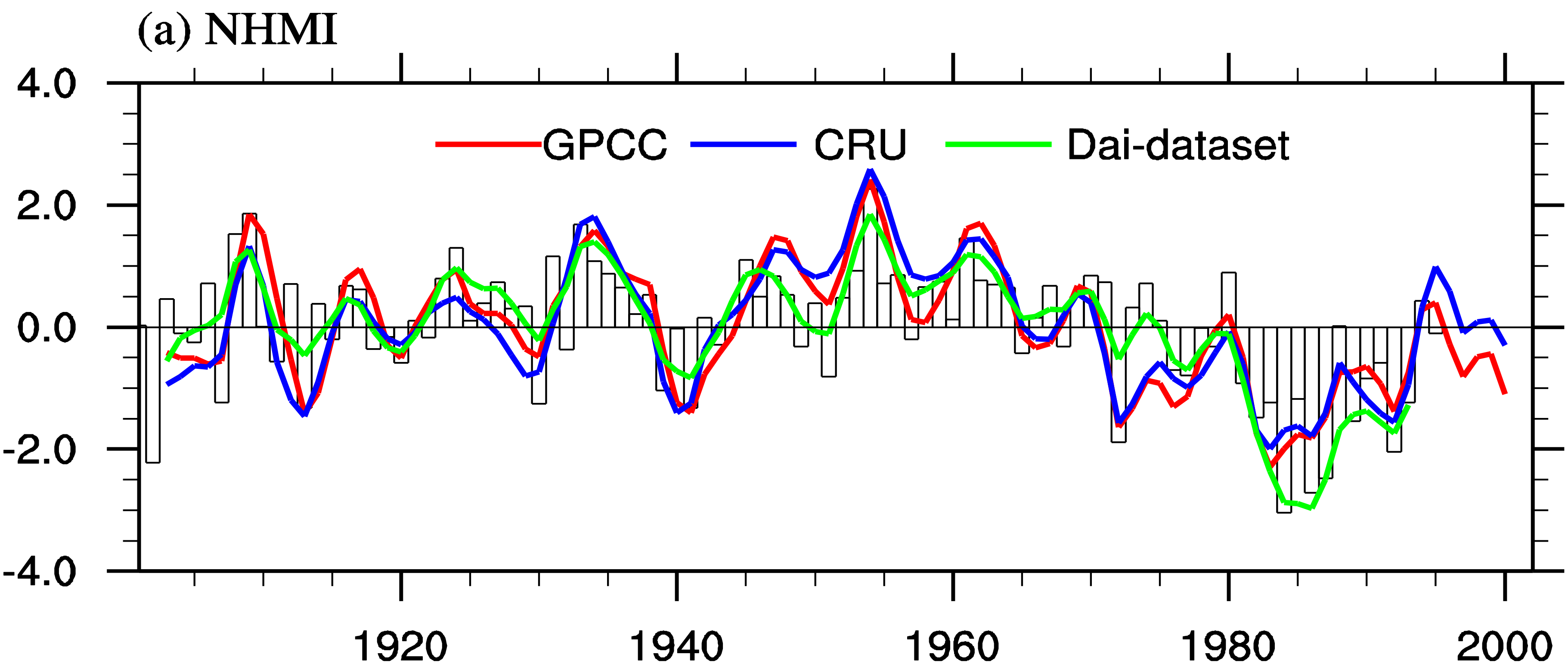
JJA –DJF UV850 & Precipitation

Space and time scales in the monsoon



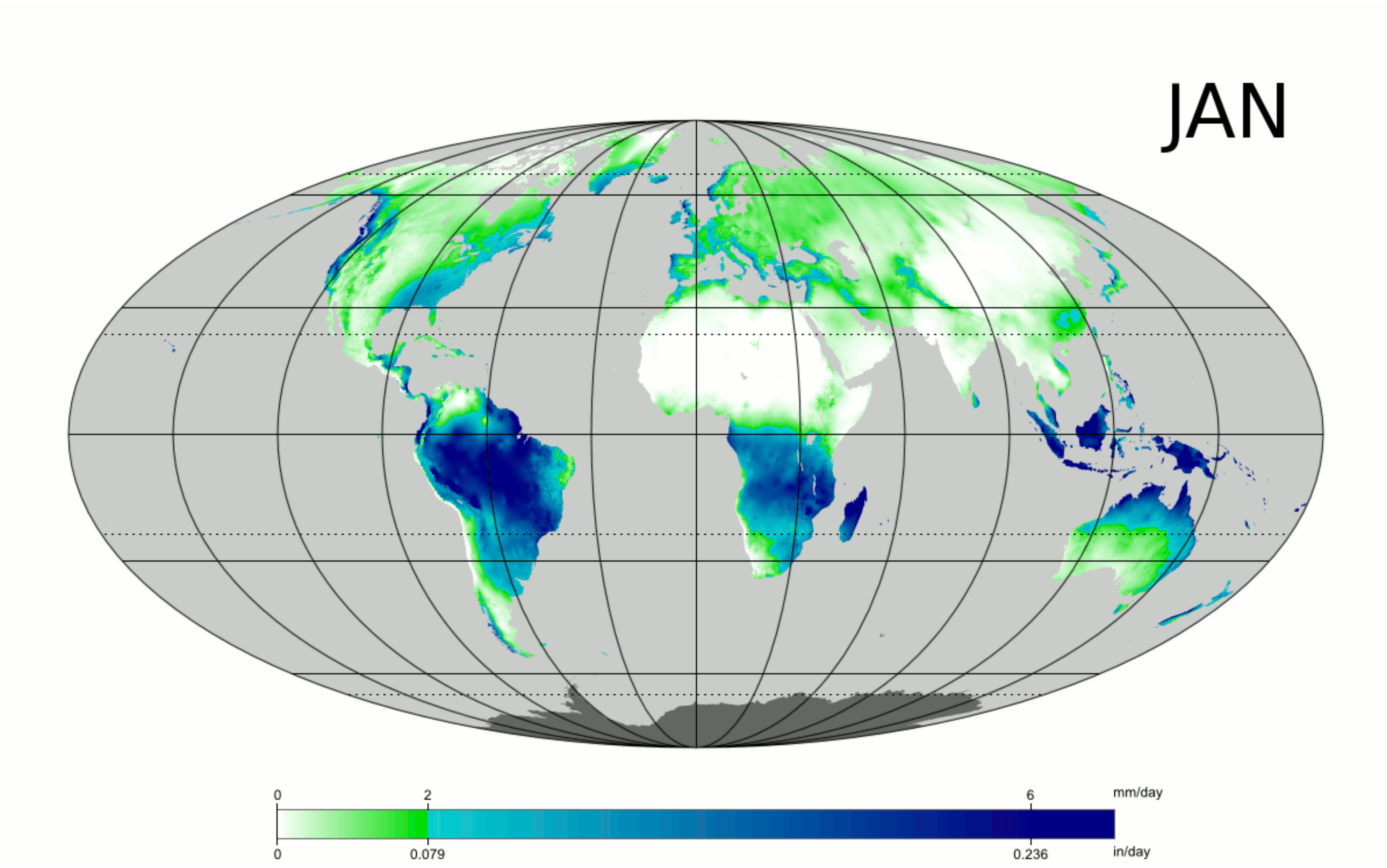
Courtesy: Andy Turner

Changes of NH land monsoon precipitation



Zhang Lixia, Tianjun Zhou, 2011: An assessment of monsoon precipitation changes during 1901-2001, ***Climate Dynamics****, 37, 279-296*

How to understand the observed changes at decadal scales?




Ocean-Atmosphere Interaction

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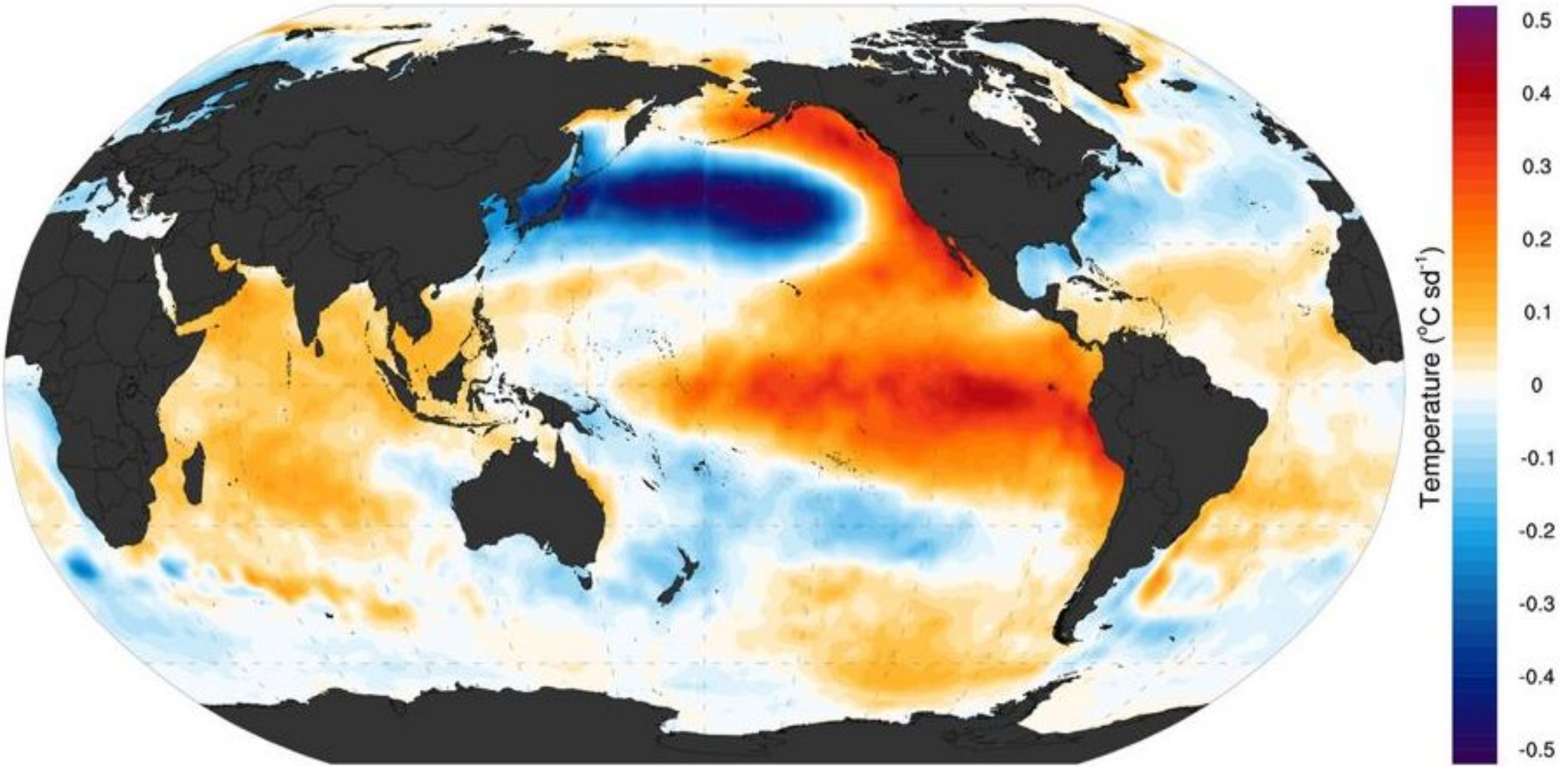
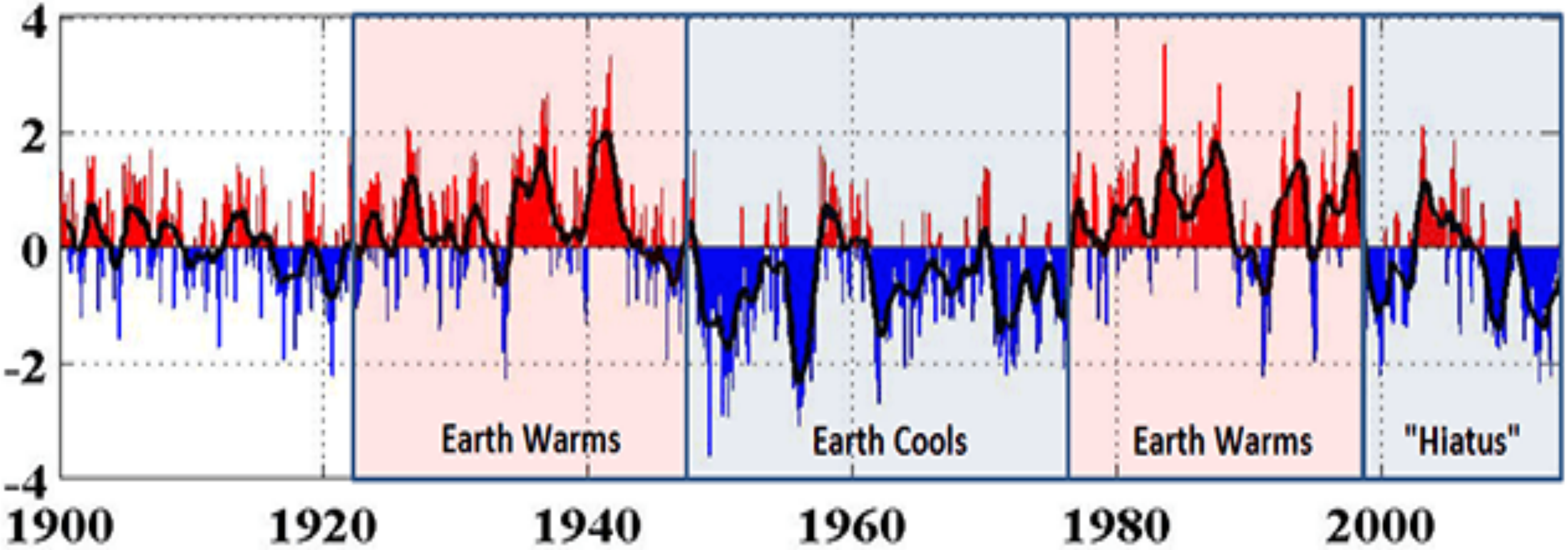
Pacific Decadal Oscillation

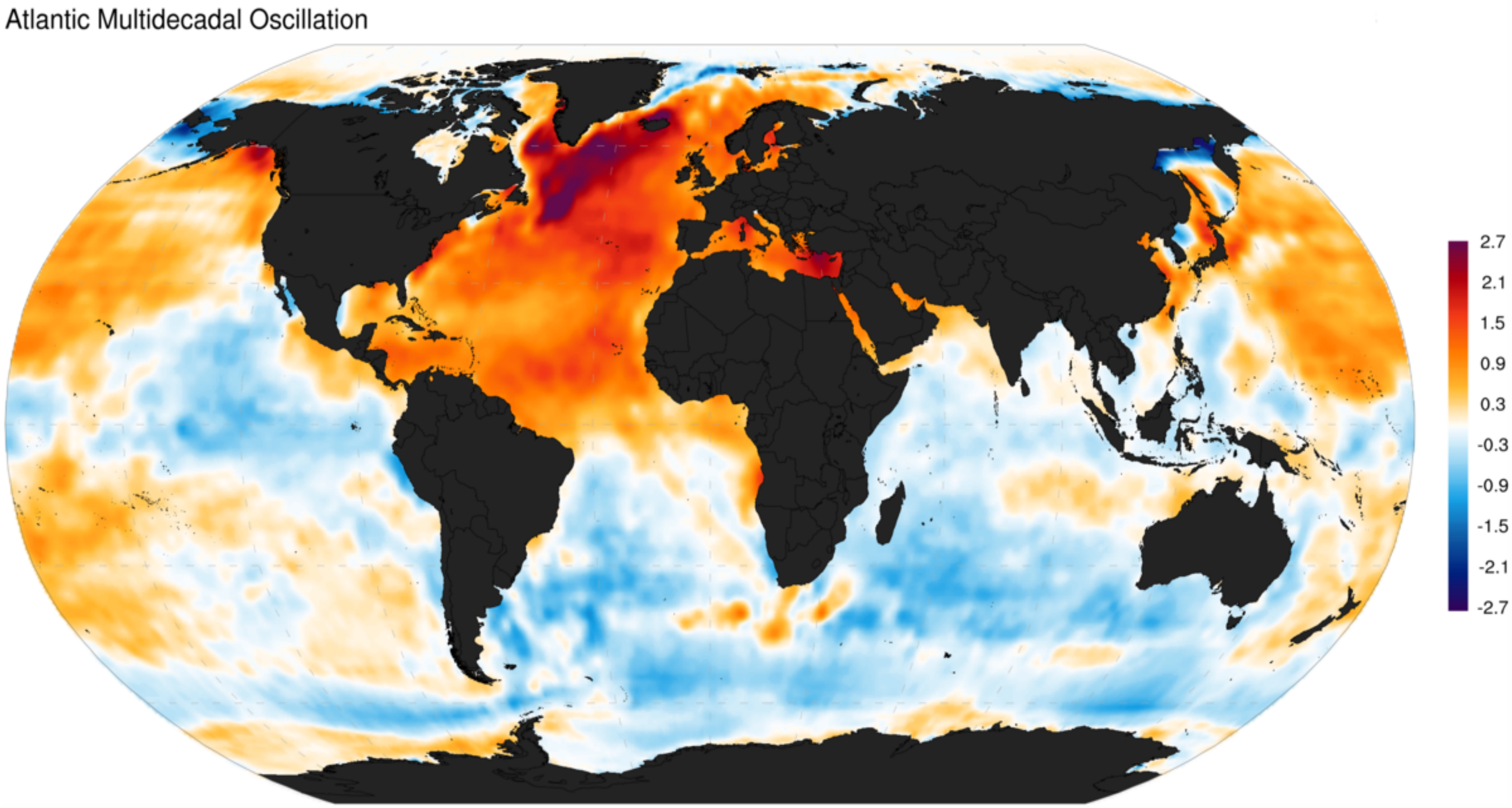


Pacific Decadal Oscillation Index

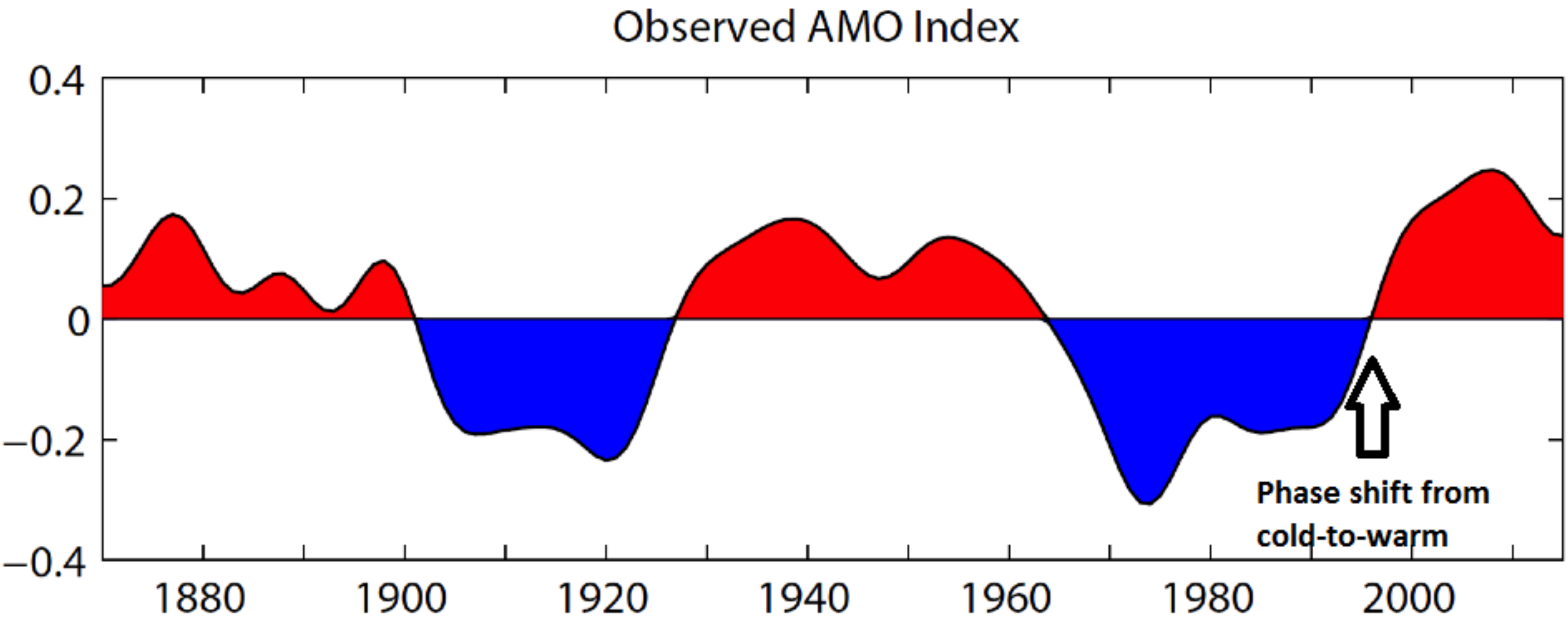
Monthly values for the PDO index: 1900-2013



Atlantic Multidecadal Oscillation

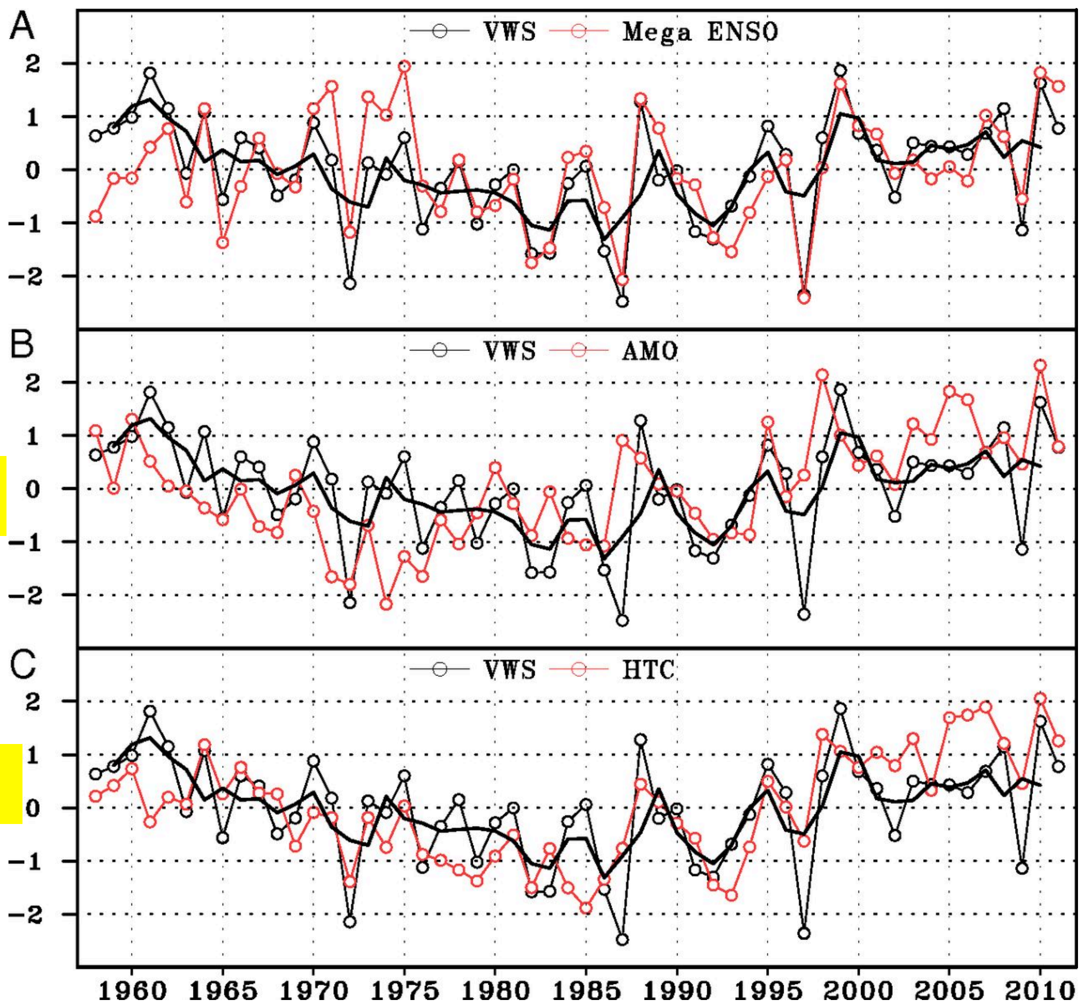


Atlantic Multidecadal Oscillation index



Contribution of IPO and AMO to GM changes

Northern Hemispheric summer monsoon (NHMI) circulation index (VMS) in relation to the mega-ENSO, AMO, and hemispheric thermal contrast (HTC).



IPO

Cor=0.77

AMO

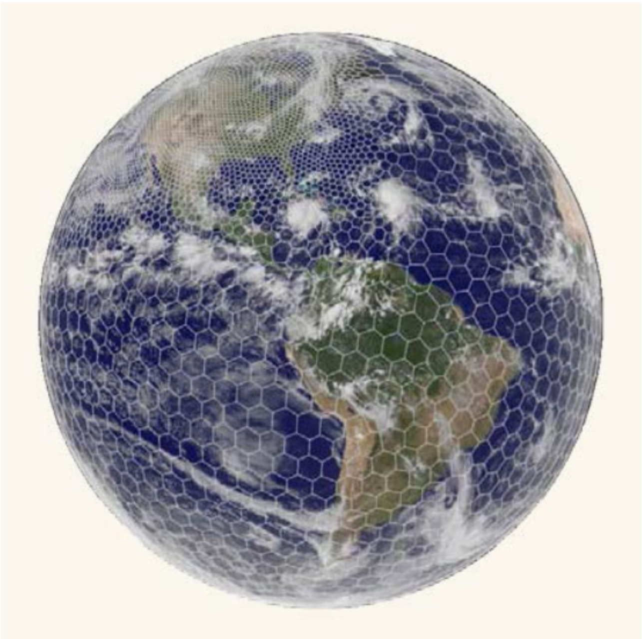
Cor=0.44

HTC

Cor=0.63

Wang et al. PNAS 2013;110:5347-5352

Is PDO forcing a mechanism for GM change?



We demonstrate the hypothesis by numerical modeling

Model & Experiments

- NCAR CAM2: T42L26
- Global SST-forced 15-member ensemble simulation.
- Time period:

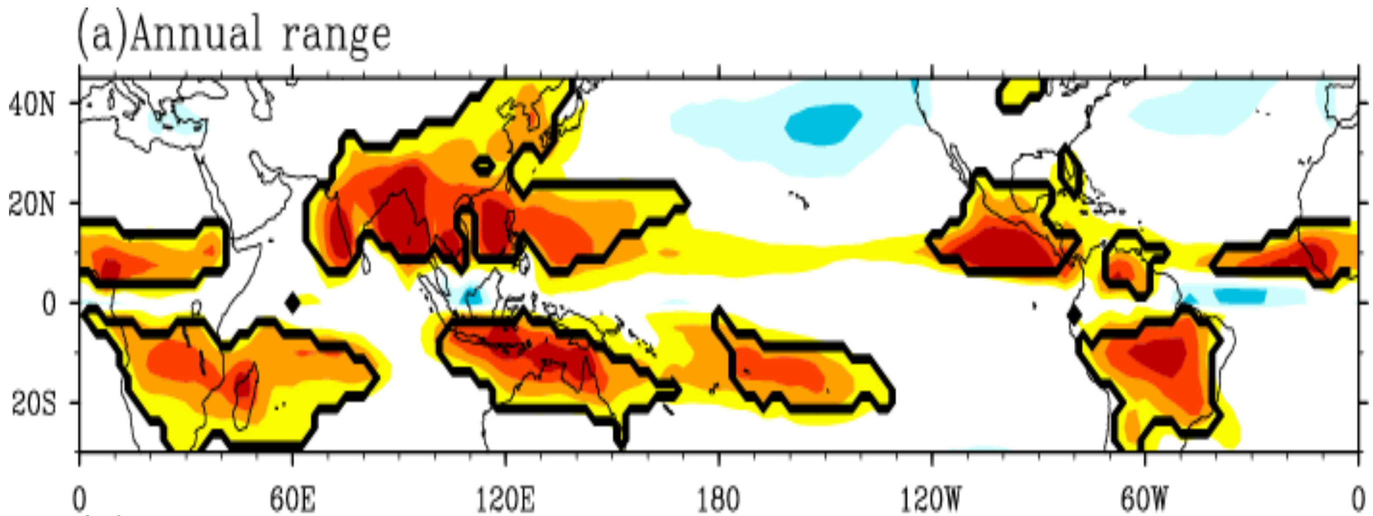
  January 1949 to October 2001

Observational SST changes are specified.

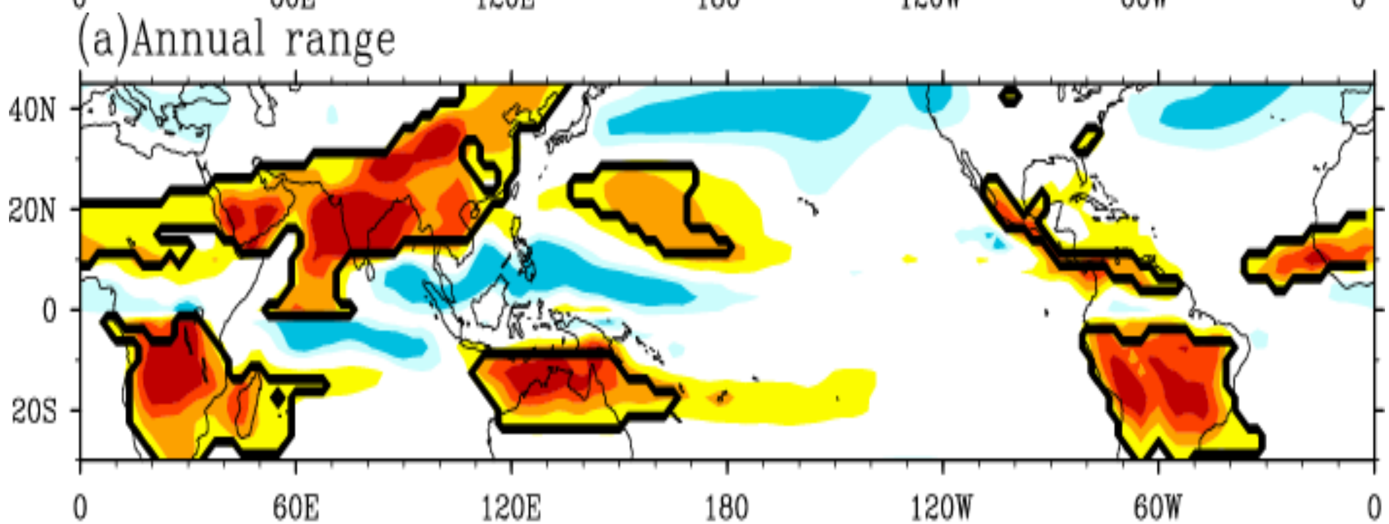
Zhou T., R. Yu., **Hongmei LI** et al. 2008 Ocean forcing to changes in global monsoon precipitation over the recent half century, ***Journal of Climate***, **21** (15), 3833–3852

Global land monsoon domain

OBS

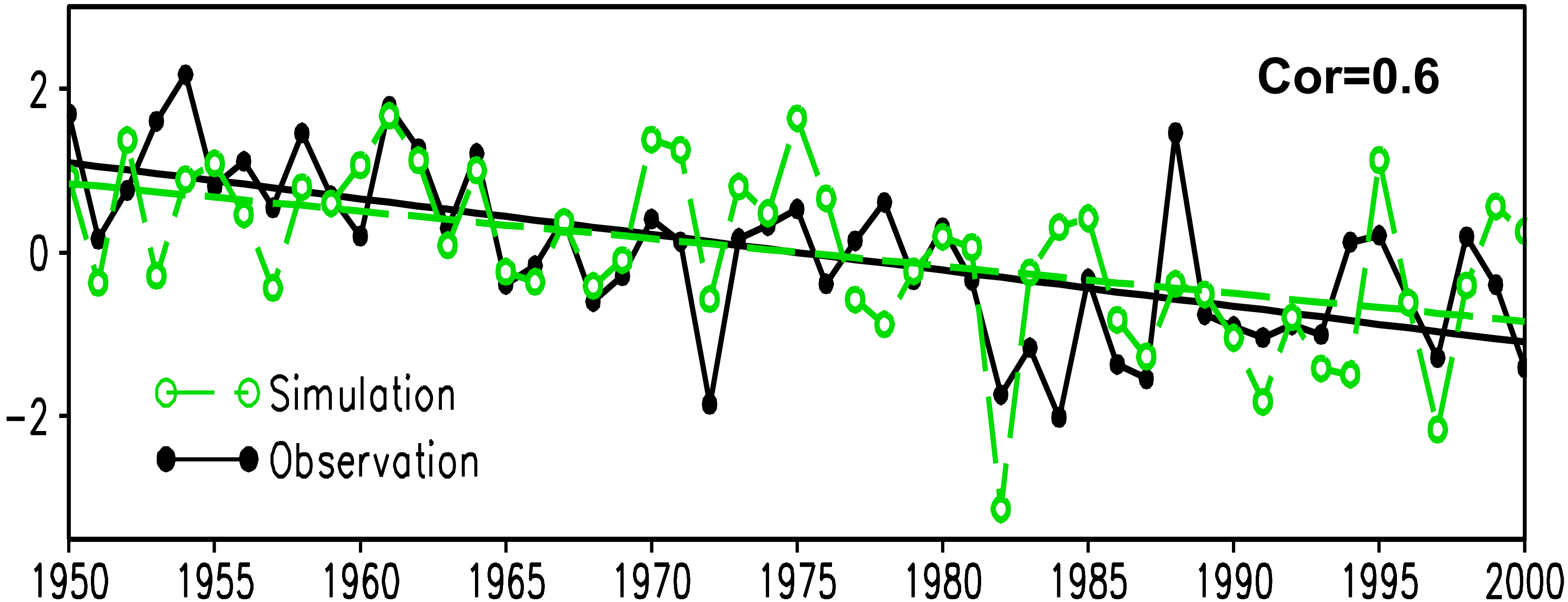


CAM2



Zhou T., R. Yu., **Hongmei LI** et al. 2008 Ocean forcing to changes in global monsoon precipitation over the recent half century, ***Journal of Climate***, **21** (15), 3833–3852

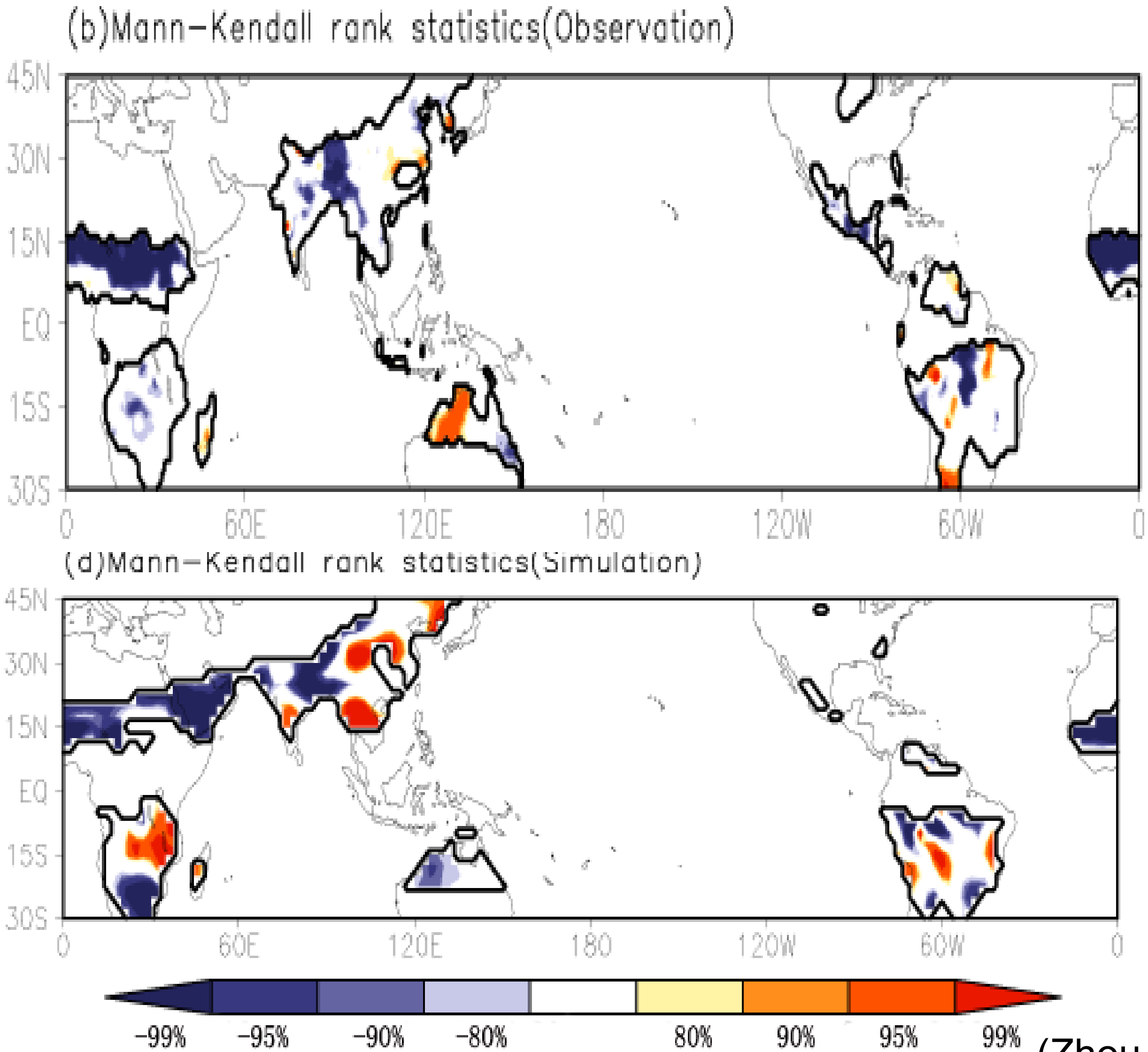
The observed and simulated Global Land monsoon index



SST-driven AGCM ensemble simulation, with 12 realizations

Zhou T., R. Yu., **Hongmei LI** et al. 2008 Ocean forcing to changes in global monsoon precipitation over the recent half century, ***Journal of Climate***, **21** (15), 3833–3852

The Mann-Kendall rank statistics of the observed and simulated AR trend within land monsoon domain



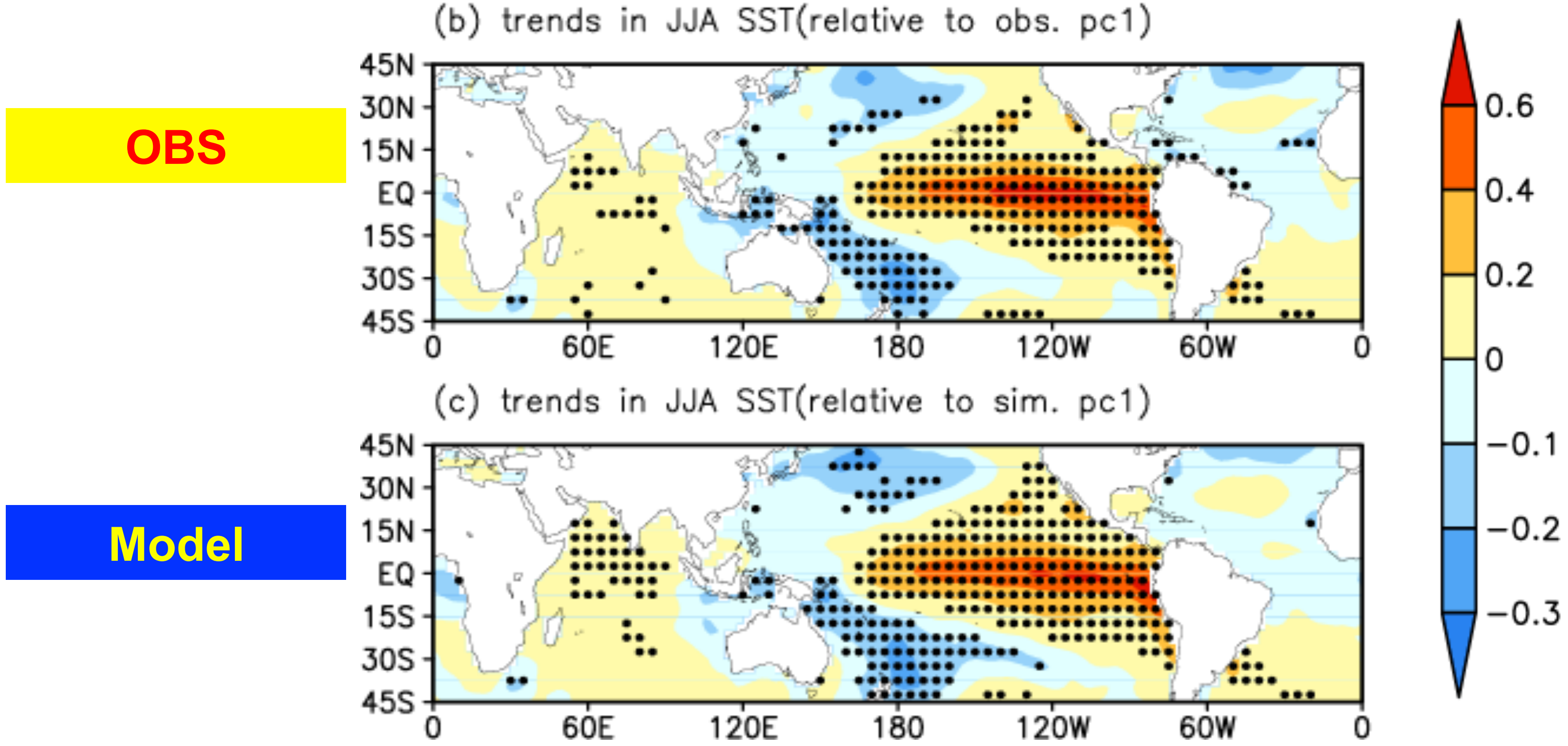
Observation

Simulation

(Zhou et al. 2008 J. Climate)

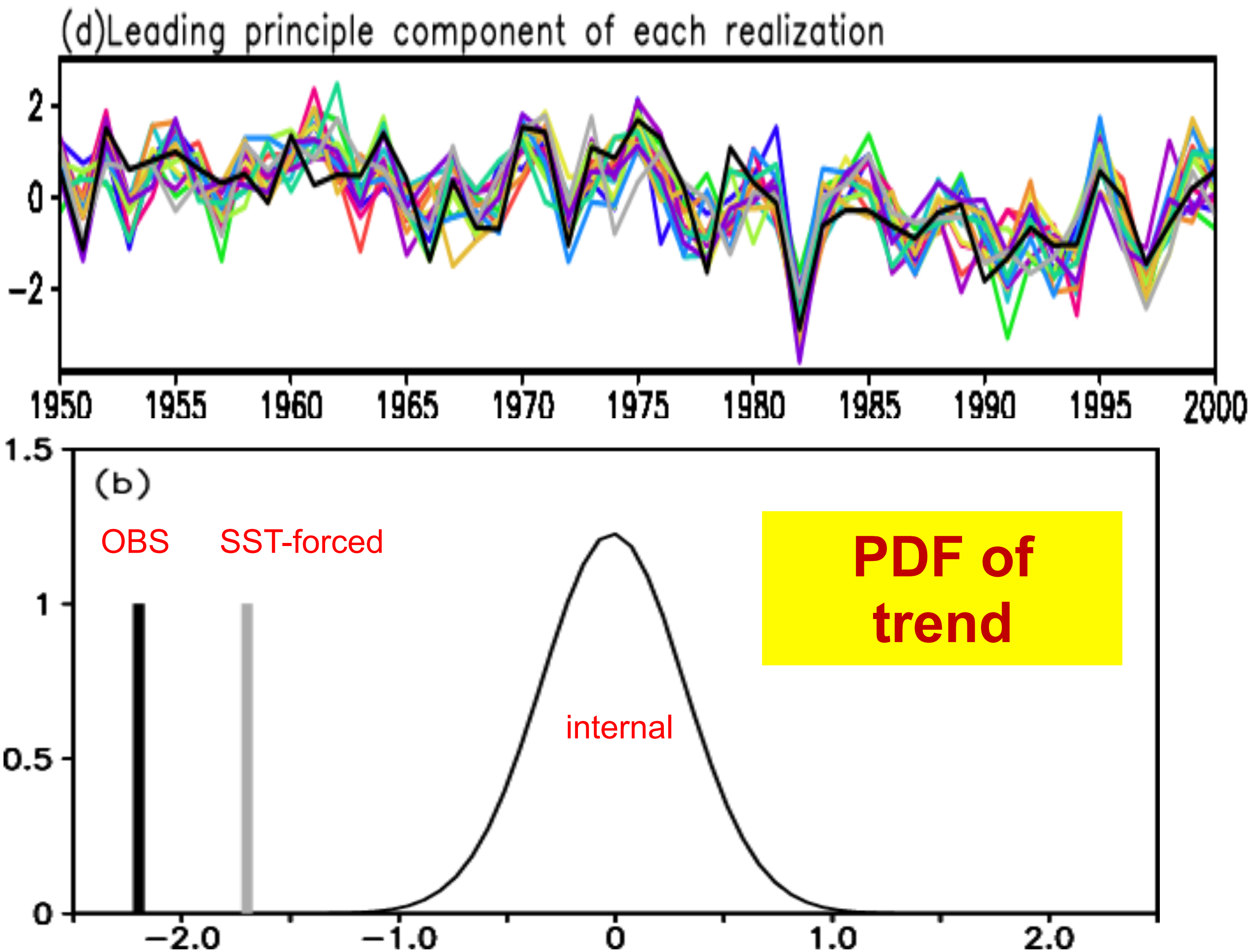
SSTA congruent with the weakening trend of global land monsoon precipitation

Inter-decadal Pacific Oscillation: IPO/PDO



Zhou T., R. Yu., **Hongmei LI** et al. 2008 Ocean forcing to changes in global monsoon precipitation over the recent half century, ***Journal of Climate***, **21** (15), 3833–3852

Forced Signal vs Internal noise



Sqrt(E/I)	3.31
Ext. vs. T.	0.92
Int. vs. T	0.08
Ext.	**0.92**
Int.	**0.08**
Total	1.00

Zhou T., R. Yu., **Hongmei LI** et al. 2008 Ocean forcing to changes in global monsoon precipitation over the recent half century, ***Journal of Climate***, **21** (15), 3833–3852

Point # 1

- When forced by historical sea surface temperatures covering 1949-2001, the ensemble simulation with AGCM successfully reproduced the weakening tendency of global land monsoon precipitation.
- This decreasing tendency was driven by the warming trend over the central-eastern Pacific and the western tropical Indian Ocean, which is the tropical lobe of PDO/ IPO.
- Similar mechanism applies to the recent recovery of GM.

Zhou T., R. Yu., **Hongmei LI** et al. 2008 Ocean forcing to changes in global monsoon precipitation over the recent half century, ***Journal of Climate***, **21** (15), 3833–3852

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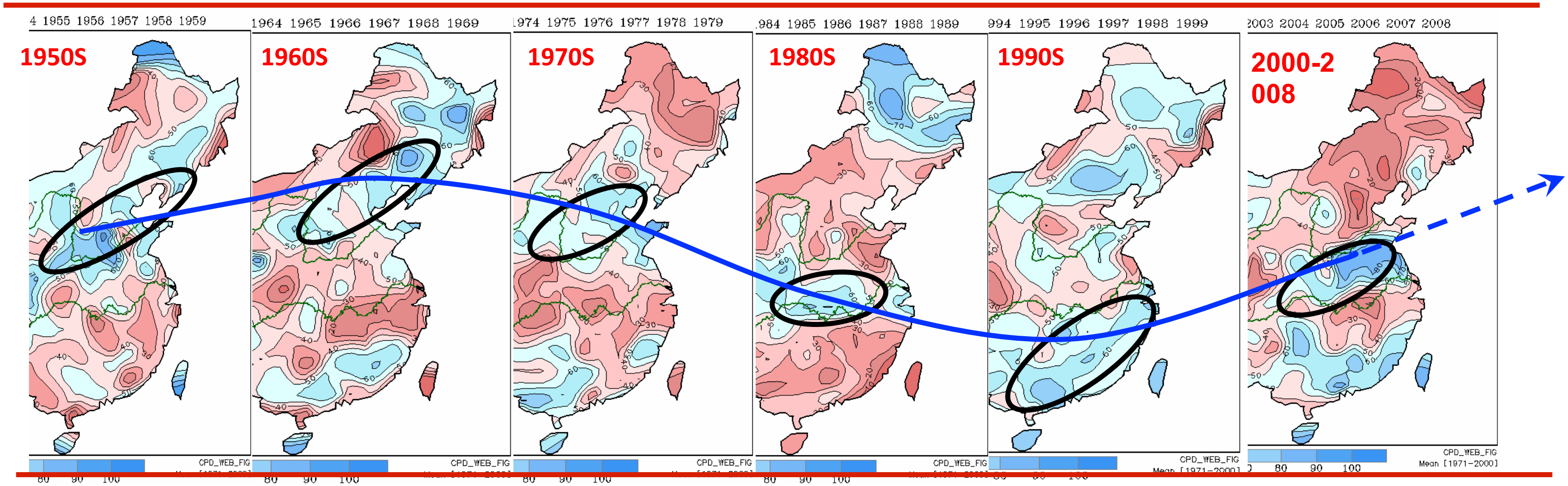
Decadal Changes of summer rainfall

20世纪　　蓝色：降雨频次高；红色：降雨频次低　　21世纪



最高频次 90%　　最高频次 80%　　最高频次 60%　　最高频次 60%　　最高频次 70%

1970S　　Monsoon Weakening

(After BCC, 2010)

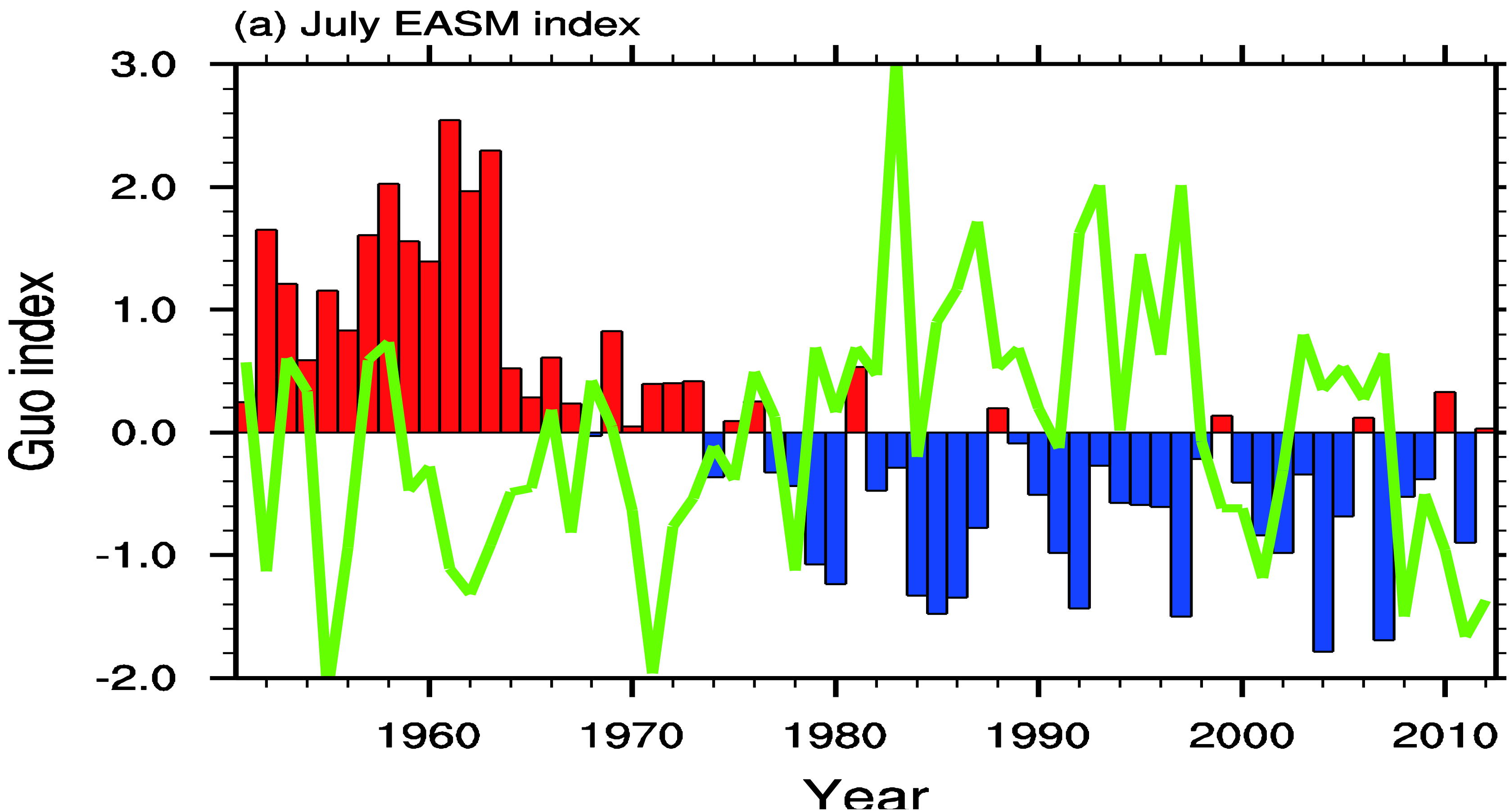
South-to-North Water Diversion Project

http://www.nsbd.gov.cn/zx/english/

South-to-North Water Diversion Project

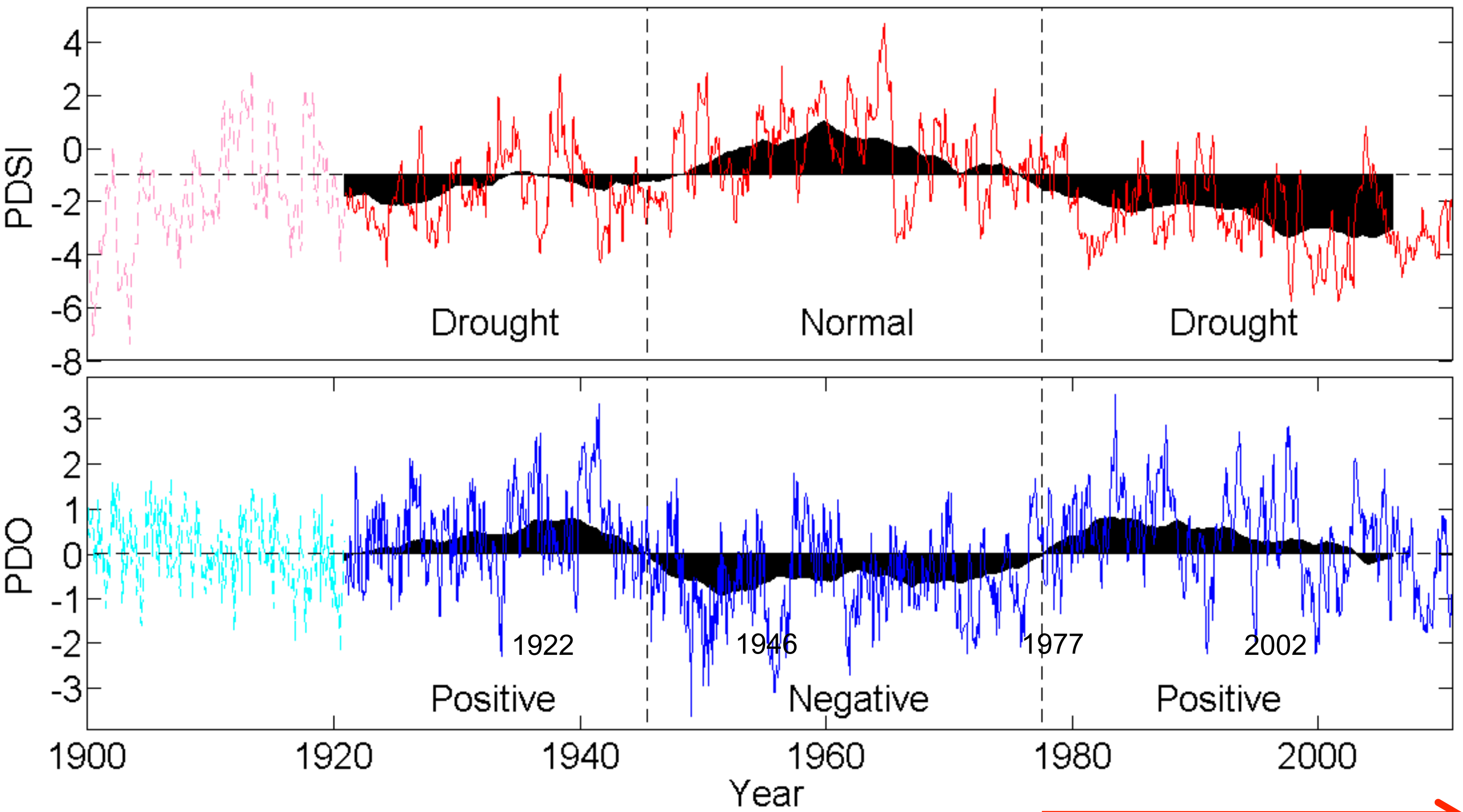
PDO and E. Asian monsoon

Monsoon index (bar)   Green: PDO index



Zhou, T., F. Song, R. Lin, X. Chen and X. Chen, 2013: The 2012 North China floods: Explaining an extreme rainfall event in the context of a long-term drying tendency [in "Explaining Extreme Events of 2012 from a Climate Perspective"]. ***Bulletin of the American Meteorological Society***, 94(9), S49-S51

PDSI index in N. China and PDO index over the 20th century



Shading: 11 yrs smoothing

Qian C. and T. **Zhou**, 2014: Multidecadal variability of North China aridity and its relationship to PDO during 1900-2010, ***J. Climate***, 27(3), 1210-1222

Again, we demonstrate the mechanism by numerical modeling

Model and Experiments

AMIP-type simulation is used to understand the driving of SST

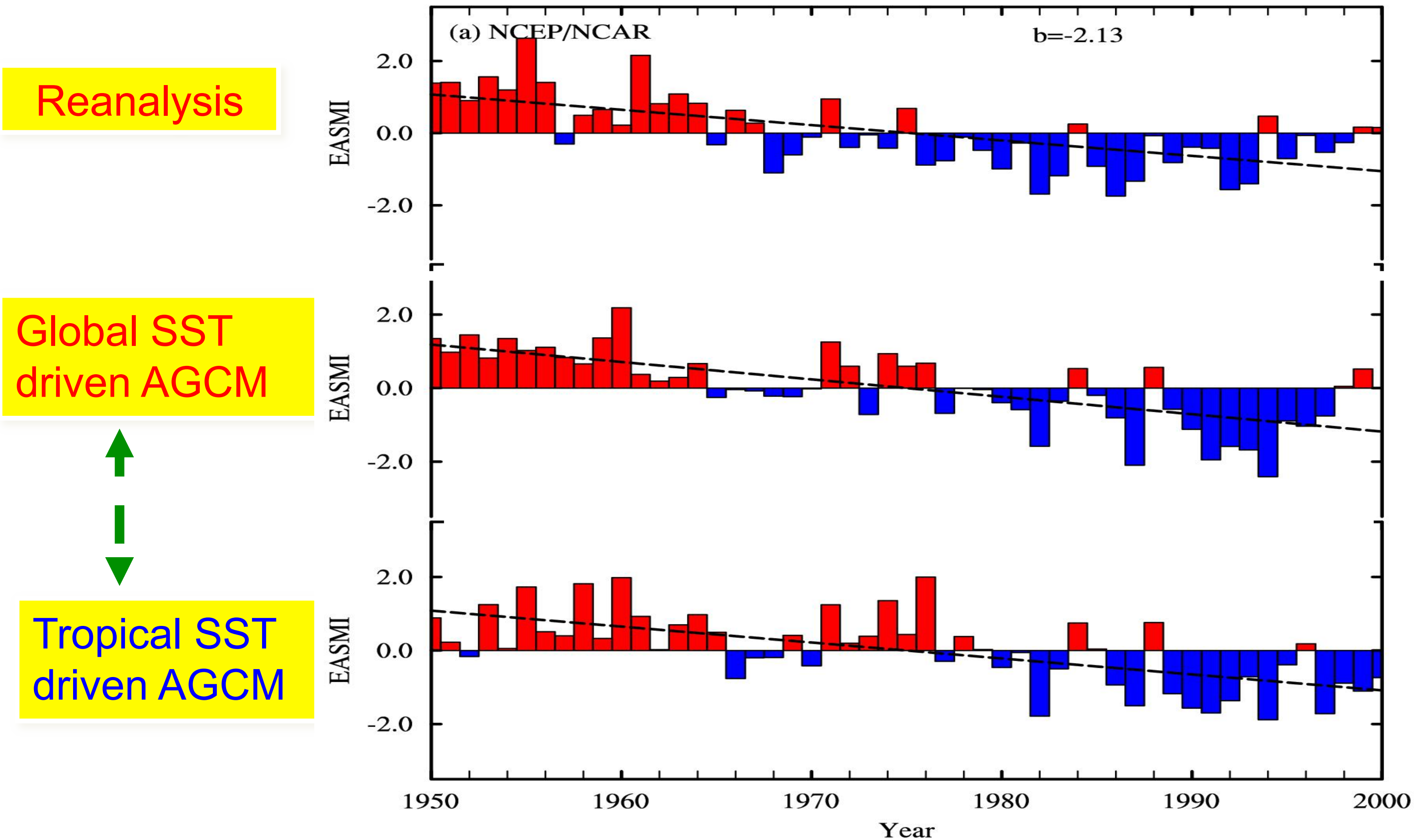
	CAM3 (T85)	CAM3 (T42)	AM2.1 (FV)
GOGA	5	5	10
TOGA	5	5	N/A
ATM	N/A	10	N/A

Definition of EASM Index:

Normalized zonal wind shear between 850 and 200 hPa averaged within (20-40N,110-140E) (After Han and Wang, 2007)

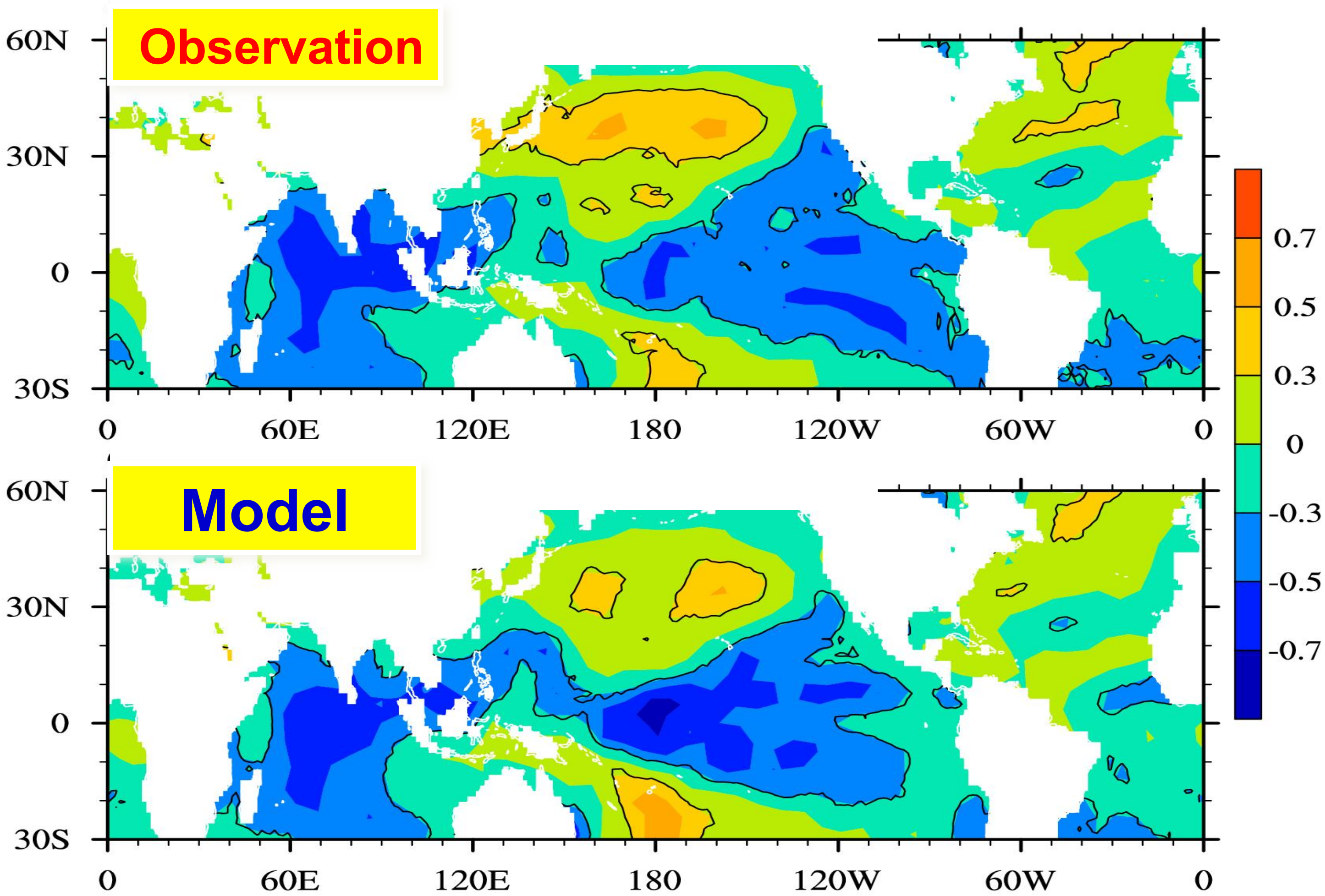
Li, Hongmei, A. Dai, **T. Zhou**, J. Lu, 2010: Responses of East Asian summer monsoon to historical SST and atmospheric forcing during 1950-2000, ***Climate Dynamics,*** **34**, 501-514

EASM index in AGCM driven by observed SST



Li, Hongmei, A. Dai, **T. Zhou**, J. Lu, 2010: Responses of East Asian summer monsoon to historical SST and atmospheric forcing during 1950-2000, ***Climate Dynamics*, 34**, 501–514

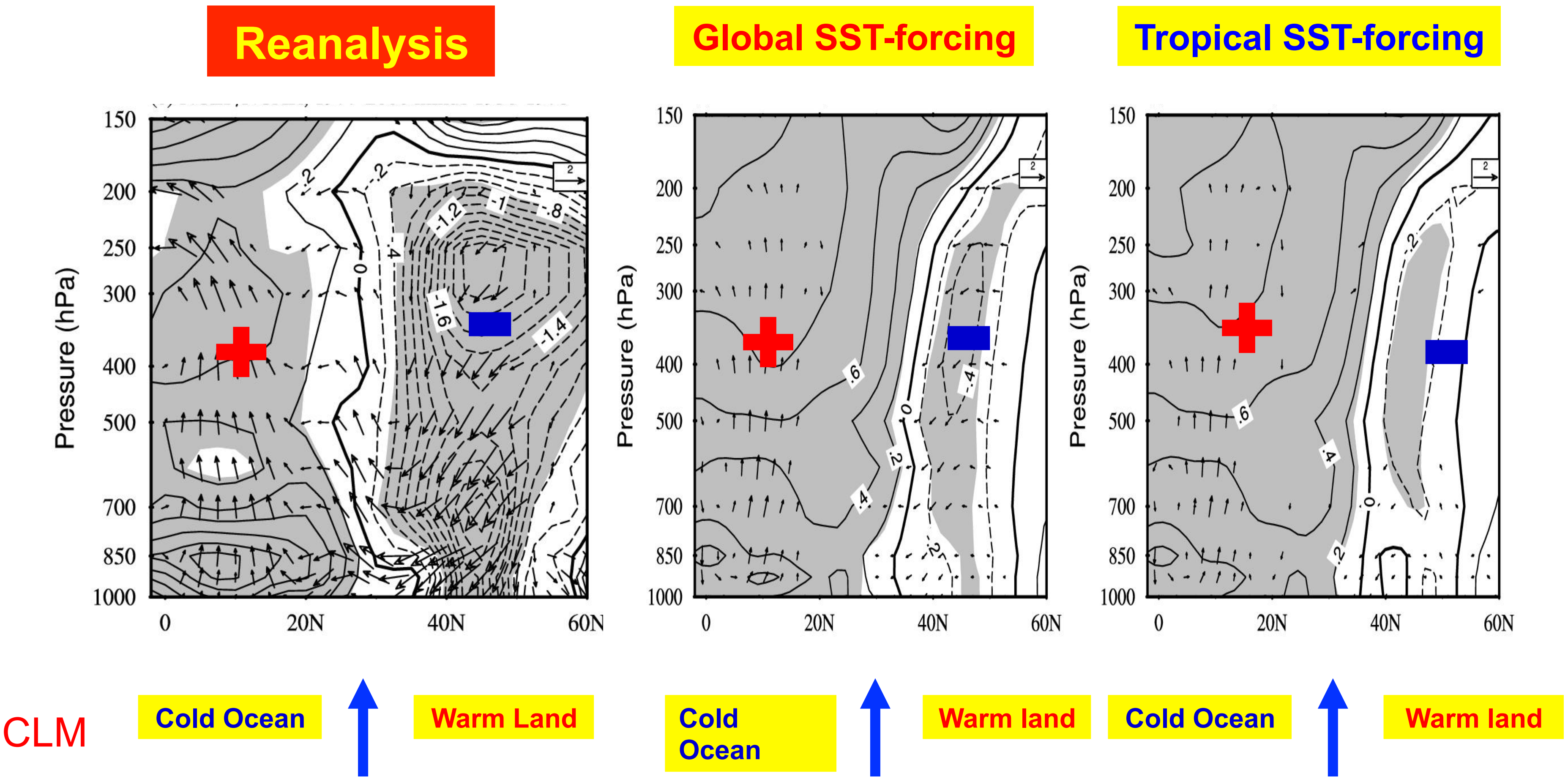
Correlations between SSTA and EASM



Li, Hongmei, A. Dai, **T. Zhou**, J. Lu, 2010: Responses of East Asian summer monsoon to historical SST and atmospheric forcing during 1950-2000, ***Climate Dynamics*, 34**, 501–514, DOI 10.1007/s00382-008-0482-7

Land-Sea Thermal Contrast change

(105-122°E average） (1980-99) －(1958-79)



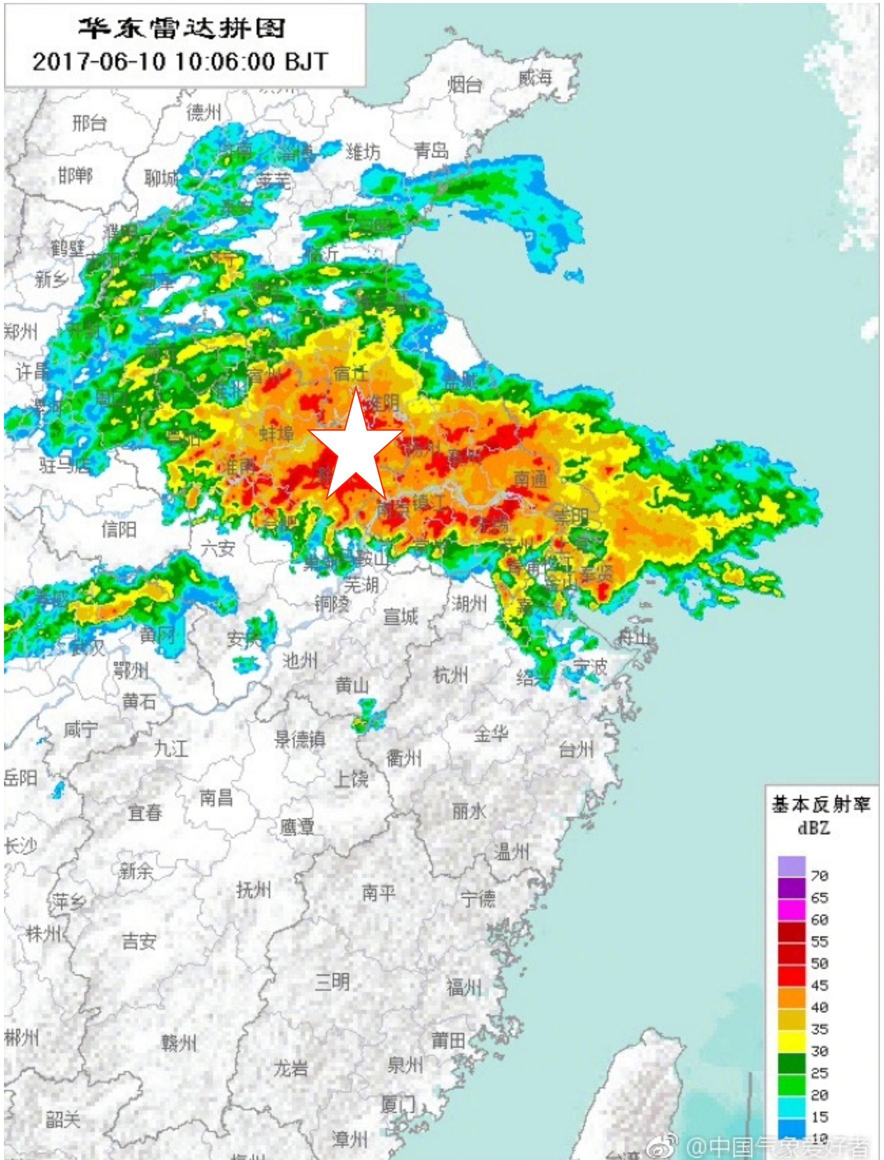
Li, Hongmei, A. Dai, T. Zhou, J. Lu, 2010: Responses of East Asian summer monsoon to historical SST and atmospheric forcing during 1950-2000, ***Climate Dynamics*, 34**, 501–514

Point # 2

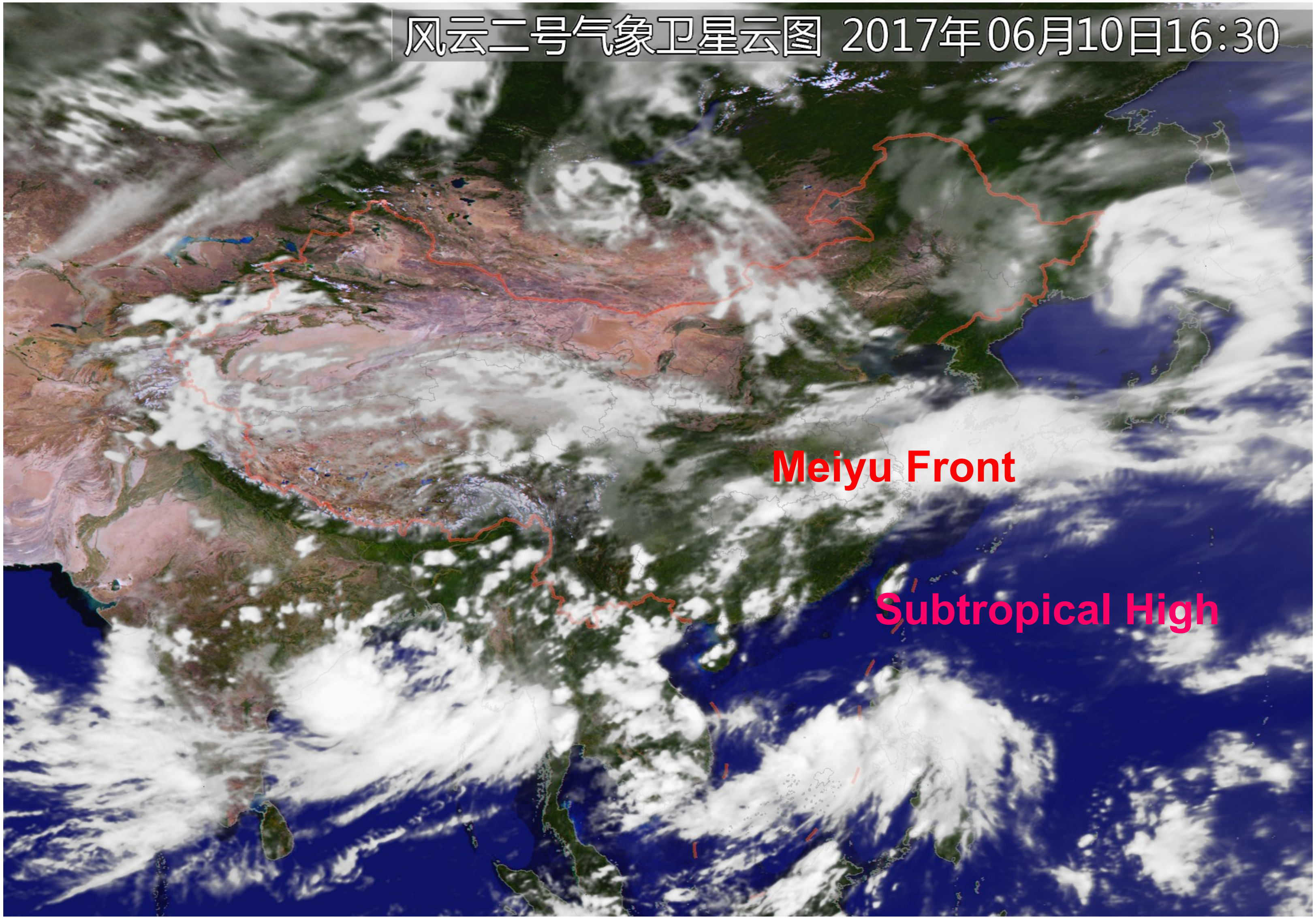
- Data diagnosis reveals an out of phase change of E. Asian summer monsoon circulation and PDO at inter-decadal time scale. This relationship is evident in both the past 50 yrs and the 20th century.
- When driven by historical SST, the AGCMs are able to reproduce to weakening tendency of E. Asian summer monsoon circulation. The response is dominated by the tropical lobe of PDO/IPO.
- The simulation of monsoon rain band changes remains to be a challenge.

Li, Hongmei, A. Dai, T. Zhou, J. Lu, 2010: Responses of East Asian summer monsoon to historical SST and atmospheric forcing during 1950-2000, ***Climate Dynamics*, 34**, 501–514

Monsoon rainband is controlled by Western Pacific Subtropical High

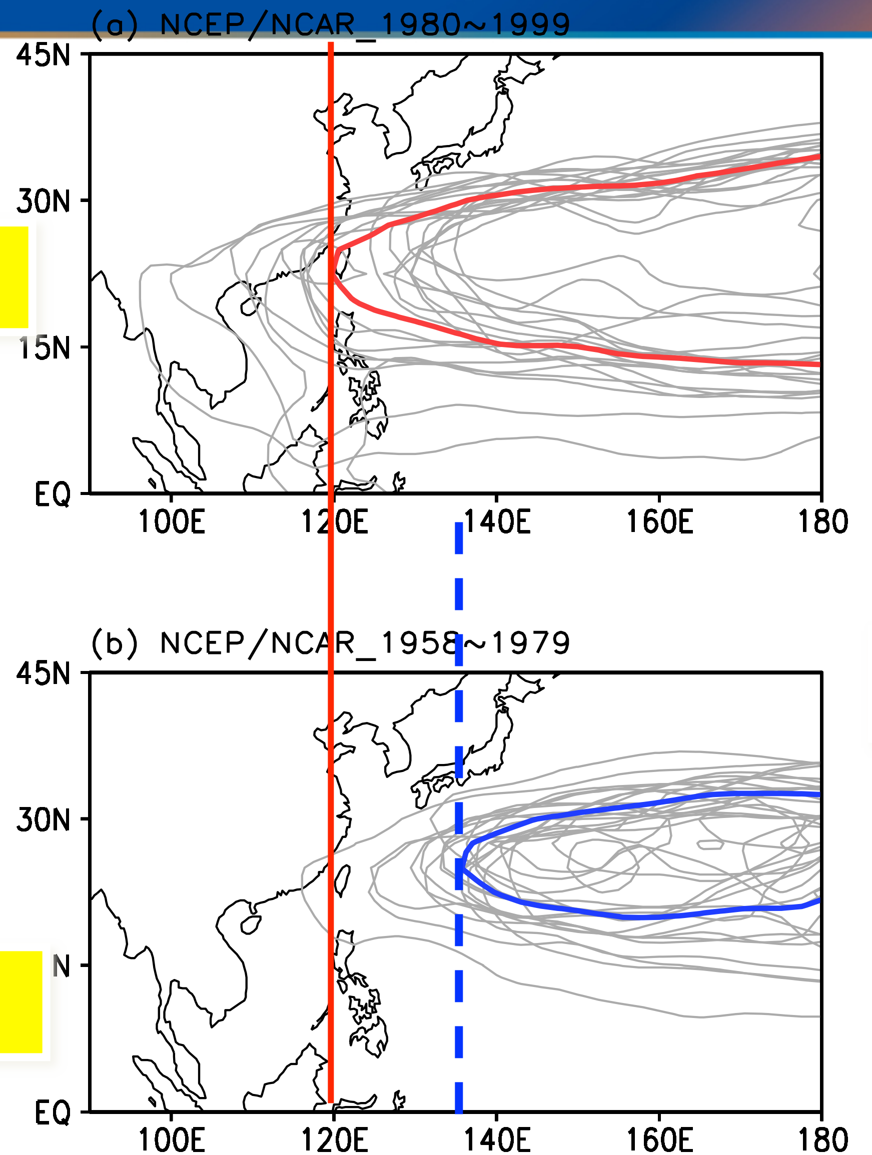


Monsoon rainband is controlled by Western Pacific Subtropical High



http://www.nmc.cn/publish/observations/china/dm/weatherchart-h000.htm

Westward Extension of WPSH



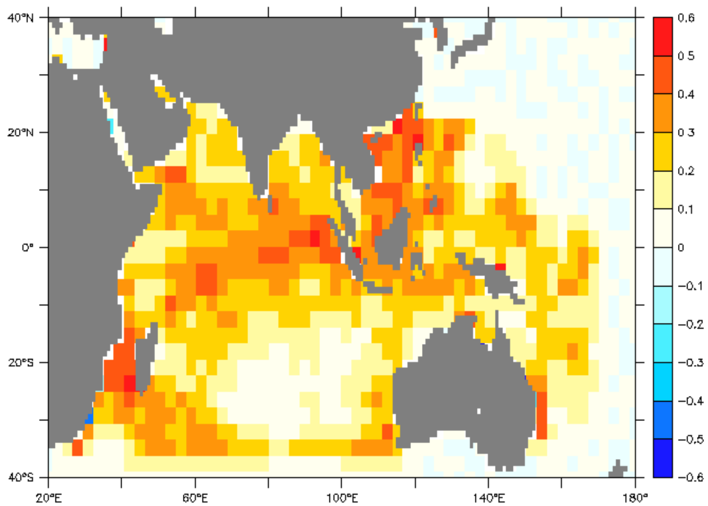
1980-99

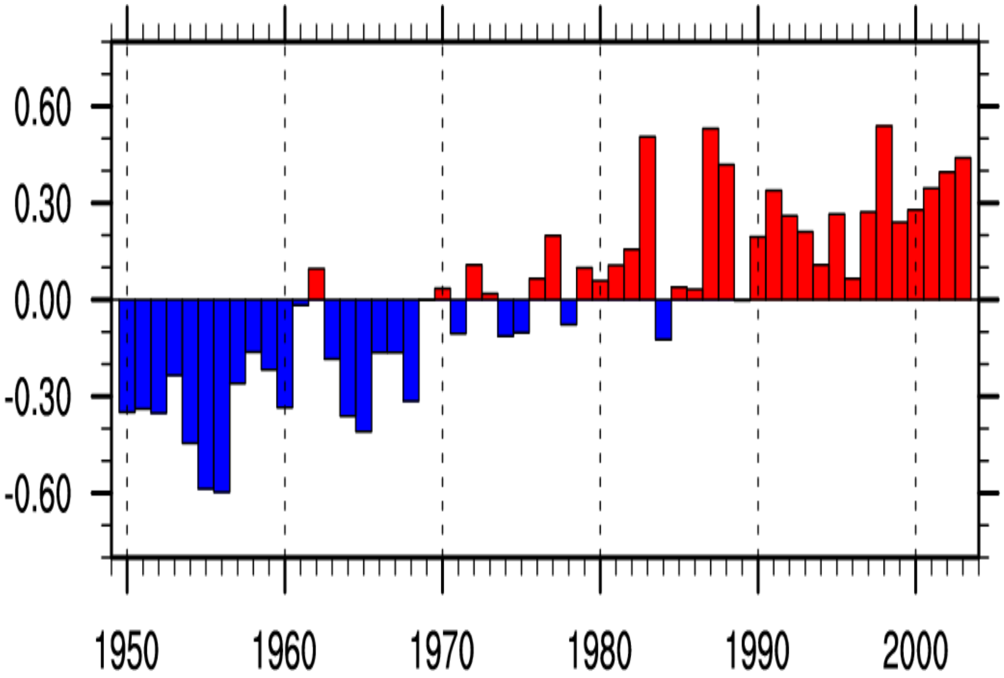
1958-79

reanalysis

Zhou, T., R. Yu, J. Zhang, H. Drange et al. 2009, Why the Western Pacific Subtropical High has extended westward since the late 1970s, ***J. Climate***, 22, 2199-2215

The warming of IWP





SST [1976-2001] – SST[1960-1990]

SSTA time series

Zhou, T., R. Yu, J. Zhang, H. Drange et al. 2009, Why the Western Pacific Subtropical High has extended westward since the late 1970s**,** ***J. Climate***, 22, 2199-2215

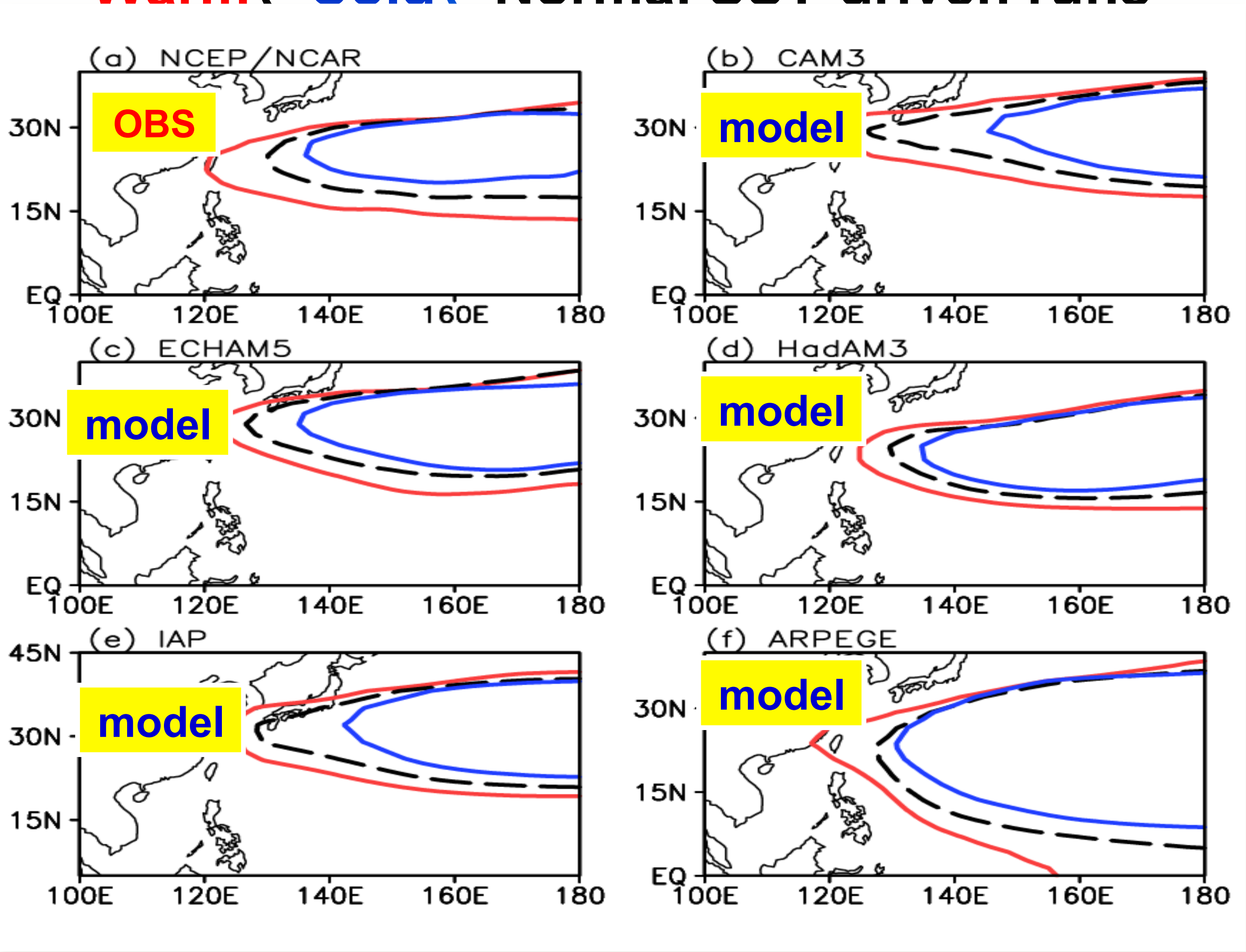
Description of 5 AGCMs

Institute	AGCM	Resolution	Convection scheme	Reference
NCAR	**CAM3**	T85L26	Deep convection is parameterized following Zhang and McFarlane (1995). Shallow and upper-level convection uses Hack (1994).	Boville et al. (2006)
MPI	**ECHAM5**	T63 L31	Tiedtke(1989) with modifications for deep convection according to Nordeng (1994).	Hagemann et al. (2006)
UKMO	**HadAM3**	2.5^o lat X 3.75^o lon L19	Gregory and Rowntree (1990) with the addition of convective downdrafts (Gregory and Allen 1991)	Pope et al. (2000)
IAP	**GAMIL**	2.8^o lat x2.8^o lon L26	Zhang-McFarlane(1995)	Wang et al.(2004)
CNRM	**ARPEGE**	T63 L31	Deep convection is represented by a mass flux scheme with detrainment as proposed by Bougeault (1985). The stratiform and shallow convection cloud formation is evaluated via a statistical method described in Ricardand Royer (1993)	Cassou et al. (2001)

Zhou, T., R. Yu, J. Zhang, H. Drange et al. 2009, Why the Western Pacific Subtropical High has extended westward since the late 1970s, ***J. Climate***, 22, 2199-2215

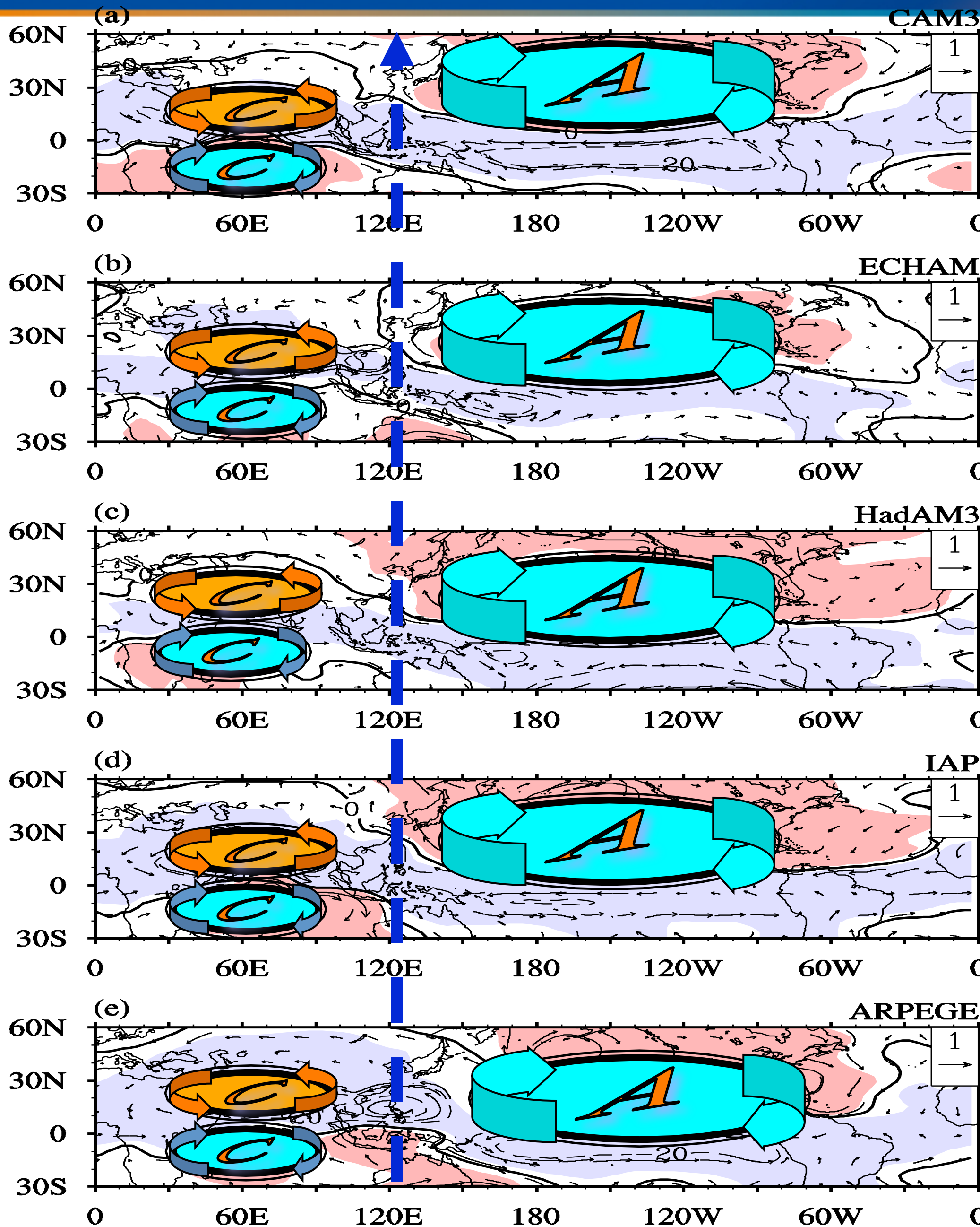
WPSH in the simulation

Warm、Cold、Normal SST-driven runs



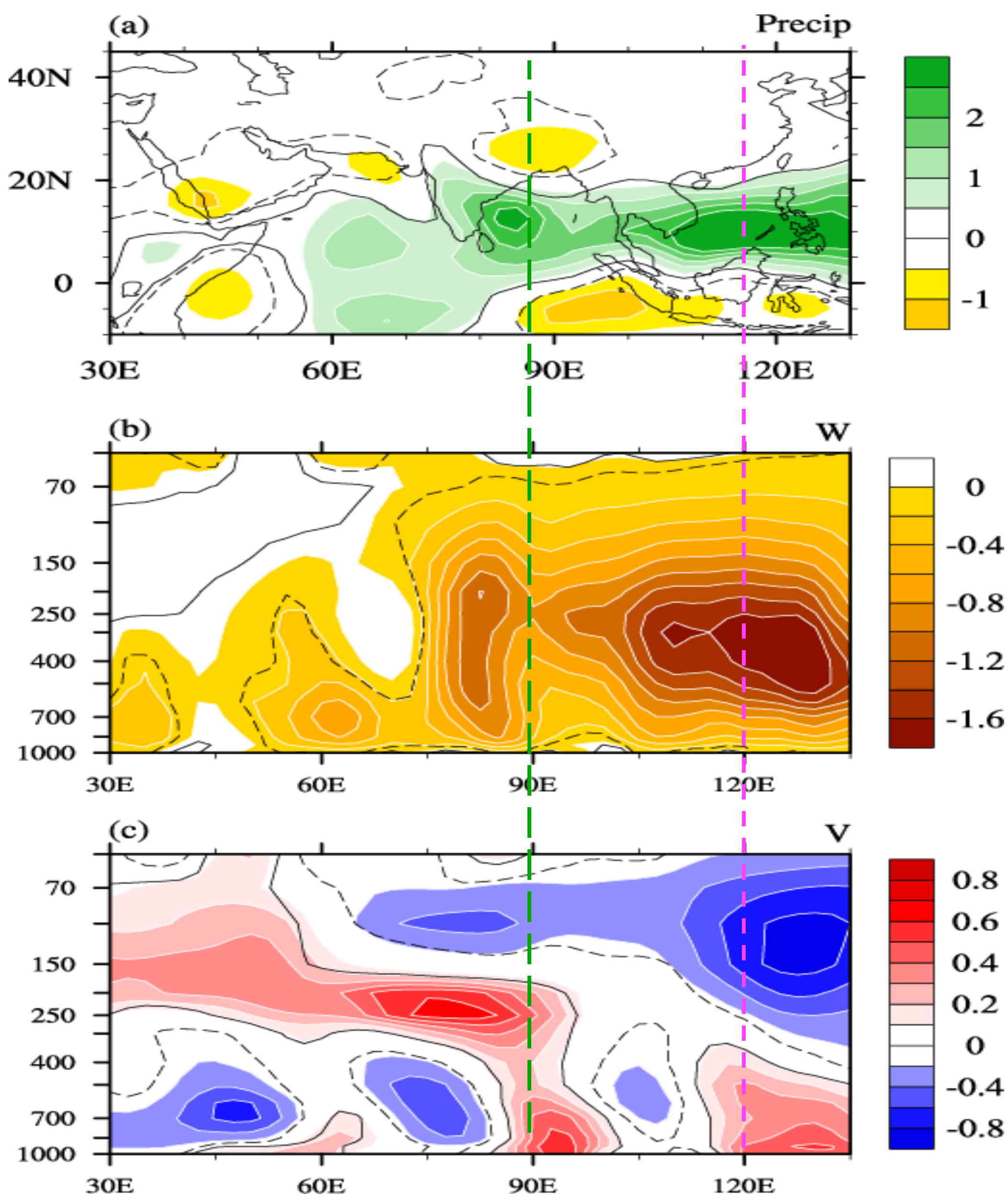
Zhou, T., R. Yu, J. Zhang, H. Drange et al. 2009, Why the Western Pacific Subtropical High has extended westward since the late 1970s, ***J. Climate***, 22, 2199-2215

Stream function at 850hPa (IOP-ION)



Zhou et al. 2009a J. Climate

Sverdrup Vorticity-balance in the model



Multi-Model Ensemble

Rainfall

$$\beta v \approx f \frac{\partial \omega}{\partial p}$$

Vertical velocity

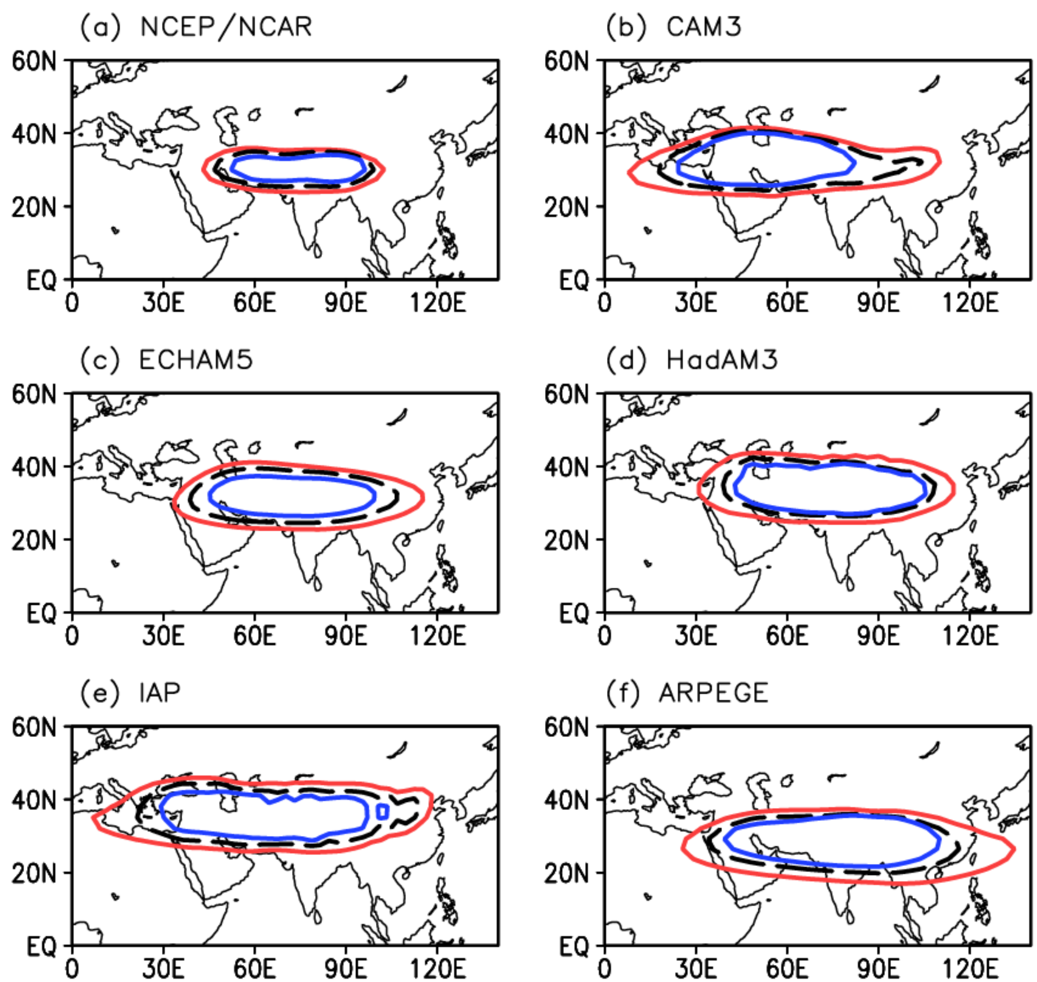
Meridional wind

0-20N average

(Zhou et al. 2009a J.

South Asian High is getting fatter

SAH in IWP warming, cooling and *control* runs



Zhou, T., R. Yu, J. Zhang, H. Drange et al. 2009, Why the Western Pacific Subtropical High has extended westward since the late 1970s**, *J. Climate***, 22, 2199-2215

Point # 3

- The westward extension of WPSH and zonal expansion of South Asian High were driven by Indo-Western Pacific warming.
- Both the negative heating in the equatorial central Pacific and Sverdrup vorticity balance are the underlying forcing mechanisms.

Zhou, T., R. Yu, J. Zhang, H. Drange et al. 2009, Why the Western Pacific Subtropical High has extended westward since the late 1970s**, *J. Climate***, 22, 2199-2215

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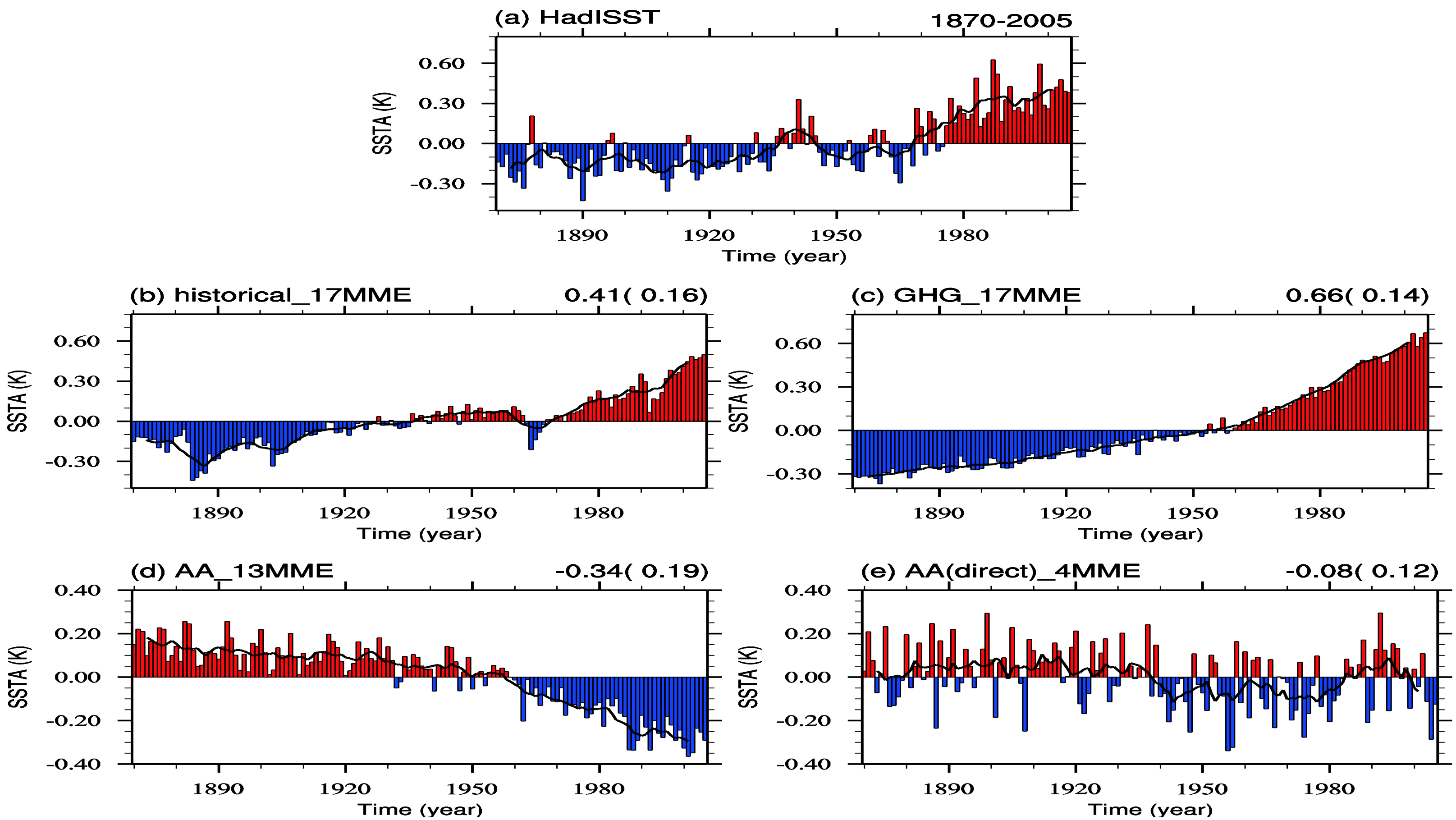
List of CMIP5 models used in our analysis

No.	Modeling center	CMIP5 model name	historical	historical GHG	hiatoric alNat	historical Misc(AA)	indirect
1	MIROC	MIROC-ESM	1	1	1	0	1
2	MRI	MRI-CGCM3	1	1	1	0	1
3	CNRM-CERFACS	CNRM-CM5	1	1	1	0	1
4	CSIRO-QCCCE	CSIRO-Mk3-6-0	1	1	1	1	1
5	NCAR	CCSM4	1	1	1	1	0
6	NOAA GFDL	GFDL-CM3	1	1	1	1	1
7	IPSL	IPSL-CM5A-LR	1	1	1	1	1
8	NASA/GISS	GISS-E2-R	1	1	1	1	1
9	LASG-CESS	FGOALS-g2	1	1	1	1	1
10	BCC	bcc-csm1-1	1	1	1	0	0
11	BNU	BNU-ESM	1	1	1	0	0
12	NOAA GFDL	GFDL-ESM2M	1	1	1	1	0
13	CCCma	CanESM2	1	1	1	1	1
14	MOHC	HadGEM2-ES	1	1	1	0	1
15	NCC	NorESM1-M	1	1	1	1	1
16	MIROC	MIROC-ESM-CHEM	1	1	1	0	1
17	NASA/GISS	GISS-E2-H	1	1	1	1	1

Indian Ocean Warming

- Indian Ocean has witnessed a significant warming trend during the twentieth century, which is revealed to be attributed to human activity.

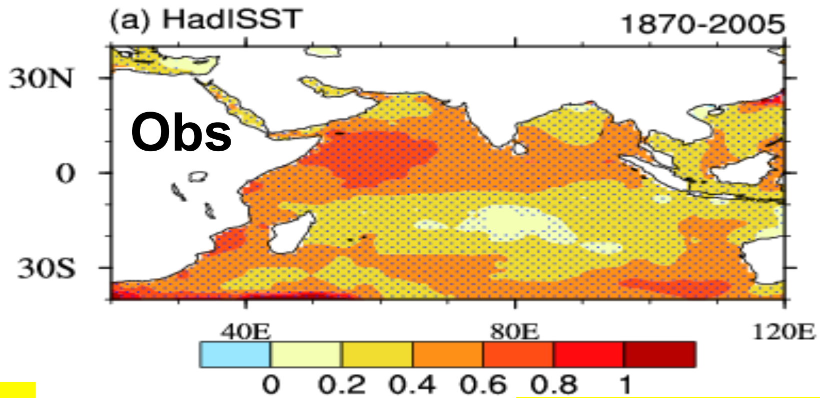


(Dong and Zhou, 2014, *Journal of Climate*)

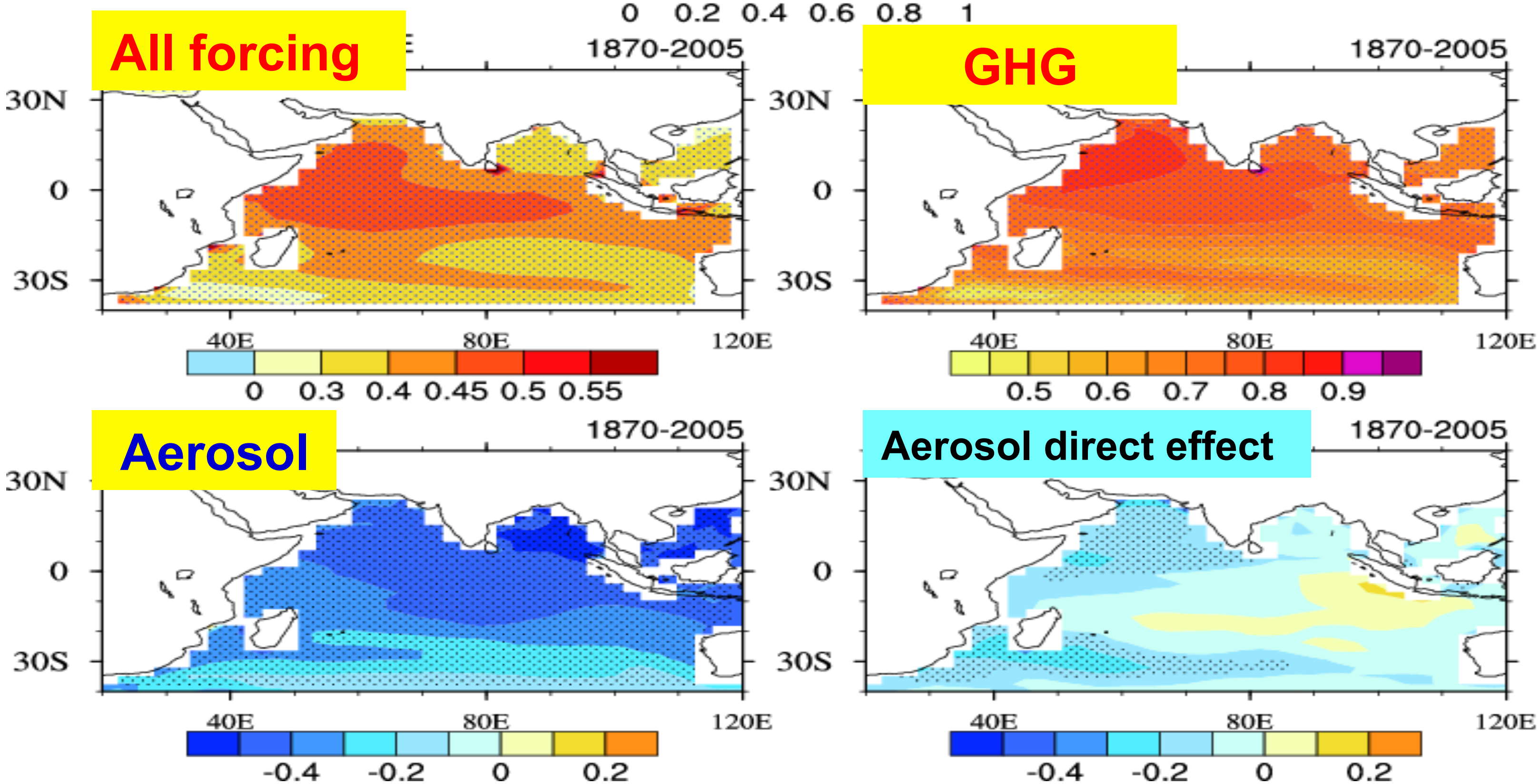
Indian Ocean Warming in 17 CMIP5 models

Basin-wide pattern

Positive IOD-like pattern

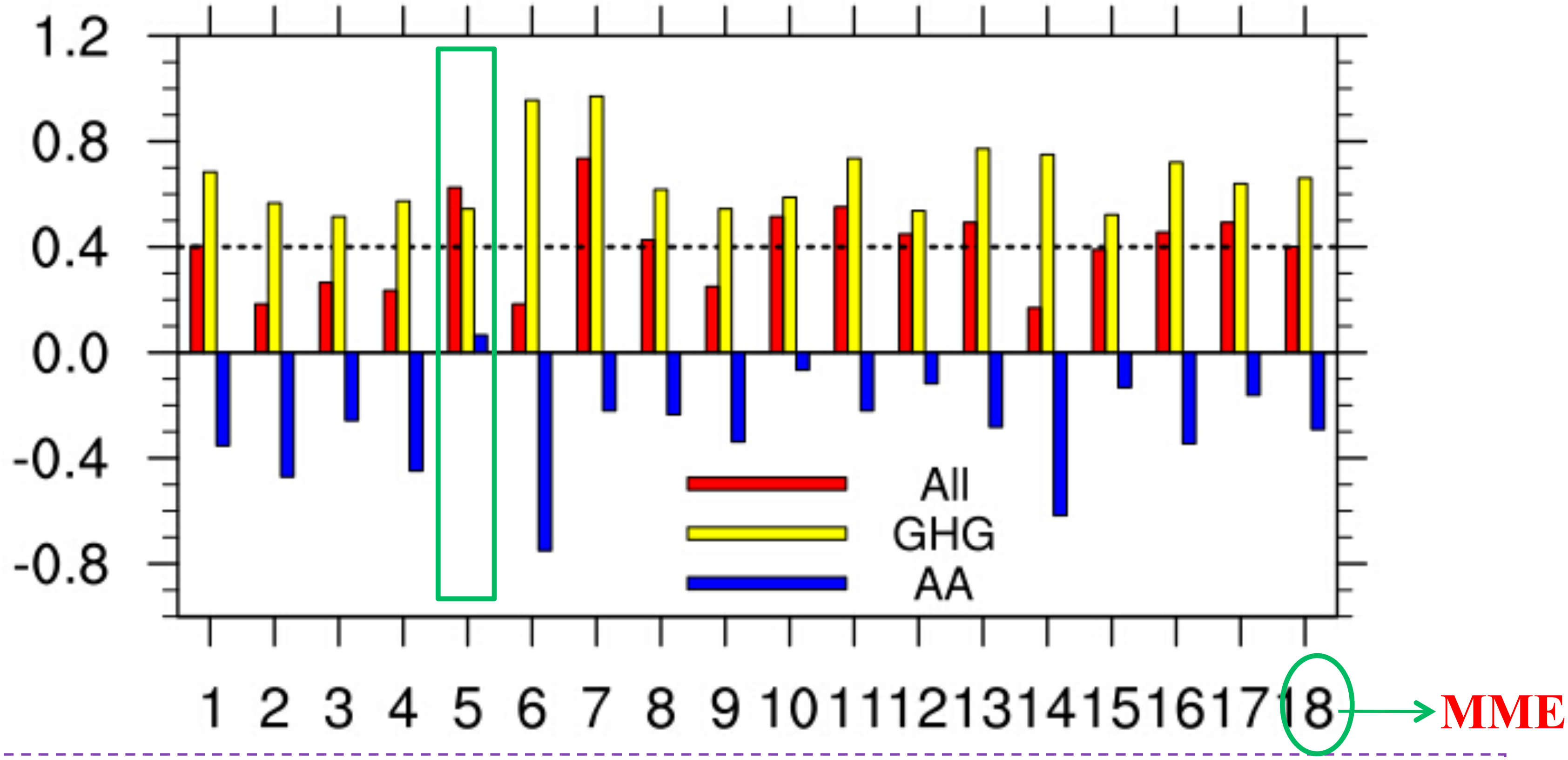


The dotted areas are statistically significant at the 1 % level by student's t-test.



Dong, L., and T. Zhou , 2014: The Indian Ocean Sea Surface Temperature Warming Simulated by CMIP5 Models during the 20th Century: Competing Forcing Roles of GHGs and Anthropogenic Aerosols, *Journal of Climate*, 27, 3348–3362

Indian Ocean SST Trends



- **Among 17 CMIP5 models, the trends under GHGs forcing are positive.**
- **AAs have negative contributions to the warming, except for CCSM4.**
- Based on MME, GHGs (AAs) account for about 163.6% (-72.7%) of the Indian Ocean SST trend in all forcing run.

Dong, L., and T. Zhou , 2014: The Indian Ocean Sea Surface Temperature Warming Simulated by CMIP5 Models during the 20th Century: Competing Forcing Roles of GHGs and Anthropogenic Aerosols, *Journal of Climate*, 27, 3348–3362

Results

Mechanisms for the Indian Ocean basin-wide warming pattern ?

Dong, L., and T. Zhou , 2014: The Indian Ocean Sea Surface Temperature Warming Simulated by CMIP5 Models during the 20th Century: Competing Forcing Roles of GHGs and Anthropogenic Aerosols, *Journal of Climate*, 27, 3348–3362

Analysis methods

$$C\frac{\partial T'}{\partial t} = D_o' + Q_{net}'$$

We can infer the **ocean heat transport** effect through the changes of the **net surface heat flux**.

$$D_o' = -Q_{net}'$$

Ocean response

$$Q_a' = (Q_S' - Q_L') - Q_H' - Q_E^{a'}$$

Atmosphere forcing

$$Q_E^{o'} = \frac{\partial Q_E}{\partial T} T' = \alpha \overline{Q_E} T'$$

Newtonian cooling ocean response

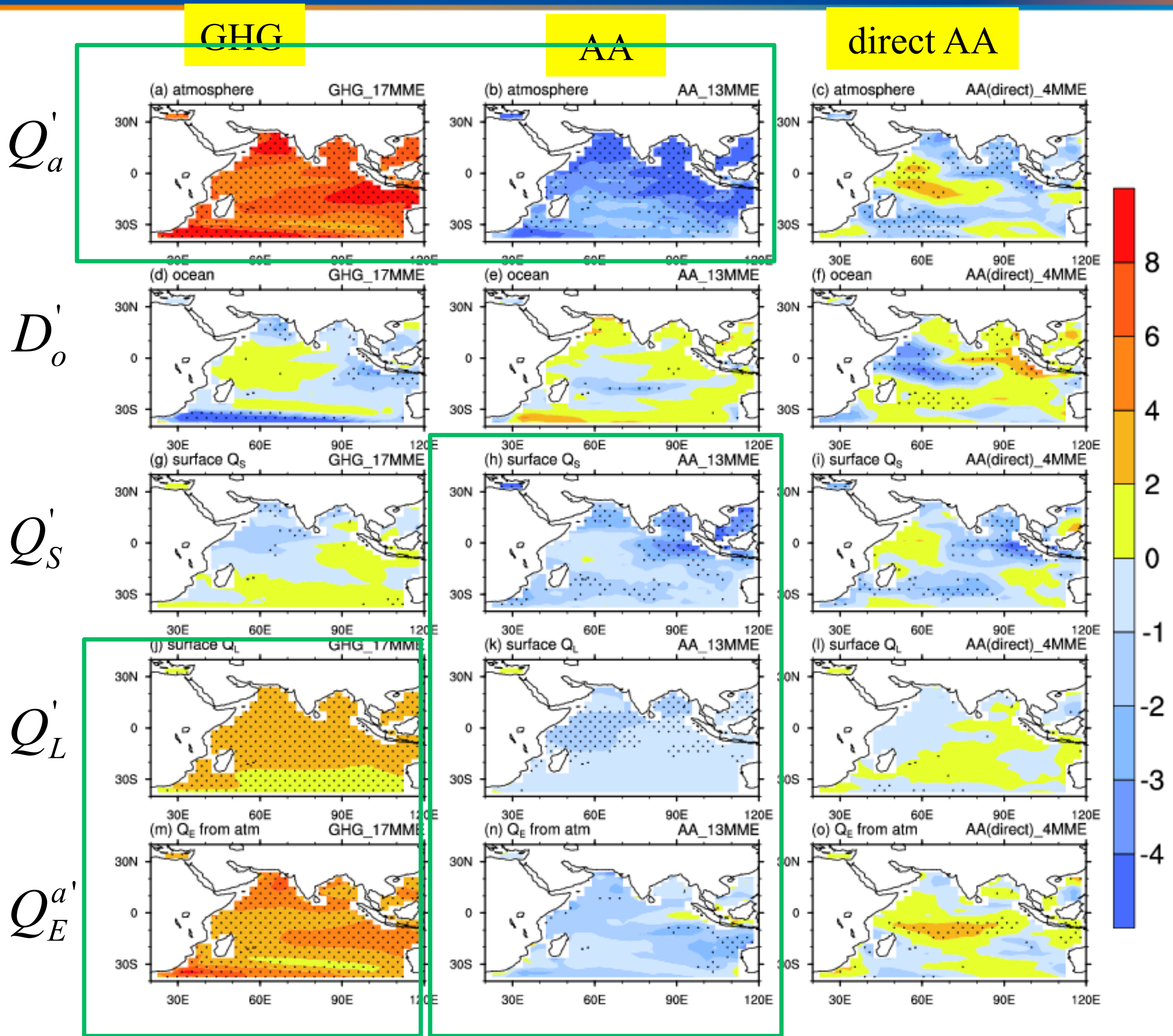
$$Q_E^{a'} = Q_E' - Q_E^{o'}$$

Atmospheric forcing

$$T' = \frac{(D_o' + Q_a')}{\alpha \overline{Q_E}}$$

Xie et al. (2010 JC)

Mixed-layer heat budget analysis



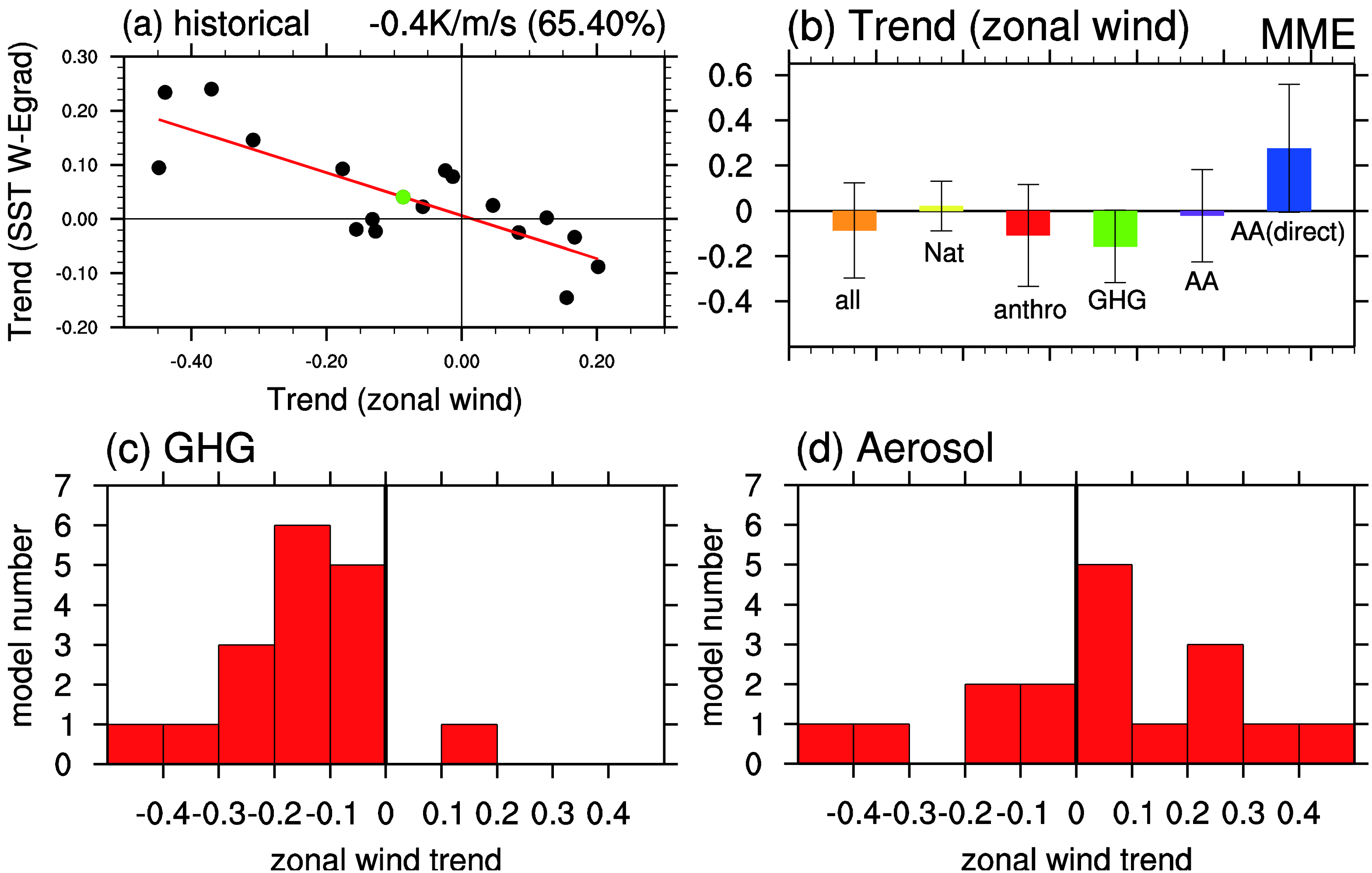
Both the basin-wide warming effect of GHGs and cooling effect of AAs, mainly through indirect aerosol effect, are established through atmospheric processes.

The dotted areas are where more than 80% models have the same sign as MME.

Results

Mechanism for the dipole-like warming pattern ?

Dong, L., and T. Zhou , 2014: The Indian Ocean Sea Surface Temperature Warming Simulated by CMIP5 Models during the 20th Century: Competing Forcing Roles of GHGs and Anthropogenic Aerosols, *Journal of Climate*, 27, 3348–3362



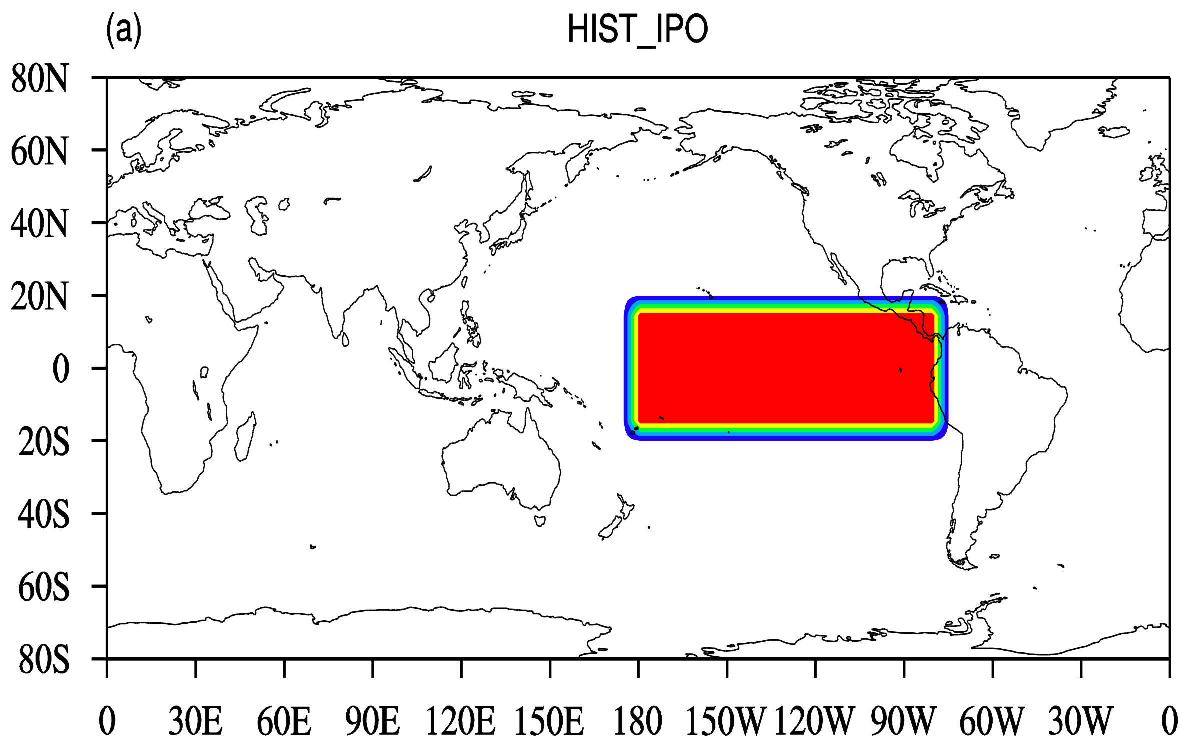
Western basin: (5°S-5°N, 50°-65°E) Eastern basin: (5°S-5°N, 85°-100°E)
Zonal wind over equator: (5°S-5°N, 50°-90°E)

The positive IOD-like warming pattern is associated with the surface easterly wind anomaly along the equator. GHGs forcing dominates the easterly trend, while AAs forcing weakens it, mainly via direct aerosol effects.

Any decadal mode in the Indian Ocean?

NO !

Numerical Exps of CESM



- ✓ SSTs were prescribed to the model climatology plus observed anomalies in the TEP domain (15°S–15°N, 80°–180°W), along with the historical external forcing and fixed pre-industrial forcing, respectively.

Dong Lu, Tianjun Zhou*, Aiguo Dai, Fengfei Song, Bo Wu, Xiaolong Chen, 2016: The Footprint of the Inter-decadal Pacific Oscillation in Indian Ocean Sea Surface Temperatures, ***Scientific Report***s,6:21251, DOI:10.1038/srep2125

Model, data and analysis methods

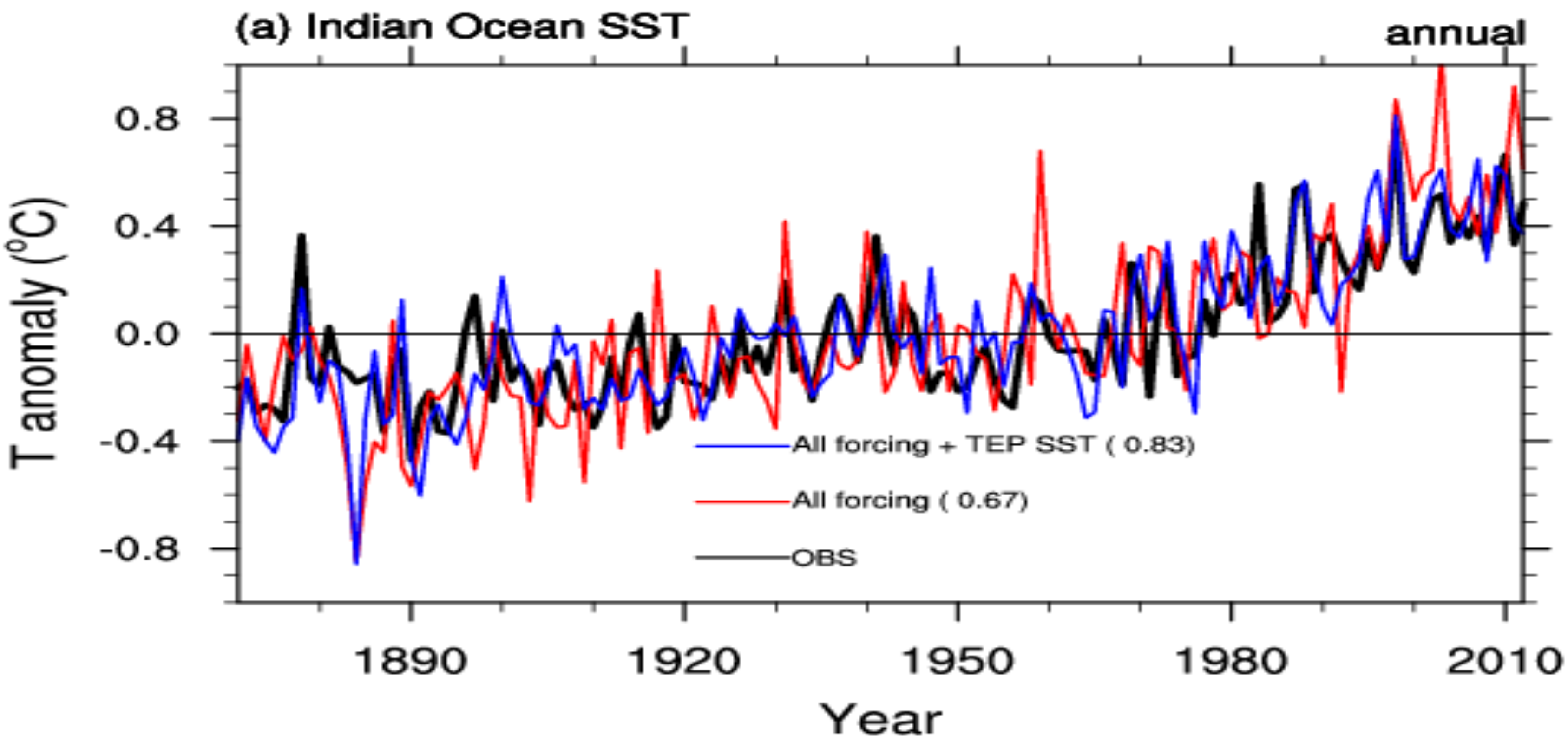
CESM1.2 Experiments

Experiment	Number (time span)
All forcing	3 (1850–2012)
All forcing + TEP SST	3 (1950–2012) 1 of the 3 (1871-2012)
piControl + TEP SST	1 (1950–2012)

- ✓ The ***All forcing*** runs were forced by the historical radiative forcing for 1850–2005 and the RCP4.5 for 2006–2012 based on CMIP5.
- ✓ In the ***All forcing + TEP SST*** and ***piControl + TEP SST*** experiments, SSTs were prescribed to the model climatology plus observed anomalies in the TEP domain (15°S–15°N, 80°–180°W), along with the historical external forcing and fixed pre-industrial forcing, respectively.

Dong Lu, Tianjun Zhou*, Aiguo Dai, Fengfei Song, Bo Wu, Xiaolong Chen, 2016: The Footprint of the Inter-decadal Pacific Oscillation in Indian Ocean Sea Surface Temperatures, ***Scientific Report***s,6:21251, DOI:10.1038/srep2125

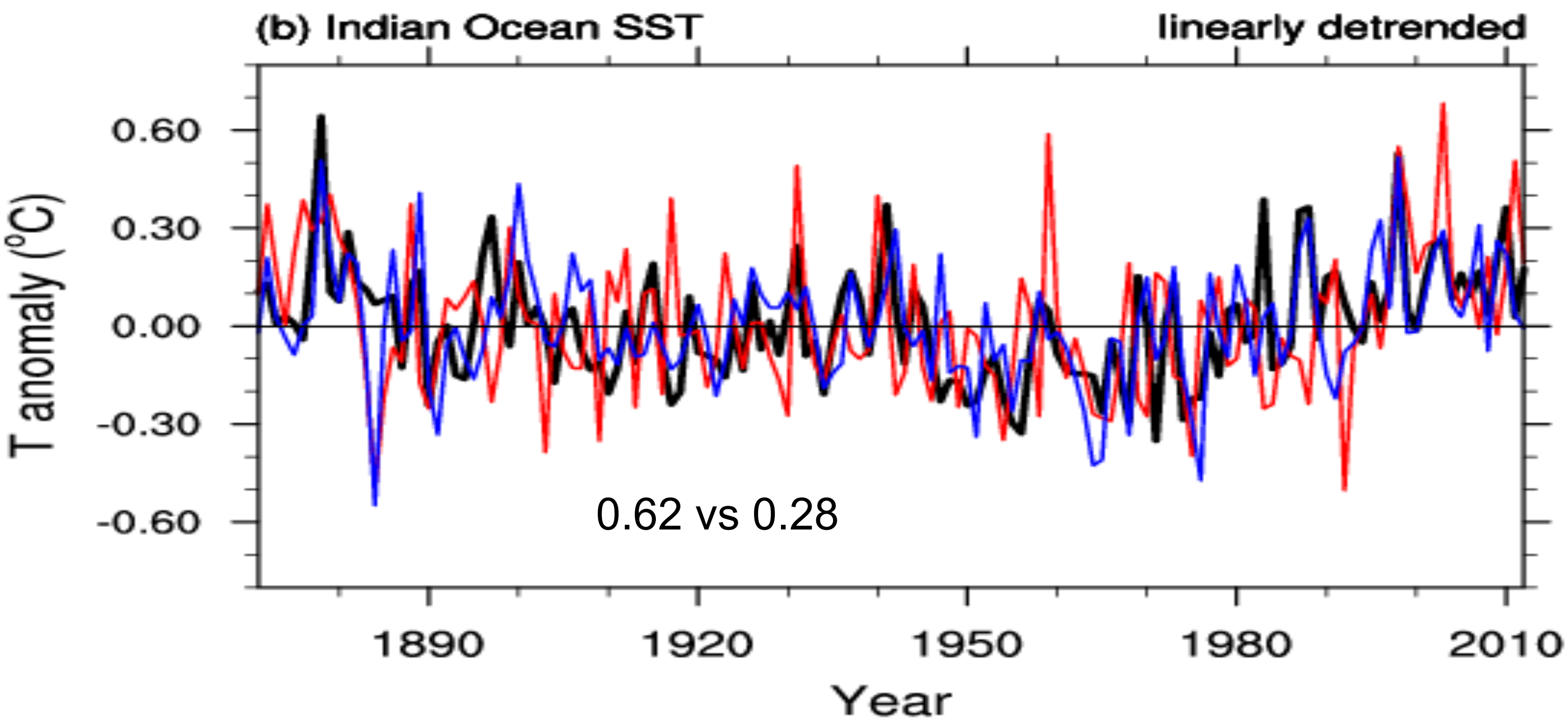
Indian Ocean SST



(**a**) Time series of the annual mean SST anomaly (°C) averaged in the Indian Ocean (20°S–20°N, 40°E–120°E) for HadISST (black), the *All forcing* run (red) and the *All forcing + TEP SST* run (blue) during 1871–2012. The values in the brackets are the correlation coefficients with the HadISST curve.

Dong Lu, Tianjun Zhou*, Aiguo Dai, Fengfei Song, Bo Wu, Xiaolong Chen, 2016: The Footprint of the Inter-decadal Pacific Oscillation in Indian Ocean Sea Surface Temperatures, ***Scientific Report***s,6:21251, DOI:10.1038/srep2125

Indian Ocean SST

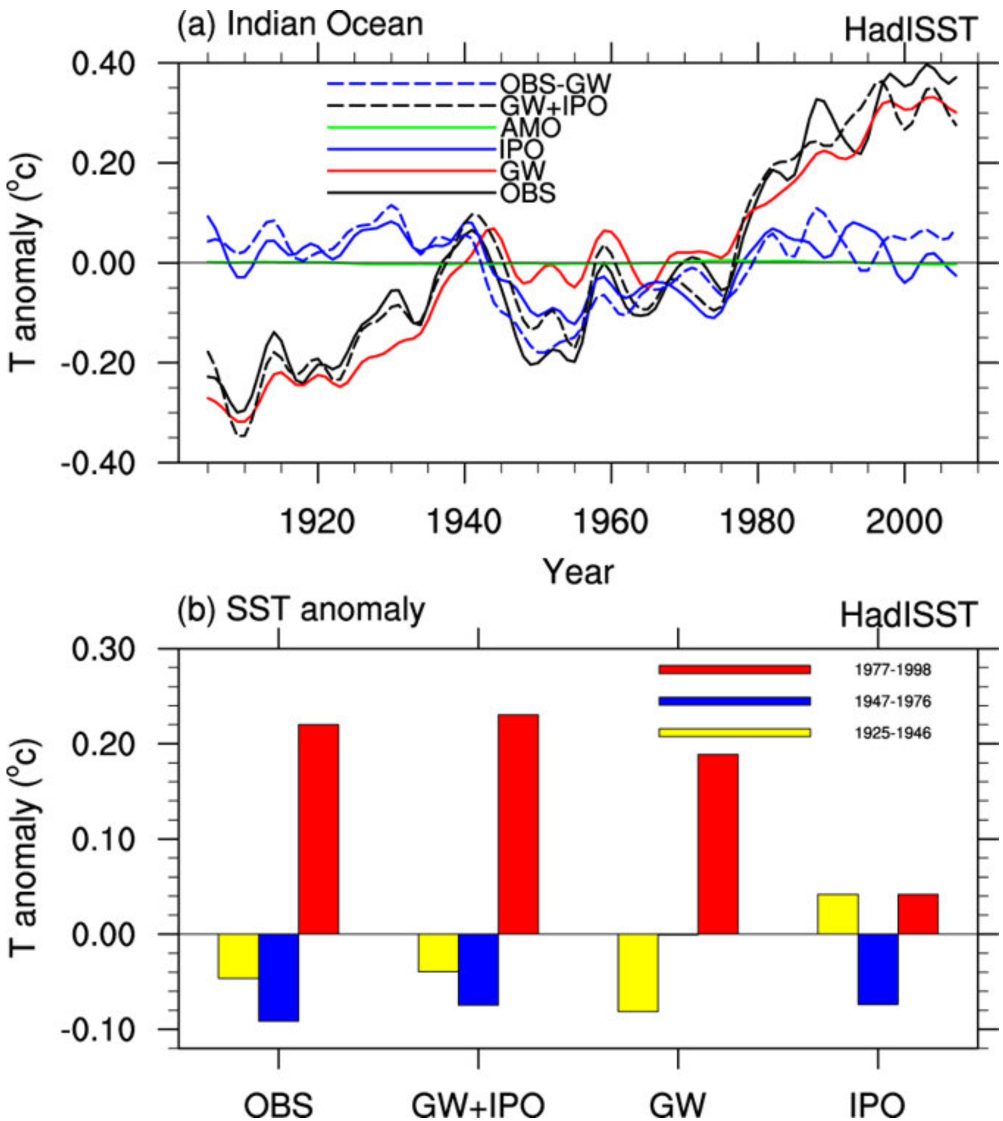


The simulated and observed IO SSTs are significantly correlated (r=0.83 for one member of the *All forcing + TEP SST* and r=0.67 for *All forcing* runs). These correlations are largely due to the long-term warming trend.

Once linearly detrended, the *All forcing + TEP SST* run still follows the observed variations closely **(r=0.62)**; however, the correlation decreases to 0.28 for the *All forcing* runs, although it is still significant.

Dong Lu, Tianjun Zhou*, Aiguo Dai, Fengfei Song, Bo Wu, Xiaolong Chen, 2016: The Footprint of the Inter-decadal Pacific Oscillation in Indian Ocean Sea Surface Temperatures, ***Scientific Report***s,6:21251, DOI:10.1038/srep2125

The Footprint of PDO on Indian Ocean SST changes



- Decadal change of Indian Ocean SST is driven by PDO from the Pacific
- The global warming hiatus was driven by cold phase of PDO, *while the Indian Ocean cooling induced by PDO has a contribution of 10%*

Dong Lu, Tianjun Zhou*, Aiguo Dai, Fengfei Song, Bo Wu, Xiaolong Chen, 2016: The Footprint of the Inter-decadal Pacific Oscillation in Indian Ocean Sea Surface Temperatures, ***Scientific Report***s,6:21251, DOI:10.1038/srep2125

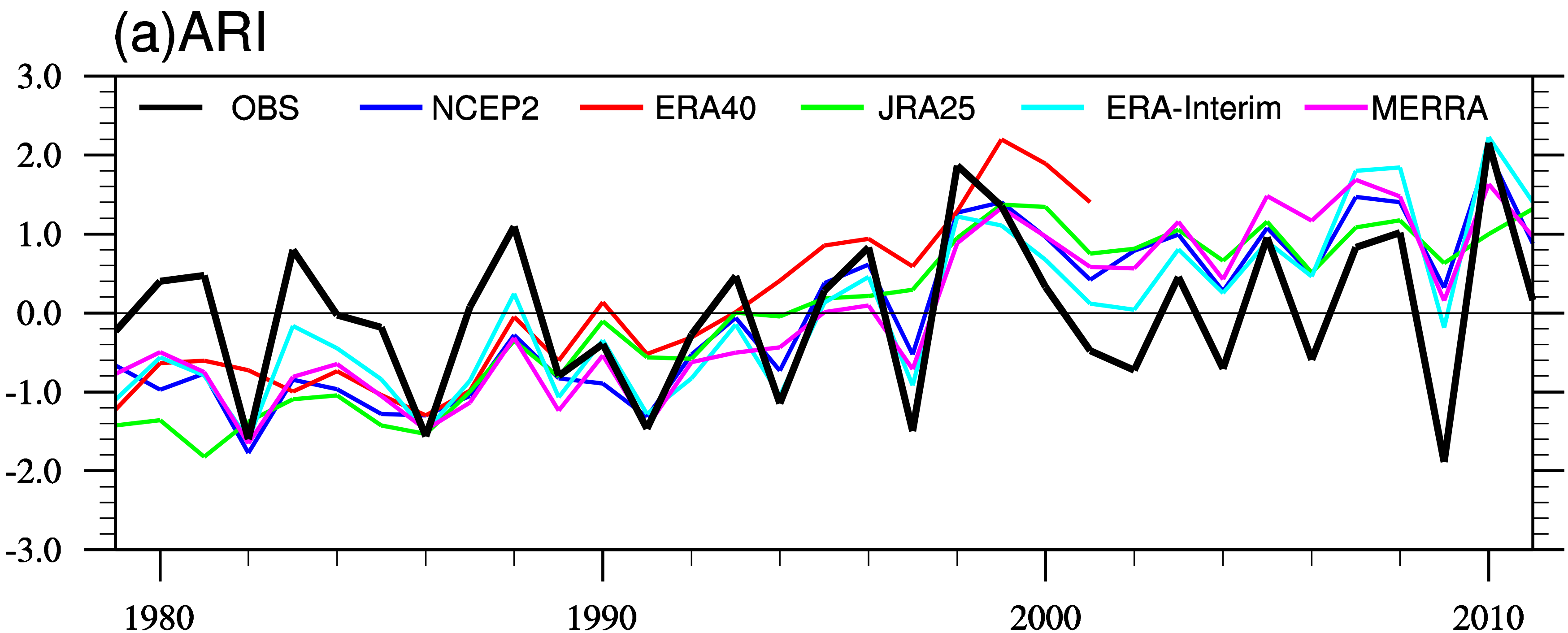
Concluding Remarks

1. Decadal variability of GM was driven by the phase change of PDO.
2. The weakening trend of East Asian summer monsoon since the 1970s was mainly driven by the phase shift of PDO.
3. Both the westward extension of WPSH and zonal expansion of South Asian High were driven by Indo-Western Pacific warming.
4. The Indian Ocean warming is dominated by the GHG forcing and offset by the aerosol cooling.
5. The PDO has a footprint in the Indian Ocean.

THANKS

http://www.lasg.ac.cn/staff/ztj

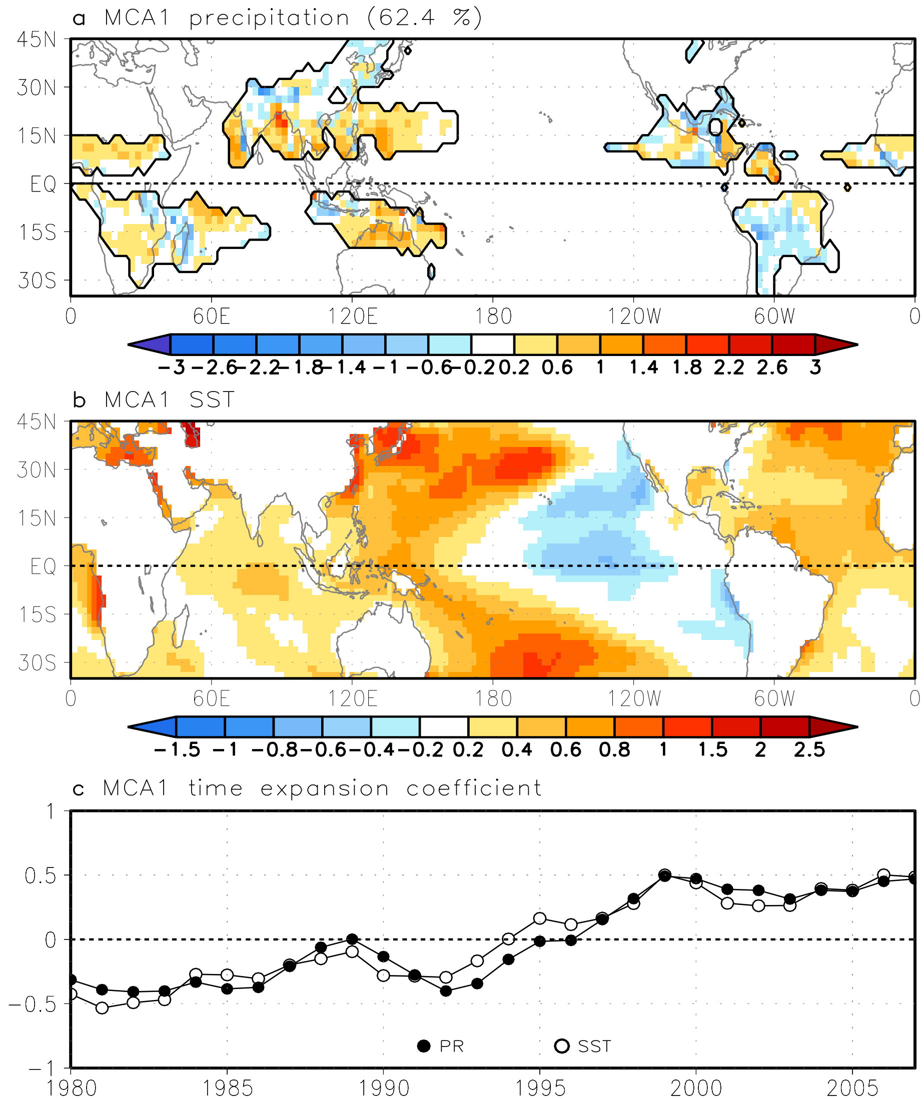
EOF PC1 of GM precipitation



- The corresponding observational ARI shows increasing tendency **for 1979-2011.**
- All five reanalysis datasets show similar but stronger increasing trends than the observation.

Lin R., T. Zhou, Y. Qian, 2014: Evaluation of Global Monsoon Precipitation Changes based on Five Reanalysis Datasets, ***J.Climate***, *27*,1271-1289

Recovery of Global Monsoon since early 1980s

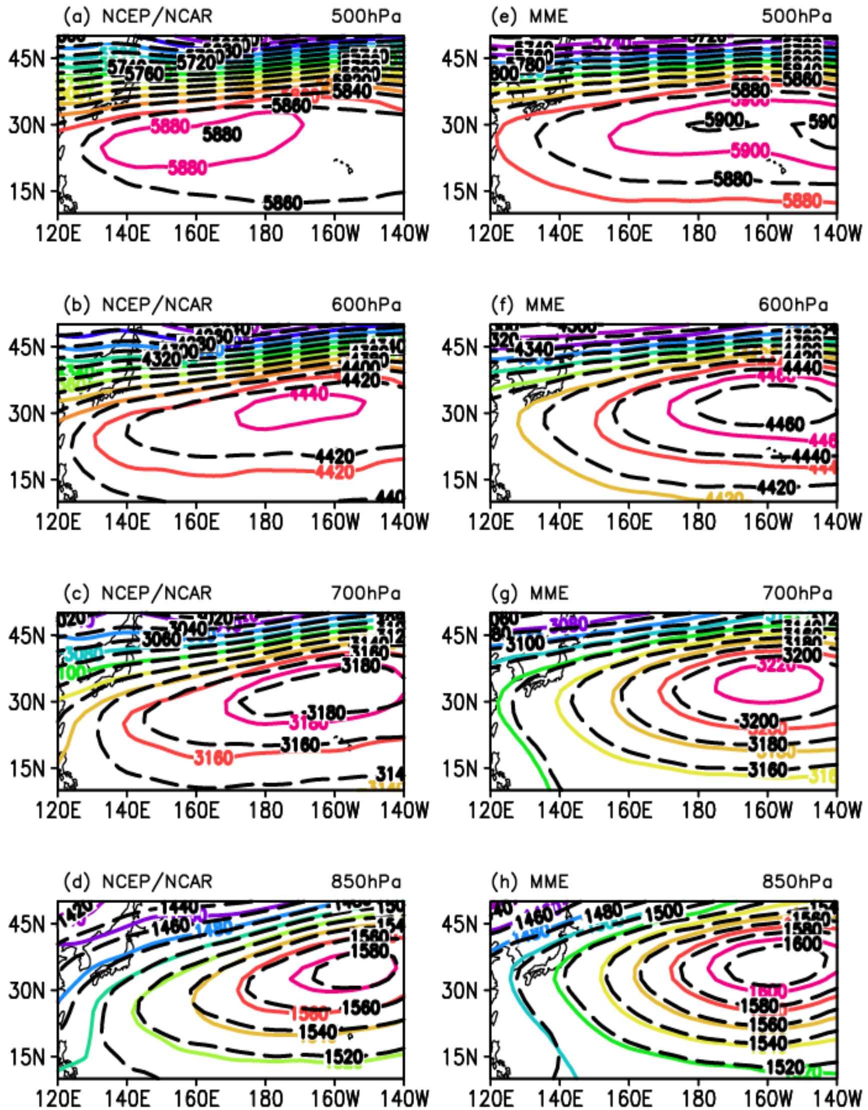


Maximum Covariance Analysis (MCA) of Monsoon precipitation and SST

3-year running mean datasets of GPCP and ERSST.

Wang et al. 2012 CD; 2013, PNAS

Westward extension of WPSH in the vertical



Zhou, T., R. Yu, J. Zhang, H. Drange et al. 2009, Why the Western Pacific Subtropical High has extended westward since the late 1970s**, *J. Climate***, 22, 2199-2215