Institute of Atmospheric Physics, Chinese Academy of Sciences

# Decadal Variability of the Asian Summer Monsoon

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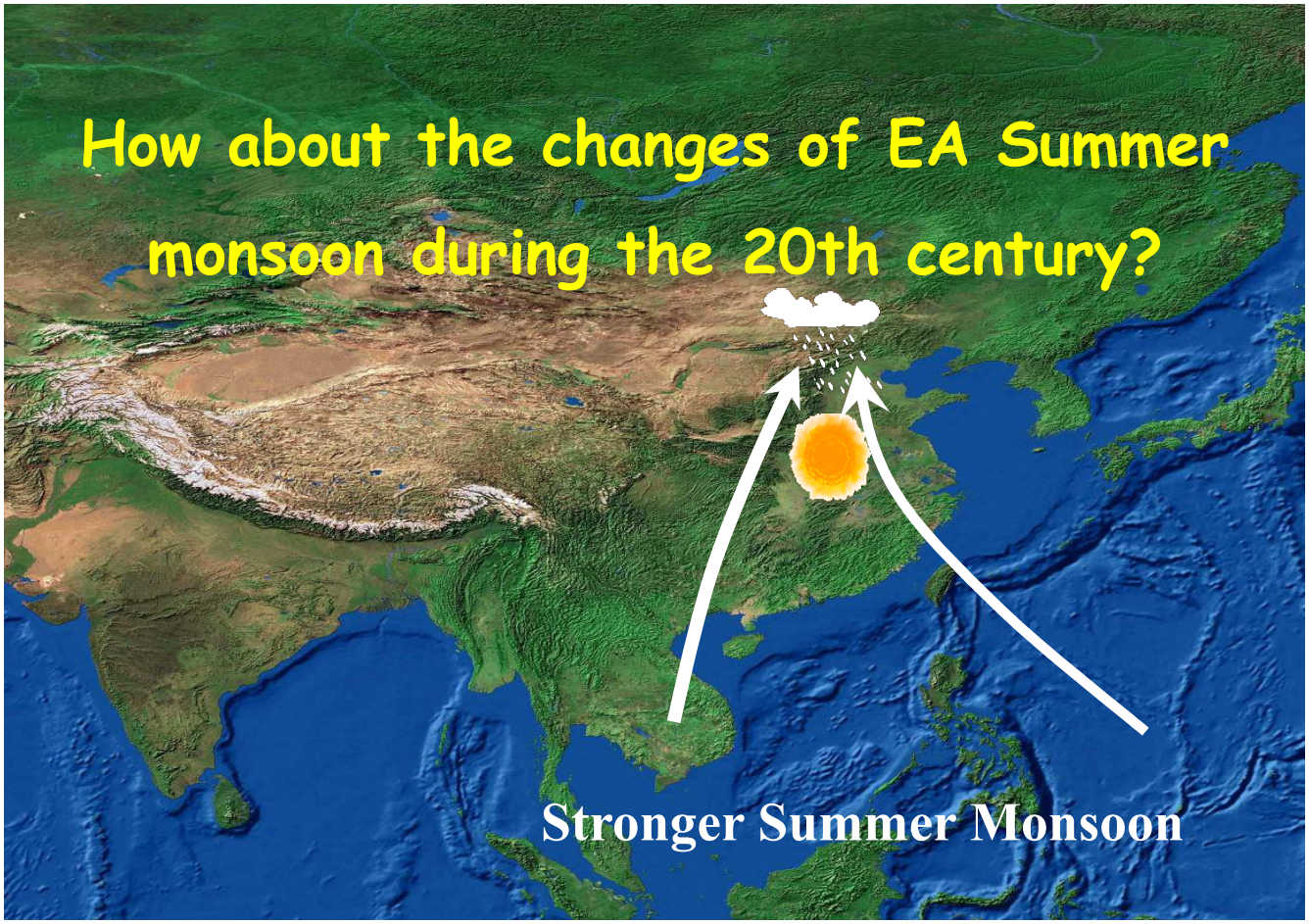
CLIVAR-ICTP Workshop on Decadal Climate Variability and Predictability: Challenge and Opportunity

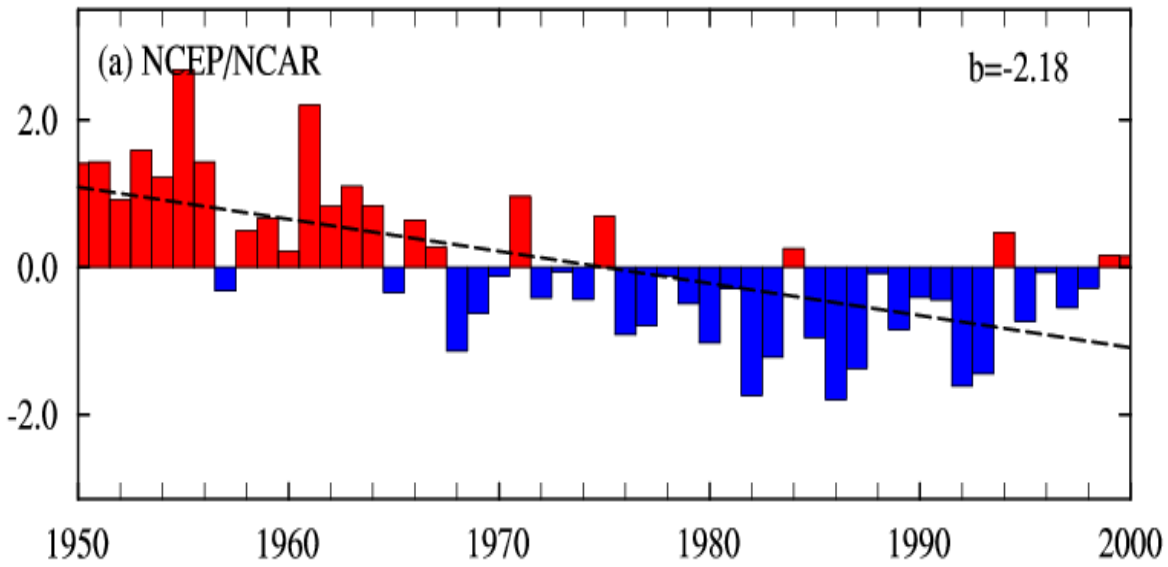
Trieste, Italy 16-20 November 2015

# Outline

1. East Asian summer monsoon change
2. South Asian summer monsoon change
3. Connections among regional monsoon changes
4. Mechanisms: internal & external forcings
5. Overview of GMMIP for CMIP6
6. Summary

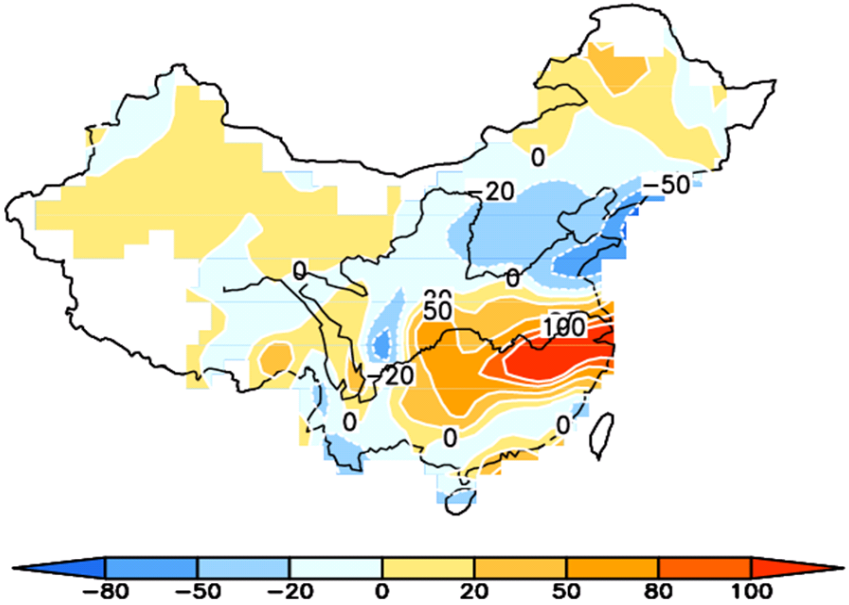

How about the changes of EA Summer monsoon during the 20th century?
Stronger Summer Monsoon

# EA summer monsoon circulation index




Zhou, T., D. Gong, J. Li, B. Li, 2009: Detecting and understanding the multi-decadal variability of the East Asian Summer Monsoon – Recent progress and state of affairs. ***Meteorologische Zeitschrift***, 18 (4), 455-467

# Rainfall changes associated with weakening of monsoon circulation

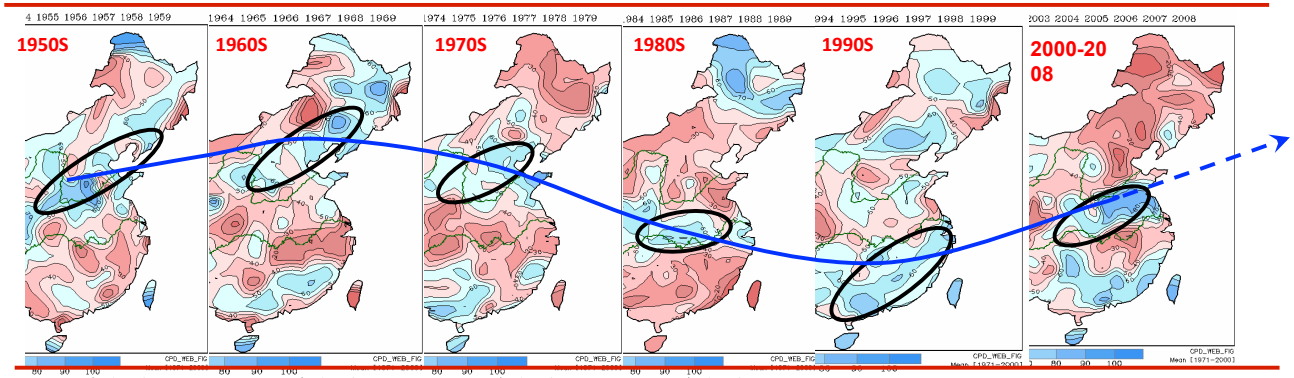



## JJA Rainfall anomalies

Zhou, T., D. Gong, J. Li, B. Li, 2009: Detecting and understanding the multi-decadal variability of the East Asian Summer Monsoon – Recent progress and state of affairs. ***Meteorologische Zeitschrift***, 18 (4), 455-467

# 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



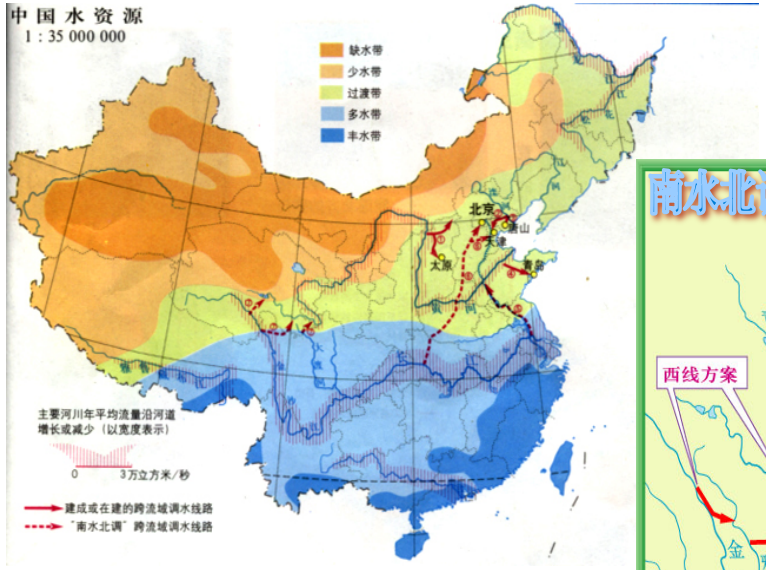

最高频次 90%　最高频次 80%　最高频次 60%　最高频次 60%　最高频次 70%

1970S　**Monsoon Weakening**

(After BCC, 2010)

# South-to-North Water Diversion Project

## Transport water from YZ river to N. China by channels





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


How about the changes of South Asian
Summer monsoon during the 20th century?

# Indian monsoon rainfall changes

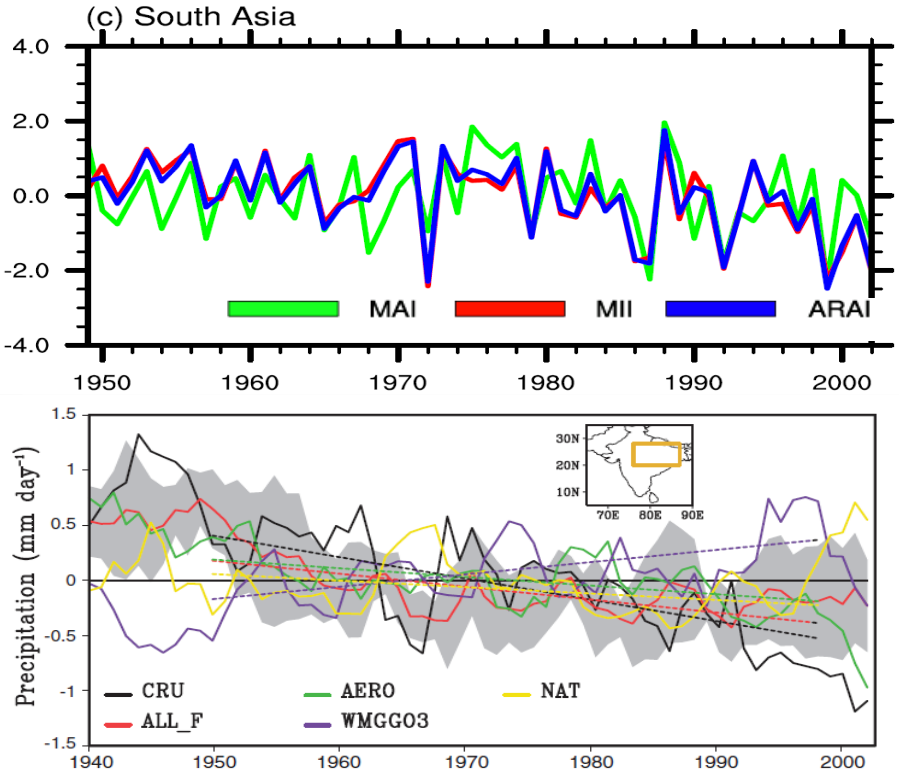
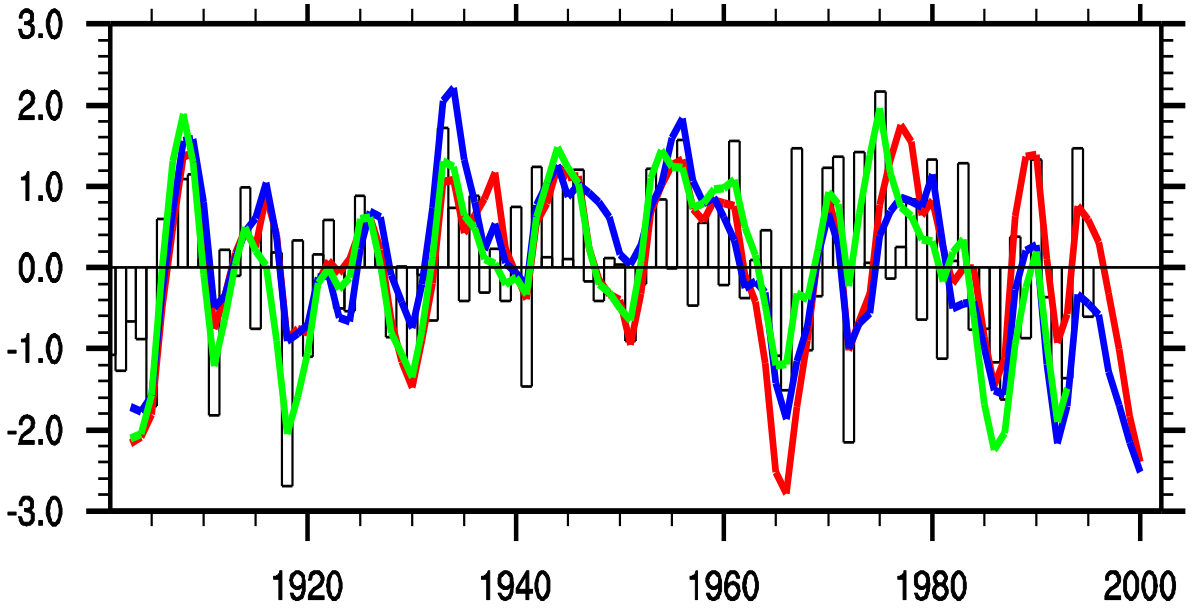



**Fig. 1.** Five-year running mean June-September average precipitation anomalies over central-northern India (76° to 87°E, 20° to 28°N; see the orange box in the inset map). Anomalies are calculated as

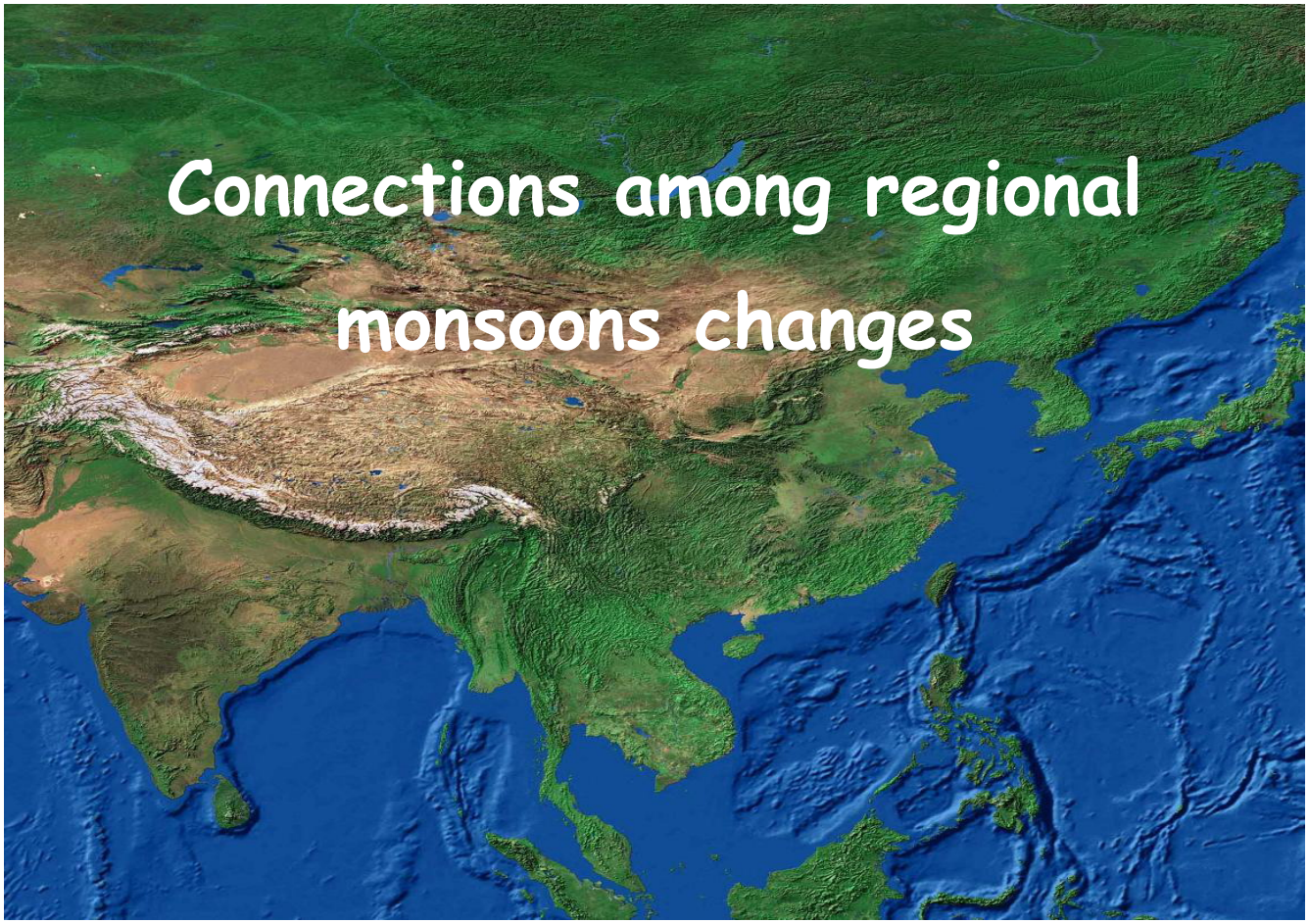
Zhou et al. 2008: *Geophysical Research Letters*, 35, L16707, doi: 10.1029/ 2008GL034881

Bollasina et al. 2011, Science

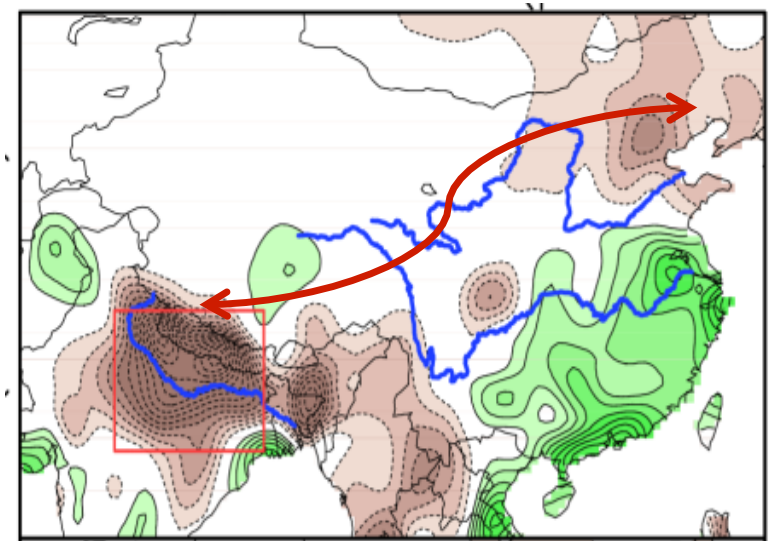
# Indian monsoon precipitation changes




Zhang Lixia, and Tianjun Zhou, 2011: An assessment of monsoon precipitation changes during 1901–2001, *Climate Dynamics*, , 37, 279-296, DOI 10.1007/s00382-011-0993-5


Connections among regional
monsoons changes

# Changes of S. Asia and E. Asia summer rainfall

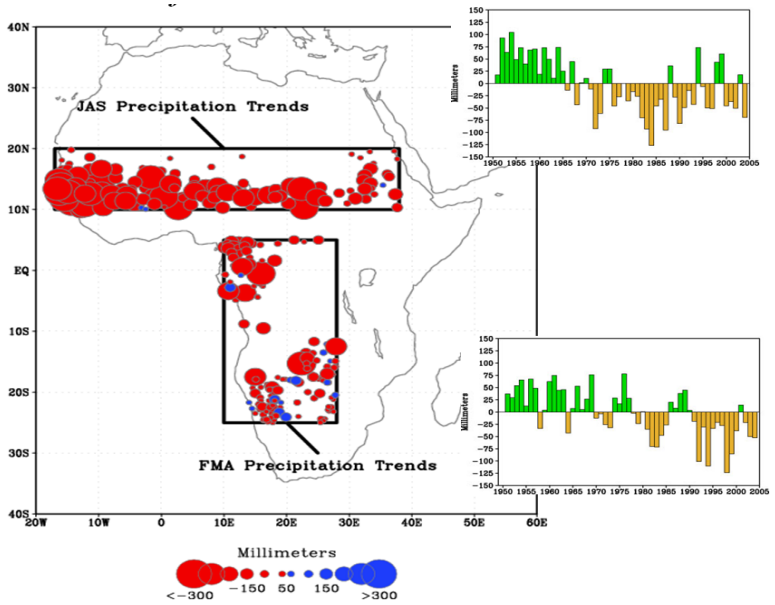


Linear trend in summer rainfall in the post--1950 period is plotted at 0.5 mm/day/ century interval in the 0.5° resolution CRU TS 3.1 data; zero-contour is omitted. The South-Flood North-Dry pattern is manifest.

Nigam & Zhou, 2013: The South-flood north-drought pattern over eastern China and the drying of the Gangetic Plain, in ***Climate Change: Multidecadal and Beyond***

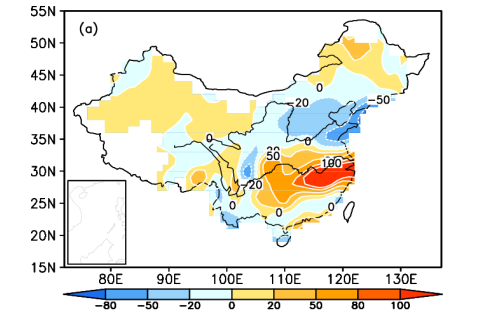
# Coherent long term changes across different monsoons

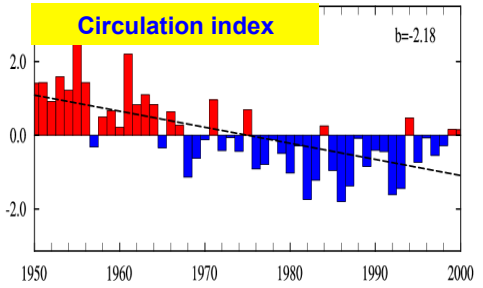
**African rainfall**




Hoerling et al. (2006) J. Climate

**E Asian rainfall**

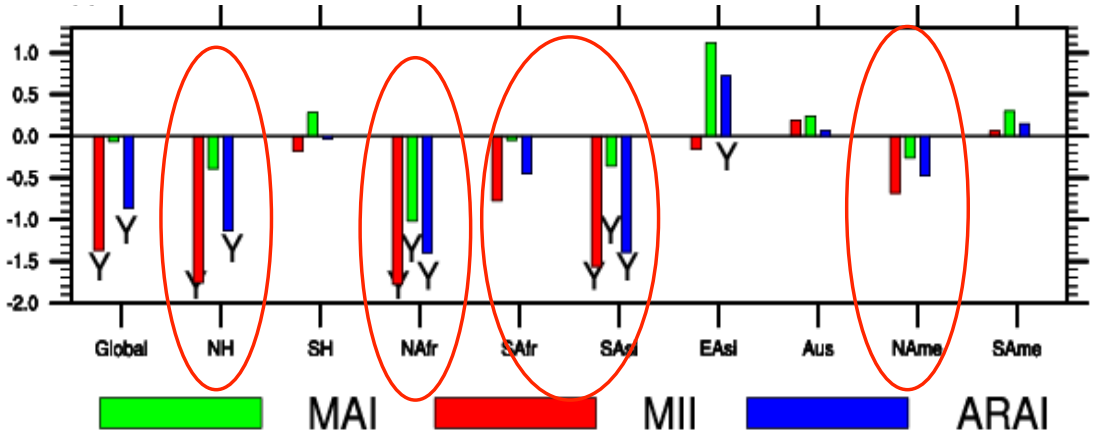



Zhou et al. (2009) Meteorologische Zeitschrift

## Regional monsoon rainfall changes

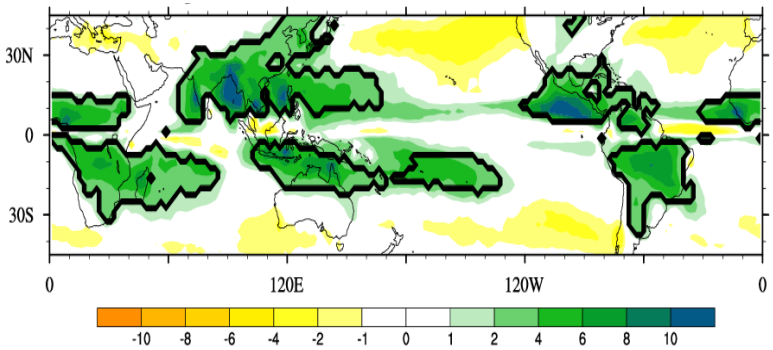
Trends of monsoon rainfall Area, intensity, and amount (1948-2003)




**Monsoon Area** **Intensity** **Amount**

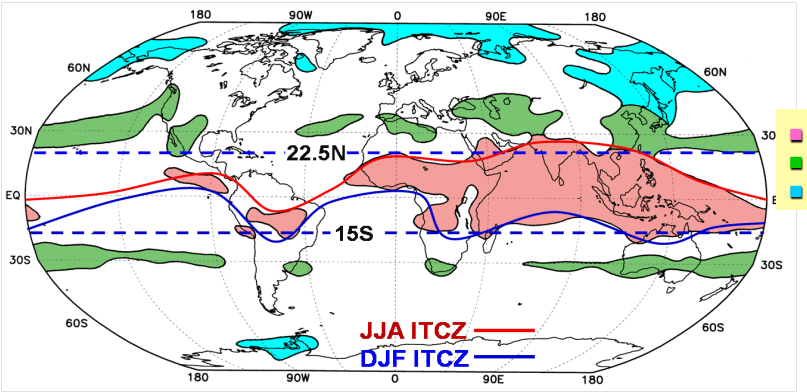
(Zhou et al. 2008 GRL)

# Asian Monsoon and Global Monsoon




**Defined based on rainfall**

Wang and Ding (2006)

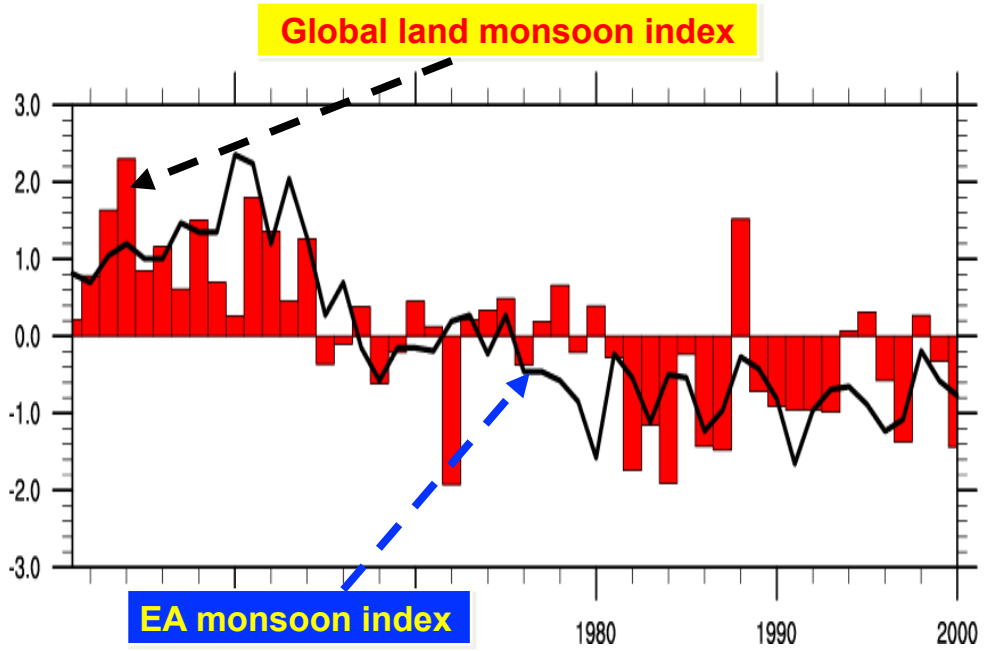



- tropical monsoon
- subtropical monsoon
- temperate-frigid monsoon

**Defined based on wind**

Li and Zeng (2003,2005)

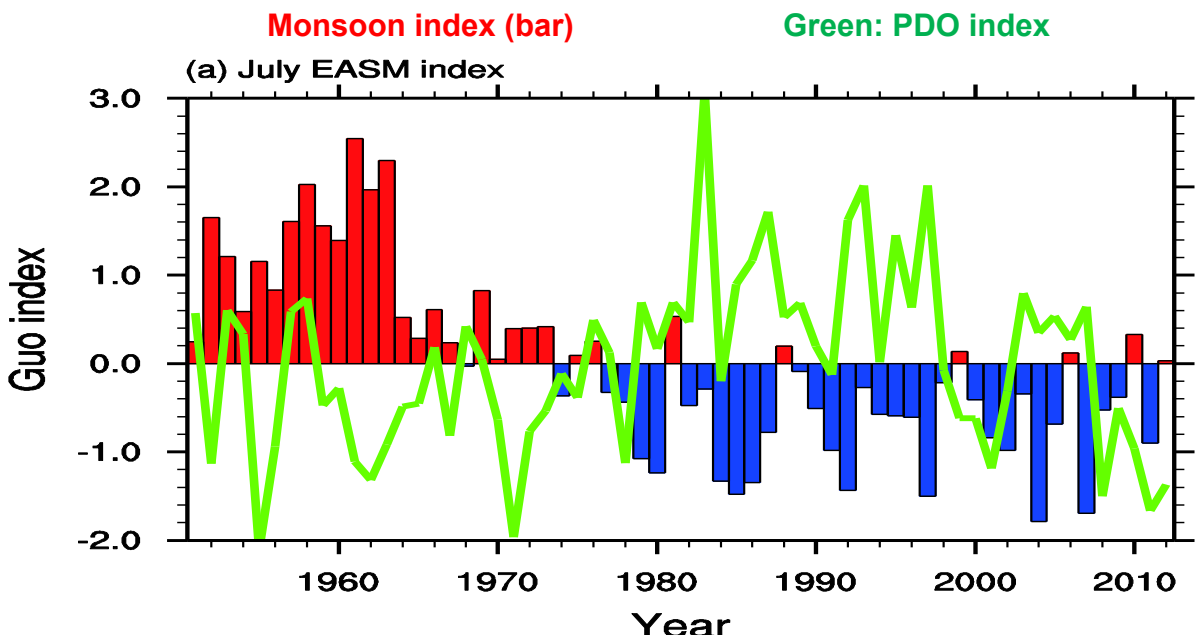
# Changes of EASM: A Much Bigger Picture




**Zhou T.,** L. Zhang, **Hongmei LI** 2008 Changes in global land monsoon area and total rainfall accumulation over the last half century, ***Geophysical Research Letters***, 35, L16707, doi:10.1029/2008GL034881


Mechanisms ?

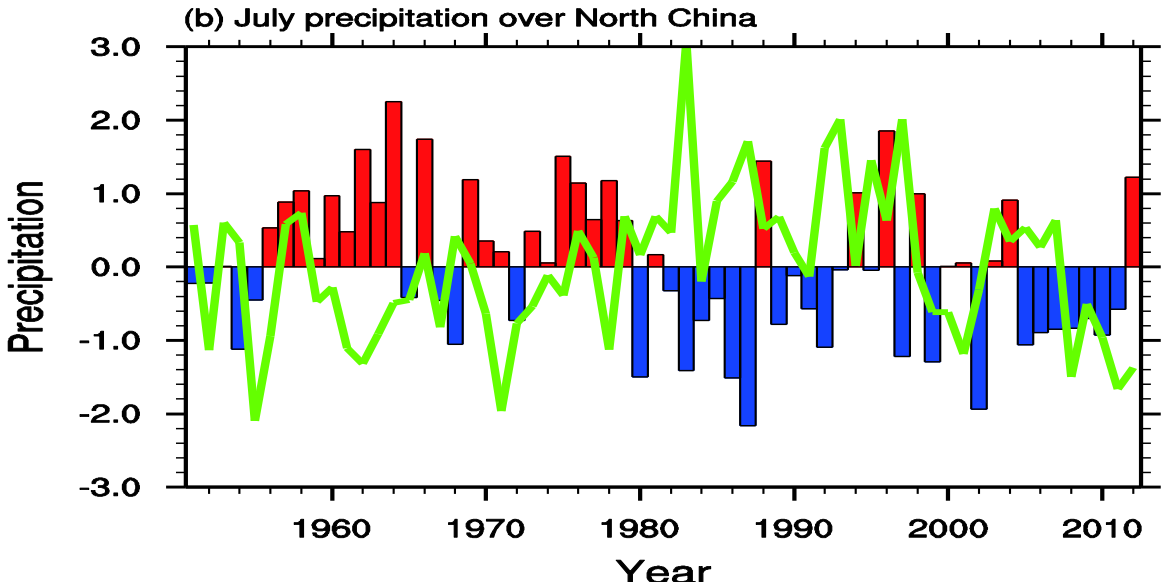
# PDO and E. Asian monsoon




**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

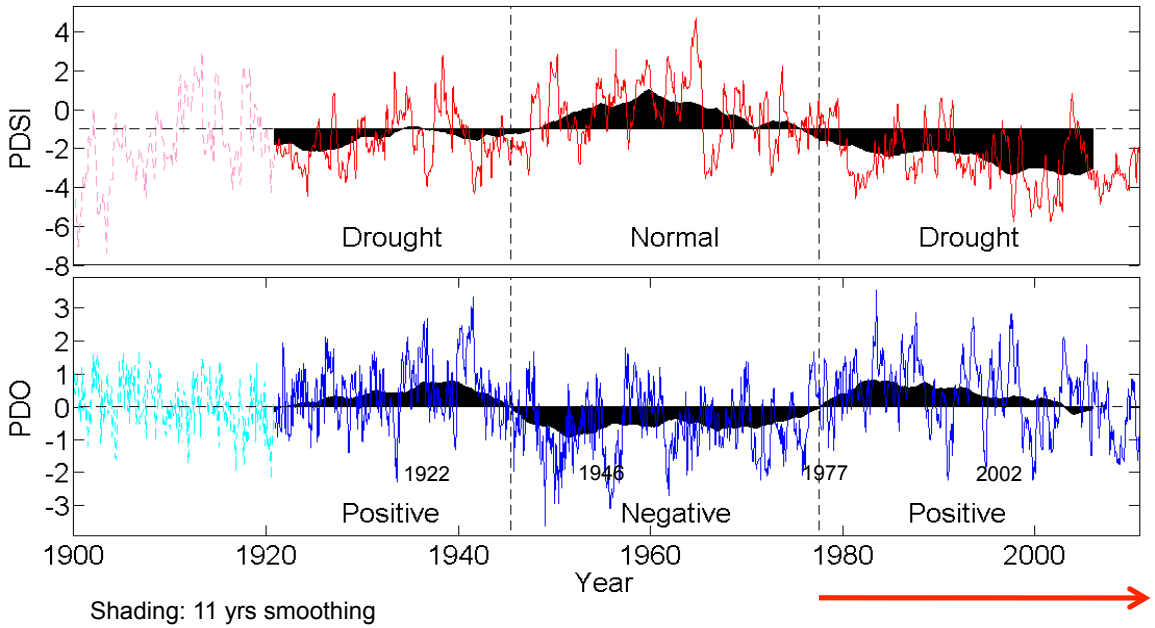
# PDO and E. Asian monsoon

**Precipitation in N. China (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




**Qian C.** and T. **Zhou**, 2013: Multidecadal variability of North China aridity and its relationship to PDO during 1900-2010, ***J. Climate***, DOI: 10.1175/JCLI-D-13-00235.1

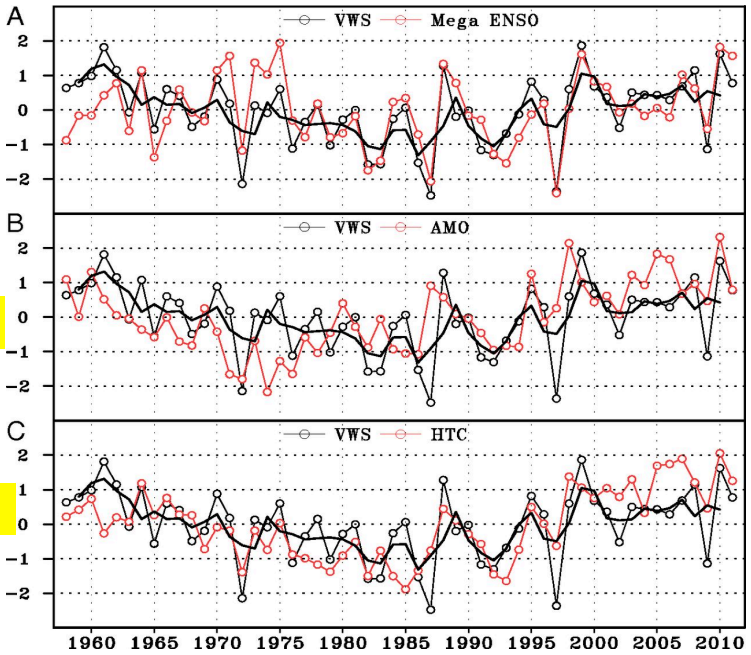
# Contribution of IPO and AMO

**Win shear index for the Northern Hemispheric summer monsoon**

**-IPO**

**AMO**

HTC




**Cor=0.77**

**Cor=0.44**

**Cor=0.63**

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

# Model and Experiments

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

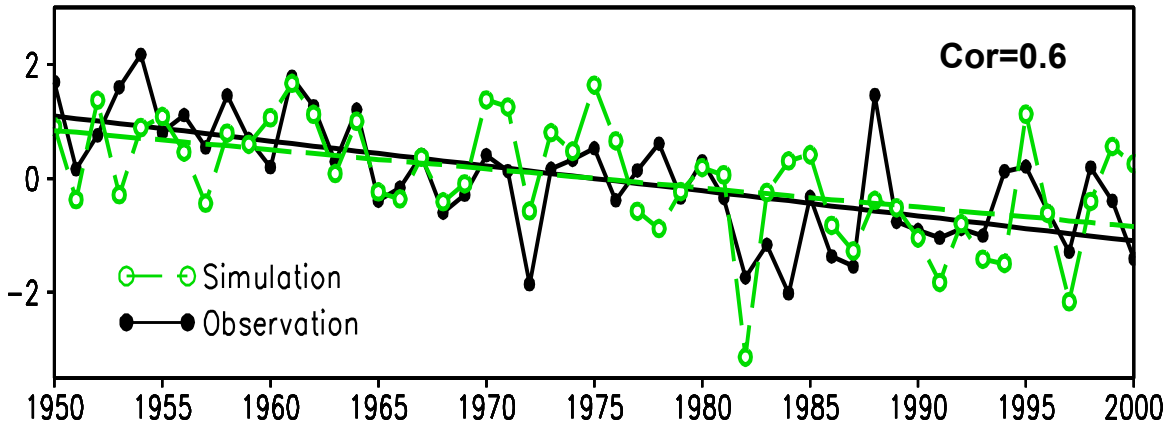
| | CAM3 (T85) | CAM3 (T42) | AM2.1 (FV) |
|---|---|---|---|
| GOGA | 5 | 5 | 10 |
| TOGA | 5 | 5 | N/A |
| ATM | N/A | 10 | N/A |

**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

# The observed and simulated Global Land monsoon index




SST-driven AGCM ensemble simulation, with 12 realizations

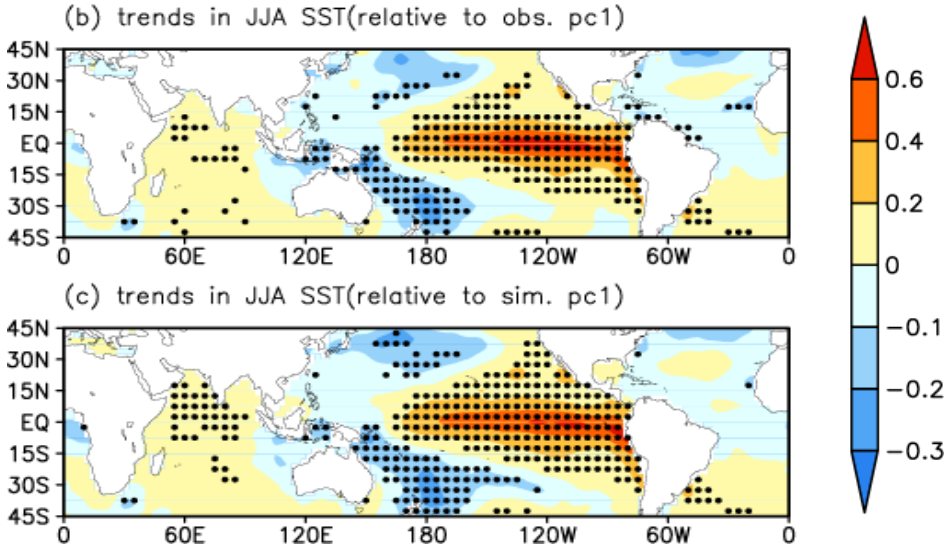
**Zhou T.,** R. Yu., **Hongmei LI** et al. 2008 Ocean forcing to changes in global monsoon precipitation over the recent half century, ***Journal of Climate***, **21** (15), 3833–3852

# SSTA congruent with the weakening trend of global land monsoon precipitation

## Pacific Decadal Oscillation: PDO

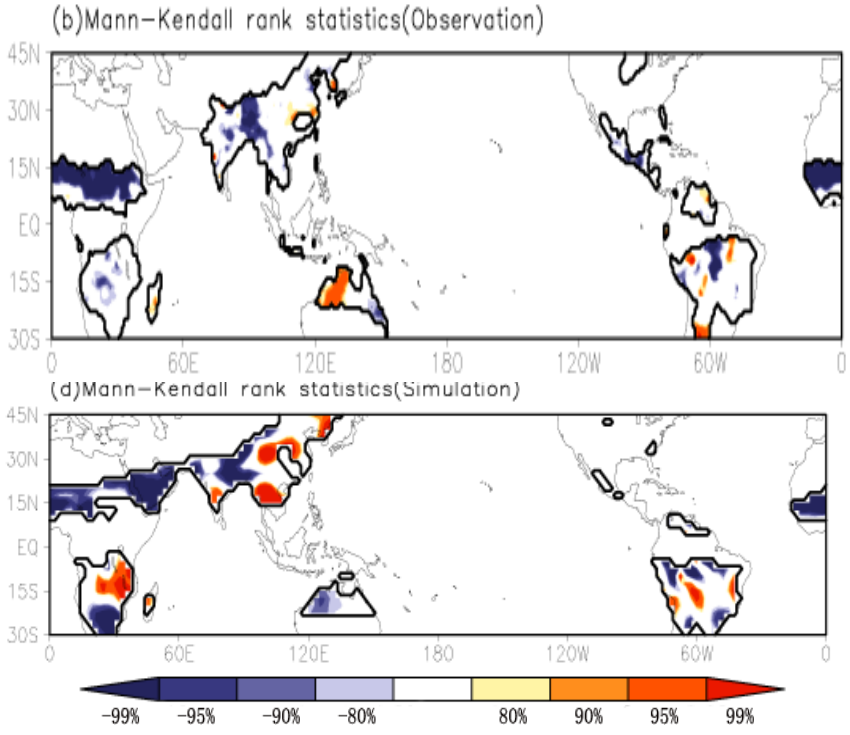
OBS

Model




**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 rainfall Annual Range trend within land monsoon domain




**Observation**

**Simulation**

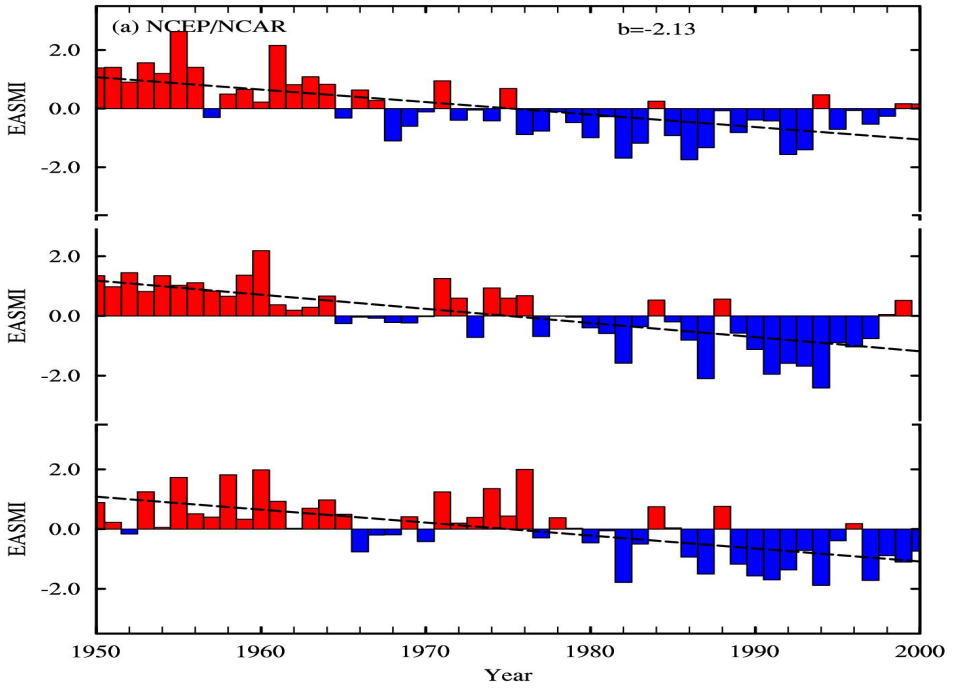
Zhou et al. 2008 J. Climate

# EASM index in AGCM driven by observed SST

Reanalysis

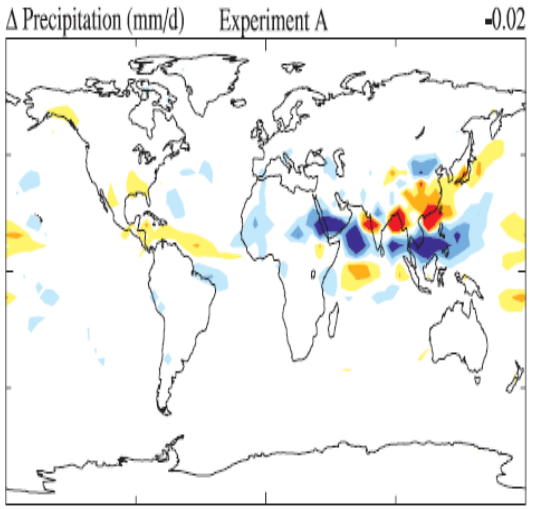
Global SST driven AGCM

Tropical SST driven AGCM

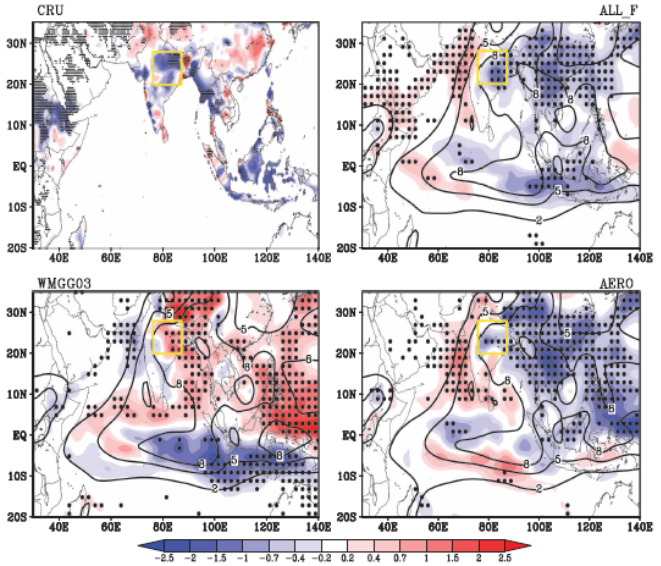



**Li, H.**, A. Dai, **T. Zhou**, J. Lu, 2010: Responses of East Asian summer monsoon to historical SST and atmospheric forcing during 1950-2000, ***Climate Dynamics*, 34**, 501–514

# Aerosol forcing

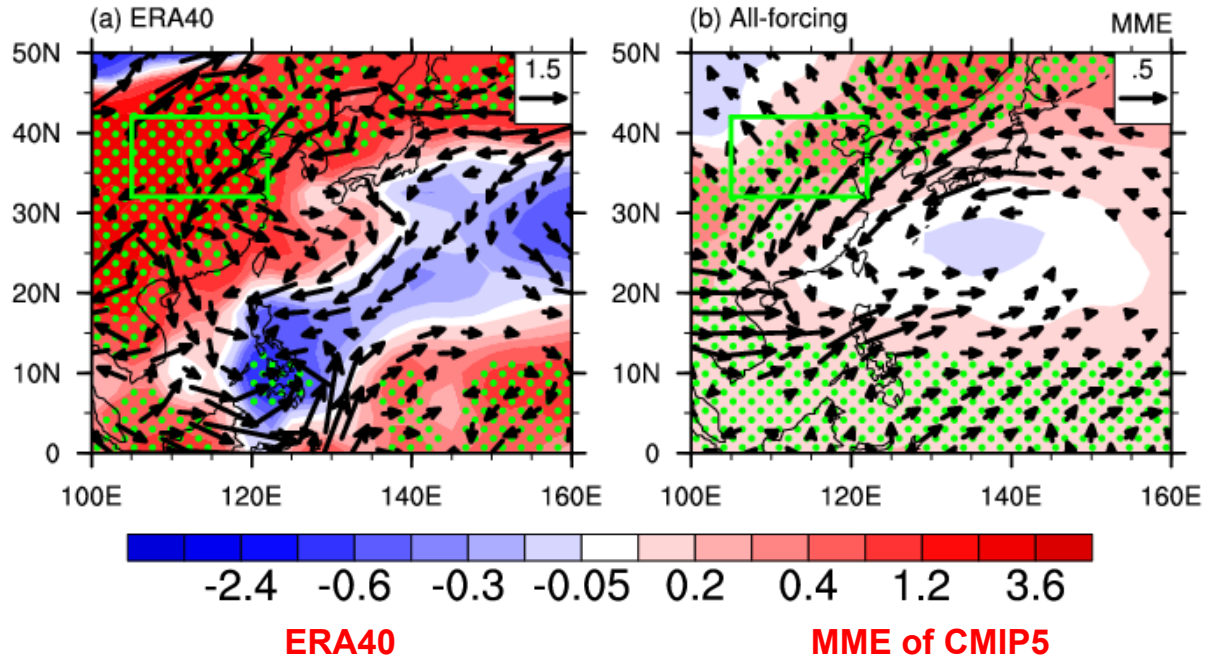



Menon et al. 2002, Science




Bollasina et al. 2011, Science

# Linear trends of SLP and 850 hPa winds (1958-2001)




Song F., **T. Zhou**, and Y. Qian, 2013: Responses of East Asian summer monsoon to natural and anthropogenic forcings in the 17 latest CMIP5 models. *Geophysical Research Letters, 10.1002/2013GL058705*

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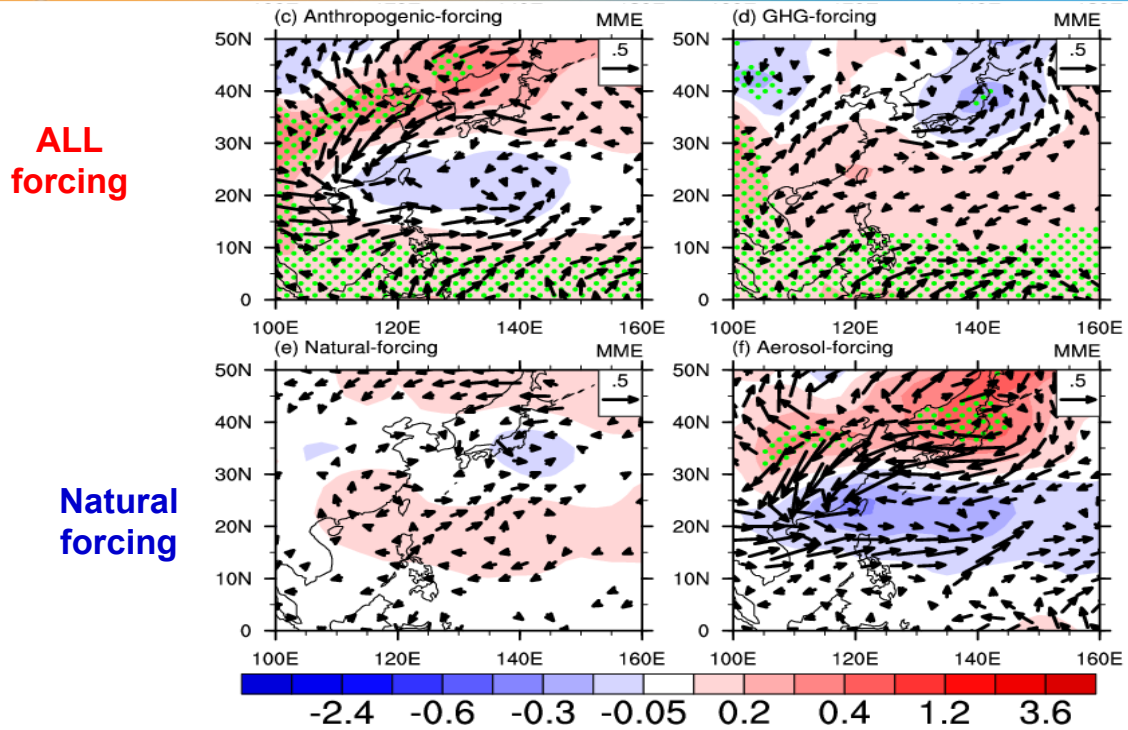



**ALL forcing**

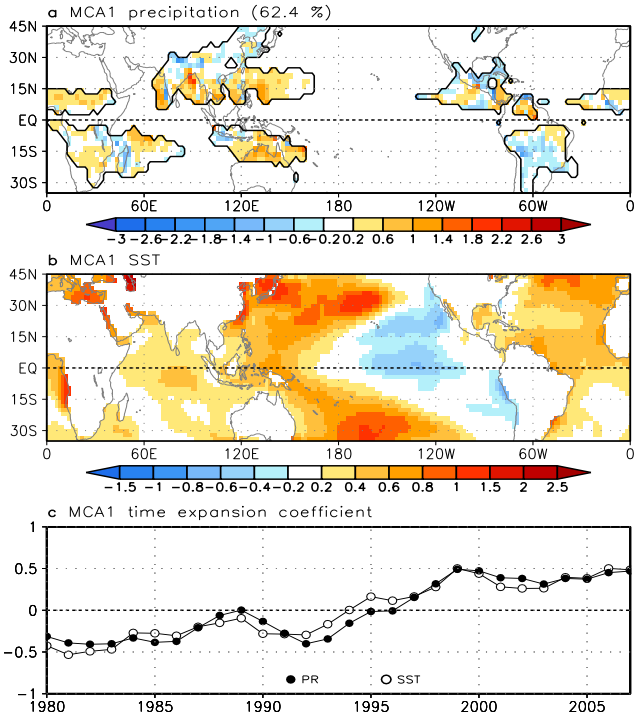
**GHG forcing**

**Natural forcing**

**Aerosol forcing**

Song F., **T. Zhou**, and Y. Qian, 2013: Responses of East Asian summer monsoon to natural and anthropogenic forcings in the 17 latest CMIP5 models. *Geophysical Research Letters, 10.1002/2013GL058705*

# Recovery of Global Monsoon since early 1980s

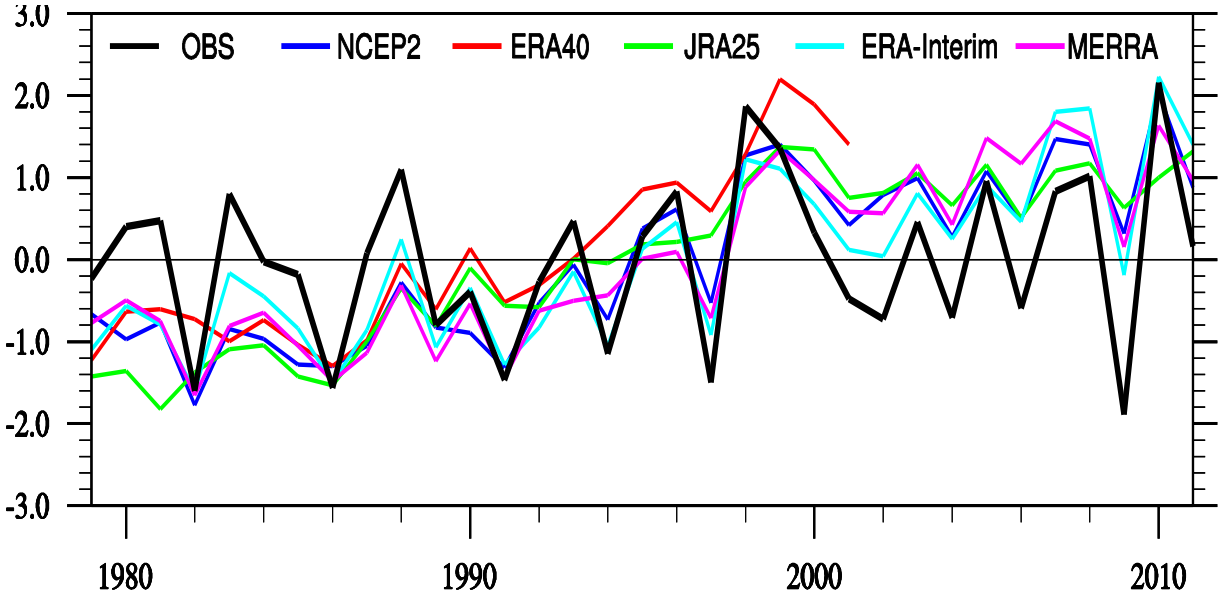



Maximum Covariance Analysis (MCA) of Monsoon precipitation and SST

3-year running mean datasets of GPCP and ERSST.

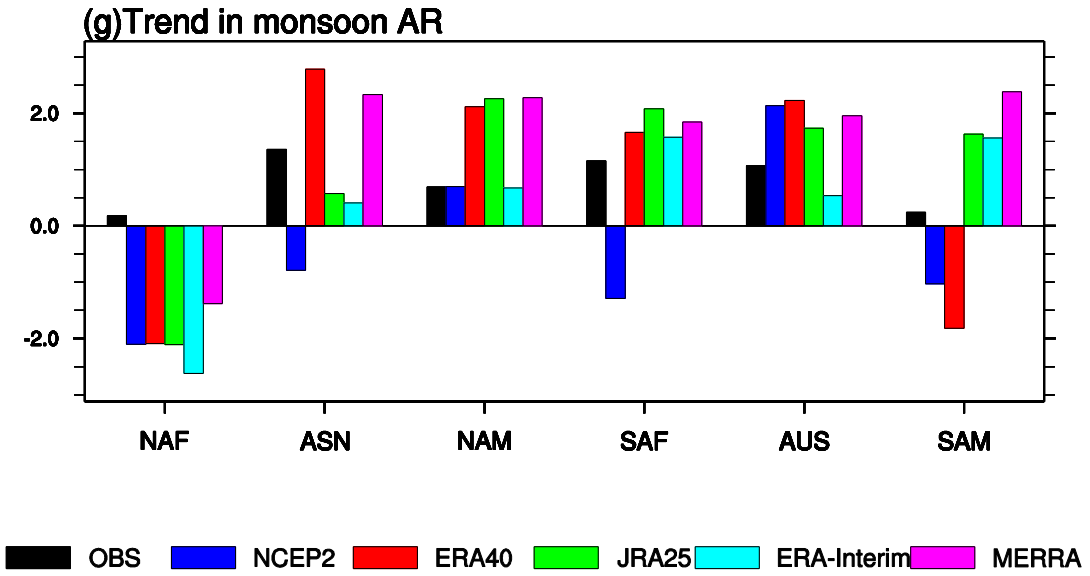
Wang et al. 2012 CD; 2013, PNAS

# Global monsoon precipitation indices derived from GPCP and re-analysis datasets



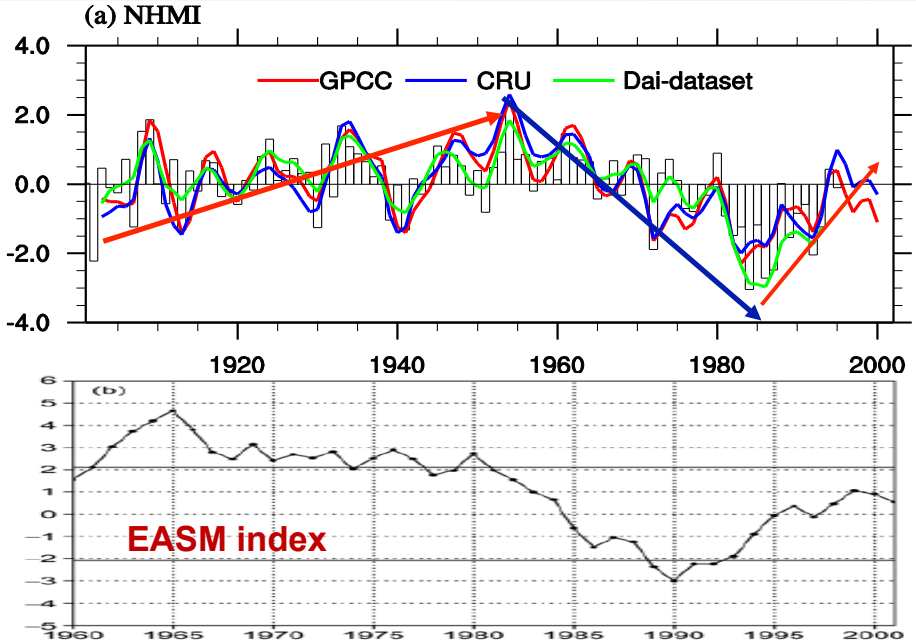

Lin, **Zhou**, Qian, 2014: Evaluation of Global Monsoon Precipitation Changes based on Five Reanalysis Datasets and Observations. ***Journal of Climate***, 27,1271-1289

# Trends of precipitation in monsoon domains over 1980-2011




Lin, **Zhou**, Qian, 2014: Evaluation of Global Monsoon Precipitation Changes based on Five Reanalysis Datasets and Observations. ***Journal of Climate***, 27, 1271-1289

# Recovery of global & EA monsoon

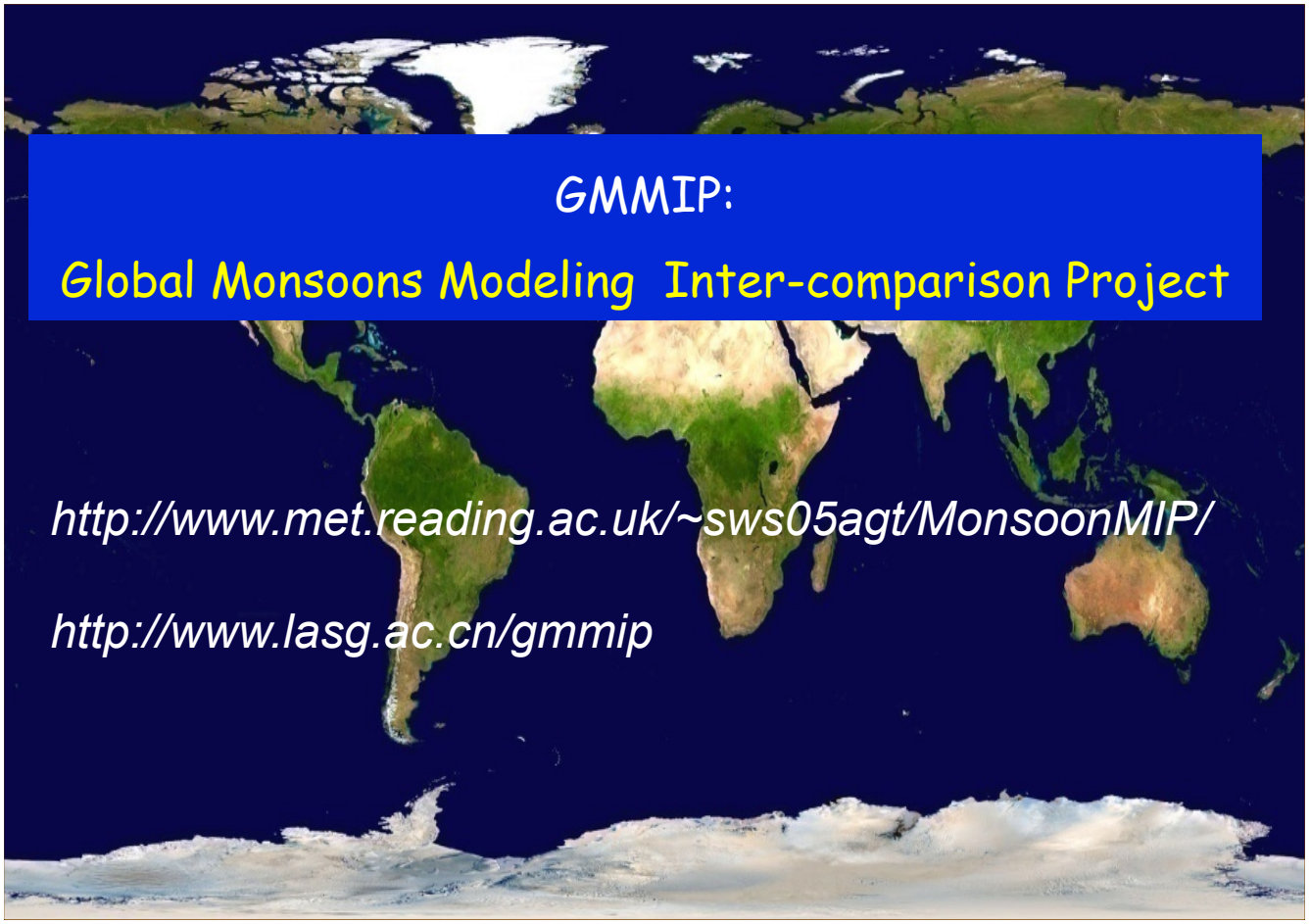



Zhang & Zhou, 2011

Liu et al., 2011


Zhang L., and T. Zhou, 2011: An assessment of monsoon precipitation changes during 1901–2001, *Climate Dynamics*, , 37, 279-296, DOI 10.1007/s00382-011-0993-5

Liu H et al. 2012, The strengthening East Asia summer monsoon since the early 1990s. ***Chin Sci Bull***, 2012, 57: 1553-1558, doi:10.1007/s11434-012-4991-8


GMMIP:
Global Monsoons Modeling Inter-comparison Project
http://www.met.reading.ac.uk/~sws05agt/MonsoonMIP/
http://www.lasg.ac.cn/gmmip

## Global Monsoons Modeling Inter-comparison Project: **GMMIP**

**Co-chairs: Tianjun Zhou, Andy Turner, James Kinter III**

**1. What are the relative contributions of internal processes and external forcings that have driven the 20th century historical evolution of global monsoons?**

2. To what extent and how does the ocean-atmosphere interaction affect the interannual variability and predictability of monsoons?

3. How well can developing high-resolution models and improving model dynamics and physics help to reliably simulate monsoon precipitation and its variability and change?

◆**Tier-1:** AMIP simulation over 1870-2014

◆**Tier-2:** Pacemaker Exps of fully coupled model, 20$^{th}$ century (1870-2014) historical climate simulation with observed SST nudging in the IPO/AMO domain, respectively.

◆**Tier-3:** Eurasian orography effect Exp.

# Summary

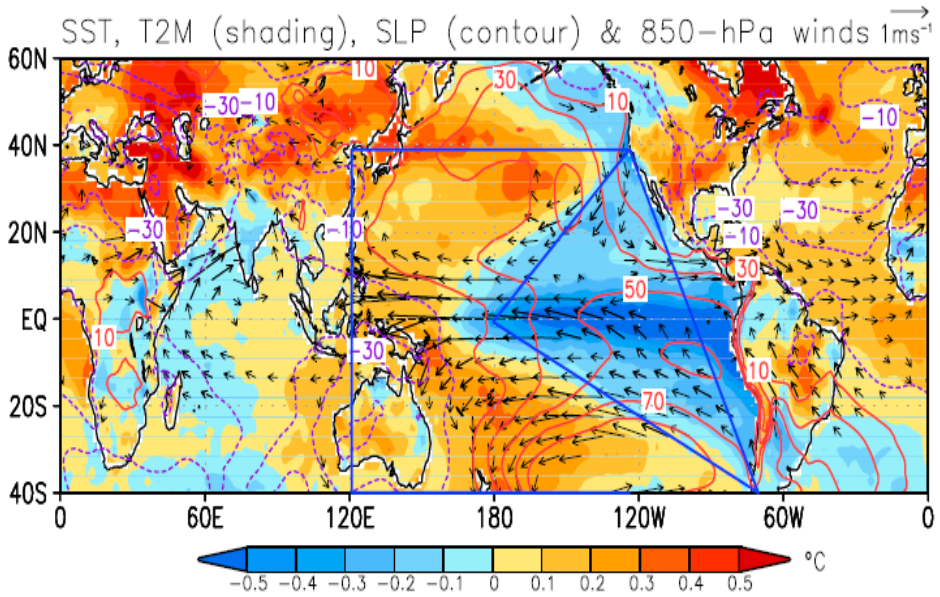
1. The weakening tendency of South and East Asian summer monsoon during 1950-2000 are local manifestations of global monsoons changes.
2. Both changes are driven by ***the interdecadal changes of Tropical Ocean SSTA, which is a tropical lobe of IPO/PDO***.
3. CMIP5 separate forcing experiments reveal that the ***aerosol forcing has driven a weakened monsoon circulation***, while ***the emission of GHG favors a stronger monsoon circulation***.
4. **GMMIP for CMIP6:** ***To understand the internal processes and external forcings in driving the 20th century changes of global monsoons by international collaborations.***

# References of the talk


1. Kitoh A.,H. Endo, K. K. Kumar, I. A. Cavalcanti,P. Goswami, **Tianjun Zhou**, 2013: Monsoons in a changing world: a regional perspective in a global context, ***J. Geophys. Res.,*** 118, doi: 10.1002/jgrd.50258
2. Man Wenmin, **Tianjun Zhou** , Johann H. Jungclaus, 2012: Simulation of the East Asian Summer Monsoon during the Last Millennium with the MPI Earth System Model, **Journal of Climate**, 25(22), 7852-7866
3. Zhang Lixia, and **Tianjun Zhou**, 2011, An assessment of monsoon precipitation changes during 1901–2001, ***Climate Dynamics***, *37*, 279-296, DOI 10.1007/s00382-011-0993-5
4. **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
5. **Zhou, T.,** and L. Zou, 2010: Understanding the Predictability of East Asian Summer Monsoon from the Reproduction of Land-Sea Thermal Contrast Change in AMIP-type Simulation, ***Journal of Climate***, 23(22), 6009-6026
6. Yu, R., and **T. Zhou**, 2007: Seasonality and three-dimensional structure of the interdecadal change in East Asian monsoon, ***Journal of Climate***, 20, 5344-5355

# Some further readings


1. Song F., **T. Zhou**, and Y. Qian, 2013: Responses of East Asian summer monsoon to natural and anthropogenic forcings in the 17 latest CMIP5 models***. Geophysical Research Letters,*** 10.1002/2013GL058705
2. **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
3. **Zhou T.**, S. Ma, L. Zou, 2014: Understanding a hot summer in central eastern China: Summer 2013 in context of multi-model trend analysis. ***Bulletin of the American Meteorological Society***, accepted and in press
4. **Qian C.** and T. **Zhou**, 2014: Multidecadal variability of North China aridity and its relationship to PDO during 1900-2010, ***J. Climate***, 27,1210-1222, DOI: 10.1175/JCLI-D-13-00235.1
5. Lin, R. **T. Zhou**, Qian, 2014: Evaluation of Global Monsoon Precipitation Changes based on Five Reanalysis Datasets and Observations***. Journal of Climate***, 27,1271-1289
6. **Zhou, T.,** D. Gong, J. Li, B. Li, 2009: Detecting and understanding the multi-decadal variability of the East Asian Summer Monsoon – Recent progress and state of affairs. *Meteorologische Zeitschrift*, 18 (4), 455-467
7. **Zhou, T.,** Yu R., Li H., et al. 2008, Ocean forcing to changes in global monsoon precipitation over the recent half century, ***J. Climate***, 21, (15), 3833–3852
8. Li, H., 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
9. **Zhou T.,** L. Zhang, and H. Li, 2008: Changes in global land monsoon area and total rainfall accumulation over the last half century**, *Geophys. Res. Lett.*, 35**, L16707, doi:10.1029/ 2008GL034881




Climate anomalies associated with the NHSM circulation index

Wang et al. 2013, PNAS

# What is GMMIP?

◆**GMMIP:**

**Global Monsoons Modeling Inter-comparison Project**

◆**One of the 17 MIPs for WCRP CMIP6**

◆**Proposed by former CLIVAR AAMP, now CLIVAR/GEWEX Monsoons Panel & CLIVAR/C20C+**

◆**Co-chairs: Tianjun Zhou, Andy Turner, James Kinter III**

◆**Secretariat: LASG/IAP**

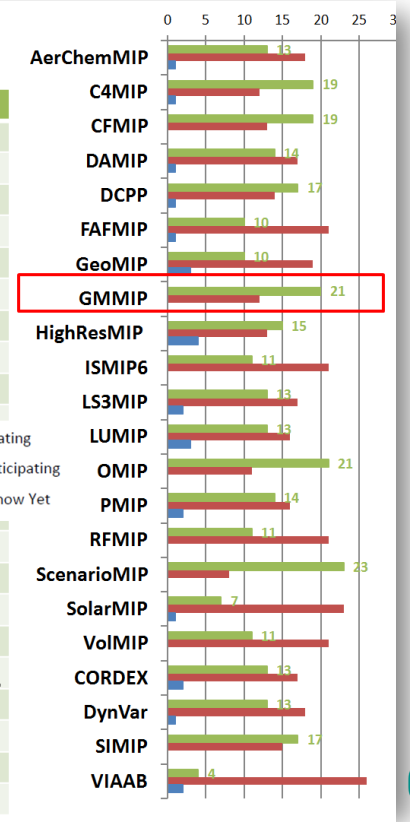
WCRP World Climate Research Programme

cmip Coupled Model Intercomparison Project

# CMIP6-Endorsed MIPs

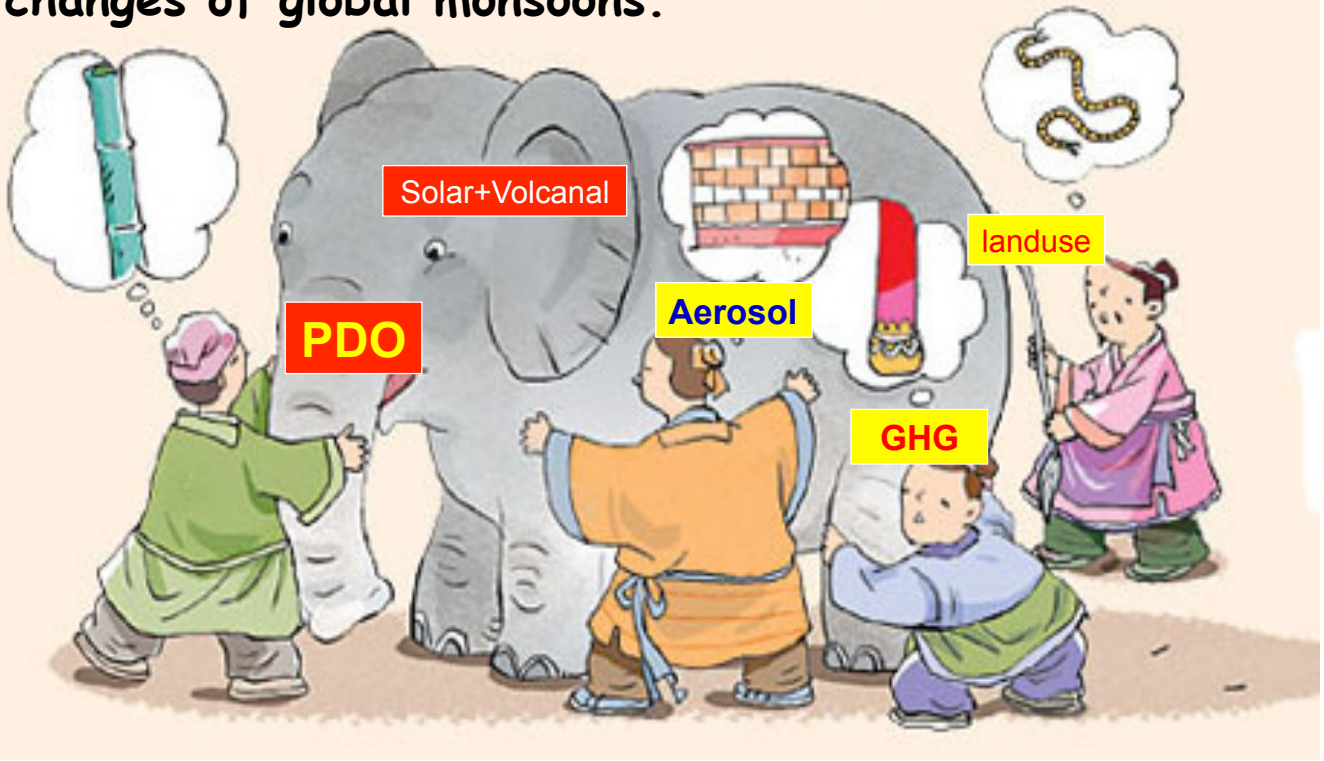
## Proposals from CMIP6-Endorsed MIPs & Model Groups' Commitments to Participate in each MIP

| | Long Name of MIP (Short Name of MIP) |
|---|---|
| 1 | Aerosols and Chemistry Model Intercomparison Project (AerChemMIP) |
| 2 | Coupled Climate Carbon Cycle Model Intercomparison Project (C4MIP) |
| 3 | Cloud Feedback Model Intercomparison Project (CFMIP) |
| 4 | Detection and Attribution Model Intercomparison Project (DAMIP) |
| 5 | Decadal Climate Prediction Project (DCPP) |
| 6 | Flux-Anomaly-Forced Model Intercomparison Project (FAFMIP) |
| 7 | Geoengineering Model Intercomparison Project (GeoMIP) |
| 8 | Global Monsoons Model Intercomparison Project (GMMIP) |
| 9 | High Resolution Model Intercomparison Project (HighResMIP) |
| 10 | Ice Sheet Model Intercomparison Project for CMIP6 (ISMIP6) |
| 11 | Land Surface, Snow and Soil Moisture MIP (LS3MIP) |
| 12 | Land-Use Model Intercomparison Project (LUMIP) |
| 13 | Ocean Model Intercomparison Project (OMIP) |
| 14 | Palaeoclimate Modelling Intercomparison Project (PMIP) |
| 15 | Radiative Forcing Model Intercomparison Project (RFMIP) |
| 16 | Scenario Model Intercomparison Project (ScenarioMIP) |
| 17 | Solar Model Intercomparison Project (SolarMIP) |
| 18 | Volcanic Forcings Model Intercomparison Project (VolMIP) |
| 19 | *Coordinated Regional Climate Downscaling Experiment (CORDEX)* |
| 20 | *Dynamics and Variability of the Stratosphere-Troposphere System (DynVar)* |
| 21 | *Sea-Ice Model Intercomparison Project (SIMIP)* |
| 22 | *Vulnerability, Impacts, and Adaptation Advisory Board for CMIP6 (VIA AB)* |




CMIP
The World Climate Research Programme's Coupled Model Intercomparison Project

**Motivation-1:** To understand the internal processes and external forcings in driving the 20th century changes of global monsoons.



# Main Experiments

**All the GMMIP partners are encouraged to conduct both the Tier-1 and Tier-2 experiments.**

| | EXP name | Integration time | Description | Model type | Motivation |
|---|---|---|---|---|---|
| Tier-1 | AMIP 20C | 1870-2014 | Extended AMIP run that covers 1870-2014. | AGCM run, min realization 3 | understand the roles of SST forcing and external forcings |
| Tier-2 | HIST-IPO | 1870-2014 | Pacemaker 20th century historical run that includes all forcing as used in CMIP6 Historical Simulation, and the observational historical SST is restored in the tropical lobe of the IPO domain (20°S-20°N, 175°E-75°W) | CGCM min realization 3 | understand the forcing of IPO-related tropical SST to global monsoon changes. |
| | HIST-AMO | 1870-2014 | Same as HIST-IPO, but the observational historical SST is restored in the AMO domain (0°-70°N, 70°W-0°) | CGCM min realization 3 | understand the forcing of AMO-related SST to global monsoon changes |

# Tiered Experiments

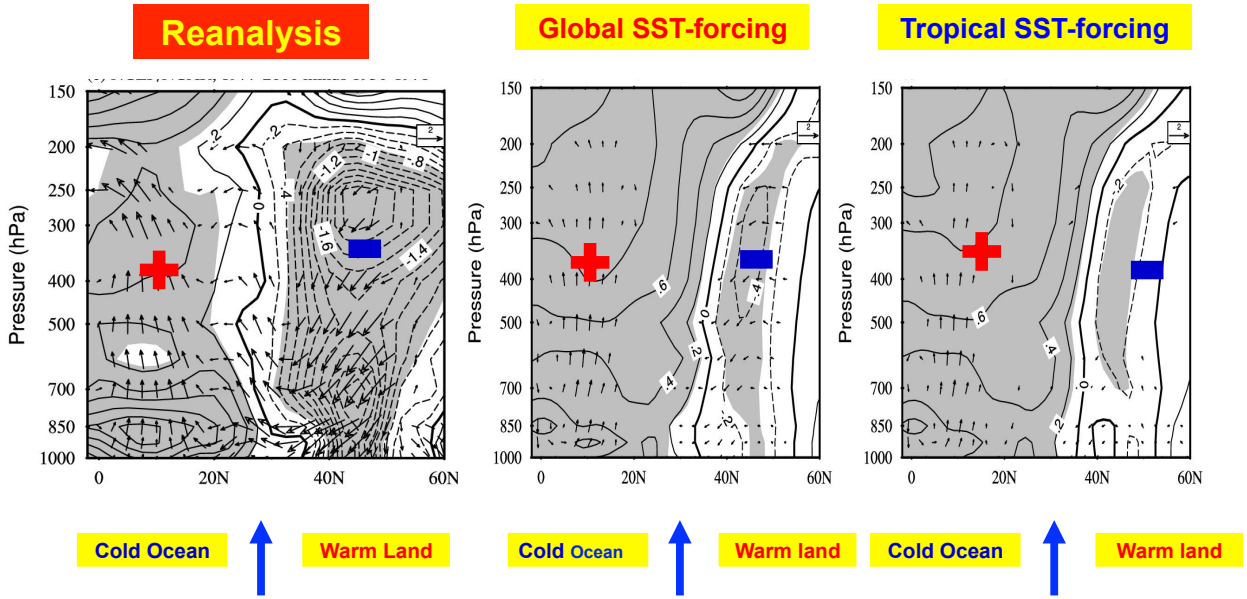
| | EXP name | Integration time | Description | Model type | Motivation |
|---|---|---|---|---|---|
| Tier-3 | DTIP | 1979-2014 | The topography of the TIP is modified by setting surface elevations to 500m | AGCM run, min realization 1 | Understanding the combined thermal and mechanical forcing of the TIP. |
| | DTIP-DSH | 1979-2014 | Surface sensible heat released at the elevation above 500m over the TIP is not allowed to heat the atmosphere | AGCM run, min realization 1 | Understanding the thermal forcing of the TIP |
| | DHLD | 1979-2014 | The topography of the highlands in Africa, N. America and S. America TP is modified by setting surface elevations to a certain height (500m), | AGCM run min realization 1 | Understanding the combined thermal and mechanical forcing of other plateaus except the TIP. |

## Primary Scientific Questions of GMMIP

1. What are the relative contributions of internal processes and external forcings that have driven the 20$^{th}$ century historical evolution of global monsoons?
2. To what extent and how does the ocean-atmosphere interaction affect the interannual variability and predictability of monsoons?
3. How well can developing high-resolution models and improving model dynamics and physics help to reliably simulate monsoon precipitation and its variability and change?
4. What are the effects of Eurasian orography, in particular the Himalaya/Tibetan Plateau, on the regional/global monsoons?

# Land-Sea Thermal Contrast change

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

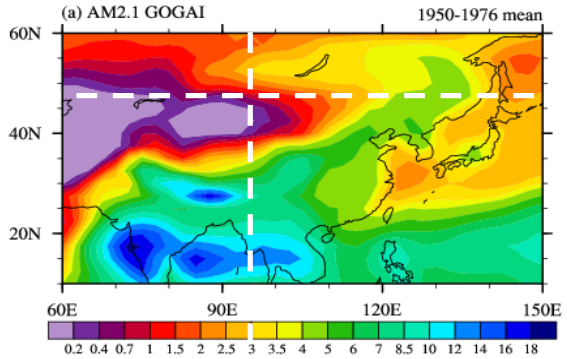


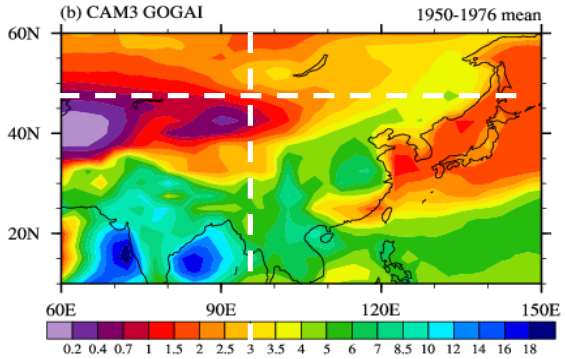

**Li, Hongmei**, A. Dai, T. Zhou, J. Lu, 2010: Responses of East Asian summer monsoon to historical SST and atmospheric forcing during 1950-2000, ***Climate Dynamics,* 34**, 501–514, DOI 10.1007/s00382-008-0482-7

# Precipitation: Mean State and Inter-decadal change

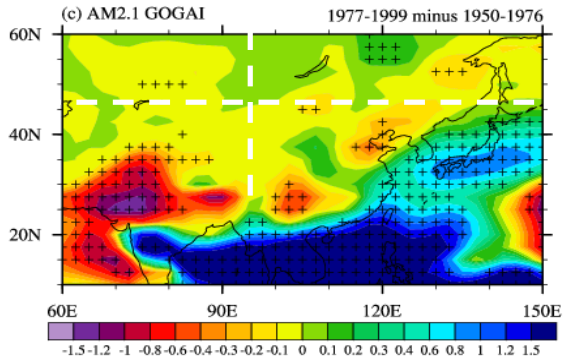
**GFDL AM2.1** | **NCAR CAM3**

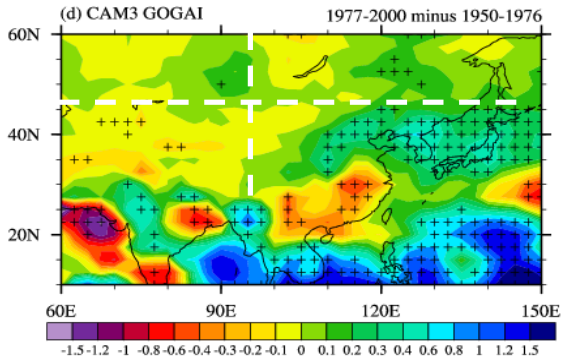
**Mean**




**Change**



# The details of 17 CMIP5 models

| No. | Model | Institute | Atmospheric resolution (lat*lon) | Member (35) |
|---|---|---|---|---|
| 1 | bcc-csm1-1 | BCC/China | 64*128 | 1 |
| 2 | BNU-ESM | BNU/China | 64*128 | 1 |
| 3 | CanESM2 | CCCma/Canada | 64*128 | 5 |
| 4 | CCSM4 | NCAR/USA | 192*288 | 3 |
| 5 | CNRM-CM5 | CNRM-CERFACS/France | 128*256 | 6 |
| 6 | CSIRO-Mk3-6-0 | CSIRO-QCCCE/Australia | 96*192 | 1 |
| 7 | FGOALS-g2 | IAP-THU/China | 60*128 | 1 |
| 8 | GFDL-CM3 | NOAA GFDL/USA | 90*144 | 1 |
| 9 | GFDL-ESM2M | NOAA GFDL/USA | 90*144 | 1 |
| 10 | GISS-E2-H | NASA-GISS/USA | 90*144 | 1 |
| 11 | GISS-E2-R | NASA-GISS/USA | 90*144 | 1 |
| 12 | HadGEM2-ES | MOHC/UK | 144*192 | 4 |
| 13 | IPSL-CM5A-LR | IPSL/France | 96*96 | 3 |
| 14 | MIROC-ESM | MIROC/Japan | 64*128 | 3 |
| 15 | MIROC-ESM-CHEM | MIROC/Japan | 64*128 | 1 |
| 16 | MRI-CGCM3 | MRI/Japan | 160*320 | 1 |
| 17 | NorESM1-M | NCC/Norway | 96*144 | 1 |

Song F., **T. Zhou**, and Y. Qian, 2013: Responses of East Asian summer monsoon to natural and anthropogenic forcings in the 17 latest CMIP5 models***. Geophysical Research Letters****, 10.1002/2013GL058705*

# External forcing agents used in 17 CMIP5 Models

| No. | Model | Natural forcings | | Anthropogenic forcings | |
|---|---|---|---|---|---|
| | | Solar | Volcanic | GHG | Aerosol |
| 1 | bcc-csm1-1 | SOLARIS | A | IIASA | **C** |
| 2 | BNU-ESM | SOLARIS | A | IIASA | E1 |
| 3 | CanESM2 | SOLARIS | S | IIASA | E1 |
| 4 | CCSM4 | SOLARIS | A | IIASA | **C** |
| 5 | CNRM-CM5 | SOLARIS | A | IIASA | E1 |
| 6 | CSIRO-Mk3-6-0 | SOLARIS | S | IIASA | E2 |
| 7 | FGOALS-g2 | SOLARIS | - | IIASA | **C** |
| 8 | GFDL-CM3 | SOLARIS | S | IIASA | E1 |
| 9 | GFDL-ESM2M | SOLARIS | S | IIASA | E1 |
| 10 | GISS-E2-H | SOLARIS | S | IIASA | **C** |
| 11 | GISS-E2-R | SOLARIS | S | IIASA | **C** |
| 12 | HadGEM2-ES | SOLARIS | S | IIASA | E1 |
| 13 | IPSL-CM5A-LR | SOLARIS | S | IIASA | E1 |
| 14 | MIROC-ESM | SOLARIS | S | IIASA | E1 |
| 15 | MIROC-ESM-CHEM | SOLARIS | S | IIASA | E1 |
| 16 | MRI-CGCM3 | SOLARIS | E | IIASA | E1 |
| 17 | NorESM1-M | SOLARIS | A | IIASA | E1 |

**S: Sato et al. (1993);**
**A: Ammann et al. (2003).**

**E: Emission is given;**
**C: Concentration is given.**

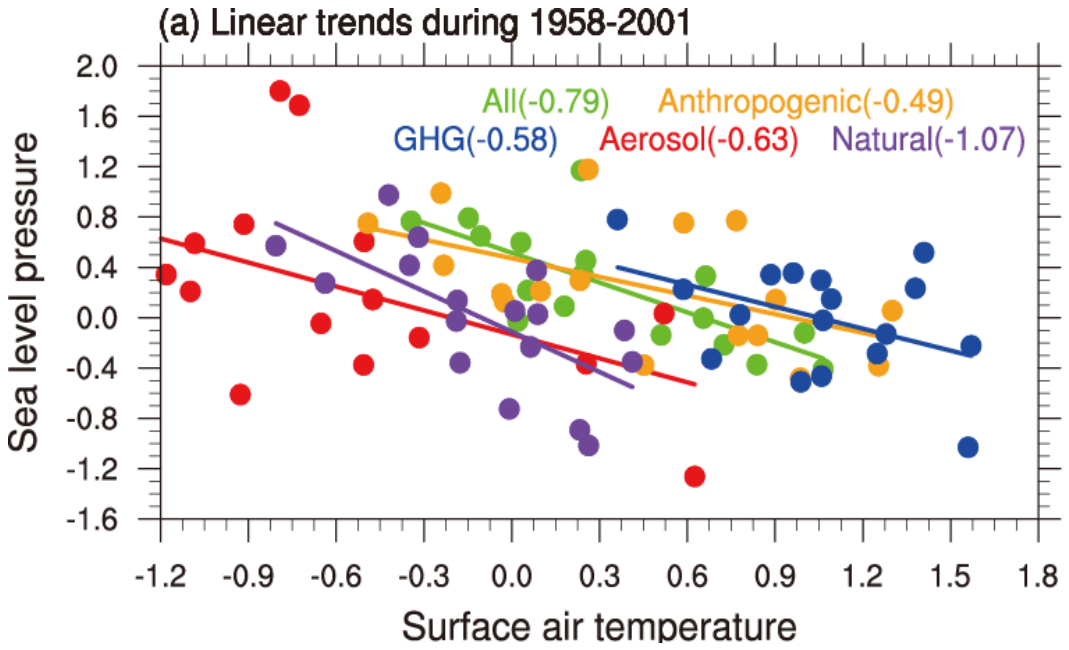
# Details of three sets of CMIP5 experiments

| Experiment description | CMIP5 label | Major purposes | Short name |
|---|---|---|---|
| Past ~1.5 centuries (1850–2005) | historical | Evaluation | **All-forcing** |
| historical simulation but with GhG forcing only | historicalGHG | Detection and attribution | **GHG-forcing** |
| historical simulation but with natural forcing only | historicalNat | Detection and attribution | **Natural-forcing** |

- **According to Taylor et al. (2009), anthropogenic-forcing is estimated by All-forcing run minus Natural-forcing run.**
- **Aerosol-forcing is estimated by Anthropogenic-forcing run minus GHG-forcing run. 105 realizations are analyzed.**

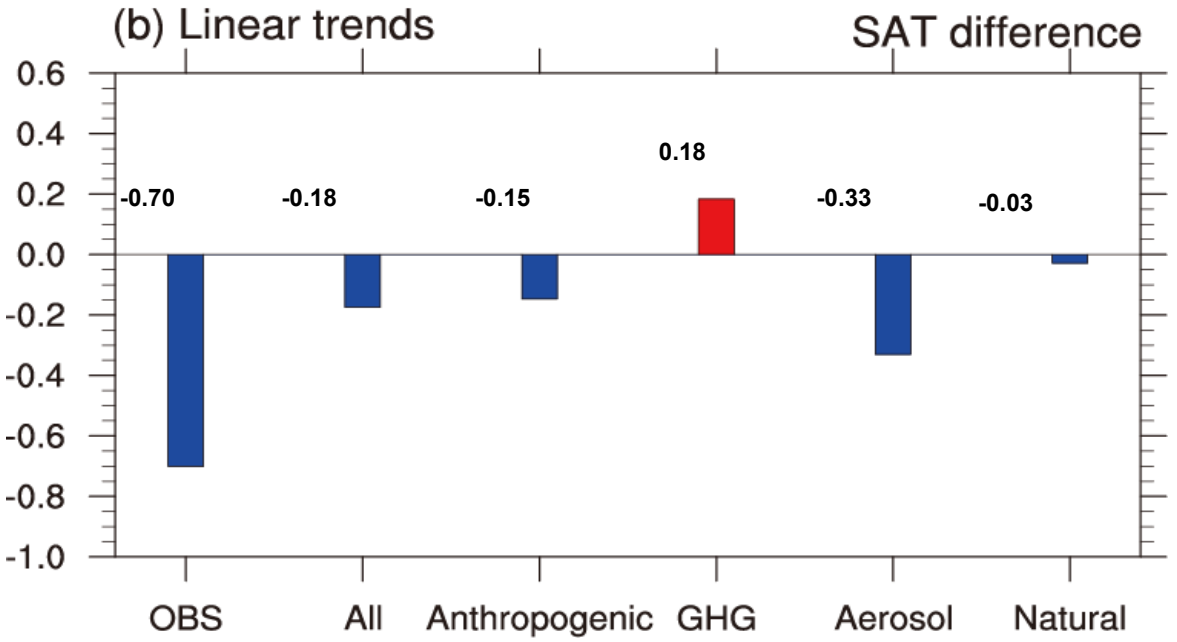
Song F., **T. Zhou**, and Y. Qian, 2013: Responses of East Asian summer monsoon to natural and anthropogenic forcings in the 17 latest CMIP5 models. *Geophysical Research Letters, 10.1002/2013GL058705*

## Higher SLP in N. China and surface cooling in central China



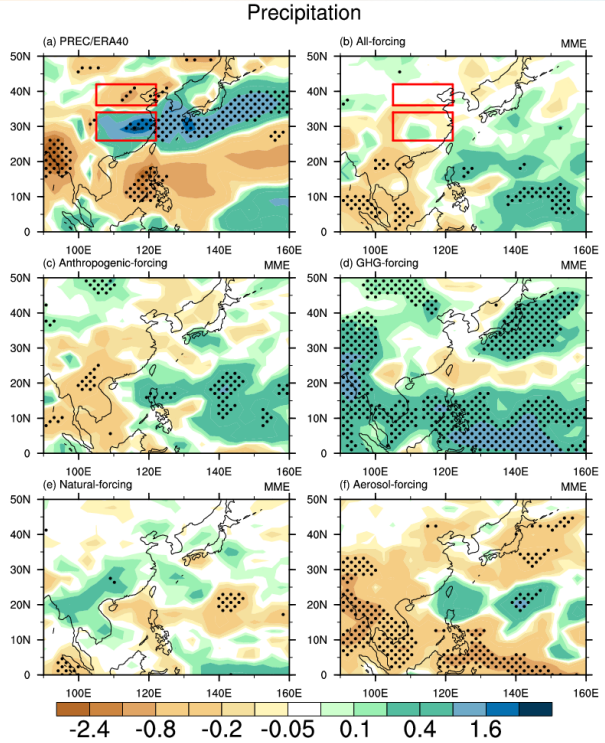

Surface cooling → weaker land-sea thermal contrast and higher SLP. → Weakened monsoon circulation.

## Trends of Land-sea thermal contrast as a measure of EASM strength




The specified external forcing agents only account for **25.6%** of the observed monsoon weakening.

# The linear trends of precipitation during 1958-2001




•**Weakness:**

**CMIP5 models are unable to reproduce the precipitation anomalies due to their low resolutions**

Song F., **T. Zhou**, and Y. Qian, 2013: Responses of East Asian summer monsoon to natural and anthropogenic forcings in the 17 latest CMIP5 models. *Geophysical Research Letters, 10.1002/2013GL058705*