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and Geophysical Fluid Dynamics(LASG)
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Asian Monsoon in a Global Perspective

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2nd ACAM Training School: Observation & modeling of atmospheric chemistry & aerosols in the Asian monsoon region

10-12 June 2017, Jinan University, Guangzhou China

Outline

1. Background

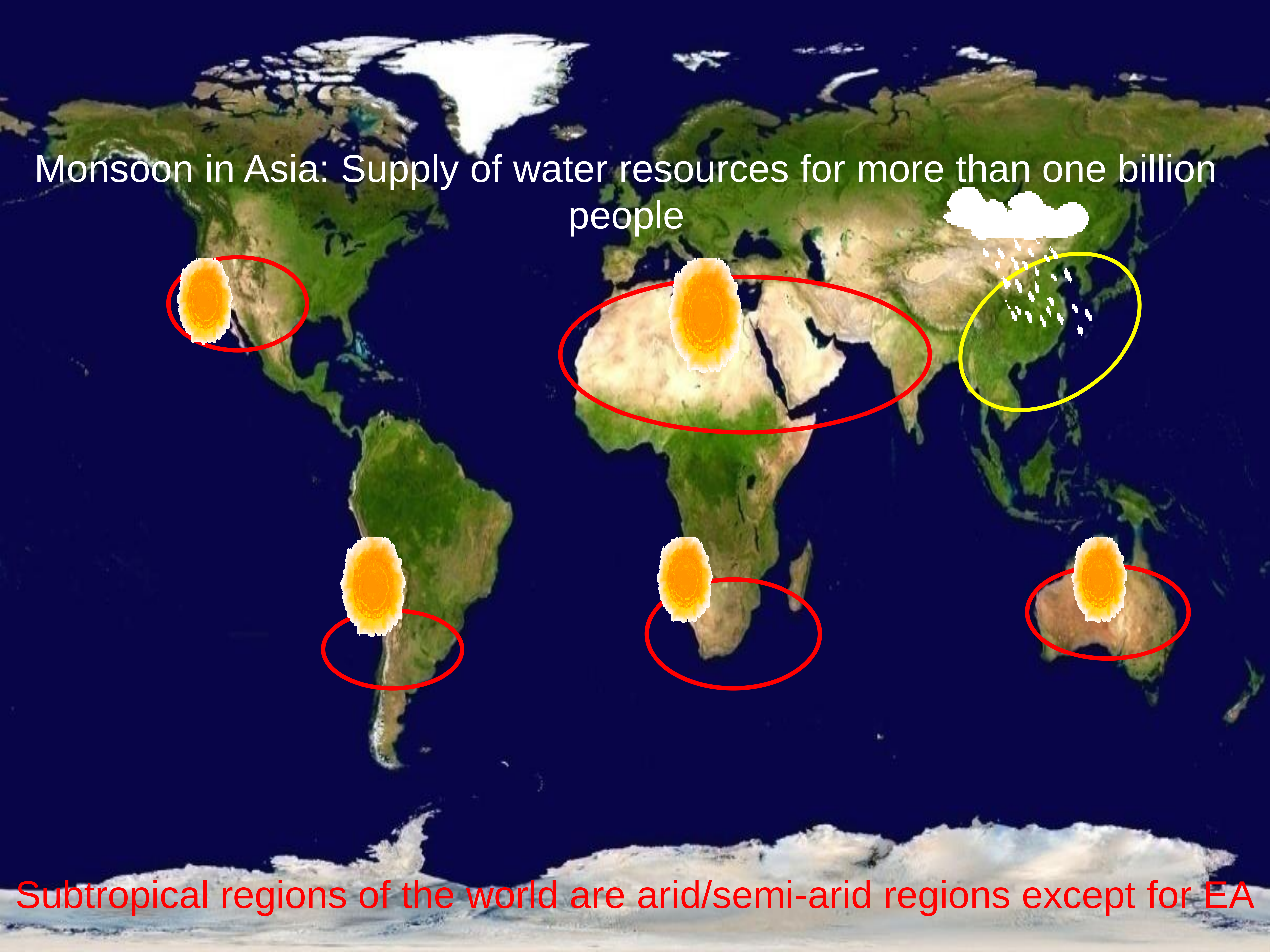
2. Overview of GM

3. Responses to external forcings

4. Concluding remarks

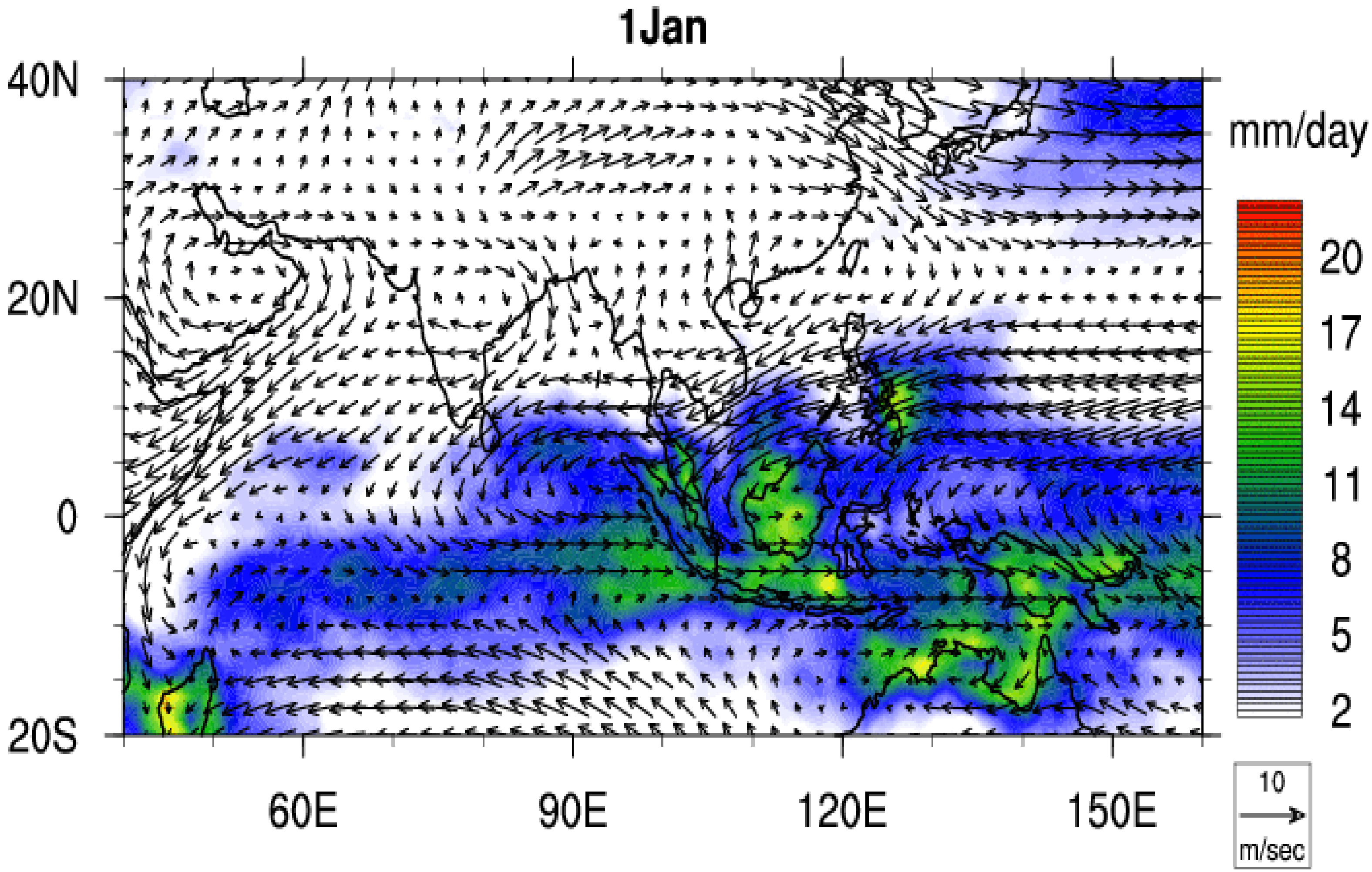
NOAA Earth Light

The majority of Asian people lives in the southern and eastern part of the continent: a monsoon region with more than 2 billion population


Monsoon in Asia: Supply of water resources for more than one billion people
Subtropical regions of the world are arid/semi-arid regions except for EA

Monsoon, manifested by wind & rainfall

Seasonal Migration of Tropical Convergence Zone (TCZ)

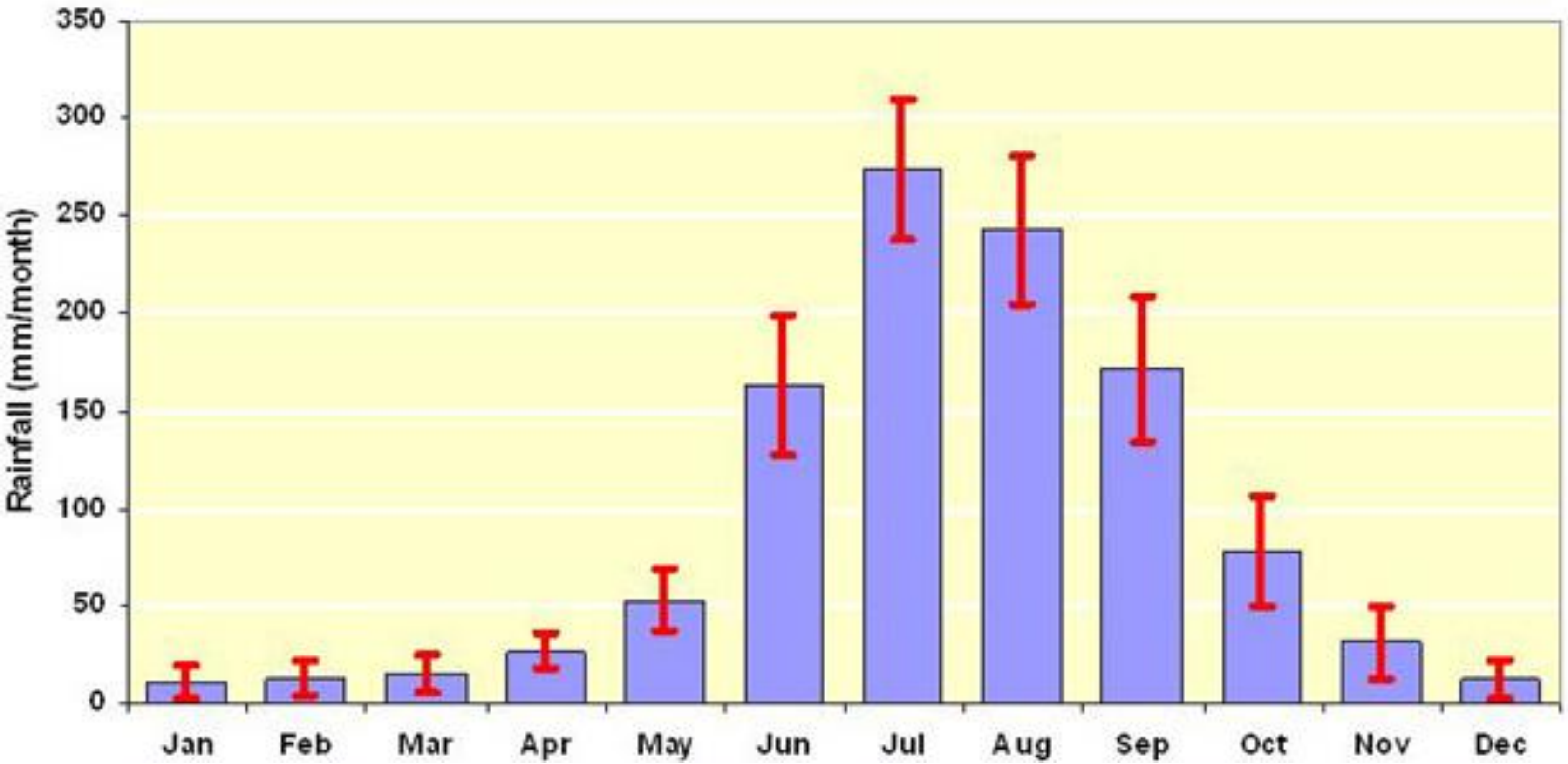


Annual evolution of daily mean Winds at 850 hPa and Precipitation

Courtesy: Roxy Mathew Koll

Monsoon, manifested by wind & rainfall

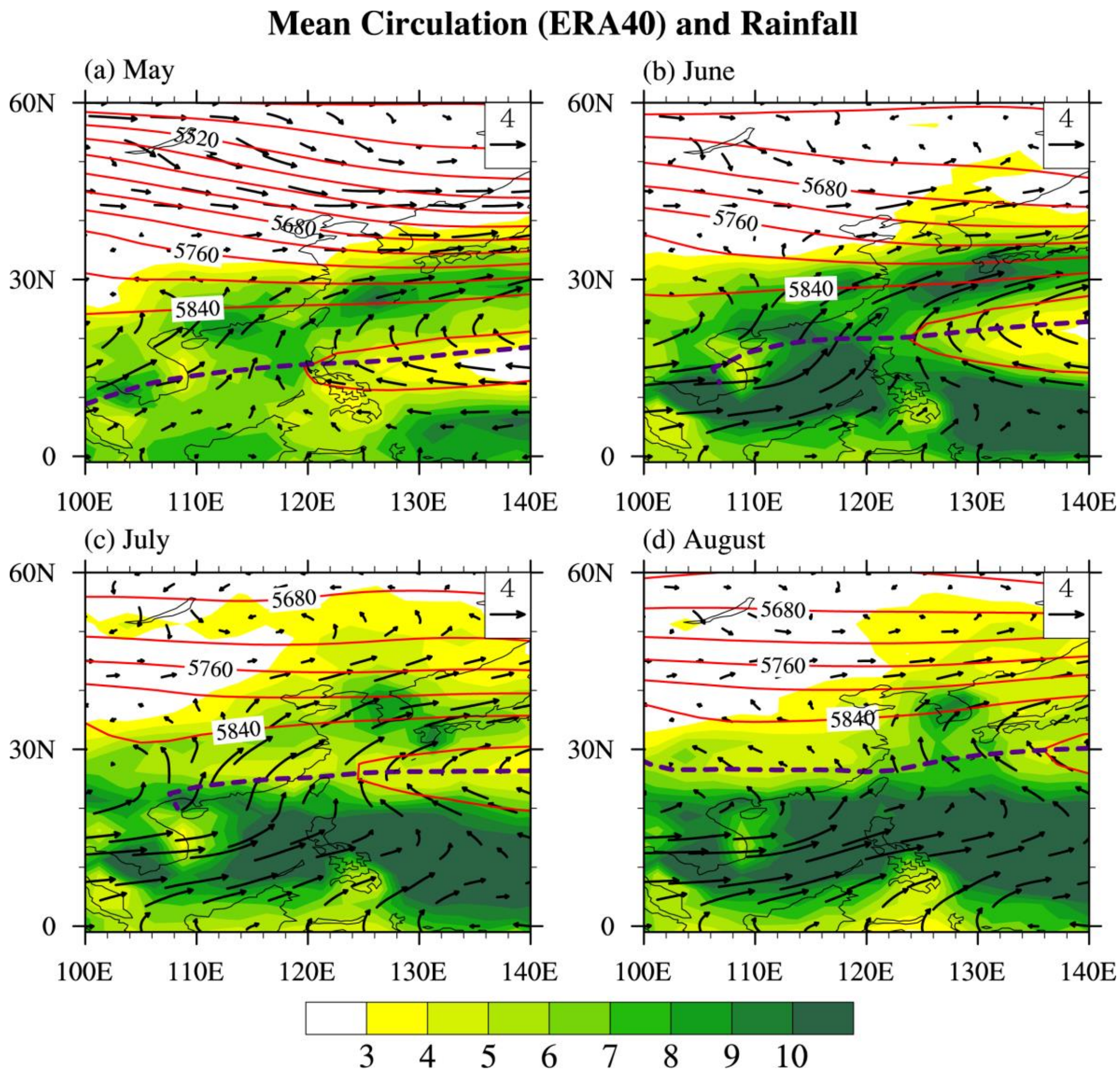
Seasonal Migration of Tropical Convergence Zone (TCZ)



Annual cycle of Indian rainfall

Courtesy: Roxy Mathew Koll

East Asian monsoon: Tropical & subtropical parts due to the existence of WPSH



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

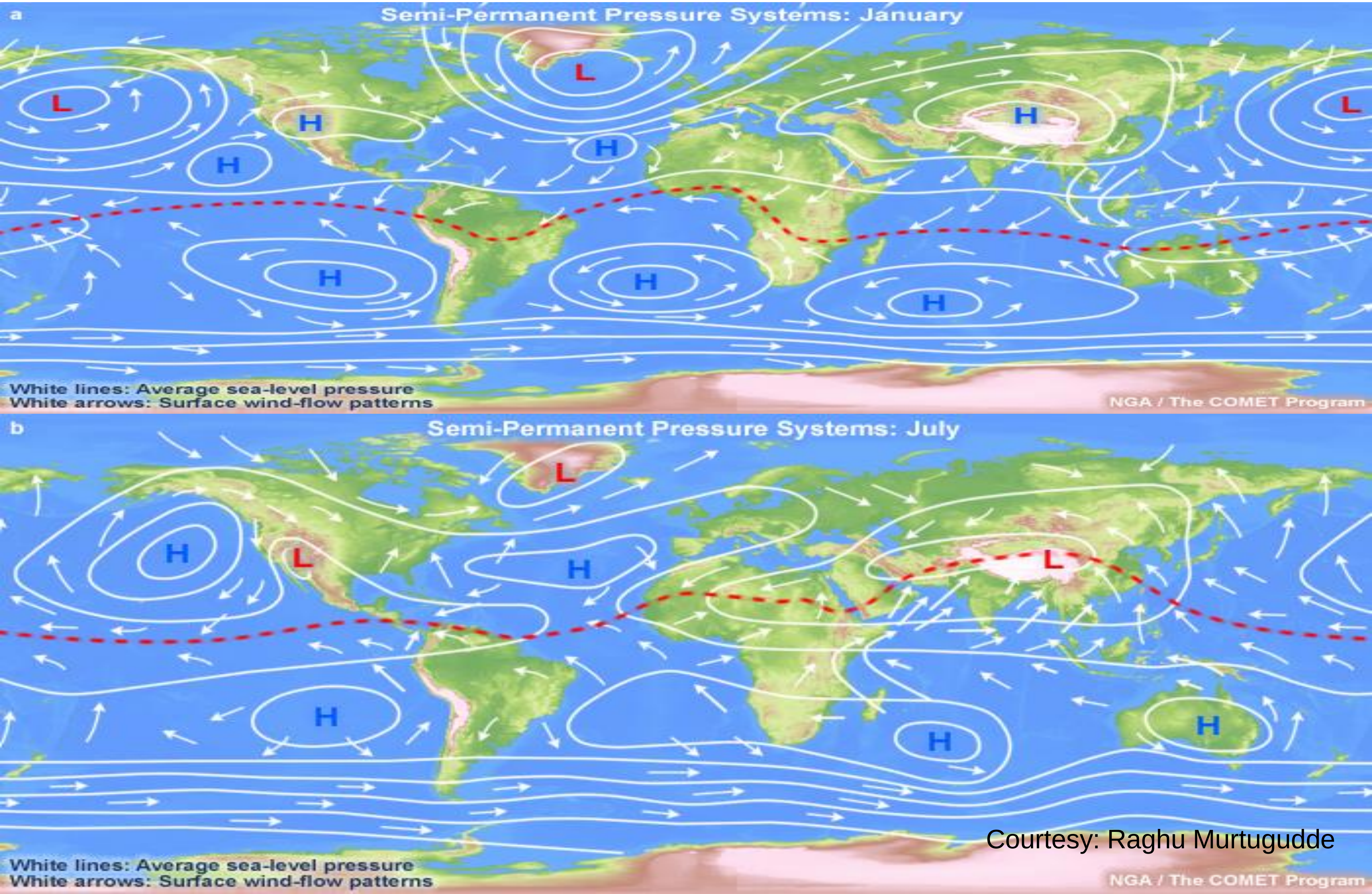
Why are there monsoons?

Monsoon Annual Cycle – Robust ?

- land-sea thermal contrast (Ts/Ps gradient)
- Orography (Tibet – elevated heat source)
  (East Africa – frictional force
  cross-equatorial flow)
- Earth's rotation (Coriolis force)
- Moisture from the tropical Indian Ocean

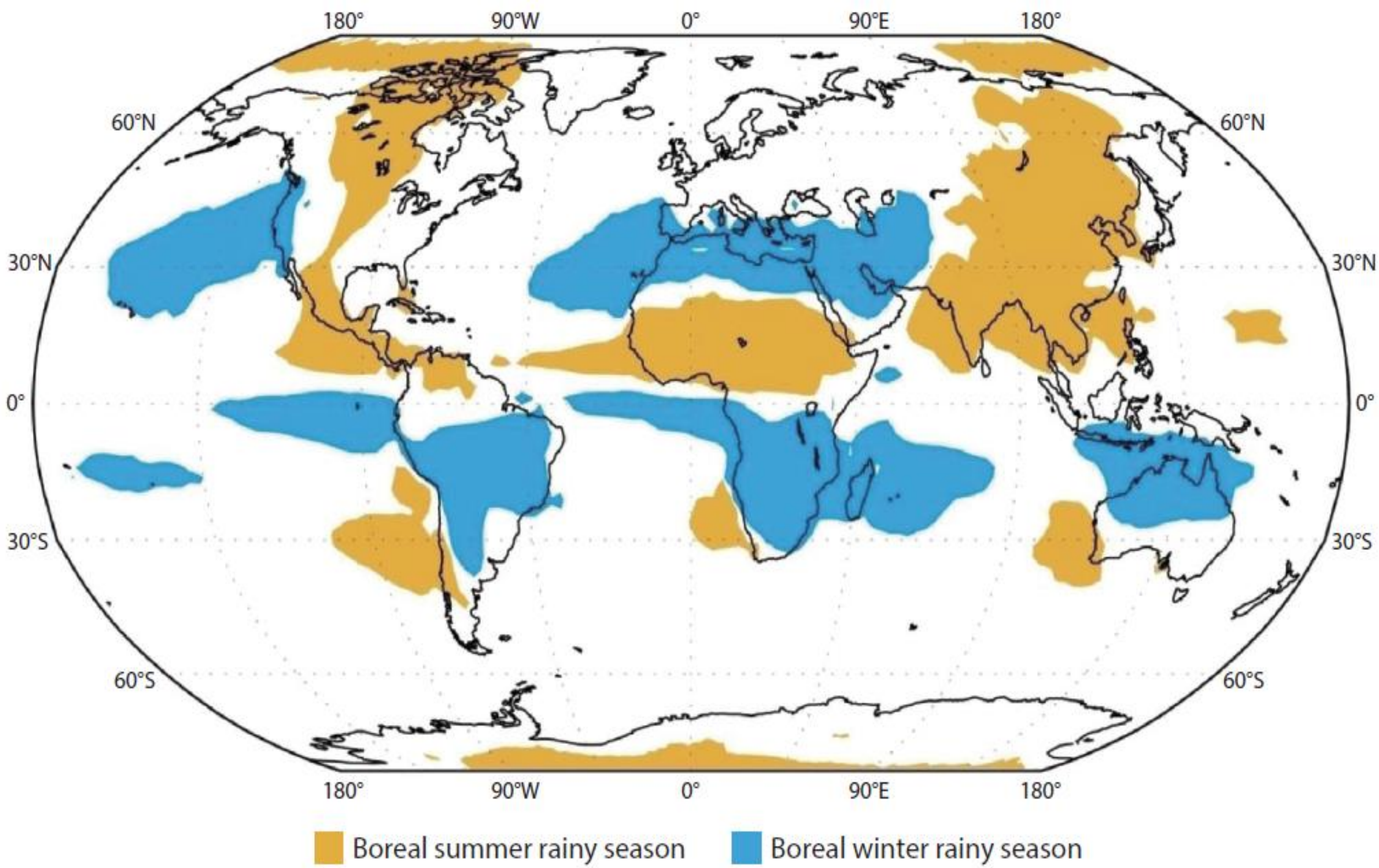
Courtesy: H. Annamalai

ITCZ – The Global Tropical Conveyor



Courtesy: Raghu Murtugudde

We should obviously be able to relate the ITCZ to rainy seasons on land



Courtesy: Raghu Murtugudde

Mean Upper-Tropospheric Temperature: 200-500 mbar

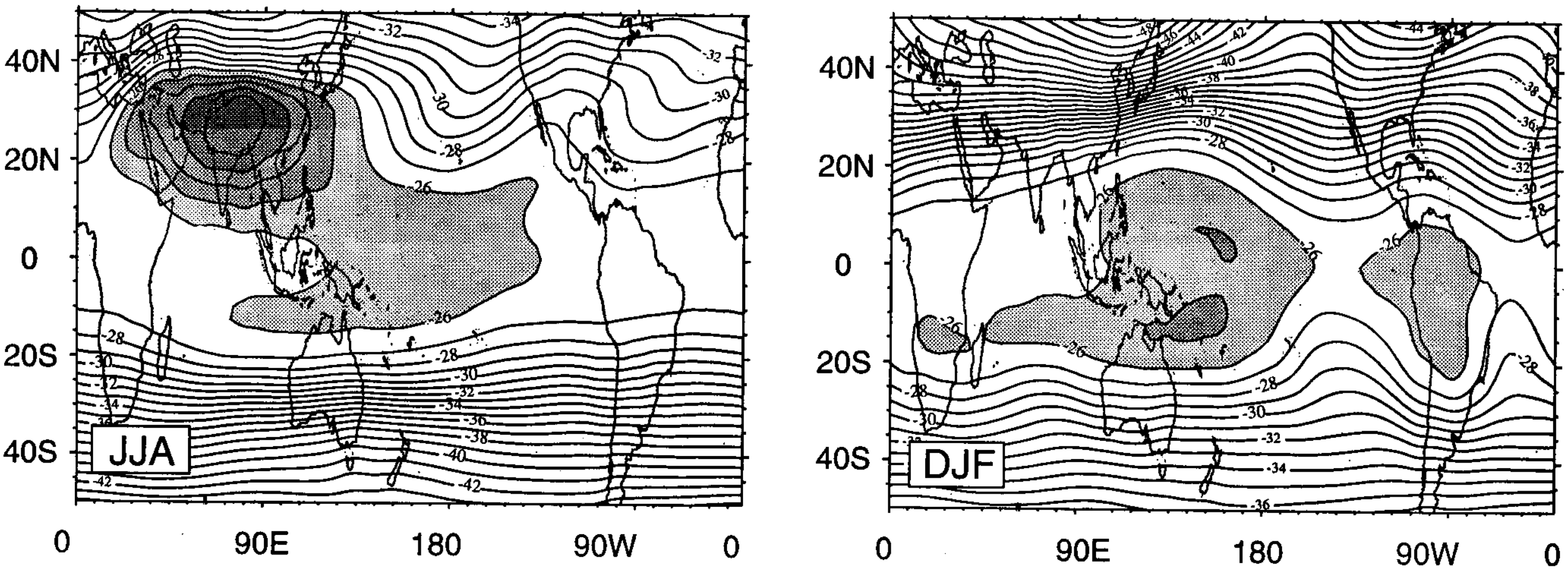
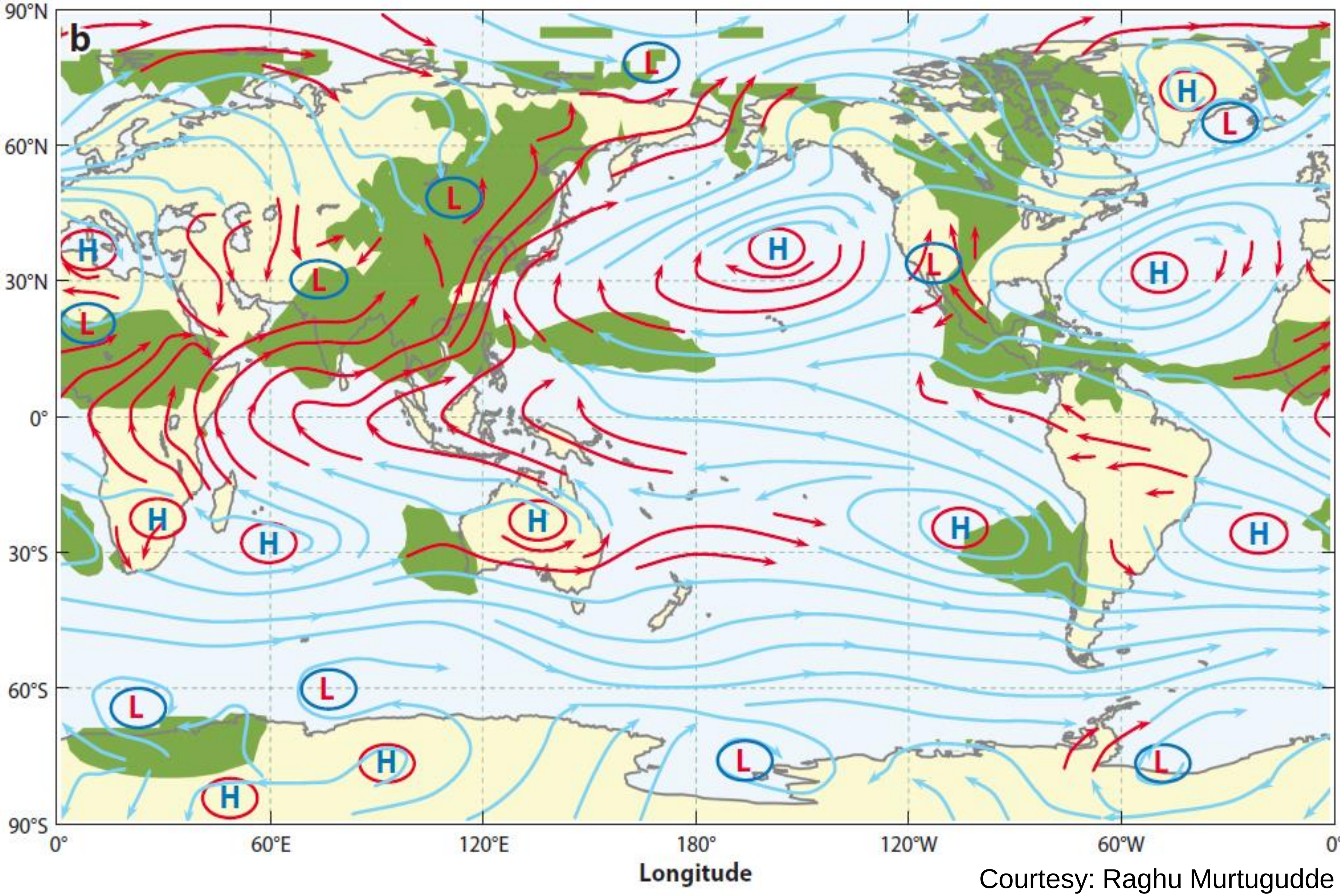


Figure 6a. Mean upper tropospheric (200–500 mbar) temperature (degrees Celsius) for the boreal summer (JJA), and boreal winter (DJF), averaged between 1979 and 1992. The boreal summer plot is based on calculations first made by *Li and Yanai* [1996]. Mean columnar temperatures warmer than –25°C are shaded.

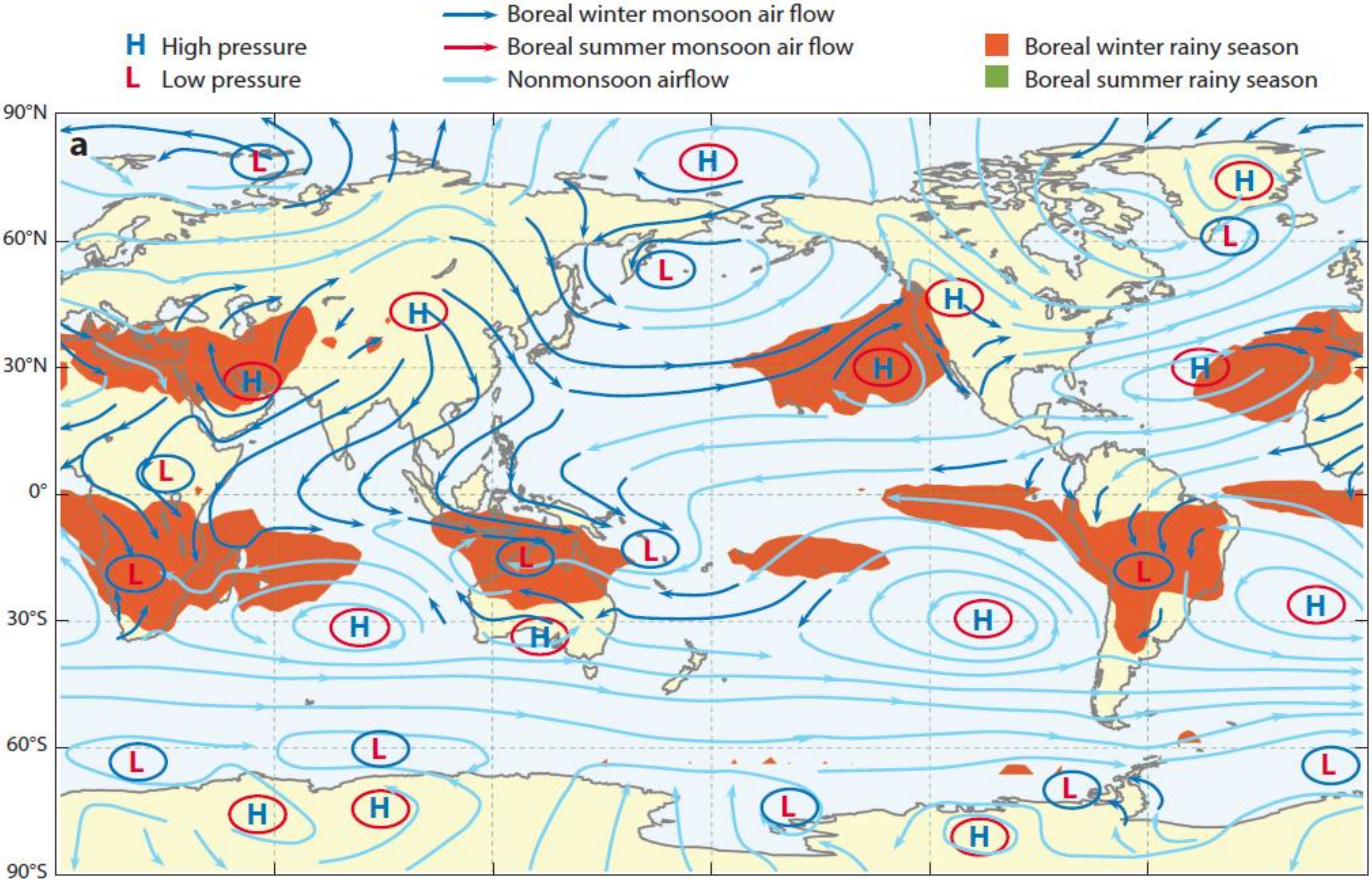
Webster et al. (1998, J. Geophys. Res)

Boreal Summer monsoon



Courtesy: Raghu Murtugudde

Boreal winter monsoon



Courtesy: Raghu Murtugudde

Indian Flood

http://i.dailymail.co.uk/i/pix/2014/09/1

Indian Flood

http://assets-cdn.ekantipur.com/images/third-party/natural-disaster

Pakistan Flood

http://i.cdn.turner.com/cnn/interactive/2010/08/world/gallery.large.pakistan.flood

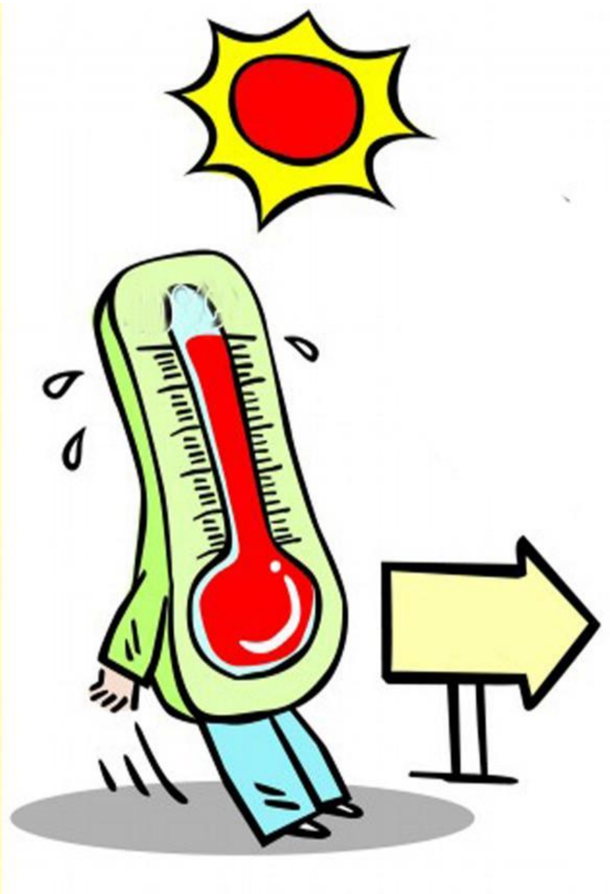

武汉站
Wuhan Railway Station
中新網
Chinanews.com
04 pm, 08 July, 2016

Extreme rainfall in Beijing: July 21, 2012

Beijing Subway

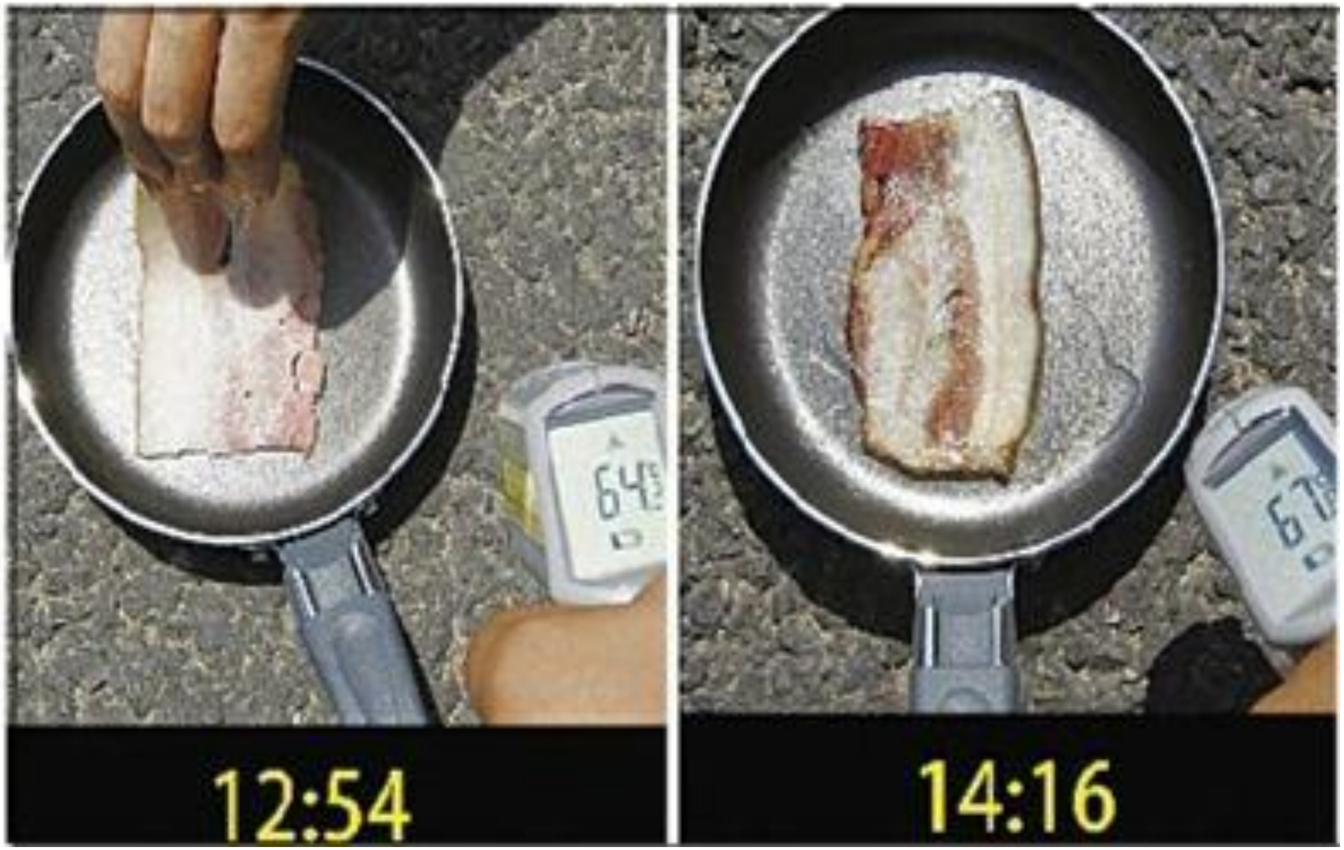
Northern suburb of Beijing

Heat Wave in China : Aug 2013



www.baidu.com

Heat Wave in China : Aug 2013



Shanghai

www.baidu.com

2008 Jan. cold surge and frozen disasters snowstorm in S. China

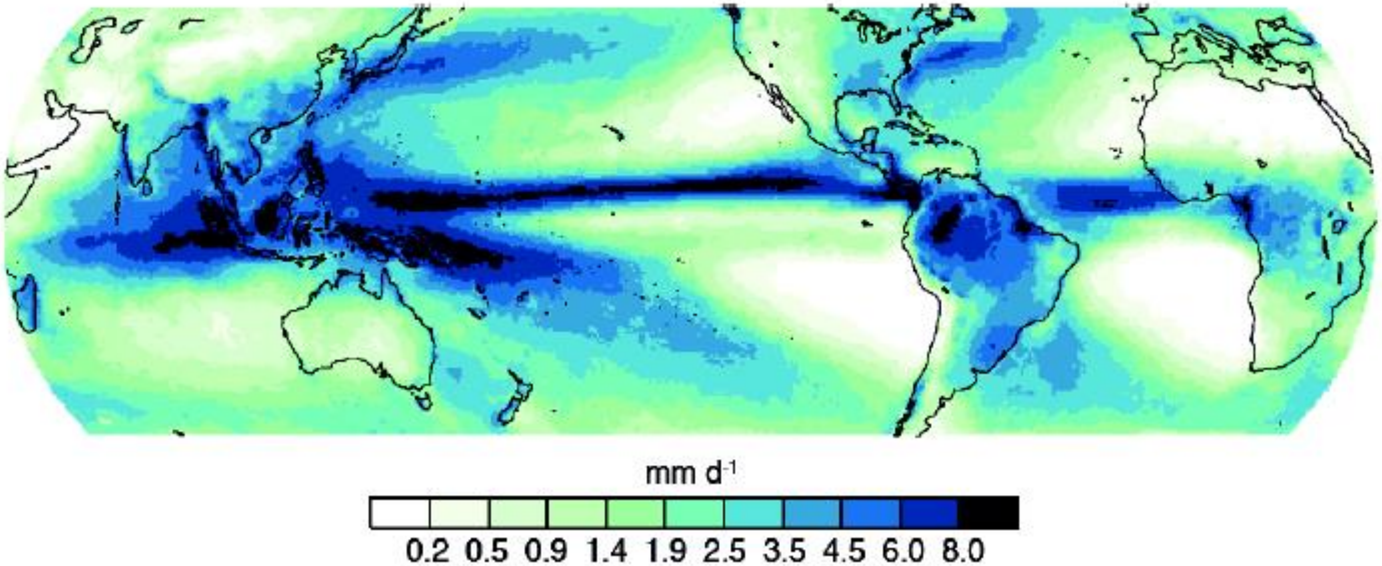
From Jan 10 to Jan 31, 2008:

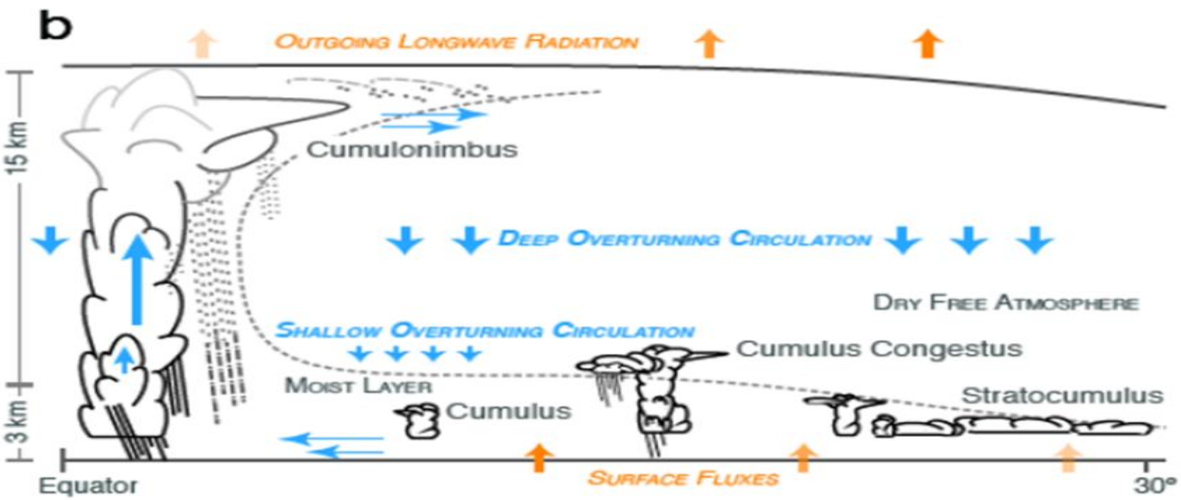
10 provinces affected, 60 people died.

Economic loss more than 53.79 billion RMB

(6 RMB=1 USD)

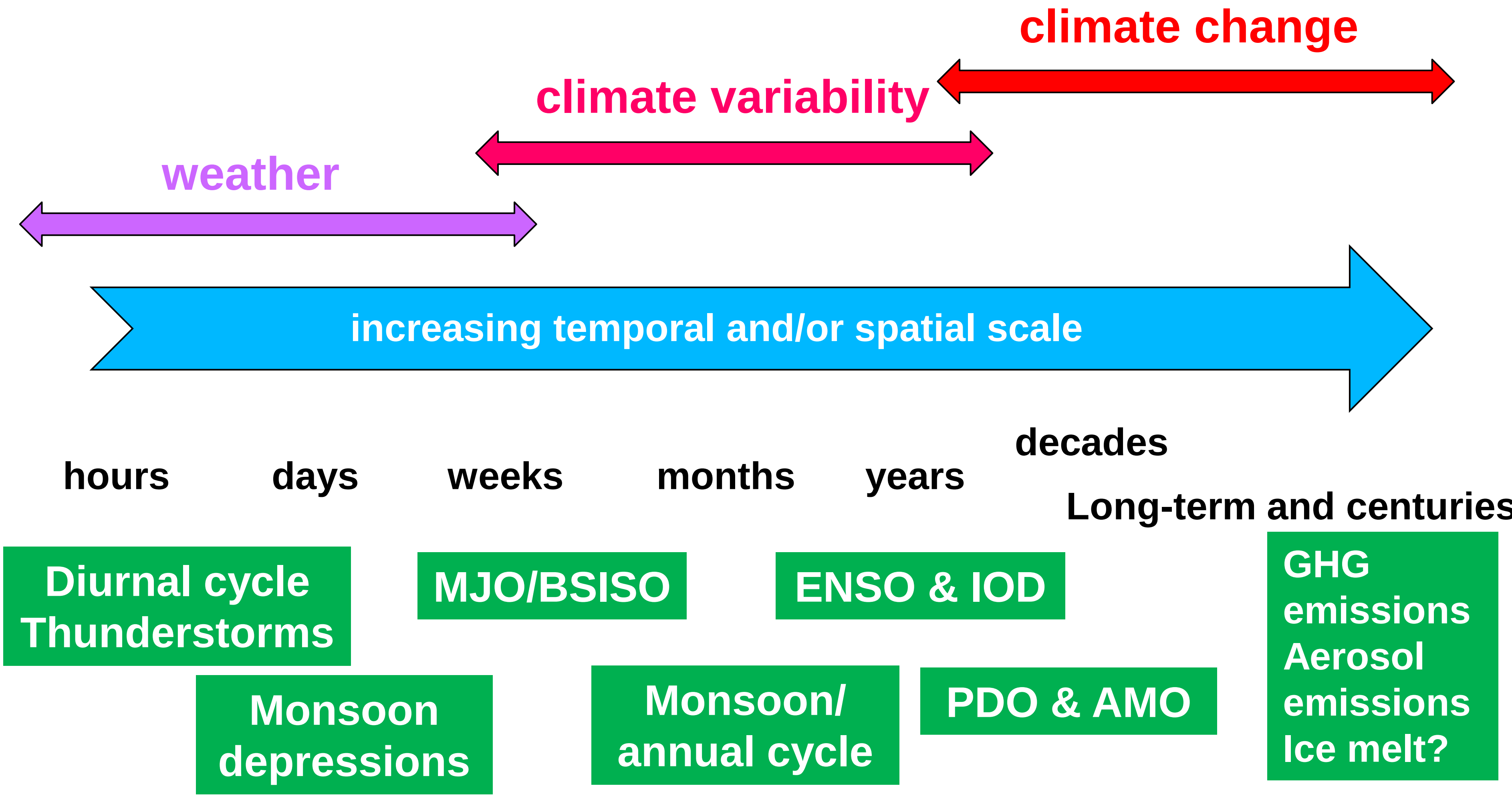
Monsoon deep convection: S&T interaction, Cloud & Radiation feedback





Bony et al. 2015 Nature Geoscience

Space and time scales in the monsoon



Courtesy: Andy Turner

We focus on the monsoon responses to external forcing agents

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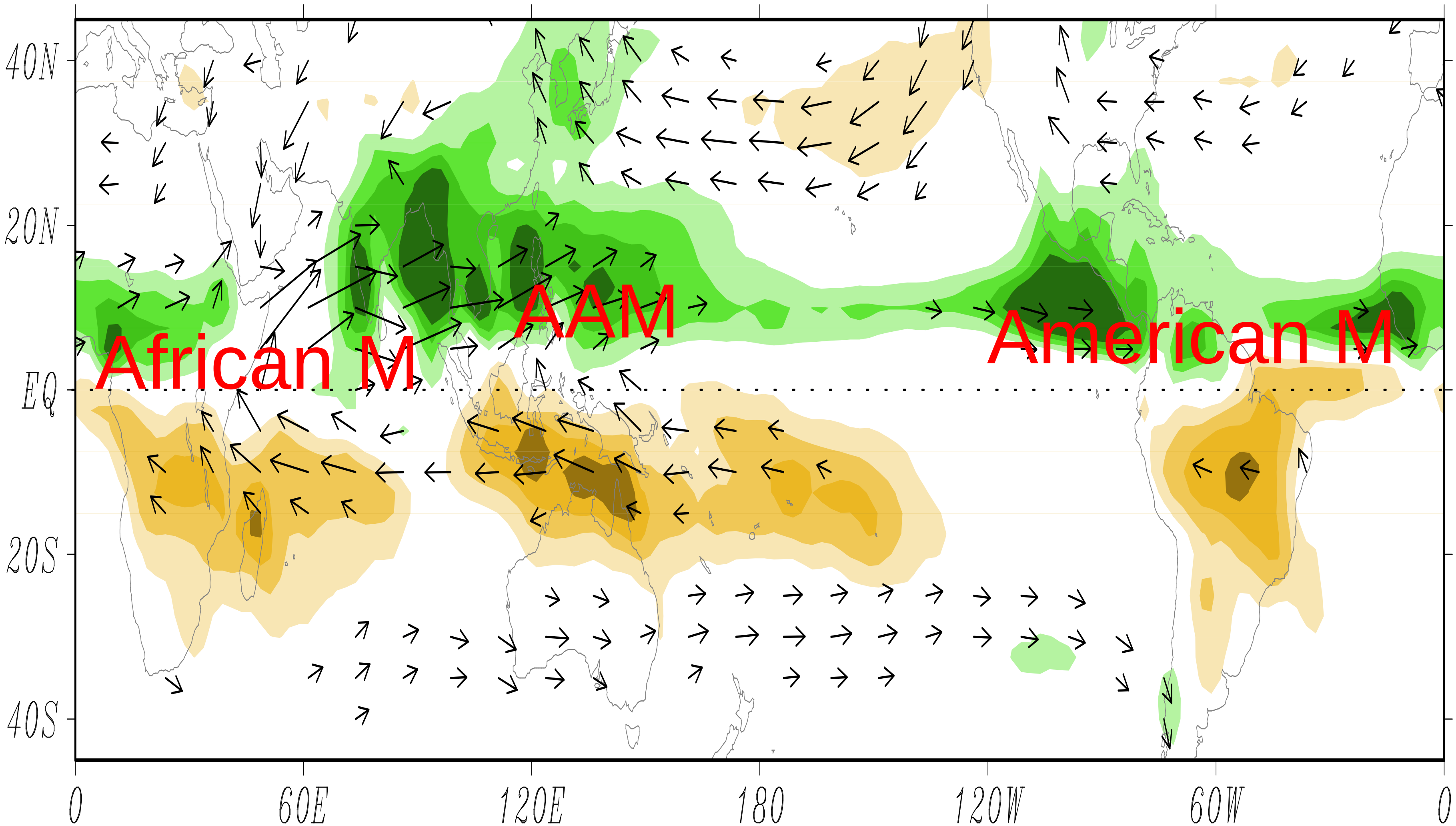
Global Monsoons



JJA –DJF UV850 & Precipitation

Monsoon Prec. Intensity and Domain

1. Monsoon Prec. Intensity:

(a) Annual Range: Local summer Minus Local Winter Prec.

AR (Annual Range) = PR_{JJA}-PR_{DJF} (in North Hemisphere)

PR_{DJF}-PR_{JJA} (in South Hemisphere)

(b) Area averaged local summer Pr at each grid within the present monsoon domain

NHMI: NH-JJA “monsoon” precipitation

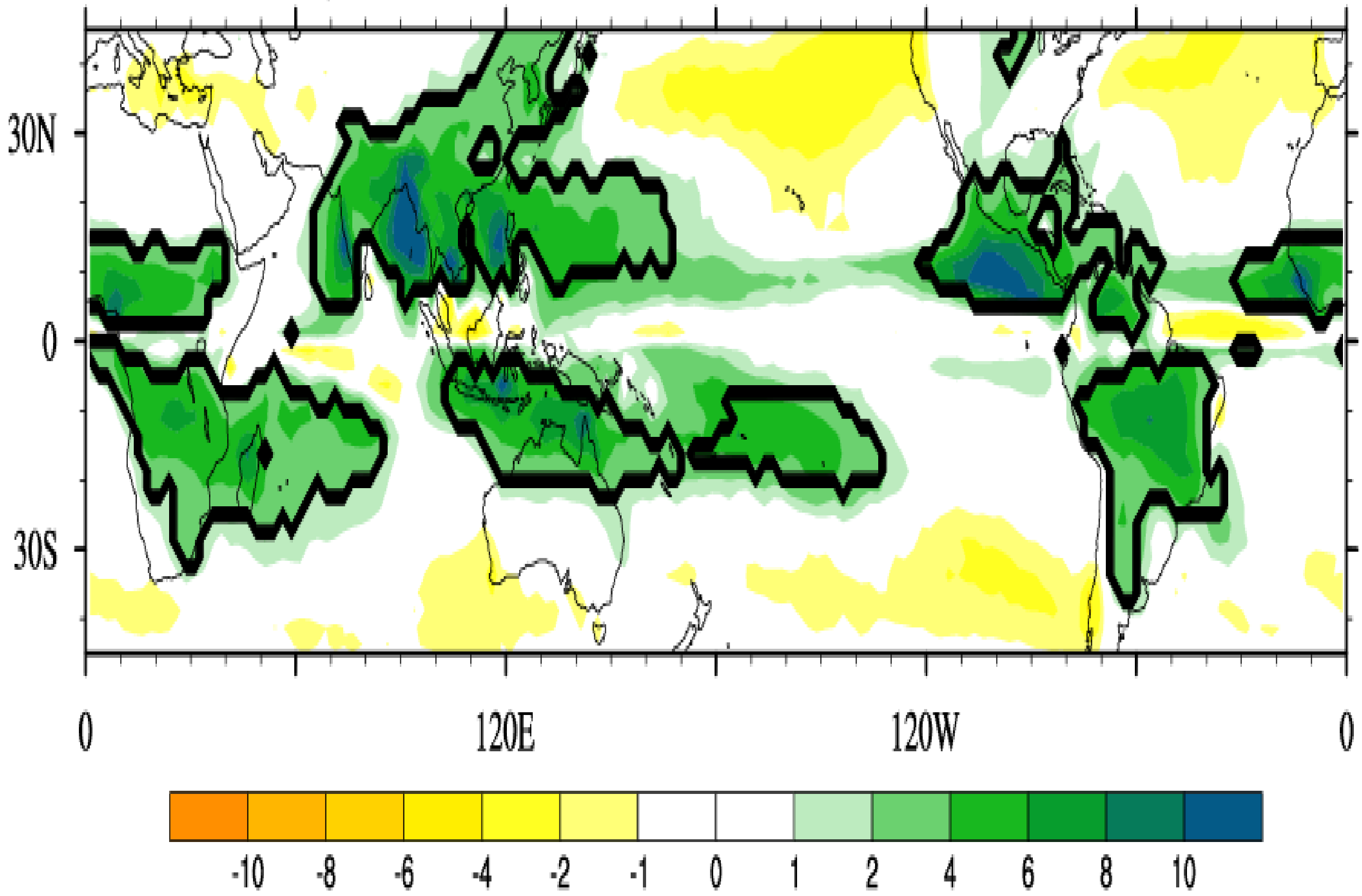
SHMI: SH-DJF “monsoon” precipitation

GMI: NHMI + SHMI

2. Monsoon Domain： AR >180mm and >35% Total annual rainfall

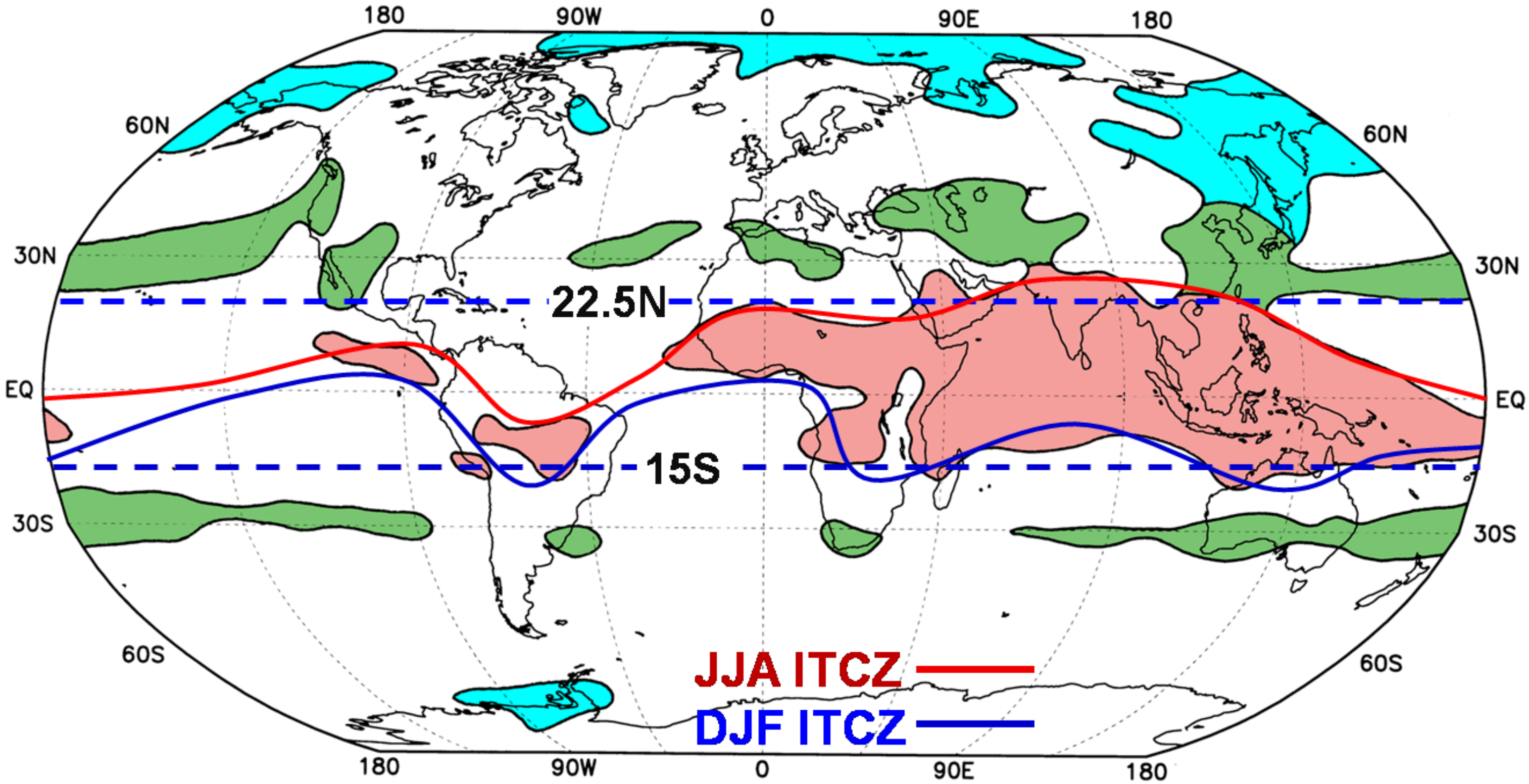
(Wang and Ding 2006 GRL)

Global monsoon domains defined by rainfall



(Wang and Ding 2006 GRL)

Global monsoon domains defined by wind

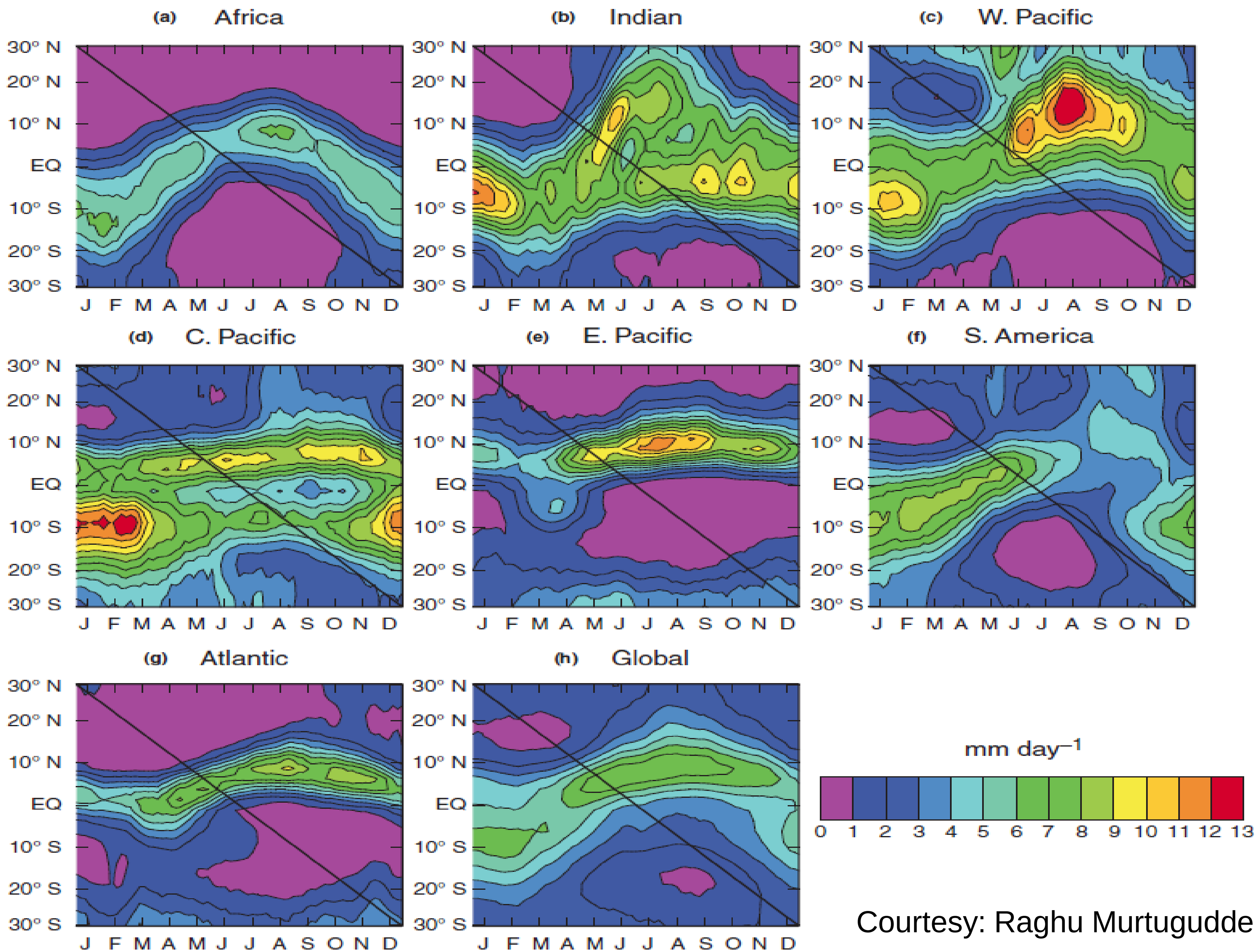


tropical monsoon
subtropical monsoon
temperate-frigid monsoon

Defined based on wind

Li and Zeng (2003,2005)

Seasonal cycles of regional monsoon rainfall



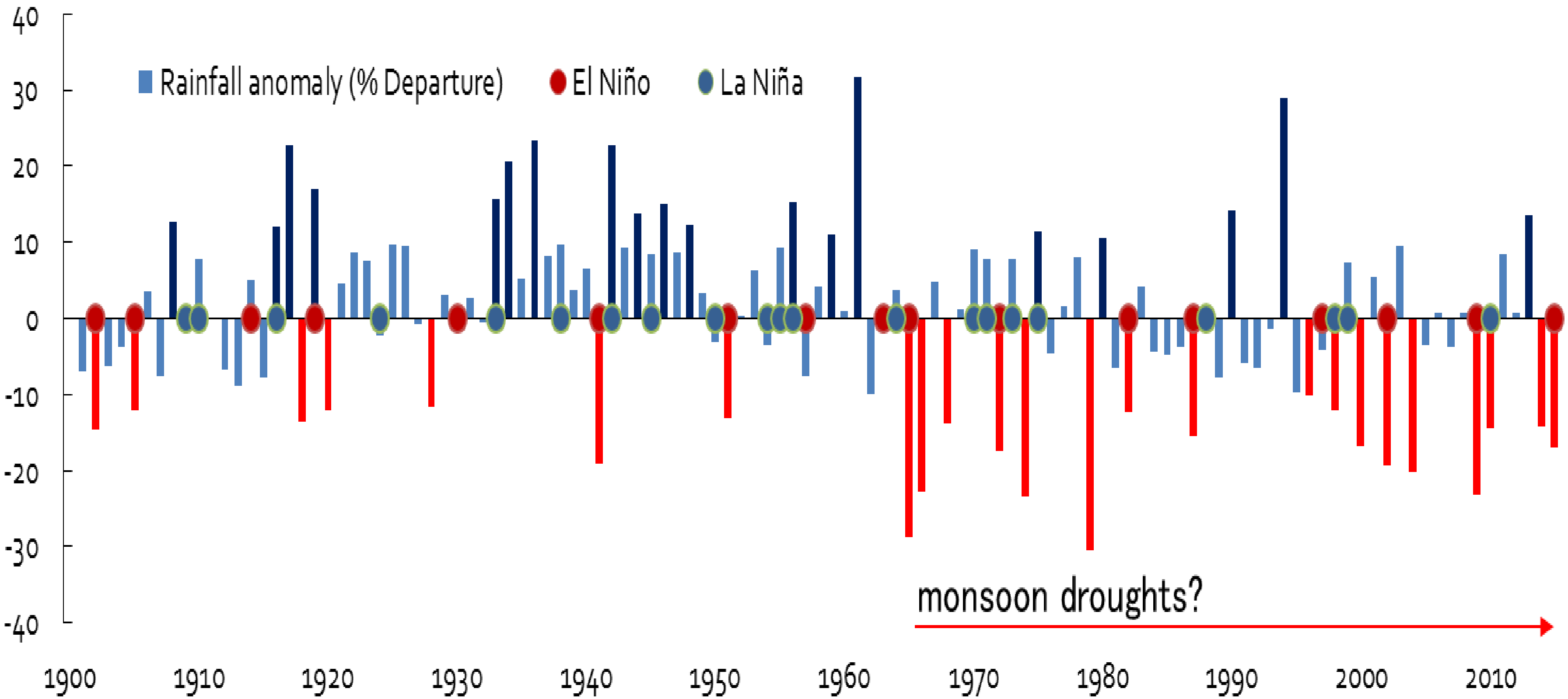
Courtesy: Raghu Murtugudde


Global monsoon changes
Photo by Fu Yunfei

Coordination among regional monsoons

- Each regional monsoon has its own characteristics due to its specific land-ocean configuration and orography, and due to differing feedback processes internal to the coupled climate system.
- There is coordination among regional monsoons: brought about by the annual cycle of the solar heating.
- There are connections in the global divergent circulation and thereby global monsoons: due to mass conservation.

The downward trend in the ISMR



Courtesy: Roxy Mathew Koll

The downward trend in the ISMR

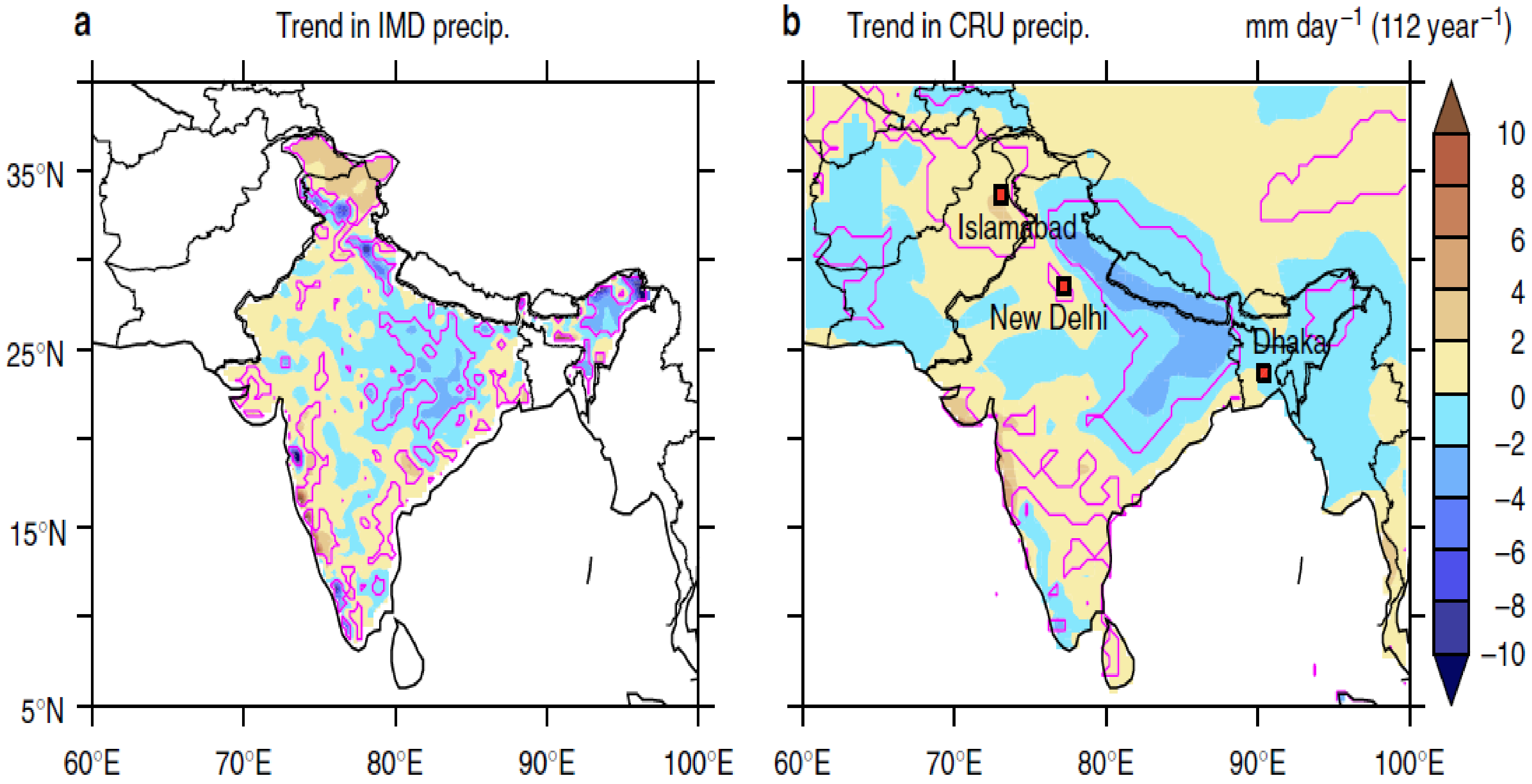
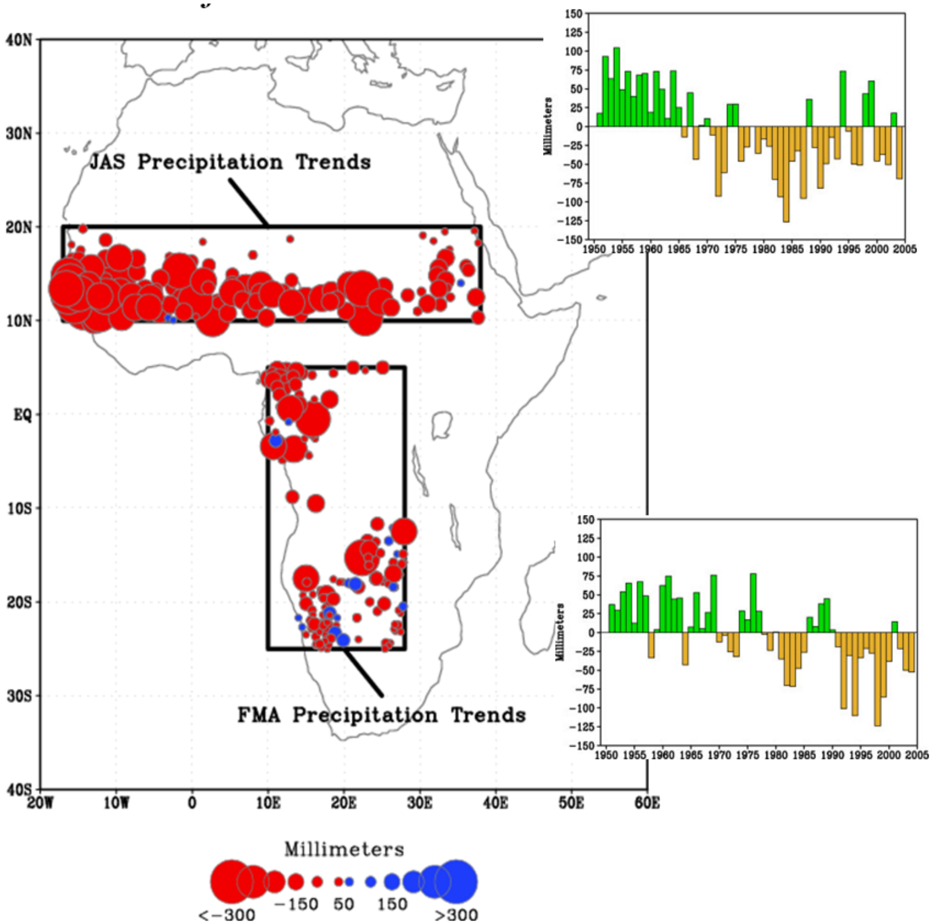


Figure 1 | Summer monsoon precipitation trends for the years 1901-2012. Observed trend in precipitation (mm day $^{-1}$ 112 year $^{-1}$) in (**a**) IMD and (**b**) CRU datasets, during June-September, for the years 1901-2012. Contours denote regions significant at the 95% confidence level.

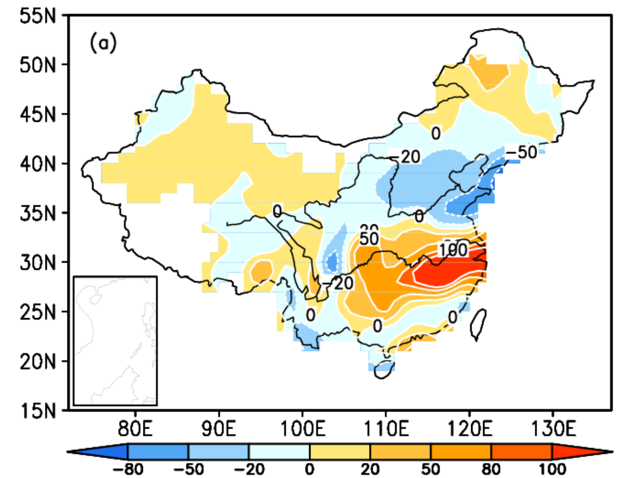
Roxy et al. 2015, Nature Communications

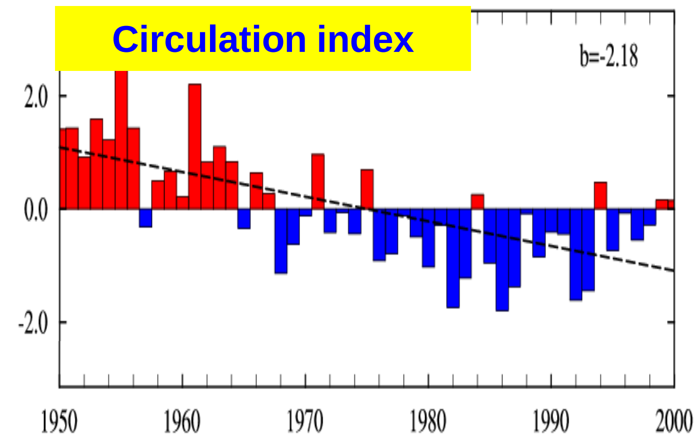
Downward trends in East Asian and African monsoons

African rainfall



E Asian rainfall

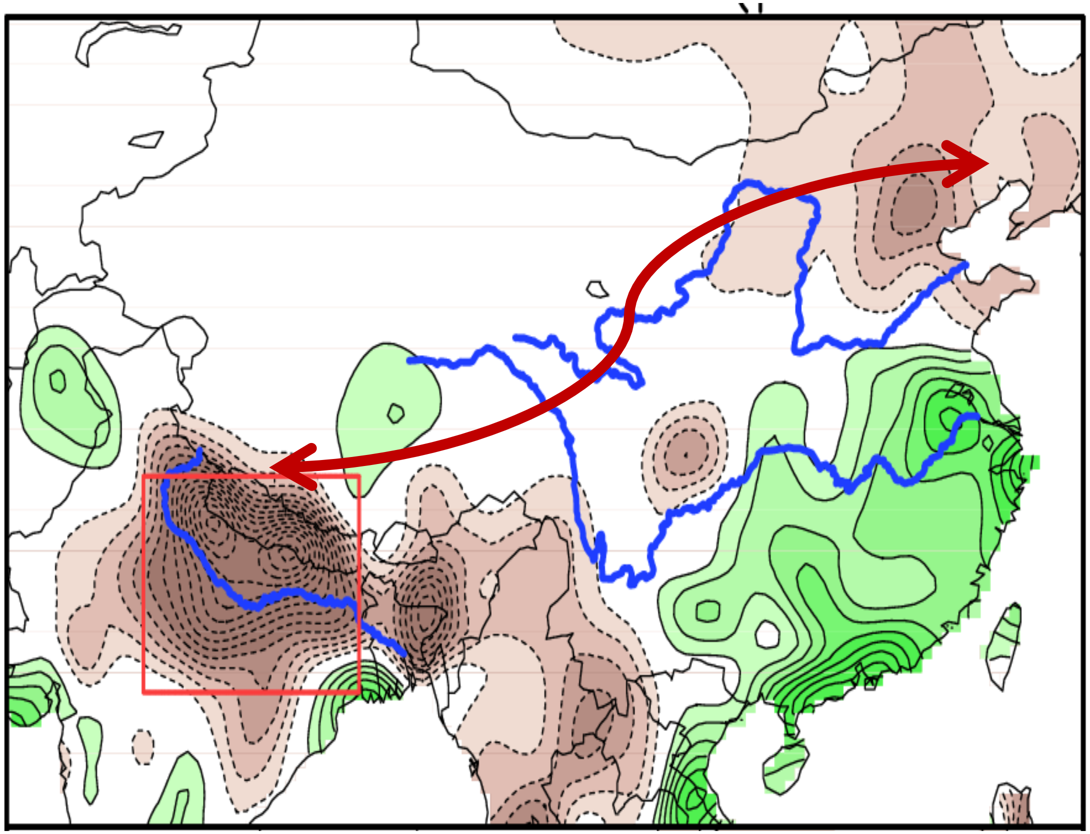




Hoerling et al. (2006) J. Climate

Zhou et al. (2009) Meteorologische Zeitschrift

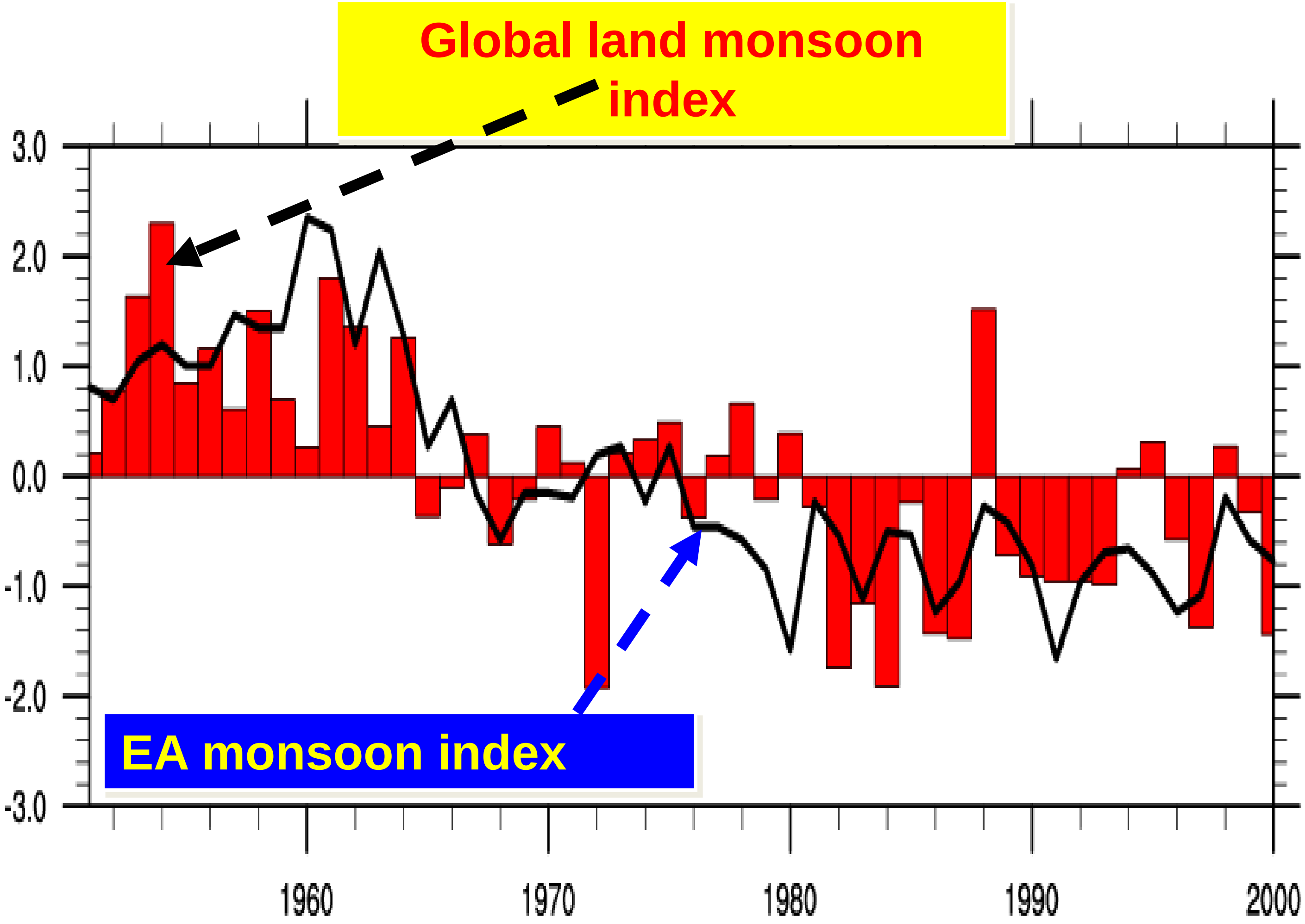
Trends of S. Asia and E. Asia summer rainfall



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.

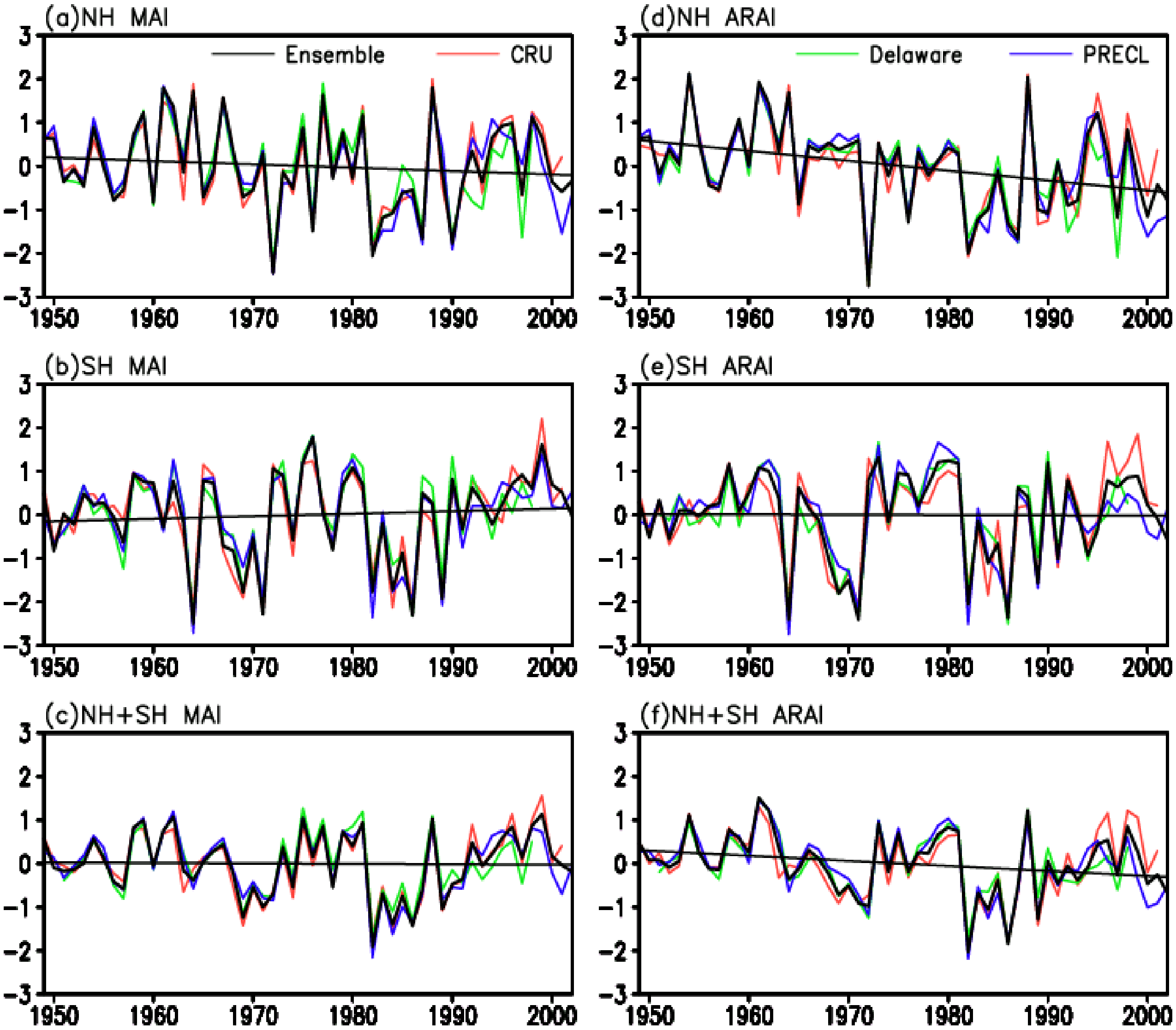
Nigam Sumant, Yongjian Zhao, Alfredo Ruiz-Barradas, **Tianjun Zhou**, 2015: The South-Flood North-Drought Pattern over Eastern China and the Drying of the Gangetic Plain, 437-359pp (Chapter 22) in: ***Climate Change: Multidecadal and Beyond***, edited by Chih-Pei Chang, Michael Ghil, Mojib Latif, John M. Wallace, 2015 World Scientific Publishing Co.

Changes of East Asian and global monsoon



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

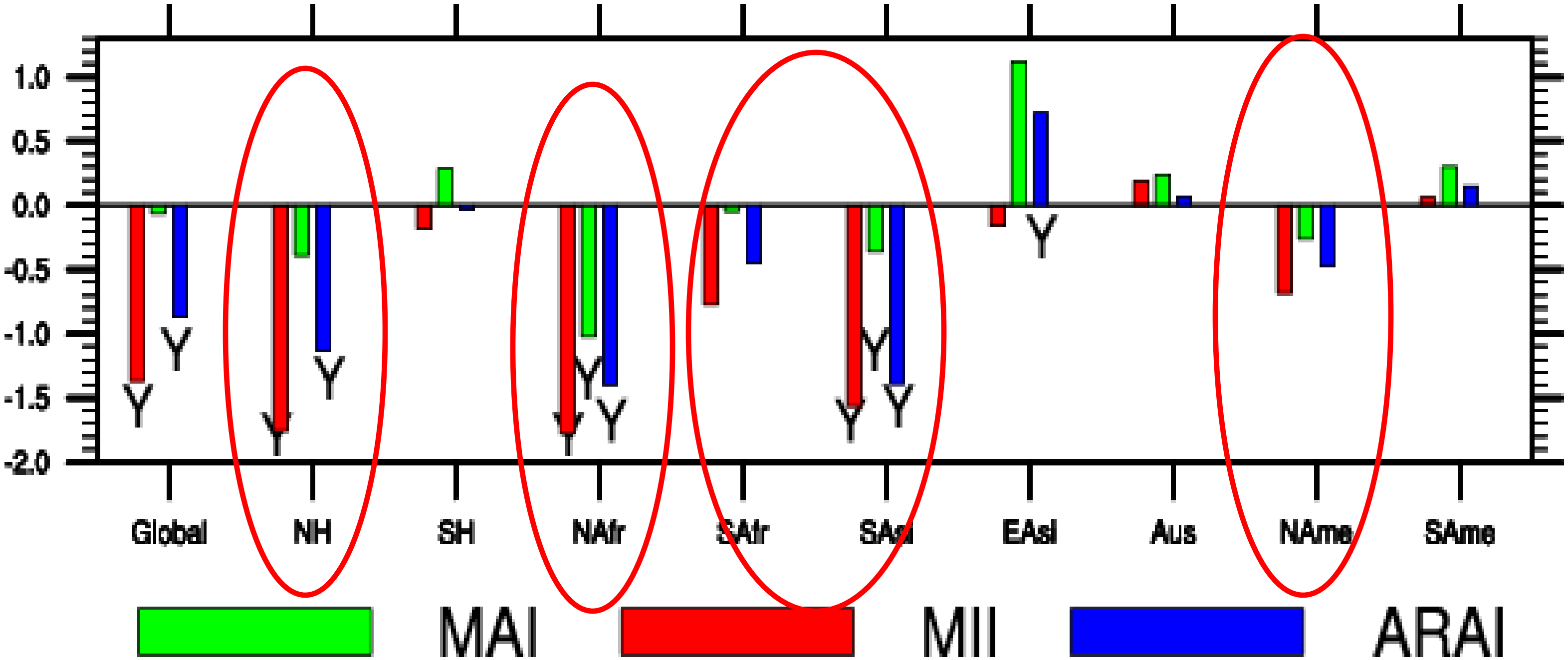
Changes of land monsoon area and total rainfall (1948-2003)



Zhou T, L. Zhang, and H. 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**

Regional monsoon rainfall changes

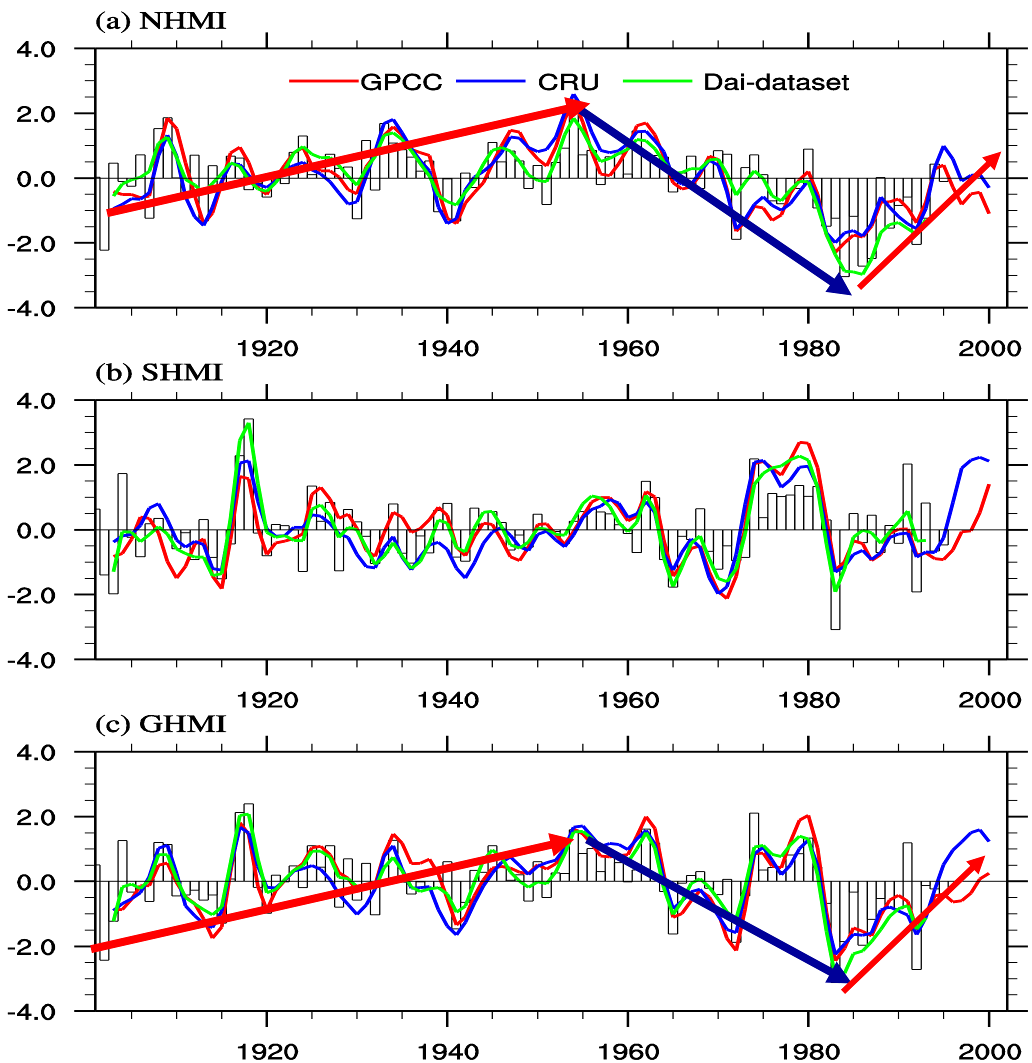
Trends of monsoon rainfall Area, intensity, and amount
(1948-2003)



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

(Zhou et al. 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)

Changes of global land monsoon precipitation

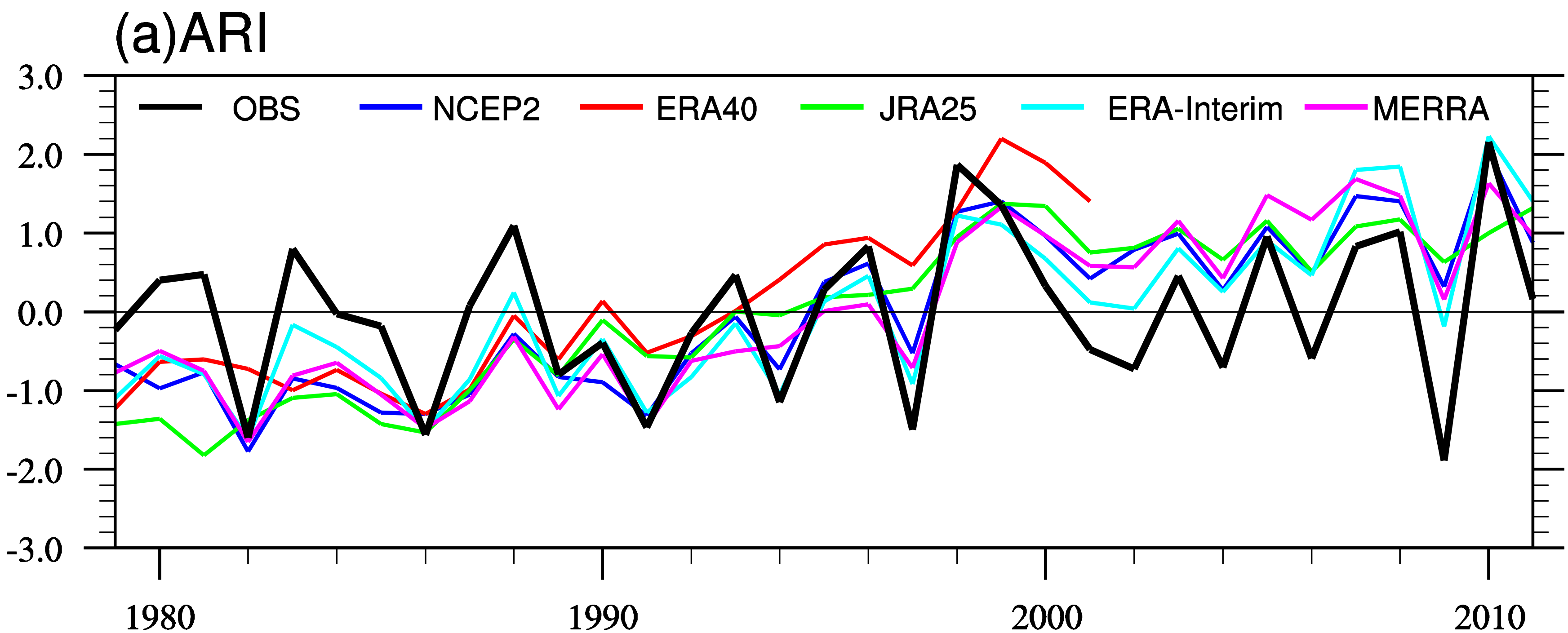


Global and NH land monsoon:

1) upward trend during 1901-1950s (95% confidence)
2) downward trend from 1950s to 1980s(95% confidence)
3) Recovering since the 1980s

(Zhang and Zhou, 2011, Clim Dyn.)

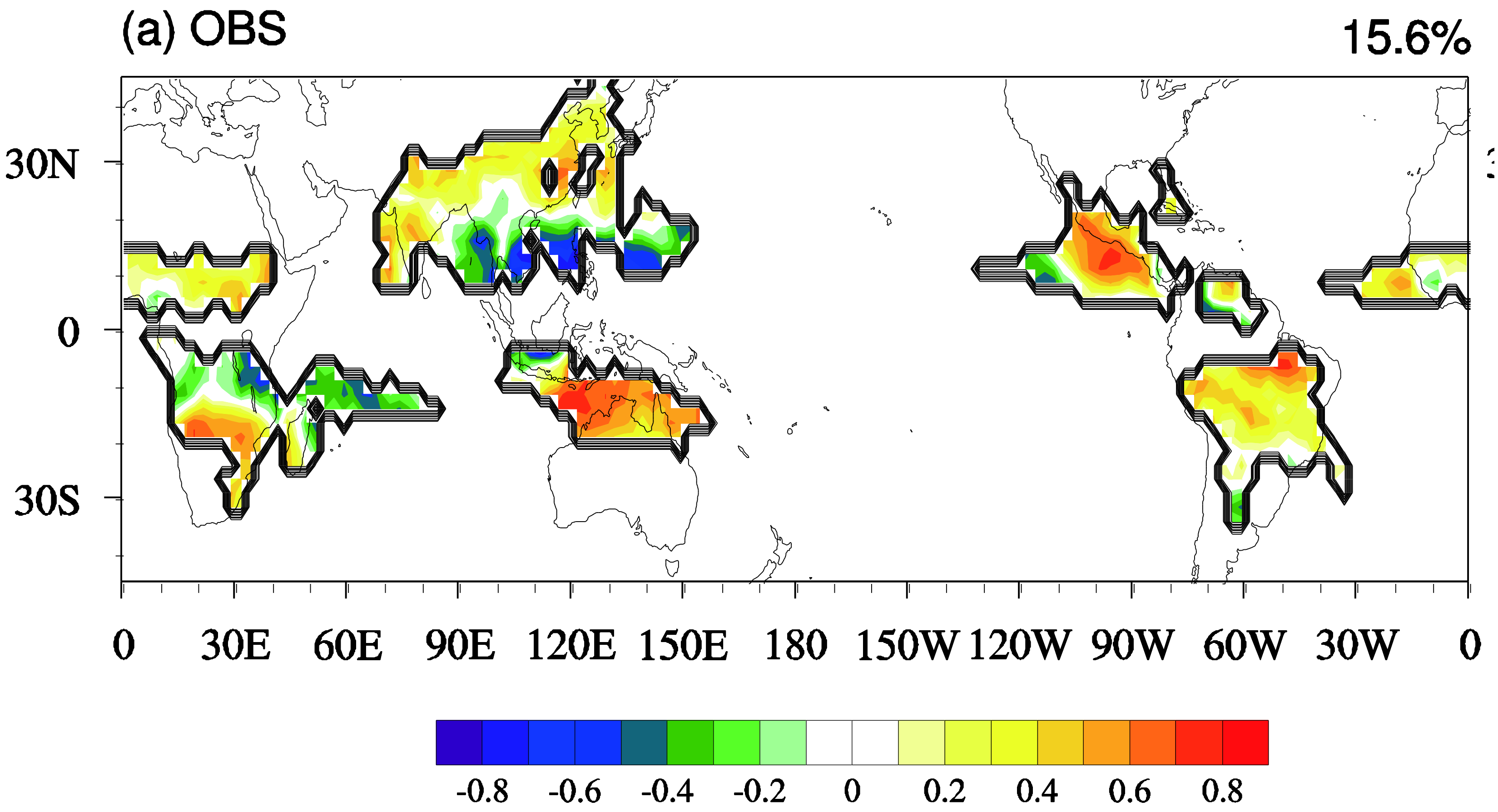
EOF PC1 of GM precipitation



- 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, ***Journal of Climate***, *27(3)*,1271-1289

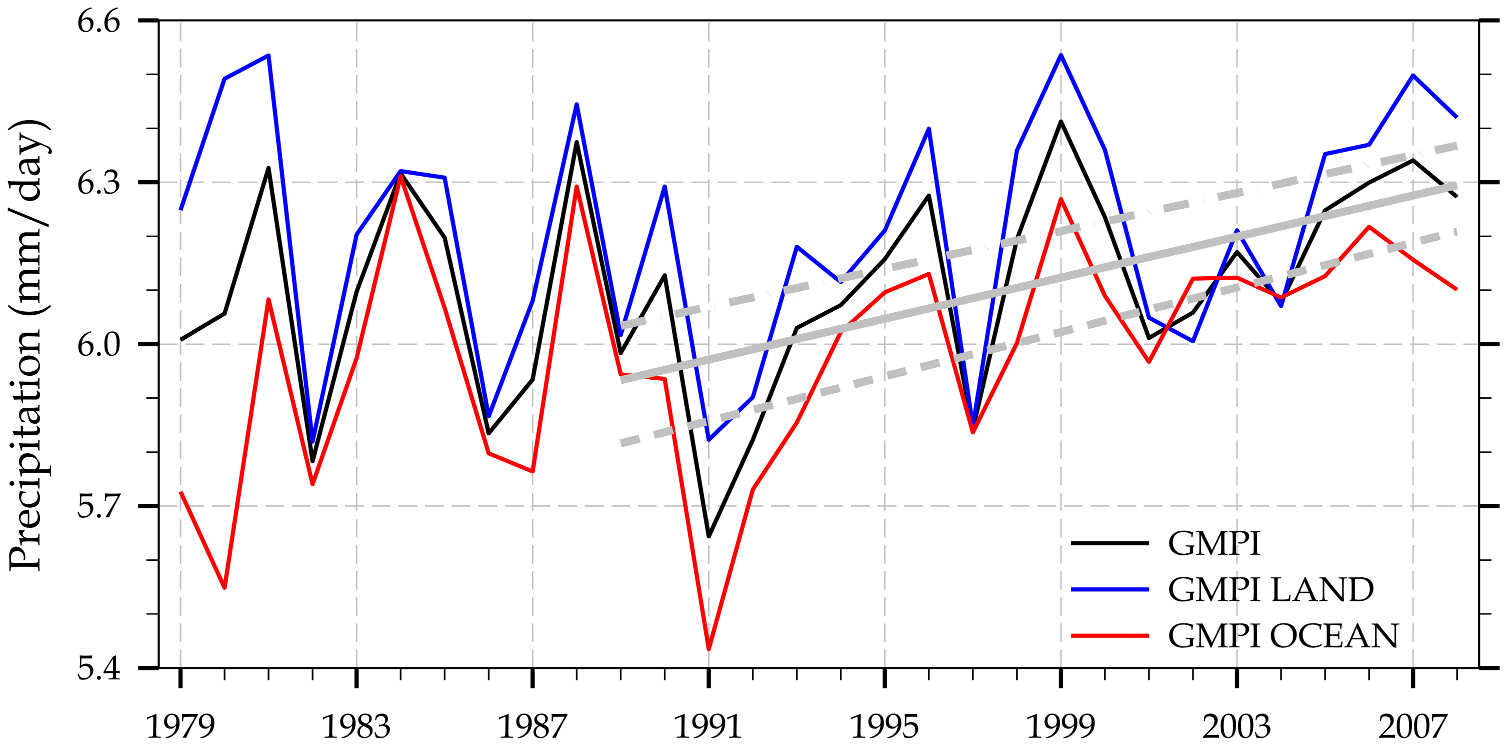
Pattern of GM precipitation trends



➢ All five reanalysis can reproduce the observed positive anomalies in Australian monsoon region and northern part of Asian region.

Lin R., T. Zhou, Y. Qian, 2014: Evaluation of Global Monsoon Precipitation Changes based on Five Reanalysis Datasets, ***Journal of Climate***, *27(3)*,1271-1289

Changes of global land monsoon precipitation



<u>global land and ocean</u> : upward trend for 1979-2009 (95% confidence level)

(Wang et al. 2012 Clim Dyn.)

Point # 1

- The GM saw decadal variability in the 20th century, with a strengthening trend prior to the 1950s, a weakening trend during the 2nd half of the century.
- An enhanced trend of Global land monsoon is witnessed since the 1980s up to present.

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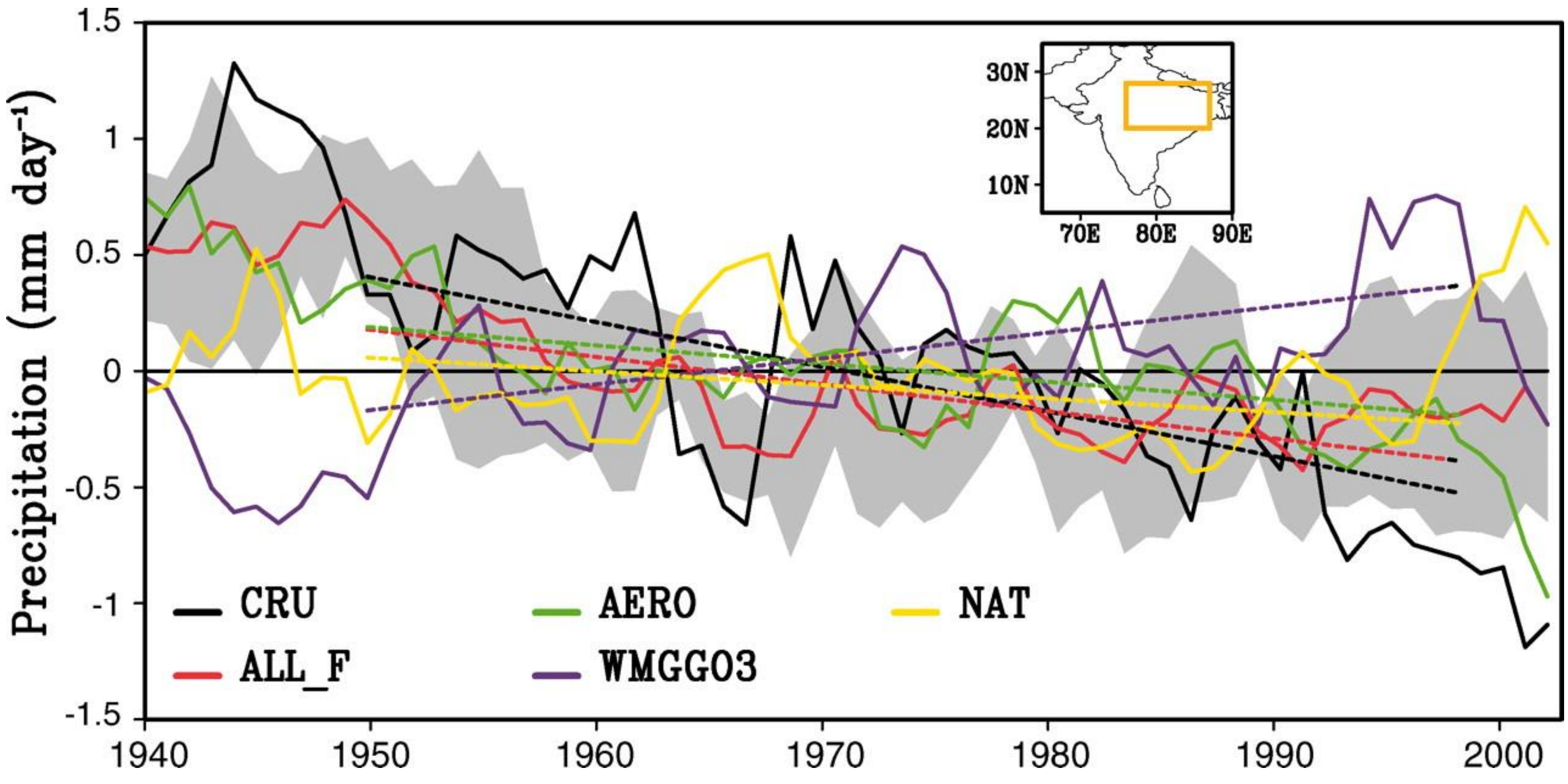
GHG & Aerosols

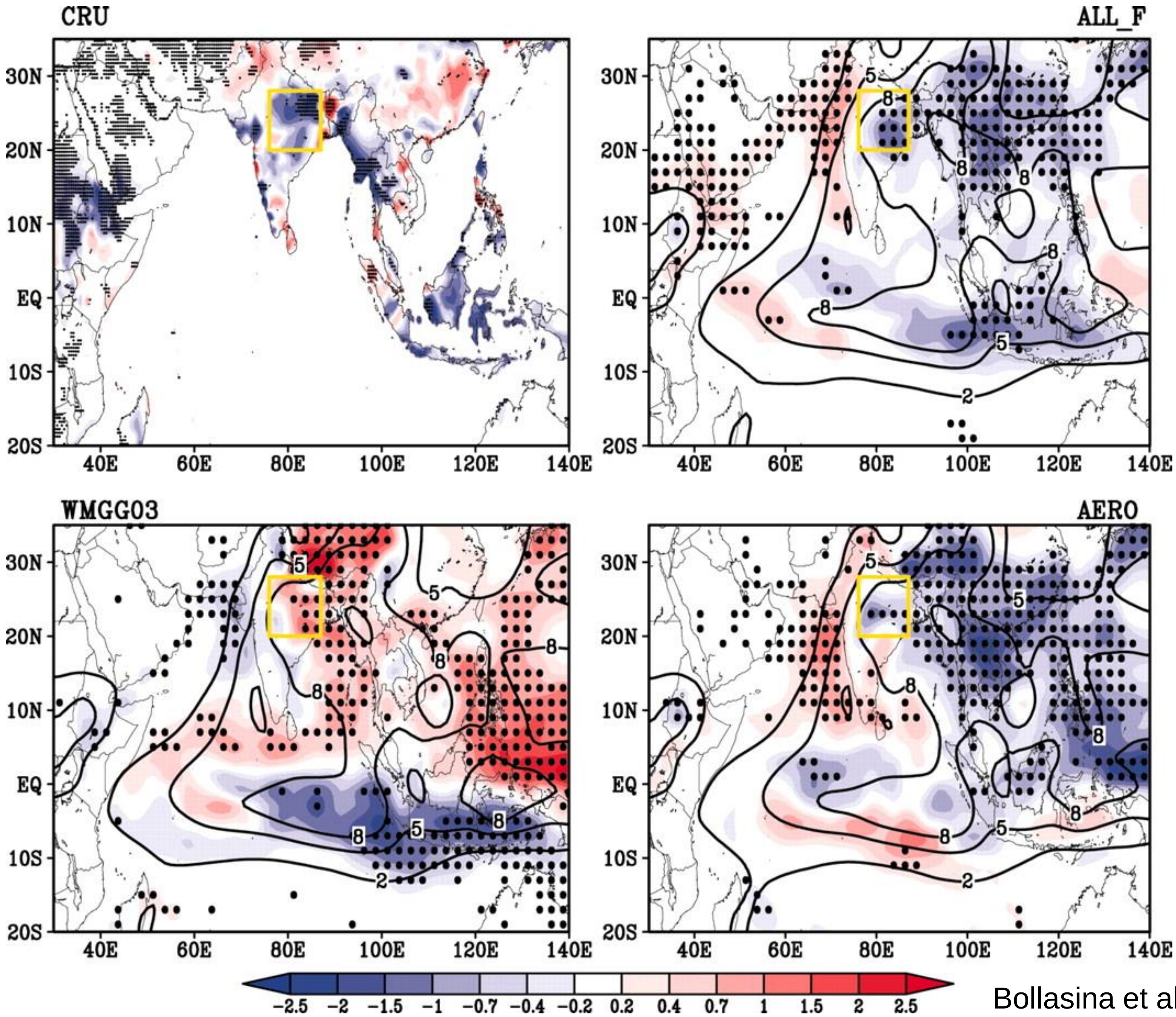
Five-year running mean June-September average precipitation anomalies over central-northern India



The red, green, blue, and yellow lines are for the ensemble-mean all-forcing (ALL_F), aerosol-only (AERO), greenhouse gases and ozone-only (WMGGO3), and natural forcing-only (NAT) CM3 historical integrations, respectively.

Bollasina et al. 2011 Science

Spatial patterns of the 1950–1999 least-squares linear trends of the June-September average precipitation [mm day^{-1} (50 years)$^{-1}$]



Bollasina et al. 2011 Science

Point # 2

- Observations show that South Asia underwent a widespread summertime drying during the second half of the 20th century, but it is unclear whether this trend was due to natural variations or human activities.
- A series of climate model experiments is used to investigate the South Asian monsoon response to natural and anthropogenic forcings. The observed precipitation decrease can be attributed mainly to human-influenced aerosol emissions.
- The drying is a robust outcome of a slowdown of the tropical meridional overturning circulation, which compensates for the aerosol-induced energy imbalance between the Northern and Southern Hemispheres.
- These results provide compelling evidence of the prominent role of aerosols in shaping regional climate change over South Asia.

Bollasina et al. 2011 Science


How about the East Asian summer monsoon ?

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*

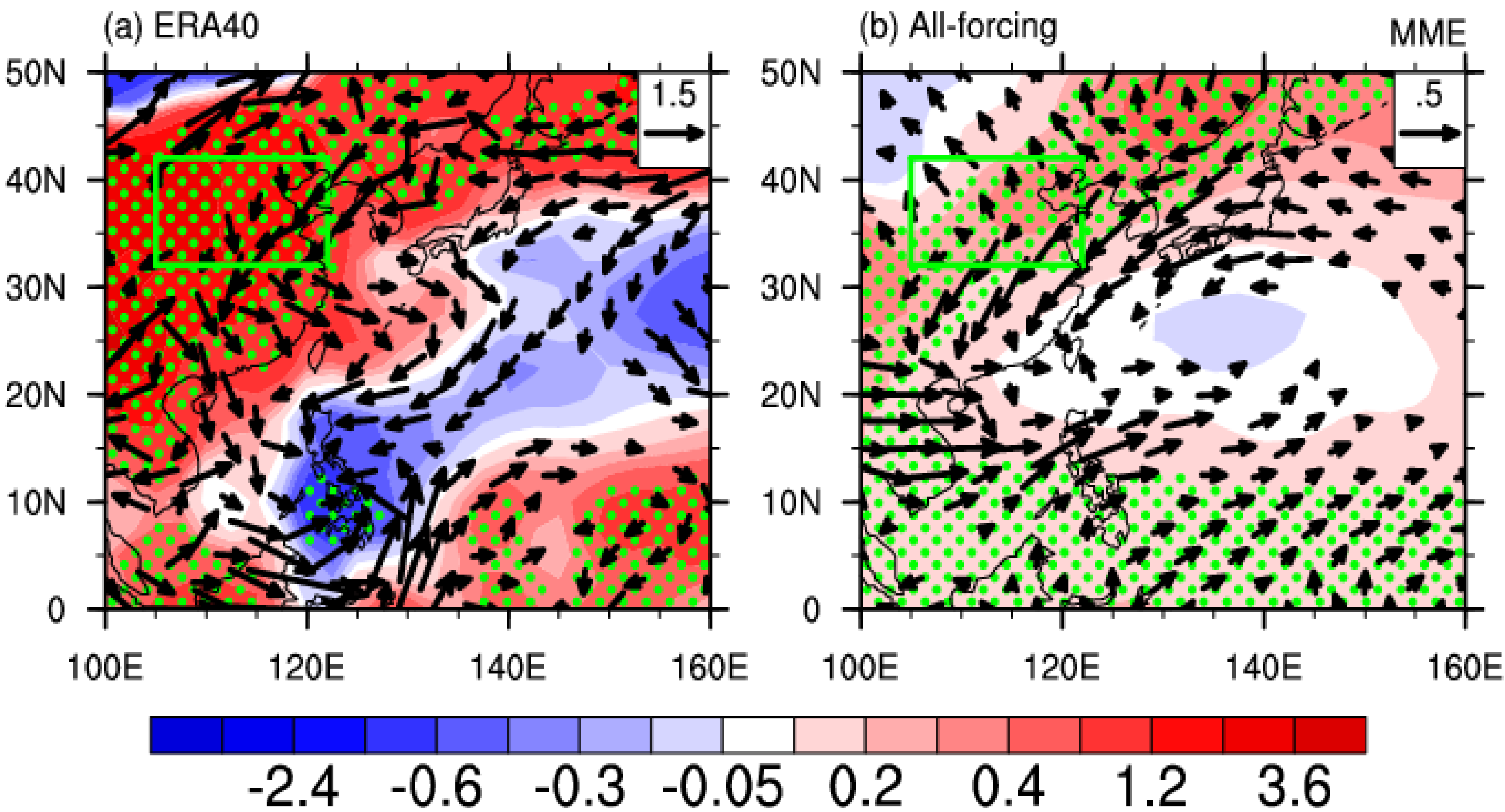
Details of three sets of CMIP5 experiments

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*

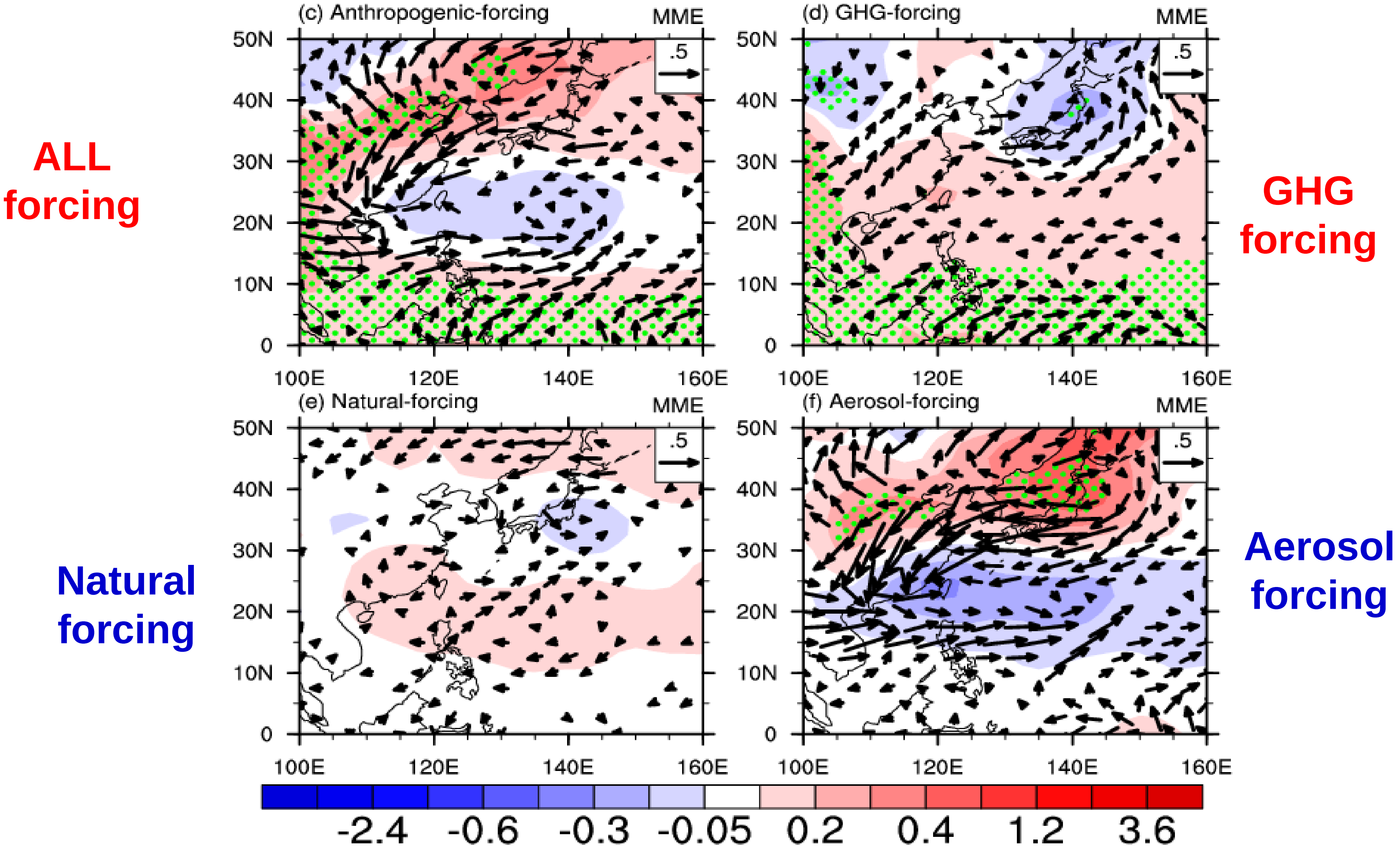
Linear trends of SLP and 850 hPa winds (1958-2001)



ERA40 **MME of CMIP5**

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*

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*

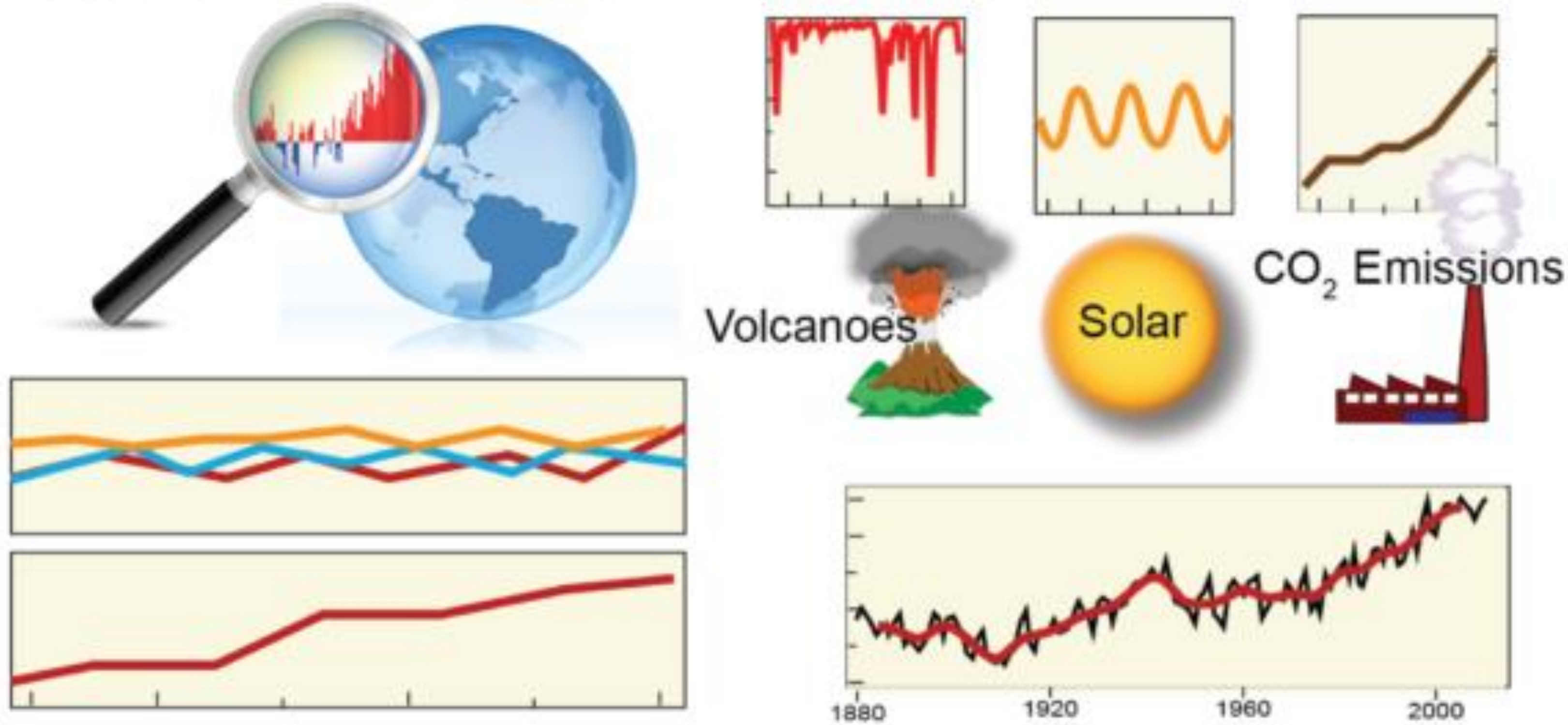
Point # 3

- The observed weakening trend of low-level EASM circulation during 1958–2001 is partly and weakly reproduced under all-forcing runs. A comparison of separate forcing experiments reveals that the aerosol forcing plays a primary role in driving the weakened low-level monsoon circulation.
- The preferential cooling over continental East Asia caused by aerosol affects the monsoon circulation through reducing the land-sea thermal contrast and results in higher sea level pressure over northern China.
- The increasing GHG forcing is favorable for an enhanced monsoon circulation.
- The models still failed in the simulation of monsoon rainband changes.

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*

D&A of monsoon rainfall response to external forcings

Detection and Attribution as Forensics



Detection: finding something out of the ordinary – a "signal" emerging from the noise

Attribution: determining the cause of the detected trend

Observation and Model Data

- ◆**Observation**: daily Rain-gauge data from CMA
- ◆**CMIP5 20c historical climate simulation**:
  - ✓ALL forcing run :11 models, 54 ensemble members
  - ✓ANThropogenic foring: 6 models,26 members
  - ✓GHG forcing: 10 models,34 members
  - ✓AA forcing: 8 models, 22 members
  - ✓NATural forcing: 11 models,37 members
- ◆PIcontrol: 10 models, ~ 6000 yrs

Ma, S., **T. Zhou**, D. Stone, D. Polson, A. Dai, P. Stott, H. Storch, Y. Qian, C. Burke, P. Wu, L. Zou, and A. Ciavarella, 2017: Detectable anthropogenic shift toward heavy precipitation over eastern China. ***Journal of Climate***, 30, 1381-1396

Optimal fingerprinting Method

Optimal fingerprinting--Total least squares detection method

$$y = \sum_{i=1}^{m} (X_i - \upsilon_i)\beta_i + \upsilon_0$$

•y, observed trend, a rank-n vector, where n is the number of daily precipitation intensity bins, with n=20 used in this analysis**;**

•X**,** fingerprints or anomalous signals, model simulated climate responses to external forcings, a matrix with one column for each external climate forcing**;**

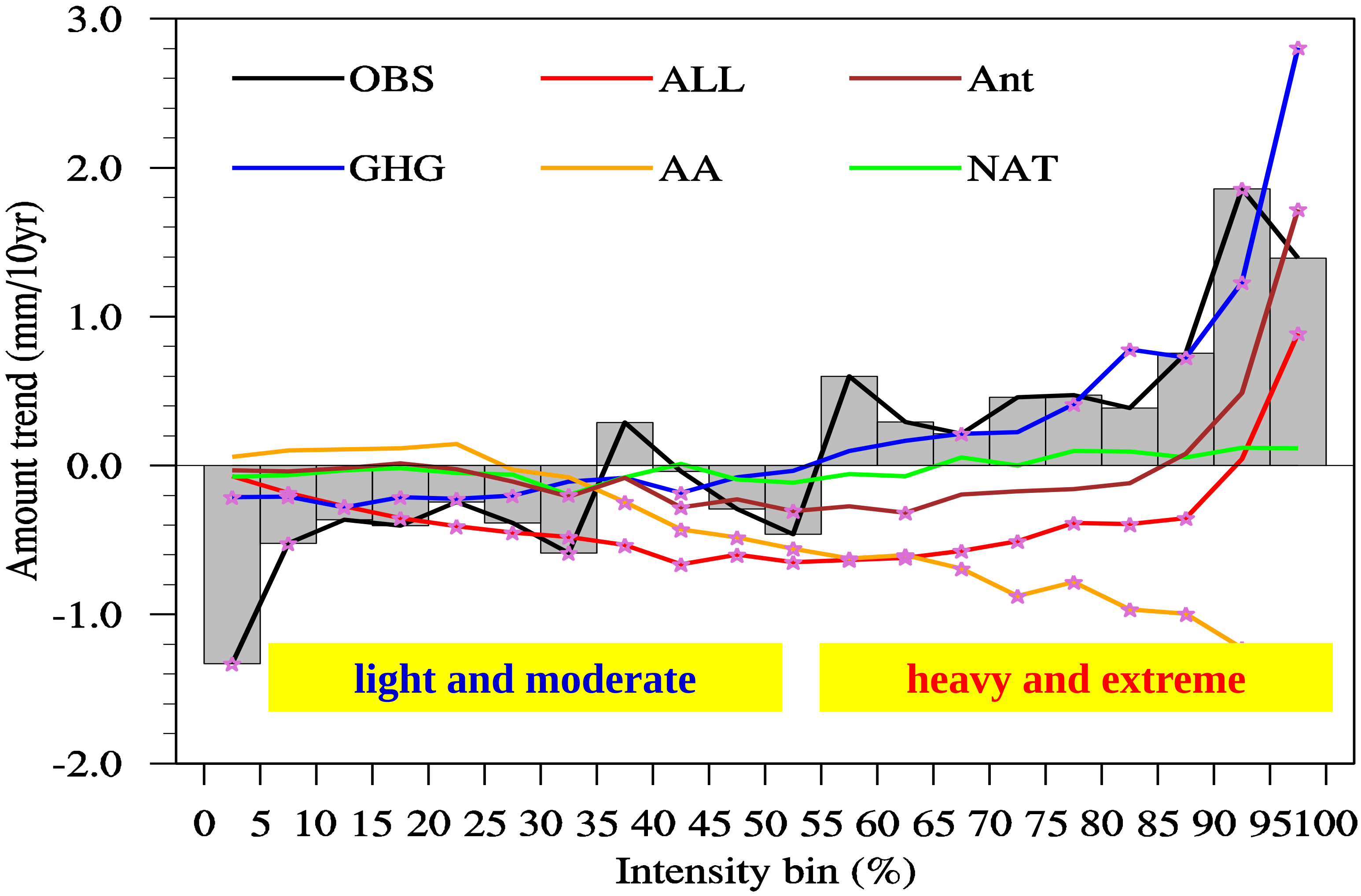
•**υi, sampling noise**, estimated from the preindustrial control simulations and intra-ensemble differences;

•υ0, noise in the observations

•β, scaling factors, inconsistent with 0 indicate a detectable signal, consistent with 1, then the model-simulated response patterns are consistent with the observed changes.

Ma, **Zhou**, Stone, et al., 2017: Detectable anthropogenic shift toward heavy precipitation over eastern China. ***Journal of Climate***, 30, 1381-1396

Trend of PDF in precipitation amount

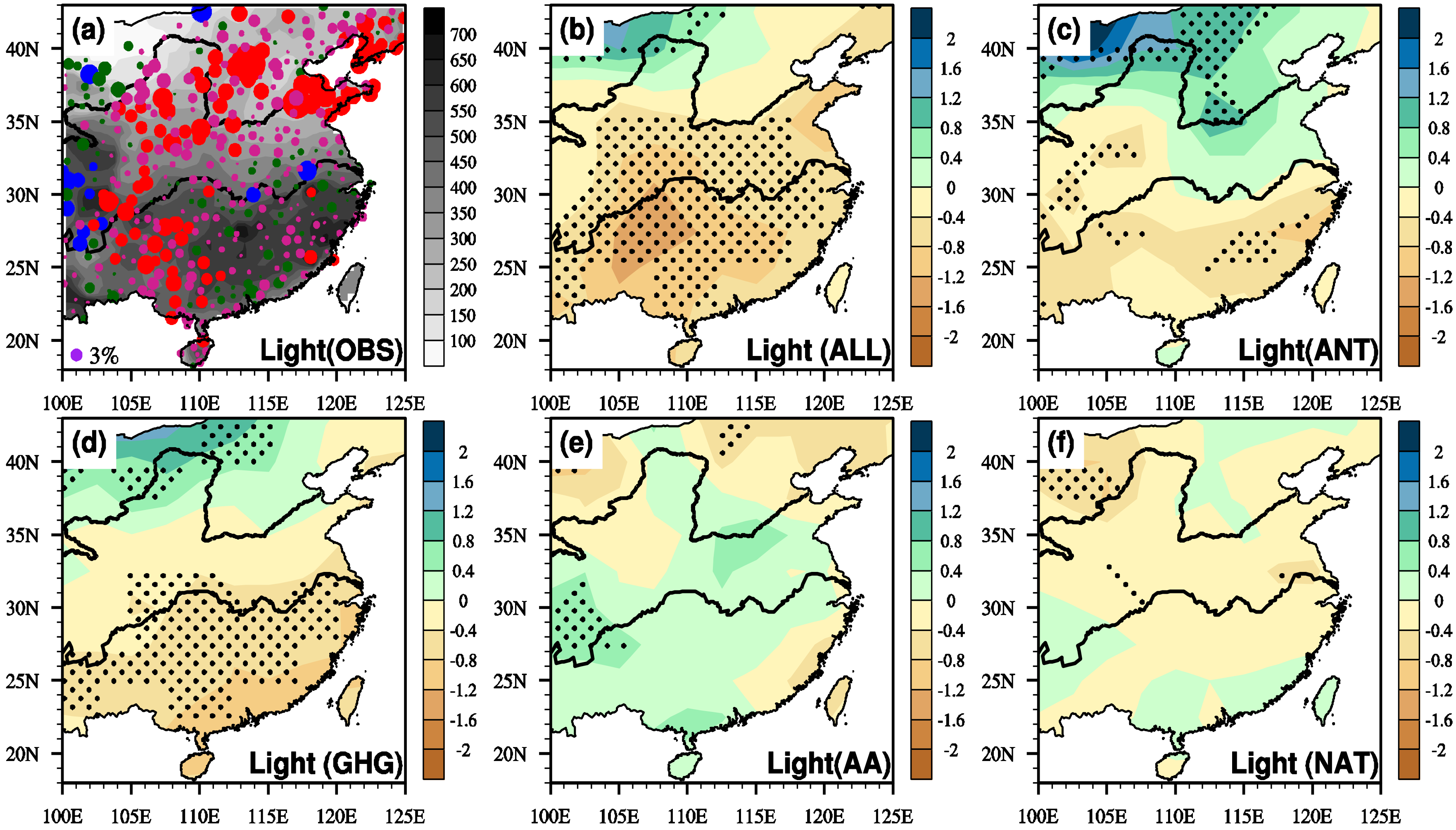


Observation: a shift toward heavier precipitation

Simulation: The observed shift is well simulated with anthropogenic forcings.

Ma, **Zhou**, Stone, et al., 2017: Detectable anthropogenic shift toward heavy precipitation over eastern China. ***Journal of Climate***, 30, 1381-1396

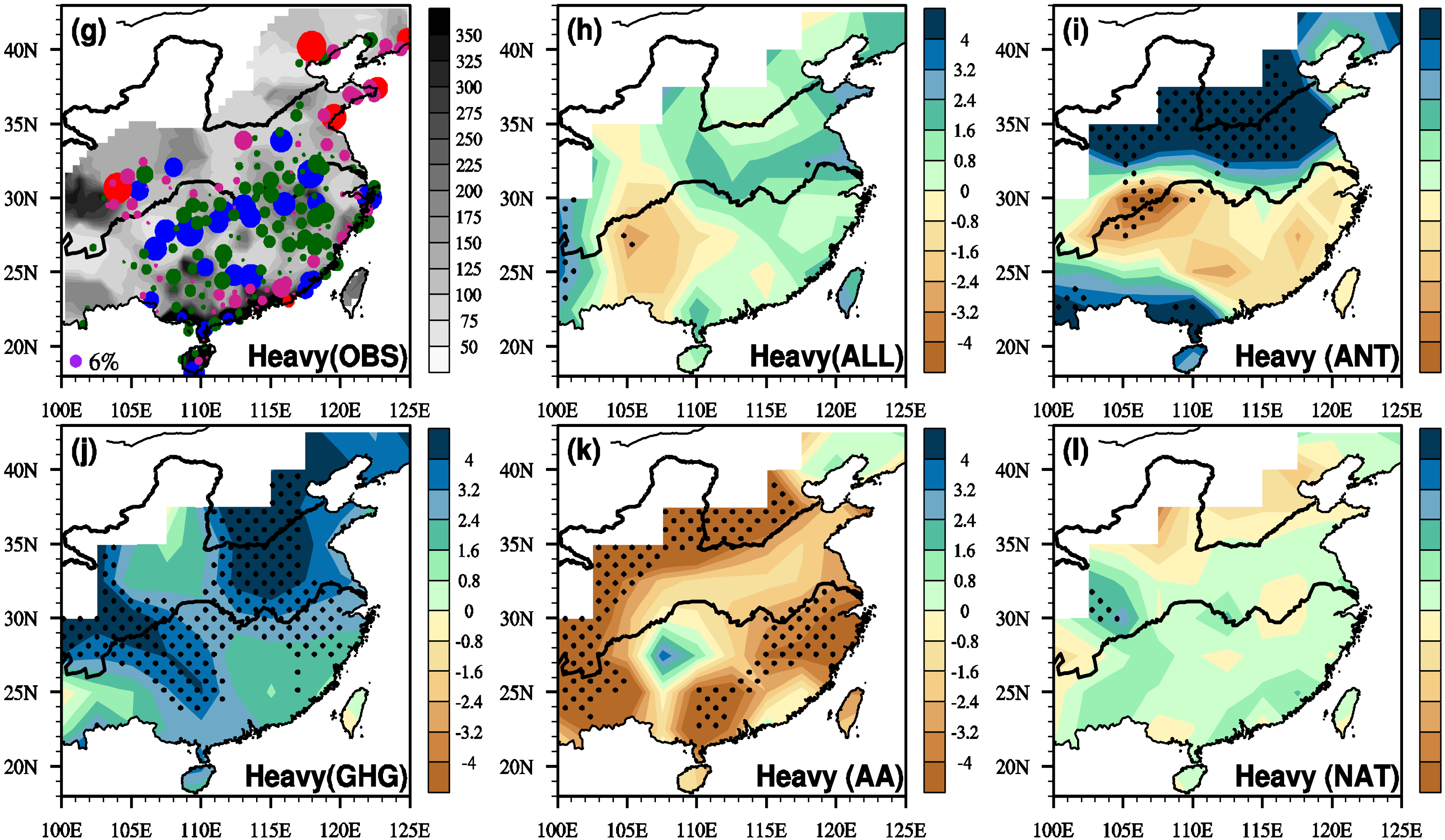
Linear trends of light precipitation



The observed decrease in light precipitation mainly come from the contribution of GHG forcing. Anthropogenic aerosols partly offset the contribution of the GHGs.

Ma, **Zhou**, Stone, et al., 2017: Detectable anthropogenic shift toward heavy precipitation over eastern China. ***Journal of Climate***, 30, 1381-1396

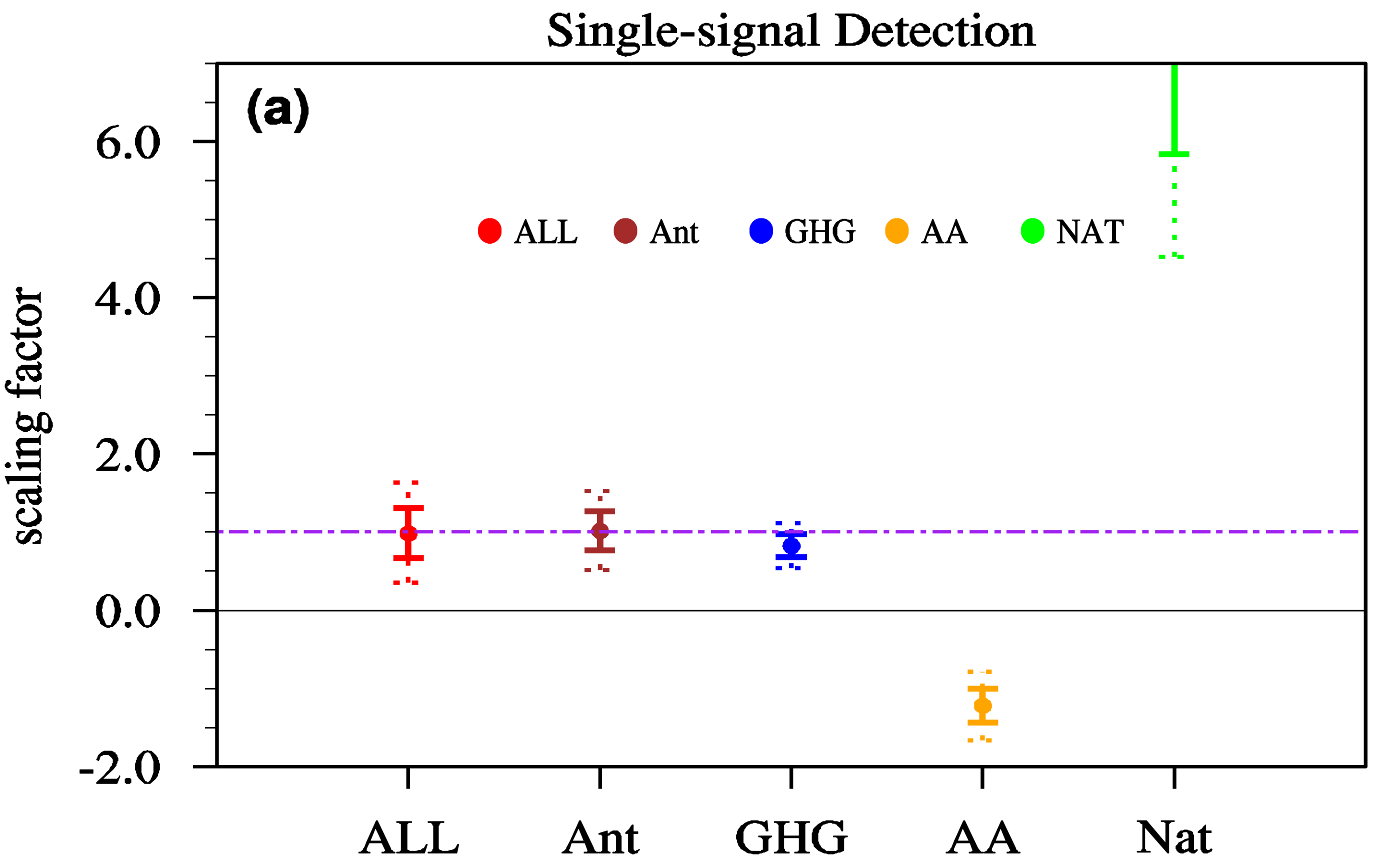
Linear trends of heavy precipitation



The observed increase of heavy precipitation is dominated by the GHG forcing.

Ma, **Zhou**, Stone, et al., 2017: Detectable anthropogenic shift toward heavy precipitation over eastern China. ***Journal of Climate***, 30, 1381-1396

Optimal detection



Solid symbols: best estimates of regression coefficients (β);

Solid error bars: 5-95% uncertainty ranges of β;

Dashed error bars: 5-95% uncertainty ranges of β when the internal variability is doubled.

- ANT forcing determines the forced changes in the ALL forcing run.
- The detected responses in ALL and ANT forcing runs are dominated by GHG forcing.

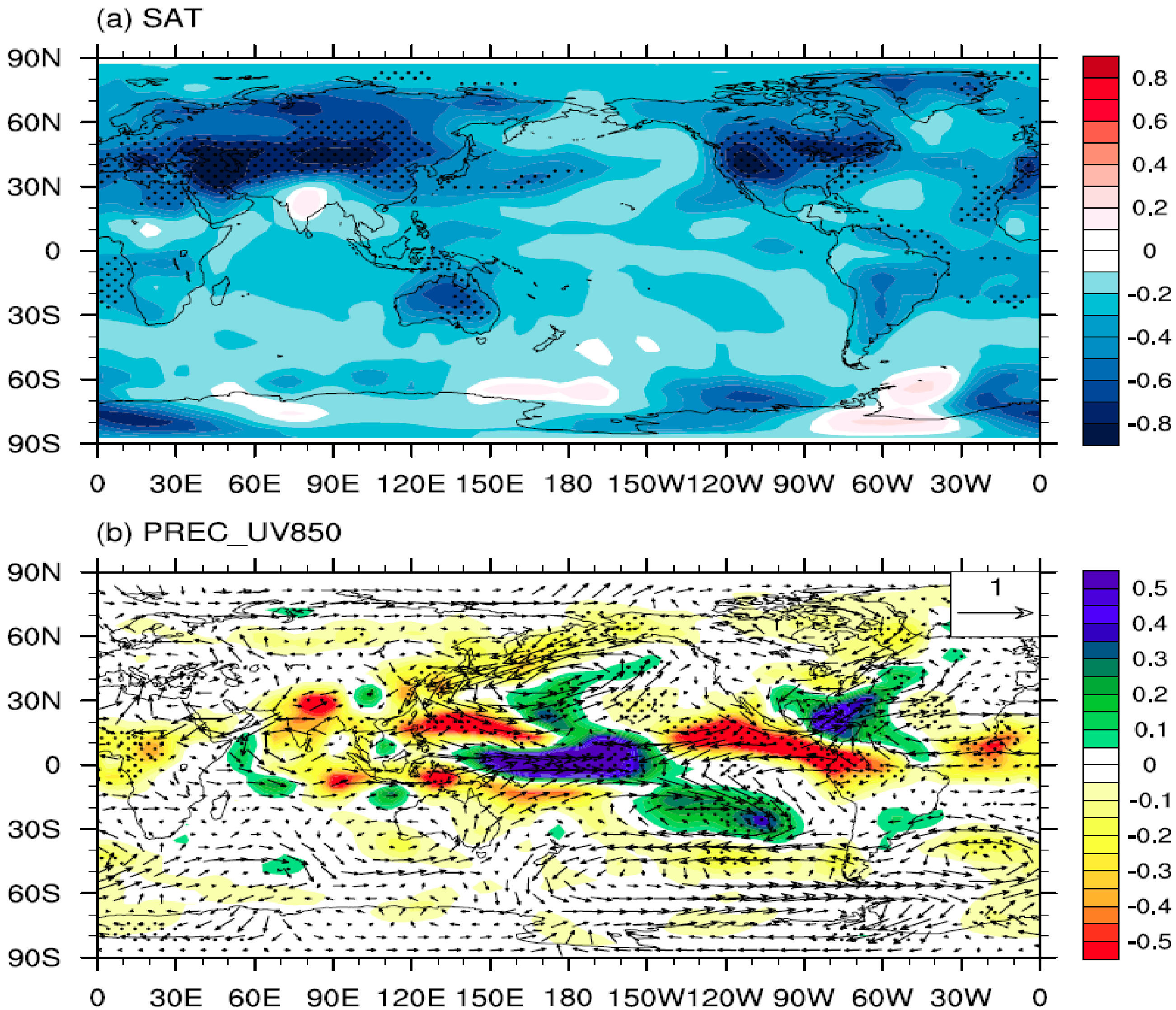
Ma, **Zhou**, Stone, et al., 2017: Detectable anthropogenic shift toward heavy precipitation over eastern China. ***Journal of Climate***, 30, 1381-1396

Point # 4

- The anthropogenic forcing has a detectable and attributable influence on the amount distribution of daily precipitation over EC during the second half of the 20th century.
- The observed shift from weak precipitation to intense precipitation is due primarily to the contribution of GHG forcing, with AA forcing offsetting some of the effects of the GHG forcing.
- Increasing of moisture and changes of monsoon circulation , resulting mainly from GHG-induced warming, favors heavy precipitation over eastern China.


Volcanic aerosols

Summer climate after large volcanic eruptions



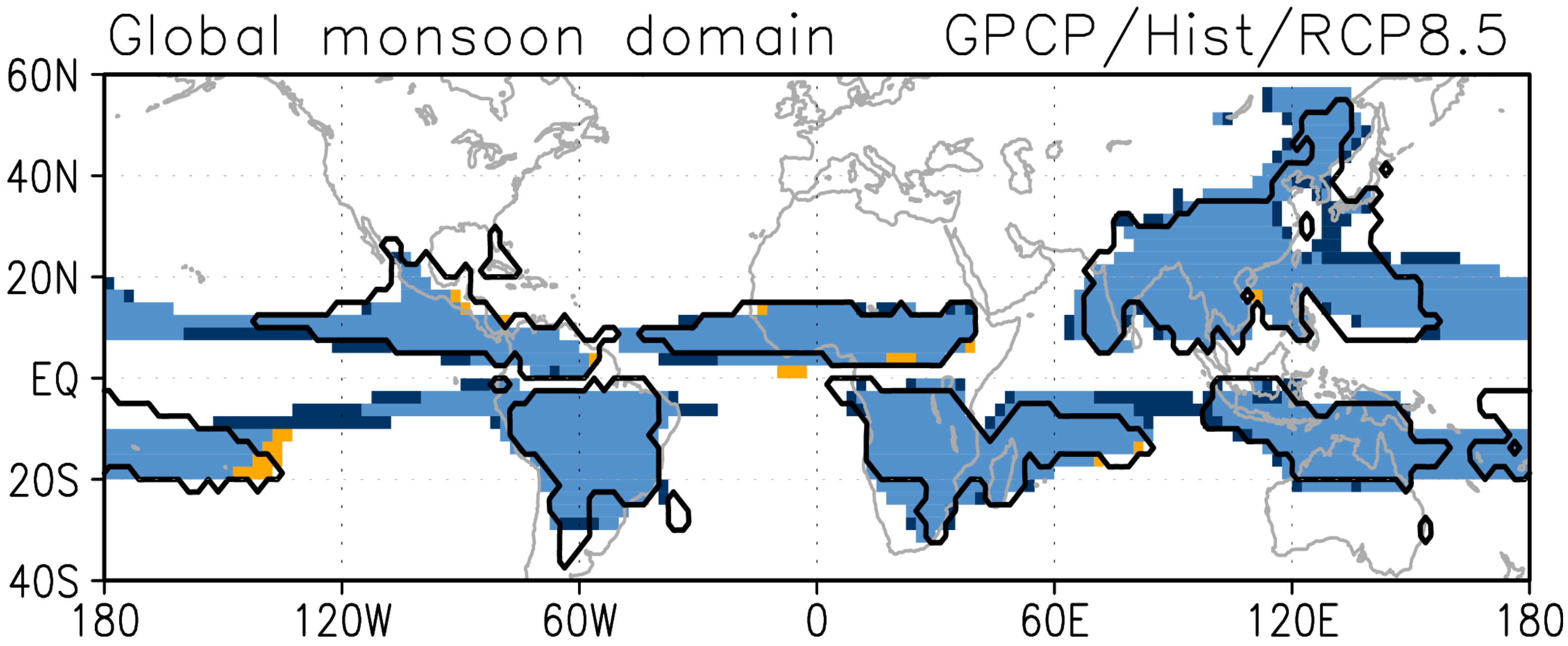
Man, W., **T. Zhou,** , J. H. Jungclaus, 2014: Effects of Large Volcanic Eruptions on Global Summer Climate and East Asian Monsoon Changes during the Last Millennium: Analysis of MPI-ESM simulations, ***Journal of Climate***, 27, 7394-7409

Changes under Global warming

Global Monsoon: Area (GMA)

Black Contour: GPCP **Shading: MME of 29 CMIP5 models**

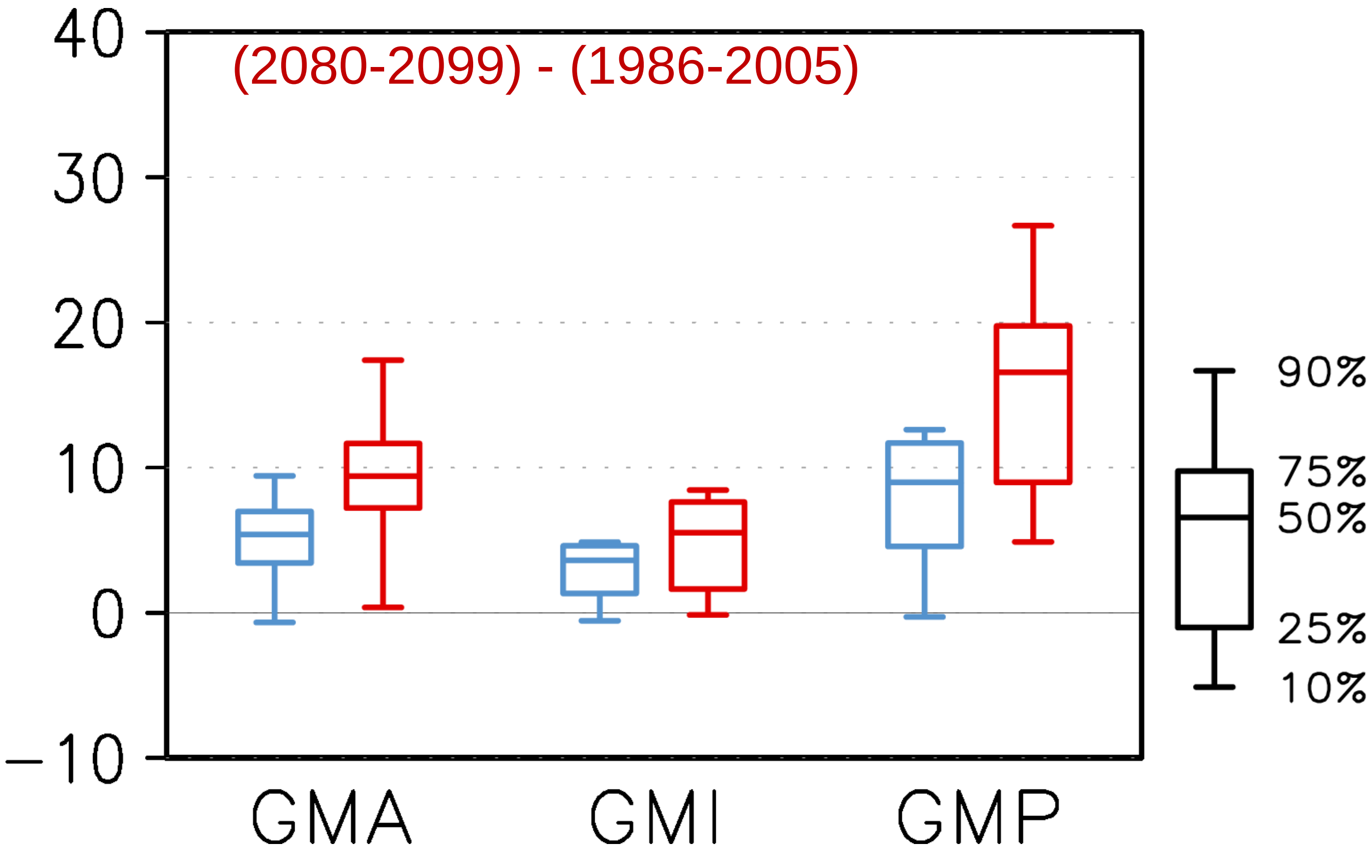
Yellow shading: only in present **Dark blue: only in future**



The global monsoon area will expand mainly over the central to eastern tropical Pacific, the southern Indian Ocean, and eastern Asia.

Kitoh, A., H. Endo, K. Krishna Kumar, I. F. A. Cavalcanti, P. Goswami, and T. Zhou, 2013: Monsoons in a changing world: a regional perspective in a global context. ***J. Geophys. Res. Atmos.*****,** 118, doi:10.1002/jgrd.50258

Future change (%): GMA, GMI & GMP



GMP: global monsoon total precipitation

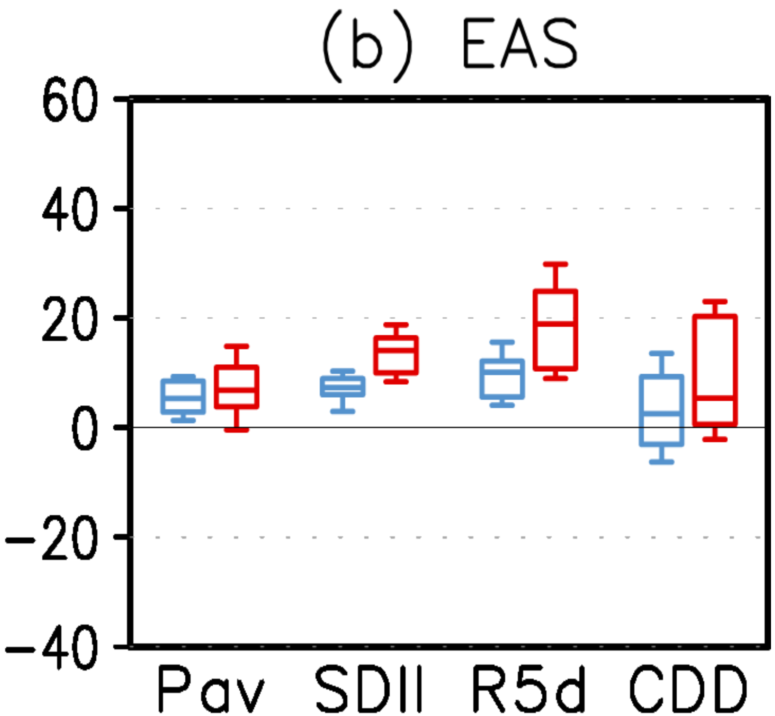
Blue: RCP4.5

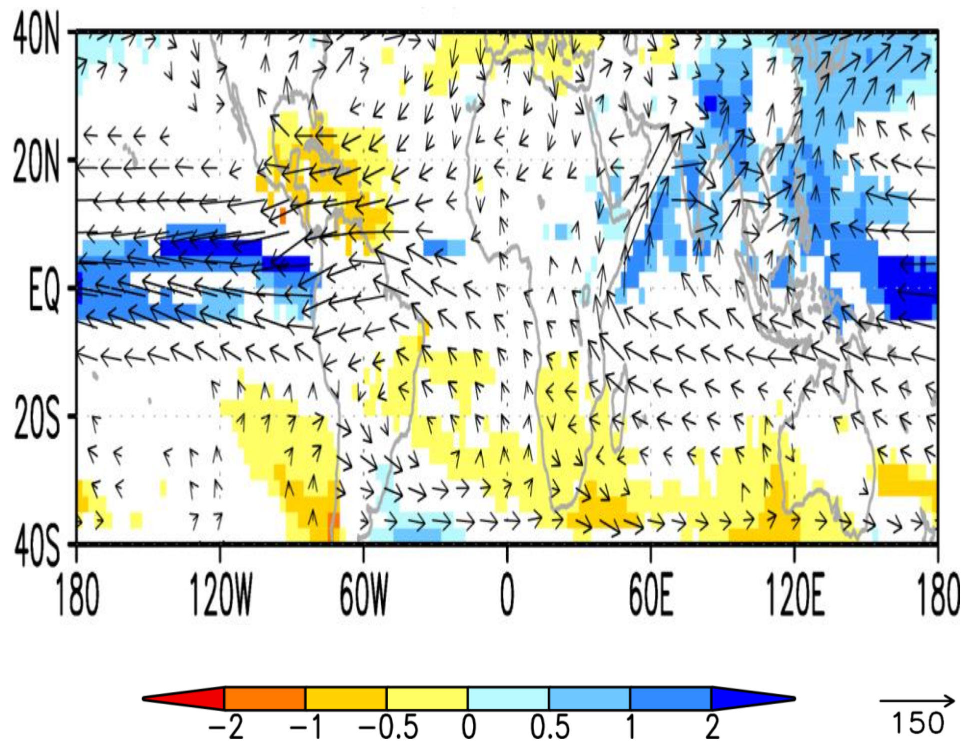
Red: RCP8.5

- GMP shows an increase in the RCP4.5 scenario and more so in the RCP8.5 scenario
- monsoon-related precipitation will significantly increase in a warmer climate

Kitoh, A., H. Endo, K. Krishna Kumar, I. F. A. Cavalcanti, P. Goswami, and T. Zhou, 2013: Monsoons in a changing world: a regional perspective in a global context. ***J. Geophys. Res. Atmos.*****,** 118, doi:10.1002/jgrd.50258

Future change ratio of Pav, SDII, R5d and DD over E. Asia





Blue: RCP4.5 Red: RCP8.5

shading: Precipitation
vector: vertically integrated water vapor flux

Kitoh, A., H. Endo, K. Krishna Kumar, I. F. A. Cavalcanti, P. Goswami, and **T. Zhou**, 2013: Monsoons in a changing world: a regional perspective in a global context. ***J. Geophys. Res. Atmos.***, 118, doi:10.1002/jgrd.50258

Point # 5

1. The global monsoon area defined by the annual range in precipitation *is projected to expand mainly* over the central to eastern tropical Pacific, the southern Indian Ocean, and eastern Asia.
2. The global monsoon precipitation *intensity* and the global monsoon *total precipitation* are also projected to increase. Indices of *heavy precipitation* are projected to *increase much more than those for mean precipitation*.
3. The projected increase of the global monsoon precipitation can be attributed to an *increase of moisture convergence due to increased surface evaporation and water vapor in the air column* although *offset to a certain extent by the weakening of the monsoon circulation*.

THANKS

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