Global Monsoon Response to External Forcing and Internal Feedbacks

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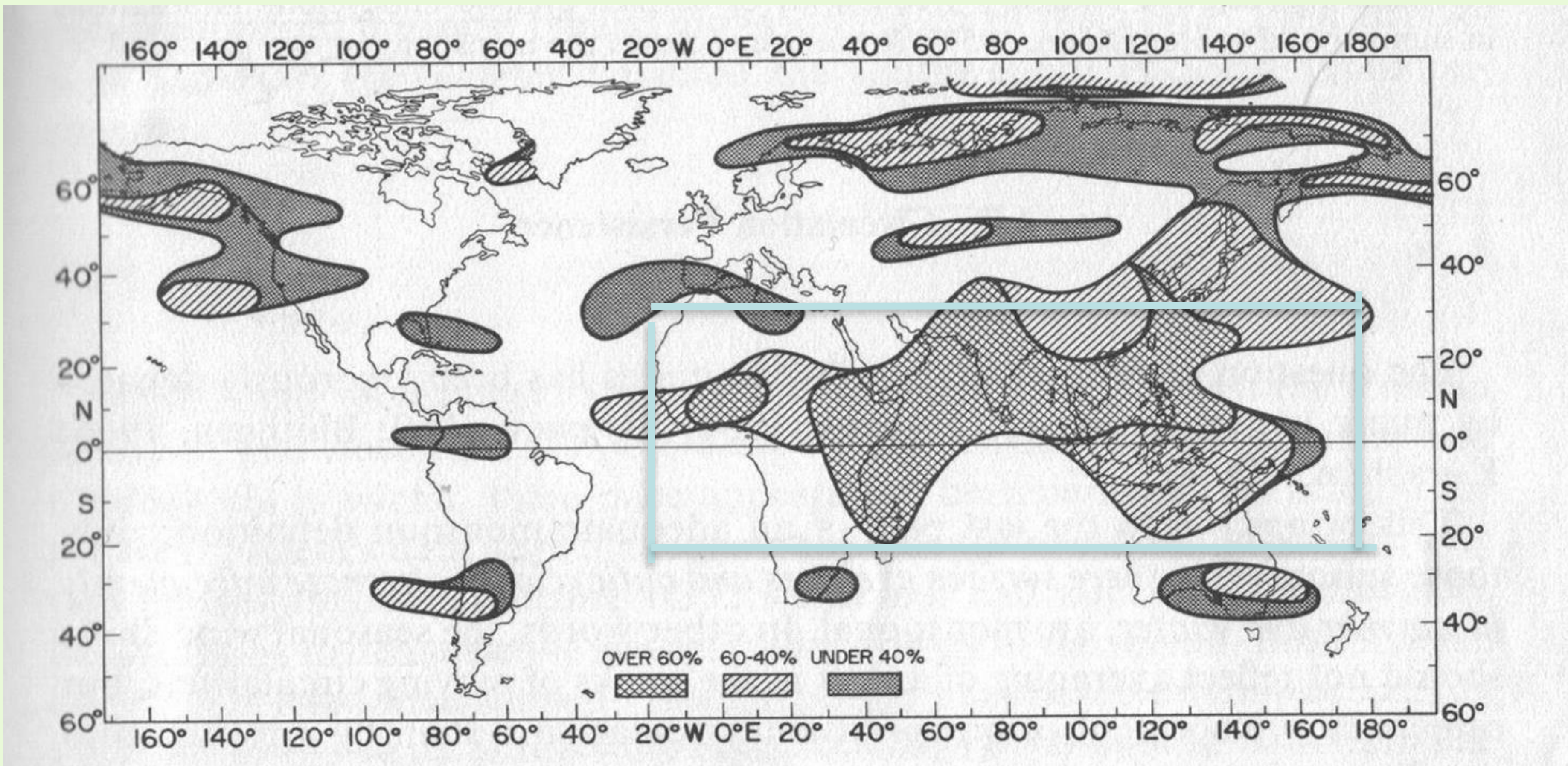
1. Emerging concept of Global Monsoon

Traditional Definition of monsoon domains by winds

Hann (1908) , Khromov (1957) and Ramage (1971) map,

Mid-20th century debate: annual march of westerlies



Annual reversal of surface winds

Ramage (1971) added Strength and Steadiness criteria

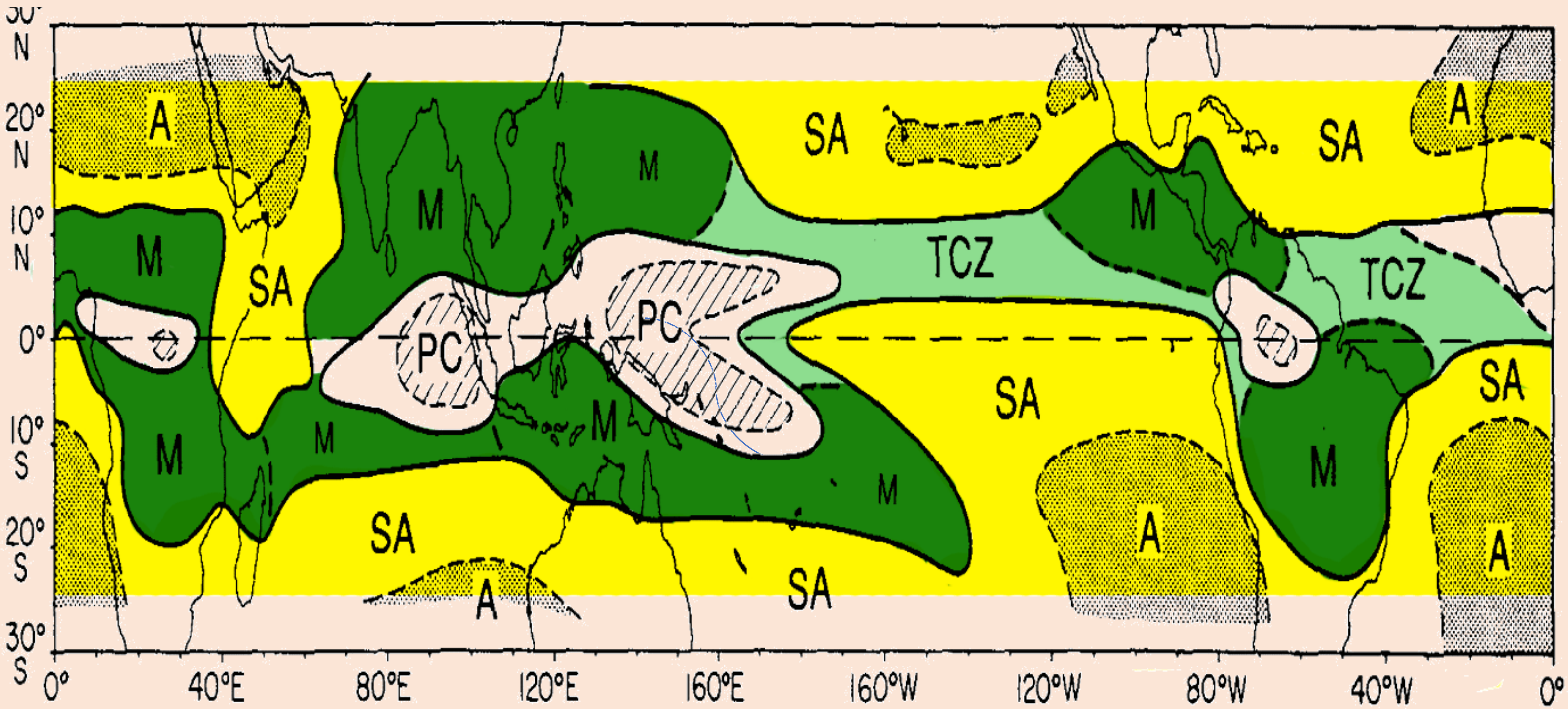
- Prevailing wind direction shifts at least 120 degree between January and July
- Average frequencies of the prevailing wind direction in January and July >40%

Why delineate monsoon domain by rainfall

- Monsoon is characterized by contrasting rainy summer and dry winter
- Monsoon rainfall impose greatest impacts on human and society. (social-economic impacts)
- Monsoon rainfall plays essential roles in determining Atmospheric General Circulation and Hydrological Cycle. (Scientific importance)

Delineating monsoon domains based on precipitation is imperative and advantageous.

Early attempt to define Tropical Monsoon with OLR (Rainfall)



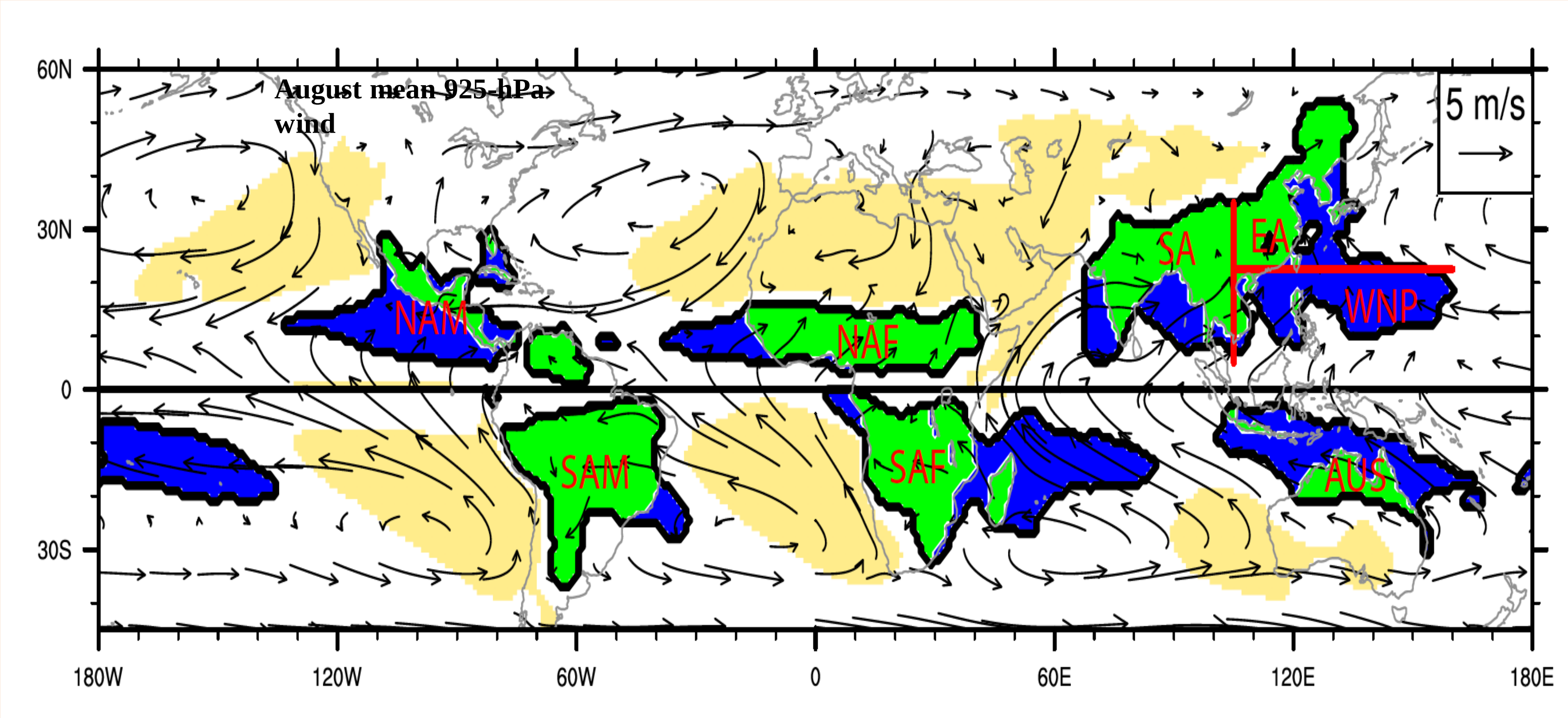
M: Monson; SA: Semi-Arid; A: Arid; PC: perennial; TCZ: Trades convergence Zone

- Extension to western hemisphere and southern Africa.
- Tropical monsoons entail substantial oceanic regions.

Reproduced from Wang 1994, Climatic regimes of tropical convection and rainfall**.** *J. Climate*, 7, 1109-1118.

Variability of American Monsoon Systems (VAMOS, Mechoso, 2000).

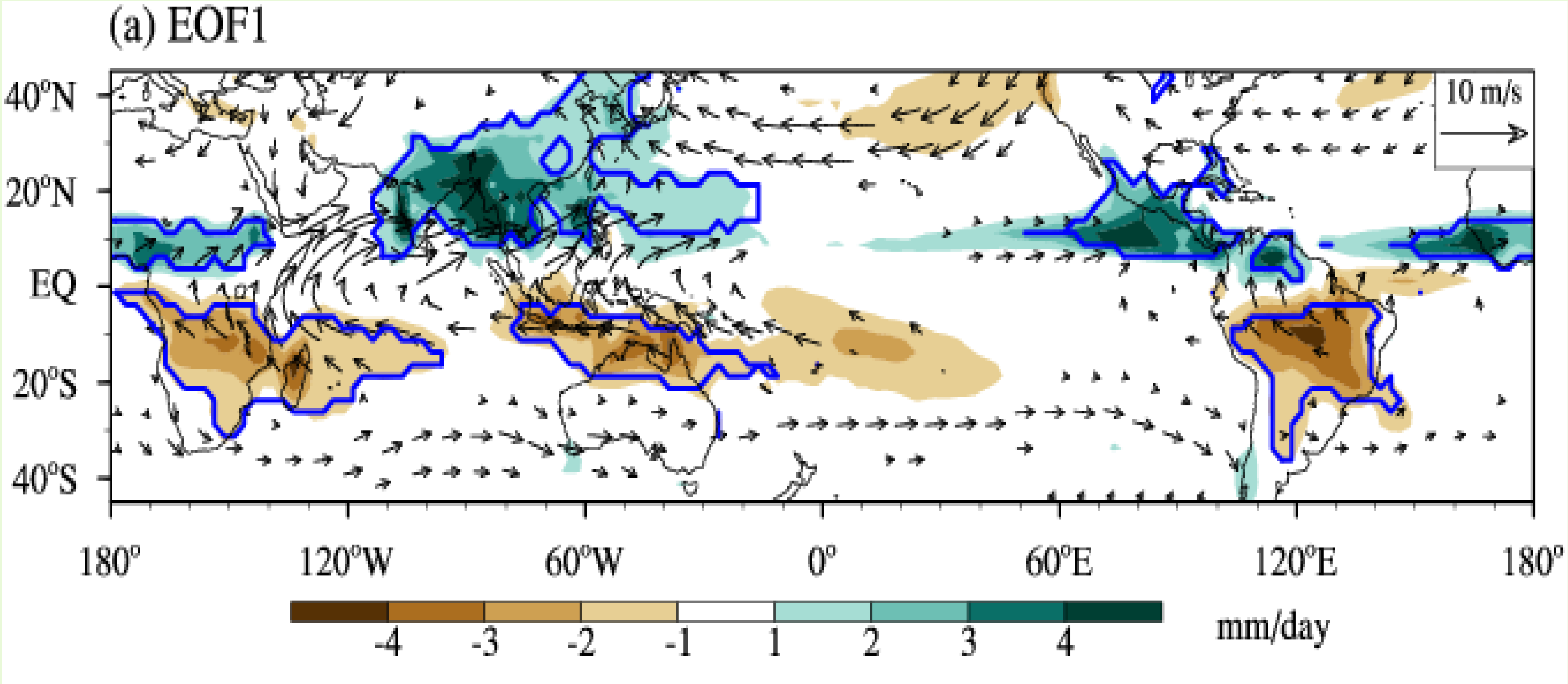
Global monsoon domains defined by precipitation characteristics

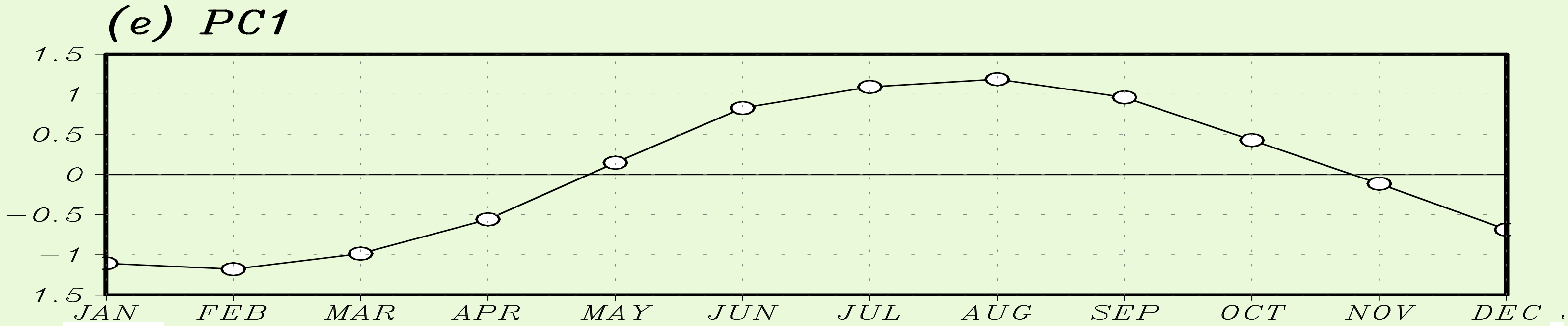


GM covers about 28% of the Earth's land and affects two-third of the global population. It includes eight regional monsoons

Monsoon criteria by rainfall: (1) Annual range exceeds 300 mm (or 2mm/day) ; (2) Local summer precipitation exceeds 55% of the annual total precipitation; **Arid regions**: Local summer precipitation rate is below 1 mm/day. Local summer : NH MJJAS and SH: NDJFM. Criteria follow Wang and Ding 2008, *Dyn. of Atmos. and Ocean.*

GM is the defining feature of annual variation of Earth's climate





GM is primarily an hemispheric antisymmetric mode

Wang, B., and Q. Ding, 2006: Changes in global monsoon precipitation over the past 56 years. *Geophys. Res. Lett.*, 33, L06711

What is Global Monsoon?

Climate perspective:

GM represents the dominant mode of Annual Variation of the Global Tropical precipitation and Circulation

Physical perspective:

GM is a forced response of the coupled climate system to annual cycle of solar insolation (Wang 2006: The Asian Monsoon)

This generic GM concept applies to geological time scale when ocean-land configuration dramatically different from today.

It also establishes the basis for understanding the astronomical theory of monsoon climate change (Milankovich 1930, 1941).

2. GM plays pivotal roles in atmospheric general circulation and hydrological cycle

GM and ITCZ

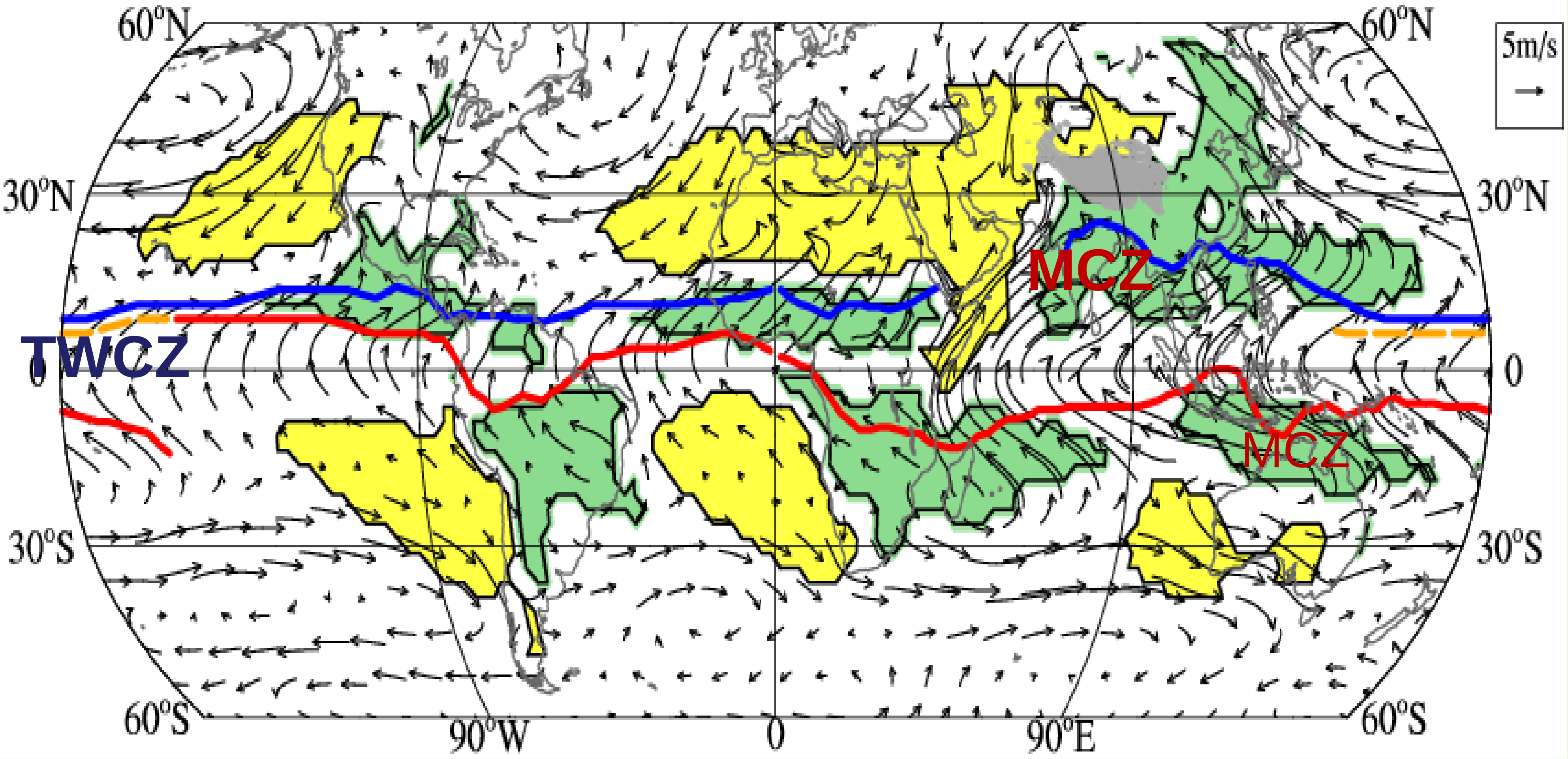
Monsoon and Deserts/Subtropical High

GM and Hadley circulation

GM and global mean precipitation

GM and Hydrological cycle

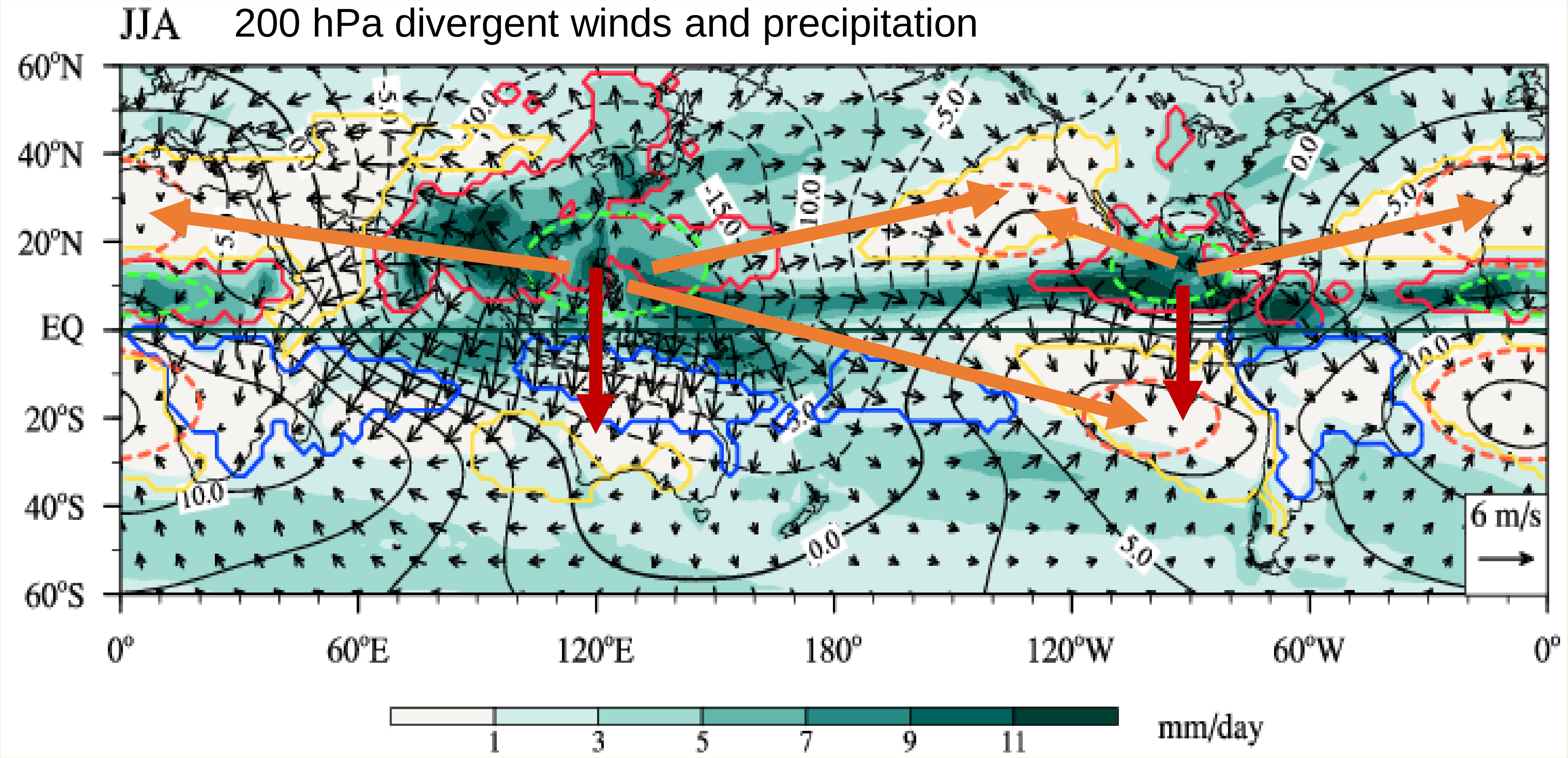
GM drives annual variations of ITCZ



August minus February 925hPa winds: blue (red) is ITCZ position in Aug (Feb).

- ITCZ consists of migrating MCZ and quasi-stationary trade wind convergence zone(TWCZ).
- About three quarters of the ITCZ is embedded within the monsoon convergence zone (MCZ).

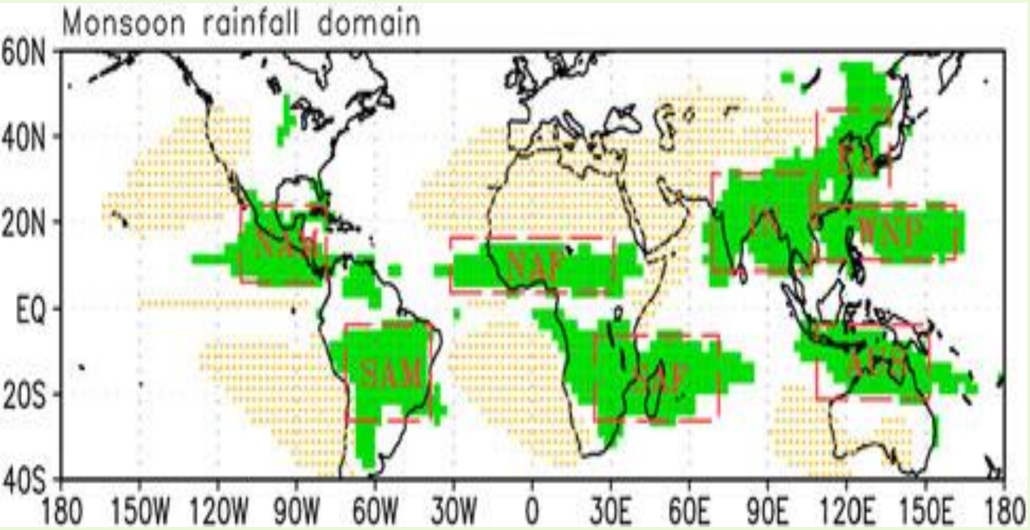
GM drives Annual Variations of Hadley Circulation

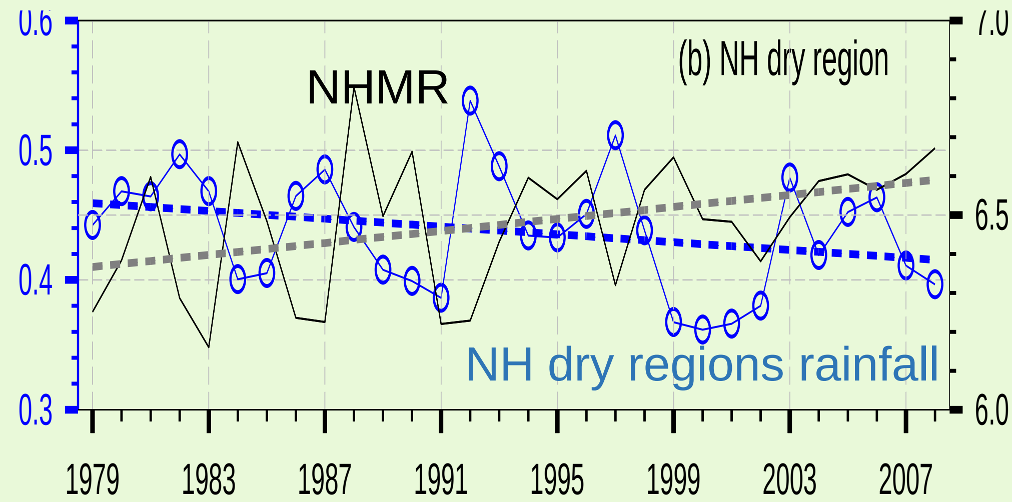


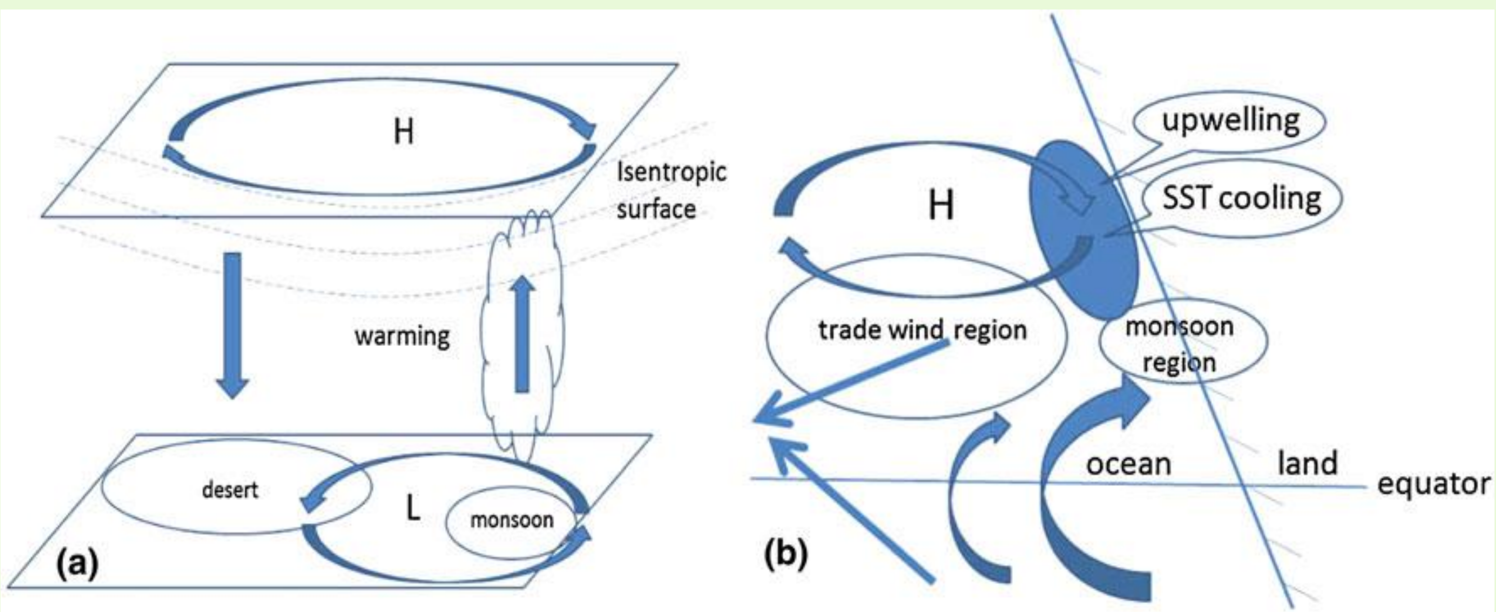
- "**Lateral monsoons**" (Webster et al. 1998) form the backbone of the **Hadley circulation**.
- **"Transverse monsoon"** drives **Subtropical High and Desert** and the Pacific **Walker circulation**.
- During NH summer, Subtropical High and Desert is driven by **transverse monsoon** not the Hadley cell.

Monsoon-Deserts coupling

Monsoon-Desert coupled variability
(Wang et al. 2012)







Hoskins 1996
Rodwell and Hoskins 1996

Hoskins and Wang 2006

3. GM rainfall response to Anthropogenic Forcing

- ❖ CMIP6 models' projected future changes
- ❖ Physical understanding the projected changes

- Wang, B., M. Biasutti, M. P. Byrne, C. Castro, C.-P. Chang, K. Cook, R. Fu, A. M. Grimm, K.-J.Ha, H. Hendon, A. Kitoh, R. Krishnan, J.-Y. Lee, J.P. Li, J. Liu, A.Moise, S. Pascale, M. K. Roxy, A. Seth, C.-H. Sui, A. Turner, S. Yang, K.-S. Yun, L. Zhang, and T. Zhou, 2020: **Monsoons climate change assessment.** *Bulletin American Meteorology Society,* doi: https://doi.org/10.1175/BAMS-D-19-0335.1.
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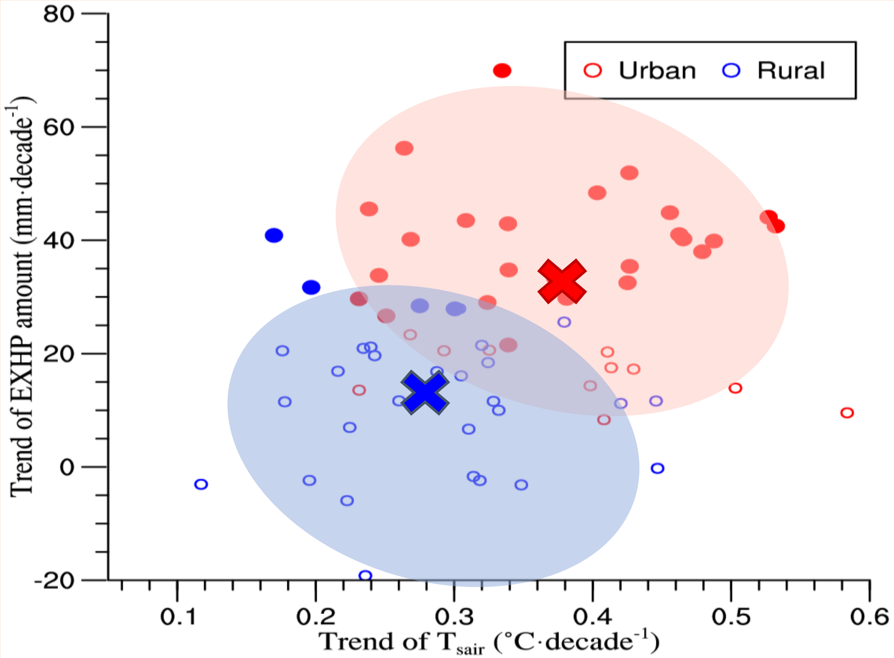
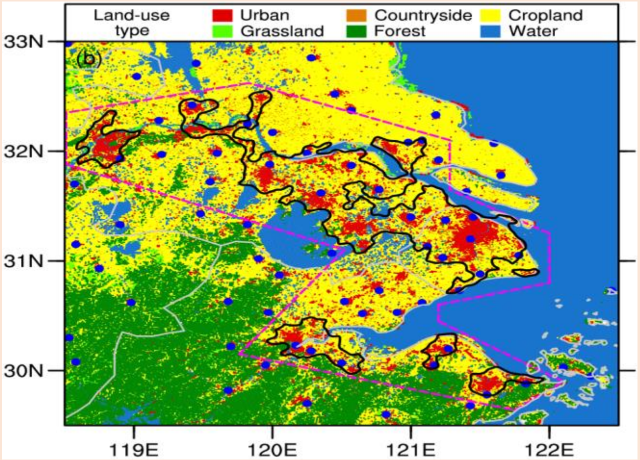
Urbanization has caused a significant rise in the intensity and frequency of extreme rainfall events



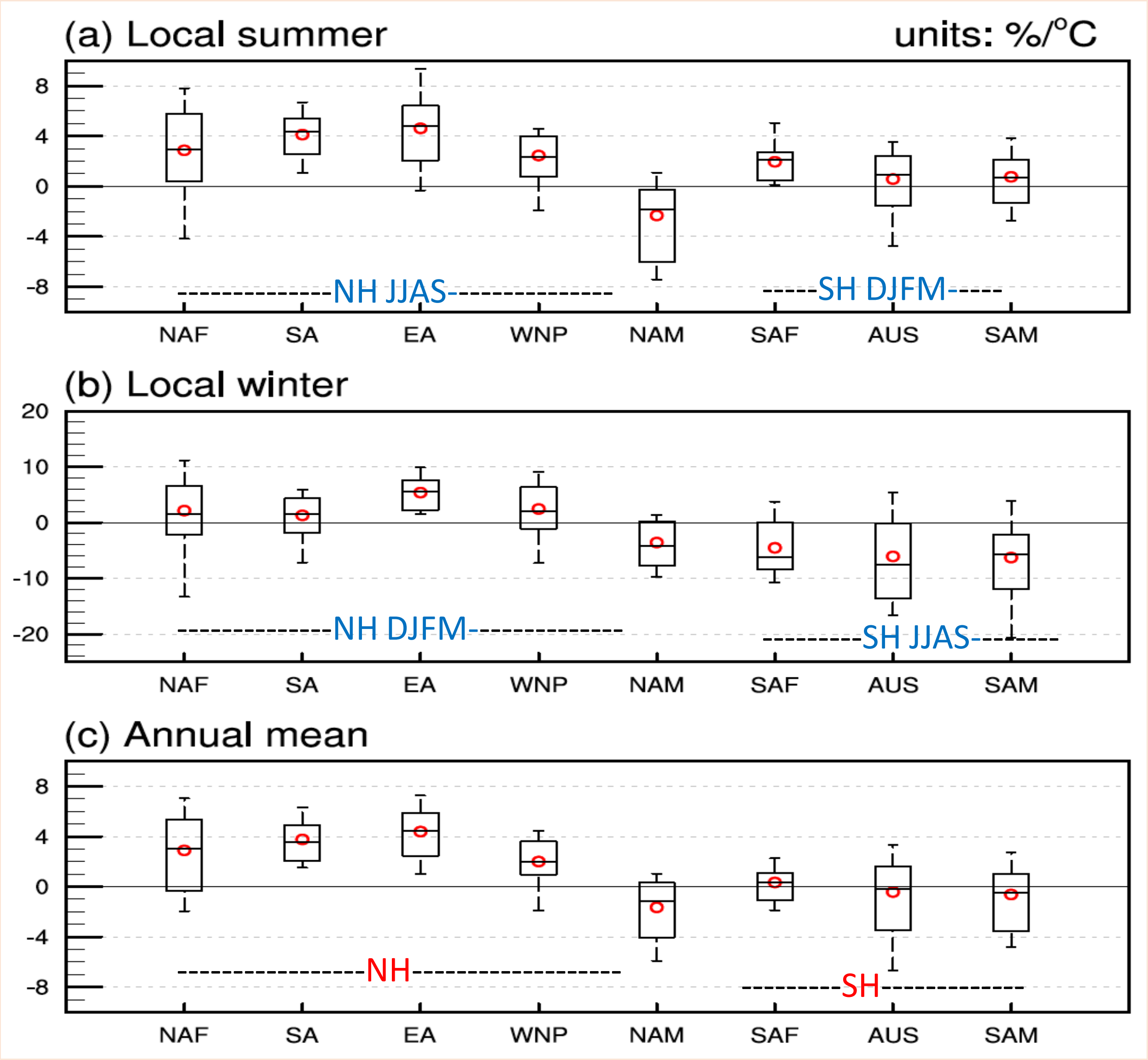


Mean trends	T_{sair} (°C·decade⁻¹)	EXHP amount (mm·decade⁻¹)
Rural	0.28	12.8
Urban	0.38	32.6

The surface air temperature and extremely hourly rainfall trends (EXHP) for urban stations and rural stations in the Yangzi River Delta, calculated from changes from 1975-1996 to 1997-2018, during MJJAS.

Jiang et al. 2020.

Regional Land Monsoon precipitation sensitivity (%/^oC)



The box: 17%- 83% (likely). The Whiskers: 5%-95% (very likely)

- LMP will very likely increase in South Asia (4.1%/K) and East Asia (4.6%/K), likely increase in northern Africa (2.9% /K), and likely decrease in North America (-2.3%/K).
- NHM increase vs. SHM unchanged.
- NH shows increasing Asian-Australian-African monsoons vs. decreasing North American monsoon (E-W asymmetry)
- SH shows significant decrease in winter rainfall.

Jin et al. (2020) J. Climate

A Simple Theoretical Framework for attribution of precipitation changes

Moisture conservation equation for steady motion

$$P = E - \langle \omega \frac{\partial q}{\partial p} \rangle - \langle \boldsymbol{V_h} \cdot \nabla q \rangle, \qquad (1)$$

Taking a two-layer approximation of the troposphere with the interface at 500-hPa, assuming the mean specific humidity in the lower troposphere equals the q_{850}, and neglecting upper tropospheric q,

$$\langle \omega \frac{\partial q}{\partial p} \rangle \approx \frac{1}{g}(\omega_{500} \cdot q_{850}), \text{ and } \langle \boldsymbol{V_h} \cdot \nabla q \rangle \approx \frac{1}{g}(\boldsymbol{V_{850}} \cdot \nabla q_{850}),$$

Two-layer approximation Equation

$$P \approx E - \frac{1}{g}(\omega_{500} \cdot q_{850}) - \frac{1}{g}(\boldsymbol{V_{850}} \cdot \nabla q_{850}), \qquad (2)$$

Change of regional mean precipitation <DP’> is approximated by

$$< DP' > \approx < DE' > - D < \frac{1}{g}(\omega_{500} \cdot q_{850}) > - D < \frac{1}{g}(V_{850} \cdot \nabla q_{850}) >, \qquad (3)$$

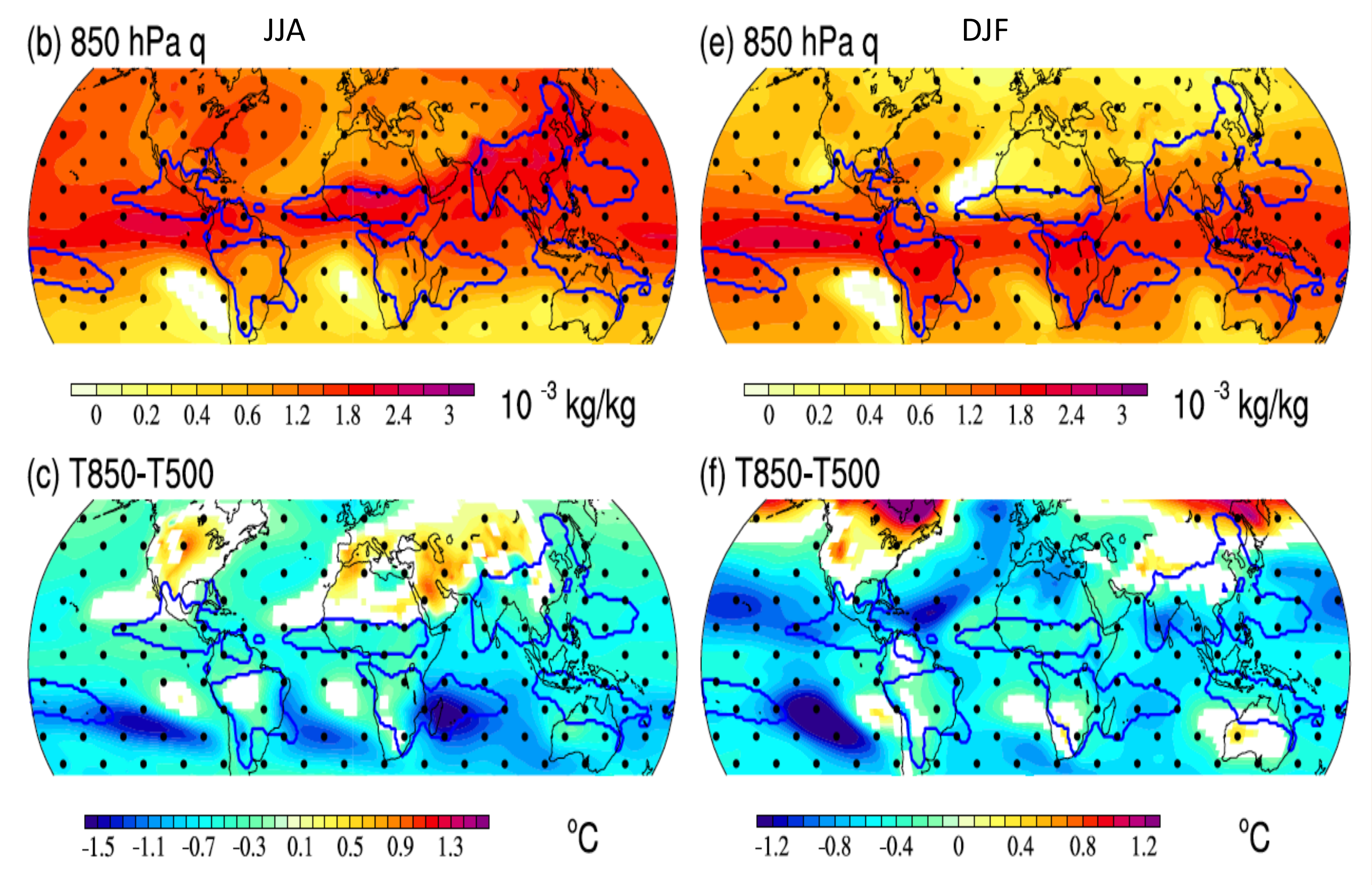
Evaporation small

Primary contributor

negligible

Jin et al. 2020

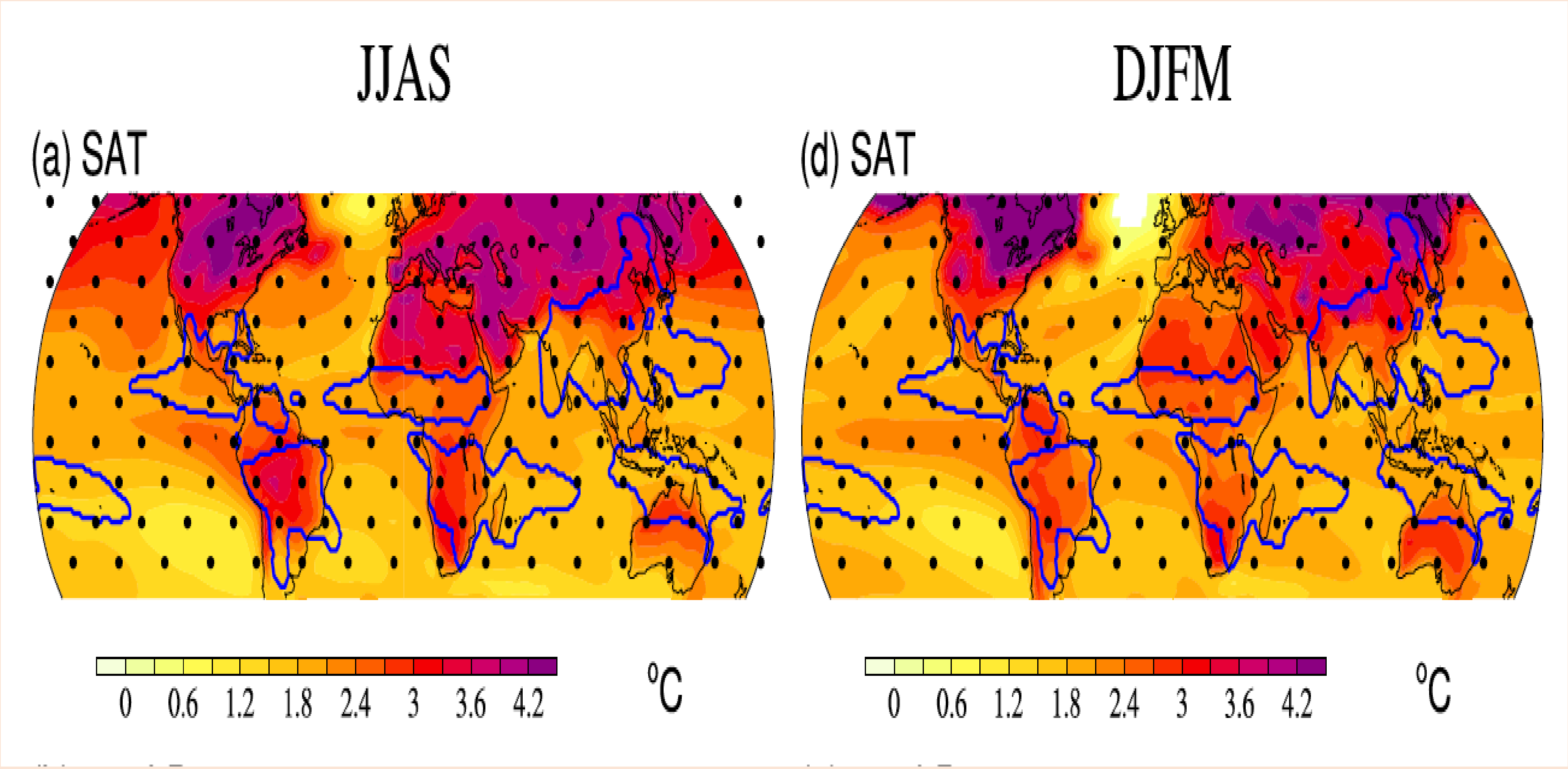
Uniform Changes of thermodynamics: Specific Humidity and Dry Static Stability



In summer monsoon regions, specific humidity and dry static stability increase nearly uniformly.

The two thermodynamic effects offset each other.

Change of surface warming pattern drives monsoon circulation (Dynamics)

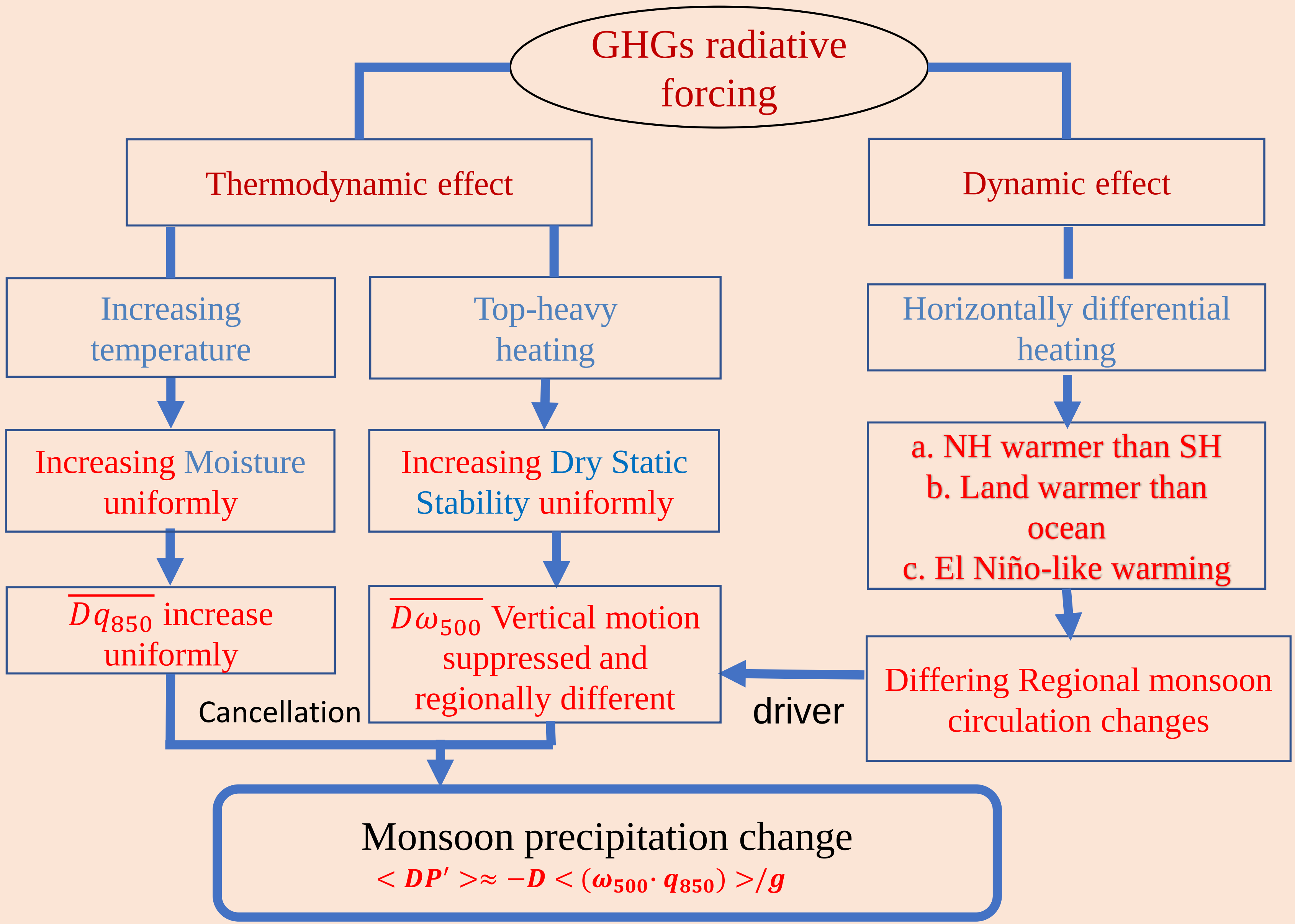


NH warmer-than SH--- enhances NHM while weakens SHM

Land warmer-than Ocean --- enhances Asian-NAF monsoon but not NAM

El Nino-like warming---- weaken NAM and global monsoon in general

How GHG radiative forcing drives Monsoon change



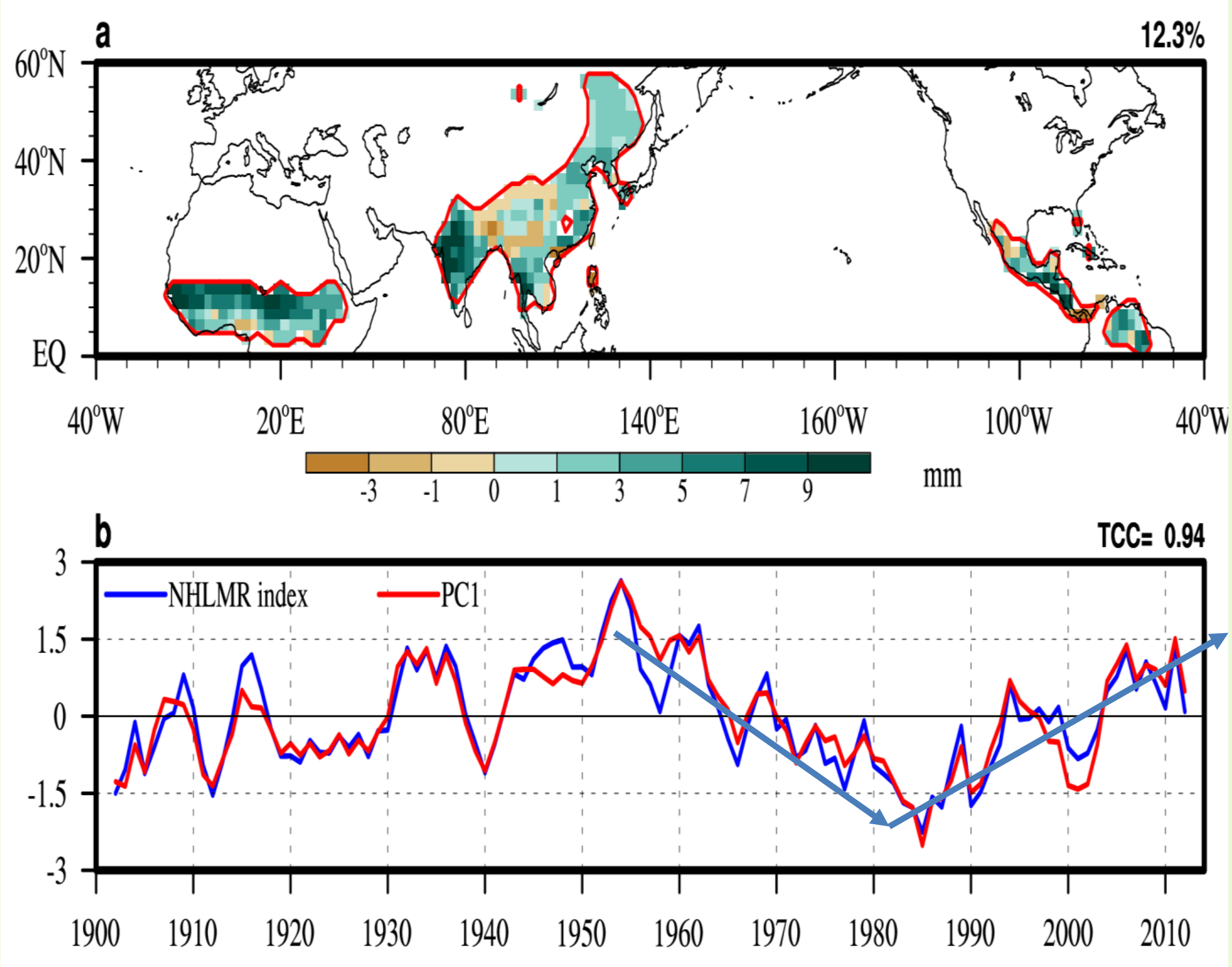
Modified from Wang et al., 2020

4. GM Variability due to Internal Feedbacks:

Multidecadal variations: coherent-global
Interannual variations: regional and global
Intraseasonal variability: regional

Multidecadal variations:
hemispheric scale and driven by global SST modes

NH LMR shows a coherent decadal Variation



The leading mode of NHLMR shows a nearly- homogeneous pattern.

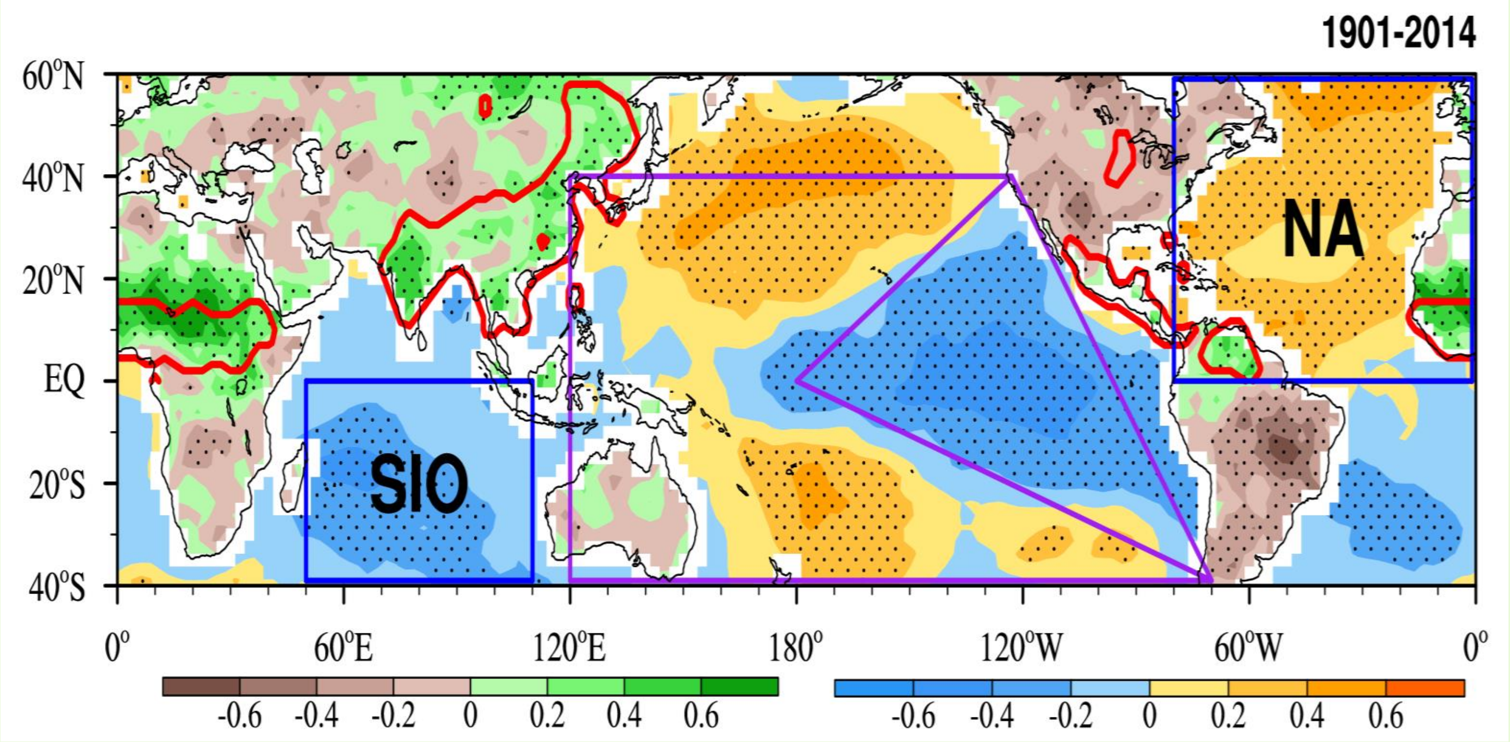
A large NHSM rainfall trend: since 1979: A 9.5% increase per 1°C global warming.

- The decadal NHLMR displays large-amplitude fluctuations (3.6% per decade).
- <u>Decadal variation may have a major contribution to the total precipitation change in a time scale of 2-3 decades (near future projection).</u>

Wang et al. 2012

What drives the NHSM-L interdecadal variation?

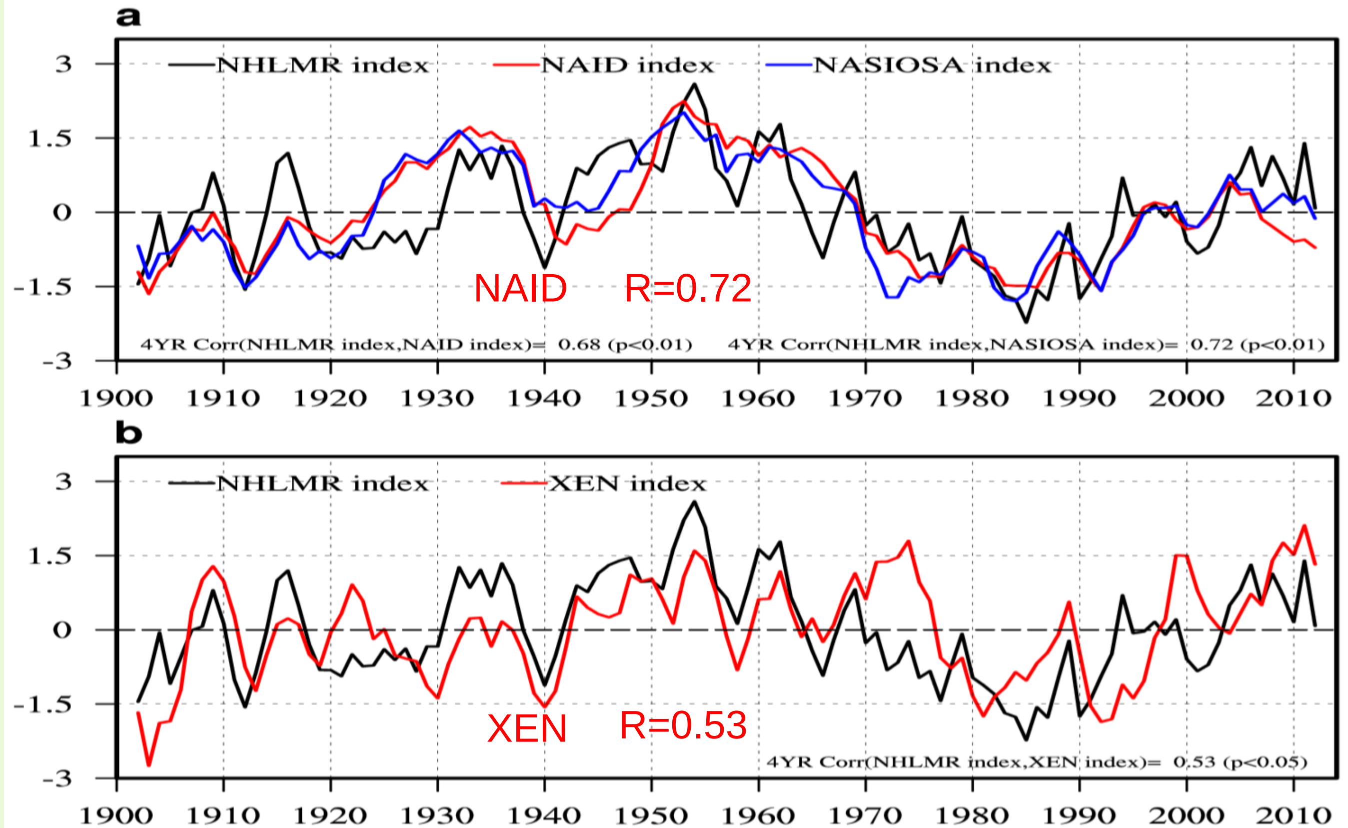
SST anomalies associated with the decadal NHLMR



NAID index = SSTA [North Atlantic-South Indian Ocean]
Extended ENSO (XEN) index= SSTA [(W. Pac K-shape)-(E. Pacific triangle)]

Wang et al. 2018)

Decadal NHLMR is linked to two modes of Global SST Variations

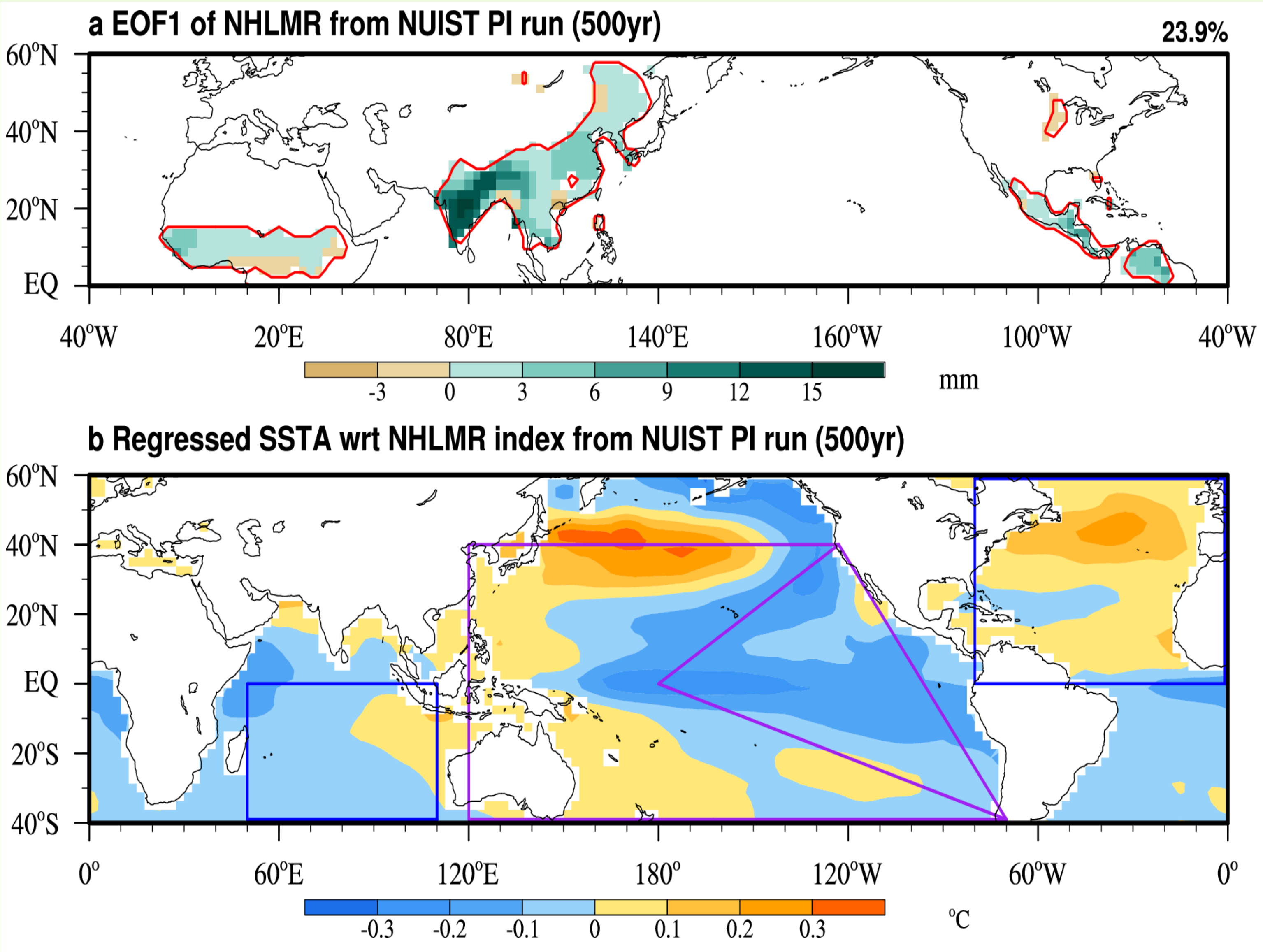


NHLMR index = 0.59*NAID +0.37*XEN,

NAID and XEN explains 35% and 14% of the total NHLMR variance

What causes the Decadal variability?

NHLMR decadal variation is largely an Internal variability: Results from 500-y Preindustrial CTL Exp.



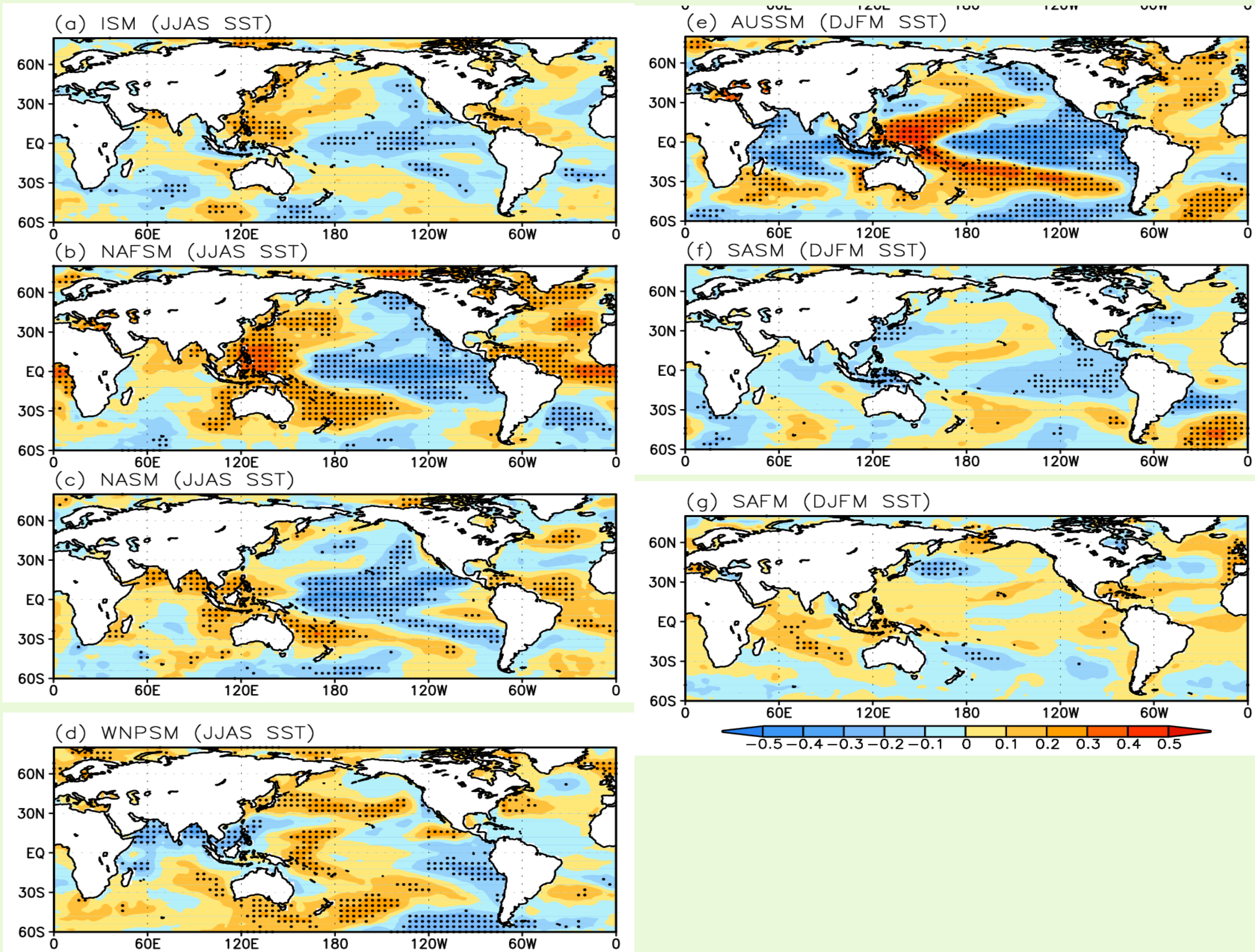
Numerical simulation suggests that the decadal variability of the NHLMR is likely a result of the global SST anomalies associated with the NAID and XEN SSTA.

Interannual variations driven by ENSO

Regional monsoon precipitation linking to global SST

NH JJAS

SH DJFM

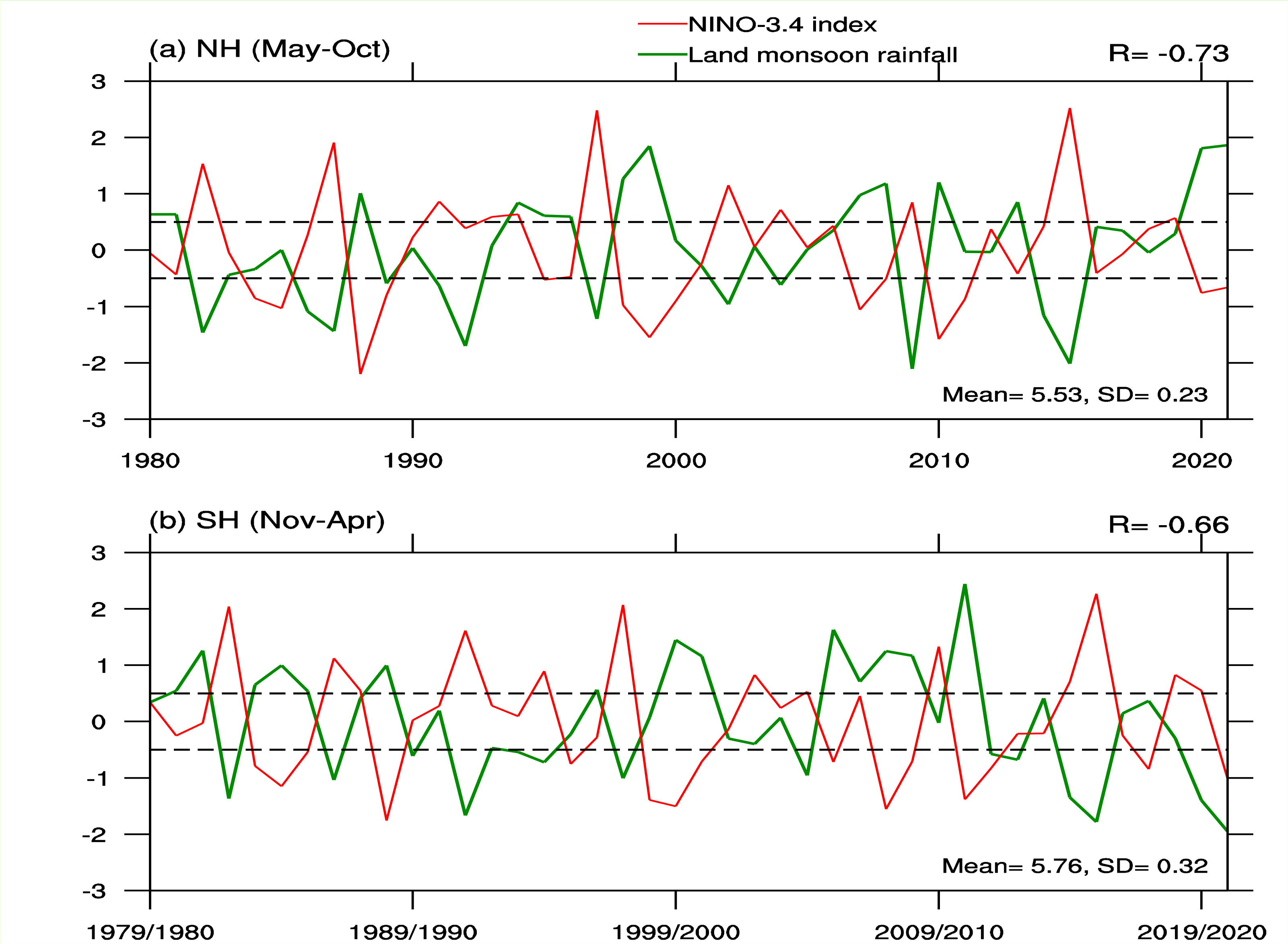


Remarks on Regional Monsoon Variability

- ❖ Over the past 55 years all regional summer monsoons have non-stationary relationship with ENSO except the Australian monsoon.
- ❖ Since the 1970s, the regional monsoon–ENSO relationships have been generally enhanced except for the Indian summer monsoon.
- ❖ Regardless the large regional differences, the monsoon precipitations over land areas of all tropical monsoon regions are significantly correlated with the ENSO.

Yim et al. 2014

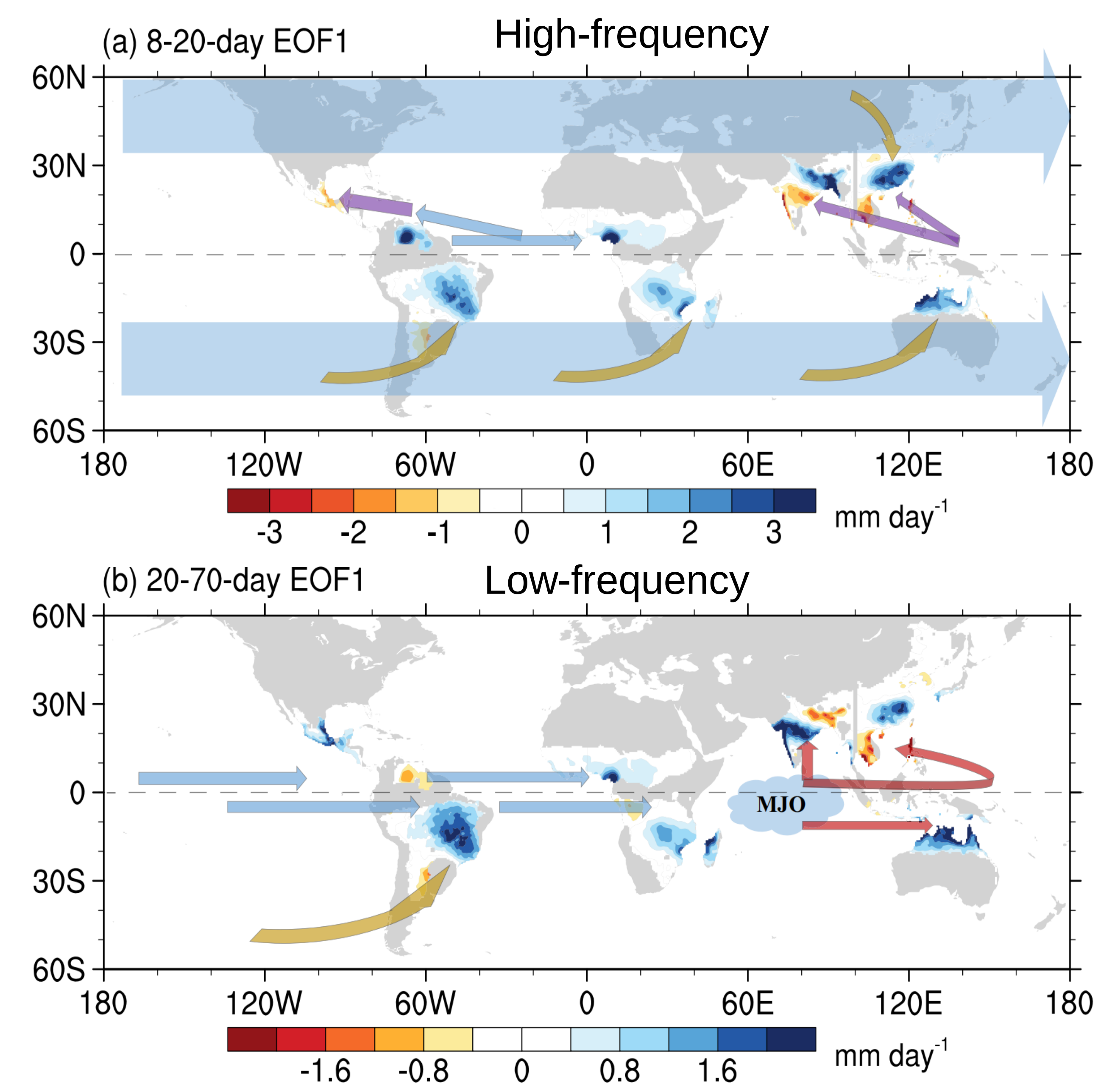
ENSO drives GM interannual variability



Wang and He 2022

Intraseasonal variability:
Regional atmospheric internal dynamics

ISV processes over regional monsoons



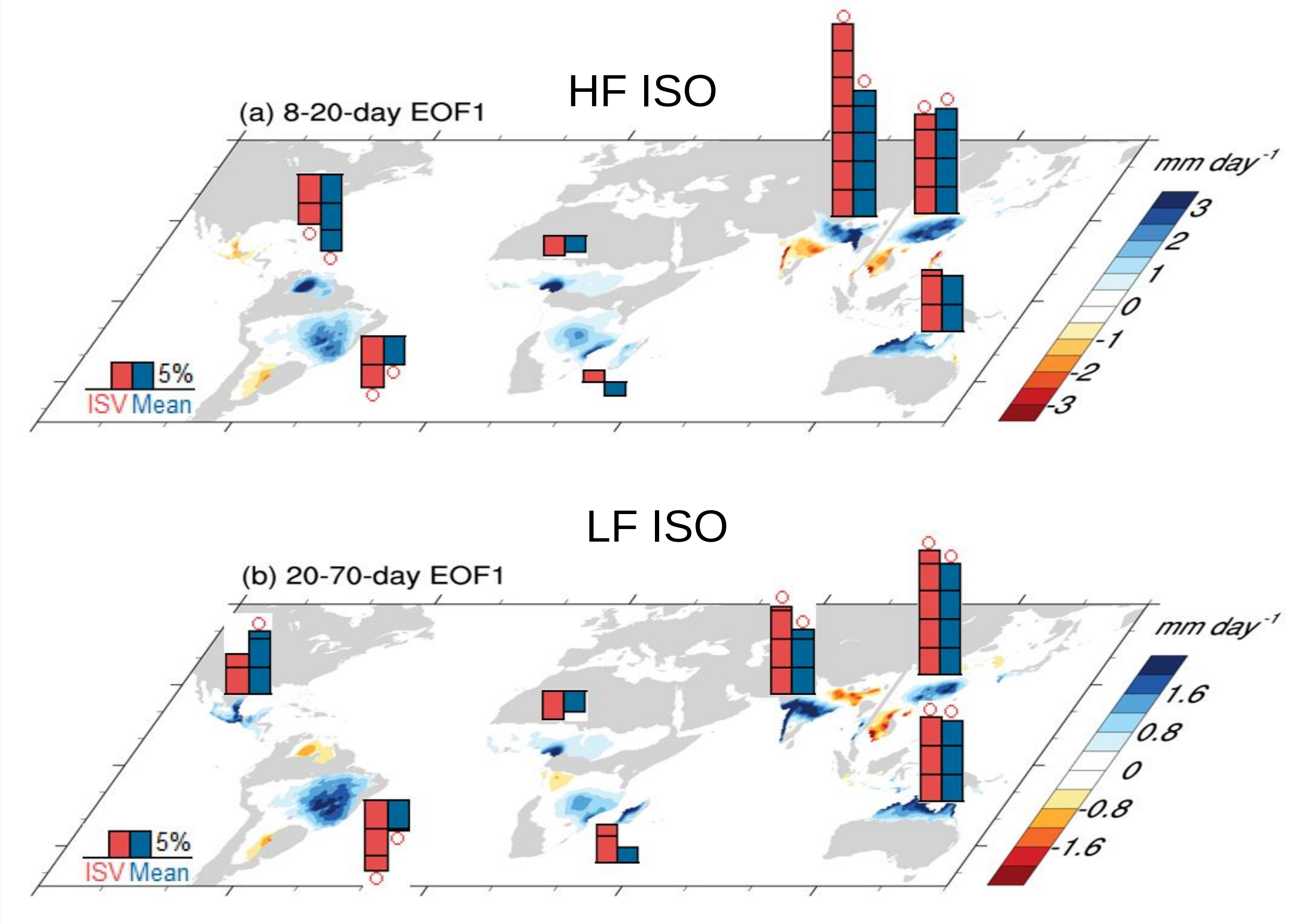
Leading modes of HFISVs in NHLM originate from different convectively coupled equatorial waves, while from mid-latitude wave trains for SHLM and EA monsoon.

MJO directly regulates LFISVs in Asian-Australian monsoon and affects American and African monsoons by exciting Kelvin waves and midlatitude teleconnections.

ISV contribute 30-50% of the daily precipitation variability

Liu et al. 2022

Intensified intraseasonal variability of Asian-Australian monsoon (1979-2020)



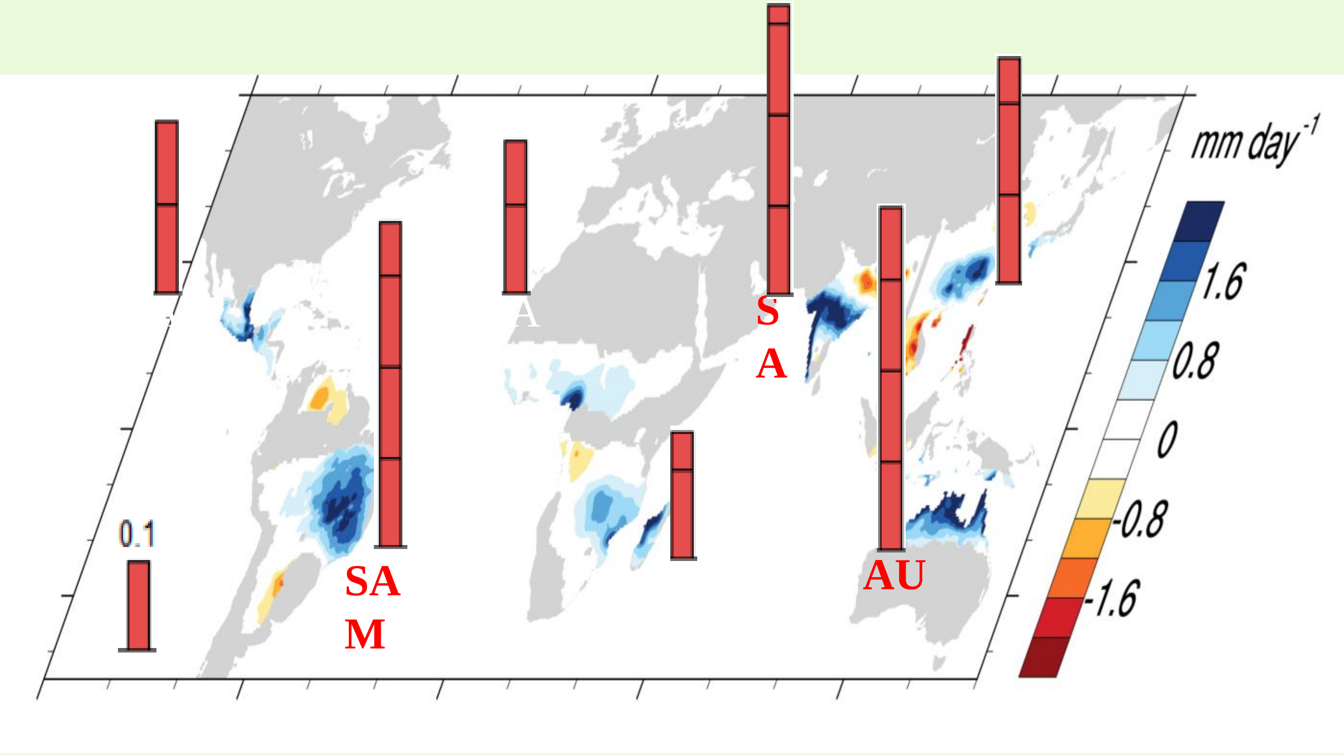
HF ISVs have considerably intensified over Asian monsoon but weakened over American monsoon

LF ISV intensified over Asian-Australian Monsoon, while decreased over SAM.

Liu et al. 2022

Subseasonal prediction skills

12 models (Vitart et al. 2017) MME show higher subseasonal prediction skills over AU, SA, and SAM monsoons Where the LF-ISV contributions are larger than other monsoons.



MME Correlation Skill of weekly precipitation anomalies averaged from Week 2 to Week 4

Accurate prediction of global land monsoon rainfall on a sub-seasonal (2–8 weeks) time scale has become a worldwide demand.

Liu et al. 2022


Thank you for your comments!

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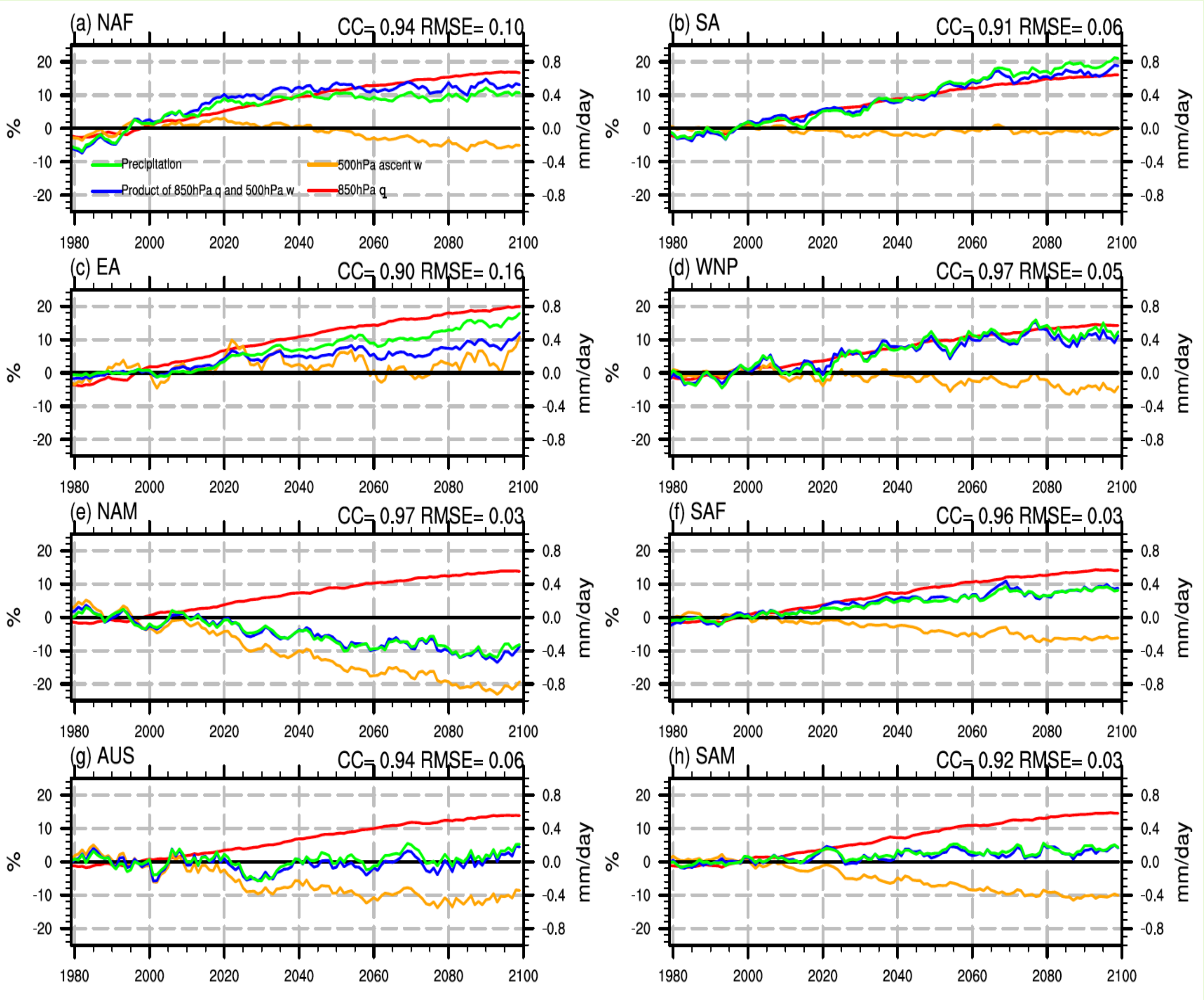
Remarks on global monsoon

- ❖ GM system is a global scale, annual reversal of the three-dimensional monsoon circulation accompanied by seasonal migration of the heavy precipitation zones.
- ❖ GM rainfall-released latent heat plays a critical toles in driving the subtropical high and deserts, ITCZ, Hadley and Walker circulation, hydrological cycle, and global precipitation change.
- ❖ The variability of the regional monsoons across time scales may vary differently. But, they may remain to be coordinated and **coherent** (intrinsically interrelated), especially under changing orbital

Regional LMR changes differ by vertical motion not moisture content change



Green: simulated precipitation $< DP' >$

Blue, vertical moisture advection $< -\frac{1}{g}(\omega_{500} \cdot q_{850}) >$

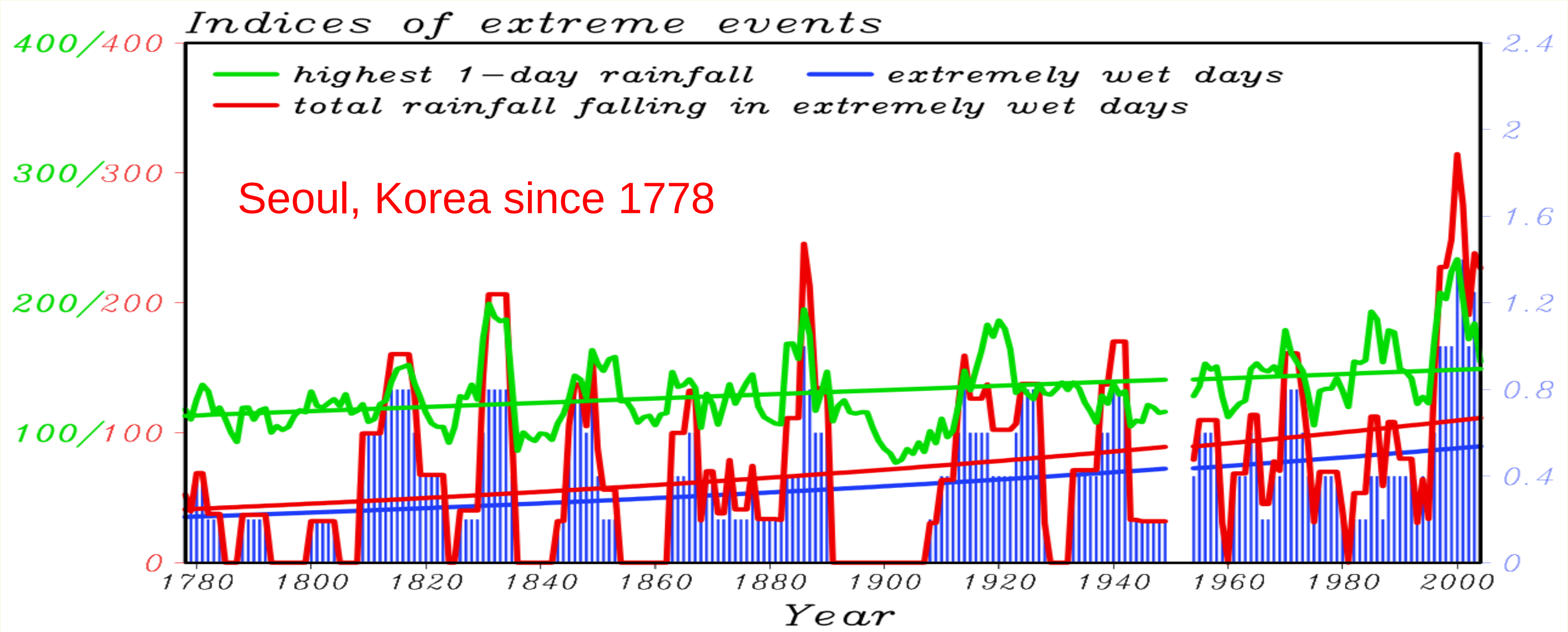
Red: $< q_{850} >$

Brown: $< \frac{1}{g}\omega_{500} >$

24MME historical run (1979–2014) and the SSP2-4.5 run (2015–2100).

Jin et al. 2020

Heavy rainfall will increase on daily-to-multiday time scale and intense rainfall on hourly time scales, due to an increased available moisture supply and convective-scale circulation changes.



Running five-year means time series. The extremely wet days are calculated as the 99th percentile of the distribution of the summer daily precipitation amount in the 227-year period. Trends are obtained by least-square regression for the green curve and logistic regression for the blue and red curve. Adopted from Wang et al. (2006)

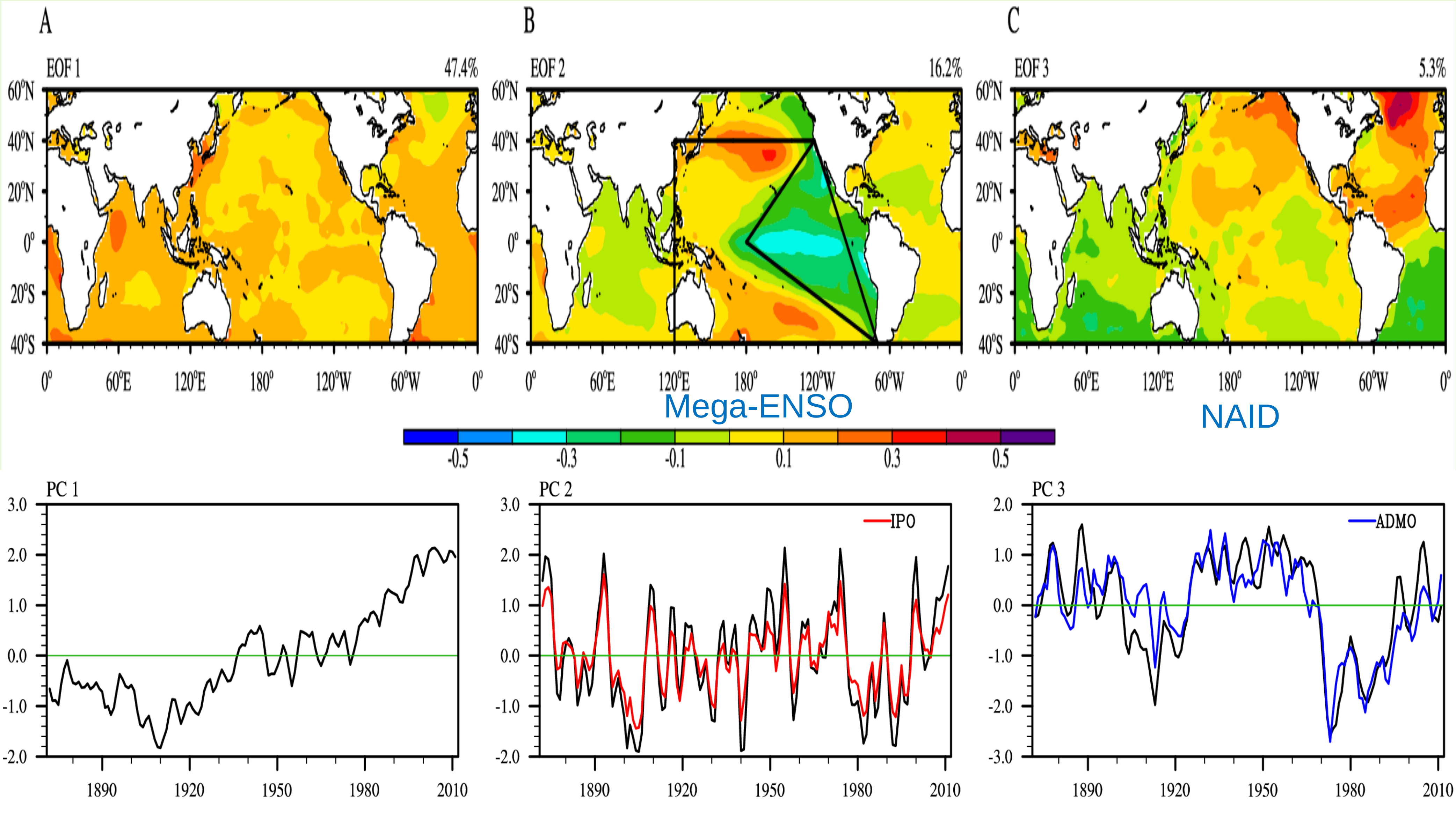
Sensitivity of extreme land monsoon precipitation to global warming

Approximately 8%K^{-1} Nearly independent of the regions, projected periods and emission scenarios.

M-Y Chang et al. 2022, *J. Climate*

How to interpret SSTA patterns assoc. with NHSM-L?

Leading EOF modes of Global SST variation (1871-2012)



The covariance matrix was used for EOF analysis.

Remarks on Regional Monsoon Variability

- ❖ The area-averaged summer precipitation intensity is generally a meaningful precipitation index for tropical monsoons.
- ❖ Over the past 55 years all regional summer monsoons have non-stationary relationship with ENSO except the Australian monsoon.
- ❖ Since the 1970s, the regional monsoon–ENSO relationships have been generally enhanced except for the Indian summer monsoon.
- ❖ Regardless the large regional differences, the monsoon precipitations over land areas of all tropical monsoon regions are significantly correlated with the ENSO.

Yim et al. 2014