Anthropogenically forced decadal change of South Asian summer monsoon across the mid-1990s

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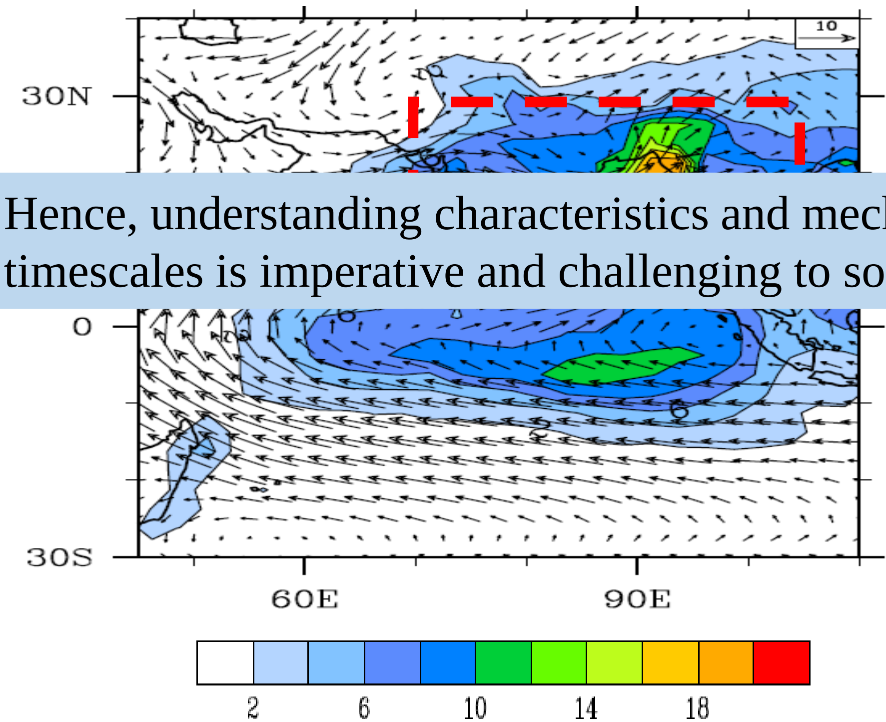
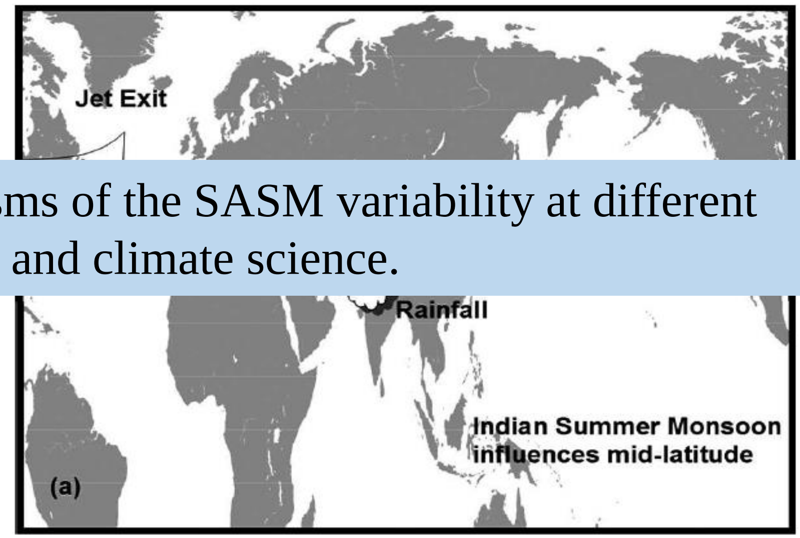
1. Introduction

The South Asian summer monsoon (**SASM**) is the most important climatic feature to society and ecosystems of South and Southeast Asia, which brings abundant rainfall (**about 80% of the annual rainfall**) in summer. The SASM also plays an important role for the global-scale atmospheric circulation.

Summer mean precipitation and 850hPa wind

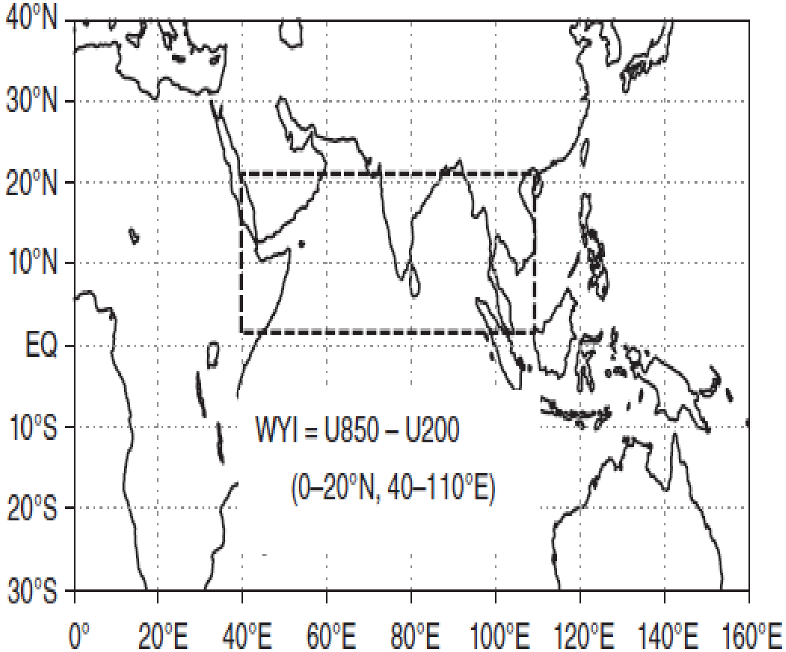


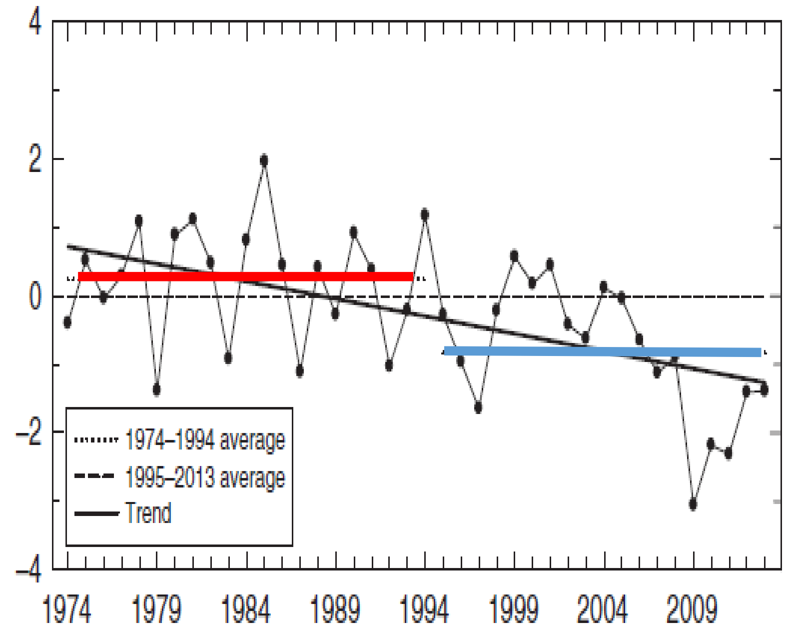


(Ding and Wang, 2005)

Hence, understanding characteristics and mechanisms of the SASM variability at different timescales is imperative and challenging to society and climate science.

Interdecadal variation of summer monsoon over the southern part of South Asia in mid-1990s





Choi et al. (2017)

The impacts of anthropogenic forcing on the SASM

- **Greenhouse Gas** (GHG)

✓ GHG forcing leads to more precipitable water in the atmosphere related to oceanic warming and an enhanced land-sea thermal contrast (i.e., **warm-ocean-warmer-land**) (Sun and Ding, 2011; Lau and Kim, 2017)

✓ GHG forcing leads to **the weakening of tropical atmospheric circulation** because of the energy and mass balance, which tends to suppress the monsoon circulation and rainfall (Ueda et al., 2006; Vecchi et al., 2006; Turner and Annamalai, 2012)

- **Anthropogenic Aerosol** (AA)

✓ AA forcing leads to **the surface and atmospheric cooling** via the aerosol-radiation interaction by scattering and absorbing the solar radiation directly and the aerosol-cloud interaction by altering the radiative properties of clouds (e.g., Li et al., 2016)

✓ The spatial heterogeneity of AA emissions concentrated over the northern hemisphere induces **the southward shift of the intertropical convergence zone** (ITCZ) (Rotstayn and Lohmann, 2002; Ming and Ramaswamy, 2011; Bollasina et al., 2011).

Aim to address the following issues:

1. To explore whether or not anthropogenic forcing plays a role in leading to the decadal change of the SASM across the mid-1990s, considering significant changes in anthropogenic GHG concentrations and AA emissions across the mid-1990s (Lamarque et al. 2010; Dong et al. 2017).

2. To quantify the relative roles of changes in GHG and AA forcings in shaping the recent decadal change, and to understand the physical processes involved.

2. Observed decadal changes of the SASM

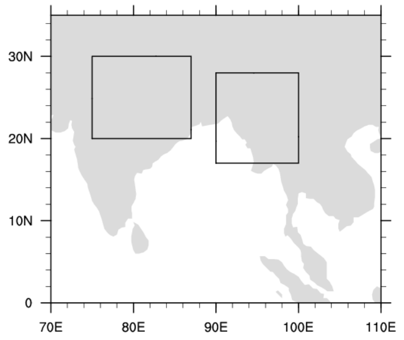
➢ **Observation/reanalysis datasets:** monthly global datasets for **1964-2011**

precipitation	CRU	0.5° × 0.5°	Mitchell and Jones 2005
	UDEL	0.5° × 0.5°	Willmott and Matsuura 2001
	PREC/L	0.5° × 0.5°	Chen et al. 2002
SLP	HadSLP2	5° × 5°	Allan and Ansell 2006
horizontal wind	NCEP/NCAR	2.5° × 2.5°	Kalnay et al. 1996
SST	HadISST	1° × 1°	Rayner et al. 2003

➢ **Indices:**

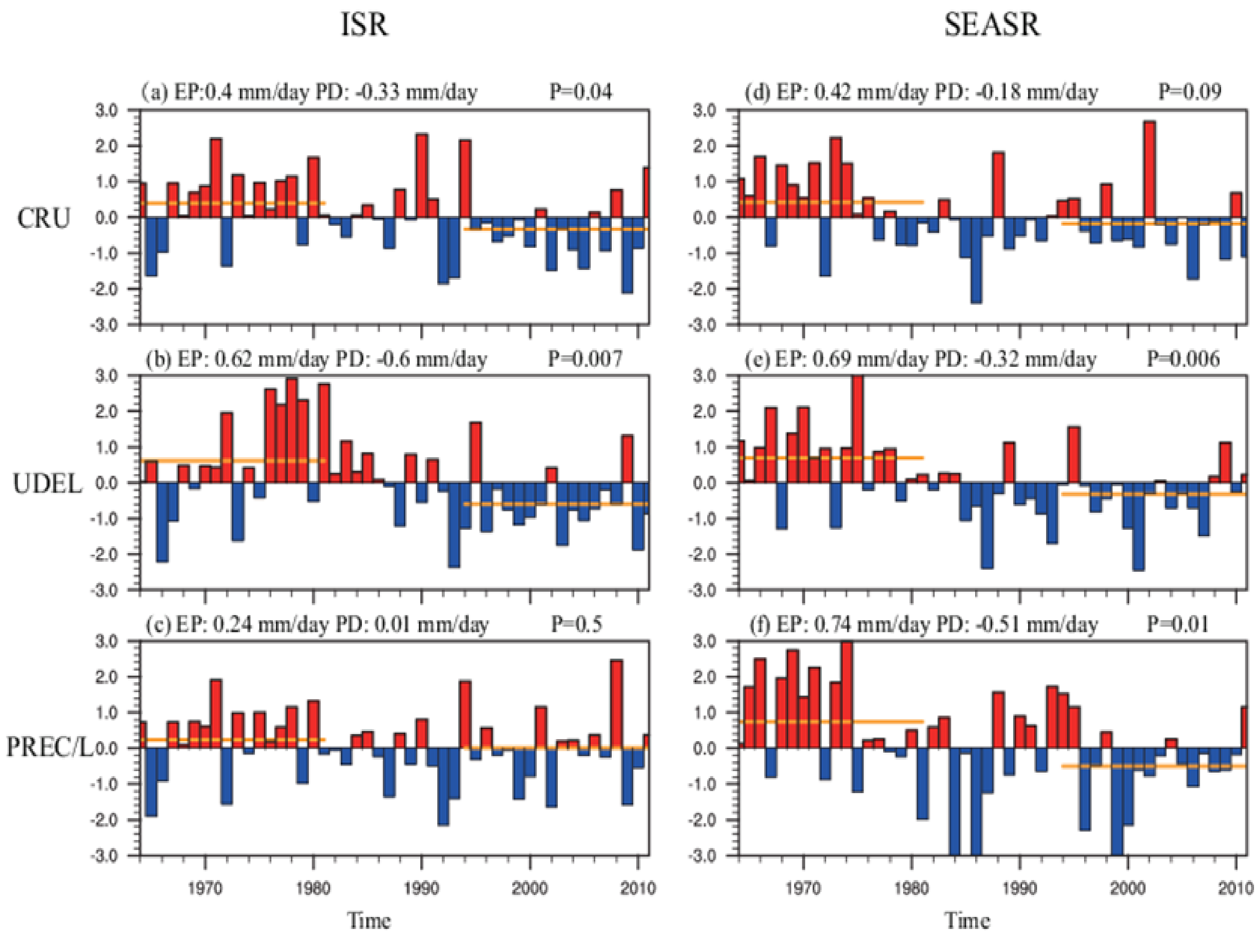
- Indian Summer Rainfall (**ISR**): the summer (June-August) averaged land rainfalls over central-northern India (20°N-30°N, 75°E-87°E)

- Southeast Asian Summer Rainfall (**SEASR**): the summer (June-August) averaged land rainfalls over northern Indo-China Peninsula (17°N-28°N, 90°E-100°E)



Observed decadal changes

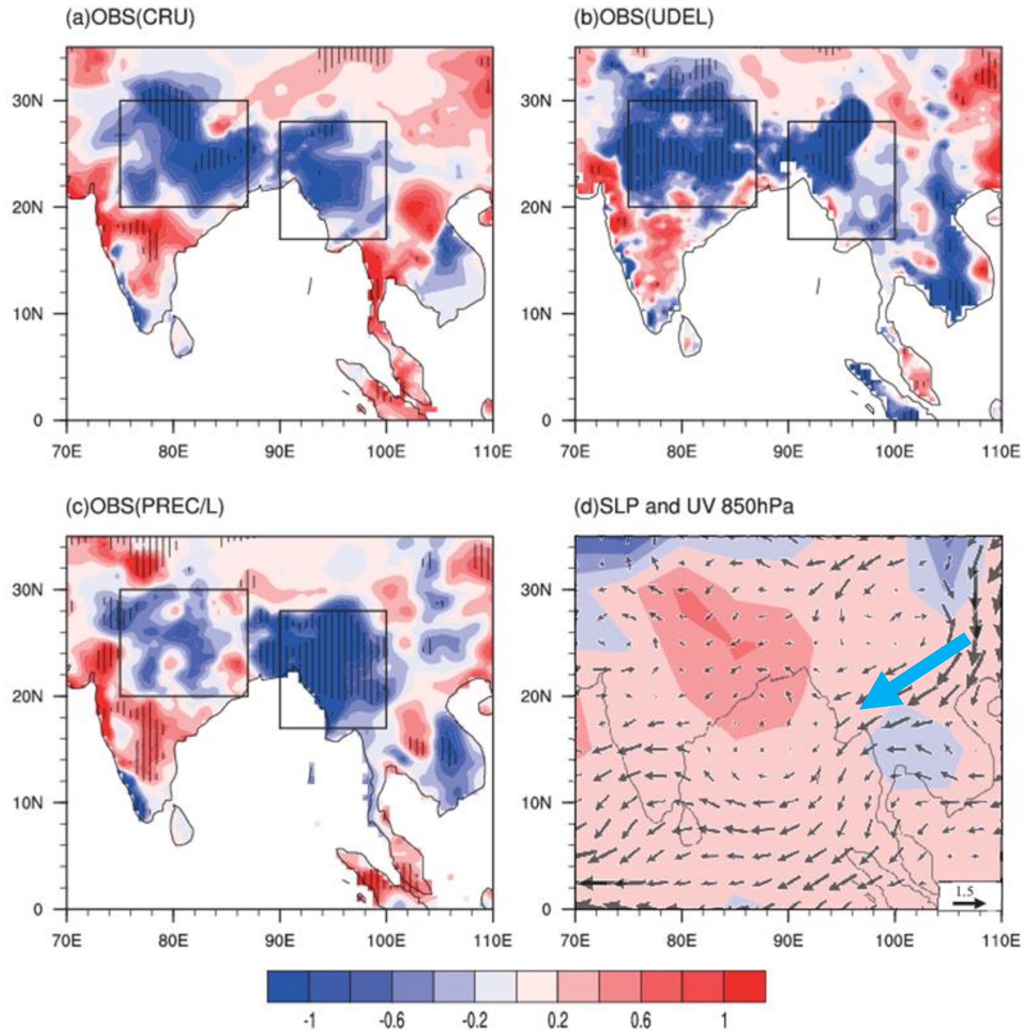
Time series for the ISR and the SEASR indices



Early period (EP, 1964-1981)

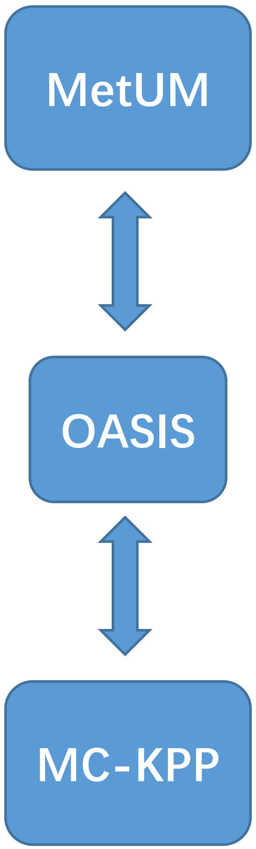
Present day (PD, 1994-2011)

The spatial distributions of differences in summer precipitation and atmospheric circulation between the PD and EP



3. Model and experiments

MetUM-GOML2: a coupled atmosphere-ocean-mixed-layer model



The atmospheric component: the Met Office Unified Model (MetUM) at the fixed scientific configuration Global Atmosphere 6.0 (GA6.0) with a horizontal resolution of 1.875° longitude and 1.25° latitude (N96), and a total of 85 vertical levels (Walters et al., 2017)

The Ocean Atmosphere Sea Ice Soil (OASIS) is used to couple the atmospheric and oceanic components every three hours.

The oceanic component: a Multi-Column K Profile Parameterization (MC-KPP) mixed-layer ocean model with the same horizontal resolution of the MetUM with 100 vertical levels and a depth of 1000m.

Experiments

Experiment	Ocean	Radiative Forcing	Member	Abv
Relaxation experiment	Relax to present day (PD, 1994-2011) mean 3D ocean temperature and salinity **to diagnose climatological temperature and salinity flux corrections**	Climatological PD greenhouse gases (GHG) over 1994-2011 and anthropogenic aerosol (AA) precursor emissions over 1994-2010 with AA after 2006 from RCP4.5 scenario (Lamarque et al. 2010, 2011)	55	R0
Coupled early period (EP, 1964-1981) experiment	Climatological temperature and salinity flux corrections from relaxation run	time mean **EP GHG** over 1964-1981 and **EP AA** precursor emissions over 1970-1981	55	EP
Coupled present day (PD, 1994-2011) experiment	Climatological temperature and salinity flux corrections from relaxation run	Climatological **PD GHG** and **PD AA** precursor emissions	55	PDGA
		Climatological **PD GHG** and **EP AA** precursor emissions	55	PDG
		Climatological **EP GHG** and **PD AA** precursor emissions	55	PDA

The response to a particular forcing is estimated by the mean difference between a pair of experiments that include and exclude that forcing.

PDGA – EP (All Forcing): the combined effect of changes in both GHG and AA

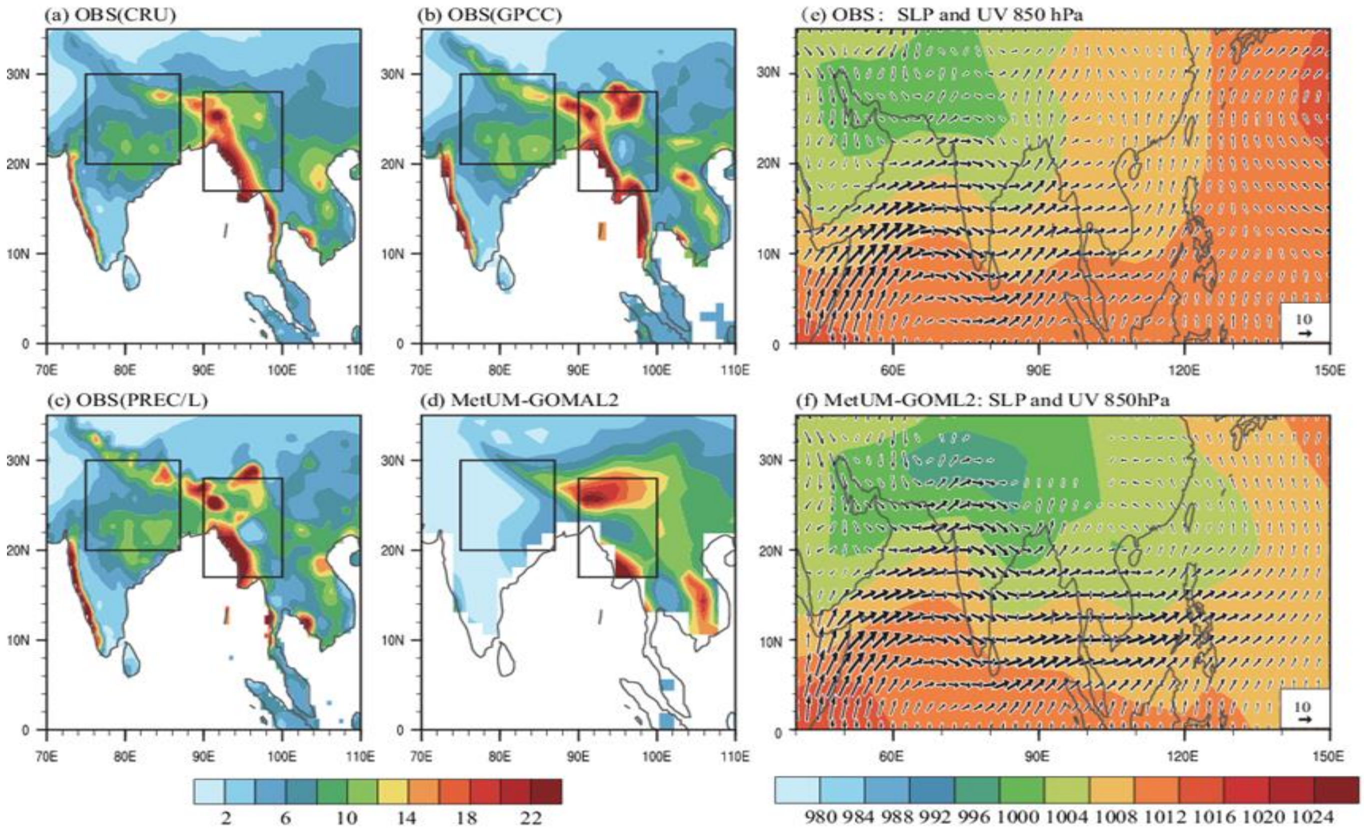
PDG – EP (GHG Forcing): the impact of change in GHG

PDA – EP (AA Forcing): the impact of change in AA emission

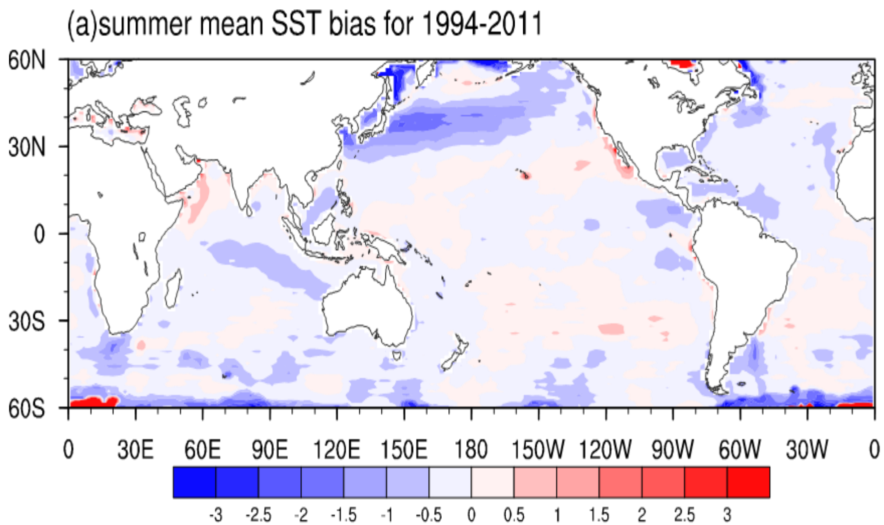
Model mean Climatology

Precipitation

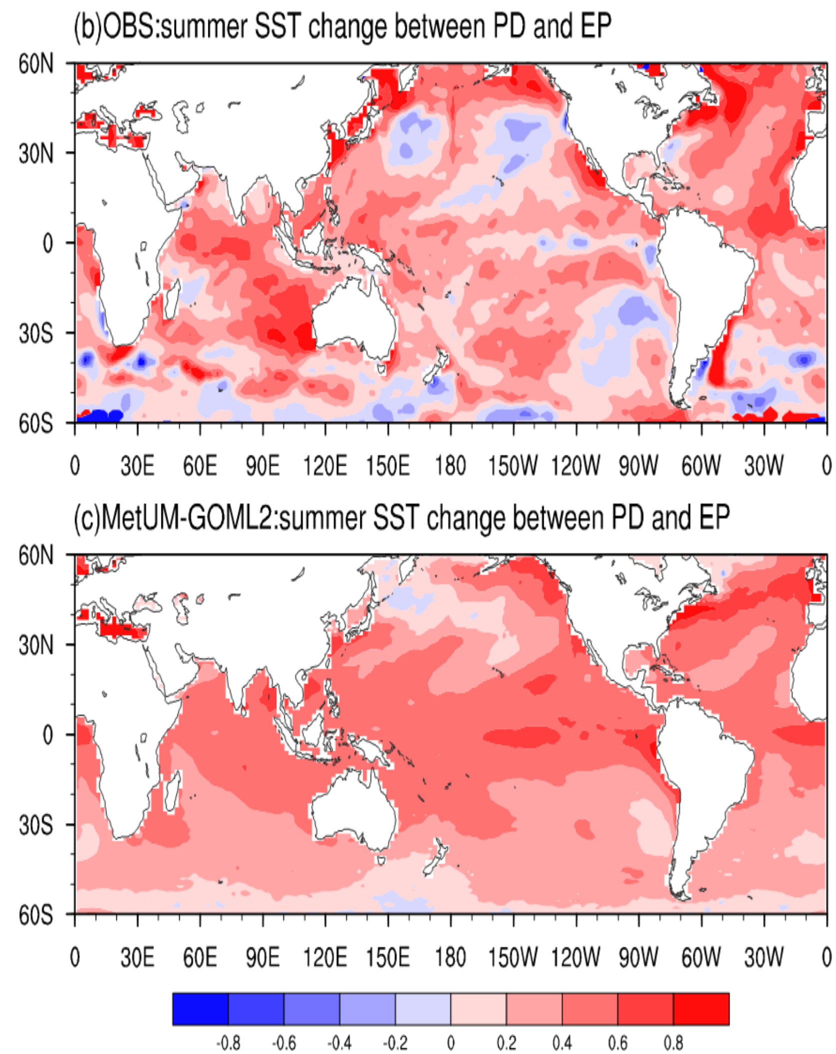
SLP and UV 850hPa



The simulated summer SSTs biases relative to HadISST



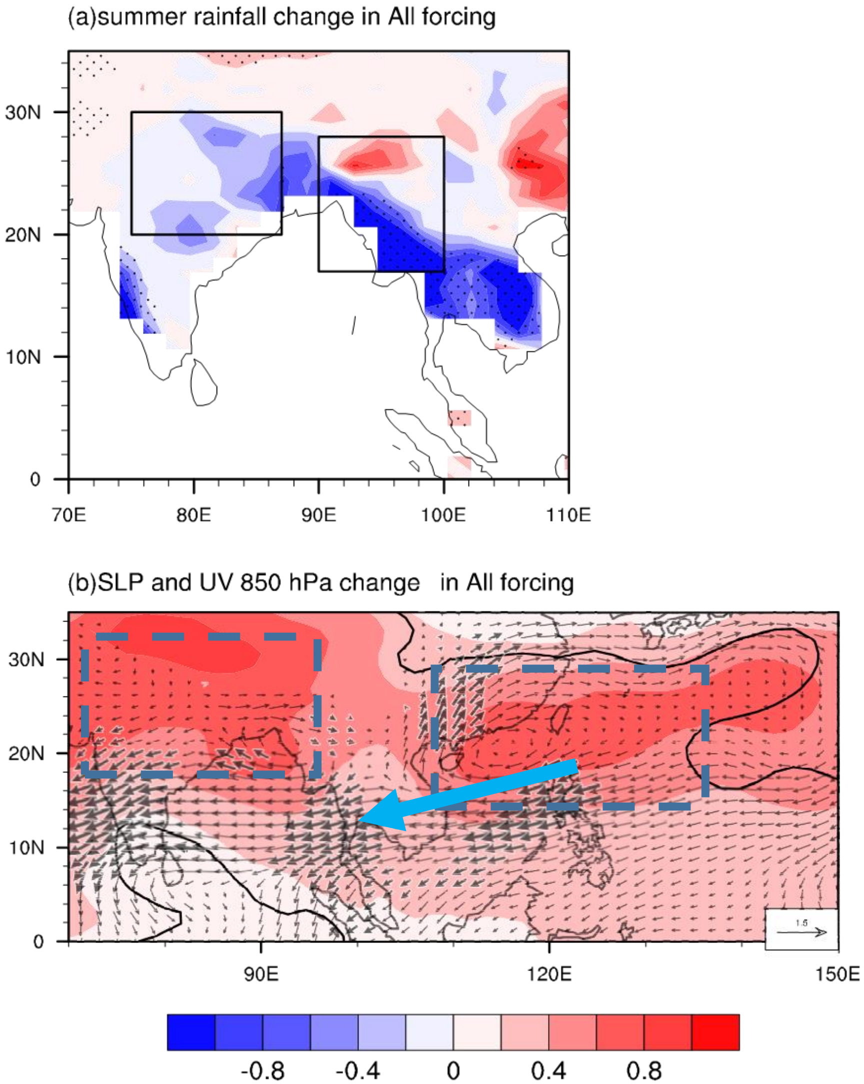
Summer mean SST difference between PD and EP



- MetUM-GOML2 simulates the essential climatological features well. It is an appropriate tool to investigate the response of regional precipitation to changes in different anthropogenic forcings.

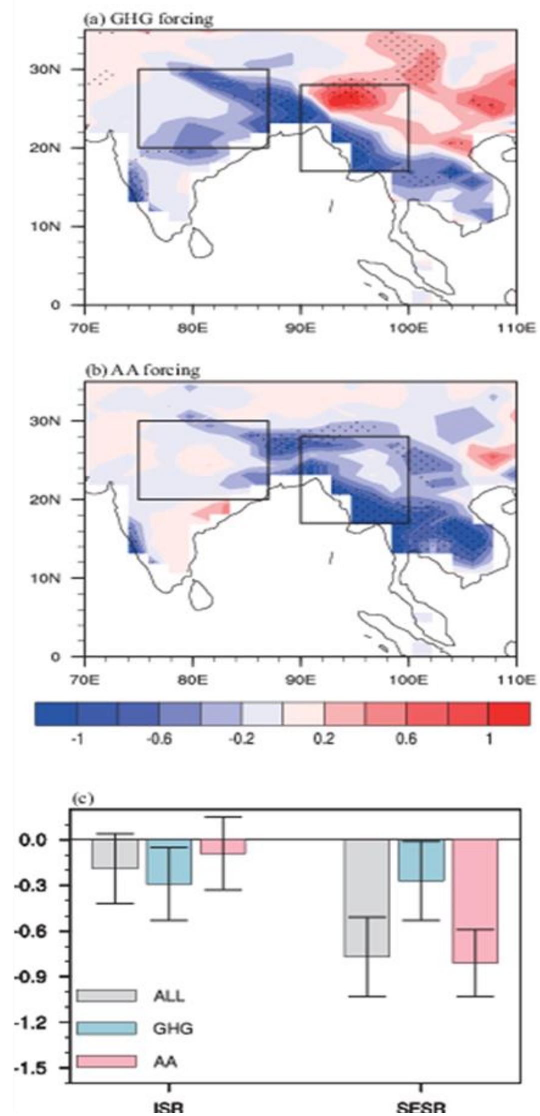
4. Model simulated changes in response to different forcings

All Forcing



GHG Forcing

AA Forcing

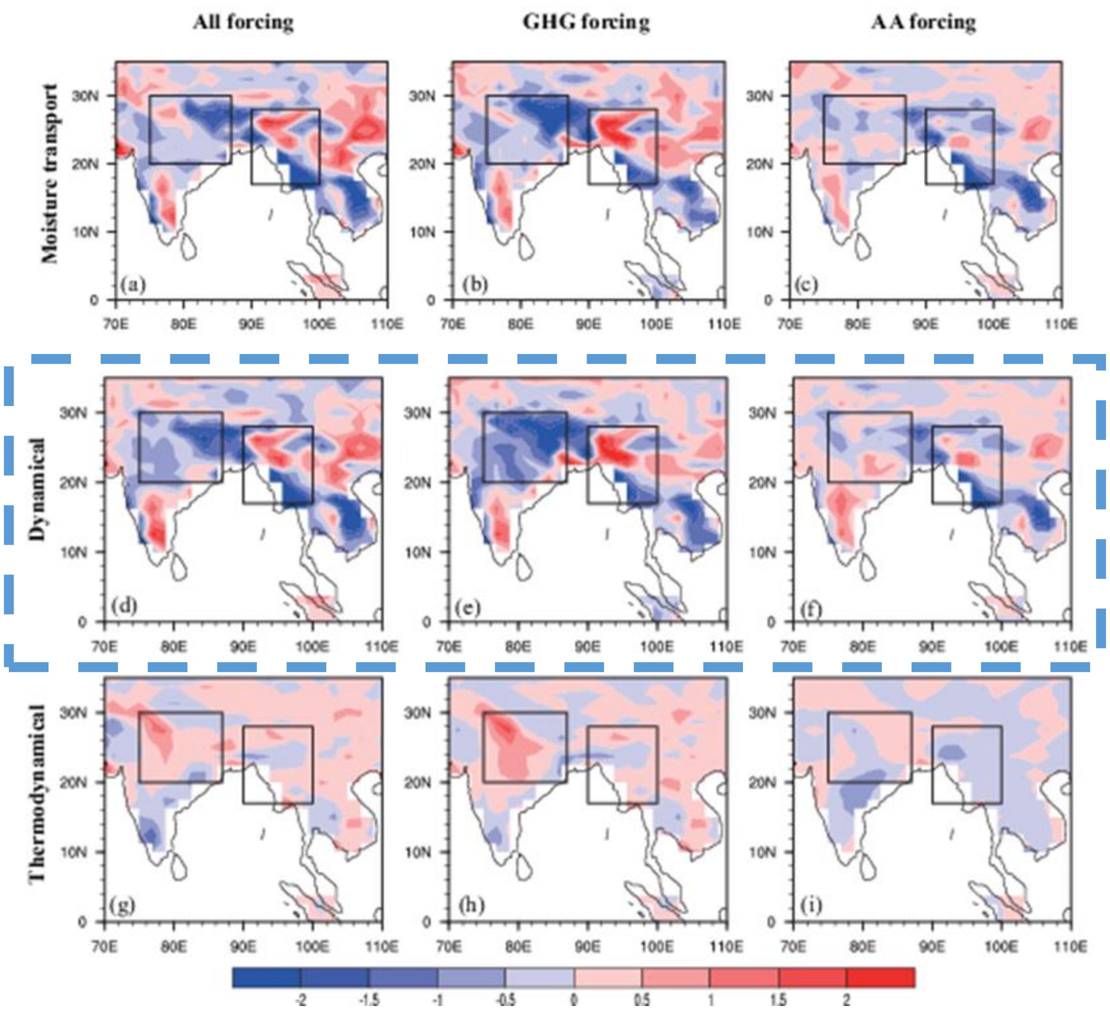


5. Physical processes for the model simulated changes in response to different forcings

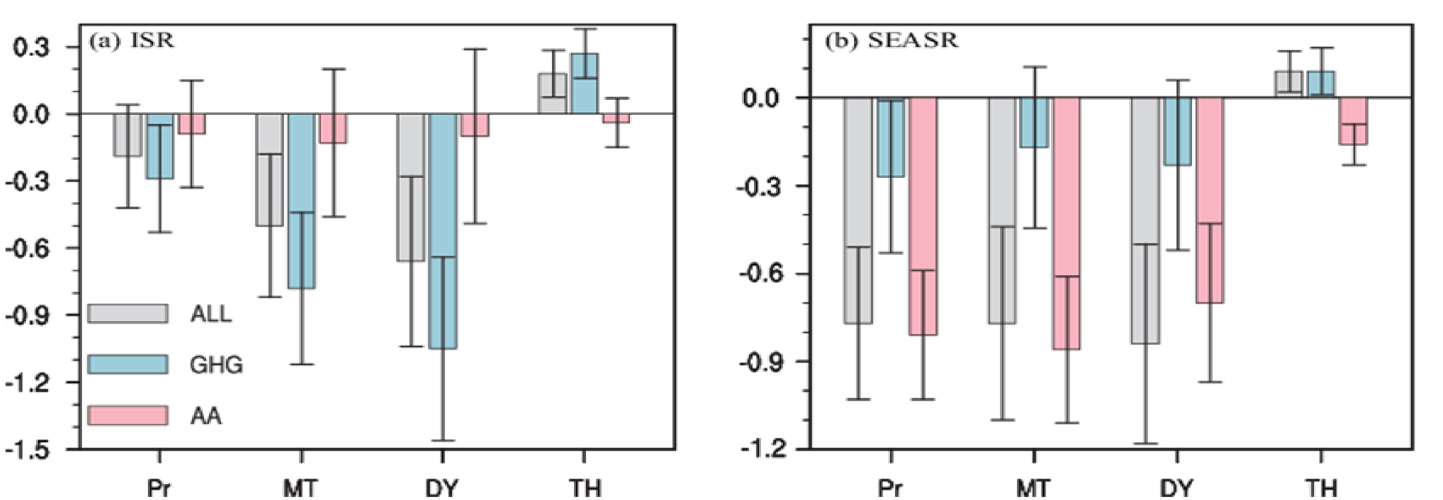
The processes related to the decadal changes

$$-\frac{1}{g\rho_w}\nabla\cdot\sum_{k=1}^{K}\delta\bar{\bar{\mathbf{u}}}_k\bar{\bar{q}}_{k,C}\overline{\overline{\Delta p}}_k$$

$$-\frac{1}{g\rho_w}\nabla\cdot\sum_{k=1}^{K}\bar{\bar{\mathbf{u}}}_{k,C}\delta\bar{\bar{q}}_k\overline{\overline{\Delta p}}_k$$



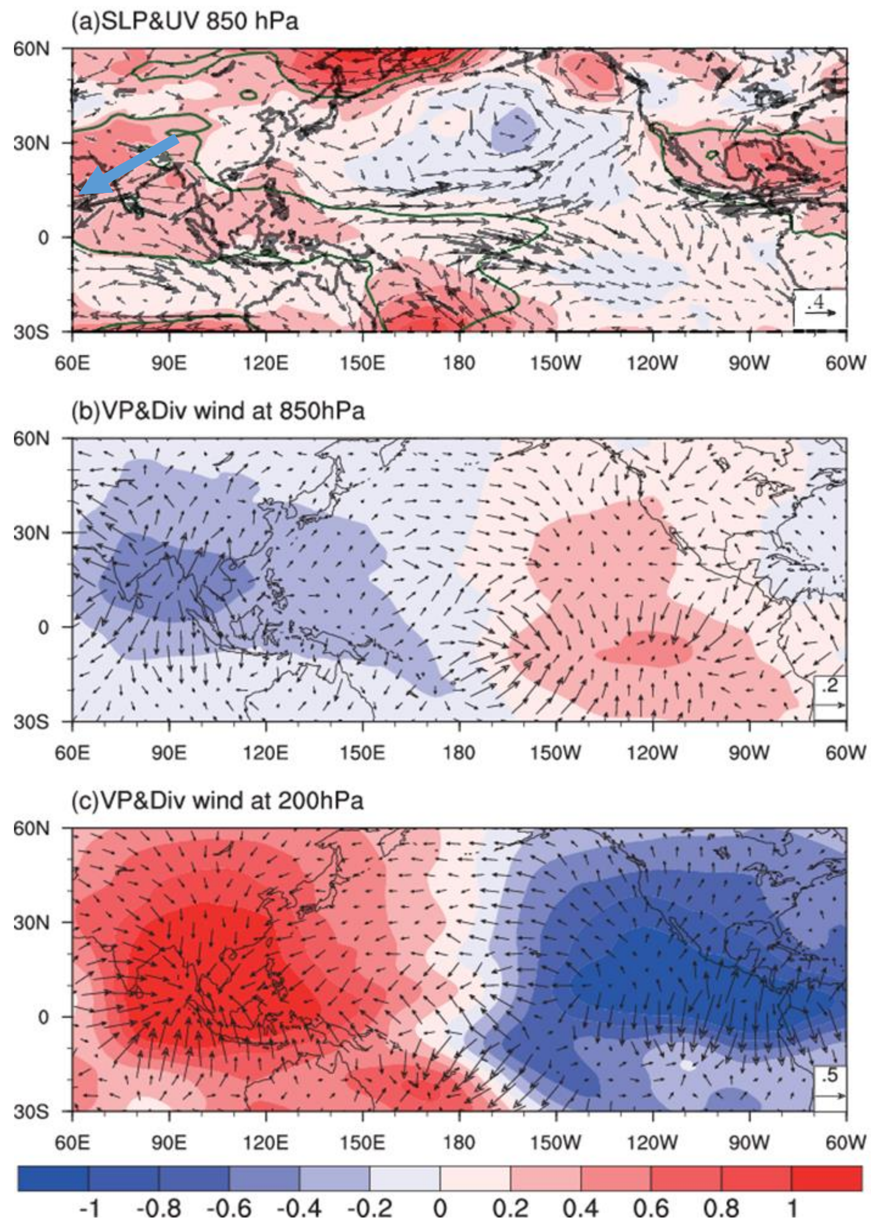
ISR **SEASR**



GHG → DY → Decreased Precipitation
GHG → TH → Increased Precipitation

AA → DY → Decreased Precipitation
AA → TH → Decreased Precipitation

Changes of atmospheric circulation induced by GHG forcing: a weakened Walker circulation



Responses to GHG forcing

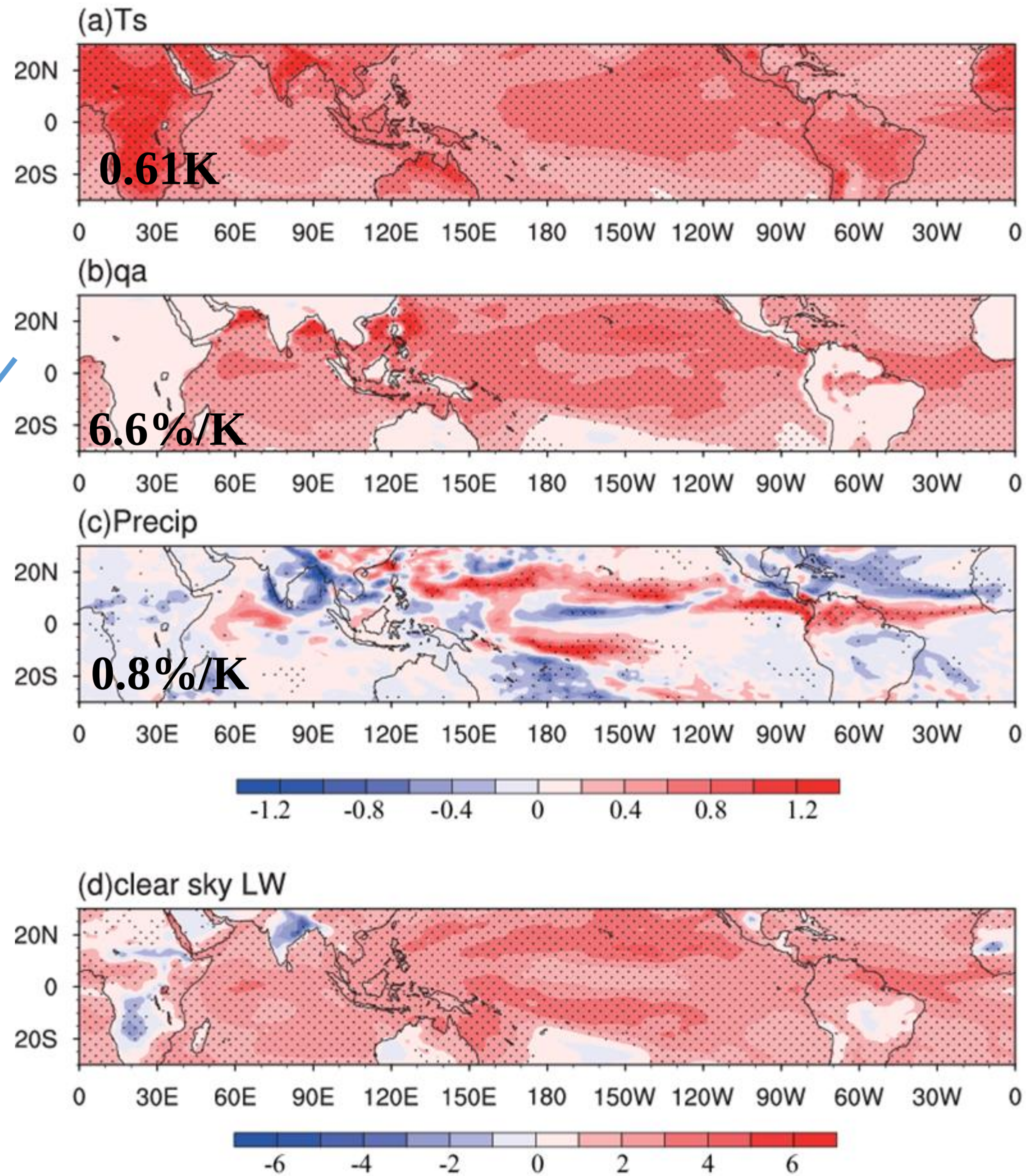
M=P/q

M: the equivalent convective mass flux

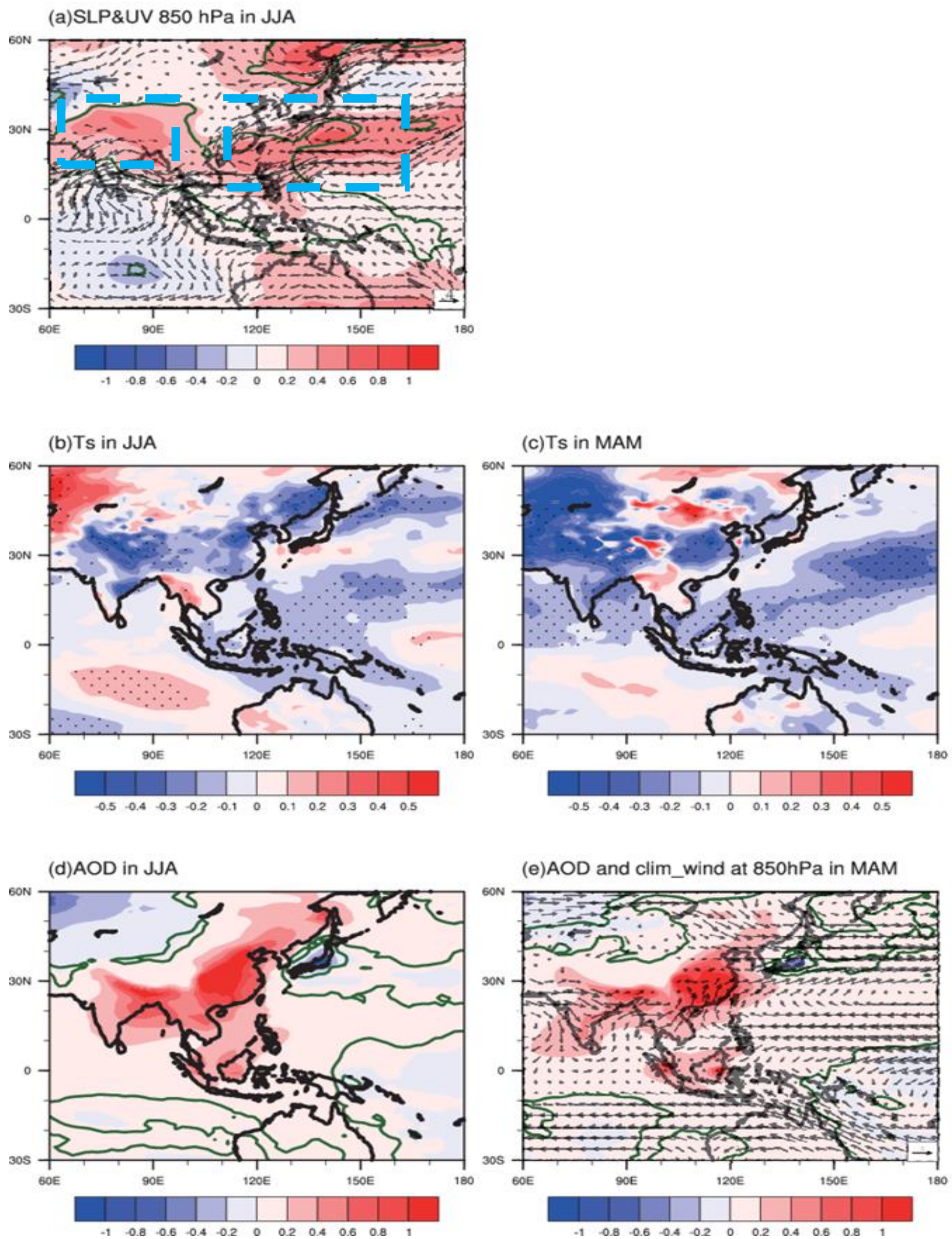
P: precipitation

q: near-surface specific humidity

The mean M decrease at 5.8% K^{-1}



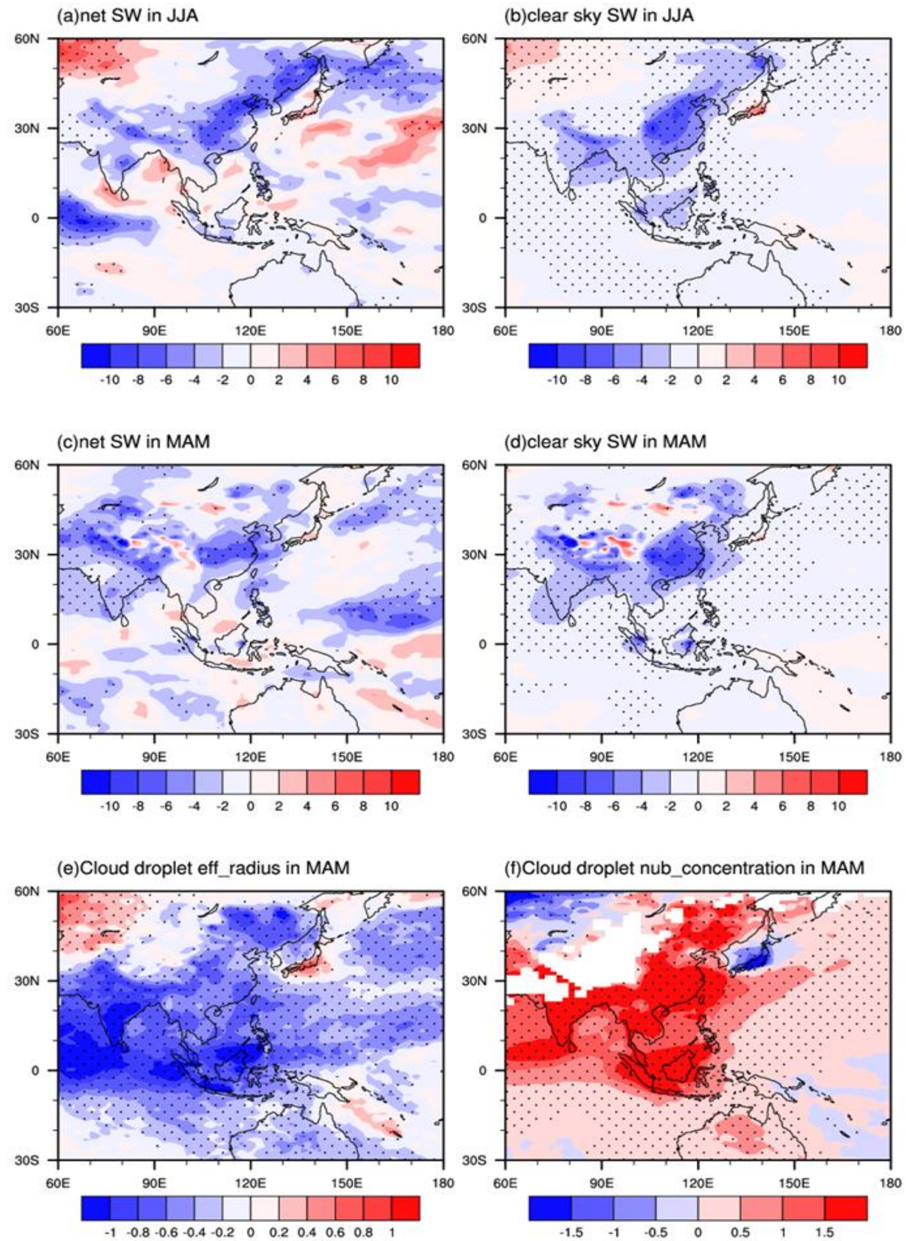
Changes of atmospheric circulation induced by AA forcing



Spatial patterns of responses to AA forcing

JJA

MAM



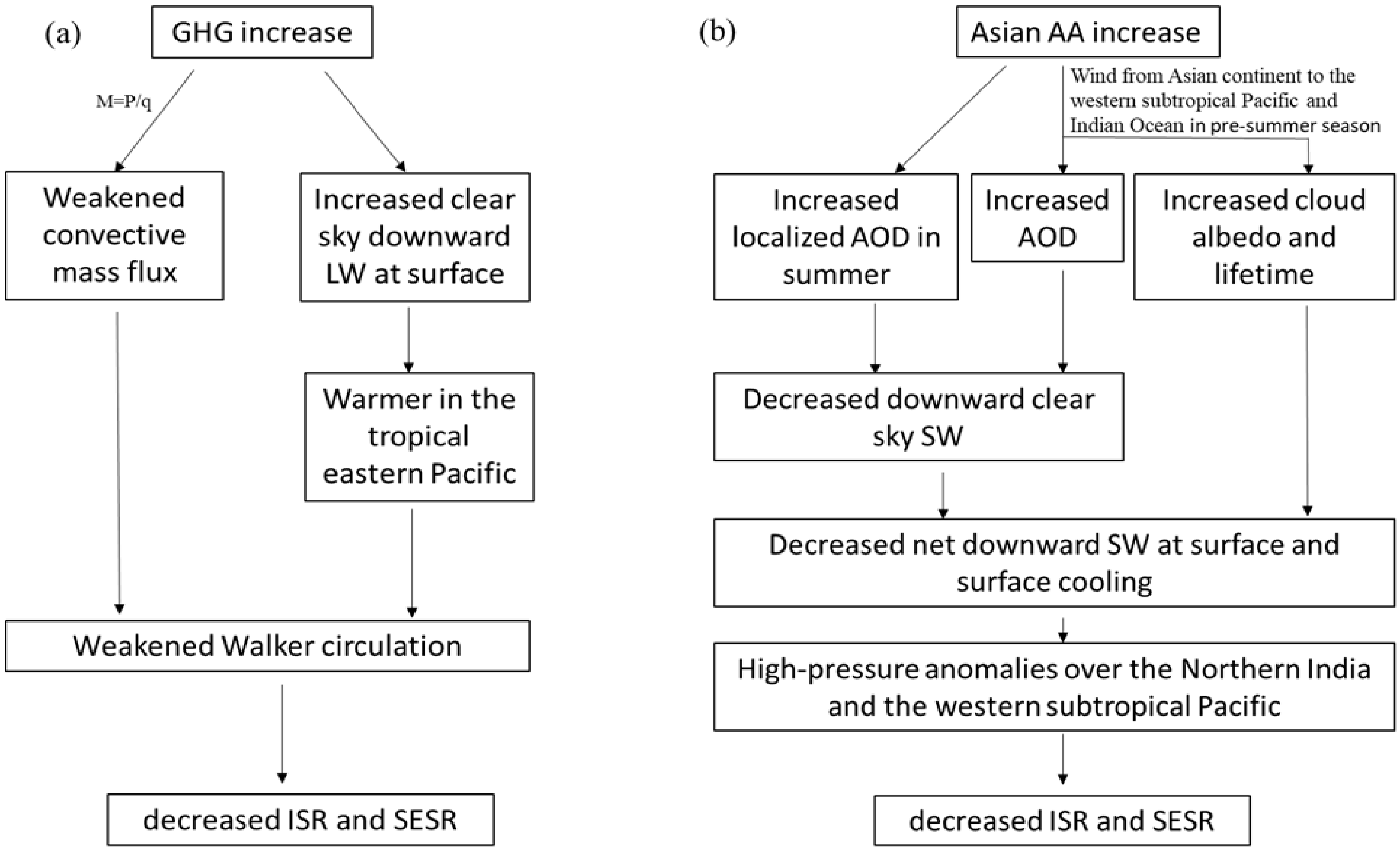
6. Conclusions

1. **Anthropogenic changes play a dominant role** for the decadal changes of the ISR and SEASR across the mid-1990s.

2. **The changes in GHG forcing** plays an important role for **the decreased ISR** with additional contribution from changes in AA forcing, while **the decreased SEASR** is mainly contributed by the changes in **AA forcing**.

3. **The dynamic processes** associated with circulation changes dominate the drought conditions over the Indian subcontinent and Indo-China Peninsula.

Schematic diagrams for the dynamic processes



THANK YOU