地球系统数值模拟与应用全国重点实验室
State Key Laboratory of Earth System Numerical Modeling and Application

The Eighth WMO International Workshop on Monsoons (IWM-8)

Constrained projection of Afro-Asian monsoon precipitation

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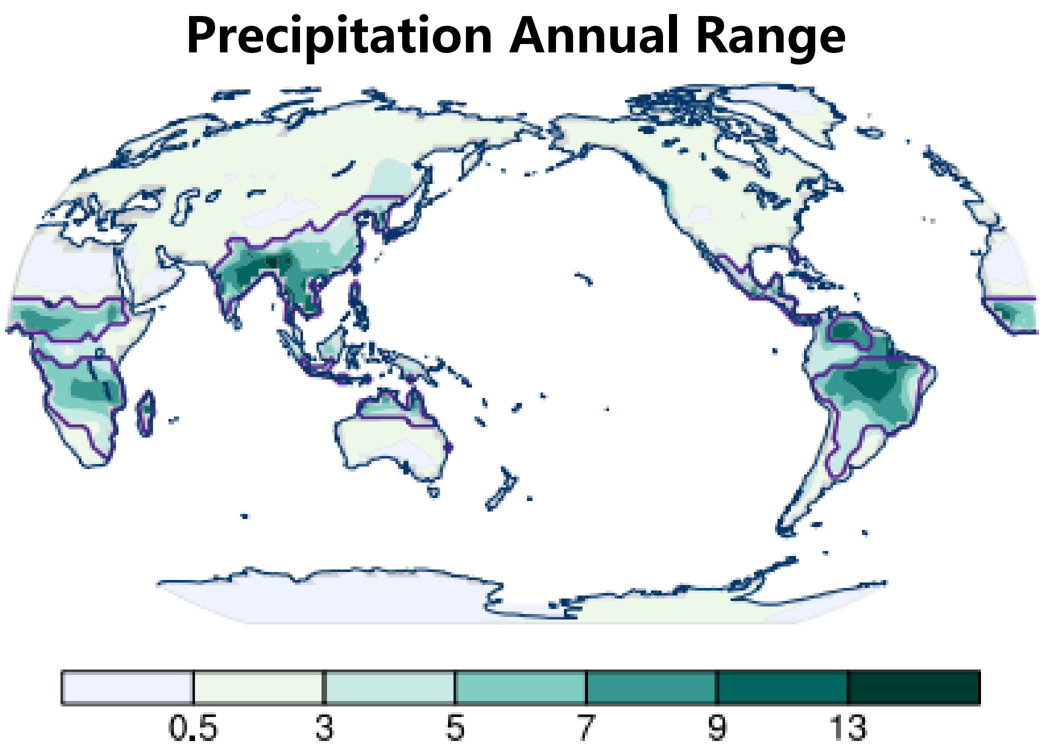
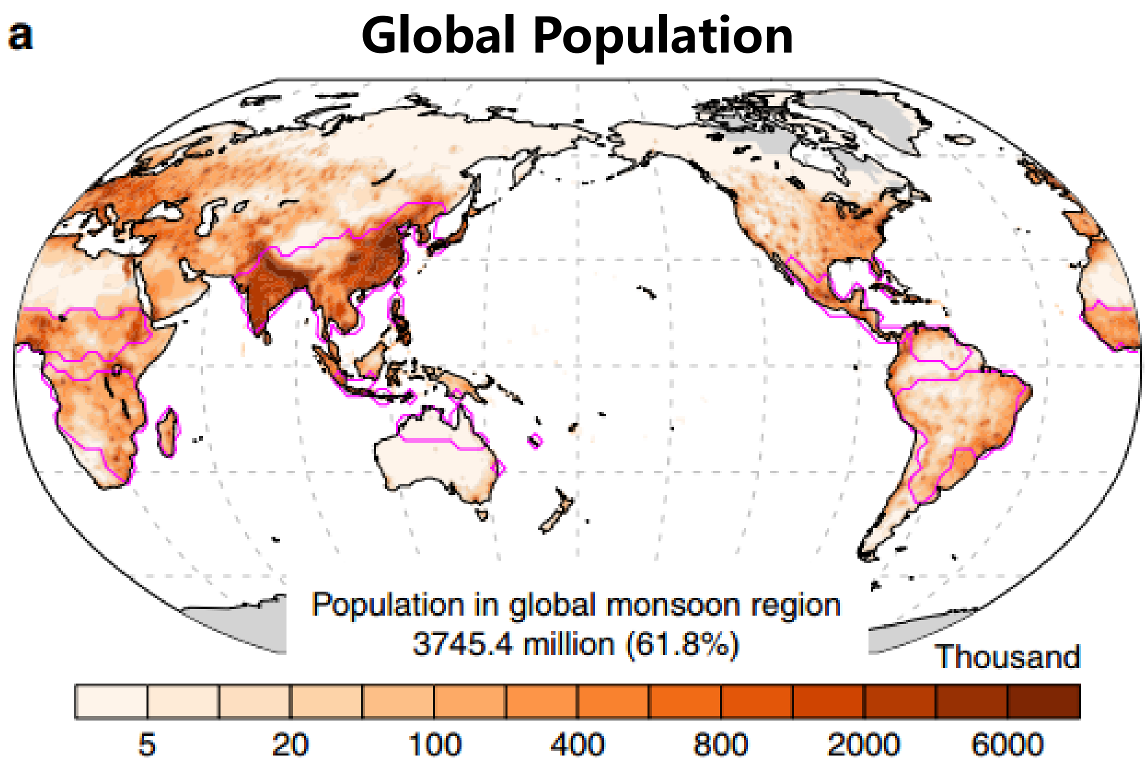
Chen, Z., **Zhou, T.***, **Chen, X.** *et al.* (2022) Observationally constrained projection of Afro-Asian monsoon precipitation. ***Nat Commun*** 13, 2552.

Introduction



(Chen Z. et al. 2020 Earth's Future)

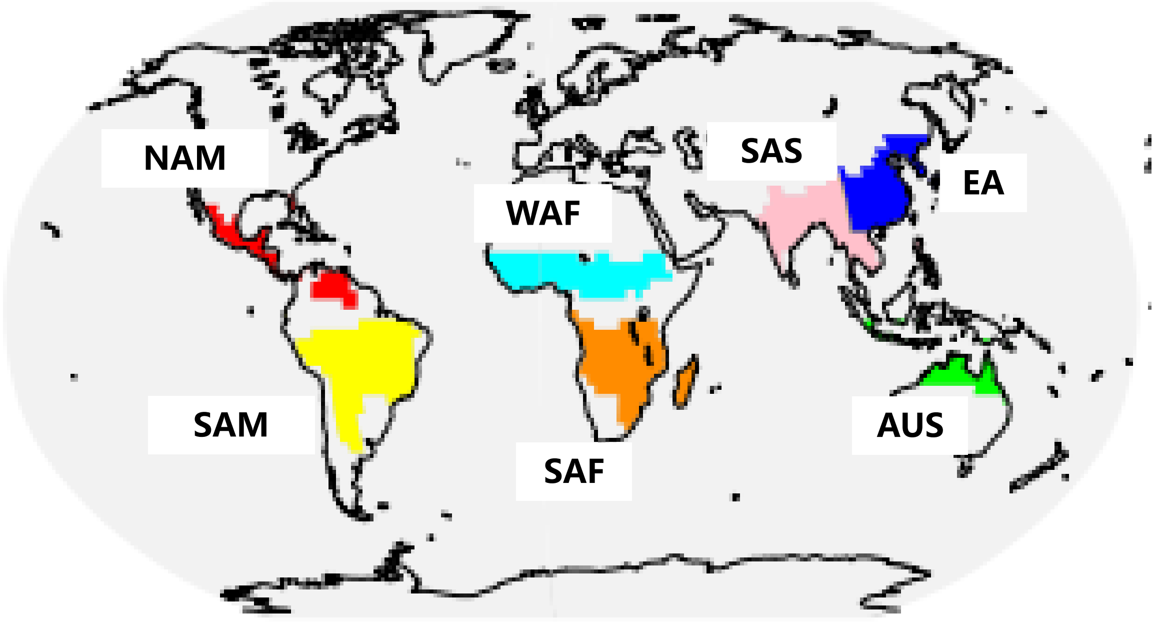


(Zhang et al., 2018)

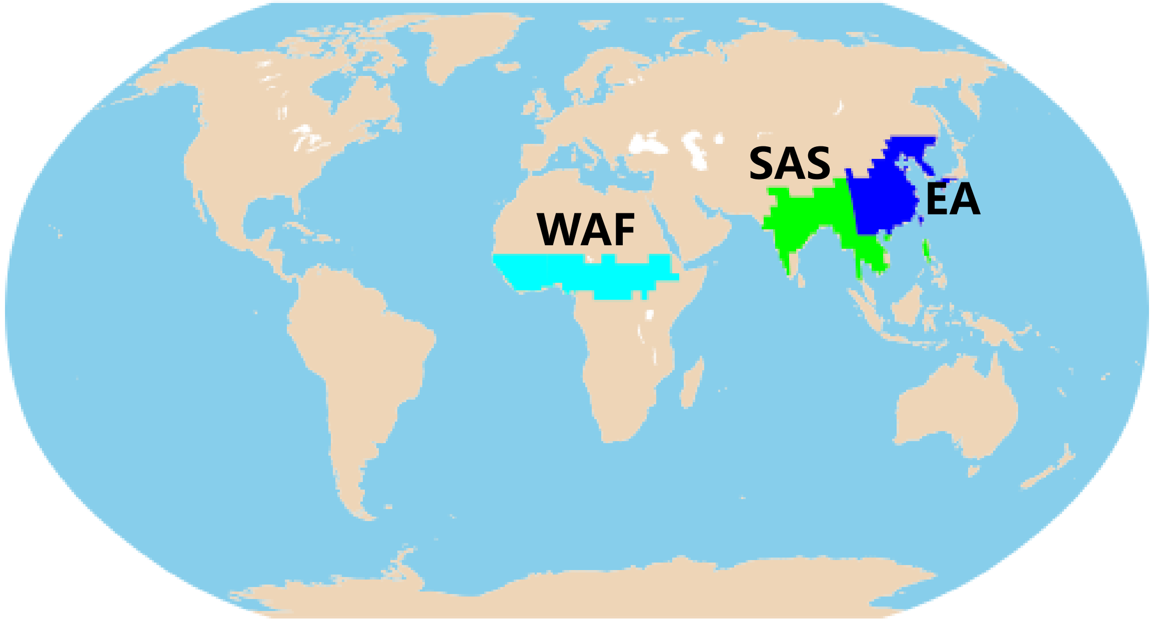
- Monsoon precipitation has large variabilities and influences the global energy budget and water cycle (e.g. Wang & Ding, 2008; Trenberth et al., 2011)
- The variability of precipitation affects the water resource sustaining two third of global population (e.g. Epule et al., 2014; Zhang et al., 2018; Wang B. et al., 2020b)

Monsoon Domain

Global Land Monsoon (GLM)



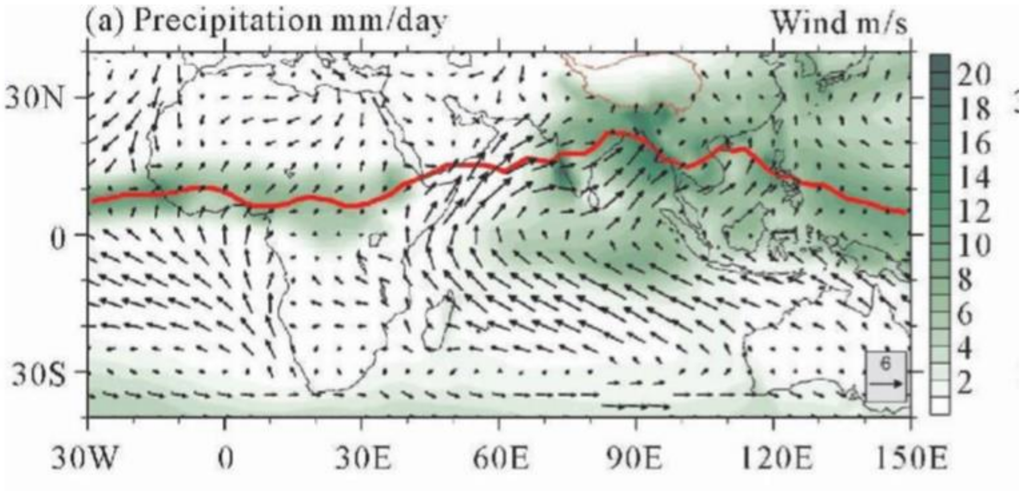
Afro-Asian Monsoon

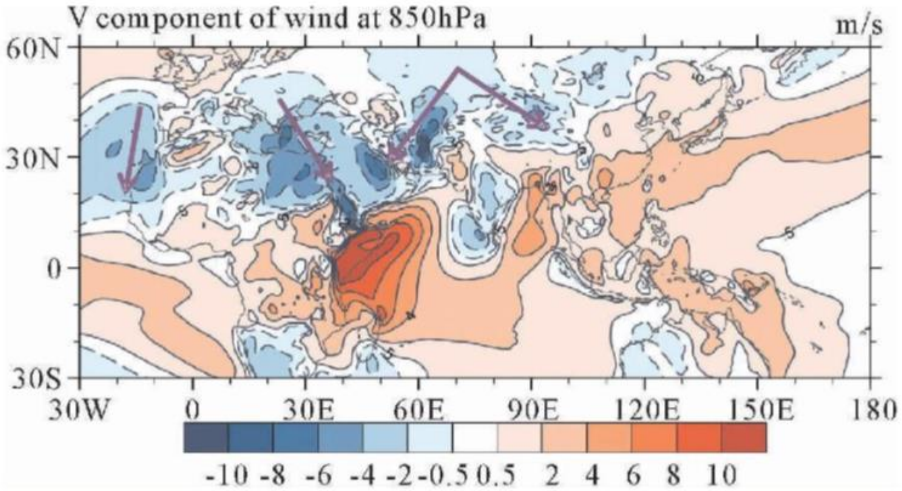


- ✓Definition (Wang et al., 2012):
  - ✓Precipitation Annual Range > 2 mm day^{-1}
  - ✓Percentage of Local Summer Precipitation > 55%

Afro-Asian Summer Monsoon (AfroASM)

Climatology of Summer Precipitation and Low-level Circulation



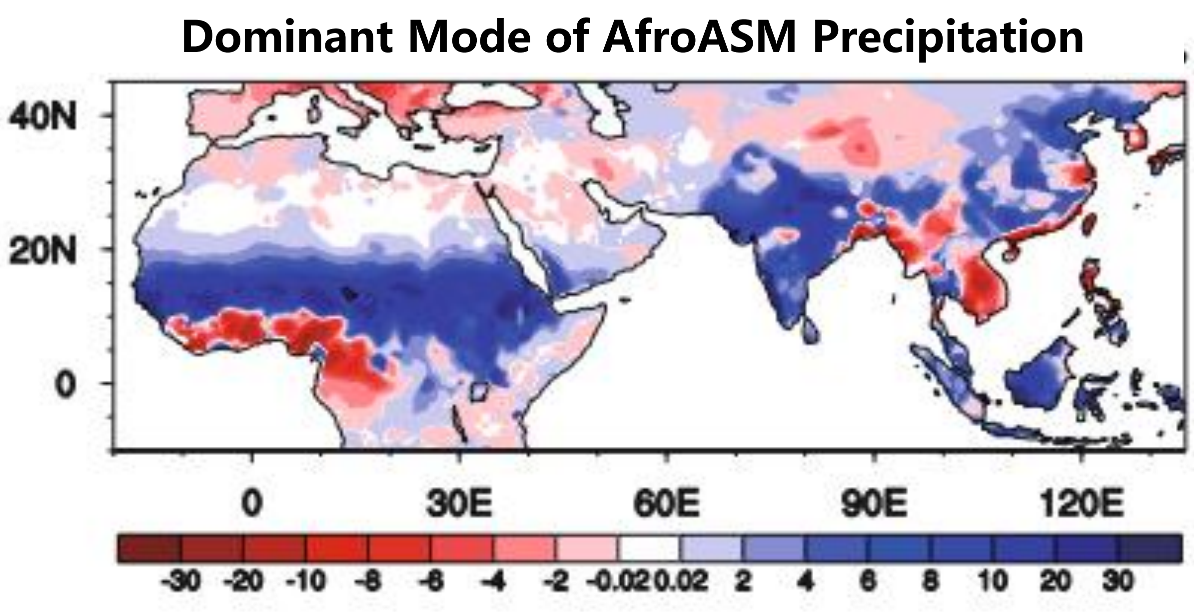


- ✓ Red cruve: precipitation maximum
- ✓ Vector: low-level wind field

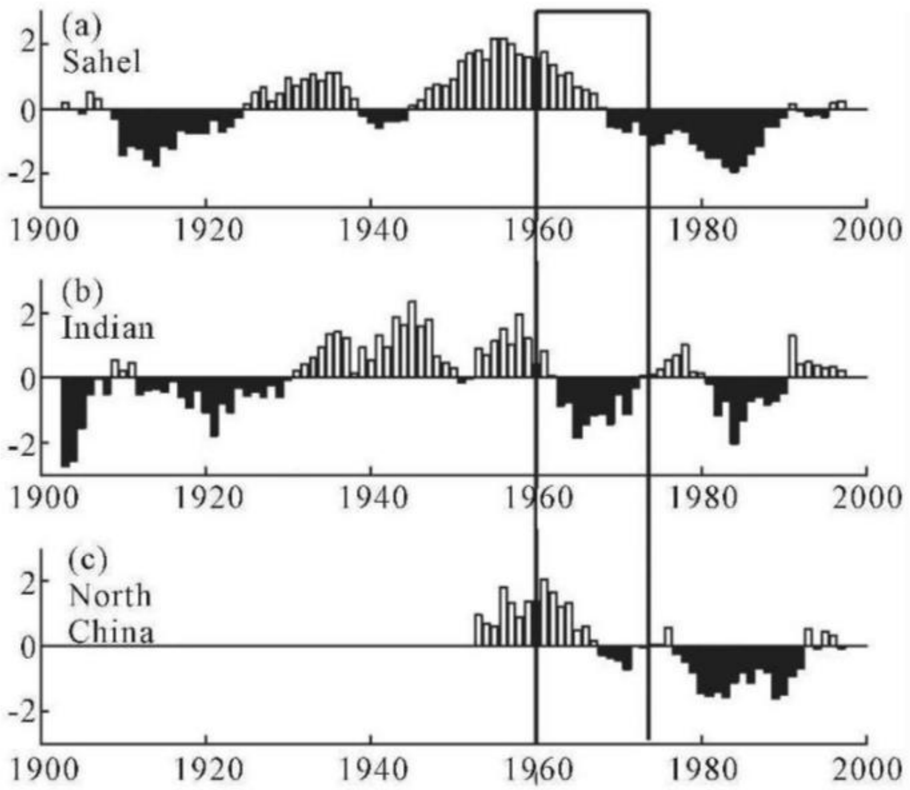
(Ding & Li, 2016 J. Trop Meteor)

- A zonally planetary-scale system, with a large-scale rainbelt on various timescales
  (e.g. Stager et al., 2010 Science; Ding & Li, 2016 J. Trop Meteor; Li et al., 2017 AAS; Ding et al., 2020 Trans. Atmos. Sci.; He et al., 2020 JC)
- AfroASM sustains billions of people living in many developing countries
  (e.g. Epule et al., 2014 Regional Env. Change; Zhang et al., 2018 Nat. Commun.; Wang et al., 2020 BAMS)

Afro-Asian Summer Monsoon (AfroASM)



(Li Y. et al., 2017 AAS)



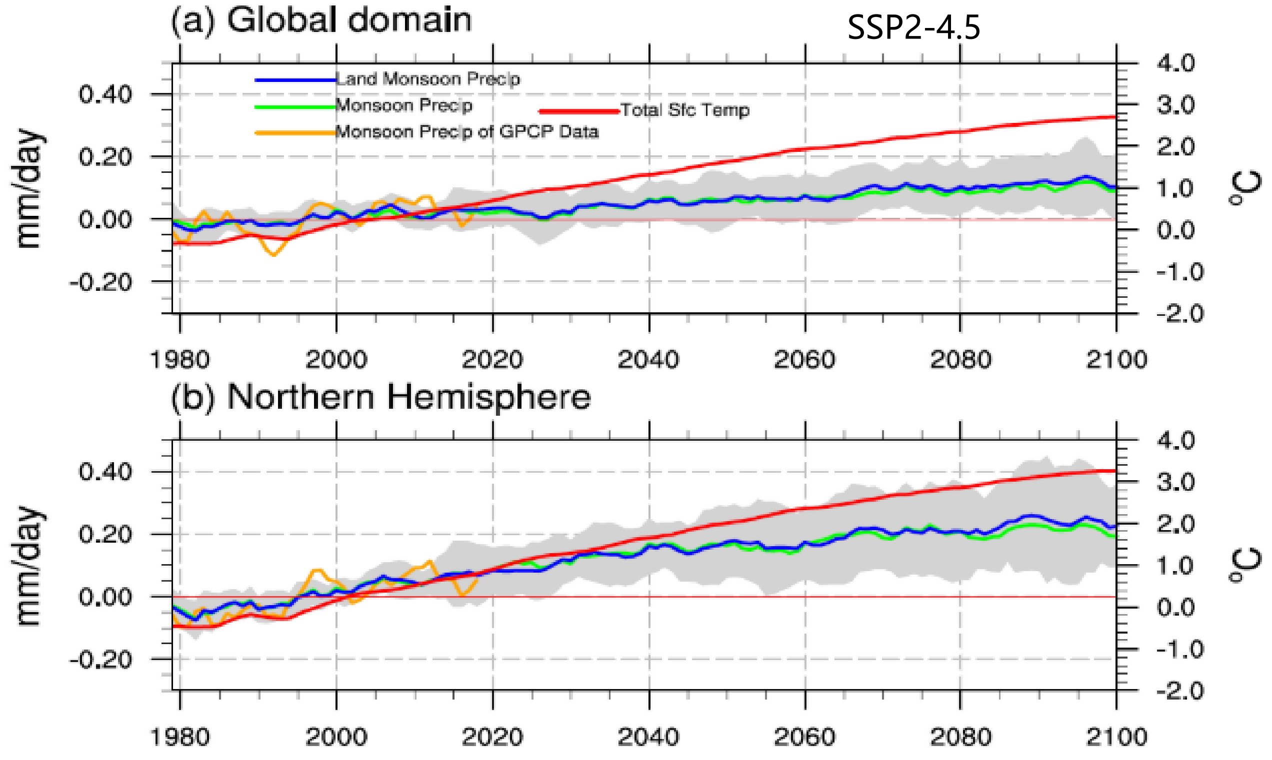
(Liu et al., 2012 JC)

- In-phase changes at various time scales due to the modulation of ITC and SST variation of North Atlantic (e.g. Ji et al., 1993 Global & Planetary Change; 严中伟和Petit-Maire, 1995 地理学报; 宋燕和季劲钧, 2001 大气科学; 宋燕等, 2009 大气科学; Stager et al., 2011 Sciences; 丁一汇和李怡, 2016 热带气象学报; Li Y. et al., 2017 AAS; 丁一汇等, 2020 大气科学学报)

ITC: Interhemispheric thermal contrast

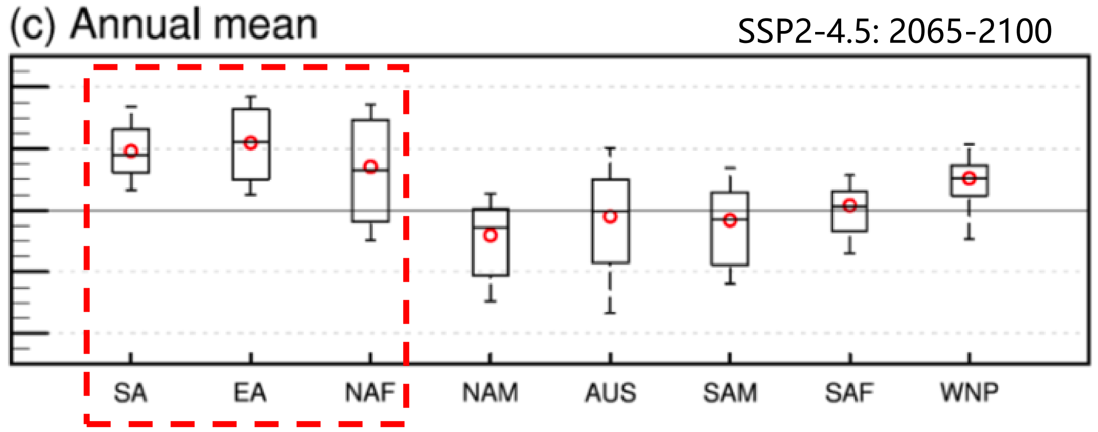
Future Projection of Monsoon Precipitation

Monsoon mean precipitation (blue & green) versus global mean SAT (red)



Wang B. et al. (2020 JC)

Future Projection of Sub-monsoon Precipitation



(Jin et al., 2020)

- A pronounce increase over global (NH) monsoon region in the future projection

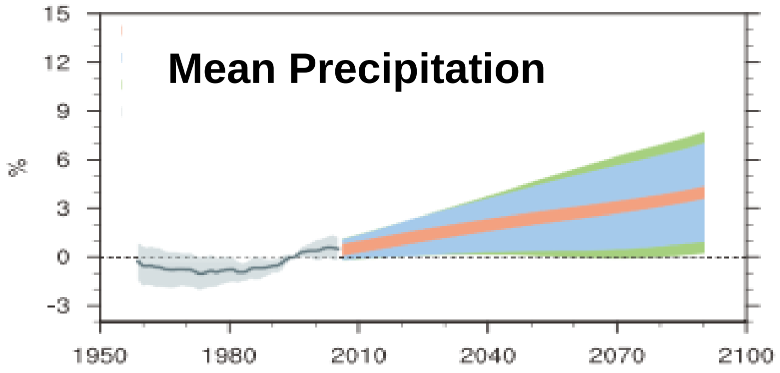
(e.g. Christensen et al., 2013; Kitoh et al., 2013 JGRA; Lee & Wang, 2014 CD; Wang B. et al. 2020 JC; Chen Z. et al., 2020 GRL; Ha et al., 2020 GRL; Moon & Ha, 2020 npj)

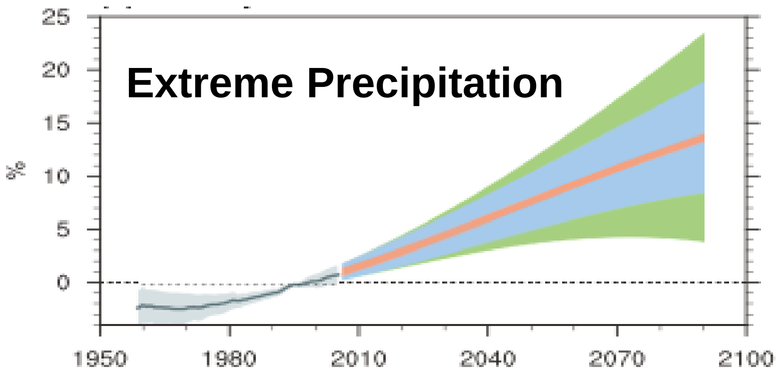
- Response of AfroASM precipitation is stronger than that over global and other sub monsoon region

(Lee & Wang, 2014 CD; Ha et al., 2020 GRL; Jin et al., 2020 JC; Chen et al., 2020 GRL; He et al., 2020 JC)

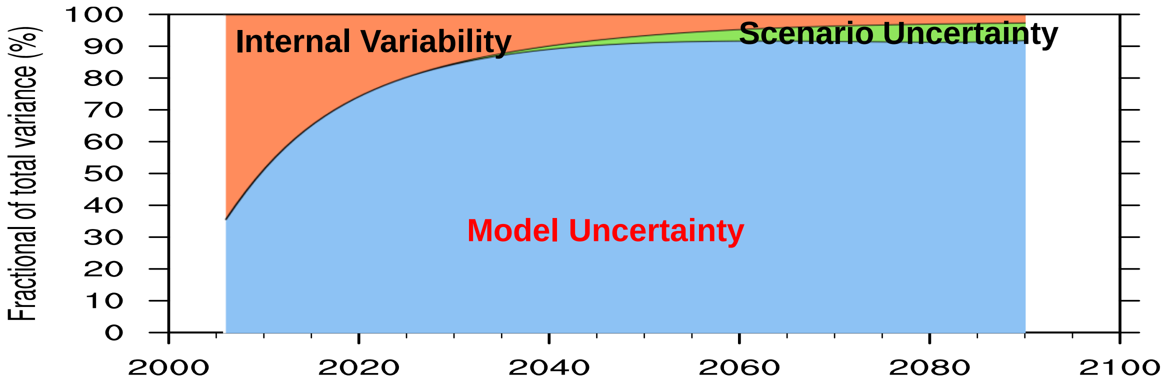
Projection Uncertainty

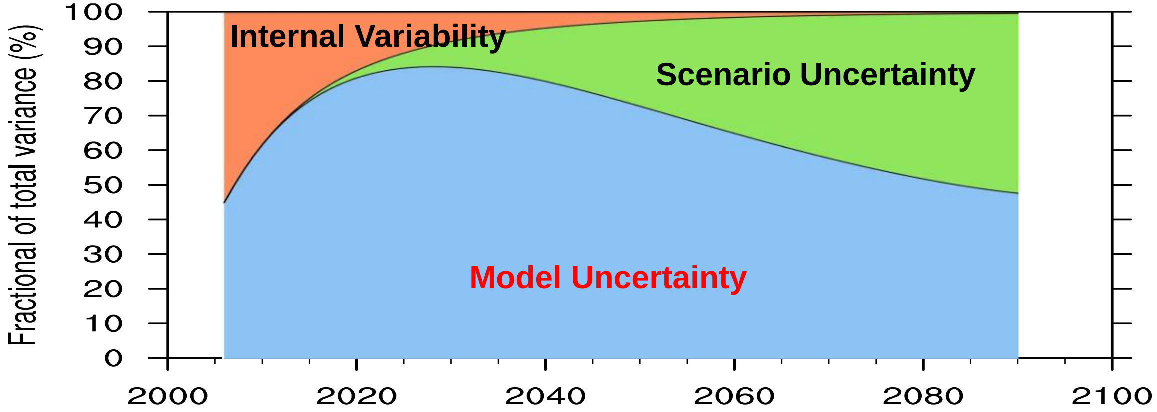
Evolution of uncertainty components





Fraction of total uncertainty



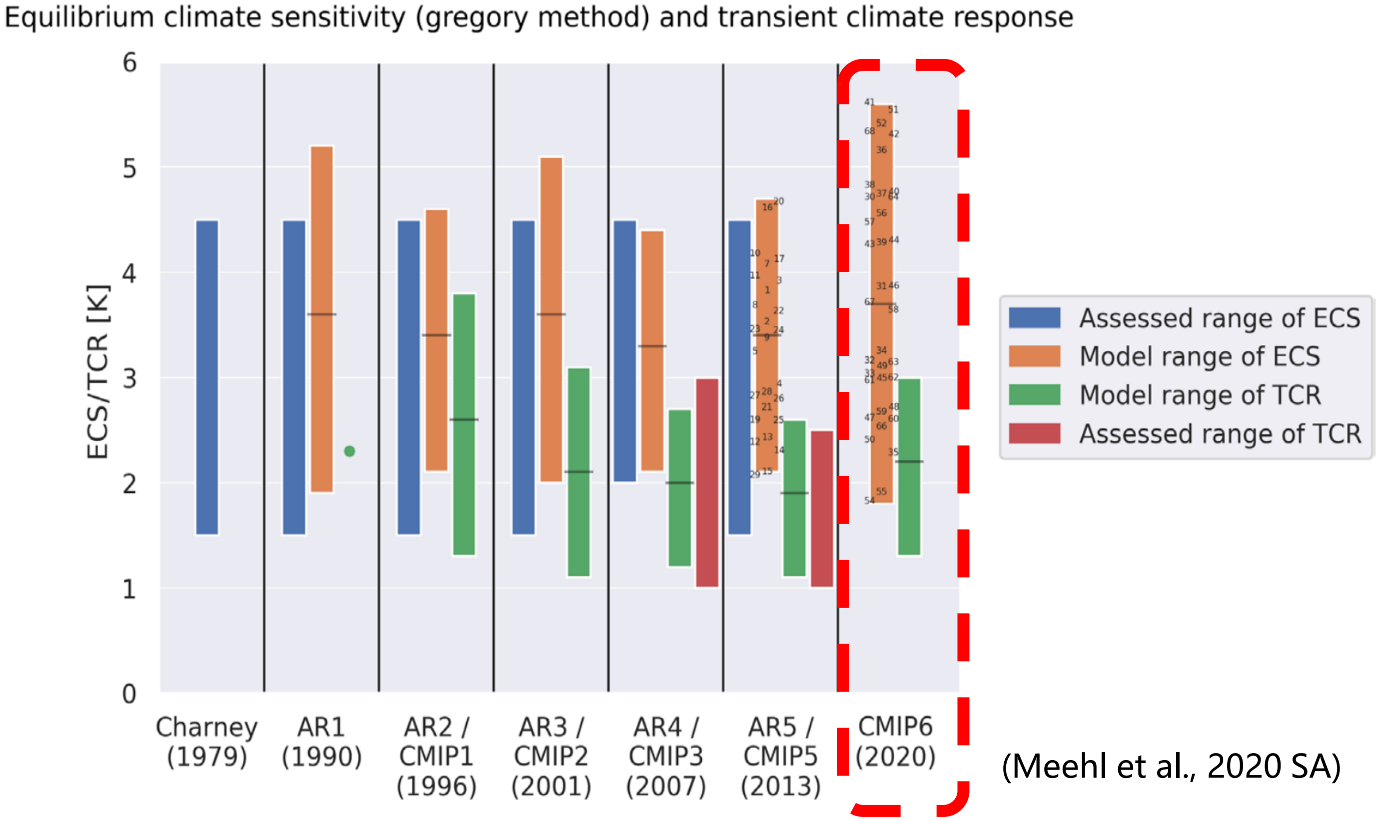


- Model uncertainty is the dominant contributor throughout the 21st century (~90%)
- Internal variability is important in the near future
- Scenario uncertainty becomes important for extreme precipitation at the end of the century

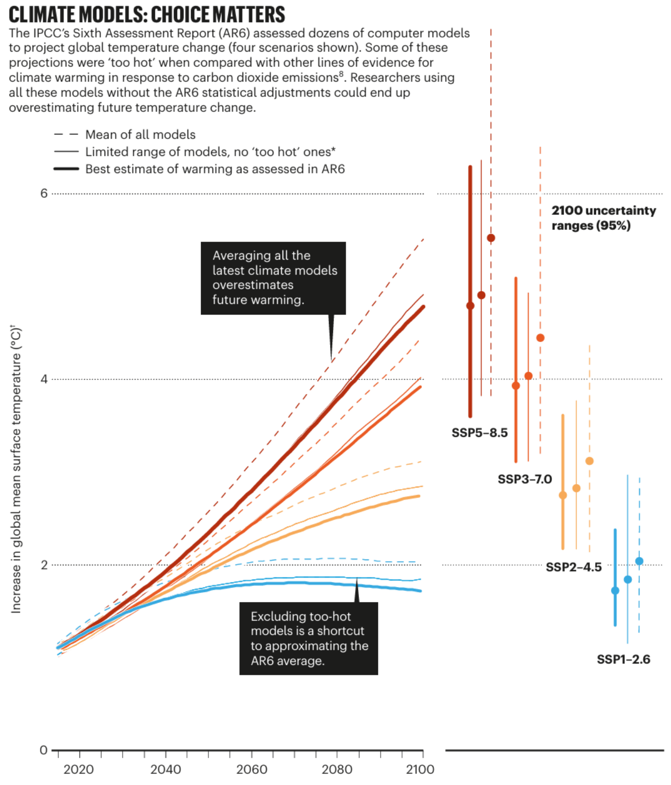
Zhou, T., Lu, J., Zhang, W., & Chen, Z. (2020). The sources of uncertainty in the projection of global land monsoon precipitation. Geophysical Research Letters, 47, e2020GL088415.

High ECS in CMIP6 models

- **ECS: equilibrium climate sensitivity**
  - **global mean surface air temperature change at equilibrium for a doubling of pre-industrial CO2**
- **The range of equilibrium climate sensitivity (ECS) is the largest of any generation of models** (Gettelman et al., 2019 GRL; Meehl et al., 2020 SA; Zelinka et al., 2020 GRL)

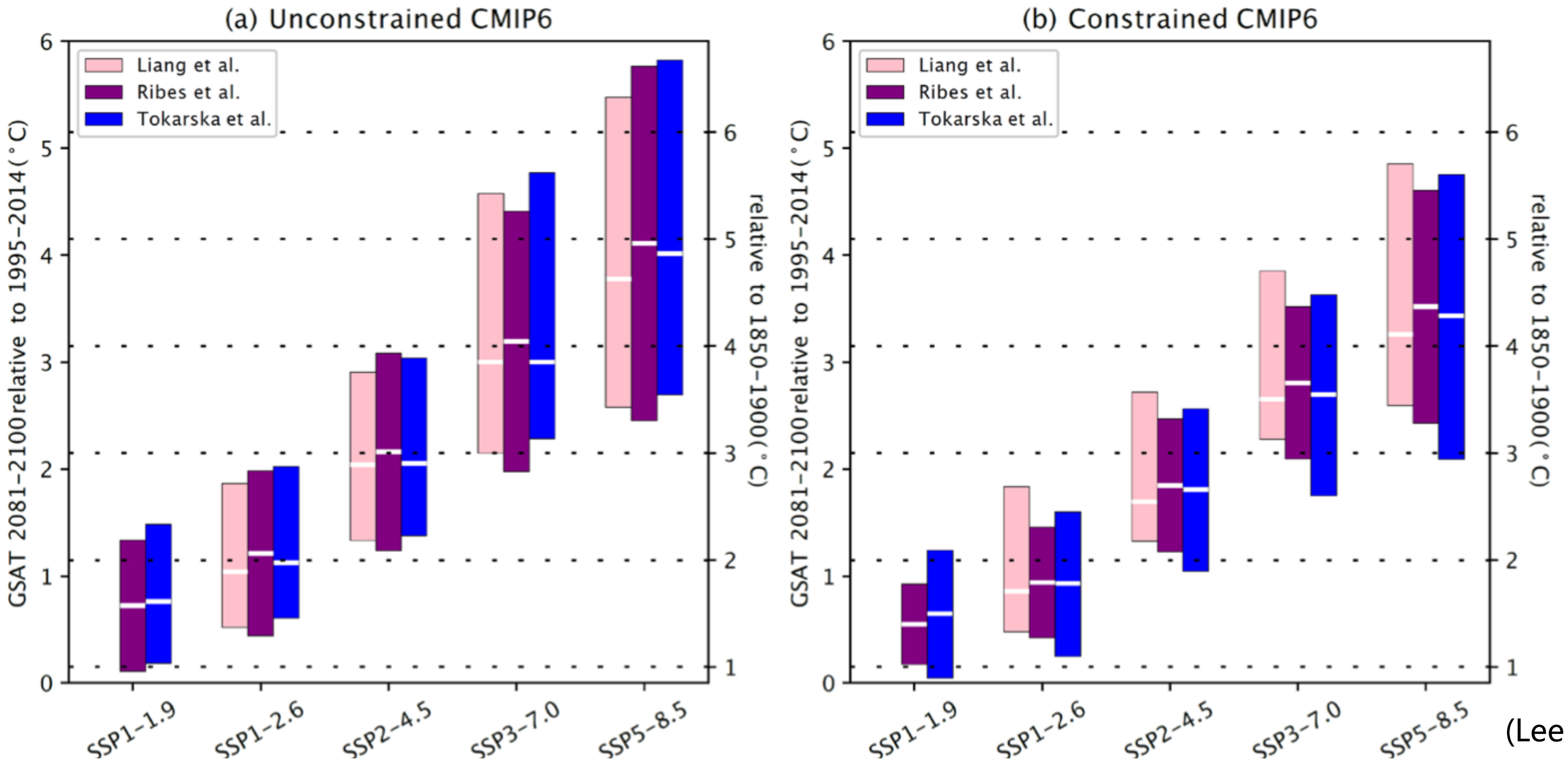


(Meehl et al., 2020 SA)



(Hausfather *et al.* 2022, *Nature*)

Constrained projection in IPCC AR6



(Lee et al., 2022 IPCC AR6 Chap4)

- Multiple lines of evidence for GSAT changes for the long-term period, 2081–2100, relative to the average over 1995–2014, for all five priority scenarios.

Questions

- **What are the future changes and uncertainty in Afro-Asian monsoon precipitation?**
- **How could high ECS of CMIP6 model impact the monsoon projection, and can we constrain the precipitation projection using observational information?**

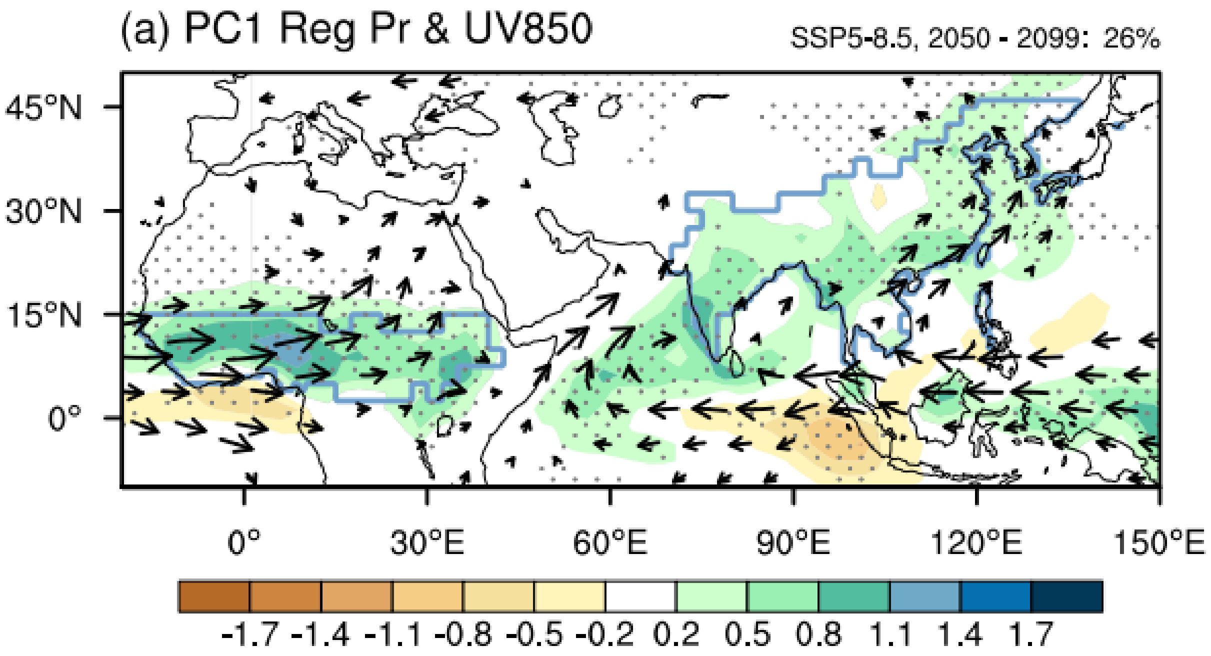
Data and Method

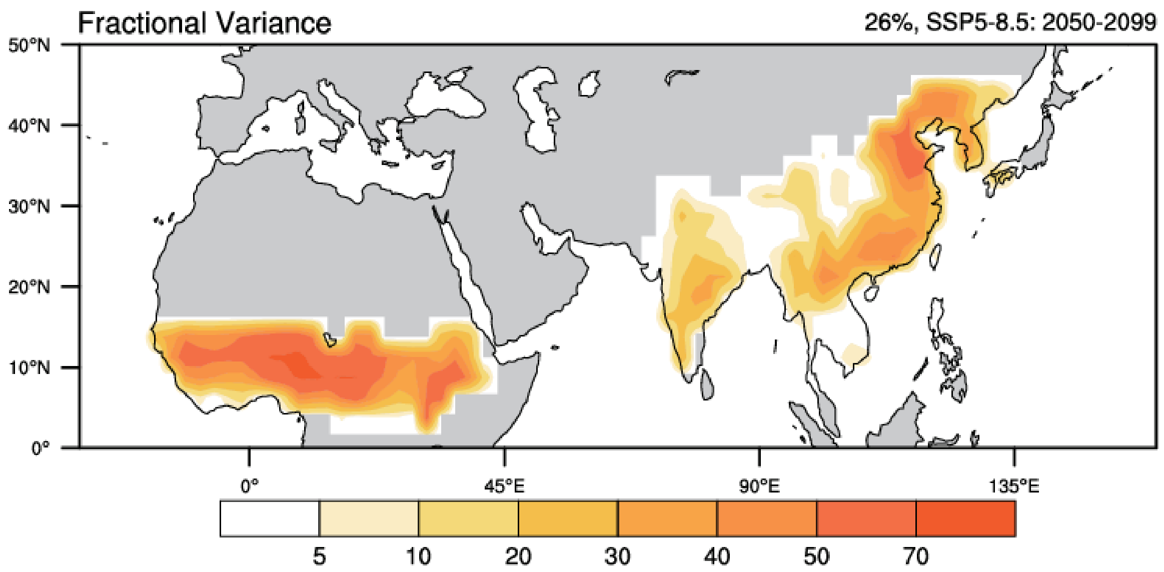
Model	Institute/Country	Lat x Lon
ACCESS-CM2	CSIRO/Australian	144 x 192
ACCESS-ESM1-5	CSIRO/Australian	145 x 192
BCC-CSM2-MR	BCC-CMA/China	160 x 320
CAMS-CSM1-0	CAMS-CMA/China	160 x 320
CESM2-WACCM	NCAR/USA	192 x 288
CNRM-CM6-1	CNRM-CERFACS/France	128 x 256
CNRM-ESM2-1	CNRM-CERFACS/France	128 x 256
CanESM5	CCCMA/Canada	64 x 128
CanESM5-CanOE	CCCMA/Canada	64 x 128
EC-Earth3	EC-Earth-Consortium/EU	256 x 512
EC-Earth3-Veg	EC-Earth-Consortium/EU	256 x 512
FGOALS-f3-L	LASG-IAP/China	180 x 360
FGOALS-g3	LASG-IAP/China	90 x 180
GFDL-CM4	GFDL-NOAA/USA	180 x 360
GFDL-ESM4	GFDL-NOAA/USA	180 x 360
GISS-E2-1-G	GISS-GISS/USA	90 x 144
HadGEM3-GC31-LL	MOHC/UK	144 x 192
INM-CM4-8	INM/Russia	120 x 180
INM-CM5-0	INM/Russia	120 x 180
IPSL-CM6A-LR	IPSL/France	143 x 144
MCM-UA-1-0	UA/USA	80 x 96
MIROC6	MIROC/Japan	128 x 256
MIROC-ES2L	MIROC/Japan	64 x 128
MRI-ESM2-0	MRI/Japan	96 x 192
MPI-ESM1-2-HR	MPI-M/Germany	192 x 384
MPI-ESM1-2-LR	MPI-M/Germany	96 x 192
NESM3	NUIST/China	96 x 192
UKESM1-0-LL	MOHC/UK	144 x 192

Surface Air Temperature	Period	Reference
BEST, 1° x 1°	1854-2018	Rodhe et al., 2013
GISTEMP, 2° x 2°	1880-2018	Lenssen et al., 2019
Cowtan & Way v2, 5° x 5°	1850-2019	Cowtan & Way, 2014
NOAAGlobalTemp v5	1880-2021	Vose et al., 2012

- **CMIP6 30 Models: Historical and SSP5-8.5**
- **Methods**
  - ✓ **Emergent Constraint** (e.g. Klein & Hall, 2015; Hall et al., 2019; Brient, 2019)
  - ✓ **Present day: 1965-2014**
  - ✓ **Future Projection: 2050-2099**

Dominated Mode of Projected Uncertainty

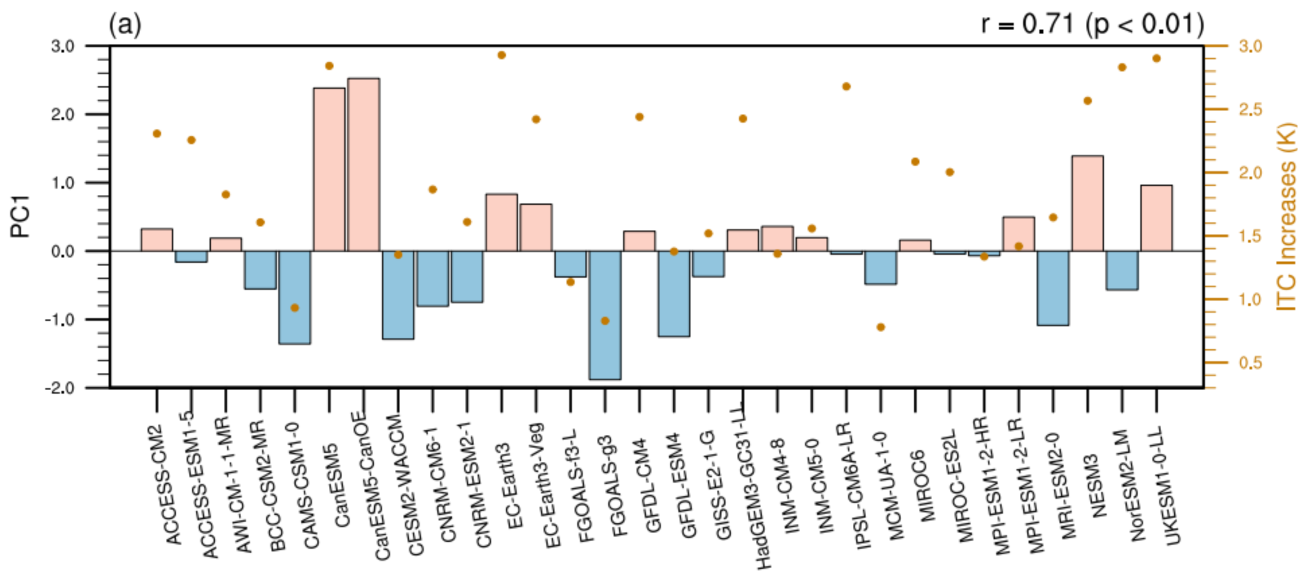




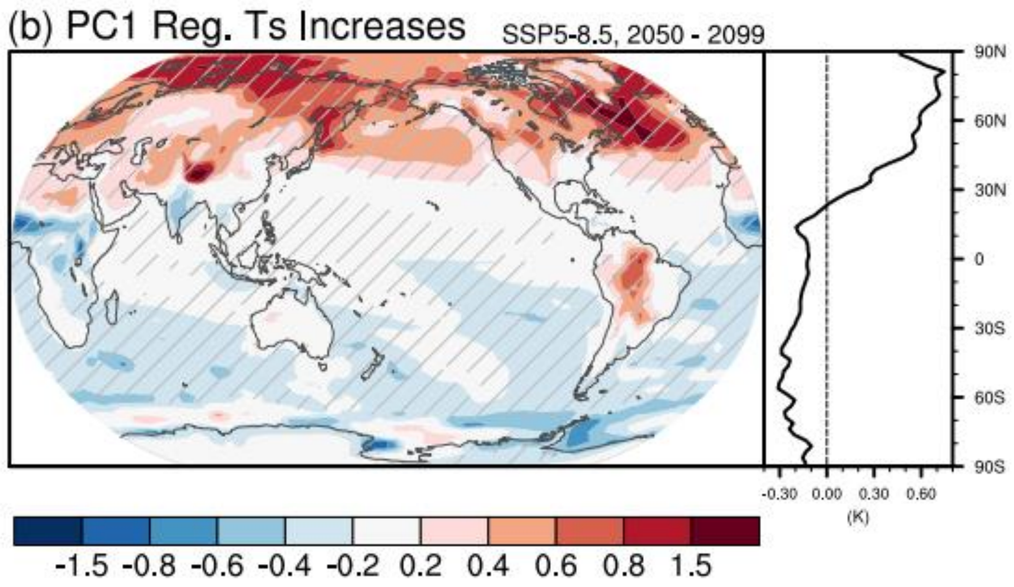
Dominated mode of uncertainty: synchronized precipitation changes in the model spread

Uncertainty in surface warming related to PC1

PC1 (bar) & ITC (dot)



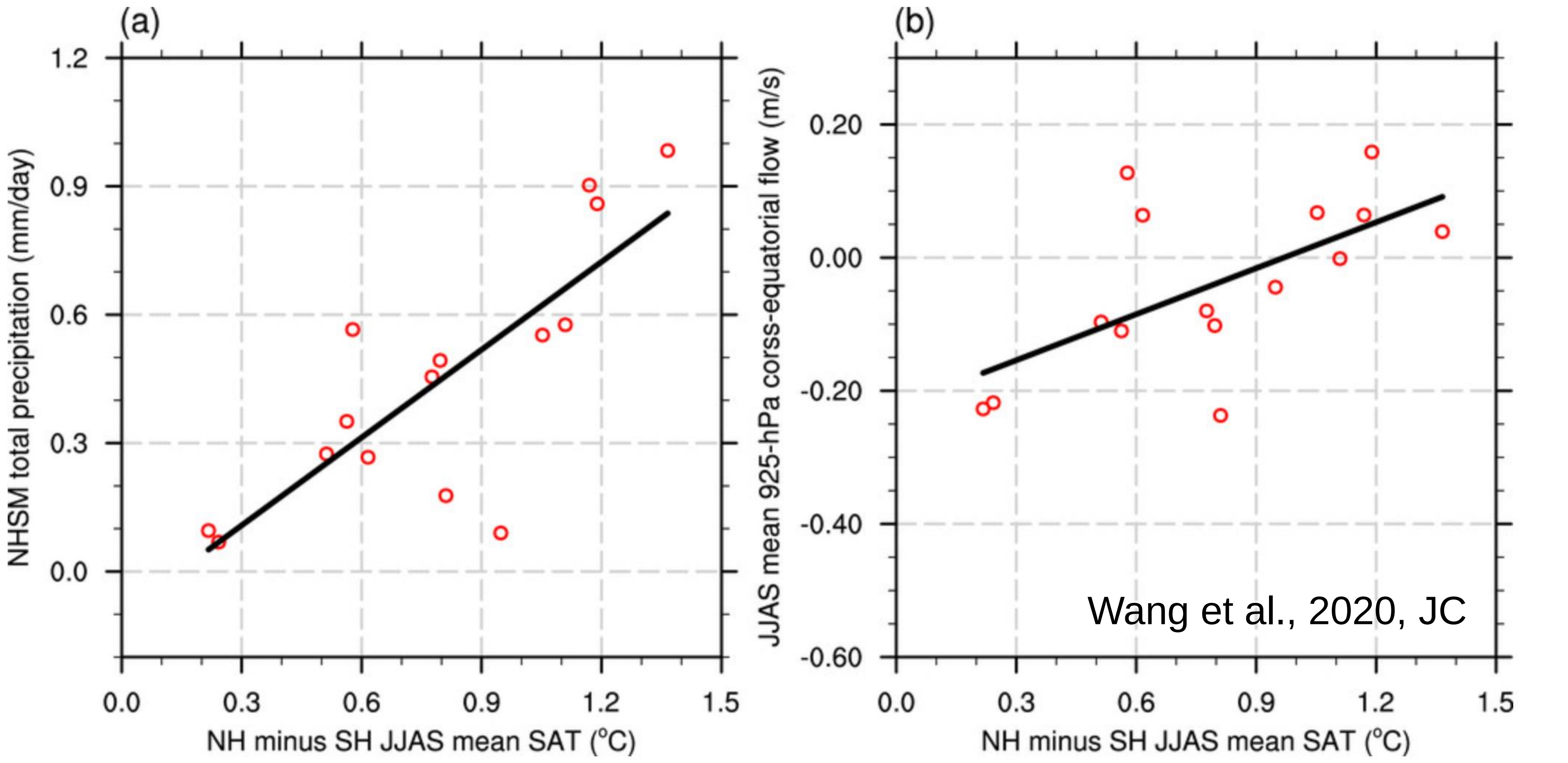
PC1-related pattern of projected Ts change



A robust"NH warmer than SH"pattern in both future and historical period (r = 0.71, p < 0.01)

ITC: Interhemispheric Thermal Contrast

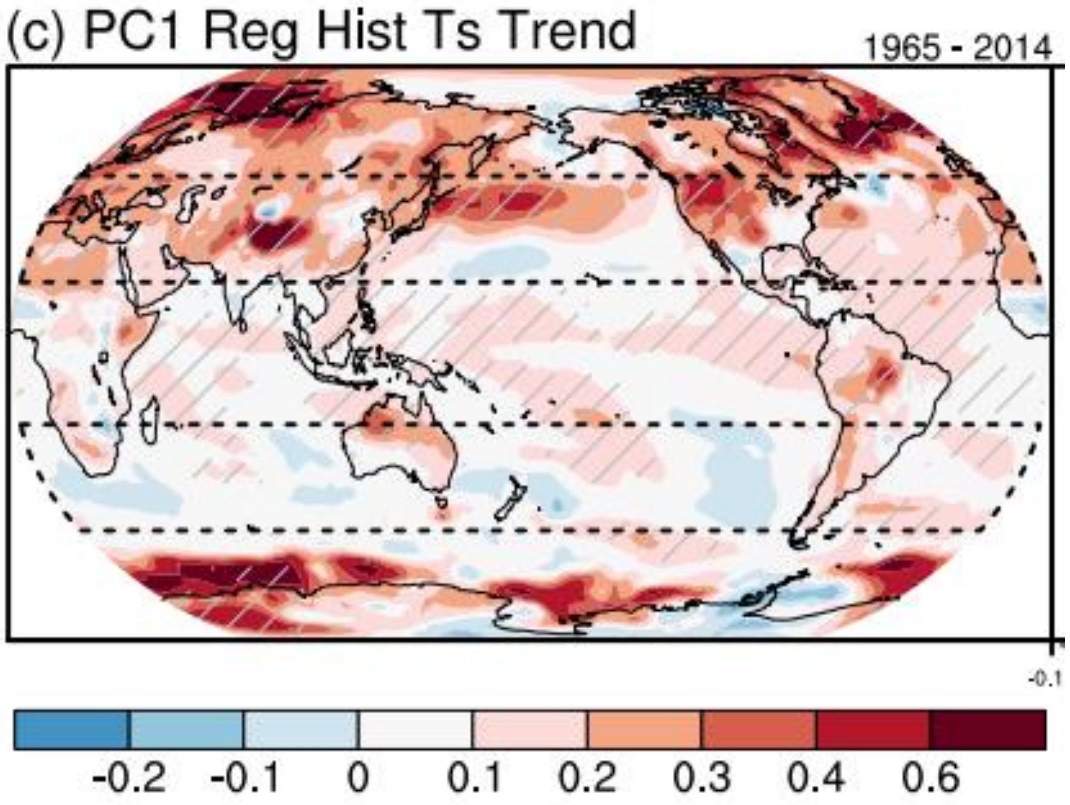
AfroASM: Afro-Asian Summer Monsoon



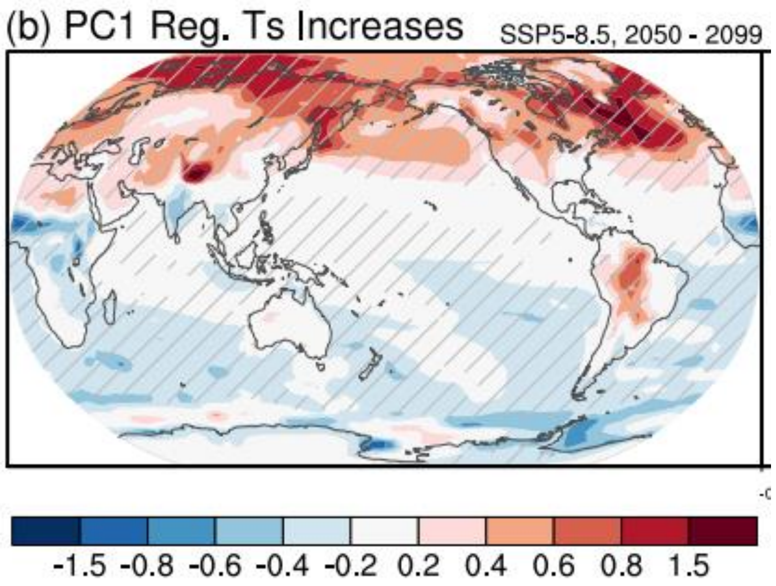
- NHSM precipitation and cross-equatorial flow is controlled by NH-SH SAT contrast.

Uncertainty related to historical simulation

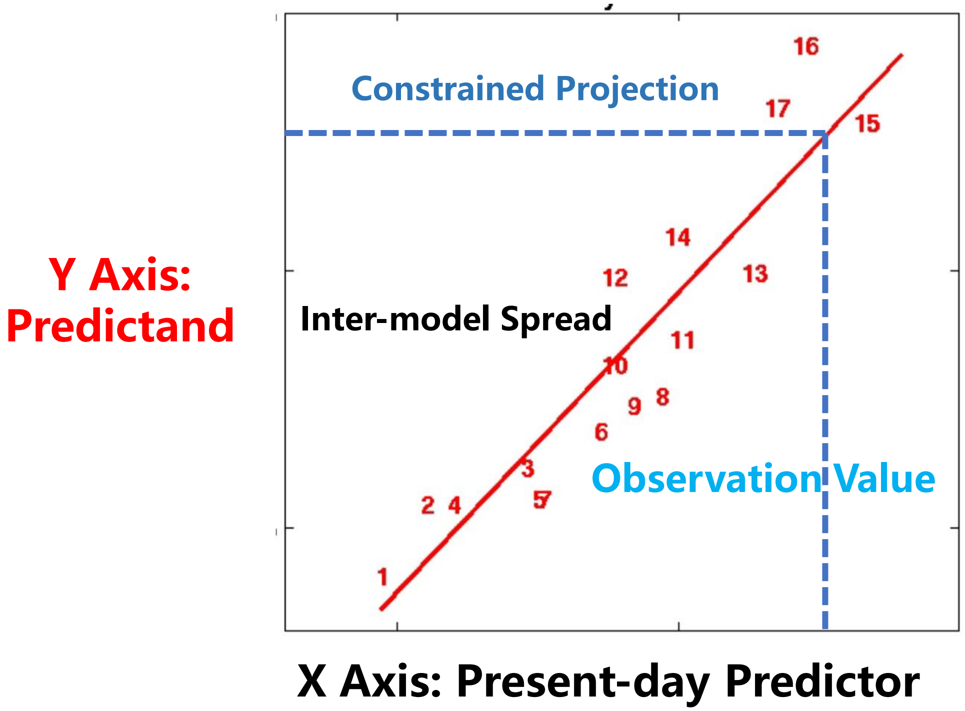
PC1-related pattern of present Ts trend



PC1-related pattern of projected Ts change

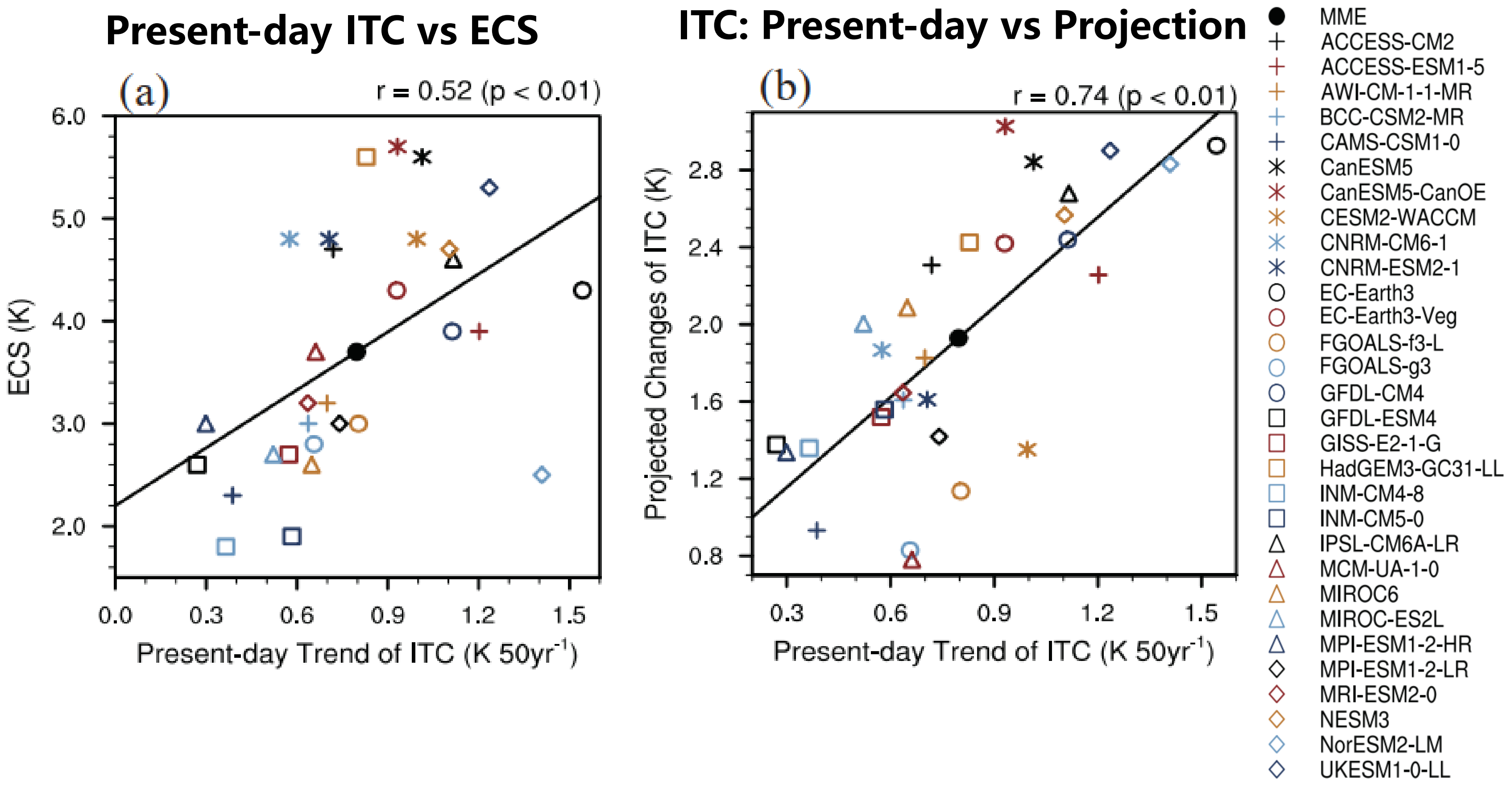


Emergent Constraint Method



- Based on the physical link between a modelled but observable variable in the present day (**Predictor**) and a projected variable in the future climate system (**Predictand**):
  - $P \sim aX + b$
- Using the present-day reliable observation (X_o), we can constrain the result in the projection:
  - $P^* = aX_o + b$
- Predictor (source of intermode uncertainty):
  - SST over cold-tongue regions (Chen X. et al., 2020 NC)
  - Convection over western Pacific (Zhou et al., 2019 ERL; Yan et al., 2019 JC)
  - SST warming difference between tropical and subtropical ocean (Biasutti et al., 2009 JC; Park et al., 2015 NC)

Inter-model Spread of ITC from ECS



Larger ECS

↓

Larger Trend of ITC in Present Day

↓

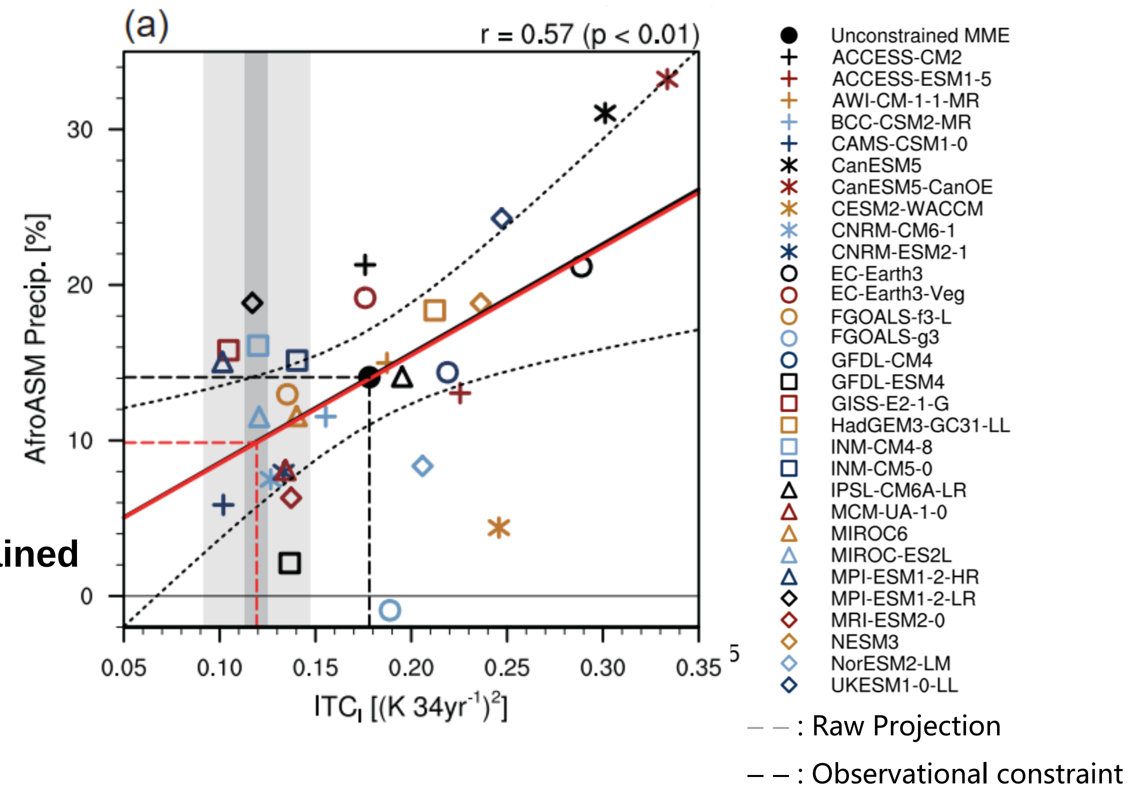
Larger Increase of Projected ITC

↓

Stronger AfroASM Precip.

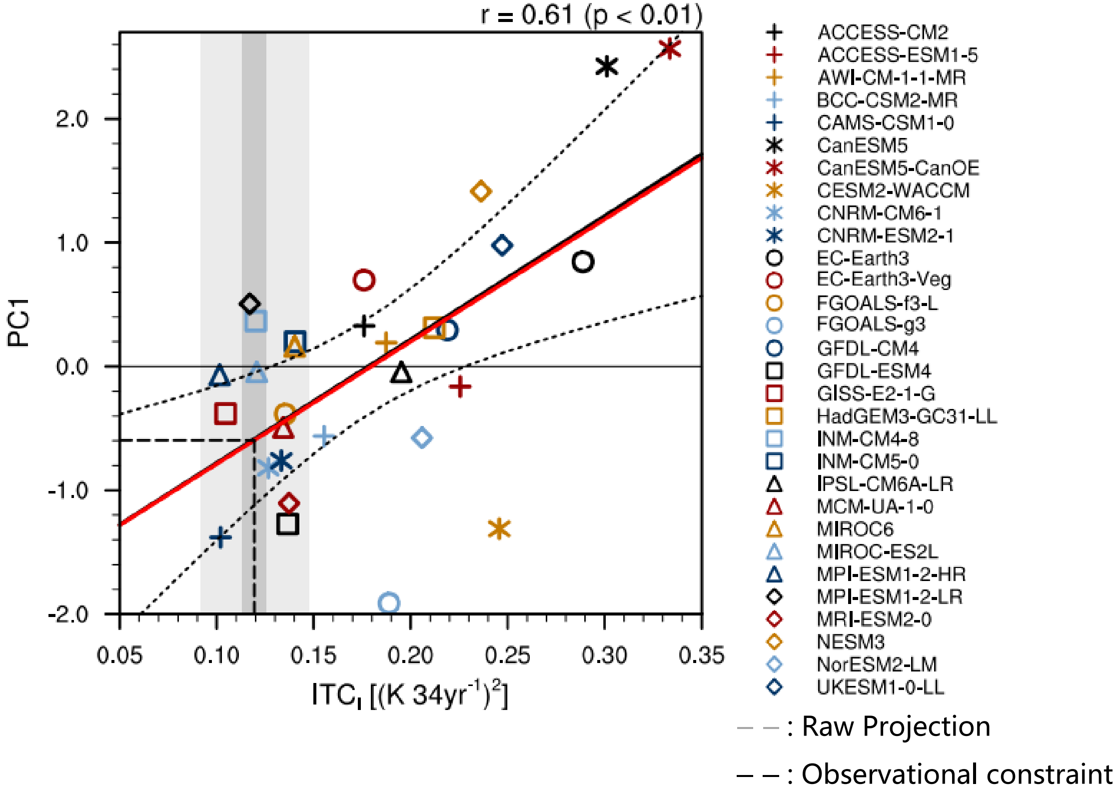
Observational Constraint on the AfroASM Precip.

Constrained AfroASM Precipitation



Constrained

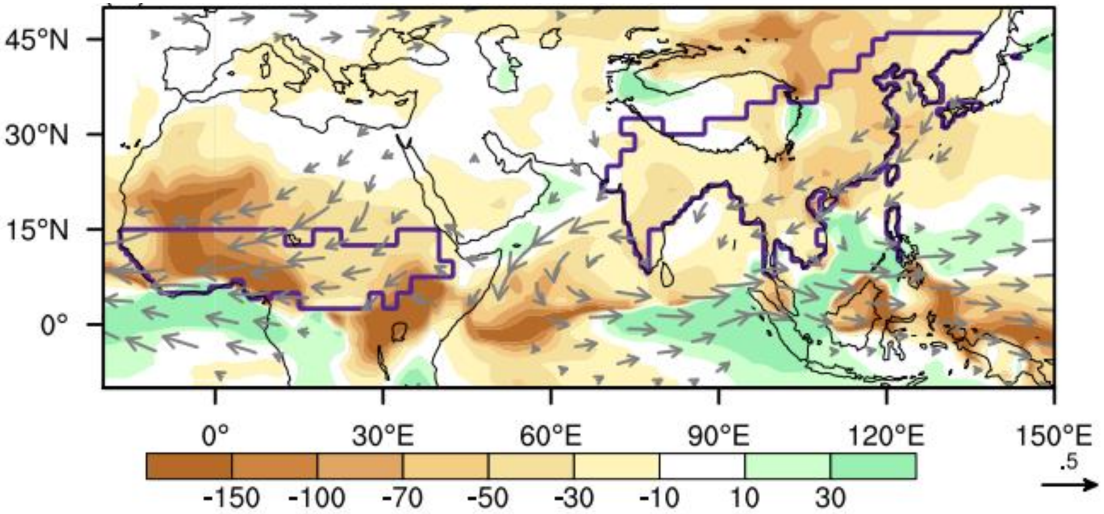
Constrained PC1



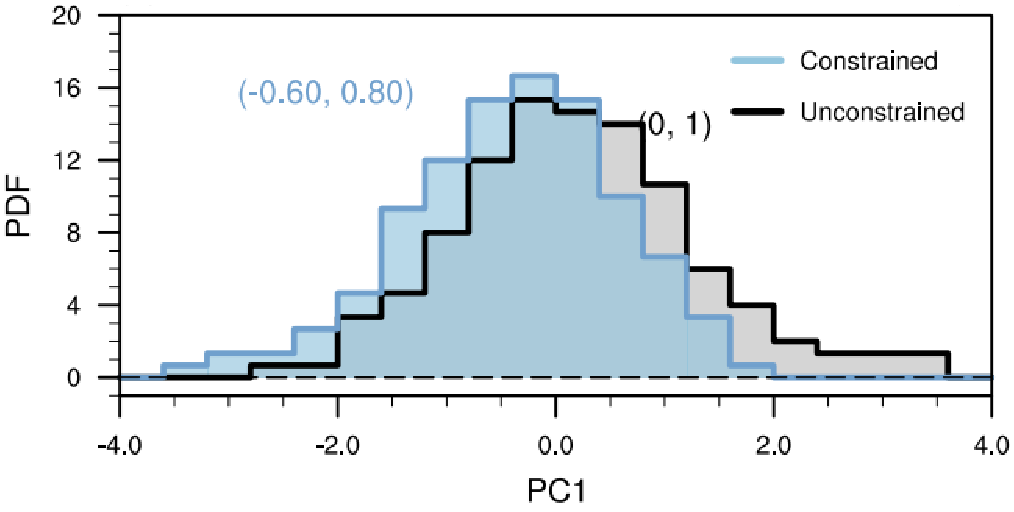
- **The ITC$_I$ can well explain the leading mode of model uncertainty in projected AfroASM precipitation.**
- **The constrained value of AfroASM precipitation is 9.5%±6.3% (PC1 = -0.60±0.80)**

Corrected AfroASM Precip. Projection

(Constrained – UnConstrained) / Unconstrained

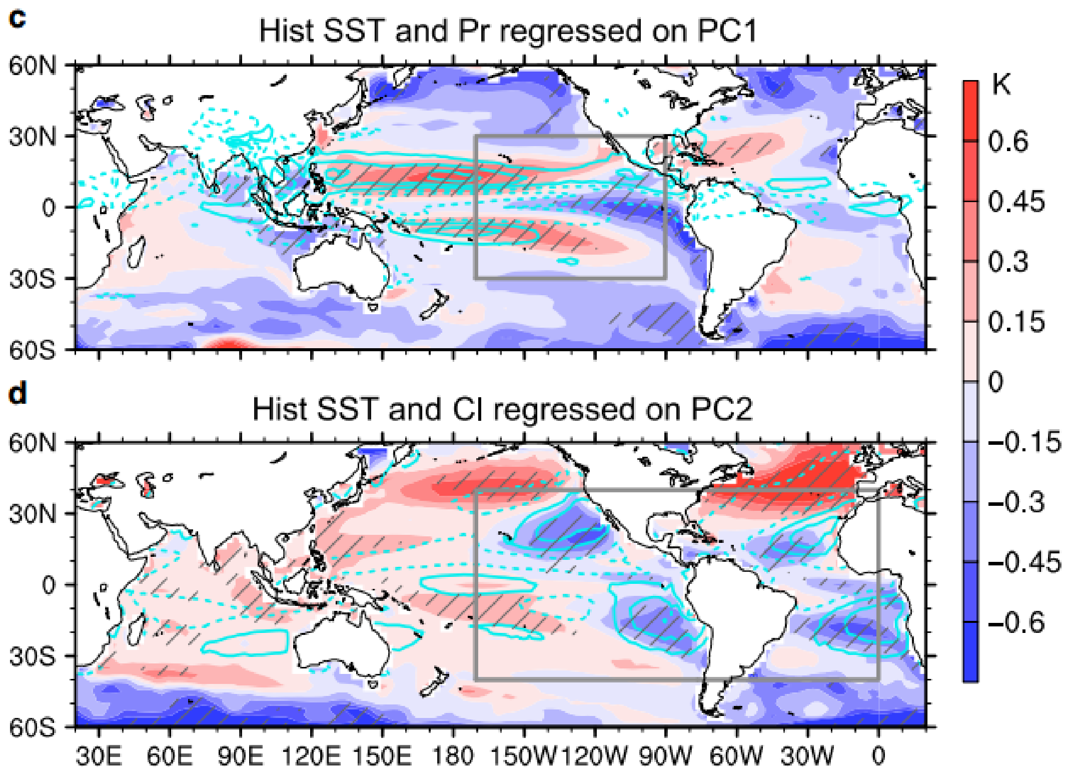


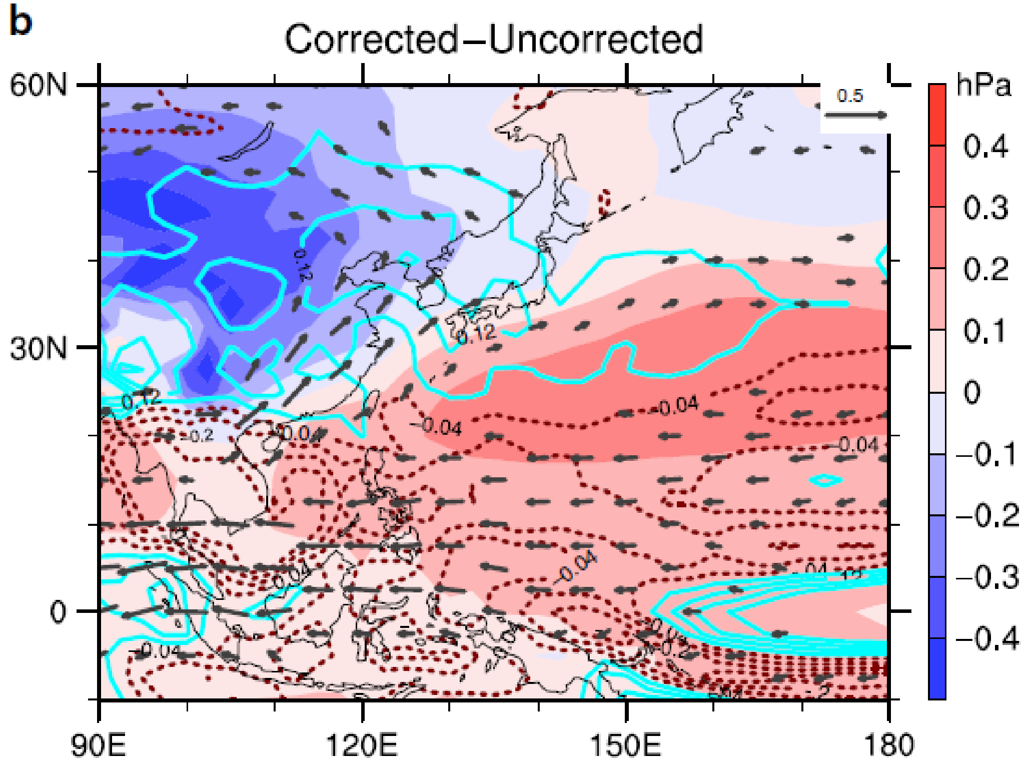
PDF of Constrained and Unconstrained PC1



- **Less increase than that in the unconstrained (raw) projection by ~30%**
- **Projected uncertainty is reduced by 10%, most form reducing the high tail of increased precipitation**
- **Constrained increases over West African, East Asian, and South Asian monsoon regions are 7%, 8%, and 12%**

Compare with other constrained results

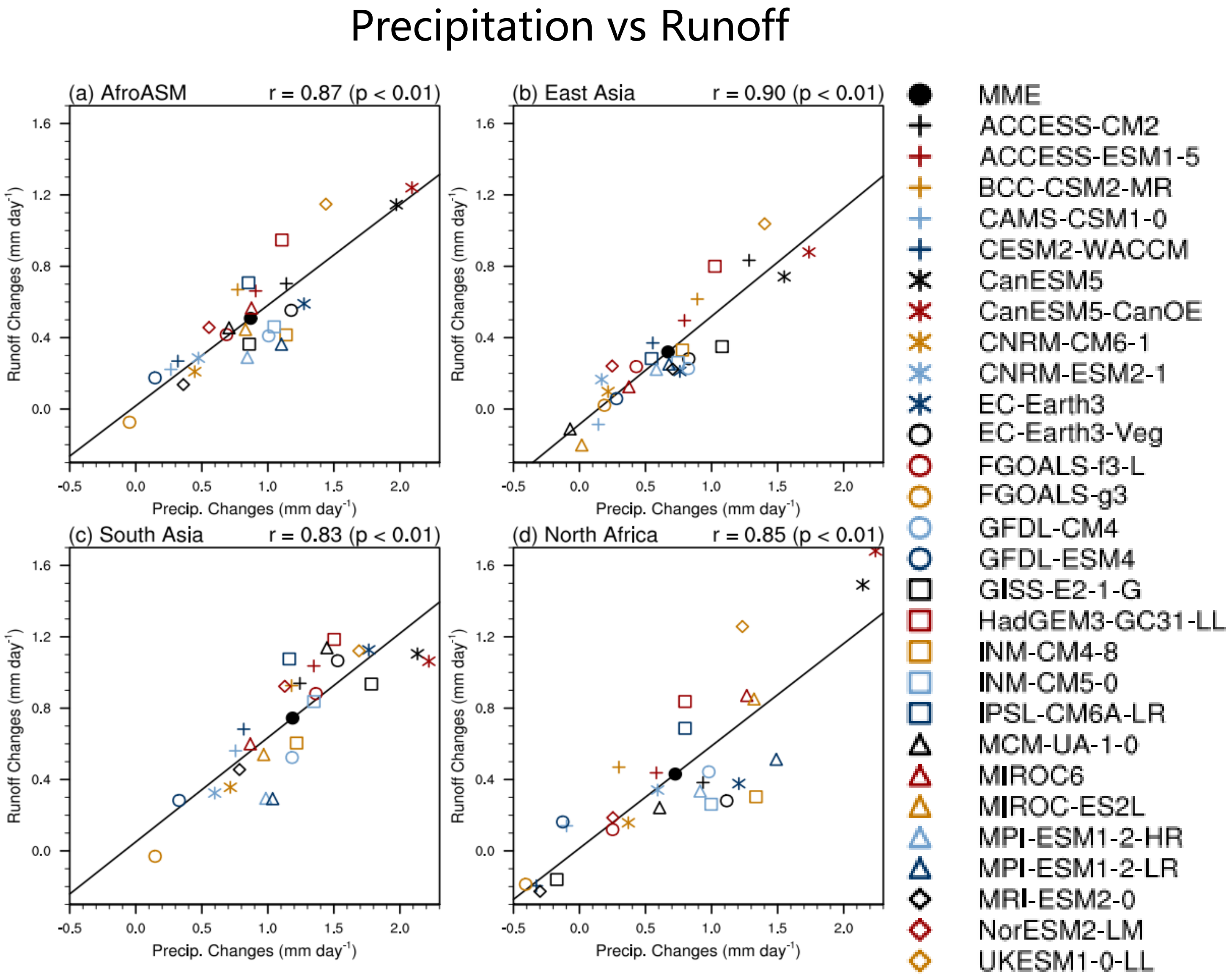




(Chen X. et al., 2020)

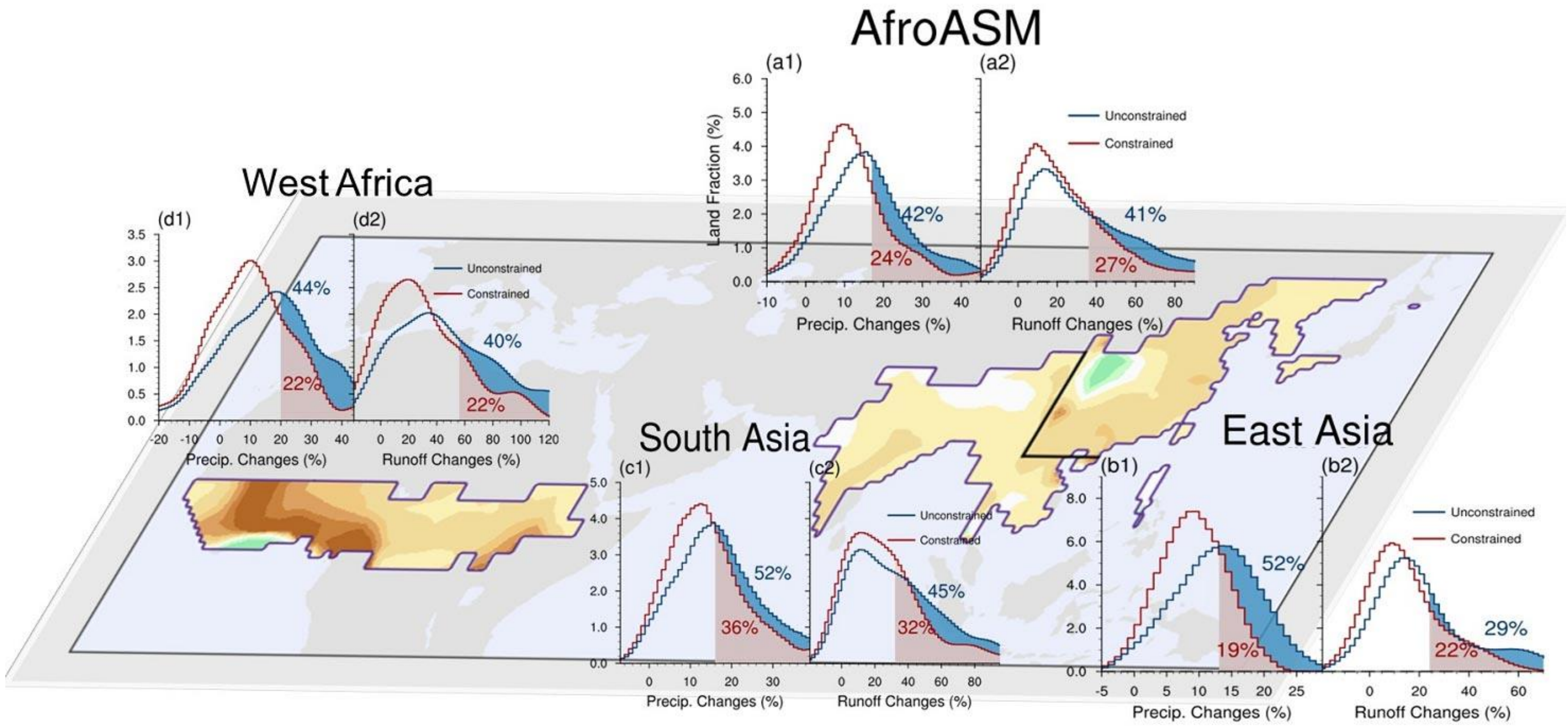
	East Asia	
	Before constraint (mm/day)	(After constraint (mm/day)
Chen X. et al., 2020 (CMIP5)	~ 0.4	~ 0.5 Indirect constraint through WNPSH
This study (CMIP6)	0.57 ± 0.61	0.47 (0.46 ~ 0.50)

Relationship btw Projected Precip. and Runoff



SSP5-8.5, 2050-2099

Impact on the Potential Water Availability



Each subplot: land fraction

- Left PDF: Pr-related
- Right PDF: Runoff-related

Shading in PDF

- significant increase

increase exceeds the range of inter-model standard deviation

- **The land area that will experience a significant increase of precipitation (runoff) is ~57% (66%) of that of the raw projection.**

Summary

- **The projected uncertainty of AfroASM precipitation**
  - **Projected spread is related to present-day ITC biases**
  - **Models with a larger present-day ITC trend tend to project a greater precipitation increase**
- **The constrained projection of AfroASM precipitation**
  - **The precipitation is projected to increase by ~10% in the constrained projection**
  - **Only ~70% of the raw projection, with the largest reduction in the West African monsoon region.**
  - **Projected uncertainty is reduced by 10%**
  - **The land area experiencing a significant increase in precipitation and potential water availability are ~57% and ~66% of the raw projection**

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Thank you for your attention!

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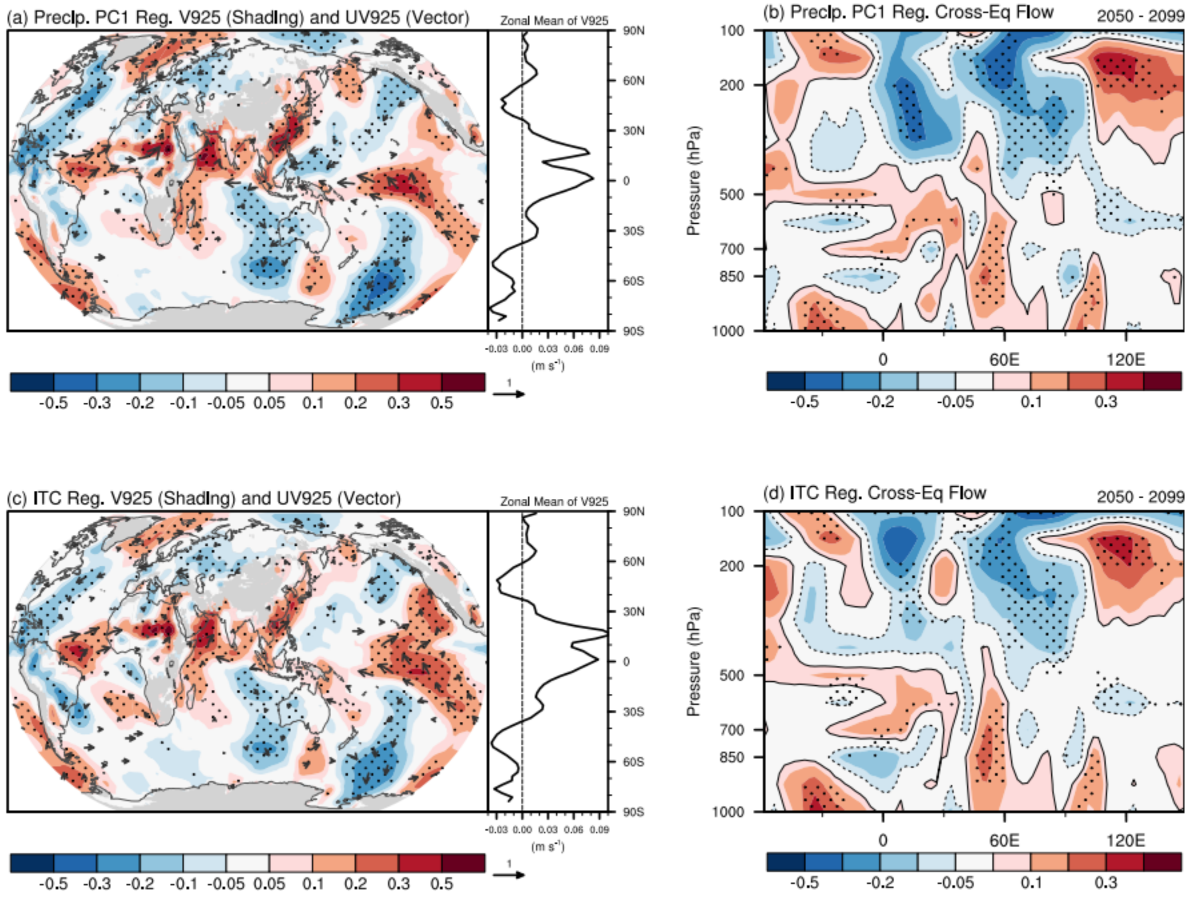
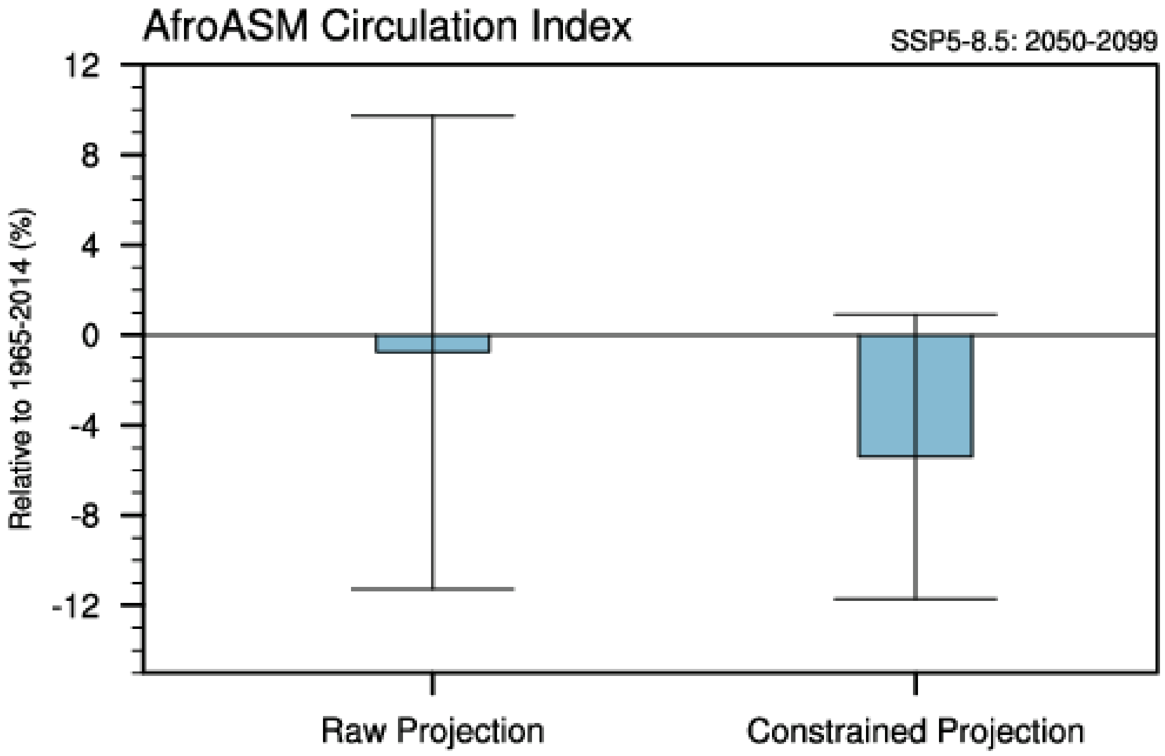
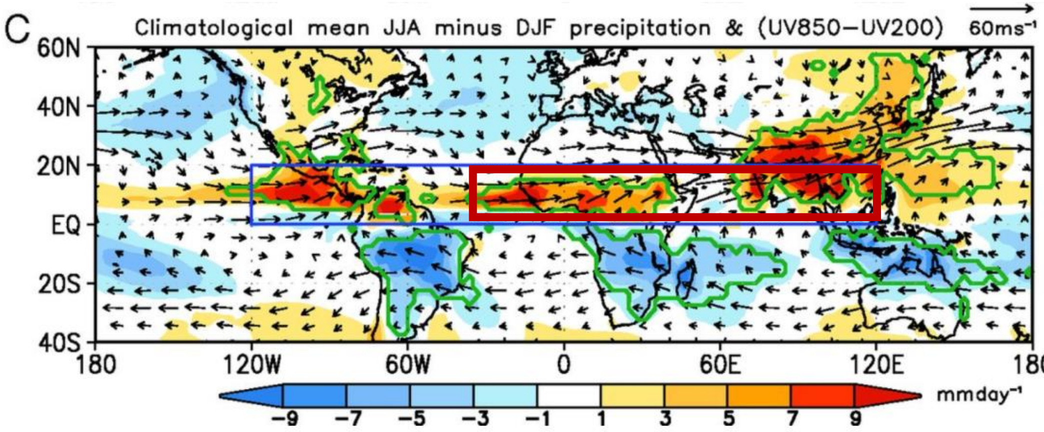
The low-level cross-equator flow

Low-level (925 hPa) circulation (vector) and meridional wind (shading) related to PC1 (a, b) and ITC (c, d)



Constrained circulation index





Wang et al. 2013 PNAS

AfroASM circulation index:

vertical shear of zonal winds between 850 and 200 hPa averaged in a zone stretching from tropical North Atlantic eastward to the Philippines (0–20°N, 30°W–120°E).