Global and regional monsoons in a changing climate

Annalisa Cherchi (CNR-ISAC, Italy)

Anja Katzenberger (PIK, Germany)

Krishnan R, Aswin Sagar, Sabin TP (IITM, India)

Andrew Turner (University of Reading, UK)

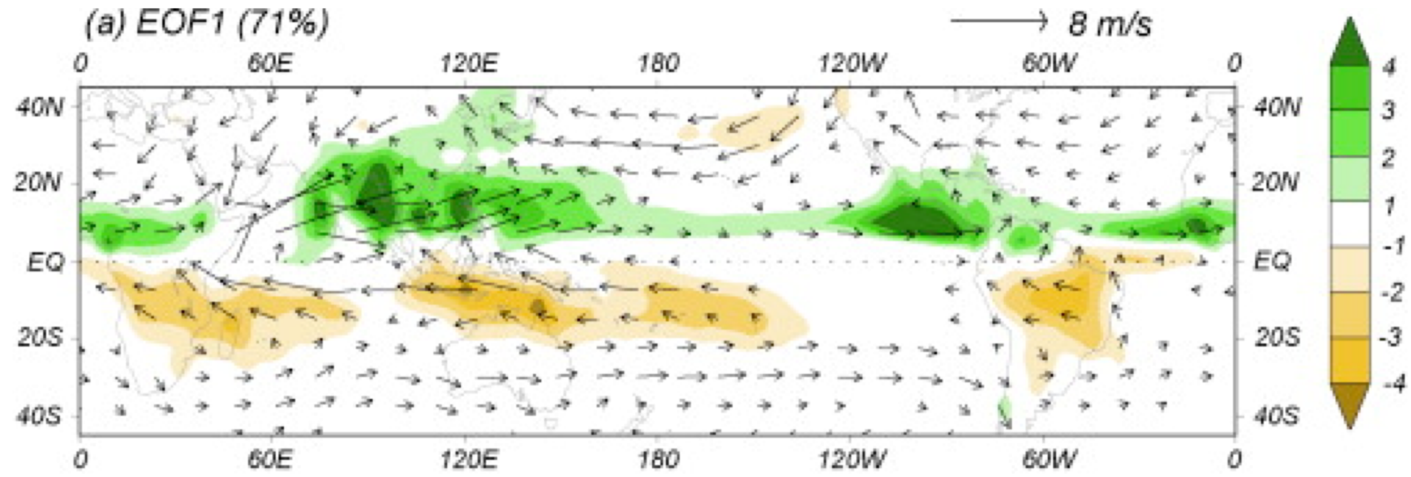
Eight WMO International Workshop on Monsoons (IWM-8), 17-21 March 2025, Pune, India

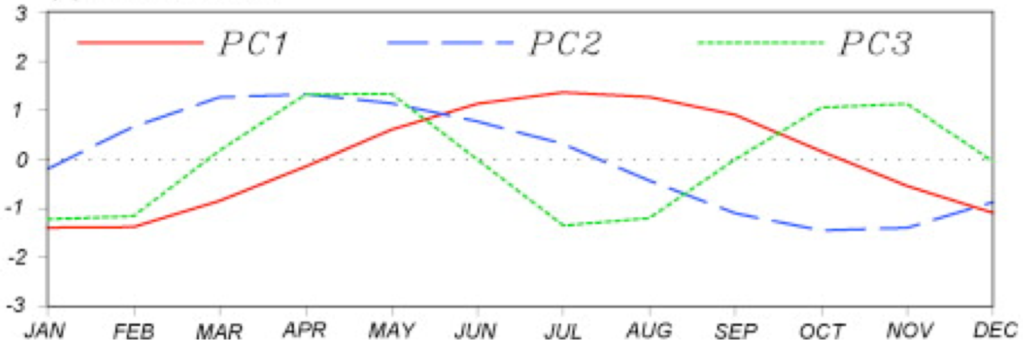
Outline:

- Background/motivation: IPCC AR6 monsoon projections
- Data & methods
- Hydrological sensitivity of global and regional monsoons
- Summary & perspectives

GLOBAL AND REGIONAL MONSOONS - background

Dominant mode of annual variation of precipitation (and wind) – hemispheric antisymmetric solstice mode (Wang and Ding, 2008)



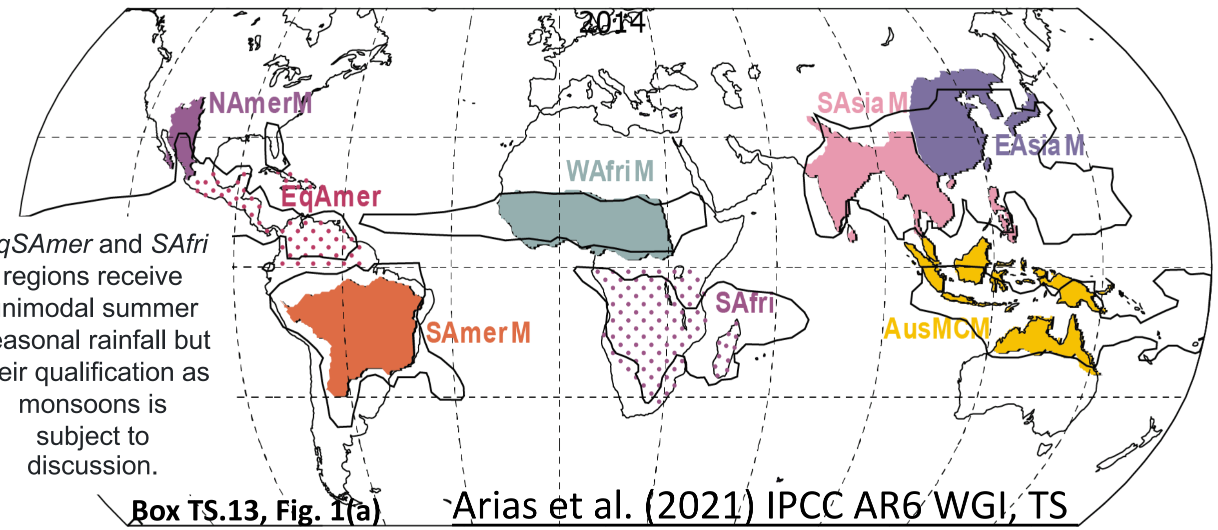


*Empirical Orthogonal Function (EOF) & normalized Principal Components (PC) of climatological monthly mean precipitation

IPCC AR6 - definition/convention: Global (black contour) and regional monsoons (colour shaded) domains

The global monsoon (*GM*) is defined as the area with local summer-minus-winter precipitation rate exceeding 2.5 mm day^{-1} (see IPCC AR6 Annex V).

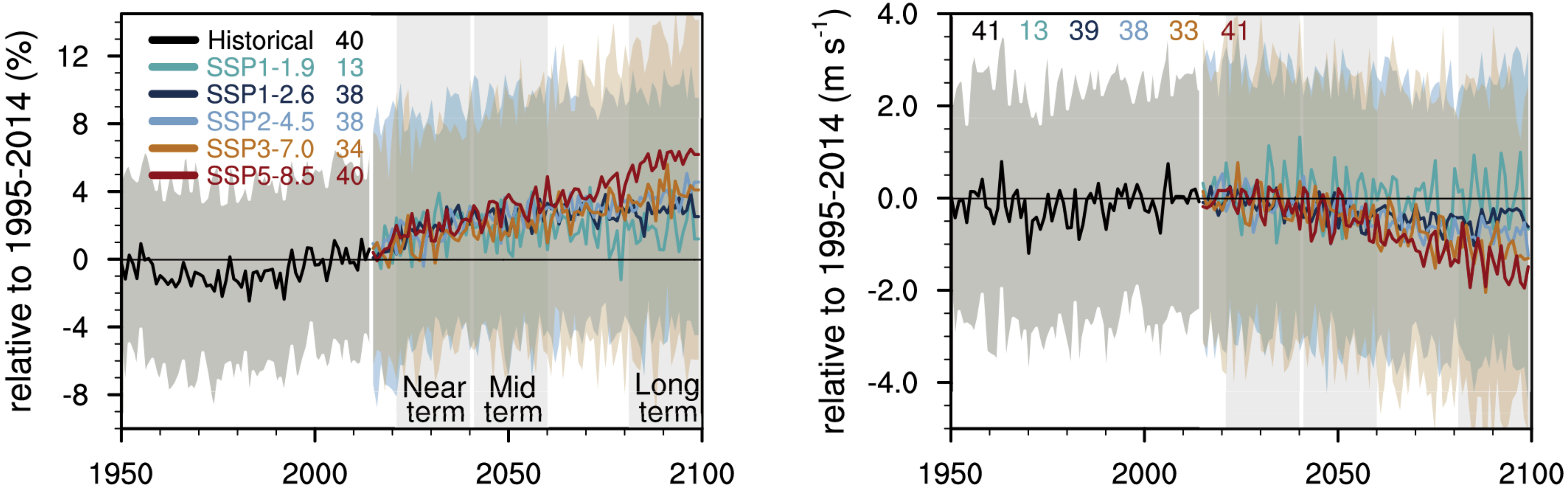
(a) Global and regional monsoon domains



EqSAmer and *SAfri* regions receive unimodal summer seasonal rainfall but their qualification as monsoons is subject to discussion.

Box TS.13, Fig. 1(a) Arias et al. (2021) IPCC AR6 WGI, TS

Future changes of GM (precipitation & circulation indices)



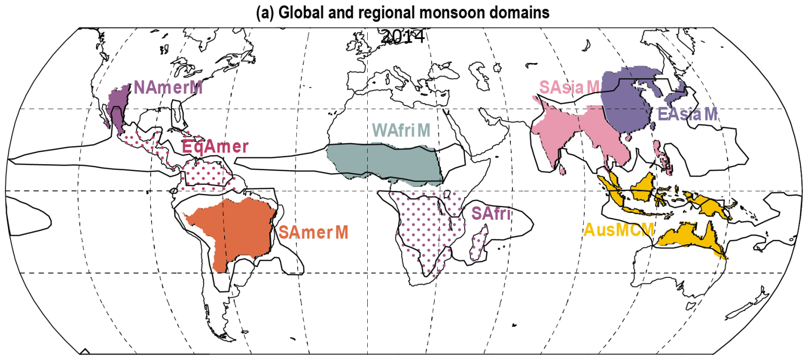
Time series of global land monsoon precipitation and Northern Hemisphere summer monsoon (NHSM) circulation index anomalies. **(a)** Global land monsoon precipitation index anomalies (unit: %) defined as the area-weighted mean precipitation rate in the global land monsoon domain, as defined by Wang et al. (2013a) **(b)** Anomalies in NHSM circulation index (unit: m s^{-1}), defined as the vertical shear of zonal winds between 850 and 200 hPa averaged in a zone stretching from Mexico eastward to the Philippines (0°–20°N, 120°W–120°E; Wang et al., 2013a). The curves show averages over the simulations, the shadings around the SSP1-2.6 and SSP3-7.0 curves show 5–95% ranges, and the numbers near the top show the number of model simulations used.

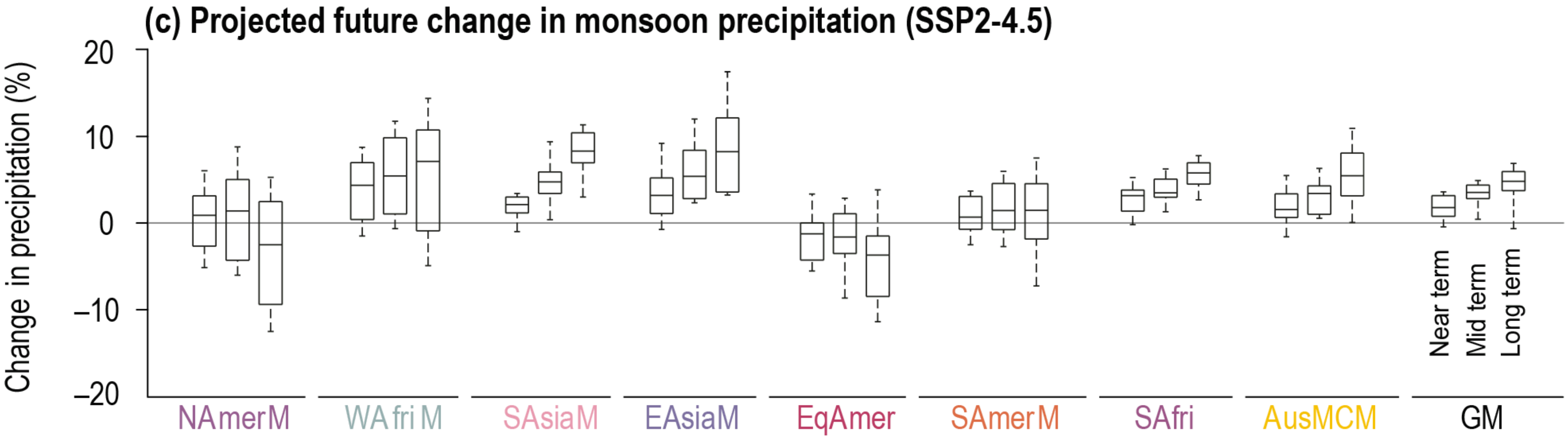
Near-term: changes in GM and related circulation will be affected by the combined effects of **model uncertainty** and **internal variability** (together larger than the forced signal) – *medium confidence;*

Long-term: it is likely that **GM land precipitation** will increase with GSAT rise (**1.3-2.4 % increase per ºC of GSAT warming**), despite weakened monsoon circulation

Lee et al. (2021) IPCC AR6 WGI, Ch 4

Future changes of monsoons precipitation





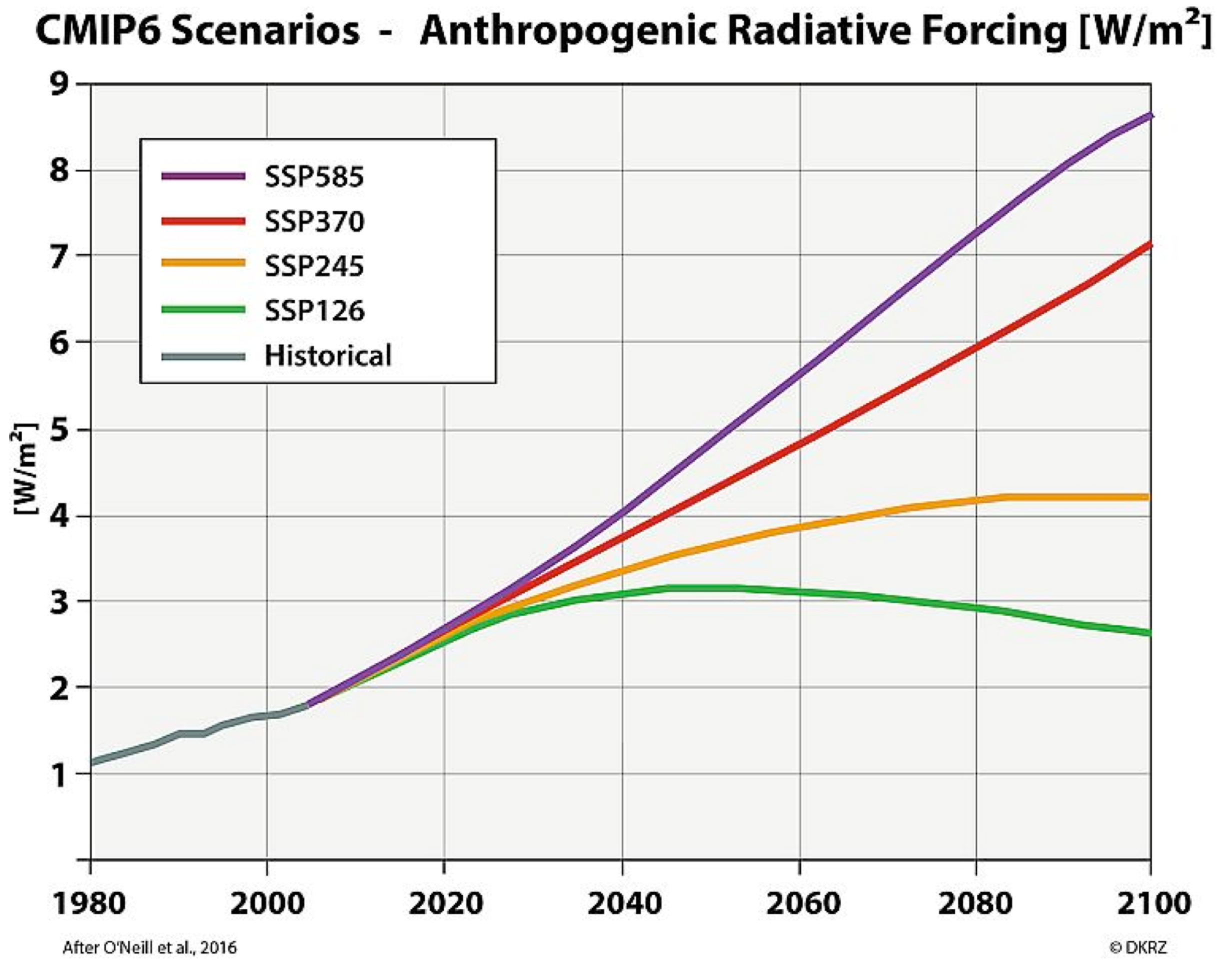
Box TS.13, Fig. 1(a,c)

Percentage change in projected seasonal mean precipitation over global and regional monsoons domain in the near term (2021–2040), mid-term (2041–2060), and long term (2081–2100) under SSP2-4.5 based on 24 CMIP6 models.

Arias et al. (2021) IPCC AR6 WGI, TS

Data (CMIP6 models & experiments):

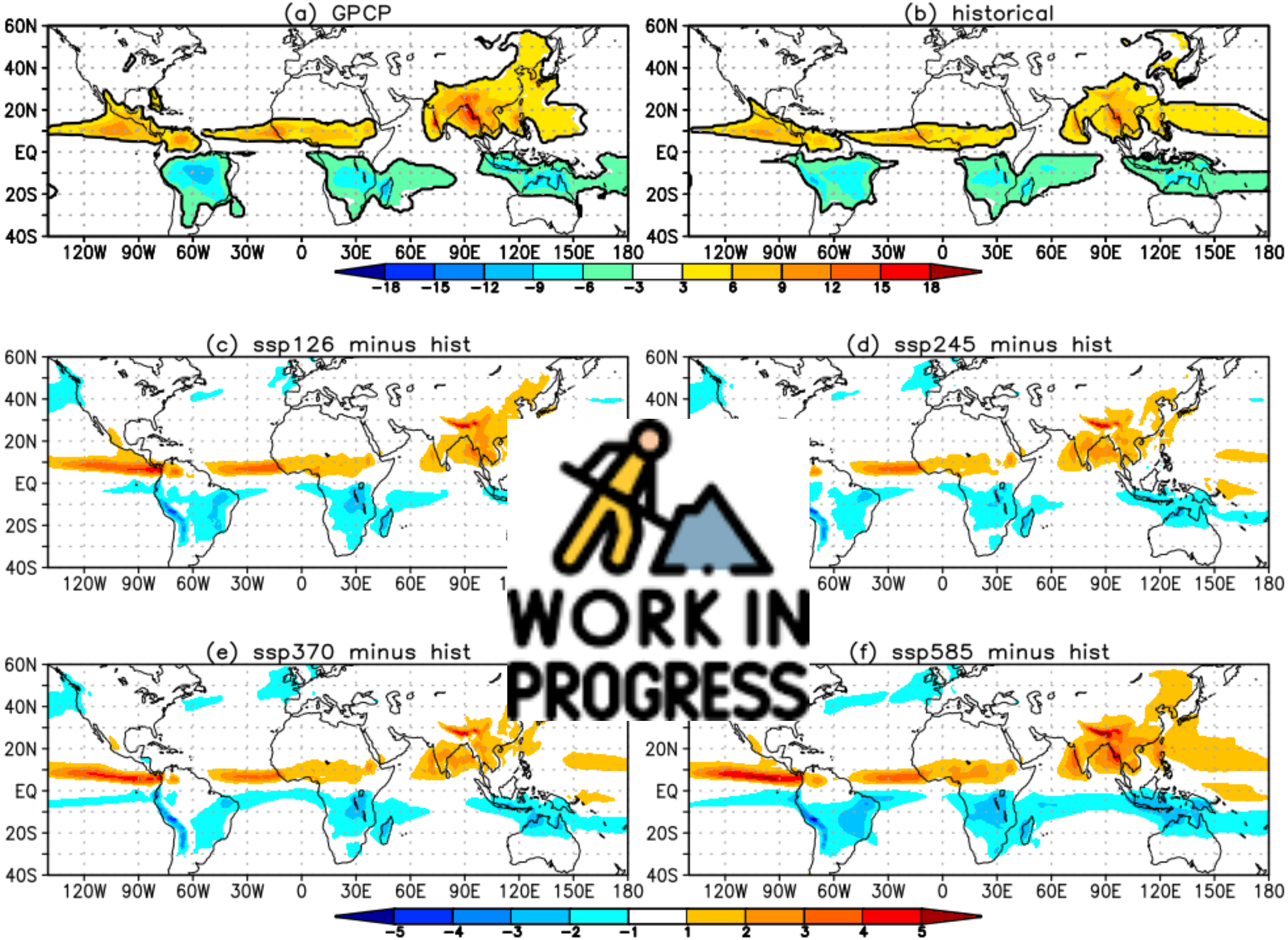
Model's name	Institute/Country
ACCESS-ESM1-5	CSIRO/Australia
BCC-CSM2-MR	BCC/China
CAMS-CSM1-0	CAM/China
CESM2-WACCM	NCAR/US
CNRM-ESM2-1	CNRM&CERFACS/France
CanESM5	CCCma/Canada
EC-Earth3	EC-Earth Consortium/EU
GFDL-ESM4	GFDL/US
INM-CM4-8	INM/Russia
IPSL-CM6A-LR	IPSL/France
MIROC6	MIROC/Japan
MPI-ESM1-2-LR	MPI-M/Germany
MRI-ESM2-0	MRI/Japan
NorESM2-MM	NCC/Norway



CMIP6 models considered (1 member for each model/simulation)
(also here in the table just 1 model per institute but working to include more, depending on local repositories availability)

JJA minus DJF precipitation (mm/d)

observation vs historical MMM (1985-2014 climatology) & change in projections with respect to hist climatology



GM (black line) is identified as JJA minus DJF exceeding 2.5 mm/d

GM region is realistic in historical MMM but precipitation is underestimated in some places

In future scenarios, precip is overall projected to increase but diversities among regional monsoons and mostly non-linearities between different scenarios seem to appear

Methodology: hydrological sensitivity of global and regional monsoons

As in Katzenberger et al (2021):

Change in summer monsoon mean rainfall (mm/d) depending on change in GMT (K) –
Stepwise difference between future periods to the reference period (1985-2014) - 20-years future periods with 5-years time steps (i.e. 2000-2019, 2005-2024, ... 2080-2099)

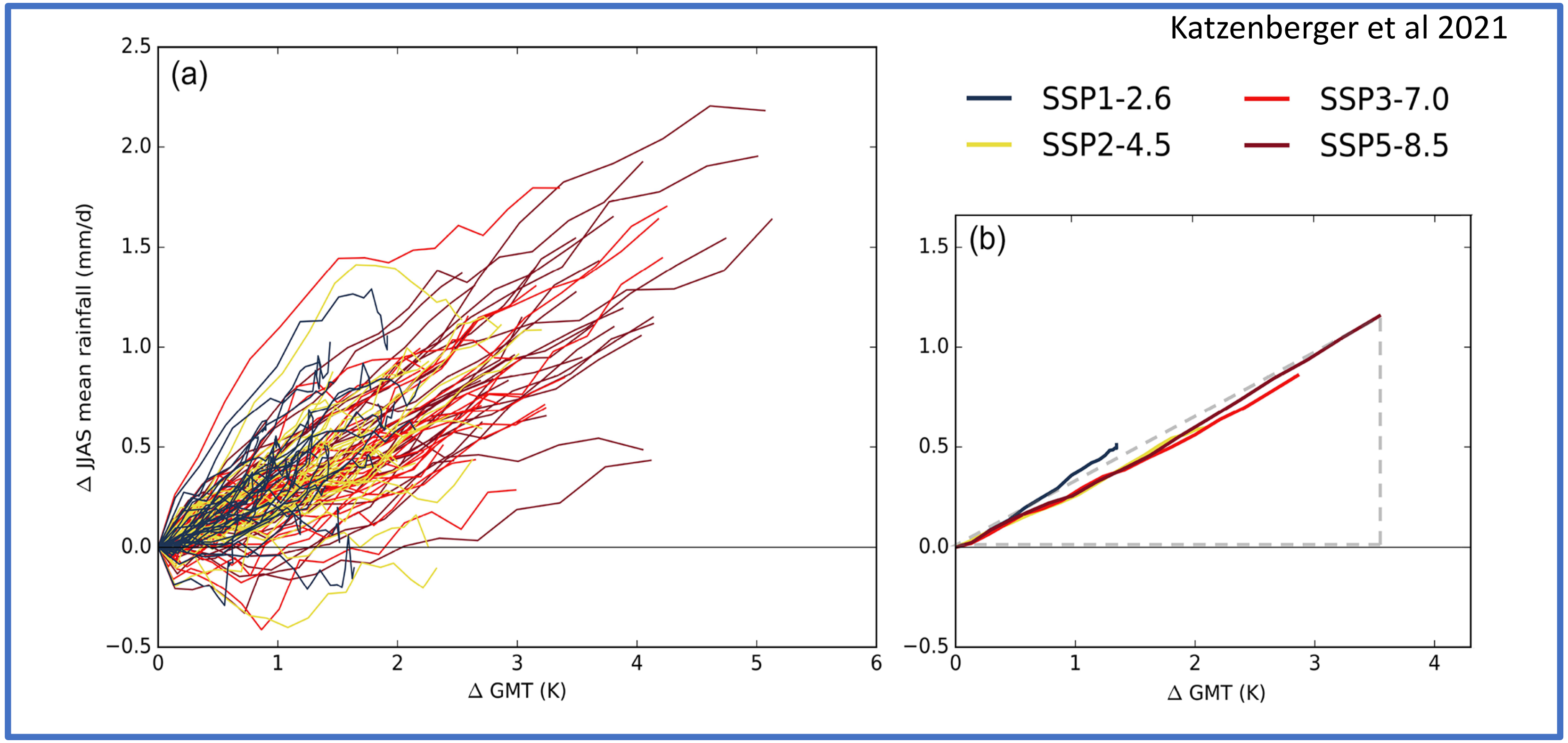
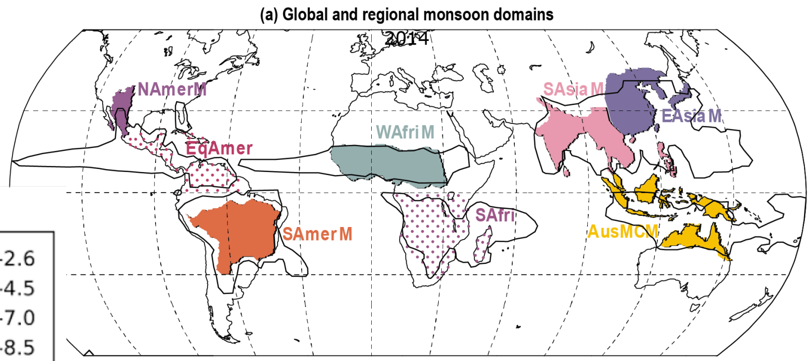
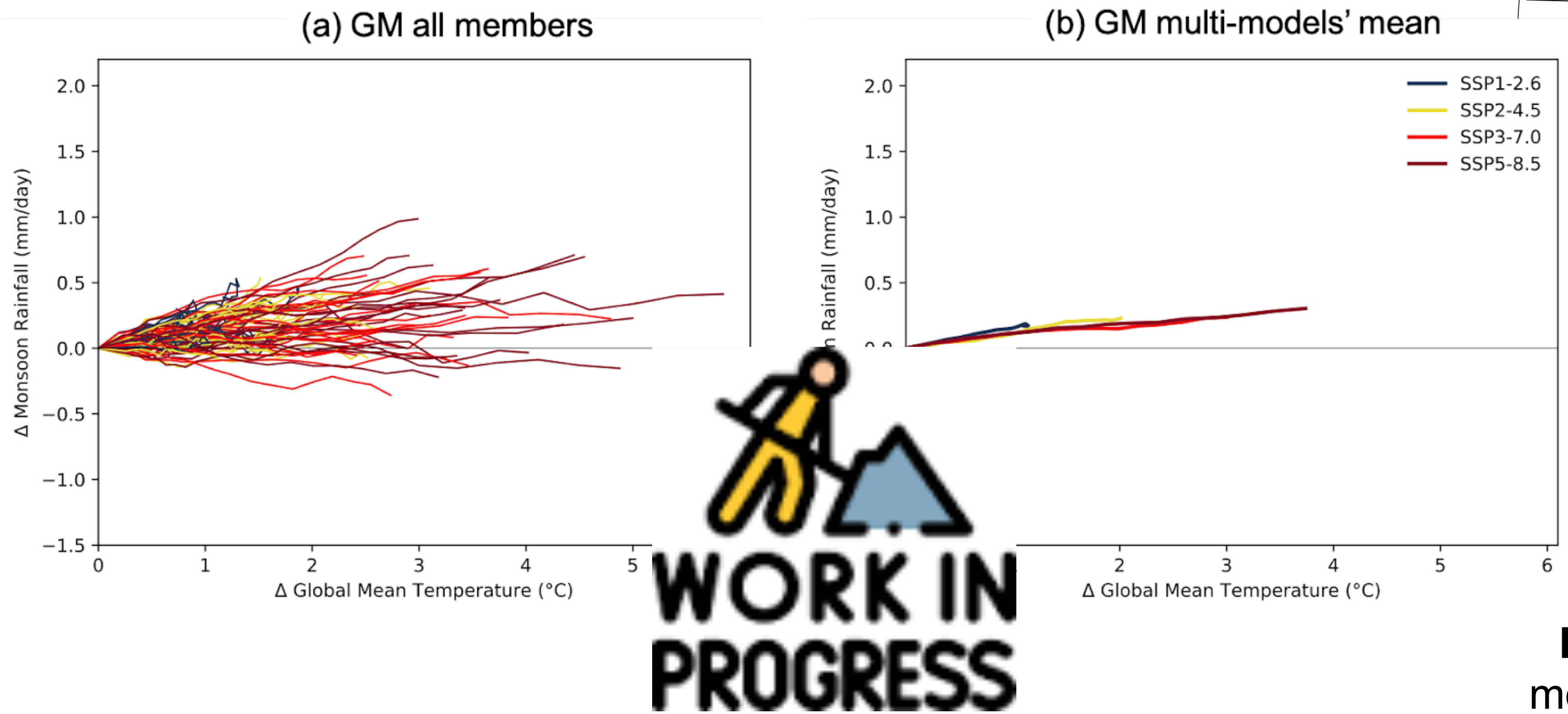


Figure here for Indian summer monsoon but we applied to GM and regional monsoons as defined in IPCC AR6

Hydrological sensitivity of global monsoon





Linear regression fitting (LFT)
monsoon rainfall per GMT increase
(mm/d per K)

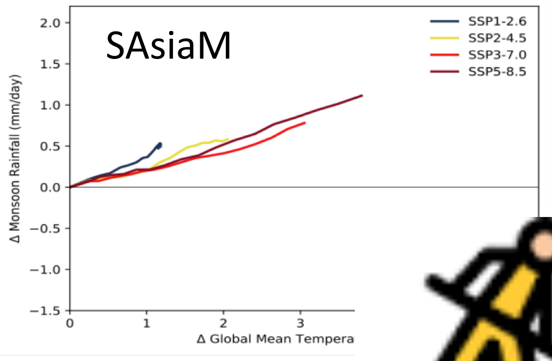
	SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5
GM	0.15	0.13	**0.06**	0.07
GM-NH	0.20	0.13	**0.05**	0.06
GM-SH	0.11	0.12	0.08	0.08
GM-EH	0.31	0.25	**0.18**	0.20
GM-WH*	0.04	0.04	-0.02	-0.03

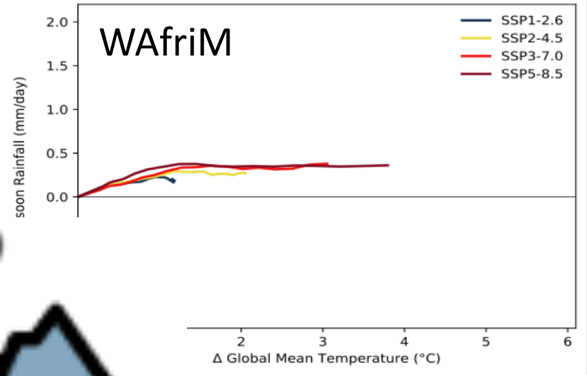
Value of the slopes (LFT) are the lowest for SSP3-7.0 but the global radiative forcing expected at the end of the century for that scenario is not – in GM, GM-NH, GM-EH

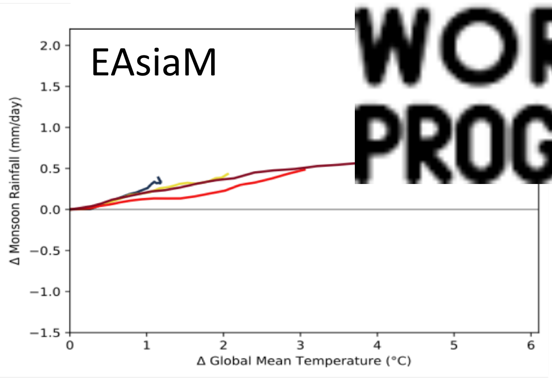
*LFT is of limited use as the change of monsoon precipitation is non-linear with respect to the GMT increase

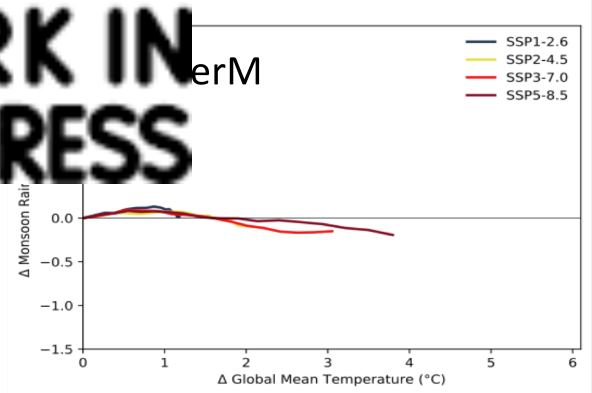
Hydrological sensitivity of regional monsoons

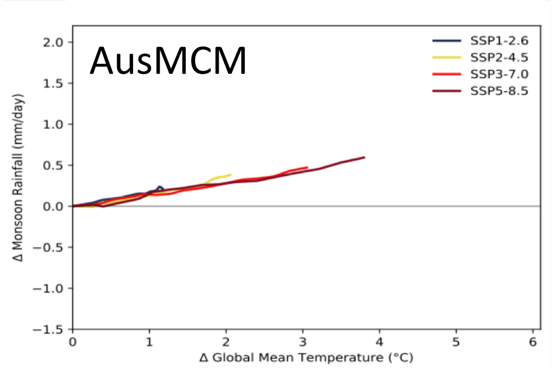
(summer precip increase as function of GWL)

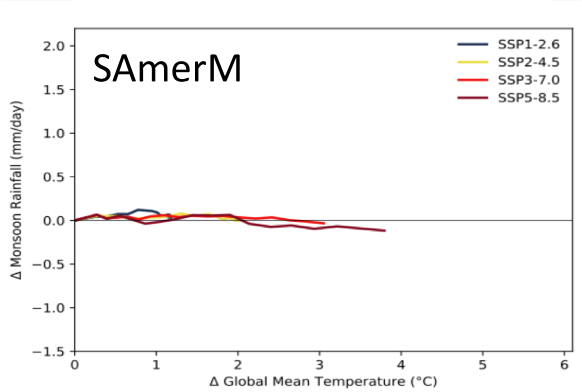


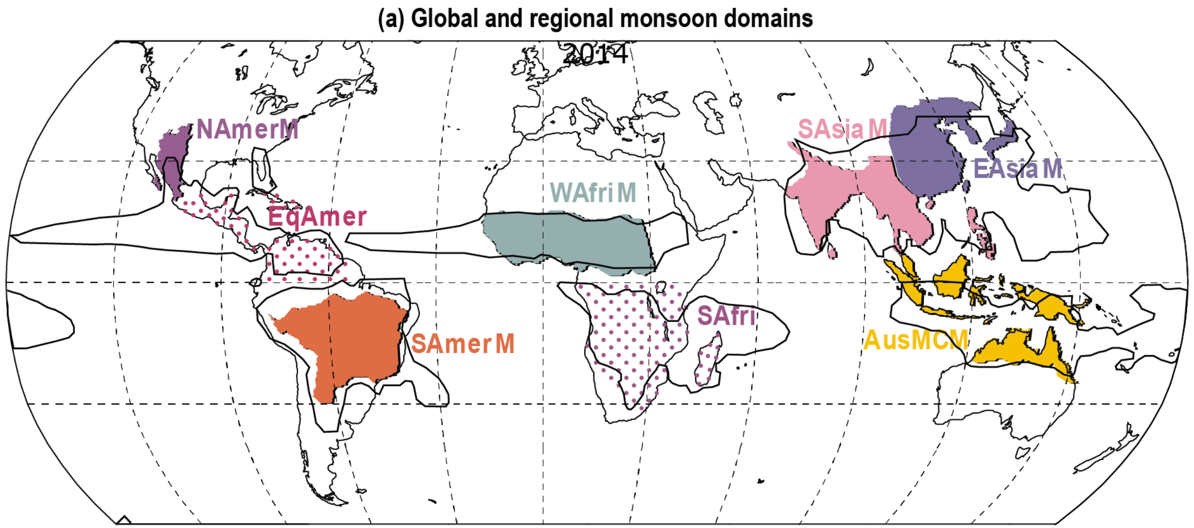












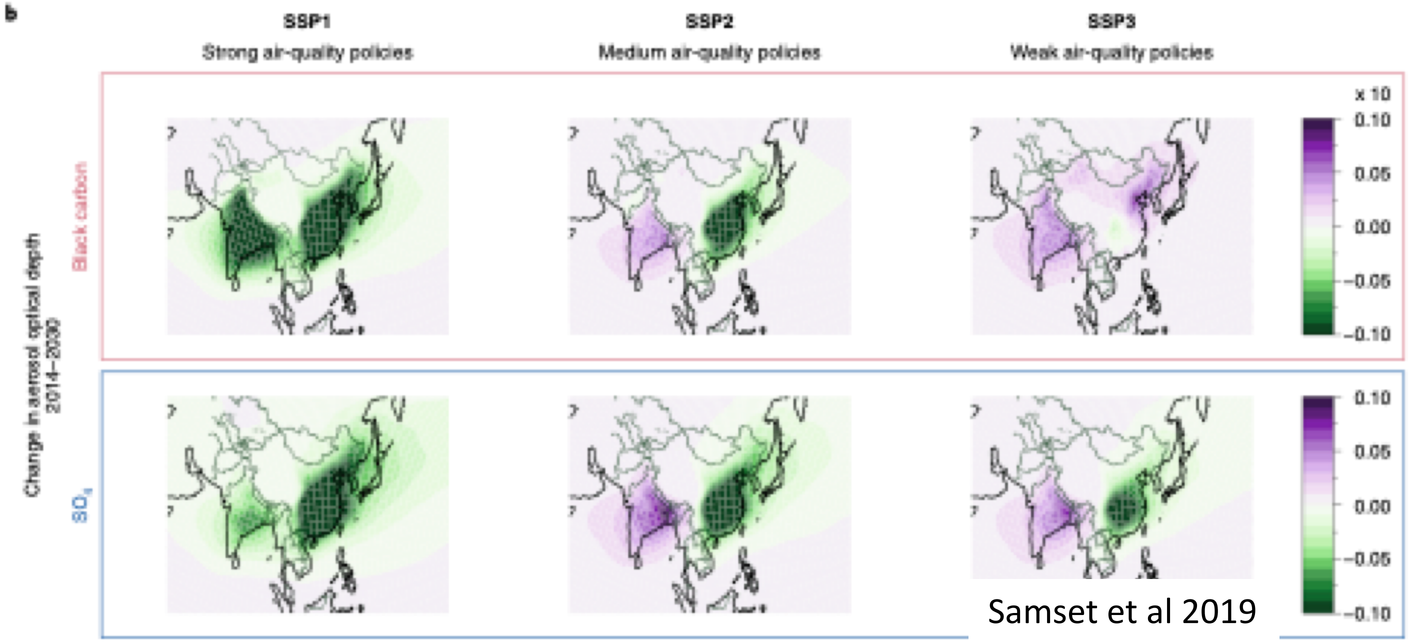
Linear regression fitting (LFT) –

monsoon rainfall per GMT increase (mm/d per K)

	SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5
SAsiaM	0.43	0.30	**0.24**	0.28
EAsiaM	0.33	0.21	**0.13**	0.15
AusMCM	0.17	0.19	0.13	0.13
NAmerM*	-0.08	-0.08	-0.11	-0.09
SAmerM*	0.04	0.01	-0.02	-0.03
WAfriM*	0.11	0.09	0.08	0.04

*LFT is of limited use as the change of monsoon precipitation is non-linear with respect to the GMT increase

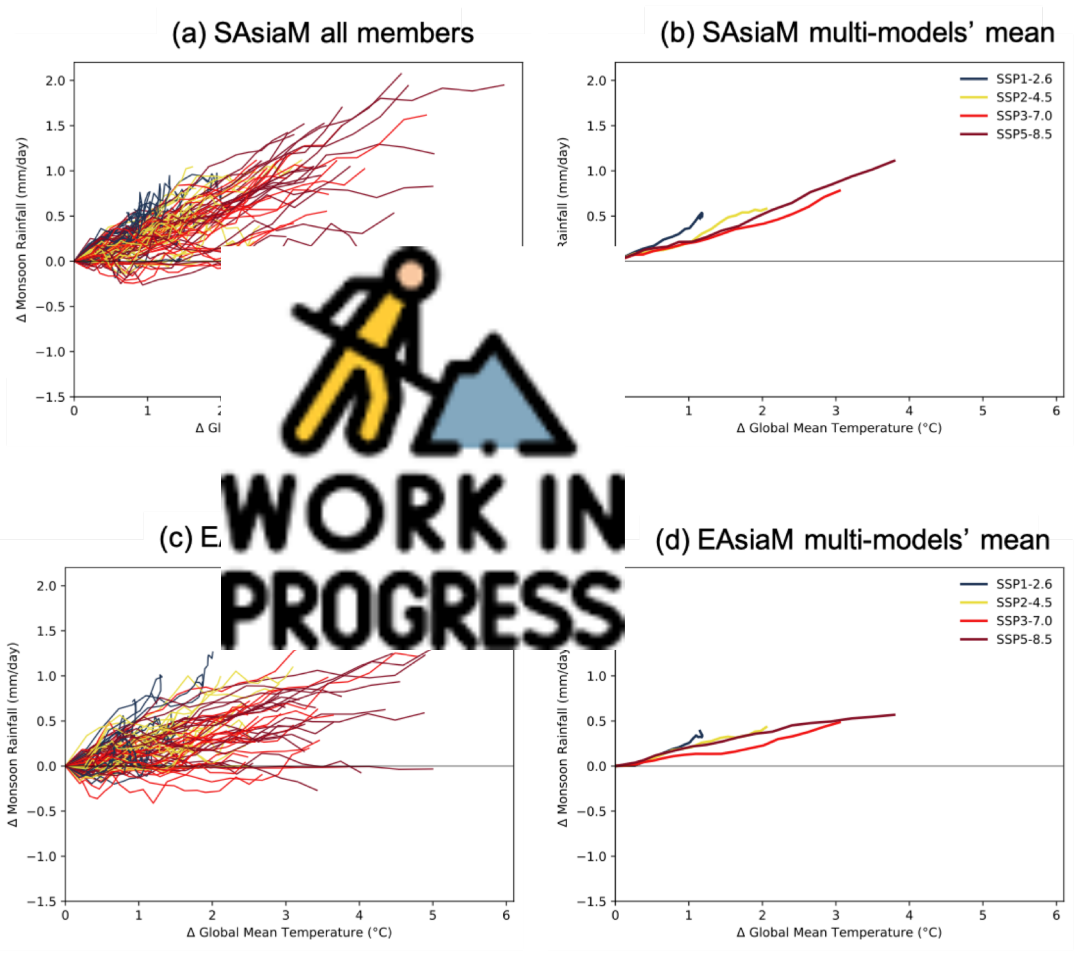
Hydrological sensitivity: the case of Asian monsoons & role of aerosols



Samset et al 2019

despite weaker air quality policies and increased black carbon and sulphates AOD in SSP3, precipitation increases less with GW compared to SSP2

Summer precipitation increase as function of GWL



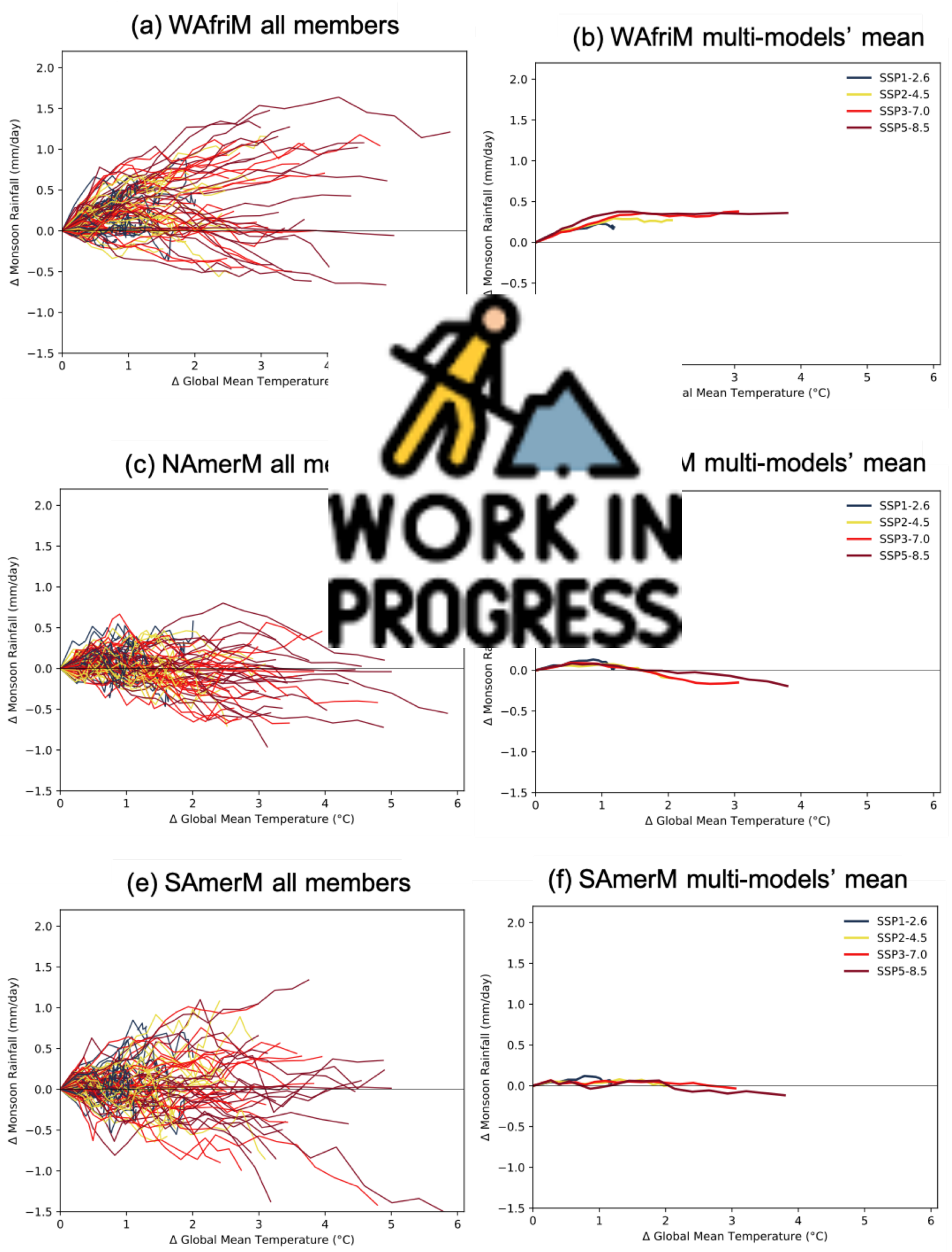
Complexity of aerosols-climate interactions, role of regional feedbacks & problems in representing all this in GCMs

Hydrological sensitivity of regional monsoons

(summer precip increase as function of GWL)

WAfriM: anthropogenic emissions & change in the temperature of the sub-tropical North Atlantic Ocean relative to the global tropical oceans (Giannini and Kaplan, 2019)

NAmerM & SAmerM: summer precipitation decrease with GW increase (as MMM) but the models' agreement in the sign of the change of summer mean rainfall to GWL is the lowest



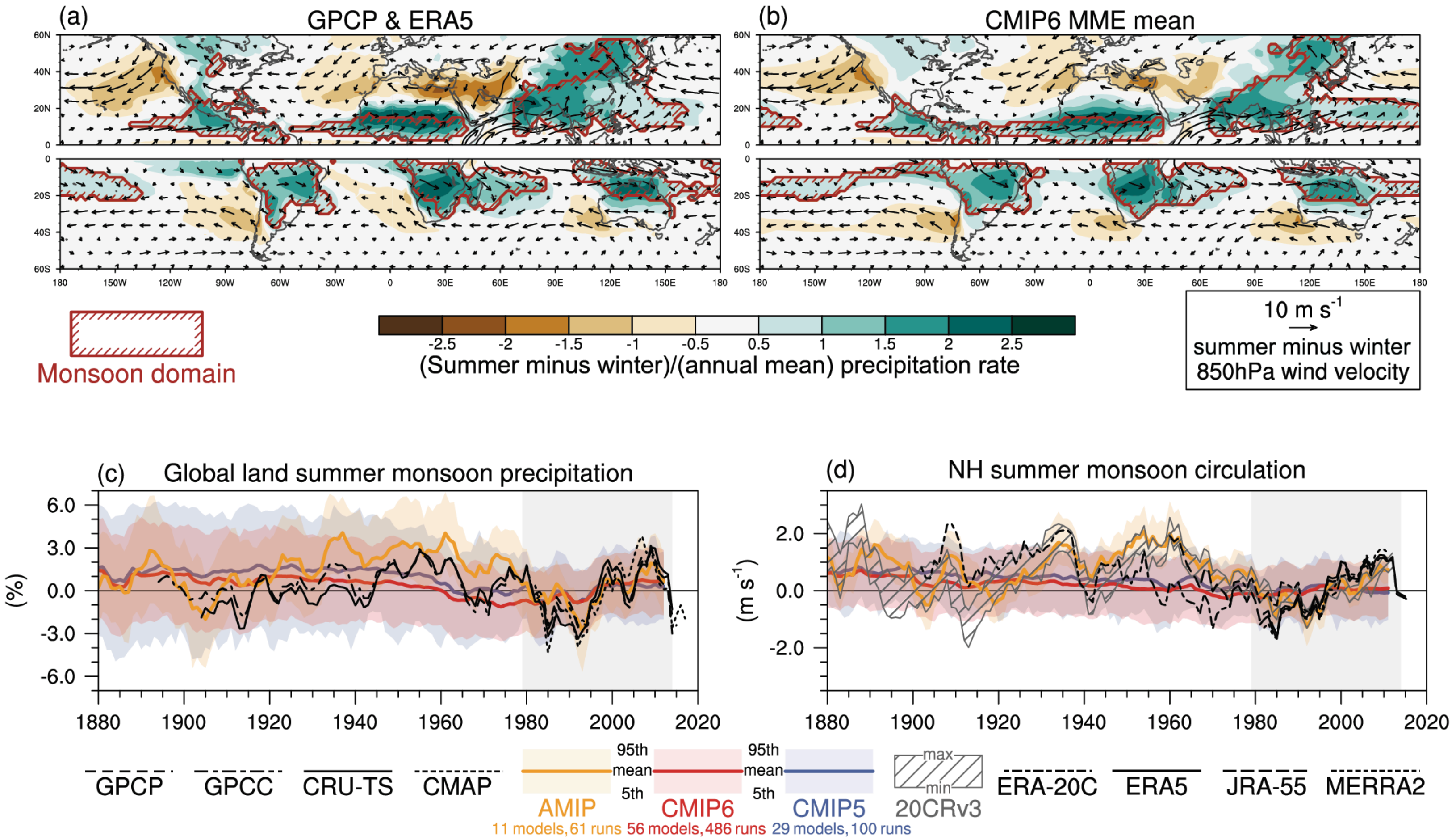
Summary & perspectives

- Monsoon precipitation increase with GW mostly for Global monsoon & Asian monsoons
- Non-linearity with radiative forcing because of diversities in response to type of anthropogenic aerosols (mostly EAsiaM)- complexity and role of local feedbacks
- WAfriM precipitation increase with GWL but with a threshold/plateau
- Models' disagreement in American monsoons

What's next:

- disentangle role of anthropogenic aerosols & SST gradient for WAfriM
- increase of the ensemble dimension to have more robust conclusions and mostly to see if disagreement in American monsoons is reduced
- role of climate sensitivity?

Global monsoon domain and intensity



- Realistic representation of monsoon domain & precipitation intensity;
    - Decline of GM precipitation then recovery in obs & models;
    - NH monsoon circulation: similar decline and then recovery

Fig. 3.17

Eyring et al. (2021) IPCC AR6 WGI, Ch 3

Decomposition of precipitation changes

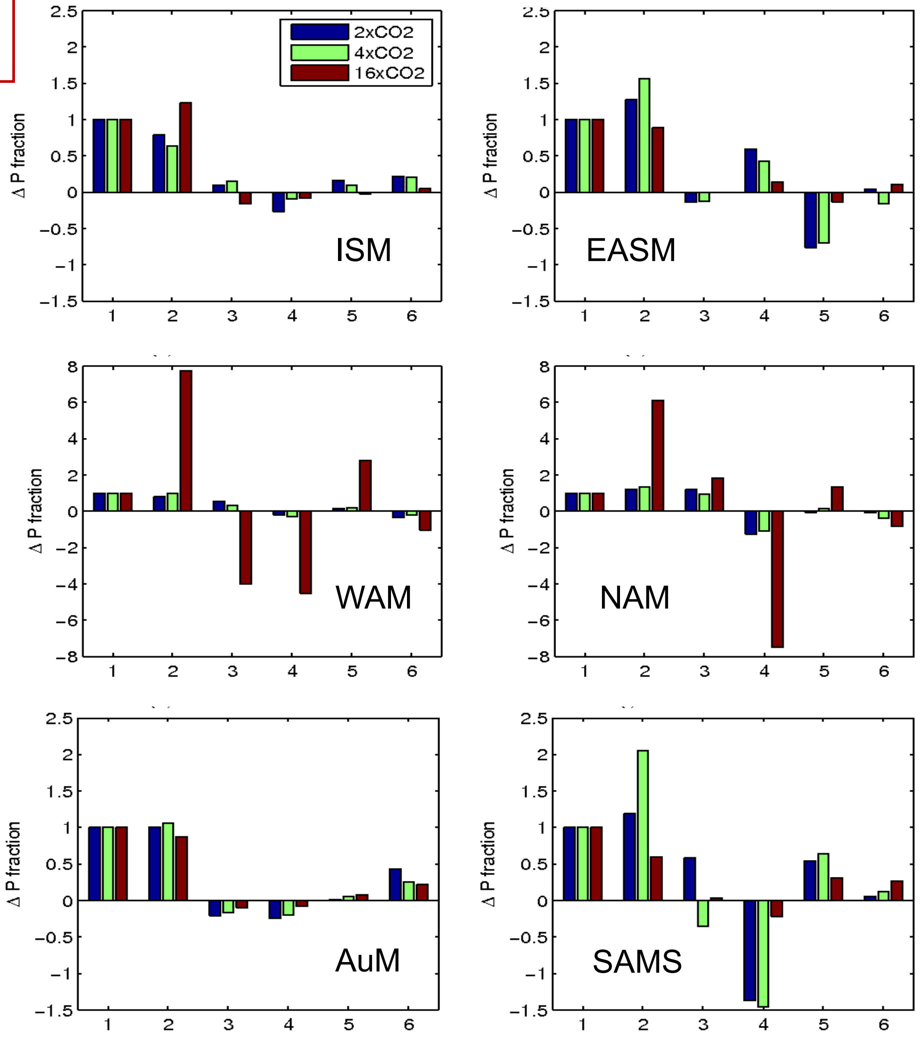
Precipitation departures

(following budget decomposition as in Chou et al., 2009)

$$P' = -\langle \overline{\omega} \partial_P q' \rangle - \langle \omega' \partial_P \overline{q} \rangle - \langle v \cdot \nabla q \rangle' + E' + q_{res}$$

q-term ω-term advection term evap

Moisture terms expressed as fraction of precipitation difference
1 - P difference
2 – q-term
3 – ω-term
4 – advection term
5 – evaporation difference
6 – residuals term (q_{res})



Cherchi et al (2011) – Clim Dyn

Thermodynamic component is positive, and in most cases it constitutes the largest contribution

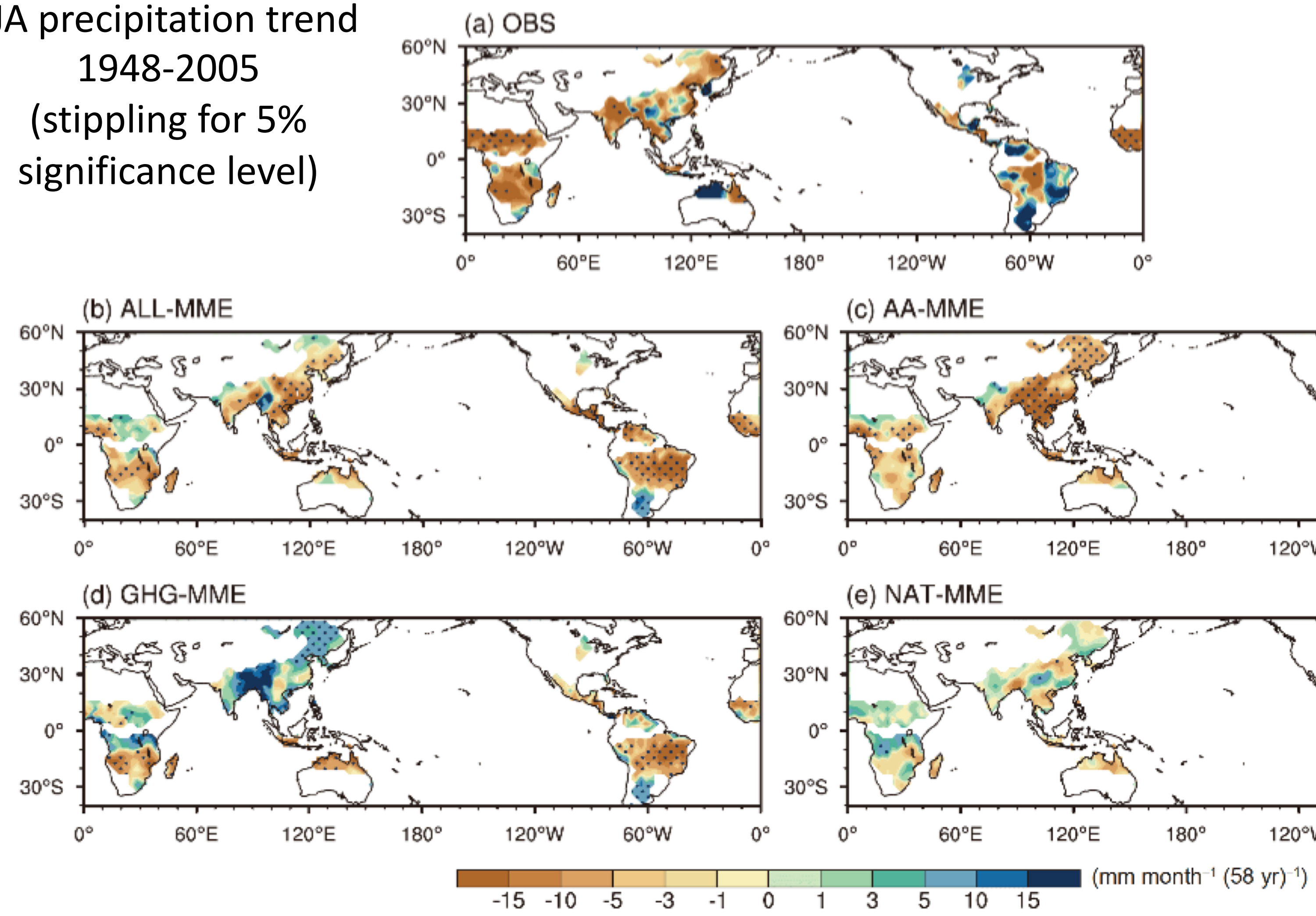
In most cases thermodynamic contribution is damped by the other terms

Monsoon systems may be organized into 2 categories: ISM, EASM, AuM where q-term dominates, and WAM, NAM and SAMS where ω-term and advection are equally important

WAM and NAM have a non-linear response to the forcing

Attribution of monsoon precipitation changes

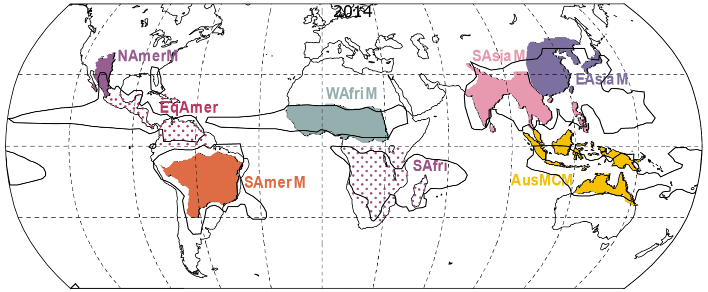
JJA precipitation trend
1948-2005
(stippling for 5% significance level)



Zhou et al (2020)

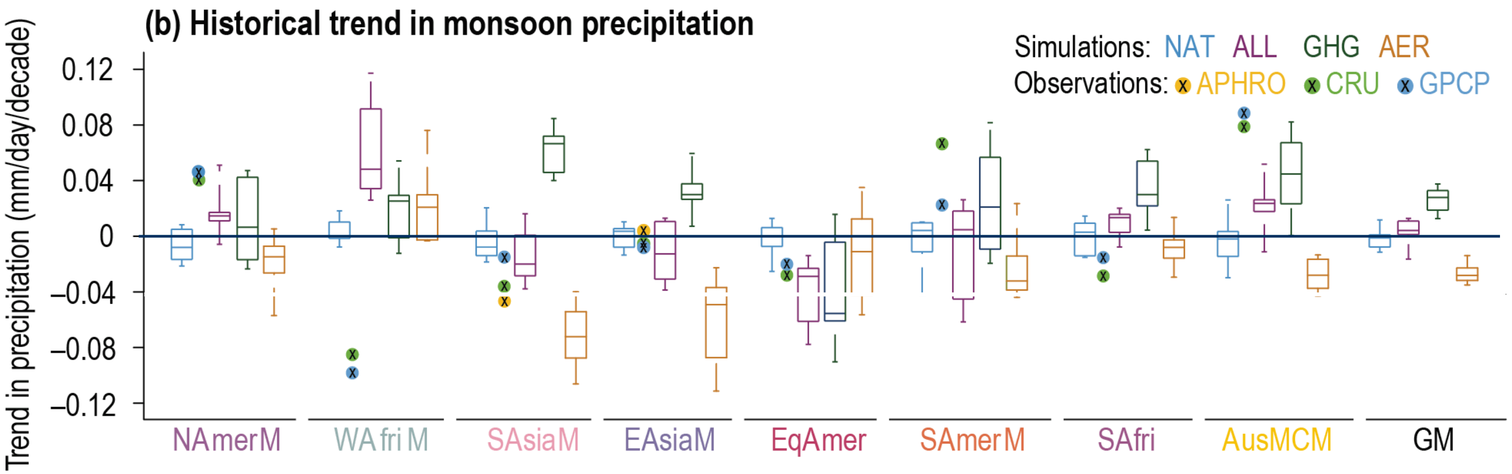
Observed drying trend is consistent with the model simulated response to anthropogenic forcing (anthropogenic aerosol forcing) - 5 CMIP5 models results

(a) Global and regional monsoon domains



Attribution of monsoon precipitation changes

Box TS.13, Fig. 1(a,b)



Global and regional monsoons precipitation trends based on DAMIP CMIP6 simulations with both natural and anthropogenic (ALL), greenhouse gas only (GHG), aerosols only (AER) and natural only (NAT) radiative forcing. Weighted ensemble means are based on nine Coupled model Intercomparison Project Phase 6 (CMIP6) models contributing to the MIP (with at least three members). Observed trends computed from CRU, GPCP and APHRO (only for*SAsiaM* and *EAsiaM*) datasets are shown as well.

- In the NH monsoon regions experienced declining precipitation from the 1950s to 1980s, which is partly attributable to the influence of anthropogenic aerosols (*medium confidence*). For GM the simulated change is dominated by the response of the NH monsoons (increase due to GHG balanced by decrease due to AER);
- In the instrumental records, GM precipitation intensity has *likely* increased since the 1980s, dominated by Northern Hemisphere summer trends and large multi-decadal variability.

Arias et al. (2021) IPCC AR6 WGI, TS