Department of Meteorology &
National Centre for Atmospheric Science

University of Reading

The effects of climate change on the global and regional monsoons – the IPCC AR6

Madeleine Nicolas (distributed via imaggeo.egu.eu)

Prof. Andy Turner (a.g.turner@reading.ac.uk)

@agturnermonsoon
www.monsoon.org.uk

Team effort

Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press. In Press.

Monsoon information in the AR6 WGI

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Summary for Policy Makers Technical Summary	**Headlines**
Chapter 2: Changing state of the climate system Chapter 3: Human influence on the climate system Chapter 4: Future global climate: scenario-based projections & near-term info.	**Global monsoon**
Chapter 8: Water cycle changes	**Regional monsoon**
Chapter 10: Linking global to regional climate change Chapter 11: Weather and climate extreme events in a changing climate Chapter 12: Climate change information for regional impact and for risk assessment Regional Atlas / Interactive Atlas	**Case studies, extremes, impacts**
Annexes	Annex V: Monsoons

The detailed, region-by-region monsoon information falls in Chapter 8

Chapter 3: Attribution

- Good but imperfect simulation of present-day GM domains
- Decline in GM precipitation 1950s-1980s, followed by recovery, in models & obs
- Similar decline and recovery in NH monsoon circulation

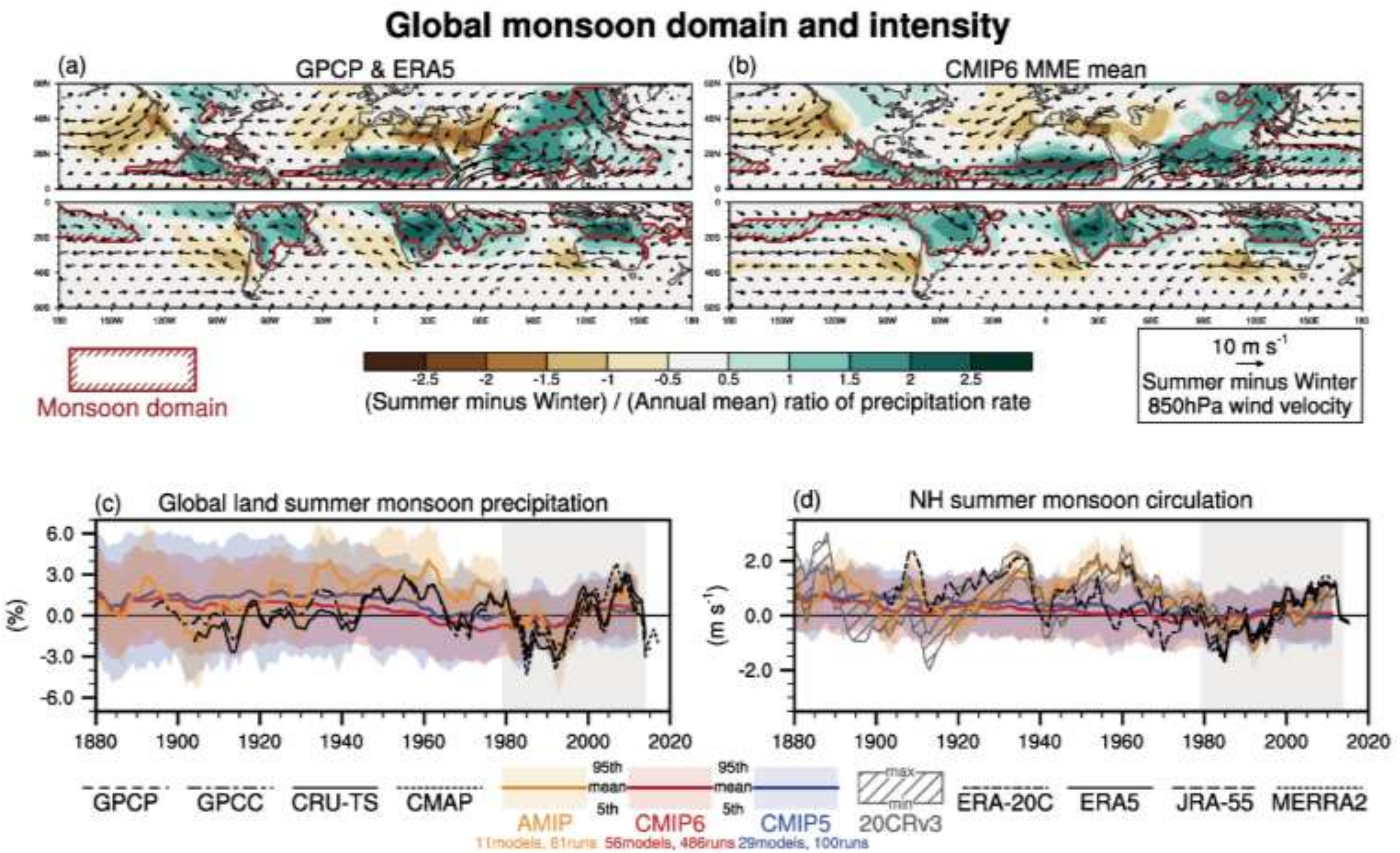
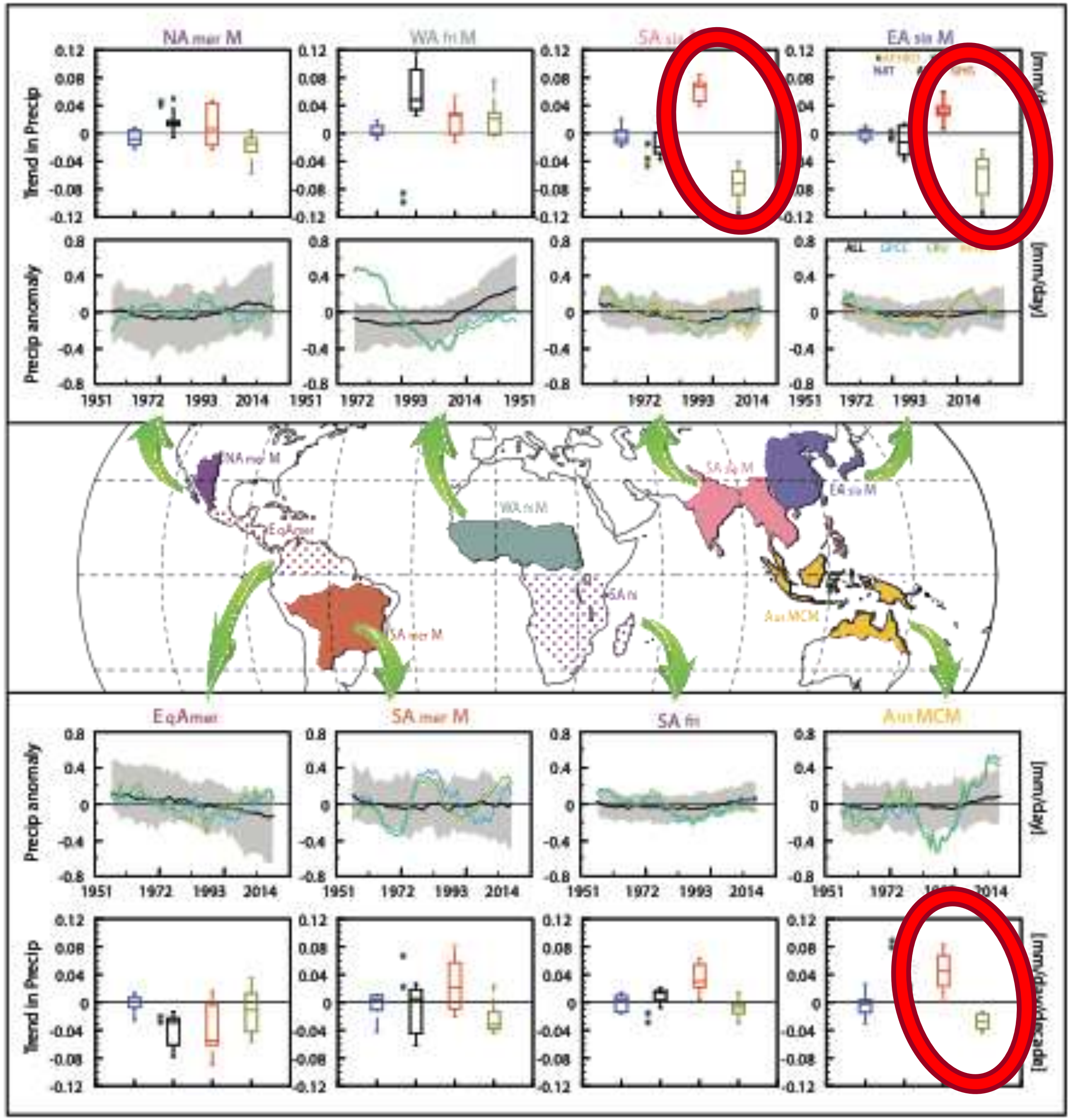


Figure 3.17: Model evaluation of global monsoon. (a-b) Climatological summer-winter range of precipitation rate, scaled by annual mean (shading) & 850 hPa wind (arrows) based on (a) GPCP and ERA5 and (b) CMIP6 MME mean 1979-2014. Red lines show monsoon domain based on Wang & Ding (2008). (c-d) 5-year running mean anomalies of (c) global land monsoon precipitation and (d) tropical monsoon circulation index (vertical shear of zonal winds, 0°-20°N, 120°W-120°E).

Ch8: Regional monsoon attribution

- Some monsoons feature clear opposing behaviour under GHG and AA conditions
  - Notably, South Asia, East Asia, Australia/MC

Figure 8.11: Regional monsoon precipitation changes from observations and model attribution as linear trends in box-whisker plots over the six regional monsoons and over two other domains (equatorial America, JJA & South Africa, DJF). Precipitation changes are computed from observations and from DAMIP CMIP6 experiments over the historical period different forcings prescribed. Observations are CRU and GPCC, and APHRODITE for SAsiaM and EAsiaM.



Ch8: Regional monsoons, 20th century

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Regional monsoon	Change	Attribution
South Asia	Weakening in second half of 20th century	Anthropogenic aerosols, opposing expected increase due to GHG
East Asia	Drying north, wetting south since 1950s	Anthropogenic forcing; PDV+ a driver of weakening since 1970s
West Africa	Wet mid-20th century, dry 1970s/1980s, some recovery from mid-1990s	Combination of NH aerosols and equatorial warming, followed by reduction in NH aerosol emissions
North America	Intensification since 1970s	Partly driven by GHG
South America	Complex: onset delayed since late 1970s; reduced rainfall during dry-to-wet transition season in southern Amazon	Anthropogenic forcing
Australia/M Cont.	Increased rain in parts of N. Australia since 1970s	Low confidence in human contributions

- In addition to 20th-century modelling, palaeoclimate proxies and modelling support strengthened NH monsoons in warmer periods of the past (South Asia, East Asia, West Africa, NAM), including due to orbital forcing

Near-term future

- “Near-term changes in global monsoon precipitation and circulation will be affected by the combined effects of model uncertainty and internal variability, which together are larger than the forced signal (*medium confidence*)” {4.4.1.4}

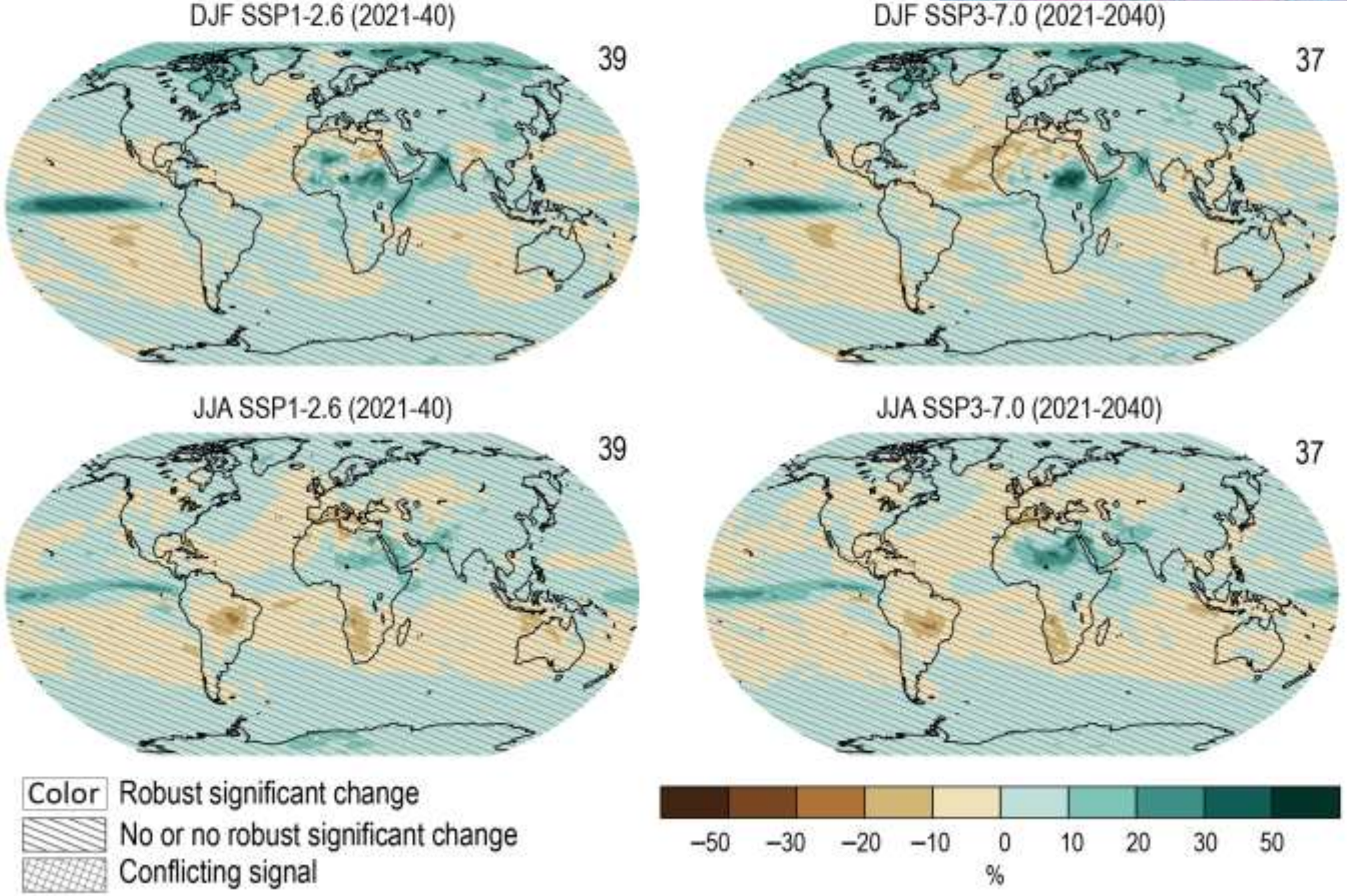

Figure 4.13: Near-term change of seasonal mean precipitation. Projected spatial patterns of CMIP6 MMM change (%) in DJF and JJA precipitation from SSP1-2.6 and SSP3-7.0 34 in 2021–2040 relative to 1995–2014. No overlay indicates regions where change is robust and likely emerges from internal variability, that is, where at least 66% of the models show a change greater than the internal-variability threshold and at least 80% of the models agree on the sign of change. Diagonal lines indicate regions with no change or no robust significant change, where fewer than 66% of the models show change greater than the internal-variability.

Long-term future

- “Based on CMIP6 models, it is *likely* that… global land monsoon precipitation will increase with GSAT rise despite a weakened monsoon circulation”
- “Global land monsoon precipitation will likely increase by 1.3–2.4 % per °C GSAT warming”
- “Monsoon precipitation responses depend on region and emission scenario” {4.5.1.5}

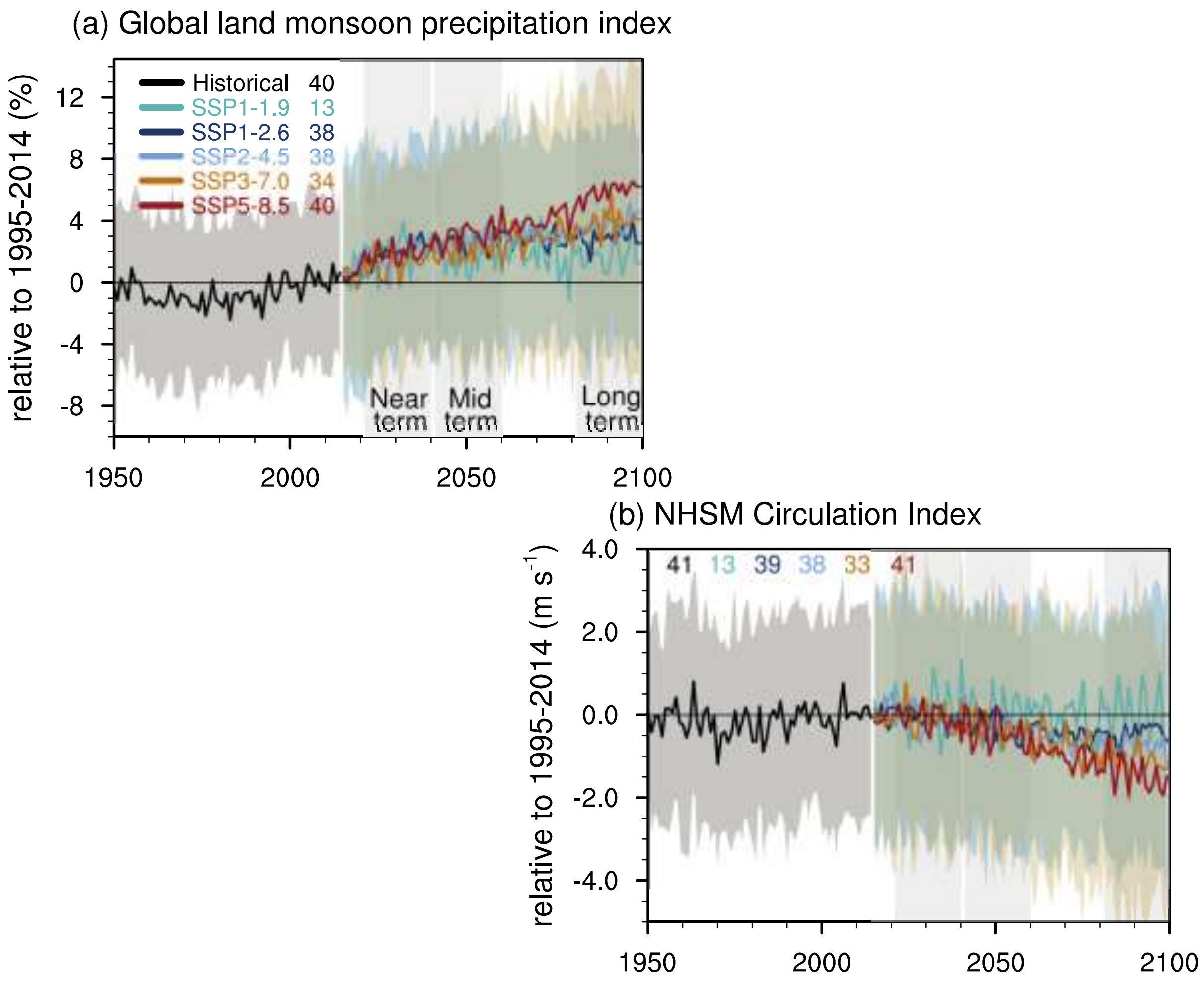

Figure 4.14: Time series of global land monsoon precipitation & NHSM circulation index anomalies. (a) Global land monsoon precipitation anomalies defined as area-weighted mean precipitation rate for the CMIP6 historical simulation for 1950–2014 and five SSPs 2015–2100. (b) Anomalies in NHSM circulation index, defined as the vertical shear of zonal winds (0°–20°N, 120°W–120°E). One realization per model. Anomalies relative to 1995–2014.

Ch8: Regional monsoons in the 21st century

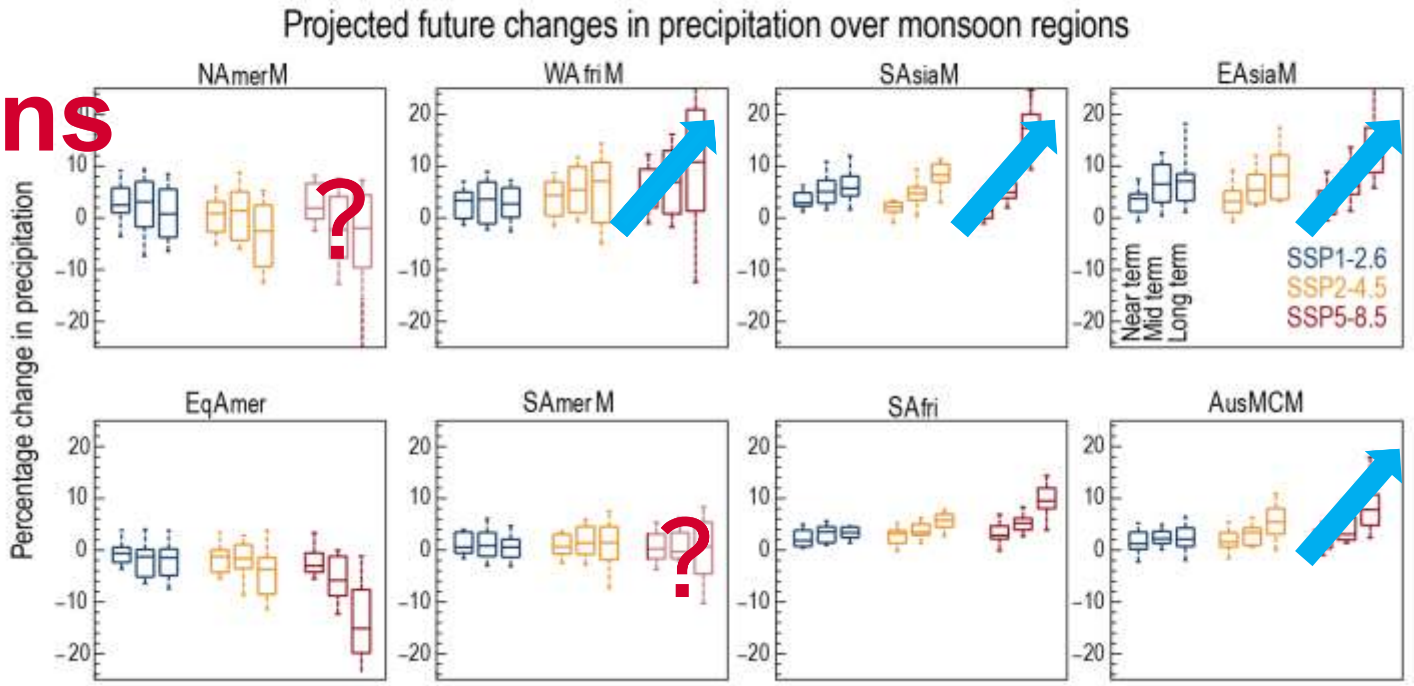

Figure 8.22: Projected regional monsoons precipitation changes. Percentage change over regional monsoon domains for near-term (2021-2040), mid-term (2041-2060), and long-term (2081-2100) periods based on 24 CMIP6 models and three SSP scenarios.

- Robust and consistent increases in various regional monsoons when under stronger emissions scenarios and further into the future
  - Notably in South Asia, East Asia, West Africa
- Some regions have considerable uncertainty
  - Especially the American monsoons

Scaling of (Indian) monsoon rainfall with warming

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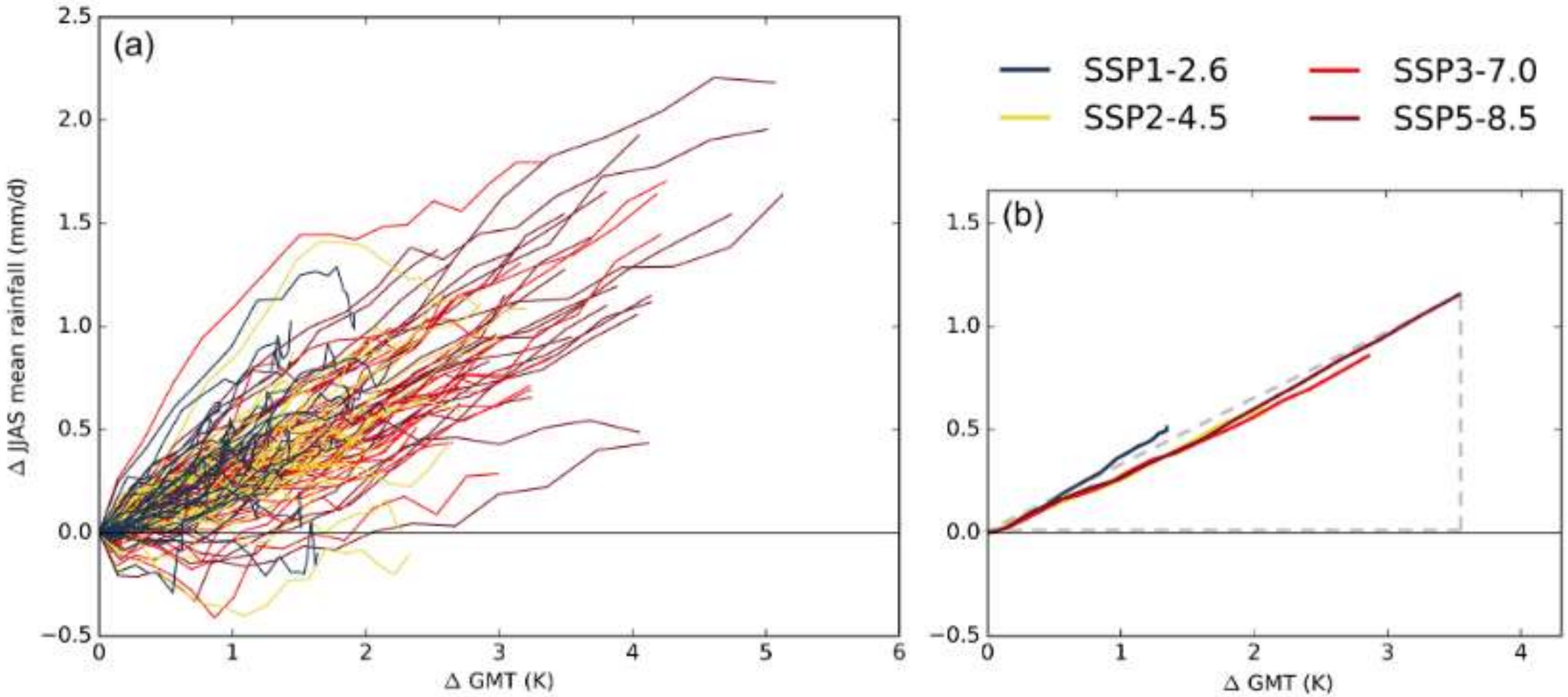
- Clear evidence for linear scaling of monsoon rainfall change with warming relative to the present day



Katzenberger Figure: Change in ISM rainfall as a function of change in GMT relative to 1985-2014. (a) each model, (b) scenario mean.

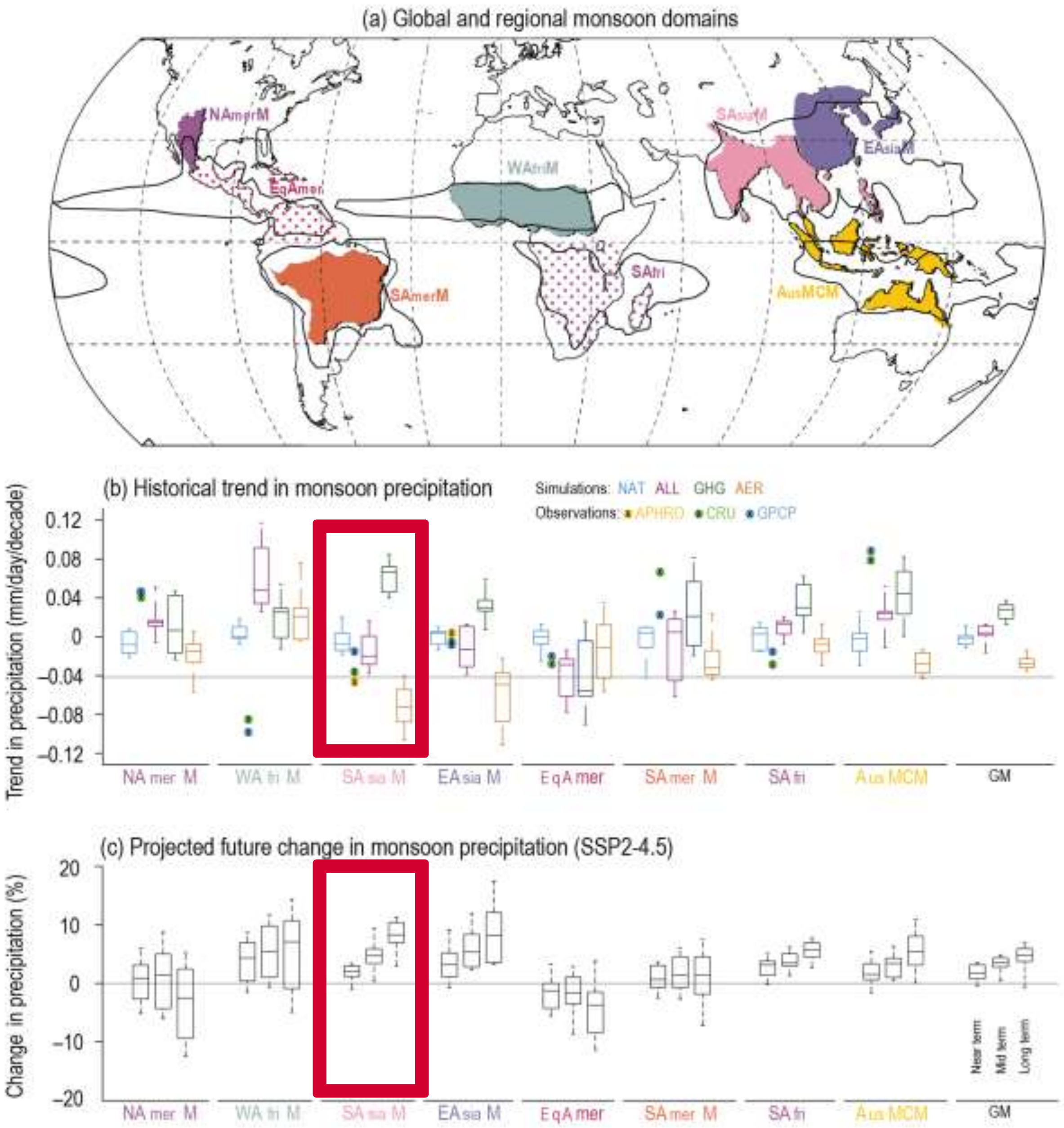
Source: Anja Katzenberger *et al.* (2021, *Earth System Dynamics*)

Low-likelihood, high-impact events

- SPM, C.3.4: "The Atlantic Meridional Overturning Circulation is *very likely* to weaken over the 21st century for emission scenarios…there is only *low confidence* in the magnitude of the trend. There is *medium confidence* that there will not be an abrupt collapse before 2100. If such a collapse were to occur, it would *very likely* cause…weakening of the African and Asian monsoons and strengthening of the Southern Hemisphere monsoons"
- Summary of CCB4.1 on climate effects of volcanic eruption: "It is *likely* that at least one large eruption will occur during the 21st century. Such an eruption would reduce GSAT for several years, decrease global-mean land precipitation, alter monsoon circulation, modify extreme precipitation… A low likelihood high impact outcome would be several large eruptions that would greatly alter the 21st-century climate trajectory compared to SSP-based ESM projections."

Technical Summary

- Combination of GHG & anthropogenic aerosol forcing fundamental to driving changes in regional & global monsoons
- Internal variability also plays a role



Box TS.13, Figure 1: Global and regional monsoons: past trends and projected changes: (a) Global and regional monsoons. GM defined where local summer-minus-winter precipitation exceeds 2.5 mm day^{-1}. (b) Global and regional monsoons precipitation trends based on DAMIP CMIP6 simulations. (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 SSP 2-4.5 based on 24 CMIP6 models.

Technical summary monsoon box

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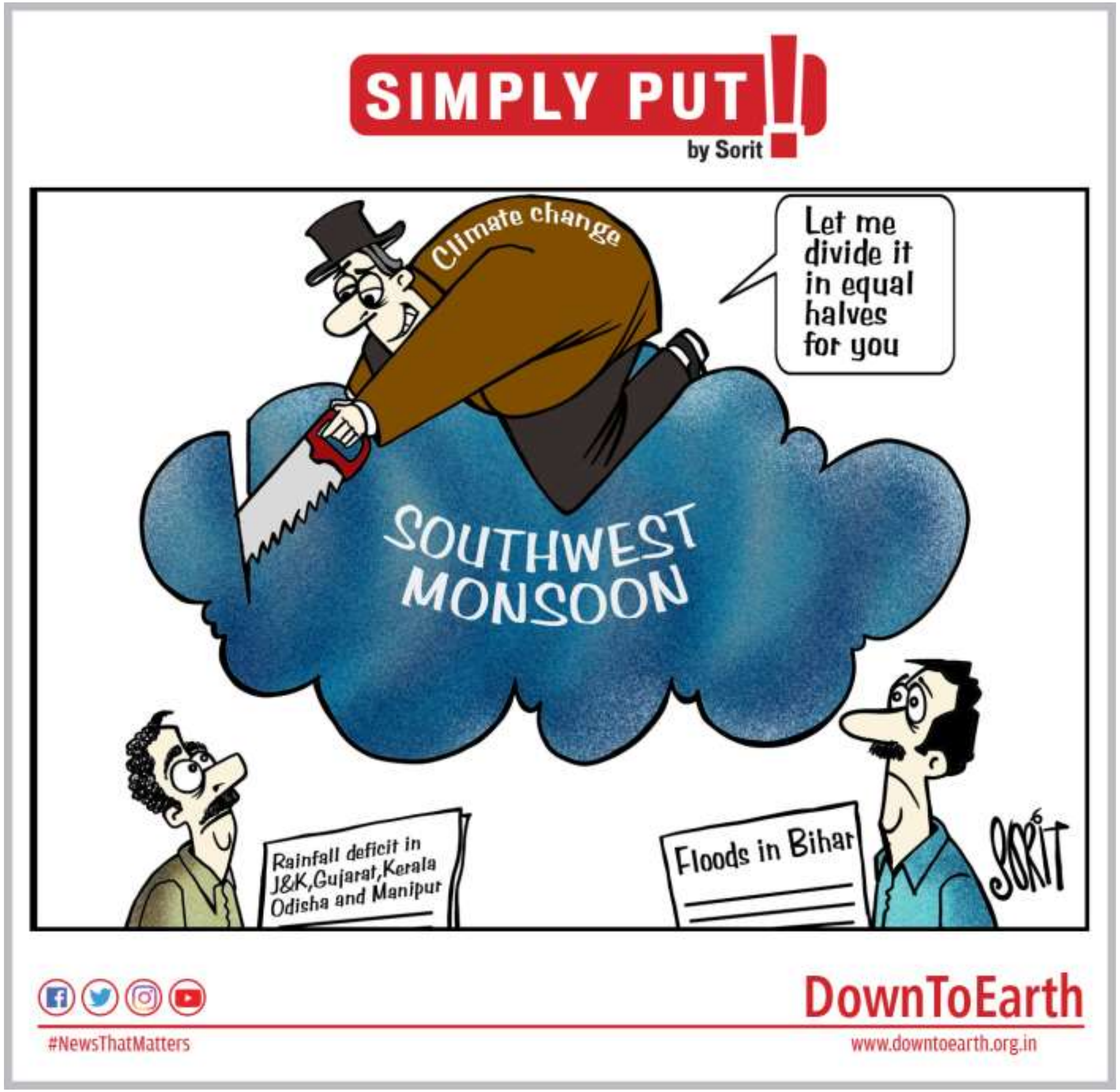
- "Global land monsoon precipitation decreased from the 1950s to the 1980s, partly due to anthropogenic aerosols, but has increased since then in response to GHG forcing and large-scale multi-decadal variability (*medium confidence*)."
- "Northern Hemispheric anthropogenic aerosols weakened the regional monsoon circulations in South Asia, East Asia and West Africa during the second half of the 20th century, thereby offsetting the expected strengthening of monsoon precipitation in response to GHG-induced warming (*high confidence*)."
- "During the 21st century, global land monsoon precipitation is projected to increase in response to GHG warming in all time horizons and scenarios (*high confidence*)."
- "Over South and Southeast Asia, East Asia and the central Sahel, monsoon precipitation is projected to increase, whereas over North America and the far western Sahel it is projected to decrease (*medium confidence*)."
- "There is low confidence in projected precipitation changes in the South American and Australian-Maritime Continent monsoons."
- At global and regional scales, near-term monsoons changes will be dominated by the effects of internal variability (*medium confidence*)."

What else?

- Intensification of the water cycle (see Ch.8)
- Increased heavy rainfall extremes (see Ch.11)
- Longer dry spells
- Heat waves…



IWM-7 Friday 25 March 2022

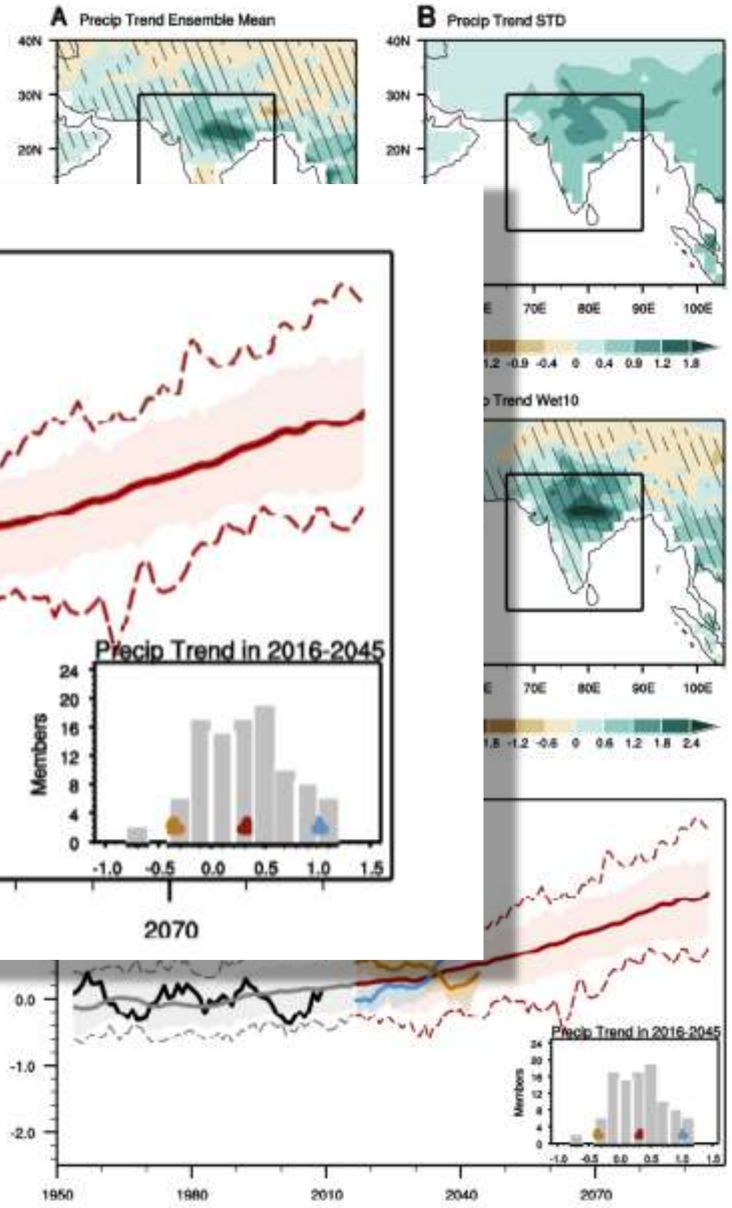
MAJOR UNCERTAINTIES

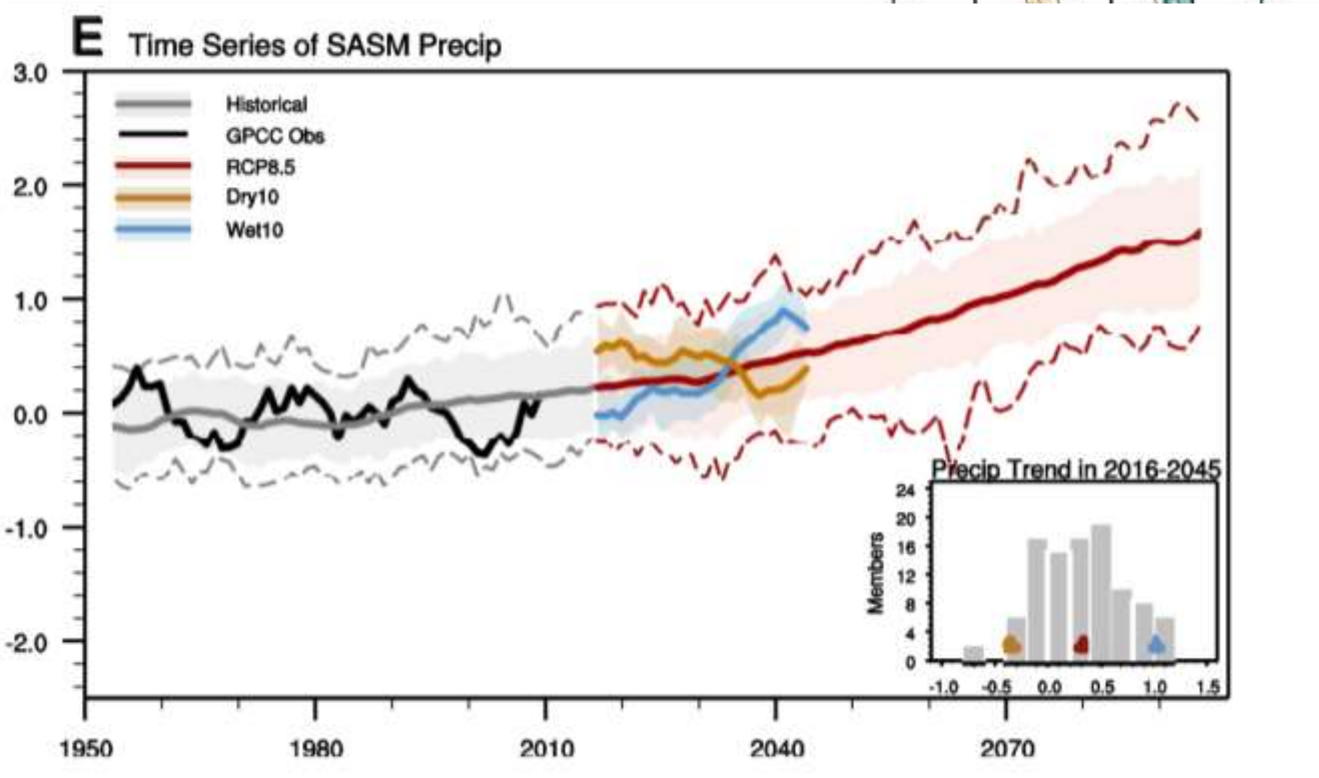
Interplay between internal variability & forced change

New experiment designs are helping understand variability and chan

- Large ensemble all be determined
  - 100 members of historical & RCP
- For individual regio near-term climate p take account of inte

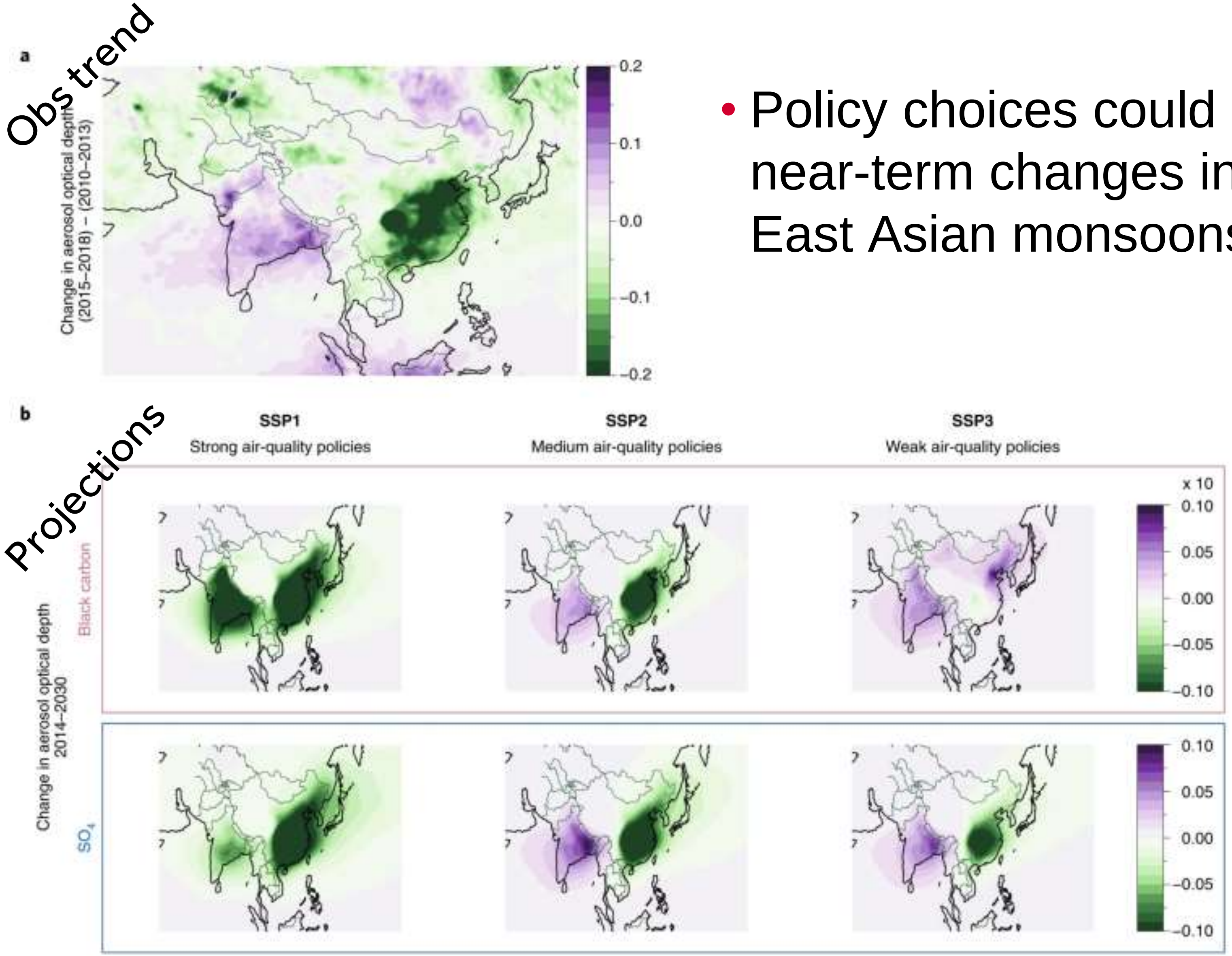
Read more in IPCC Ch10!





Source: Huang *et al.* (2020, *Science Advances*)

Near-term aerosol changes



- Policy choices could help determine near-term changes in the South and East Asian monsoons

Figure: Recent & expected emissions changes lead to striking patterns of change in aerosol loading and over South & East Asia. (a) Recent AOD changes observed by the MODIS-Terra since 2010. (b) Near-term SSP projections for black carbon and SO4, depending on assumed regional air-quality policies.

Source: Samset *et al.* (2019) Emerging Asian aerosol patterns. *Nat. Geosci.*, doi:10.1038/s41561-019-0424-5

Persistence of GCM biases

- Ch3: “AR5 assessed that CMIP5 models simulated monsoons better than CMIP3 models but that biases remained in domains and intensity (*high confidence*)”
- “CMIP6 models reproduce the domain and precipitation intensity of the global monsoon observed over the instrumental period better than CMIP5 models (*medium confidence*). However, CMIP5 and CMIP6 models fail to fully capture the variations of the NH summer monsoon circulation (Figure 3.17d), but there is *low confidence* to this assessment due to a lack of evidence in the literature”

{3.3.3.2}

Persistence of GCM biases

- Latest CMIP6 model biases are not particularly dissimilar to earlier CMIP5 & CMIP3 models
  - *e.g.*, Indian monsoon dry bias
- At current GCM scales, model resolution is not an instant solution to this problem

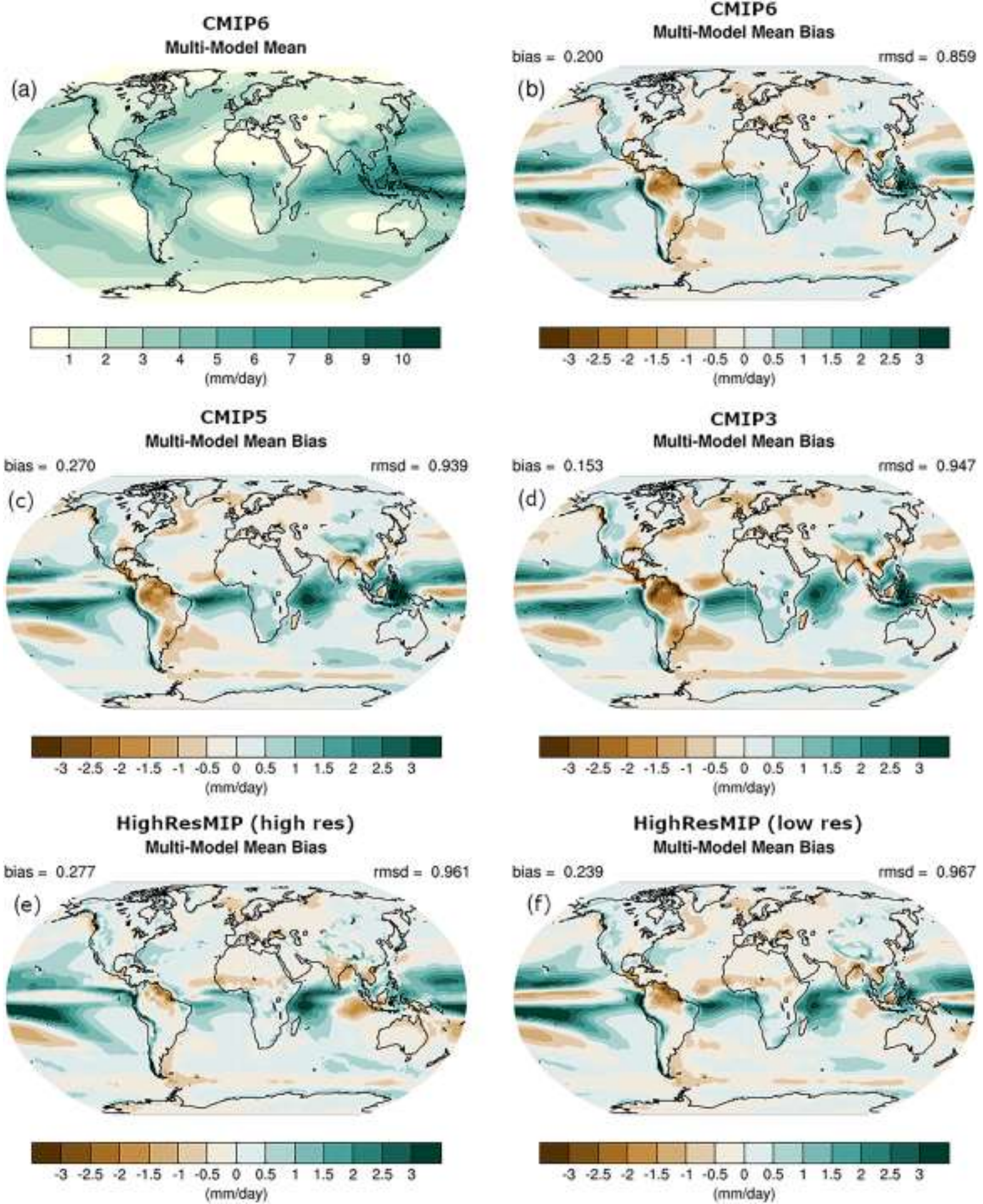


Figure: Annual mean precipitation. (a) MMM from one realization of CMIP6 historical experiments for 1995–2014; MMM bias of (b) CMIP6, (c) CMIP5 (1985–2004), (d) CMIP3 (1980–1999), (e) high-resolution, and (f) low-resolution simulations of HighResMIP ensemble (1995–2014) vs. GPCP.

Source: Bock *et al.* (2020). Quantifying progress across different CMIP phases with the ESMValTool. *JGR-A*, doi:10.1029/2019JD032321

Summary & thanks

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a.g.turner@reading.ac.uk

@agturnermonsoon

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- Monsoons are changing in complex ways
- Future projections of increased rainfall for global and South Asian monsoon, scaled with warming
- In the near-term, internal variability is likely to dominate
  - For Asian monsoons, aerosol pathways are also important
- Model biases are a long-standing issue

- Thank you for the invitation and your attention!