

Monsoon climate change in the IPCC AR6 – global and regional monsoons



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WMO IWM8 invited talk, 20 March 2025, IITM, Pune, India



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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

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

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Global monsoon domain and intensity

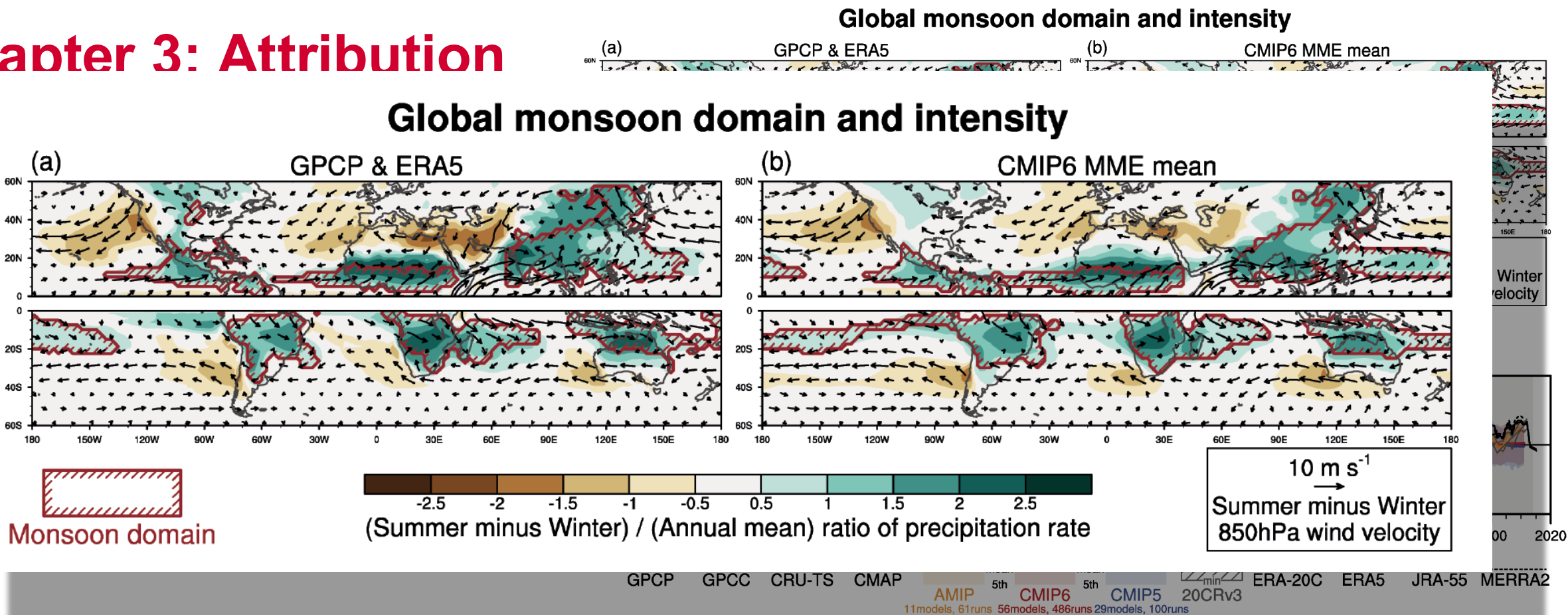
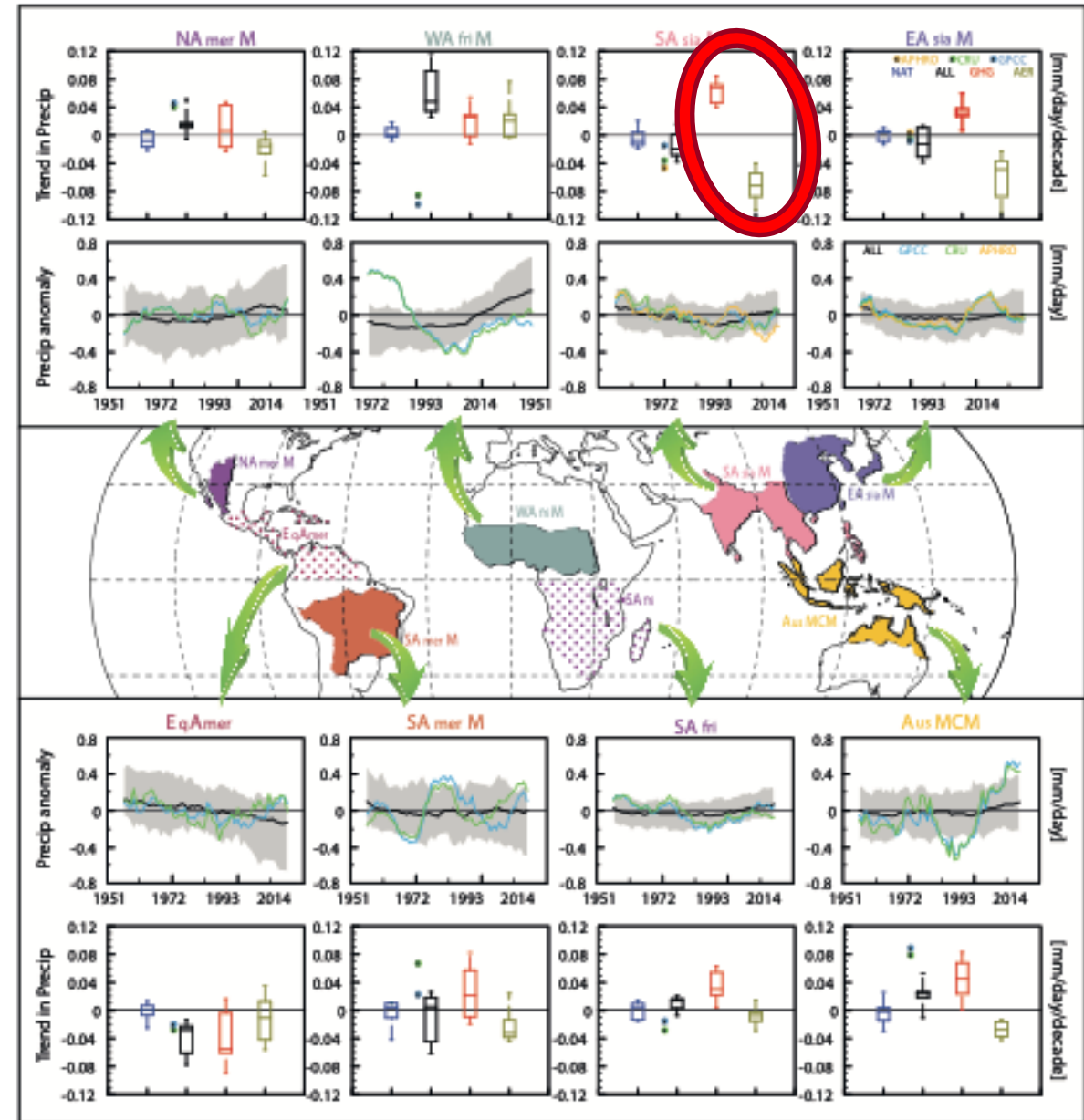


Figure 3.17: Model evaluation of global monsoon. (a-b) Climatological summer-winter range of precipitation rate, scaled by annual mean (shading) & 850 hPa wind (arrows) based on (a) GPCP and ERA5 and (b) CMIP6 MME mean 1979-2014. Red lines show monsoon domain based on Wang & Ding (2008). (c-d) 5-year 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 opposing behaviour in the 20th century 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

Regional monsoon	Change	Attribution
South Asia	Weakening in second half of 20 th 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-20 th 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}

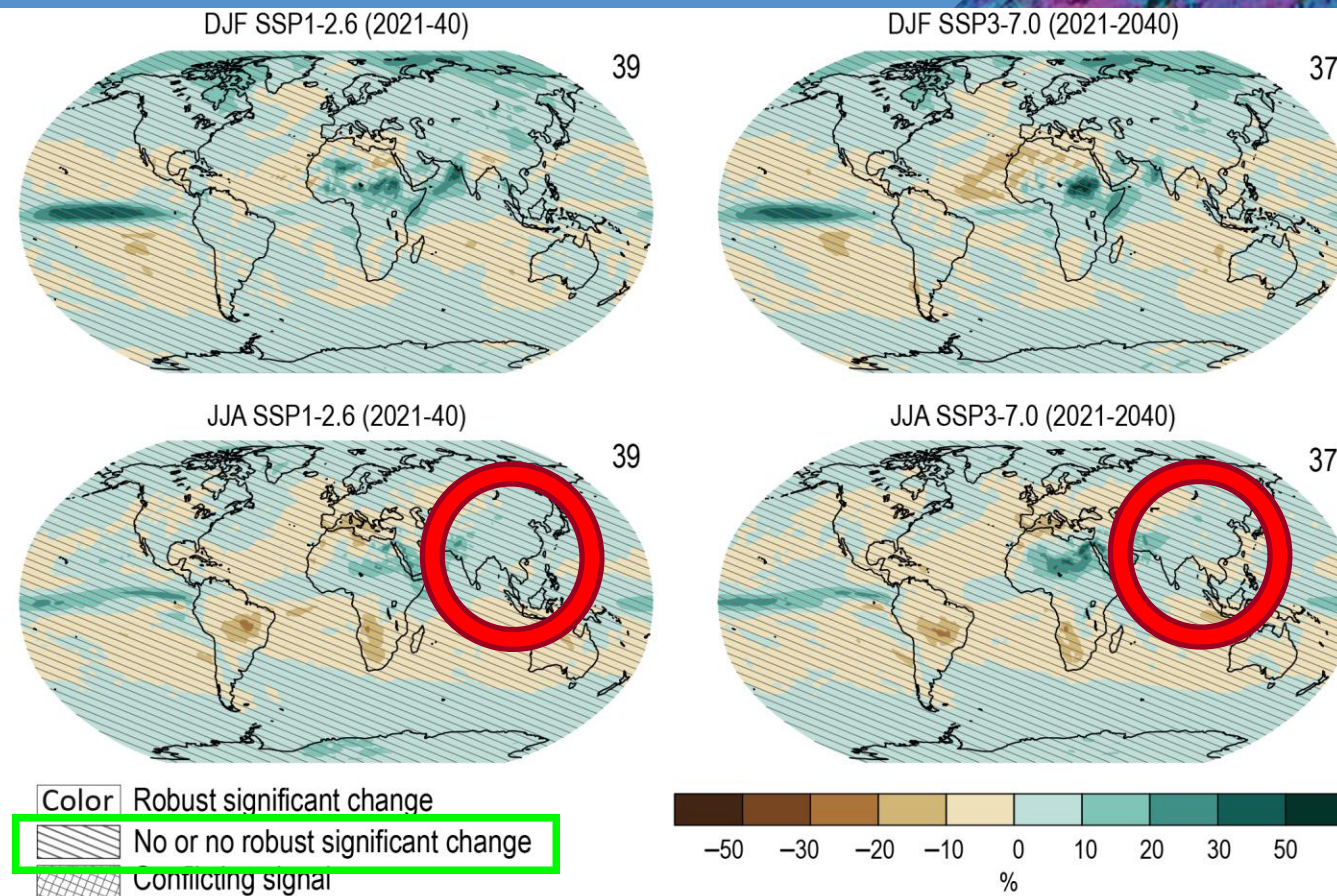


Figure 4.13: Near-term change of seasonal mean precipitation. Projected spatial patterns of CMIP6 MMM change (%) in DJF and JJA precipitation from SSP1-2.6 and SSP3-7.0 34 in 2021–2040 relative to 1995–2014. No overlay indicates regions where change is robust and likely emerges from internal variability, 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}

GSAT = global surface air temperature

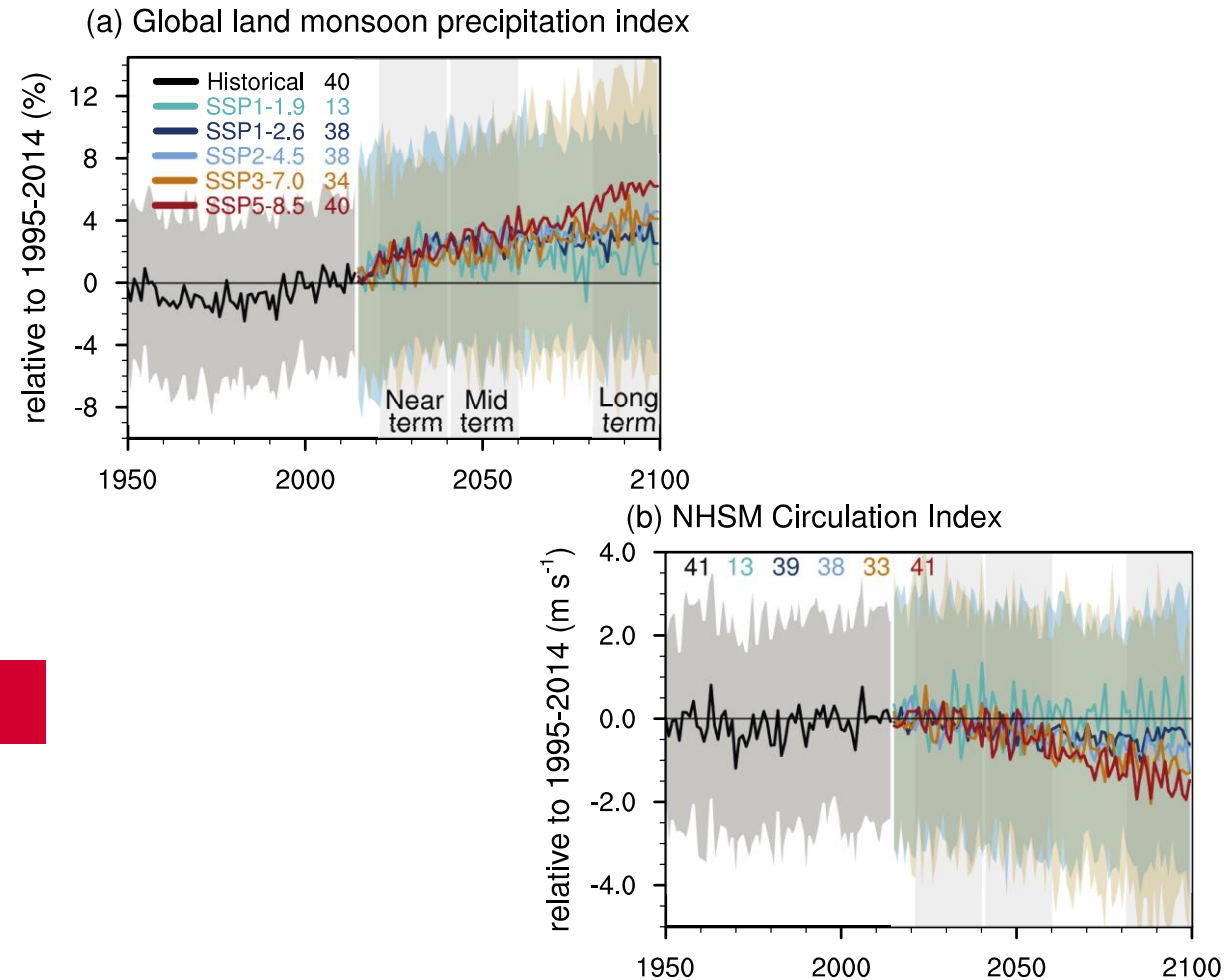
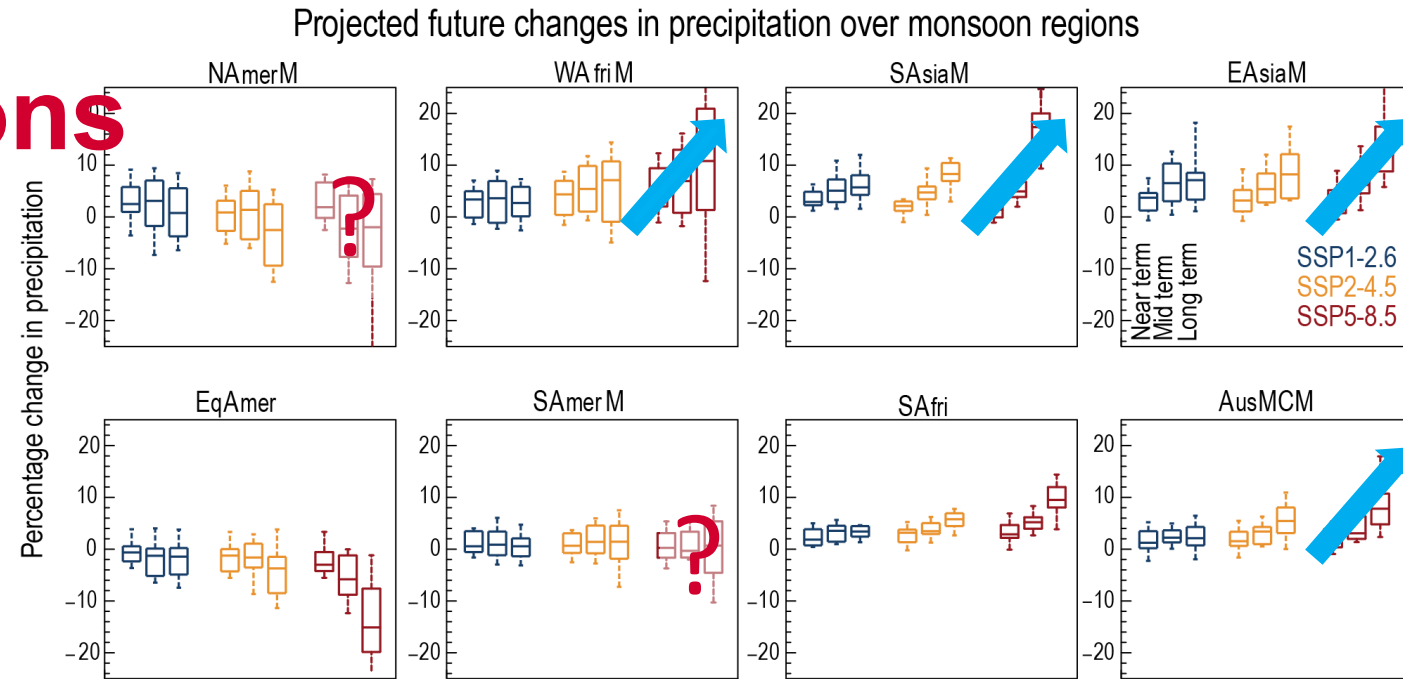


Figure 4.14: Time series of global land monsoon precipitation & NHSM circulation index anomalies. (a) Global land monsoon precipitation anomalies defined as area-weighted mean precipitation rate for the CMIP6 historical simulation for 1950–2014 and five SSPs 2015–2100. (b) Anomalies in NHSM circulation 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

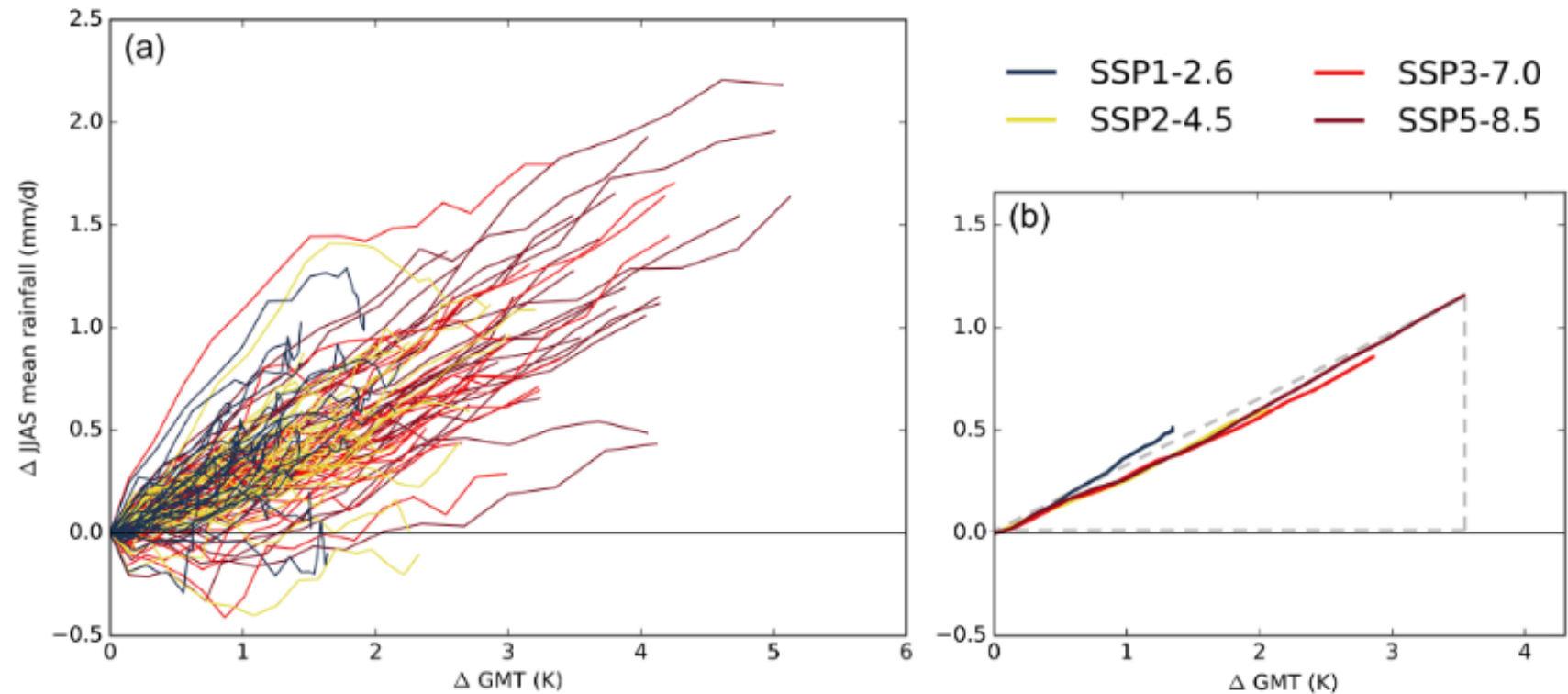
Figure 8.22: Projected regional monsoons precipitation changes. Percentage change over regional monsoon domains for near-term (2021-2040), mid-term (2041-2060), and long-term (2081-2100) periods based on 24 CMIP6 models and three SSP scenarios.



- 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

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

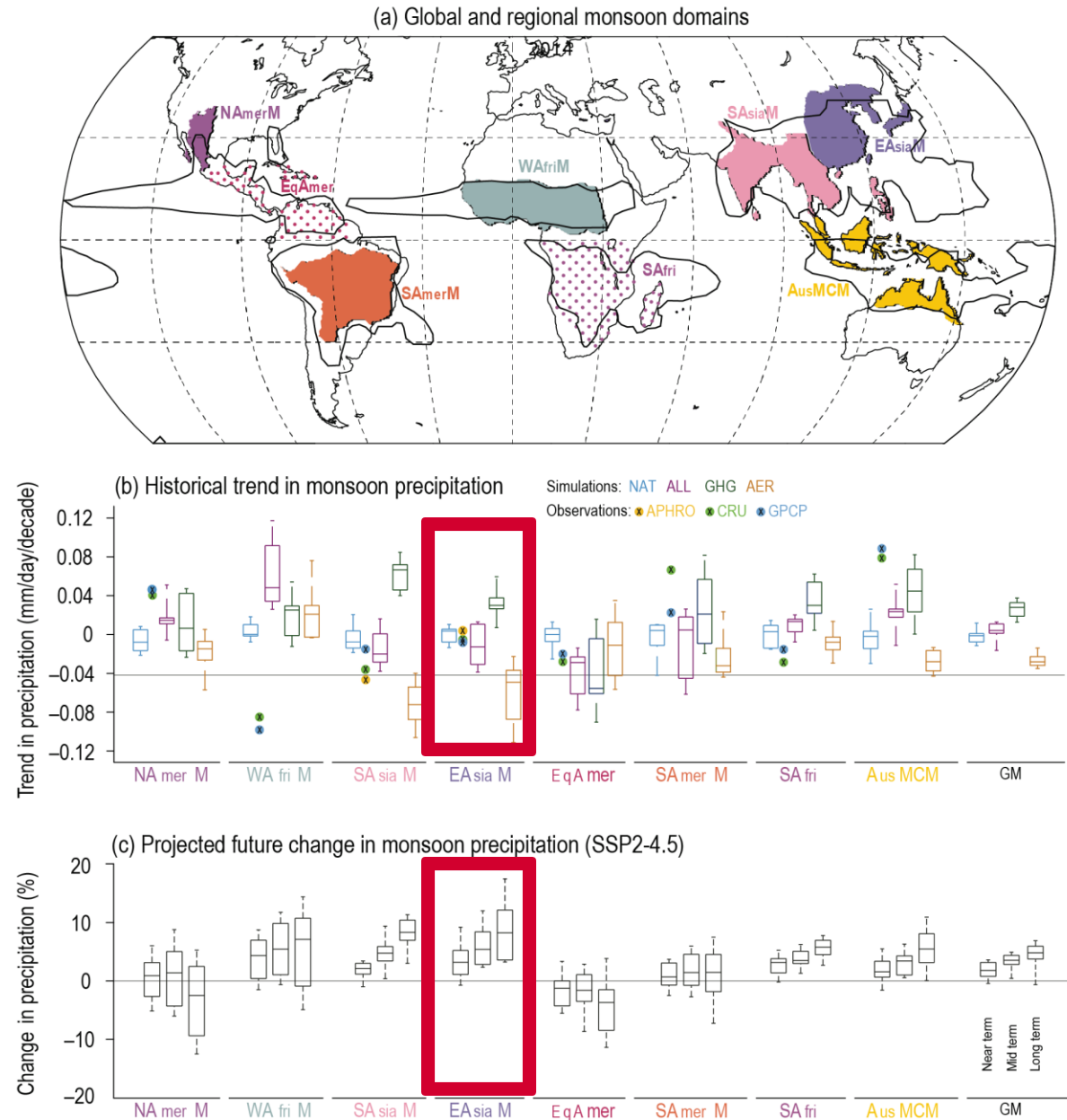


Katzengerber Figure: Change in ISM rainfall as a function of change in GMT relative to 1985-2014. (a) each model, (b) scenario mean.

Technical Summary

- Combination of GHG & anthropogenic aerosol forcing are 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.



Ch10: Indian monsoon case study

Confidence in the distilled regional climate information is enhanced when there is agreement across multiple lines of evidence. For example, the apparent contradiction between the observed decrease in Indian monsoon rainfall over the second half of the 20th century and the projected long-term increase is explained by attribution of the trends to different forcings, with aerosols dominating recently and greenhouse gases in the future (*high confidence*). For the Mediterranean region, the agreement between different lines of evidence, such as observations, projections by regional and global models, and understanding of the underlying mechanisms, provides *high confidence* in summer warming that exceeds the global average. {10.5.3, 10.6, 10.6.3, 10.6.4, Cross-Chapter Box 10.3}

Figure 10.19: Changes in the Indian summer monsoon in historical and future periods.

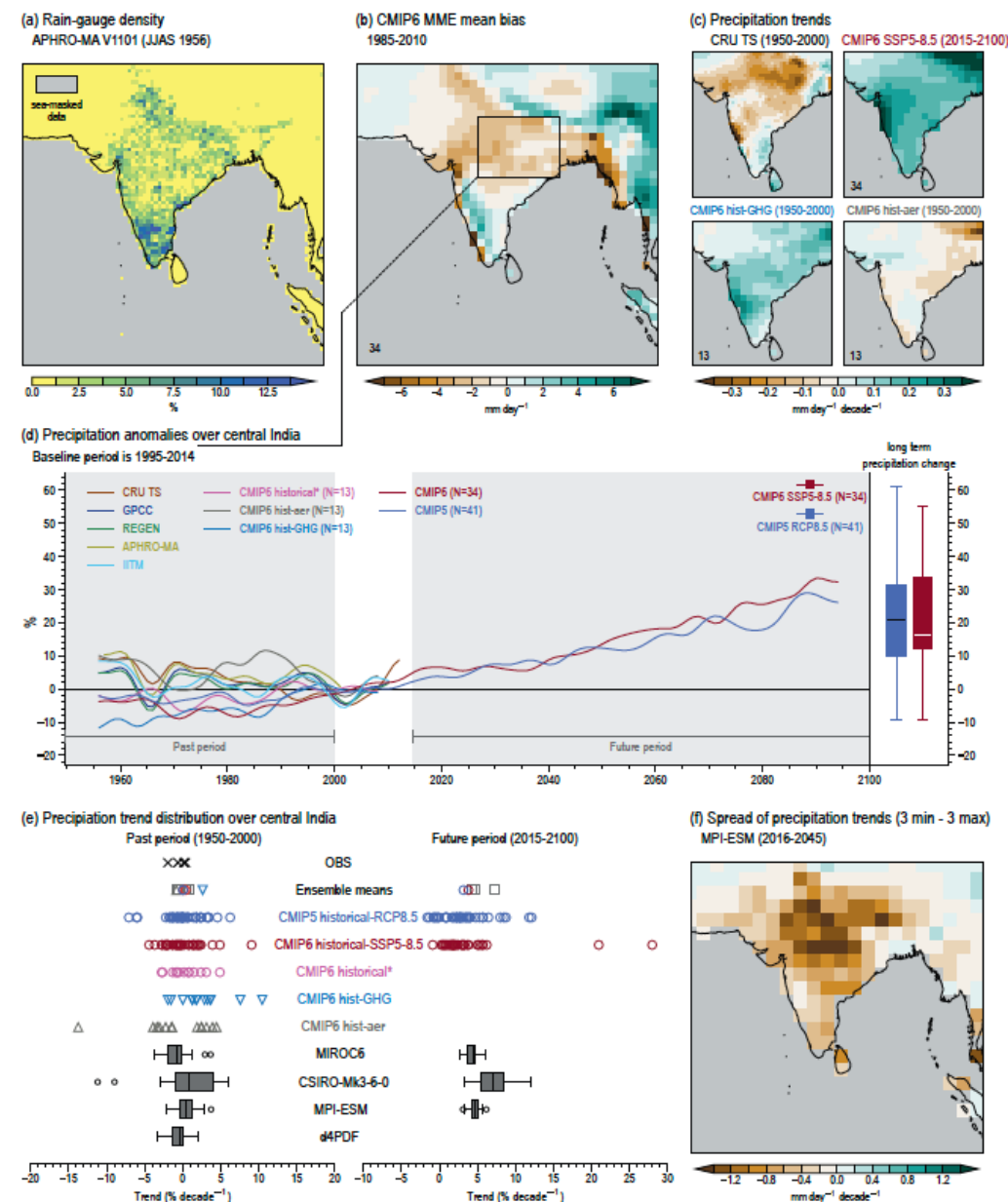


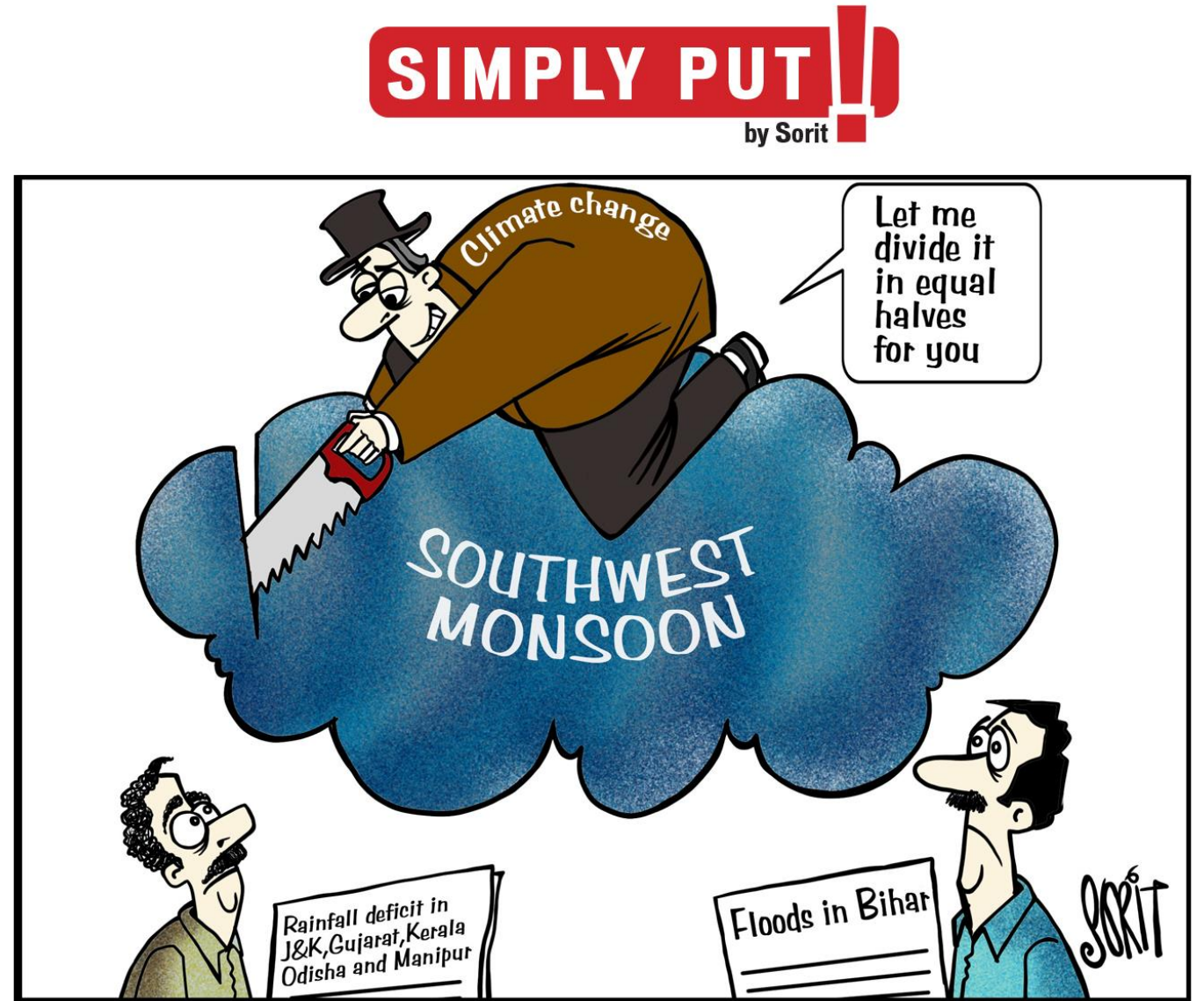
Figure 10.19 | Changes in the Indian summer monsoon in the historical and future periods.

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.”

What else?

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



#NewsThatMatters

DownToEarth

www.downtoearth.org.in

IWM8, 20 March 2025

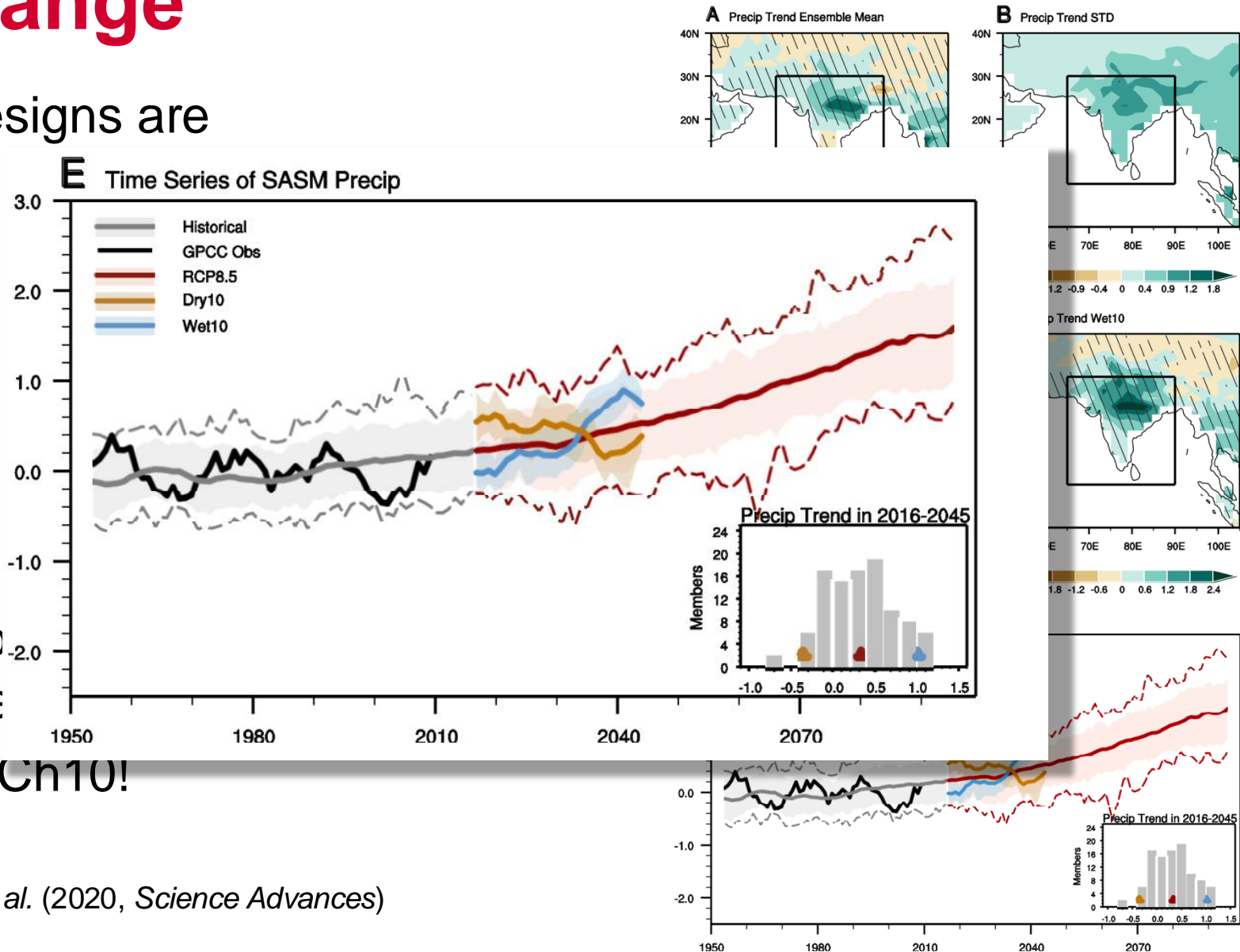
MAJOR UNCERTAINTIES

Interplay between internal variability & forced change

New experiment designs are helping understand variability and change

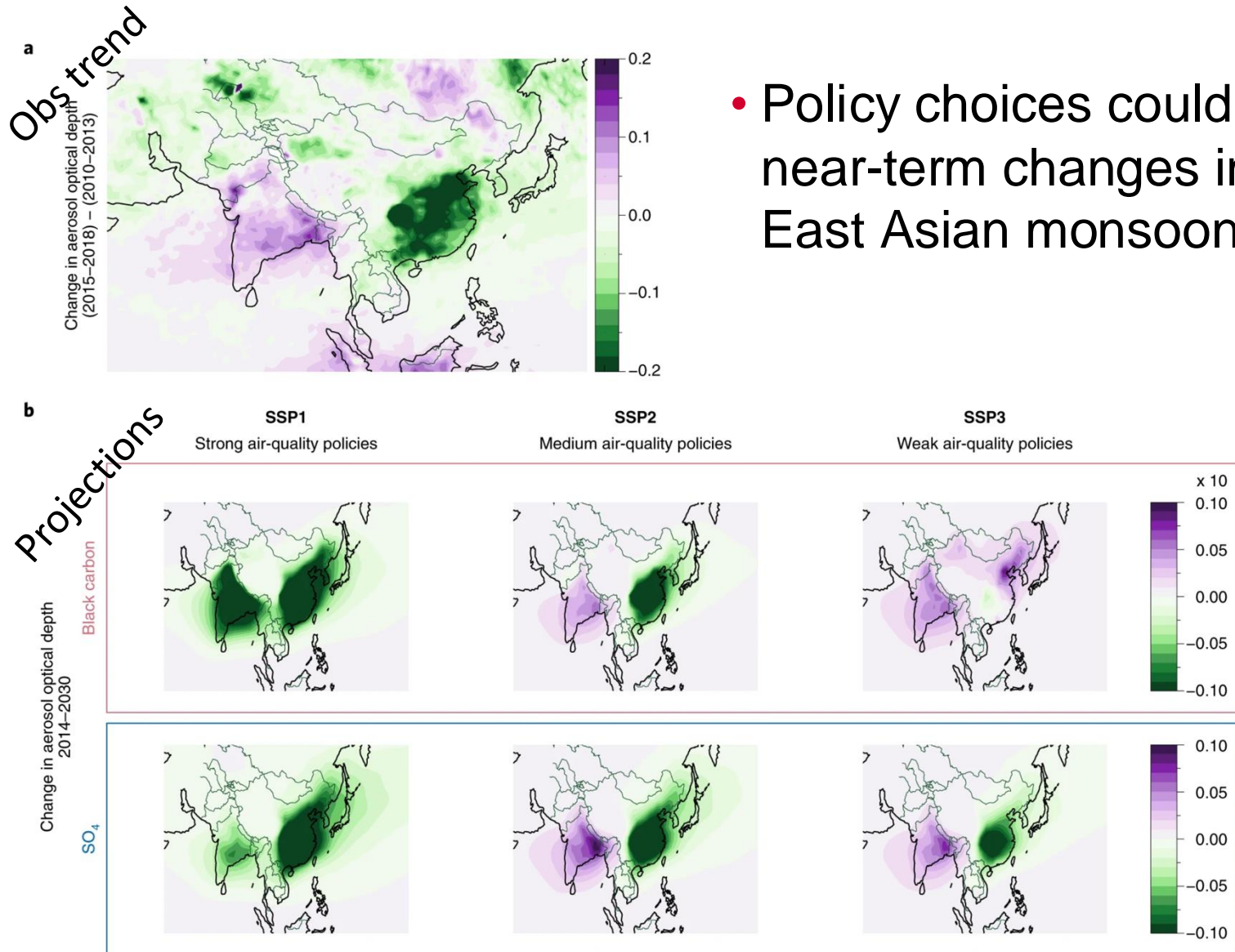
- Large ensemble all be determined
 - 100 members of historical & RCP
- For individual region near-term climate predictions take account of internal variability

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

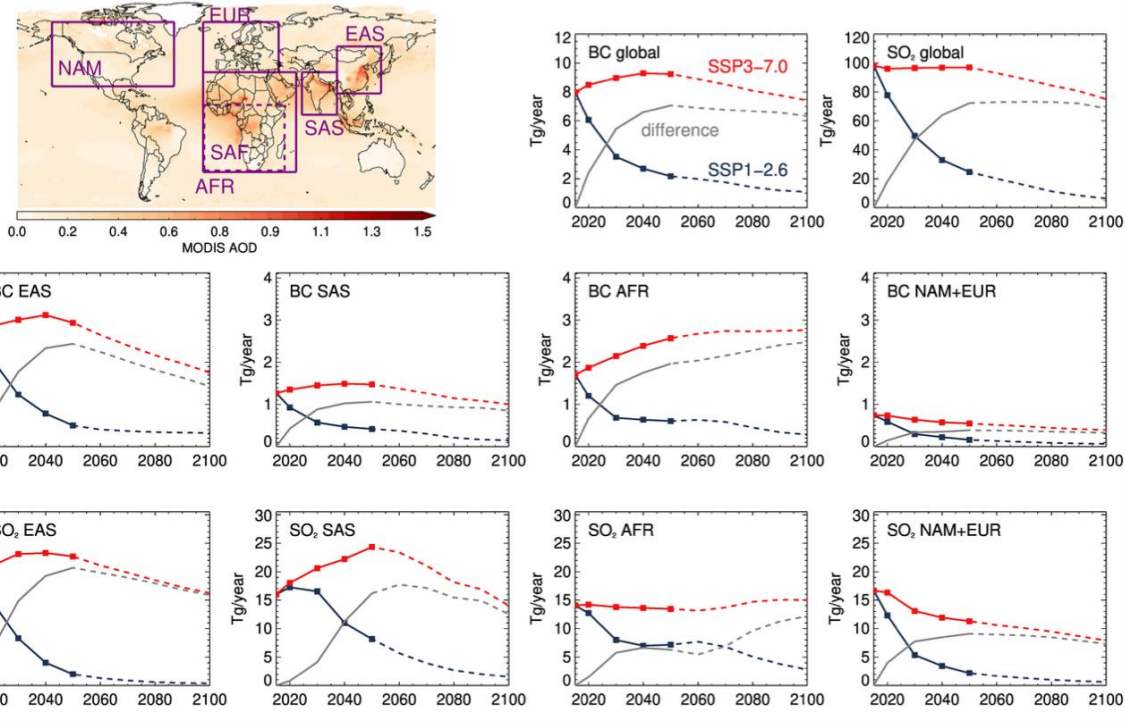
Figure: Recent & expected emissions changes lead to striking patterns of change in aerosol loading and over South & East Asia. (a) Recent AOD changes observed by the MODIS-Terra since 2010. **(b)** Near-term SSP projections for black carbon and SO₄, depending on assumed regional air-quality policies.

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

Laura Wilcox, Robert Allen, Bjørn Samset, Massimo Bollasina, Annica Ekman, Luke Fraser-Leach, Paul Griffiths, James Keeble, Paul Kushner, Anna Lewinschal, Marianne Lund, Risto Makkonen, Joonas Merikanto, Declan O'Donnell, David Paynter, Geeta Persad, Steve Rumbold, Toshihiko Takemura, Kostas Tsigradis, Sabine Undorf, Daniel Westervelt



RAMIP focus regions and projected emissions of BC and SO₂



- SSP3-7.0 baseline, with regional SO₂, BC & OC perturbations from on SSP1-2.6
- Coupled transient simulations (2015 to 2051)
- Fixed SST partners for all Tier 1 experiments and Tier 2 NH₃ experiment using 2050 emissions
- At least 10 members per transient experiment, continuing from historical simulation

Tier 1 simulations:

- **Global (BC, OC, SO₂ follow SSP1-2.6)**
- **Africa and the Middle East**
- **East Asia**
- **North America and Europe**
- **South Asia**

Tier 2 simulations:

- **South+East Asia**
- **Sub-Saharan Africa carbonaceous**
- **South Asia carbonaceous**
- **Global, with NH₃ and NO_x**

Experiment description paper (including data request) now published in GMD

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”

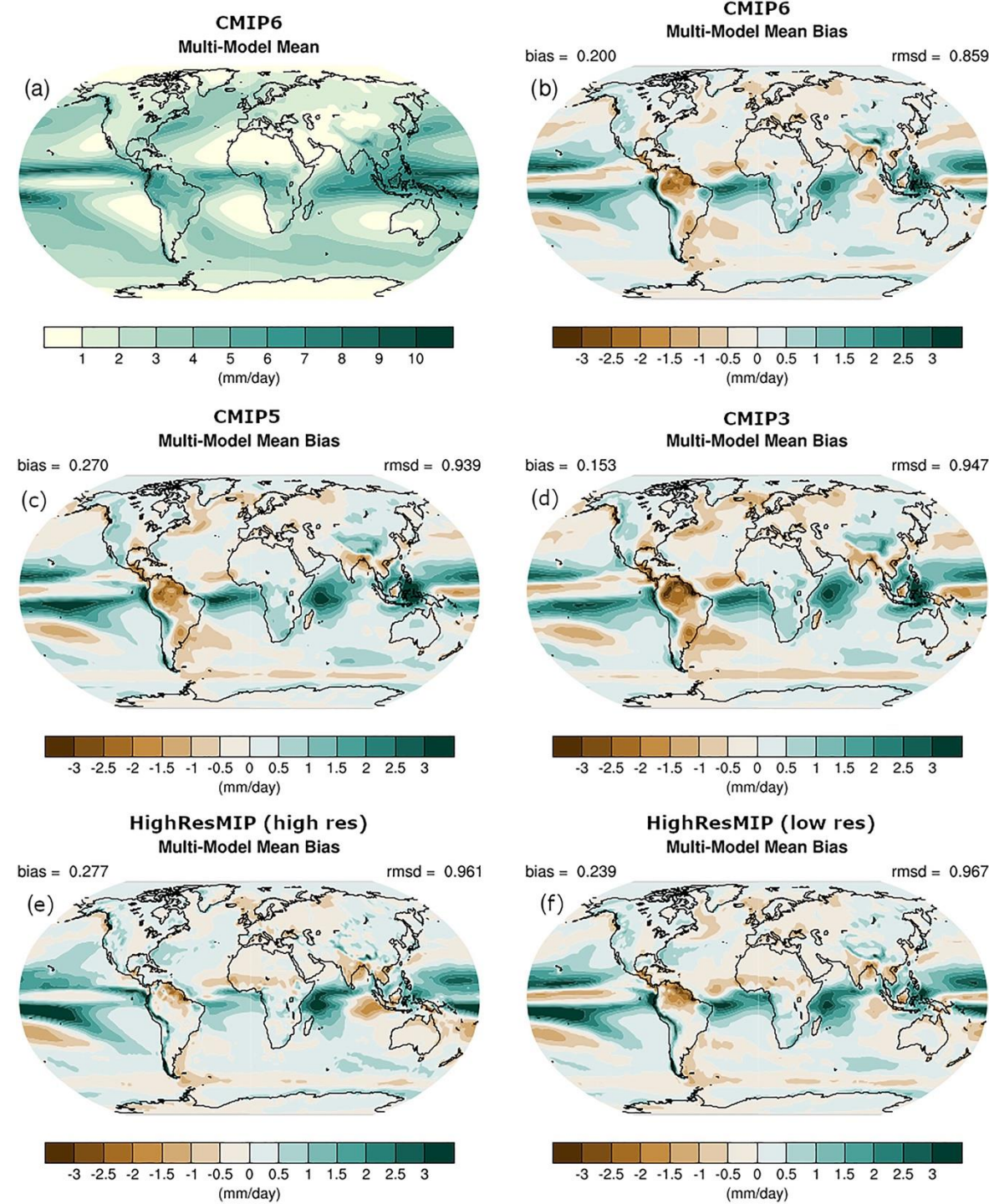
{3.3.3.2}

Persistence of GCM biases

- Latest CMIP6 model biases are not 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

- Monsoons are changing in complex ways
- Future projections of increased rainfall (for global + Asian monsoon) scale proportional to 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
- Considering multiple lines of evidence adds confidence to regional climate messages

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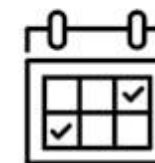
Towards the AR7



AR7 REPORTS



TOPIC



TIMELINE

Methodology Report 1	Short-Lived Climate Forcers	By 2027
Special Report 1	Climate Change and Cities	Early 2027
Methodology Report 2	Carbon Dioxide Removal Technologies, Carbon Capture Utilization and Storage	By the end of 2027
Working Group I	Physical science	To be decided at IPCC-61
Working Group II	Impacts, adaptation	To be decided at IPCC-61
Working Group III	Energy	To be decided at IPCC-61
Synthesis Report	Summary reports	By the end of 2029

Call for authors is out now

Potential topics of greater emphasis in AR7

- Upscale feedbacks
 - As we move towards the kilometre scale, do we get a different message for monsoon climate change?
- Lack of attribution studies in some key monsoon regions
- Net zero, pathways to it, overshoot and danger of taking wrong paths
- Tipping points
- Climate interventions
- AI
- ...