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Chapter 8: Water Cycle Changes

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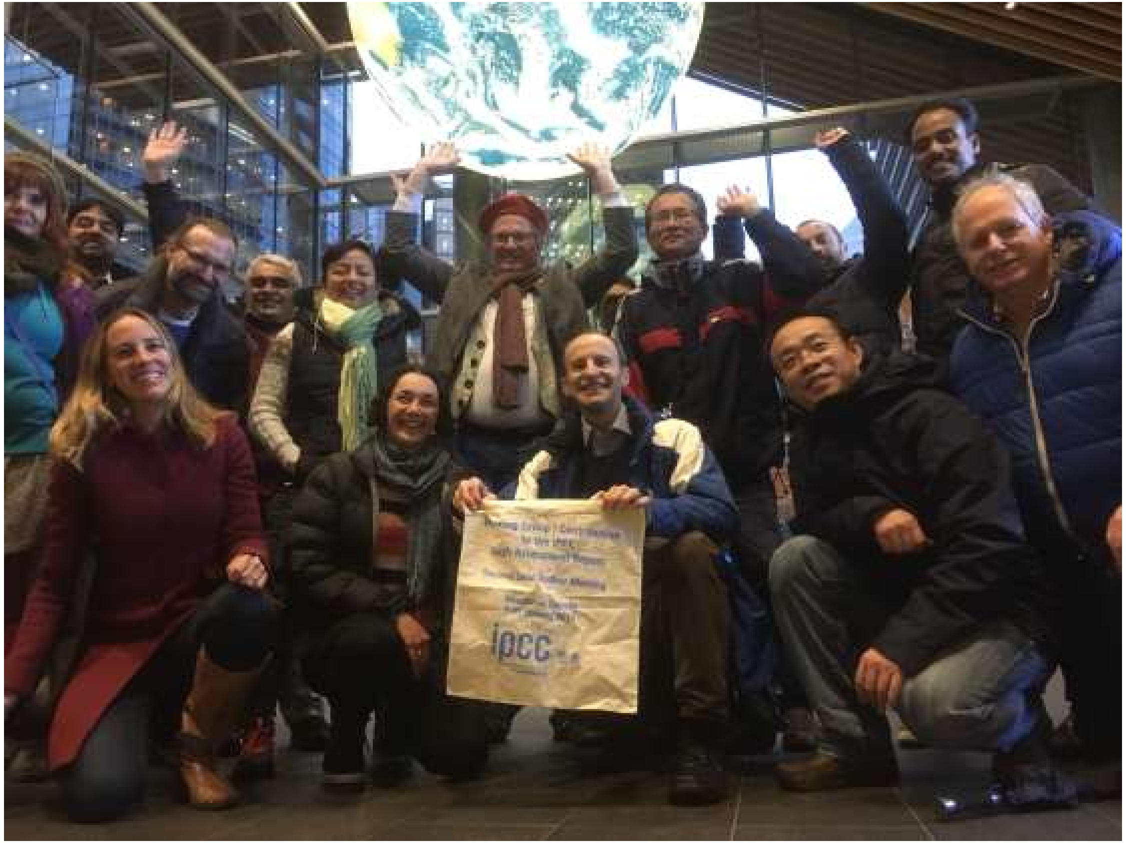
Chapter 8:
16 authors (~50 contributing authors)
1915 scientific publications assessed
4769 review comments addressed

#ClimateReport #IPCC



Chapter 8: Water cycle changes

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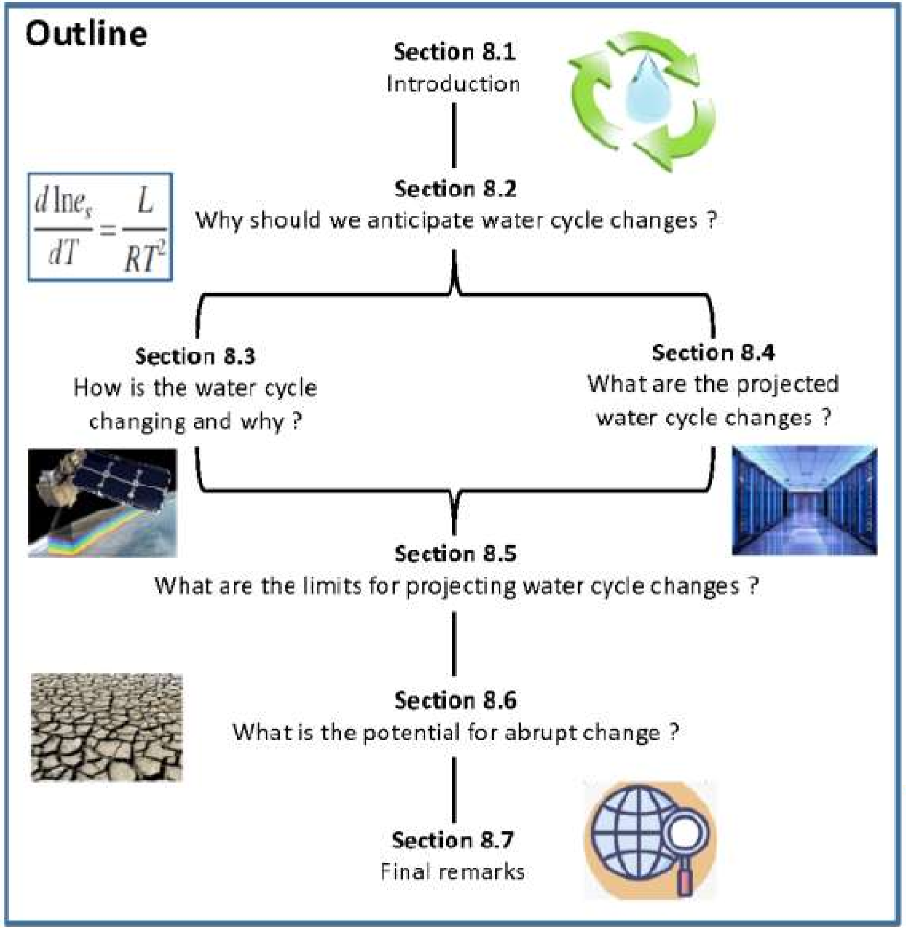
This Chapter should be cited as:
Douville, H., K. Raghavan, J. Renwick, R. P. Allan, P. A. Arias, M. Barlow, R. Cerezo-Mota, A. Cherchi, T. Y. Gan, J. Gergis, D. Jiang, A. Khan, W. Pokam Mba, D. Rosenfeld, J. Tierney, O. Zolina, 2021, Water Cycle Changes. In *Climate Change 2021: The Physical Science 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.

“ Continued global warming is projected to further intensify the global water cycle, including its variability, global monsoon precipitation and the severity of wet and dry events.



Why should we expect water cycle changes?

Boxes and FAQs

Box 8.1
Role of aerosols

Box 8.2
Changes in seasonality

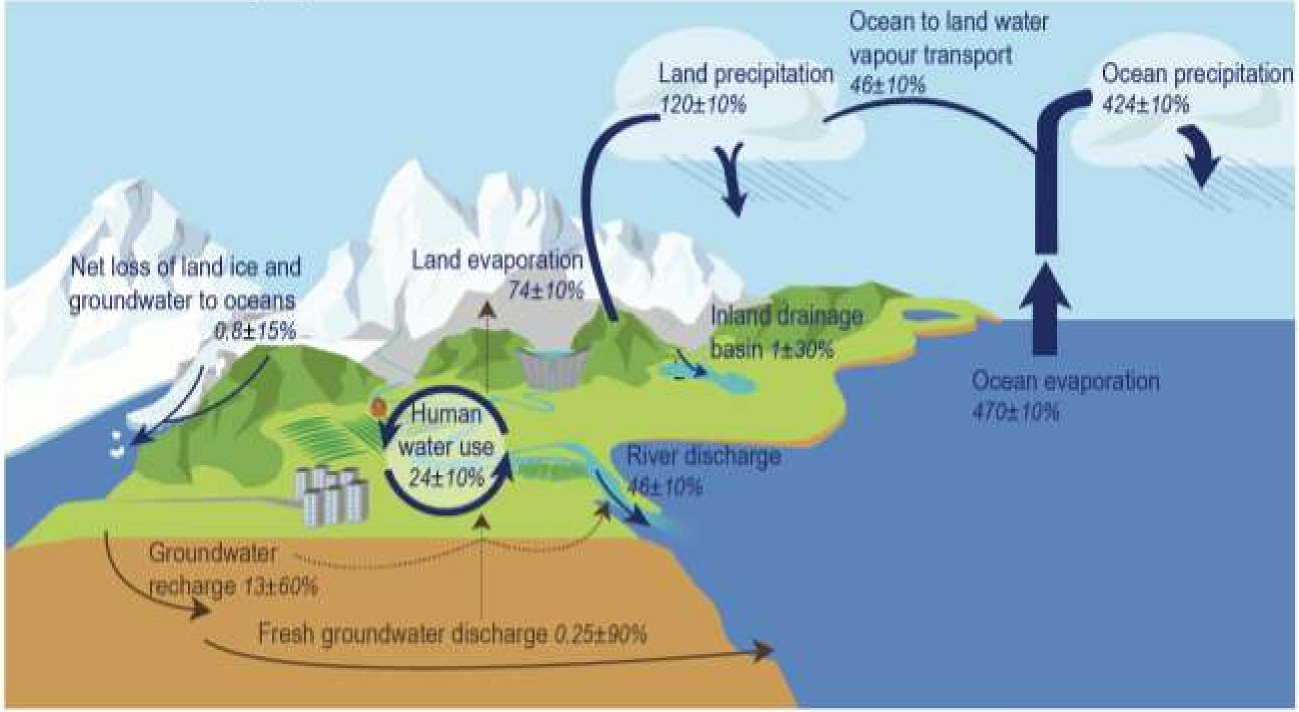
FAQ8.1
How does land use change alter the water cycle ?

FAQ8.2
Should we expect more severe floods, and why ?

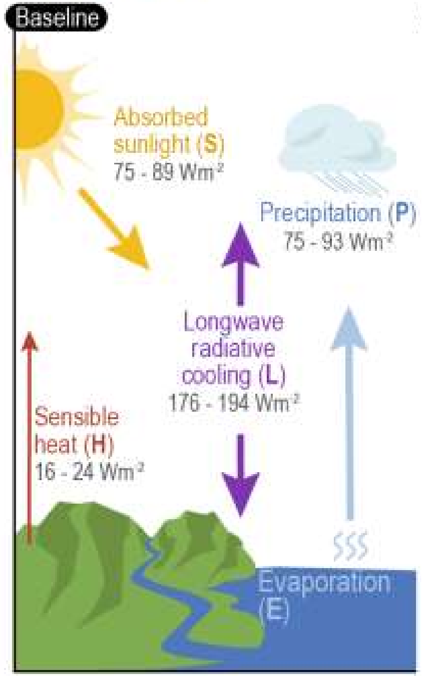
FAQ8.3
What causes drought, and will climate change make them worse ?

Global water cycle and energy budget

(b) Water fluxes
Units in thousands of km³ per year

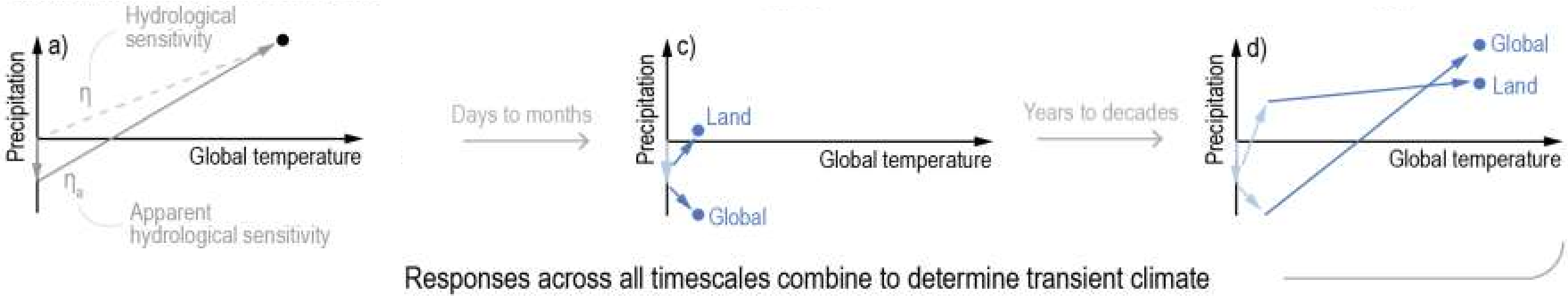


Atmospheric energy budget — P = L - S - H



Douville et al. (2021) IPCC, Ch 8 (Fig. 8.1b; Fig. 8.3a).
See also Allan et al. (2020) NYAS; Abbott et al. (2018) Nature Geosci

- …global mean precipitation and evaporation increase with global warming, but the estimated rate is model-dependent (*very likely* range of 1–3% per 1°C)… determined by a robust response to global mean surface air temperature (*very likely* 2–3% per 1°C)… partly offset by fast atmospheric adjustments to atmospheric heating by GHGs and aerosols.
- …anthropogenic aerosols… reduce global precipitation and alter large-scale atmospheric circulation patterns through their well-understood surface radiative cooling effect (*high confidence*). Fig. 8.3; 8.2.1; 8.2.2.2; Box8.1
- Lots of papers by Bjørn Samset, Gunnar Myhre & Øivind Hodnebrog to assess!!



See also Allan et al. (2020) NYAS and just published Yeh et al. (2021) npj Clim Atmos Sci

Intensification of global water cycle

- Increased moisture transport from evaporative oceans to high precipitation regions of the atmospheric circulation will drive amplified P-E and salinity patterns over the ocean (*high confidence*) while more complex regional changes are expected over land
- Greater warming over land than ocean alters atmospheric circulation patterns and on average reduces continental near-surface relative humidity which along with vegetation feedbacks can contribute to regional decreases in precipitation (*high confidence*). {8.2.1; 8.2.2.1}

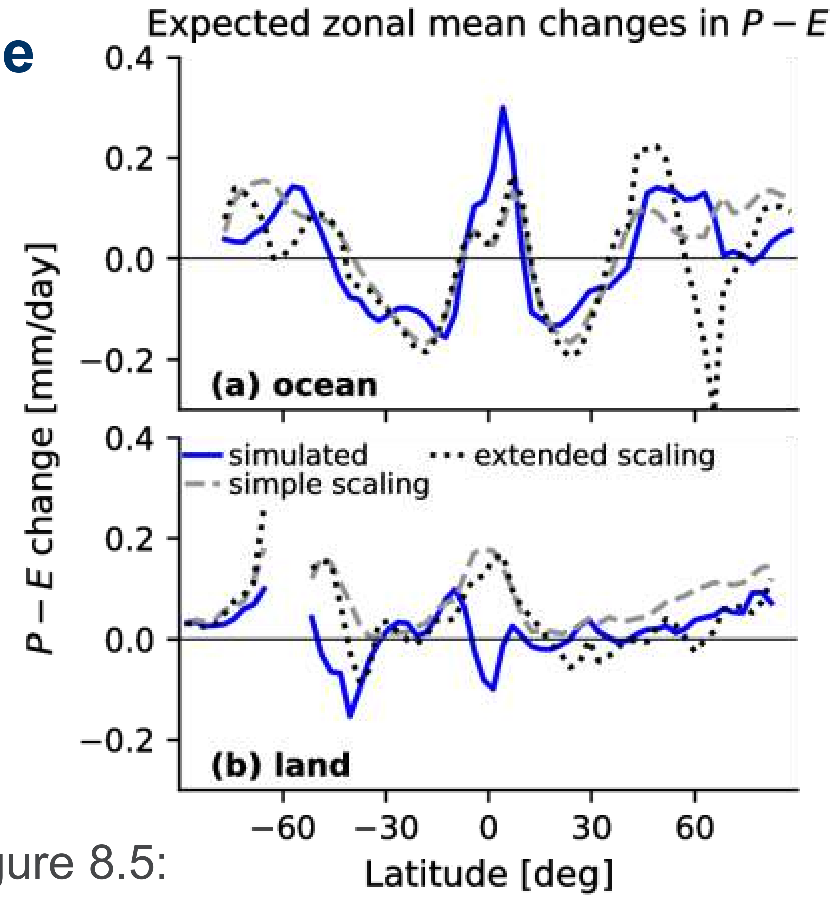
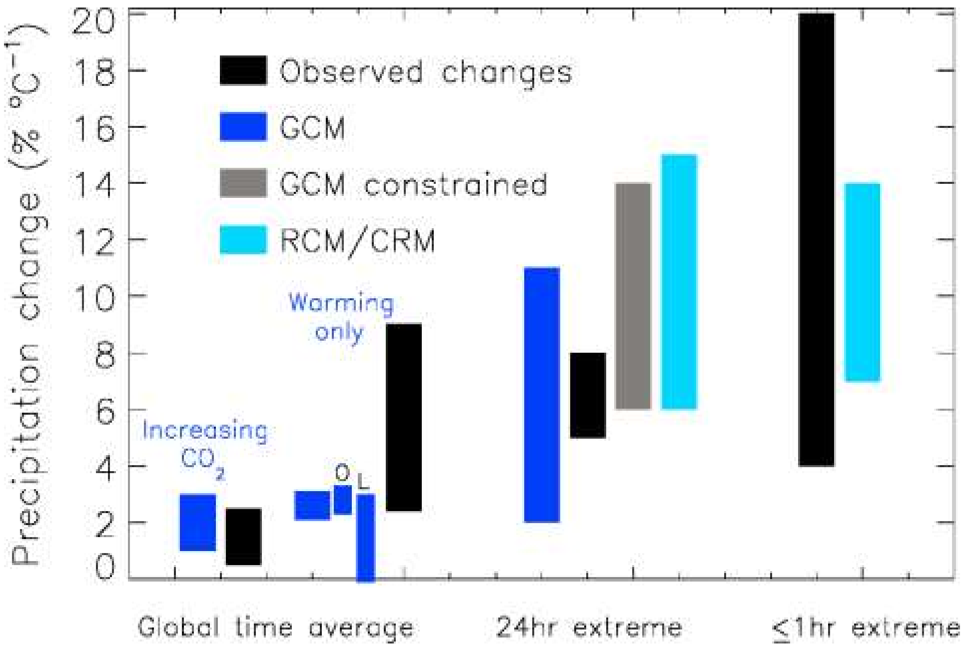


Figure 8.5:

Precipitation mean and extremes

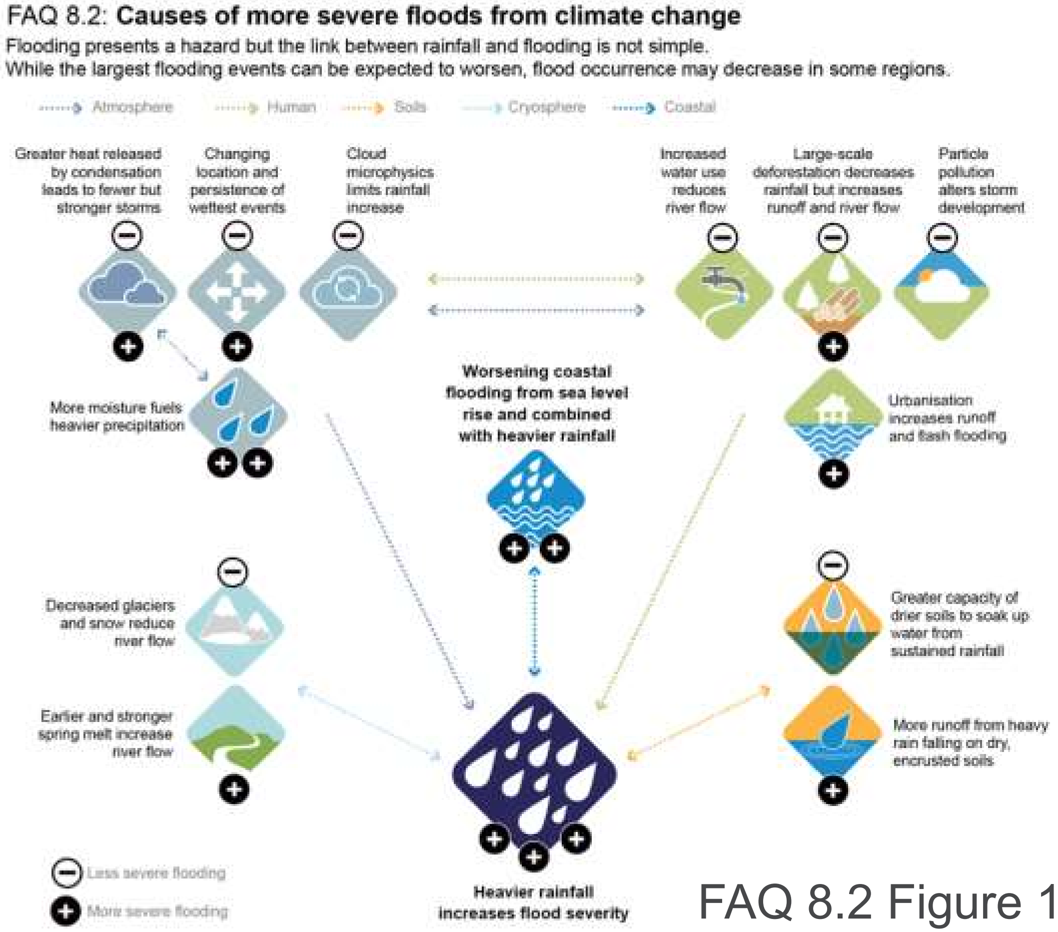


- An increase in near-surface atmospheric water holding capacity of about 7% per 1°C of warming explains a similar magnitude of intensification of heavy precipitation events (from sub-daily up to seasonal time scales) that increases the severity of flood hazards when these extremes occur (*high confidence*). {8.2.3.2}

Fig. 8.4 – see also FAQ8.2 & Chapter 11!

Will floods become more severe or more frequent as a result of climate change?

- Warming drives intensification of heavy rainfall events and associated flooding {8.2.3.2}
- Modulated by changes in atmospheric circulation
- Response also determined by catchment characteristics
  - Ice/snow cover
  - Soil moisture
  - Human water use and land use/cover change
  - Compound effects (e.g. sea level rise/heavy precipitation)



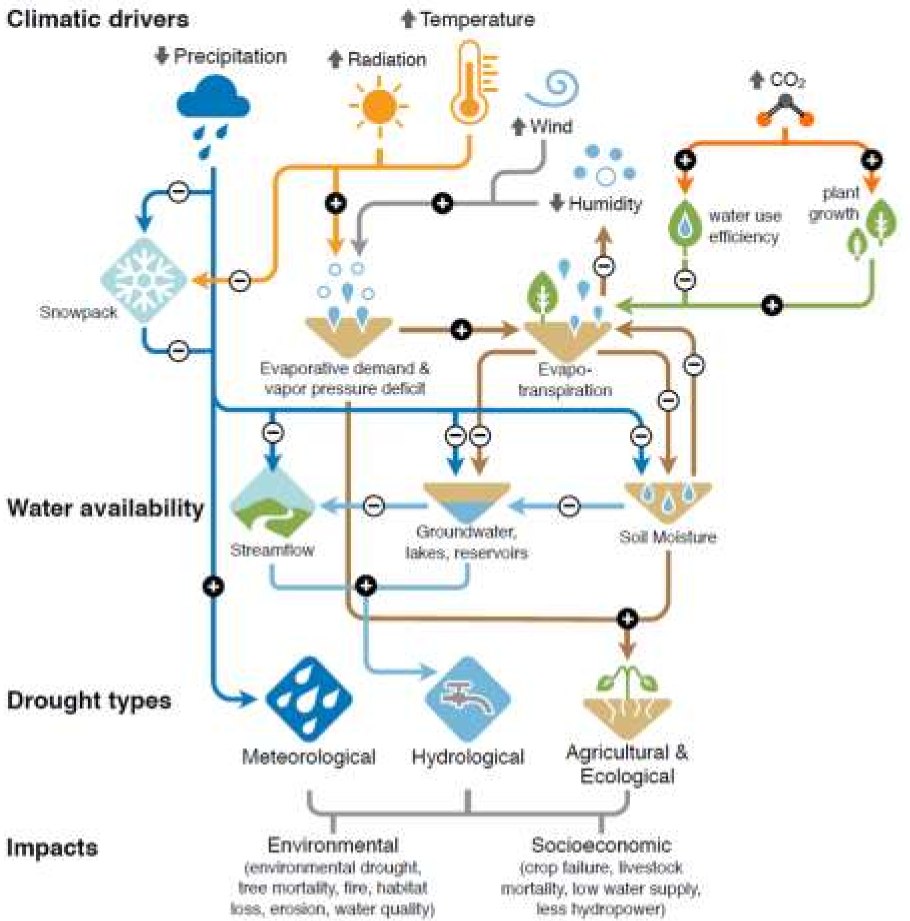
FAQ 8.2 Figure 1

Drivers of drought

8.2.3.3; Fig. 8.6 →
See also FAQ8.3

- Warming over land drives an increase in atmospheric evaporative demand and the severity of droughts (*high confidence*).
- Increasing atmospheric CO_2 concentrations increase plant growth and water-use efficiency, but there is *low confidence* in how these factors drive regional water cycle changes

What would 1921 Europe drought (van der Schrier et al. 2021) be like today or at 3°C warming?



Circulation changes and the water cycle

The severity of very wet & very dry climate events increases in a warming climate (*high confidence*) but changes in atmospheric circulation patterns alter where/how often these extremes occur with substantial regional & seasonal contrasts.

- Poleward expansion in Southern Hemisphere storm tracks (*medium confidence*)
- Weakening of tropical circulations (*medium confidence*)
- Narrowing and strengthening of ITCZ core (*medium confidence*)
- *High confidence* of thermodynamic strengthening of moisture transport into monsoons and storms
- Emerging evidence on regional ITCZ shifts

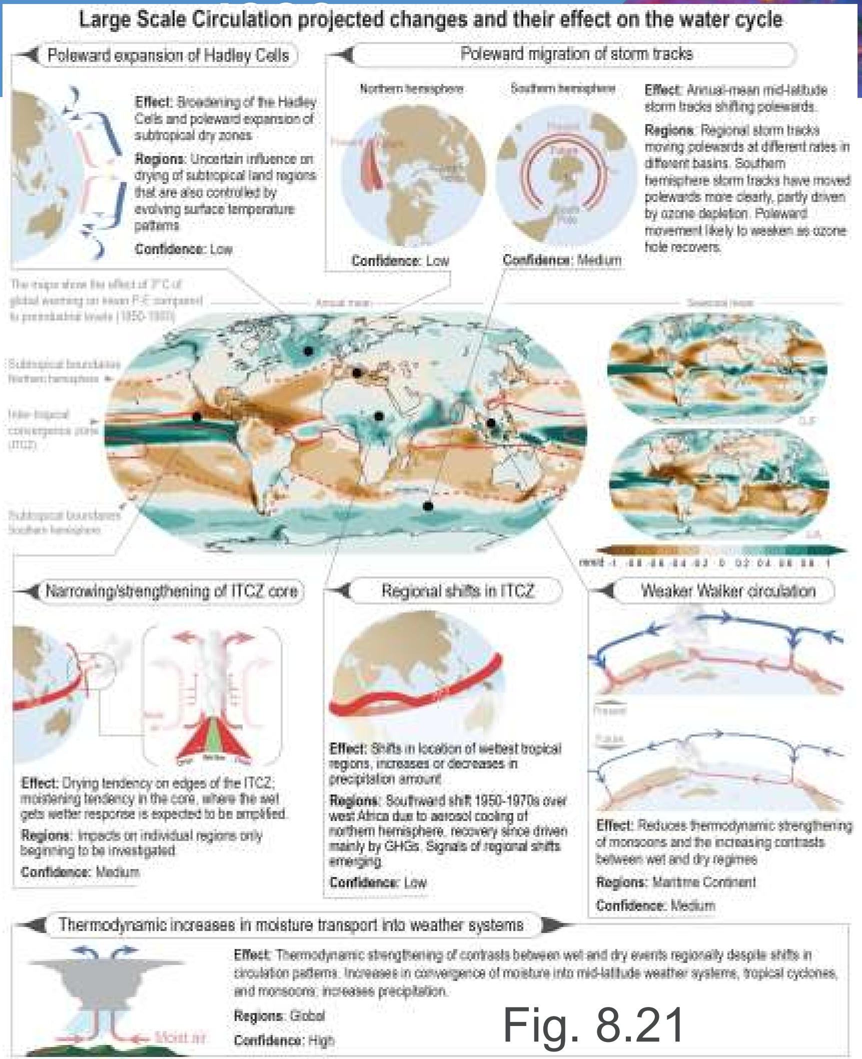
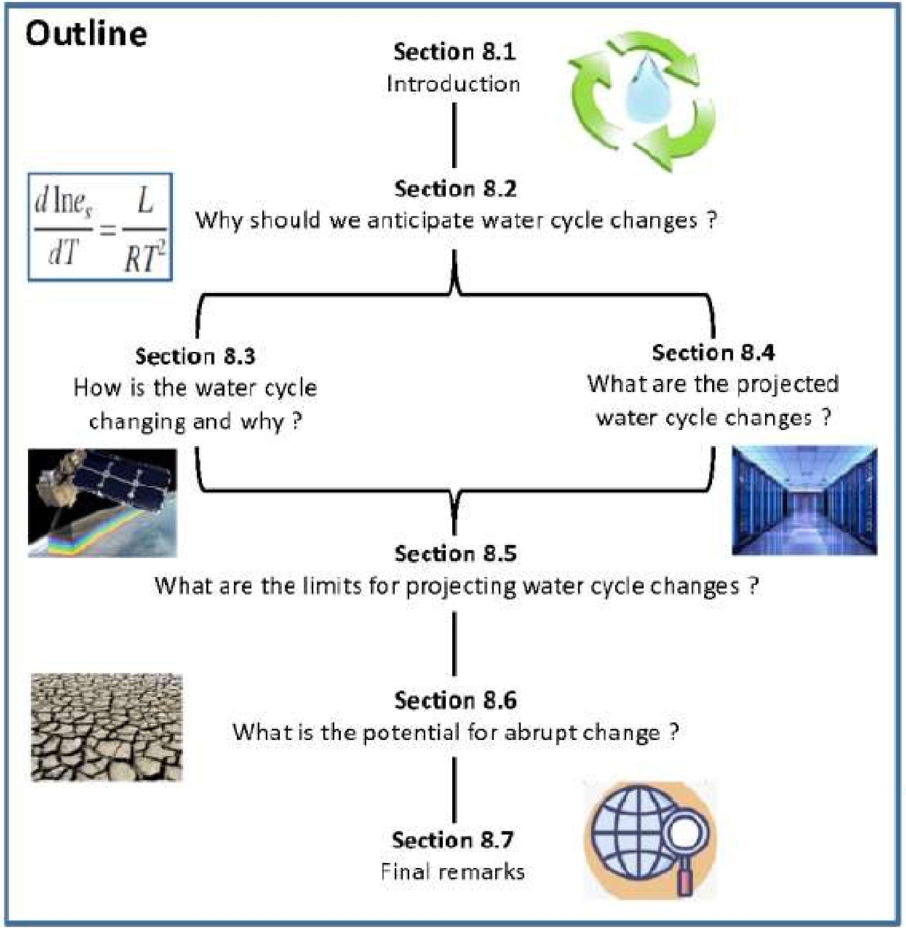


Fig. 8.21

Direct human influence on water cycle changes

- Land use change and water extraction for irrigation drive local, regional and remote responses in the water cycle (*high confidence*).
- Large-scale deforestation *likely* to decrease precipitation over deforested regions; *low confidence* in effects of limited deforestation.
- Deforestation drives increased streamflow relative to the responses caused by climate change (*medium confidence*)
- Urbanisation can increase local precipitation (*medium confidence*) and resulting runoff intensity (*high confidence*)
- A warming climate combined with direct human demand for water is expected to deplete ground water resources in dry regions (*high confidence*).

{8.2.3.4, 8.3.1.7, 8.4.1.7, FAQ8.1} see also SRCCL



How is the water cycle changing and why?

Boxes and FAQs

Box 8.1 Role of aerosols

Box 8.2 Changes in seasonality

FAQ8.1 How does land use change alter the water cycle ?

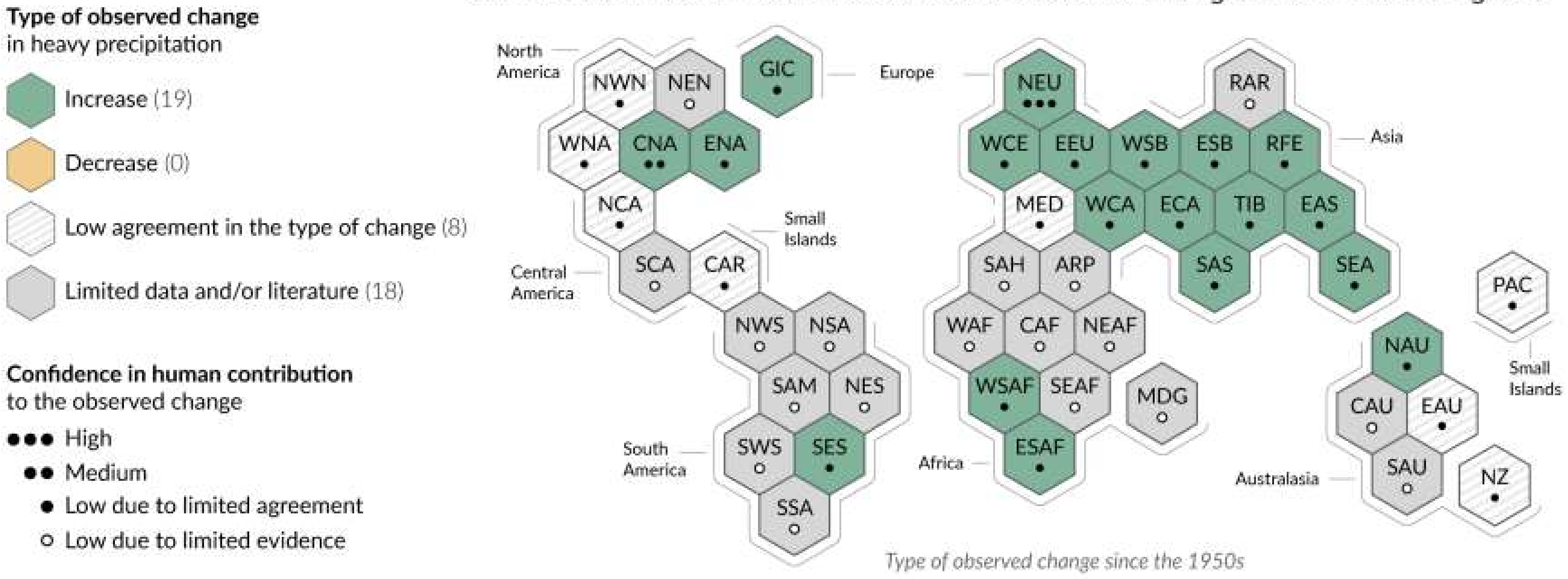
FAQ8.2 Should we expect more severe floods, and why ?

FAQ8.3 What causes drought, and will climate change make them worse ?

Climate change is already affecting every inhabited region across the globe, with human influence contributing to many observed changes in weather and climate extremes

Figure SPM.3

b) Synthesis of assessment of observed change in **heavy precipitation** and confidence in human contribution to the observed changes in the world's regions



Climate change is already affecting every inhabited region across the globe, with human influence contributing to many observed changes in weather and climate extremes

Figure SPM.3

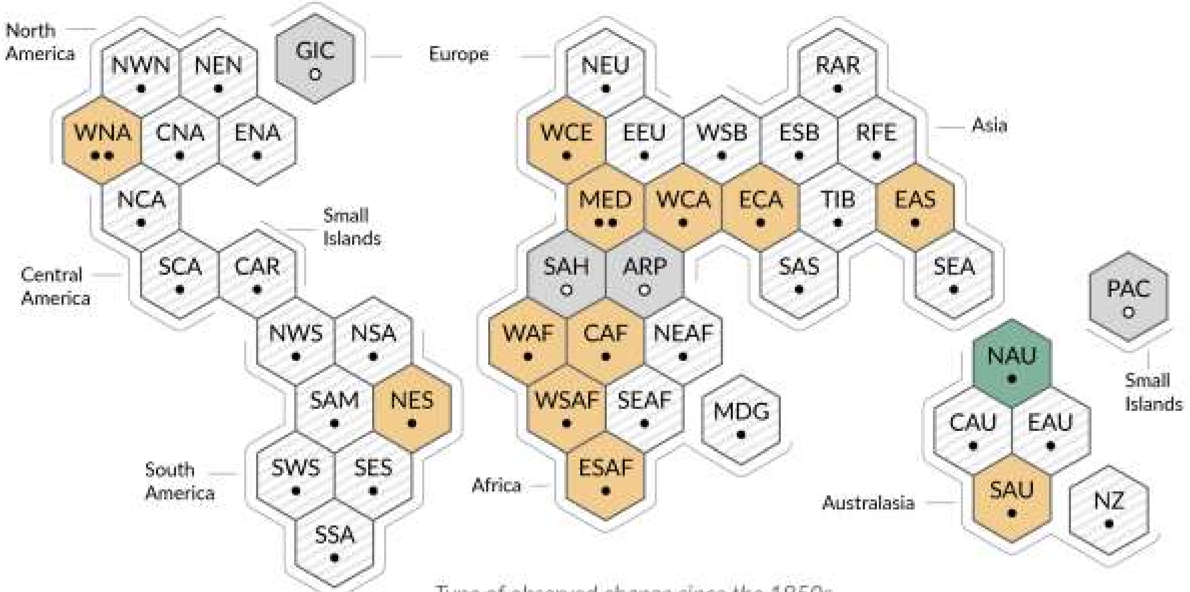
c) Synthesis of assessment of observed change in **agricultural and ecological drought** and confidence in human contribution to the observed changes in the world's regions

Type of observed change
in agricultural and ecological drought

- Increase (12)
- Decrease (1)
- Low agreement in the type of change (28)
- Limited data and/or literature (4)

Confidence in human contribution
to the observed change

- ●●● High
- ●● Medium
- ● Low due to limited agreement
- ○ Low due to limited evidence

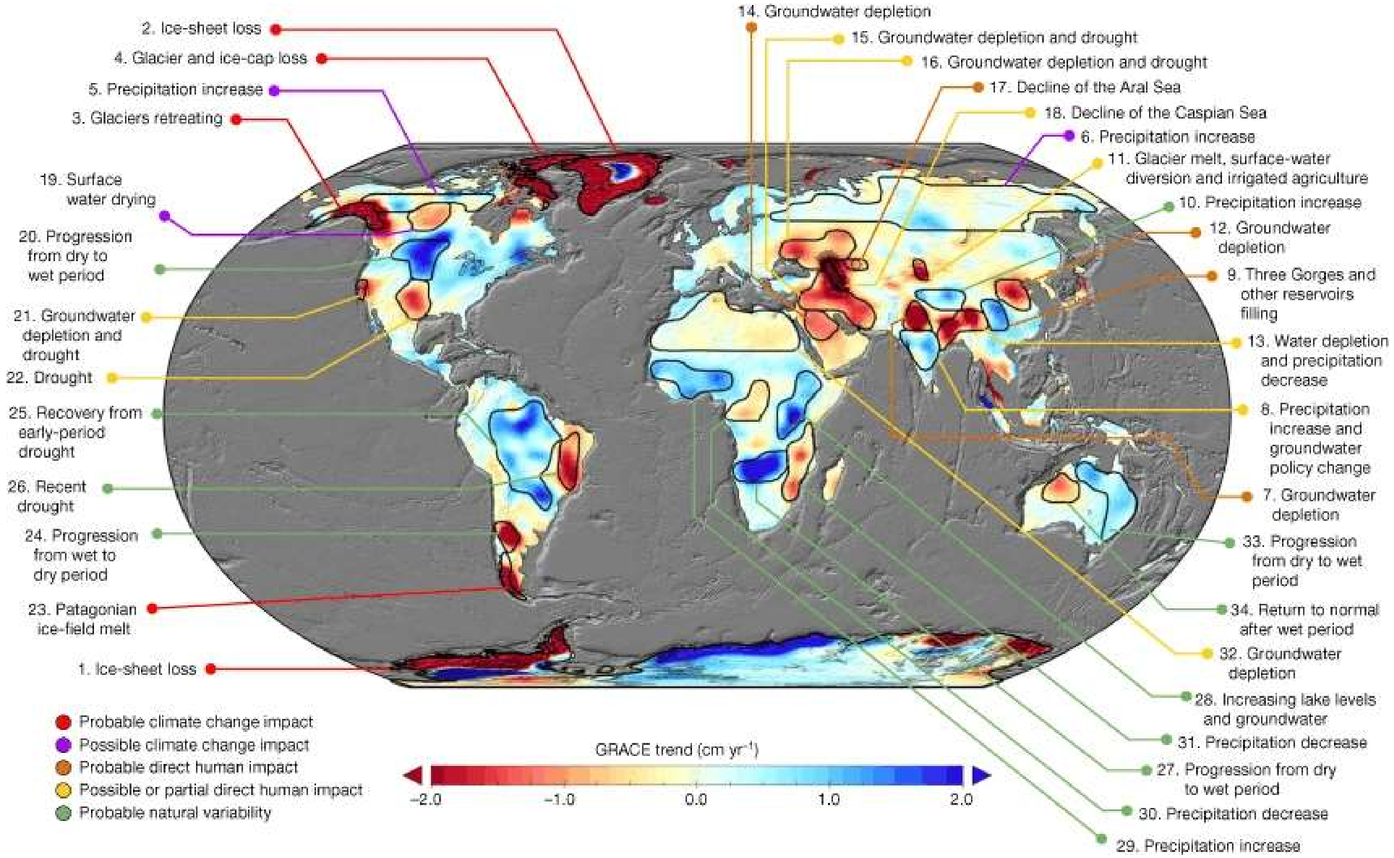


Type of observed change since the 1950s

Drivers of freshwater availability

- Internal variability
- Direct human impact
- Climate change

[Fig. 8.10: Rodell et al. (2018) *Nature* →]



Detection & attribution of water cycle change

- GHG forcing has <u>increased contrasts</u> in precipitation amounts between wet & dry seasons/weather regimes over tropical land areas (*medium confidence*) with detectable precipitation increase in northern high latitudes (*high confidence*).
- + drying in dry summer climates, e.g. Mediterranean, southwestern Australia, southwestern South America, South Africa, and western North America (*medium to high confidence*).

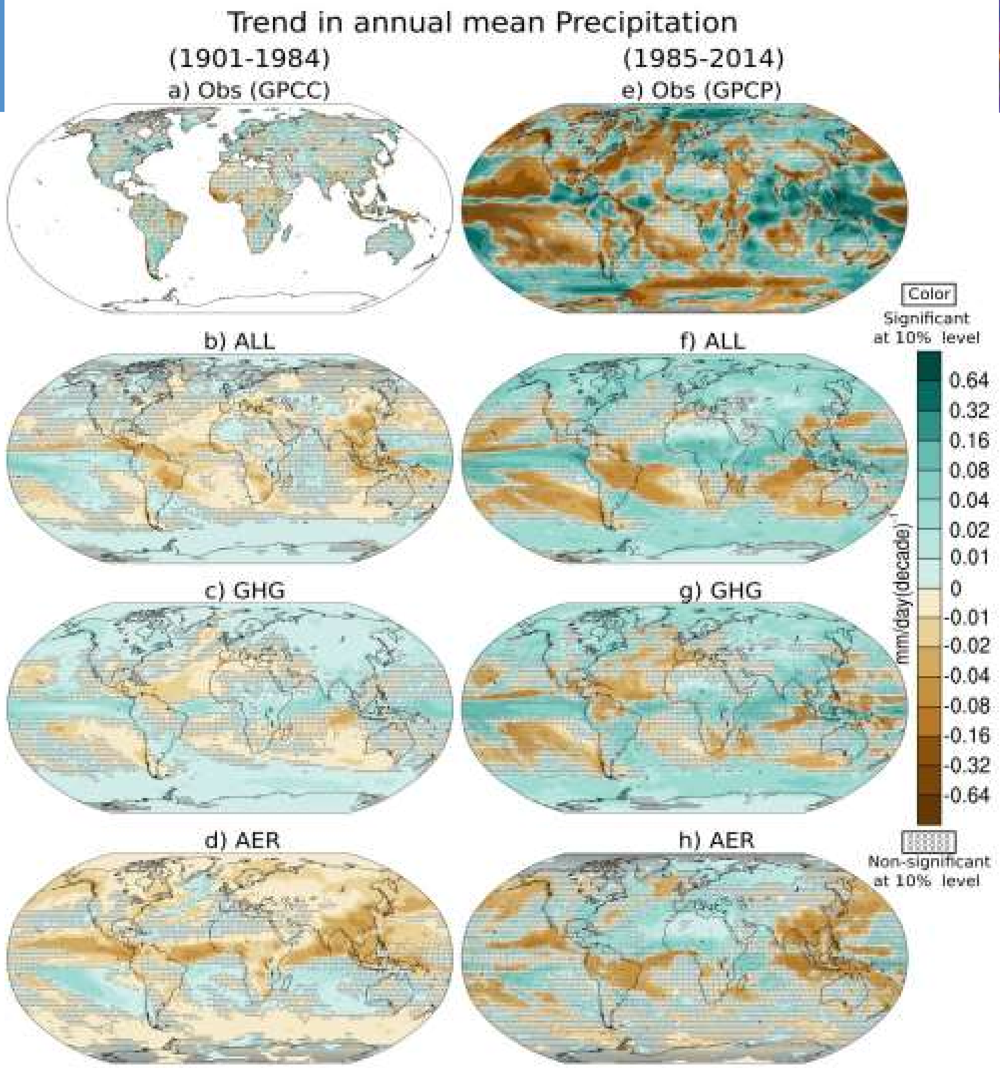


Figure 8.7

Aridity fingerprint of GHGs & aerosols

- Contrasting effects of GHGs and aerosols on precipitation and aridity
- anthropogenic factors have influenced global trends in aridity, mainly through competing changes in evapotranspiration… due to anthropogenic emissions of GHG and aerosols (*very likely*)

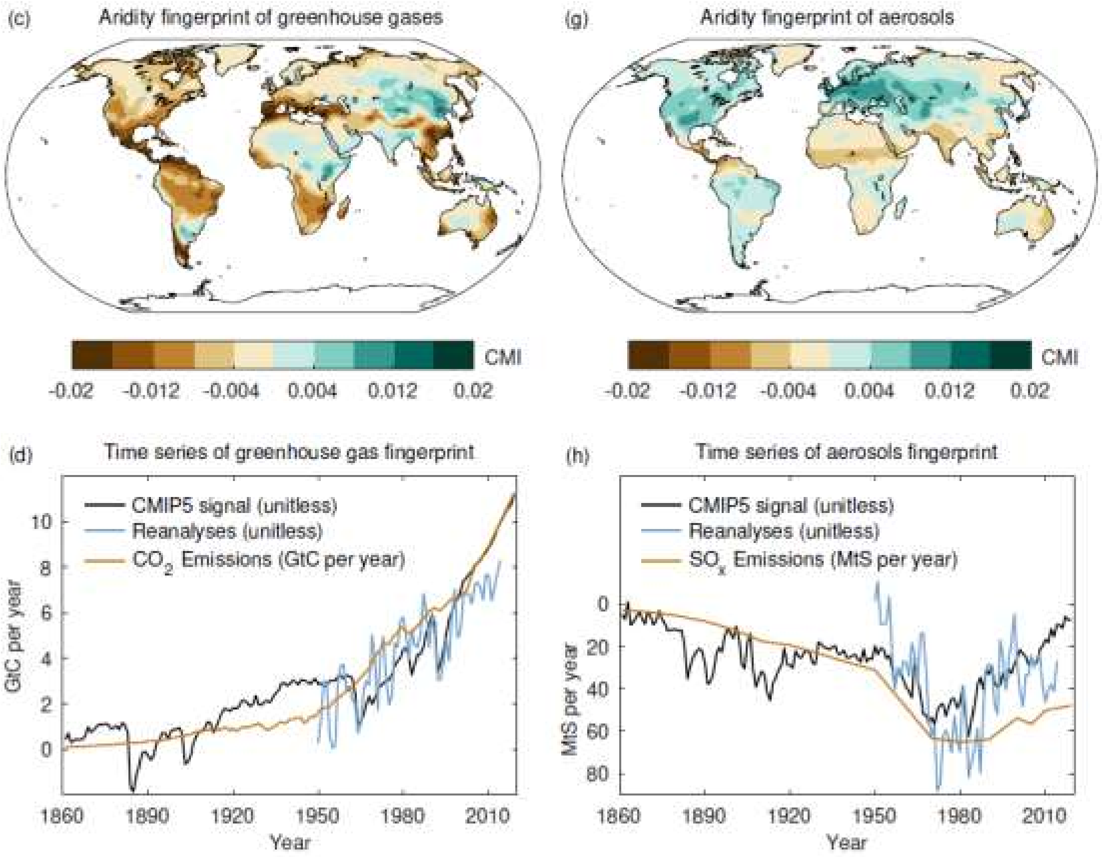
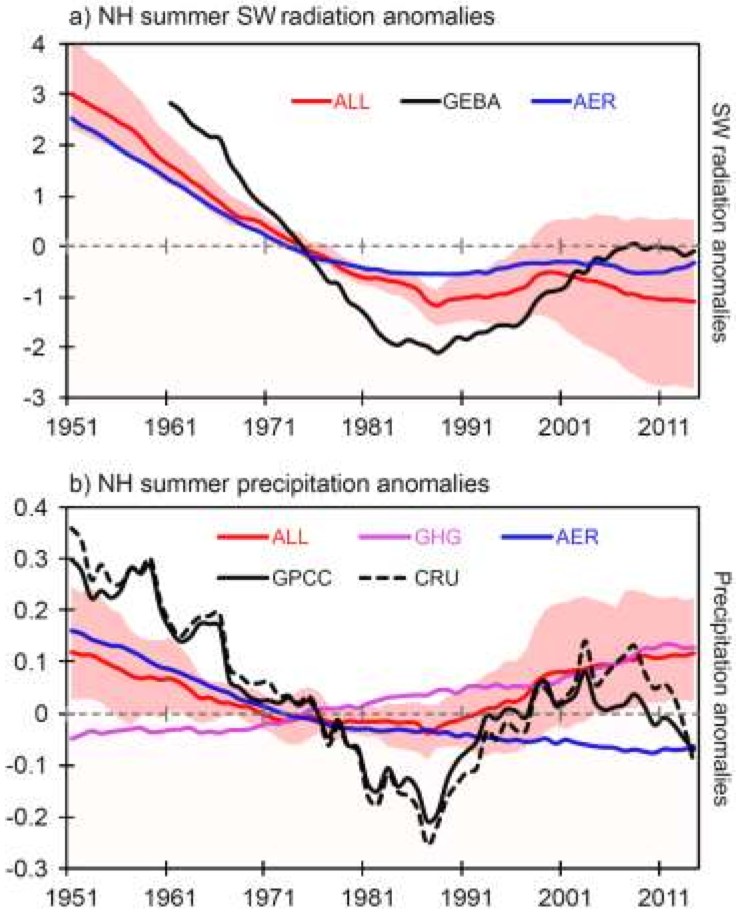


Figure 8.9 – based on Bonfils et al. (2020) Nature Clim.

Aerosol & Water Cycle Changes

- Shifts in the tropical rain belt are associated with the inter-hemispheric temperature response to the time-evolving radiative influence of anthropogenic aerosols & ongoing warming influence of GHGs
- Cooling in the Northern Hemisphere by sulphate aerosols explained a southward shift in the tropical rain belt and contributed to the Sahel drought from the 1970s to the 1980s (*high confidence*), subsequent recovery from which has been linked with GHG warming (*medium confidence*).

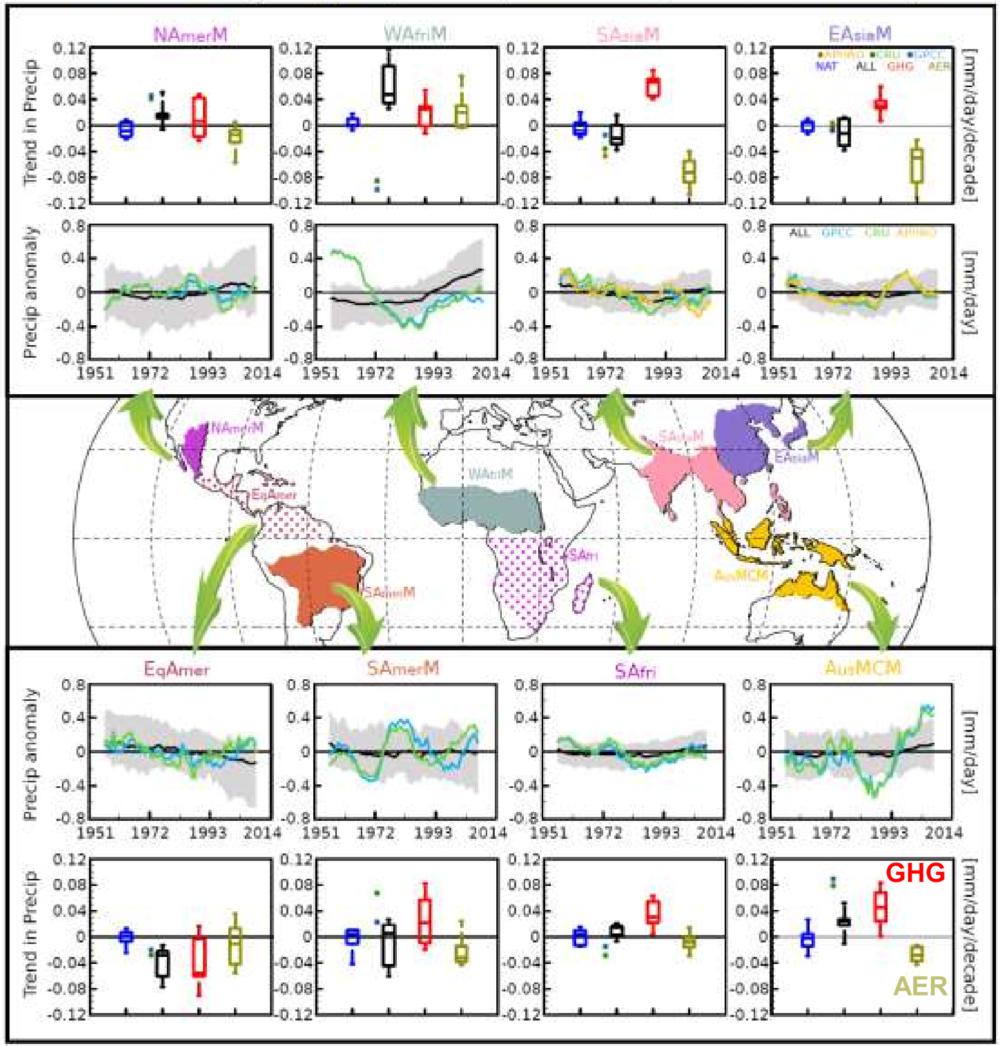
8.2.2.2; 8.3.1.3; 8.3.2.4; Box 8.1 Figure 1 →



Drivers of monsoon precipitation changes

- Observed changes in regional monsoon precipitation, especially over South Asia, East Asia and West Africa, have been limited over much of the 20th century due to increases driven by warming from **GHGs** being counteracted by decreases due to cooling from anthropogenic **aerosols** (*high confidence*).

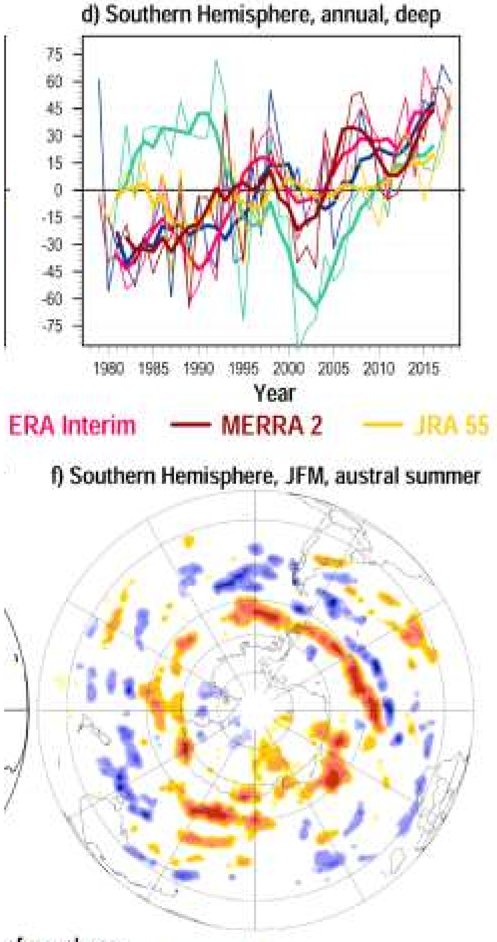
Figure 8.11 →



Mid-latitude storms

- Southern Hemisphere storm tracks and associated precipitation have shifted polewards since the 1970s, especially in the austral summer and autumn (*high confidence*). It is *very likely* that these changes are associated with a positive trend in the Southern Annular Mode, related to both stratospheric ozone depletion and GHG increases
- there is *low confidence* in recent changes in the total number of extra-tropical cyclones over both hemispheres but the number of deep extra-tropical cyclones increased in the Southern Hemisphere since 1979 (*likely*)

Fig.8.10→



Outline

Section 8.1
Introduction

$$\frac{d\ln e_s}{dT} = \frac{L}{RT^2}$$

Section 8.2
Why should we anticipate water cycle changes ?

Section 8.3
How is the water cycle changing and why ?

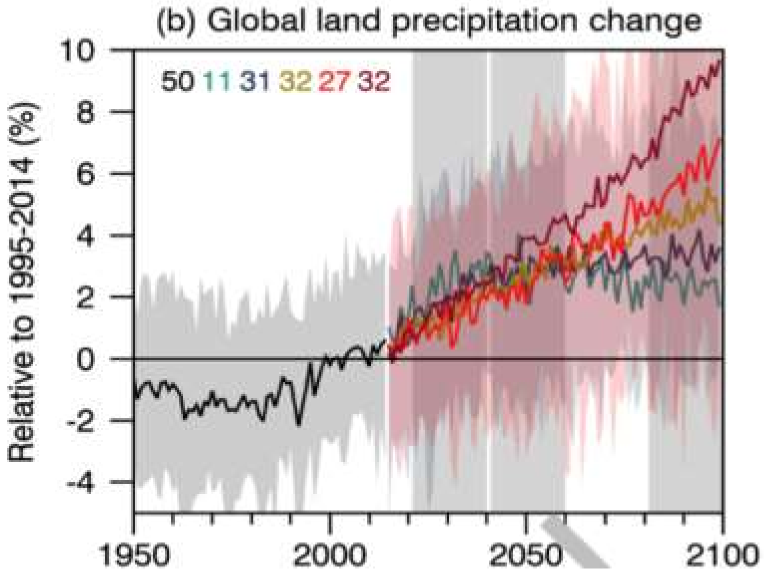
Section 8.4
What are the projected water cycle changes ?

Section 8.5
What are the limits for projecting water cycle changes ?

Section 8.6
What is the potential for abrupt change ?

Section 8.7
Final remarks

What are the projected water cycle changes?



Boxes and FAQs

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FAQ8.1
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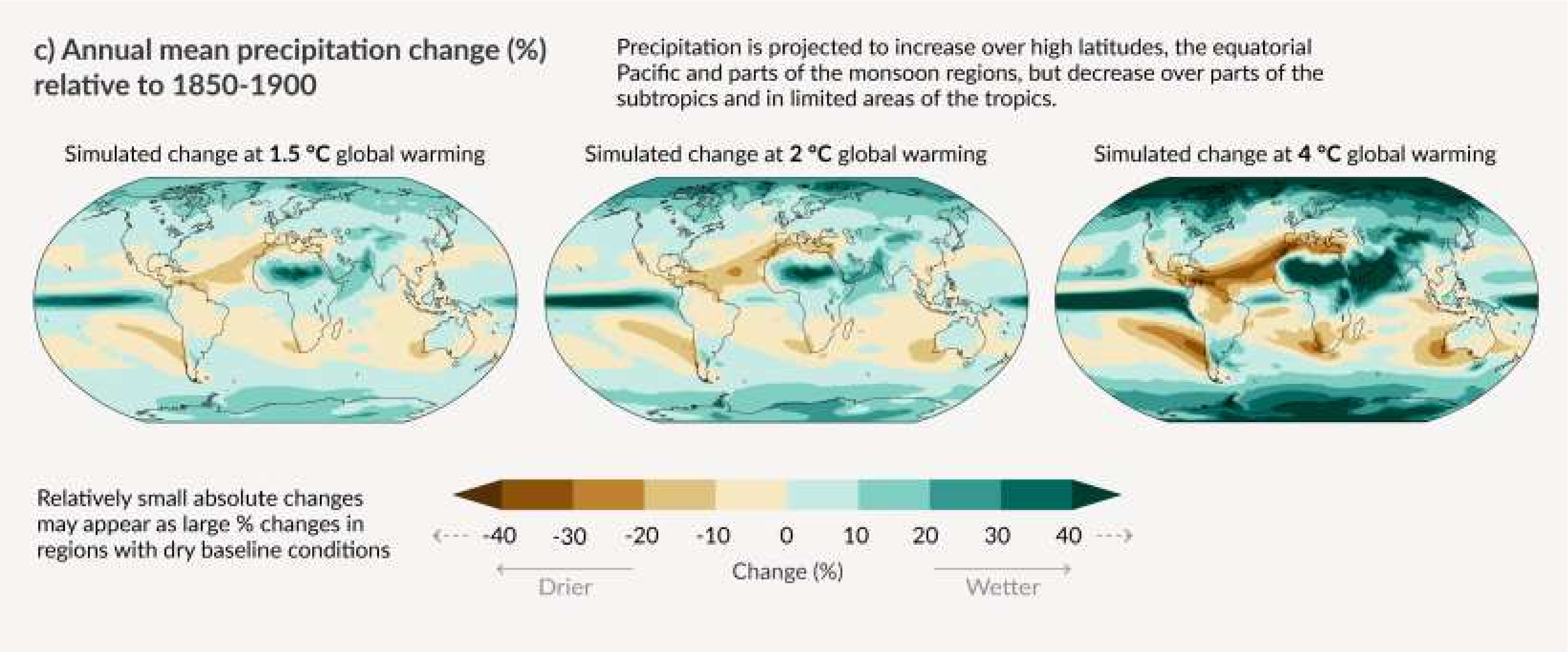
With every increment of global warming, changes get larger in regional mean temperature, precipitation and soil moisture

Figure SPM.5

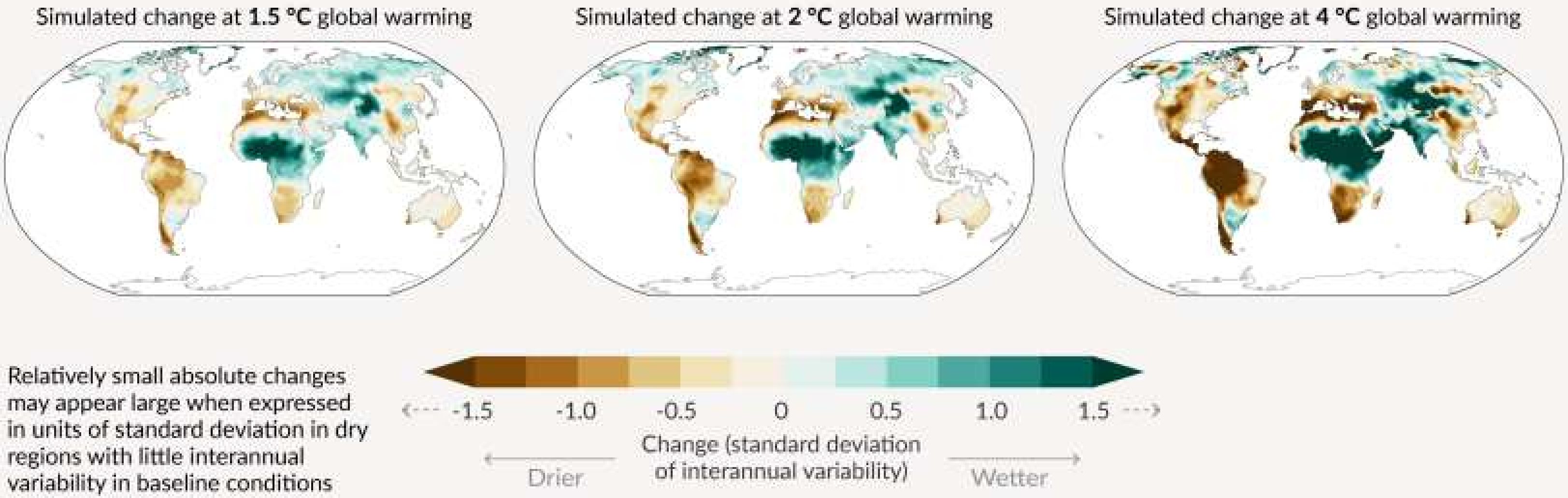


With every increment of global warming, changes get larger in regional mean temperature, precipitation and soil moisture

Figure SPM.5

d) Annual mean total column soil moisture change (standard deviation)

Across warming levels, changes in soil moisture largely follow changes in precipitation but also show some differences due to the influence of evapotranspiration.



Relatively small absolute changes may appear large when expressed in units of standard deviation in dry regions with little interannual variability in baseline conditions

Regional Projections

- precipitation is projected to <u>increase</u> over high latitudes, the equatorial Pacific and parts of the monsoon regions, but decrease over parts of the subtropics and limited areas in the tropics in SSP2-4.5, SSP3-7.0 and SSP5-8.5 (*very likely*).
- precipitation <u>decreases</u> over Mediterranean, southern Africa, Amazonia, Central America, southwestern South America, southwestern Australia and coastal West Africa

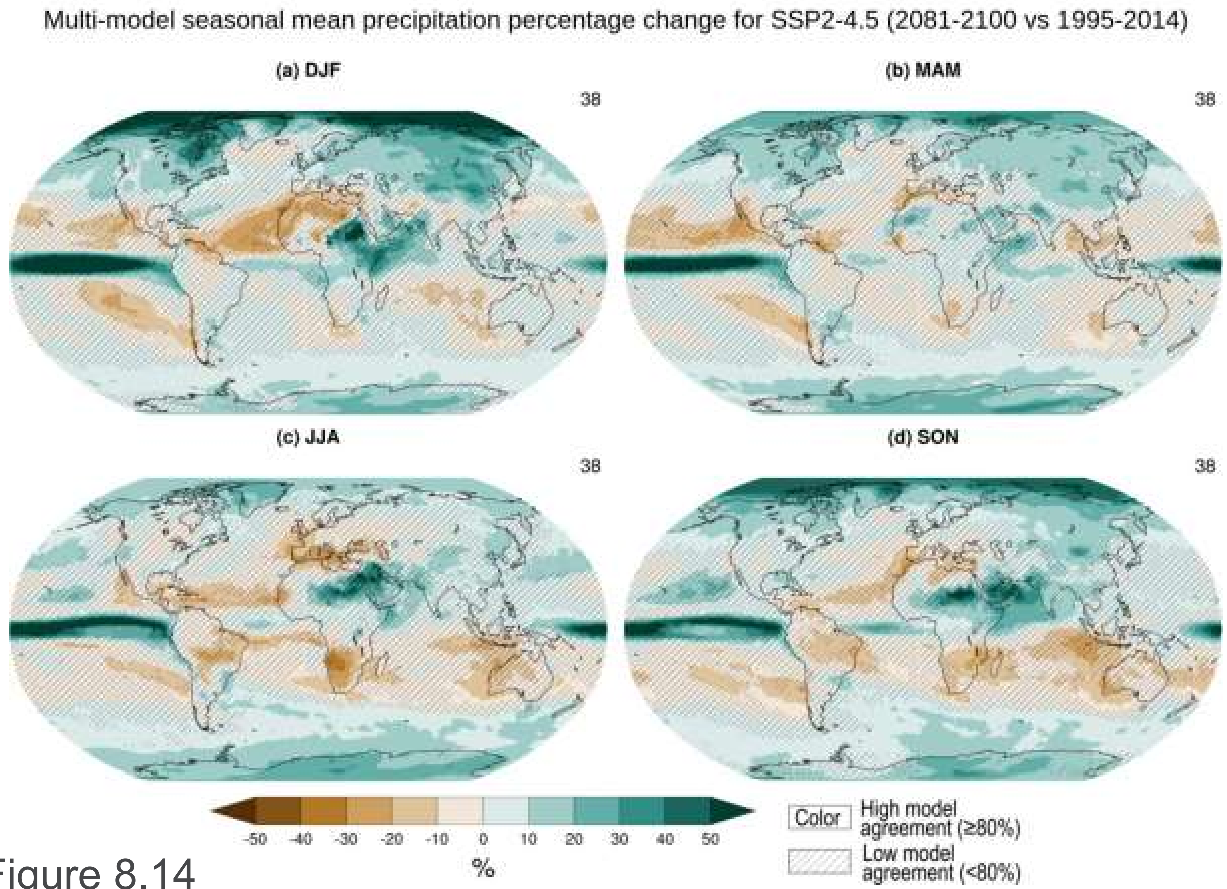
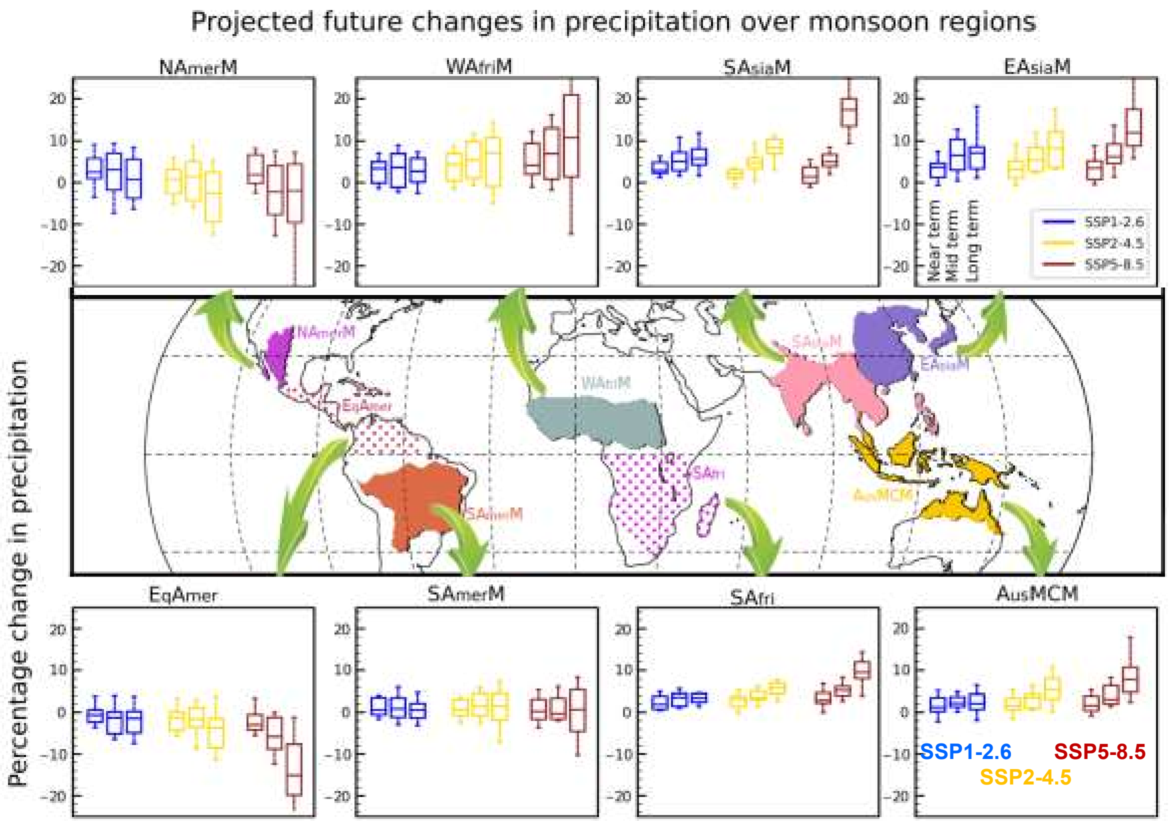


Figure 8.14

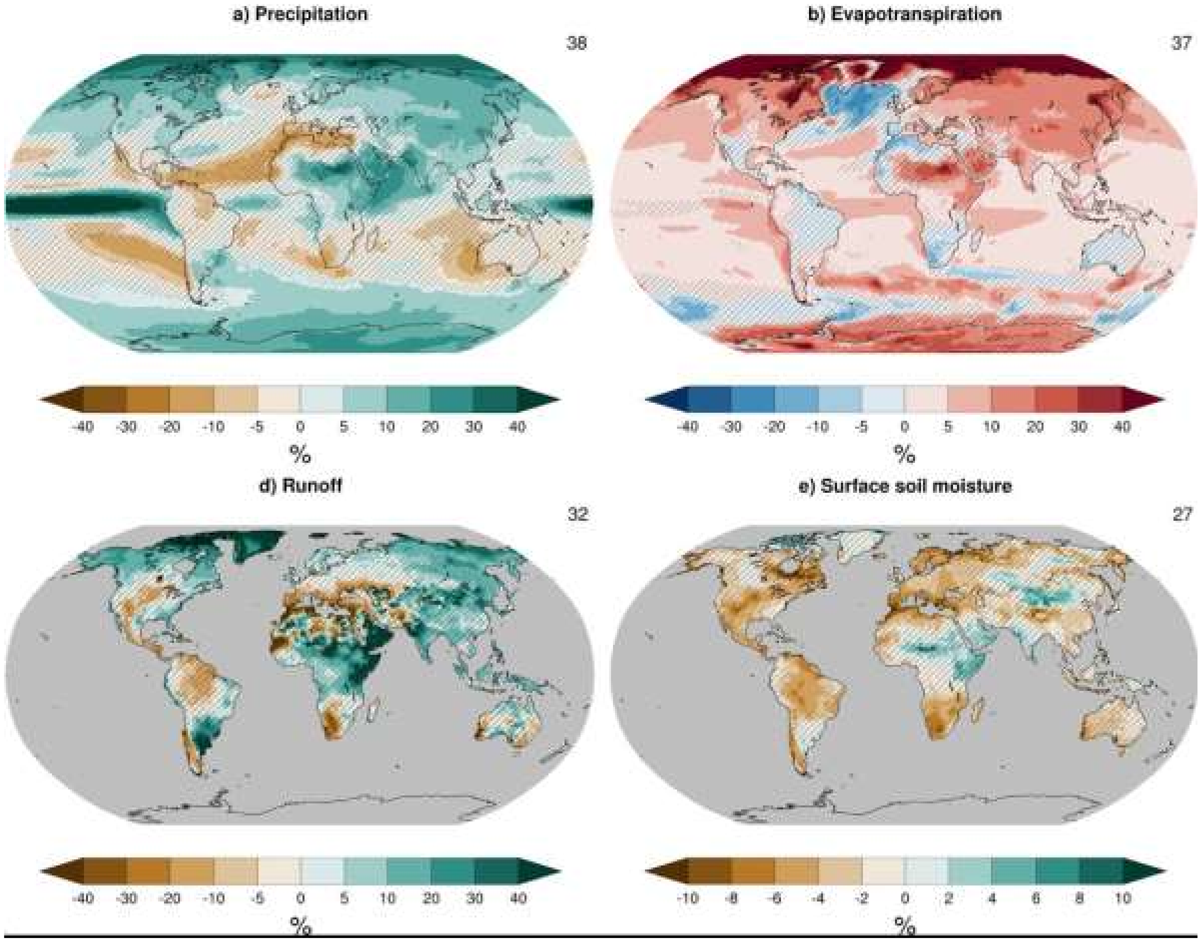
monsoon projections

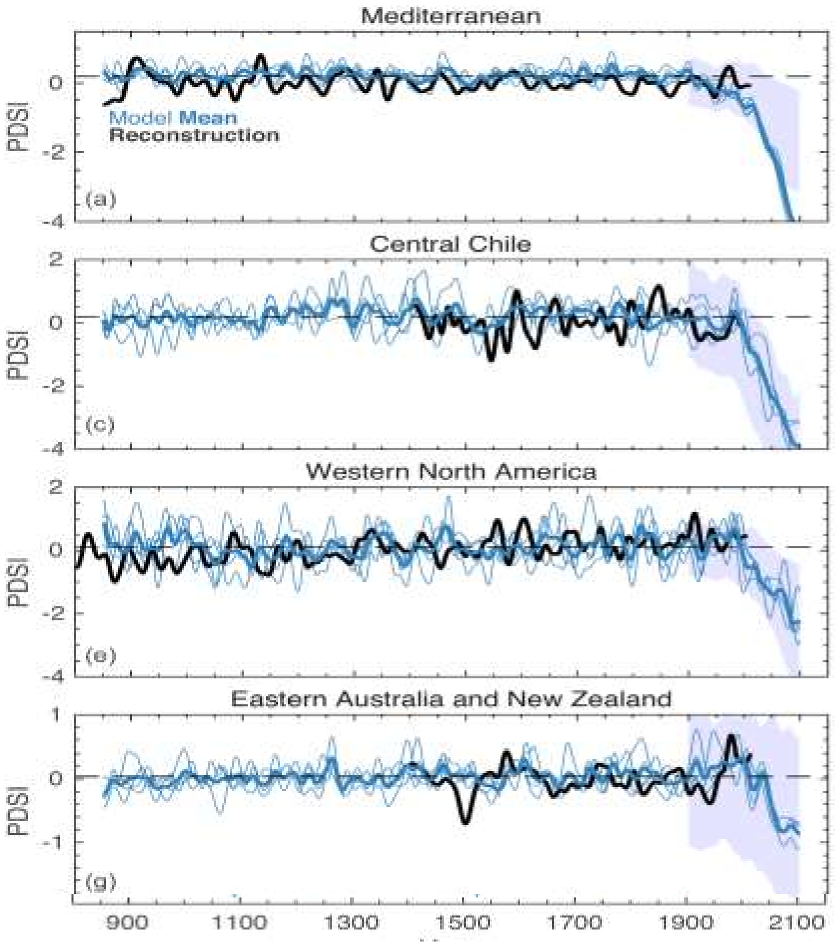


- Monsoon precipitation is projected to increase in the mid- to long term at the global scale, particularly over South and Southeast Asia, East Asia and West Africa apart from the far west Sahel (*high confidence*).
- The monsoon season is projected to have a delayed onset over North and South America and West Africa (*high confidence*) and a delayed retreat over West Africa (*medium confidence*).

See Figure 8.22; 8.2.2.2, 8.4.2.4, Box 8.2, TS.13; Table 8.2

- Projected increases in precipitation… will be associated with increased runoff in the northern high latitudes (*high confidence*).
- Runoff from small glaciers will typically decrease through loss of ice mass, while runoff from large glaciers is *likely* to increase with increasing global warming until glacier mass becomes depleted (*high confidence*). [see SROCC]
- CMIP6: increased evaporation, decreased soil moisture →
- Box TS.6 Fig. 1 →
  SSP2-4.5 (2081-2100 minus 1995-2014)





Aridity changes in context of paleo climate record

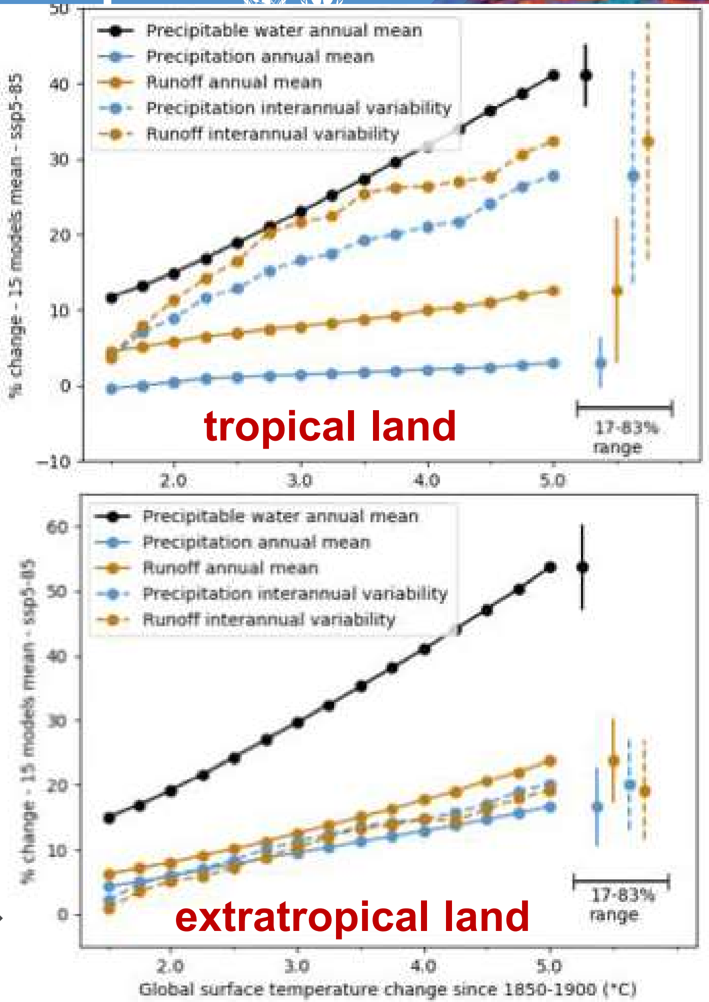
- In the Mediterranean, south western South America & western North America, future aridification will far exceed the magnitude of change seen in the last millennium (*high confidence*).

- Some tropical regions are also projected to experience increased aridity, including the Amazon basin and Central America (*high confidence*).

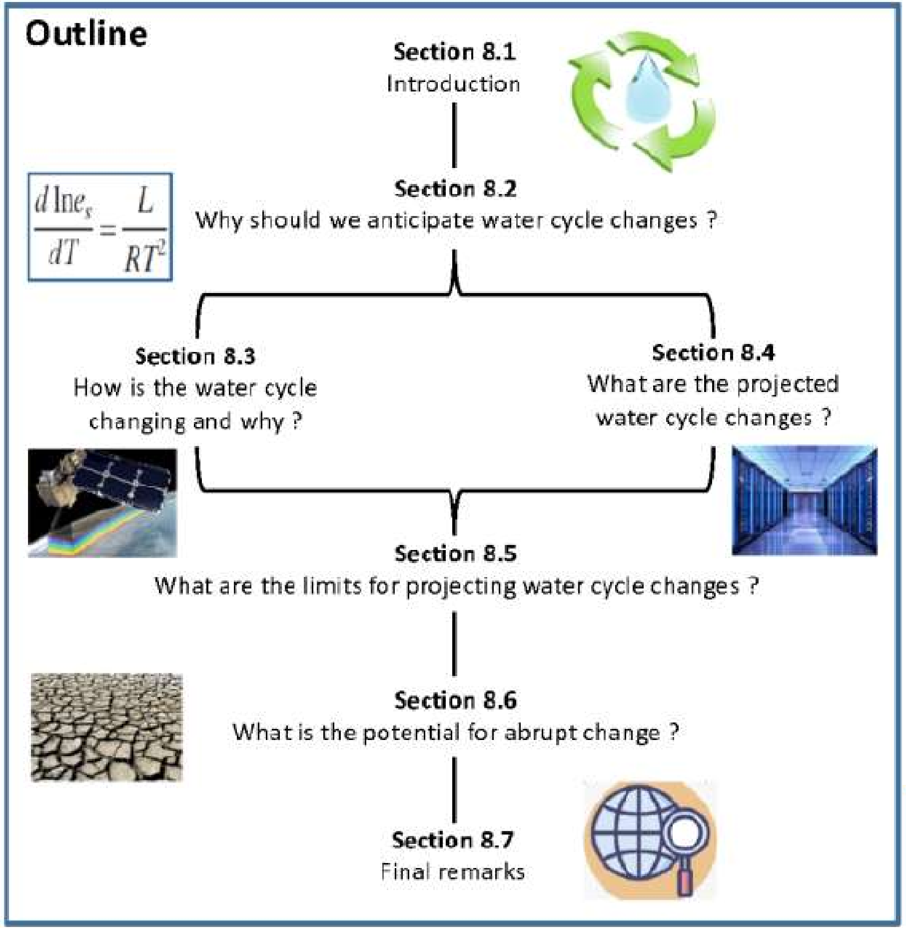
← Figure 8.20, future: RCP8.5

Increased water cycle variability

- Precipitation and surface water flows are projected to become more variable over most land regions within seasons (high confidence) and from year to year (medium confidence), especially in the tropics.
- The <u>seasonality</u> of precipitation, water availability and streamflow will increase with global warming over the Amazon (*medium confidence*) and in the subtropics, especially in the Mediterranean and southern Africa (*high confidence*).



See Box 8.2; Figure TS.12 →



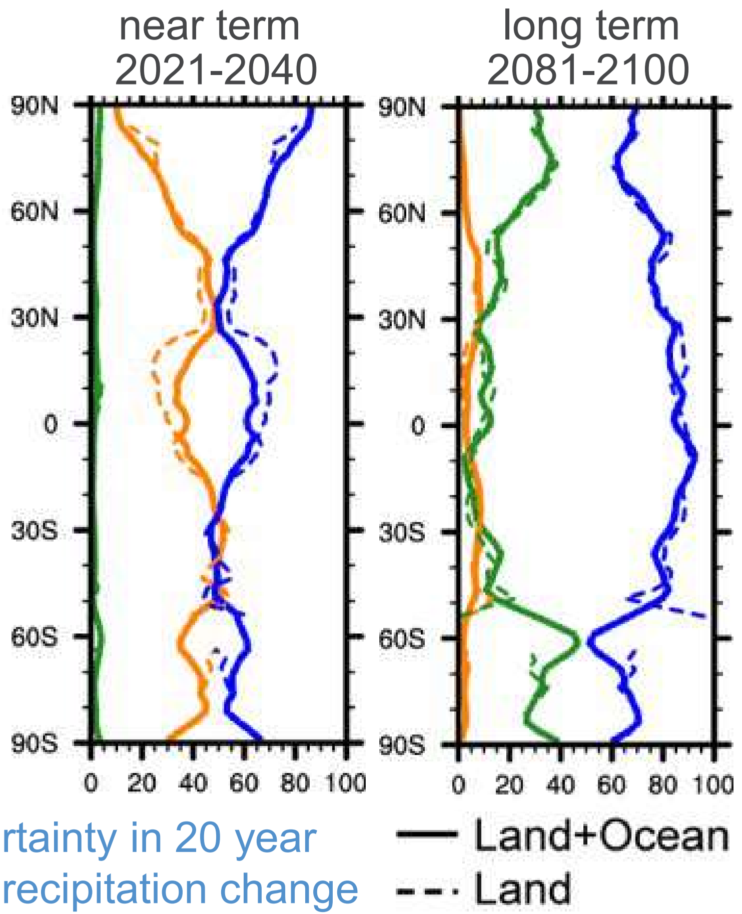
What are the limits to projecting water cycle changes?

Boxes and FAQs

Box 8.1	Box 8.2	FAQ8.1	FAQ8.2	FAQ8.3
Role of aerosols	Changes in seasonality	How does land use change alter the water cycle ?	Should we expect more severe floods, and why ?	What causes drought, and will climate change make them worse ?

Limits to projections: uncertainty due to internal variability – model – scenario

- model response uncertainty is substantial and can exceed scenario uncertainty (Fig. 8.23 →)
- Natural climate variability will continue to be a major source of uncertainty in near-term (2021–2040) water cycle projections (*high confidence*).
- Climate change studies benefit from sampling the full distribution of model outputs when considering future projections at regional scales.

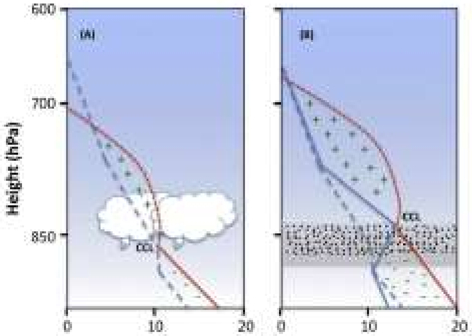


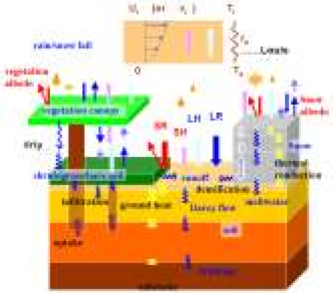
% uncertainty in 20 year mean precipitation change

Limitations in model processes

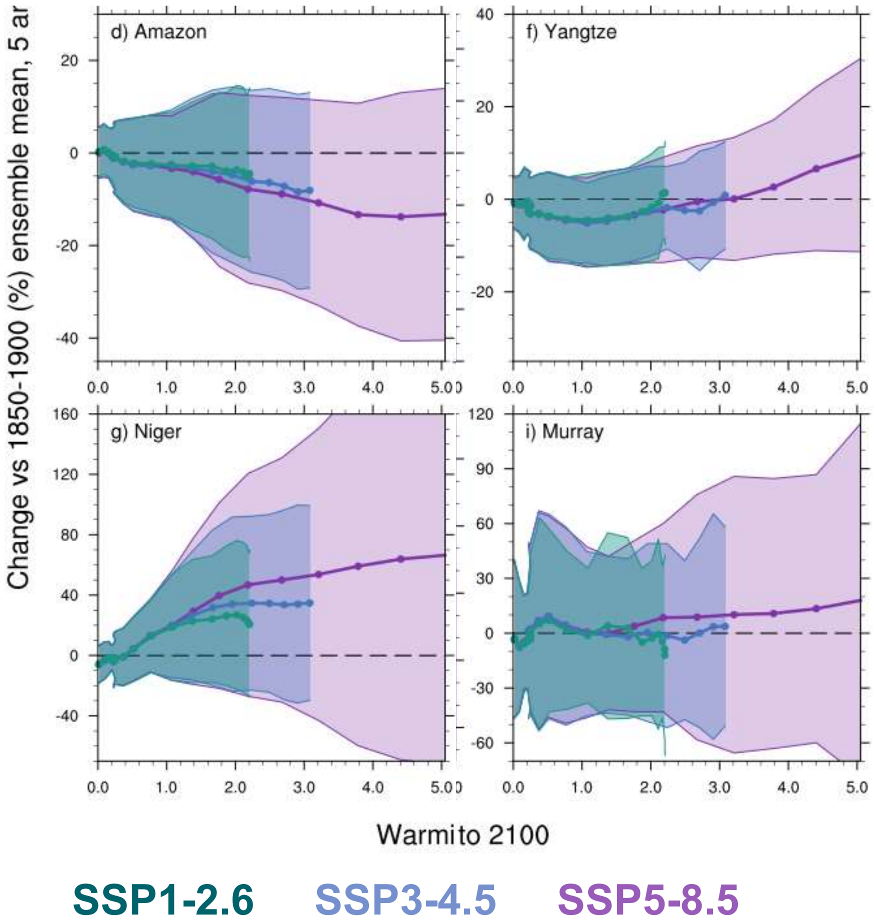
- Representation of key physical processes has improved in global climate models but they are still limited in their ability to simulate all aspects of the present-day water cycle and to agree on future changes (*high confidence*).
  - Convection: double-ITCZ bias; extreme precipitation
  - Cloud-aerosol microphysical processes (*low confidence*)
  - Land surface processes

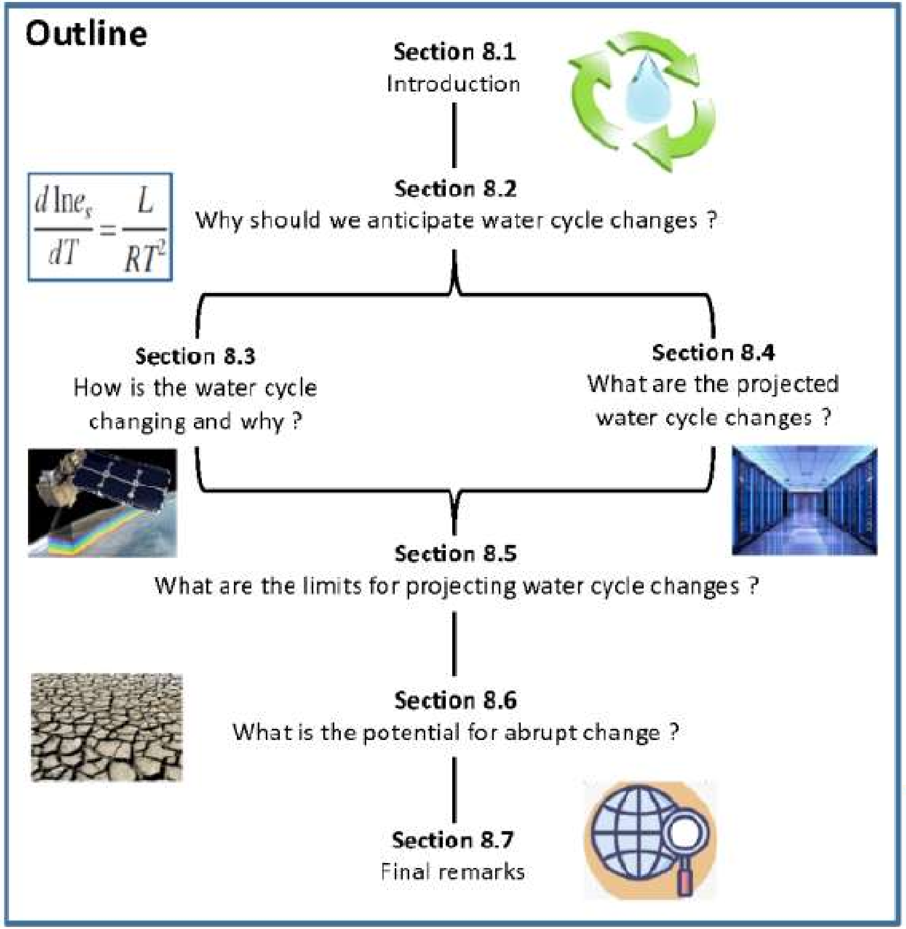
  - Higher resolution improves process representation (e.g. convection permitting) but does not solve many systematic biases





- Continued global warming will further amplify GHG-induced changes in large-scale atmospheric circulation/precipitation patterns (*high confidence*), but in some cases regional water cycle changes are not linearly related to global warming.
- Water resources fed by melting glaciers are particularly exposed to nonlinear responses (*high confidence*).
- The occurrence of volcanic eruptions (either single large events or clustered smaller ones) can alter the water cycle for several years, decreasing global mean land precipitation and altering monsoon circulation (*high confidence*).





What is the potential for abrupt change?

Boxes and FAQs

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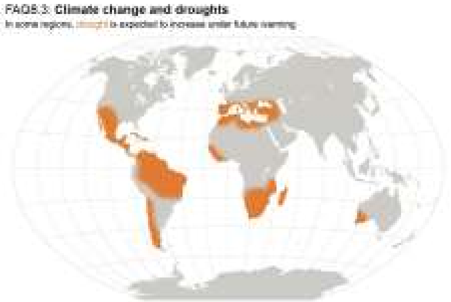
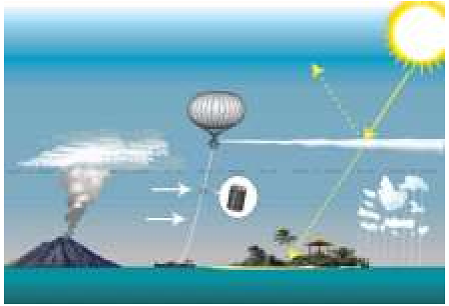
Abrupt and non-linear water cycle changes

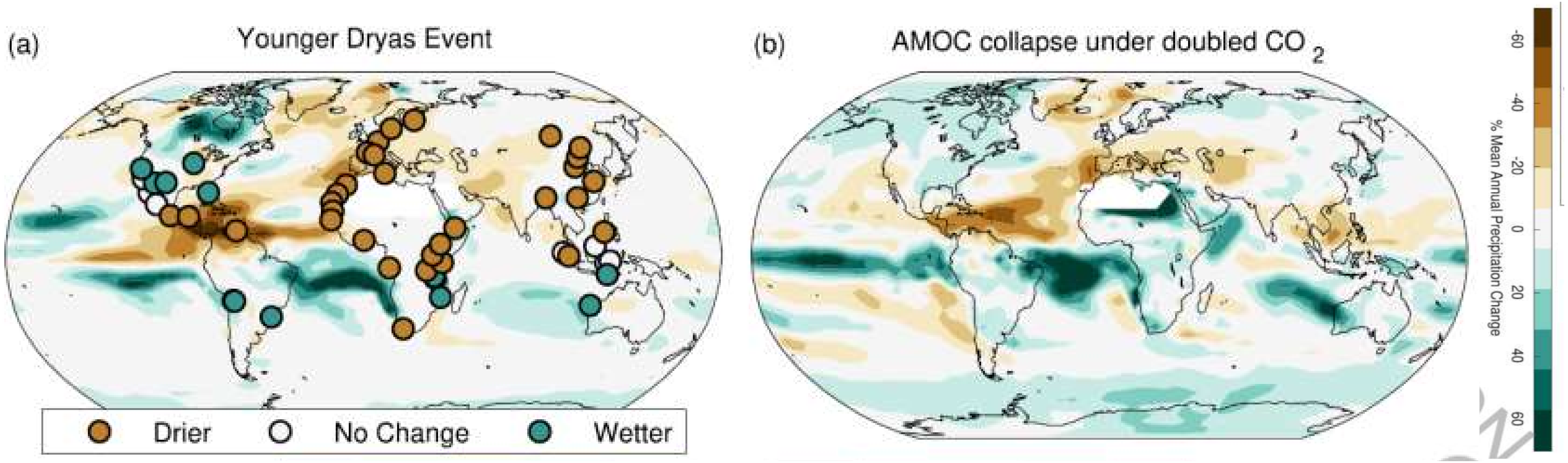
- Positive land-surface feedbacks, including vegetation/dust, can contribute to abrupt changes in aridity, but there is *low confidence* such changes will occur during 21st century.
- Continued Amazon deforestation, combined with a warming climate, raises probability this ecosystem will cross a tipping point into a dry state during 21st century (*low confidence*).
- It is *very likely* that abrupt water cycle changes will occur if Solar Radiation Management (SRM) techniques are implemented rapidly or terminated abruptly. The impact of SRM… will not fully mitigate GHG-forced water cycle changes (*medium confidence*) and can affect different regions in potentially disruptive ways (*low confidence*).

{8.2.3.4, 8.6.1, 8.6.2, 8.6.3; FAQ 8.3}





- The paleoclimate record shows a collapse in the Atlantic Meridional Overturning Circulation (AMOC) causes abrupt shifts in the water cycle (*high confidence*), such as a southward shift in the tropical rain belt, weakening of the African and Asian monsoons and strengthening of Southern Hemisphere monsoons.
- There is *medium confidence* that AMOC will not collapse before 2100, but should it collapse, it is very likely that there would be abrupt changes in the water cycle.



Some Conclusions

"…widespread, non-uniform human-caused alterations of the water cycle, which have been obscured by a competition between different drivers across the 20th century that will be increasingly dominated by greenhouse gas (GHG) forcing…"

(i) Warming is intensifying the water cycle, making very wet and very dry events and seasons more severe when they occur

(ii) Aerosol cooling has masked greenhouse gas warming effects on precipitation, particularly regional responses

(iii) There is a growing substantial direct human impact on the water cycle through irrigation, deforestation & urbanisation

(iv) Regional monsoons are projected to intensify particularly in South and Southeast Asia, East Asia & West Africa with delays affecting North & South America & West Africa

(v) Water cycle variability including precipitation and surface water flows are projected to increase over most land regions.