Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Large-scale modeling needs and opportunities for attribution science

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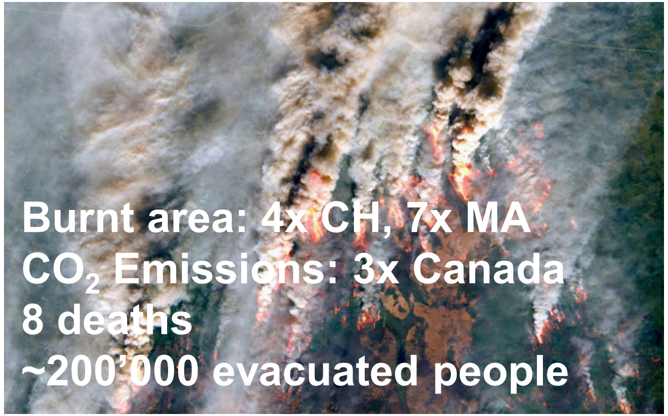
National Academies of Sciences, Engineering and Medicine
Online webinar: "Process-based modeling approaches for attribution science: challenges and opportunities"
March 11, 2025

We are in a climate emergency: And the situation worsens every year…

Attribution science is essential to link causes and effects, and allow for accountability and compensations (e.g. legal cases, climate negotiations)

Los Angeles, 2025

Valencia, Spain, 2024

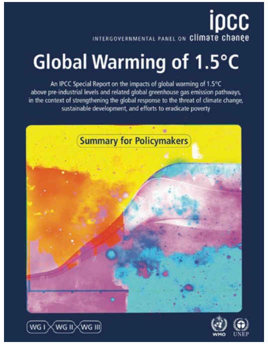


Canada, 2023

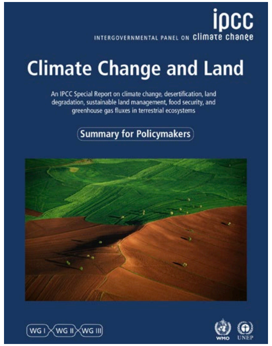
Europe, 2022

Intergovernmental Panel on Climate Change (IPCC)

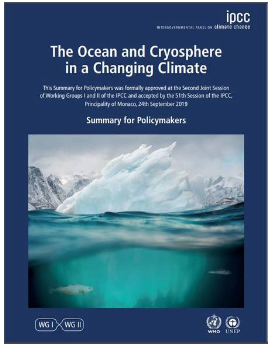
www.ipcc.ch



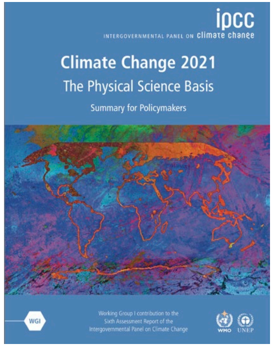
2018



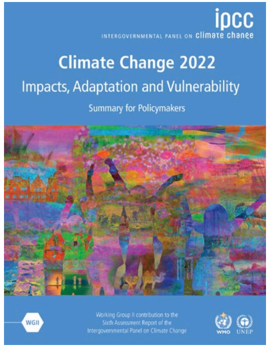
2019



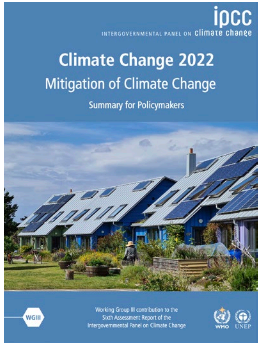
2019



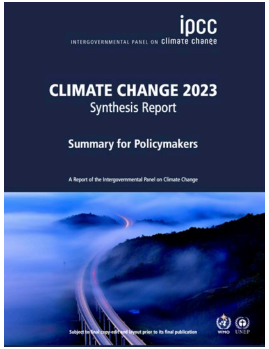
2021



2022



2022

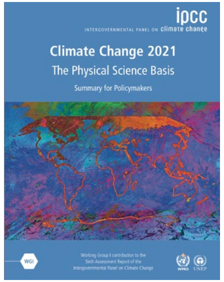


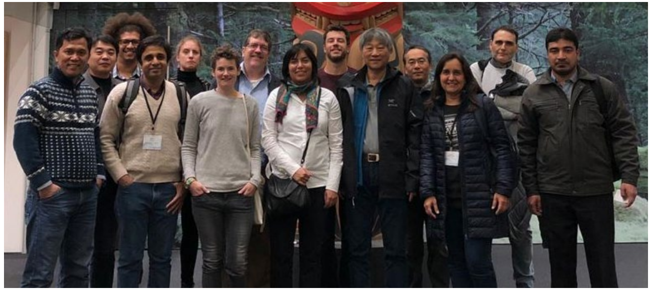
2023

Sonia Seneviratne, ETH Zurich

Intergovernmental Panel on Climate Change (IPCC)

www.ipcc.ch





11

Weather and Climate Extreme Events in a Changing Climate

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IPCC 6th Assessment Report: Assessment on changes in extreme events

https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter11.pdf

IPCC AR6 WGI, Chapter 11 team:
Sonia I. Seneviratne, Xuebin Zhang
Muhammad Adnan, Wafae Badi, Claudine Dereczynski, Alejandro Di Luca, Subimal Ghosh, Iskhaq Iskandar, James Kossin, Sophie Lewis, Friederike Otto, Izidine Pinto, Masaki Satoh, Sergio M. Vicente-Serrano, Michael Wehner, Botao Zhou

Observed changes in extremes

Evidence of observed changes in extremes has strengthened

- Human-induced climate change is already affecting many weather and climate extremes in every region across the globe
- Some recent hot extreme events would have been *extremely unlikely* to occur without human influence on the climate system

(IPCC AR6 WG1; based on Chapter 11, Seneviratne, Zhang, et al. 2021)

Temperature extremes

Heavy precipitation

Floods

Droughts

Storms

Compound events

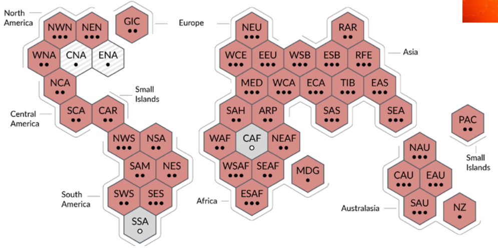
Observed & attributed changes in extremes

Climate change is already affecting every inhabited region across the globe: No region is spared from changes in climate extremes

IPCC AR6 WGI assessment already needs to be updated: Literature cut-off date in January 2021!

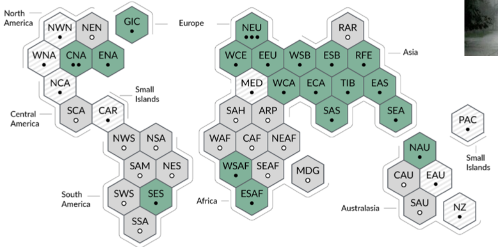
Hot extremes

Increase (41)
Decrease (0)



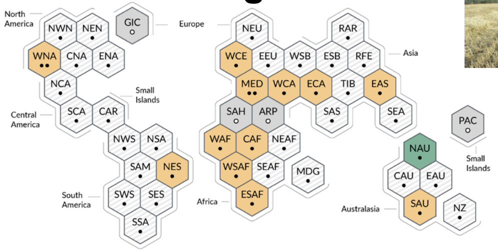
Extreme rainfall

Increase (19)
Decrease (0)



Drought

Increase (12)
Decrease (1)

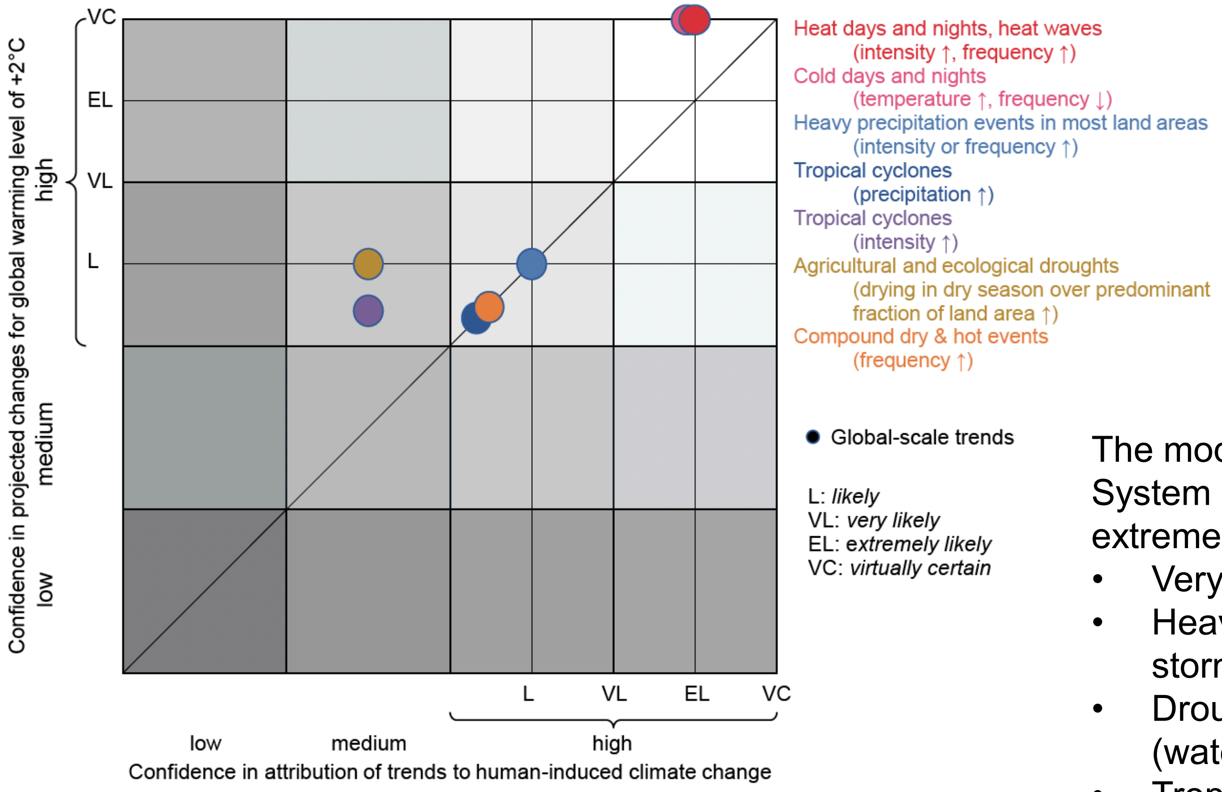


Low agreement in the type of change
Limited data and/or literature

Confidence in human contribution to the observed change

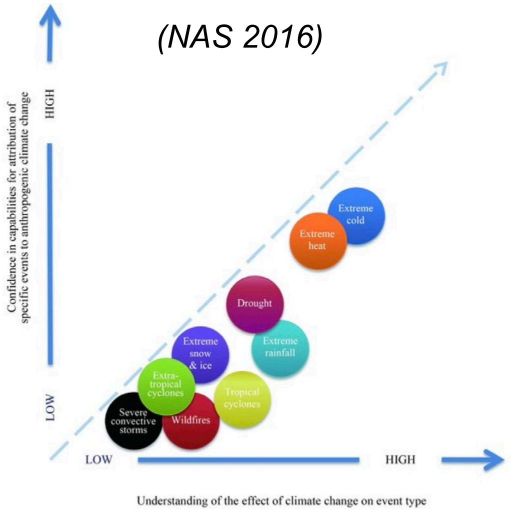
- ●●● High
- ●● Medium
- ● Low due to limited agreement
- ○ Low due to limited evidence

Confidence in attribution & modelling challenges



(Seneviratne et al. 2021, IPCC AR6 WGI, Fig. 11.5)

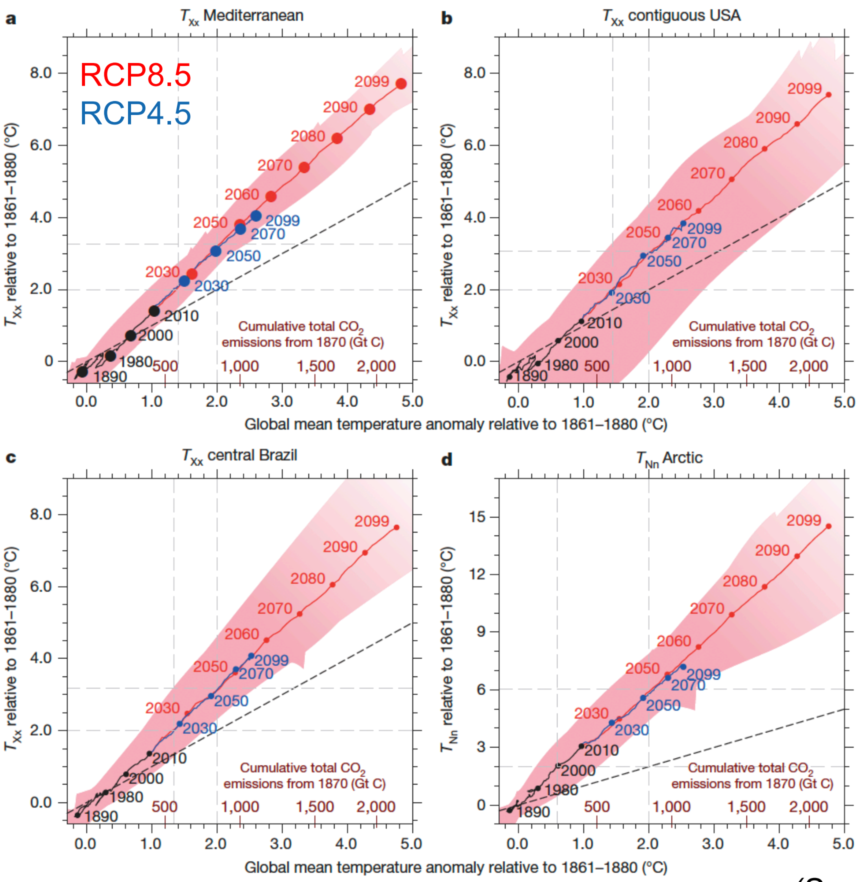
(NAS 2016)



The modelling challenges for global Earth System Models are different for different climate extremes:

- Very reliable for heatwaves
- Heavy precipitation, severe convective storms: Higher resolution
- Droughts: Better process representation (water/carbon, biology/physics interactions)
- Tropical cyclones: Dedicated models

Regional changes in extremes vs Global warming



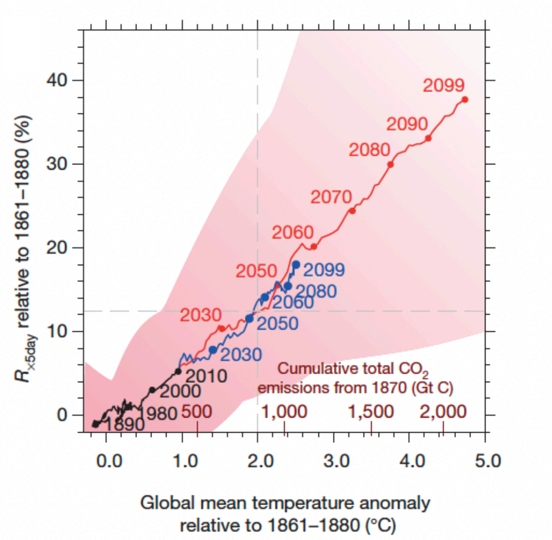
Almost linear relationship between (absolute) changes in regional extremes and global warming (and cumulative CO_2 emissions)

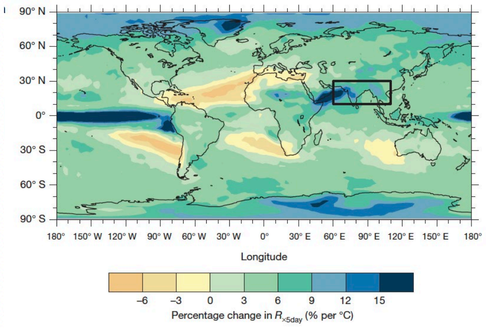
Every additional emissions of CO_2 lead to additional global warming and more intense heatwaves and other extreme events

→ causality in attribution framework

(Seneviratne et al 2016, Nature)

Regional changes in extremes vs Global warming





Almost linear relationship between (absolute) changes in regional extremes and global warming (and cumulative CO_2 emissions)

Every additional emissions of CO_2 lead to additional global warming and more intense heatwaves and other extreme events

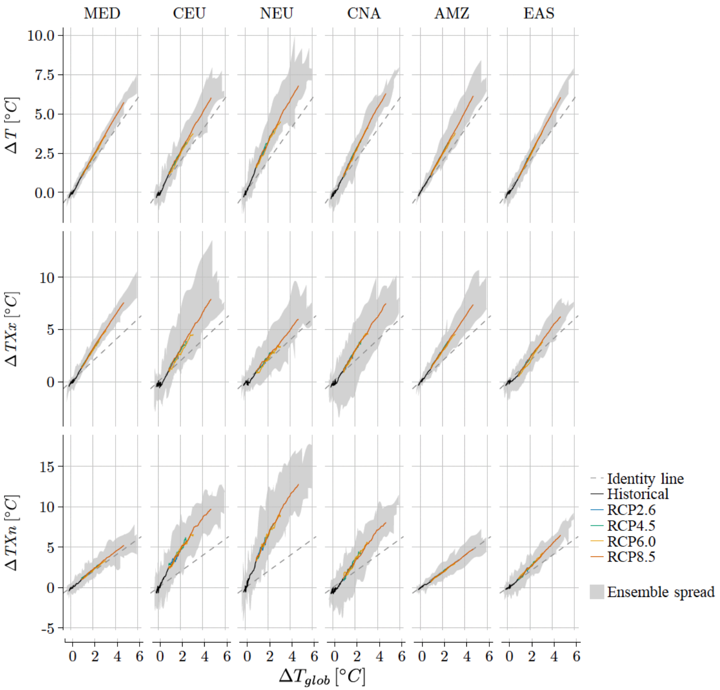
Mean multi-model response also linear for heavy precipitation, but much higher intermodel spread!

→ causality in attribution framework

(Seneviratne et al 2016, Nature)

Modelling challenges

Limited intermodel spread for temperature mean and extremes: but some challenges compared to observations (see PNW 2021 heatwave)



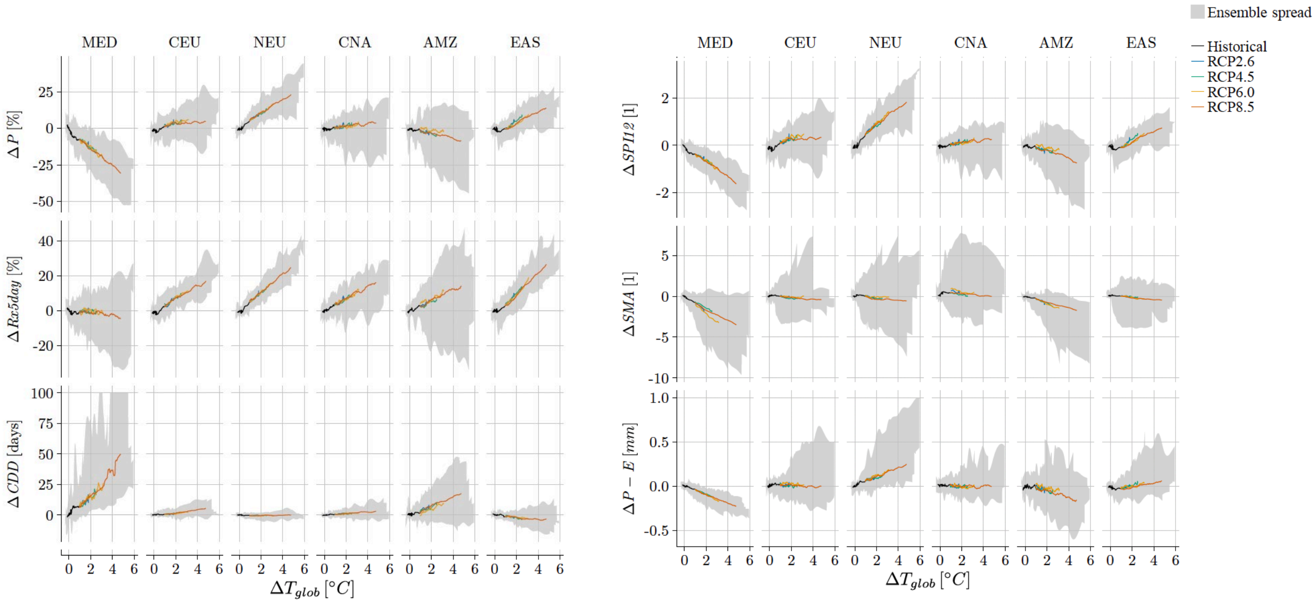
(Wartenburger et al. 2017, GMD)

MED: Mediterranean region
CEU: Central Europe
NEU: Northern Europe
CNA: Central North America
AMZ: Amazon region
EAS: Eastern Asia

(CMIP5 models; similar for CMIP6, *see Seneviratne and Hauser 2020, Earth's Future*)

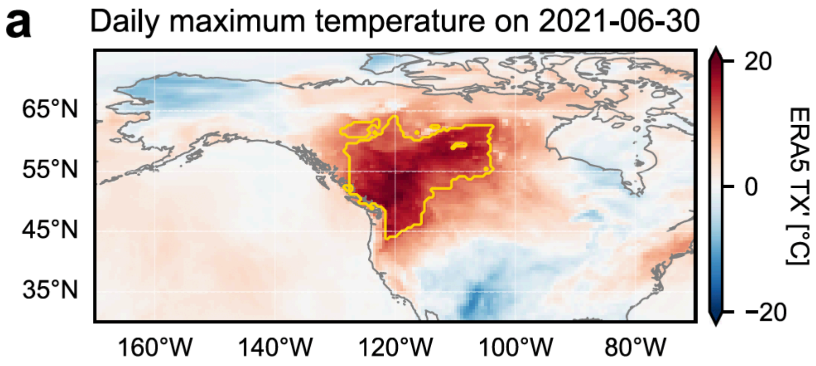
Modelling challenges

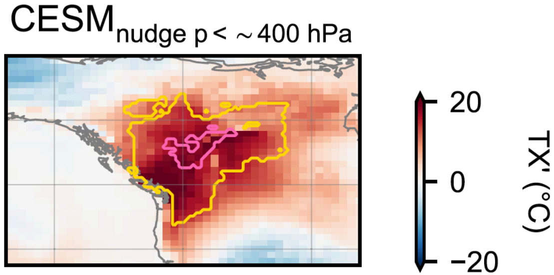
Large intermodel spread for water cycle mean and extremes

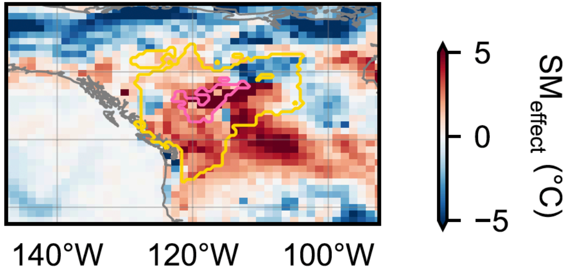


(Wartenburger et al. 2017, GMD)

Modelling challenges: Land-atmosphere interactions







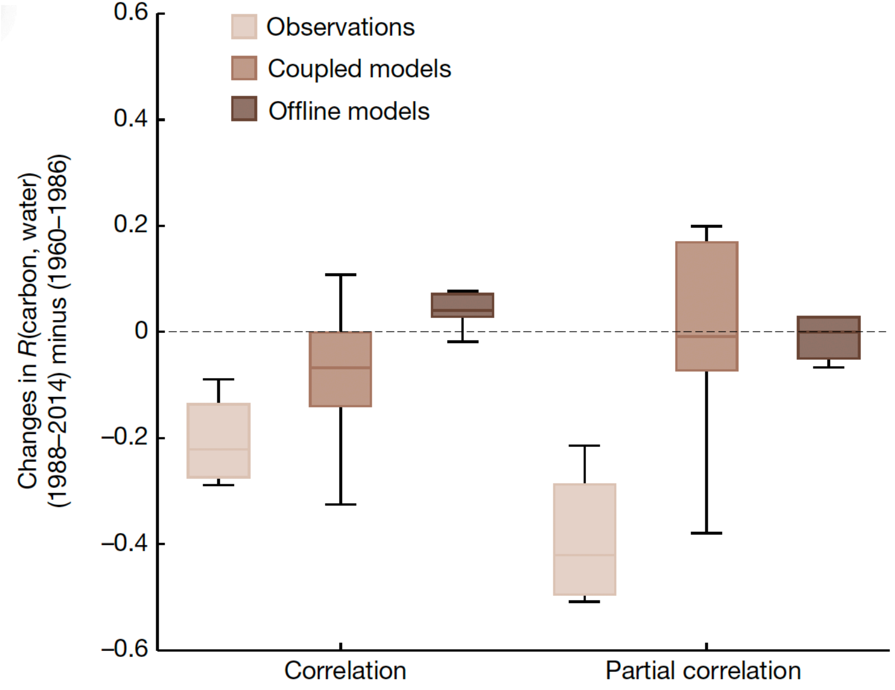
Soil moisture anomalies locally contributed up to 5ºC to 2021 Pacific Northwest heatwave! Soil moisture-temperature feedbacks often cause for record-shattering events….

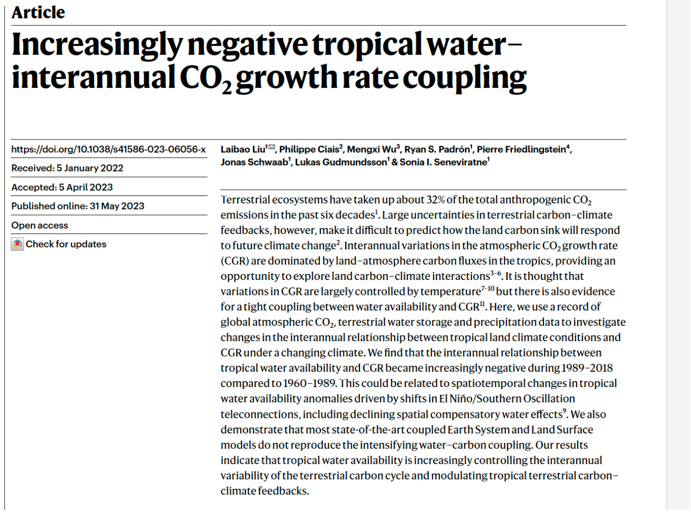
(Schumacher et al. 2022, Earth's Future)

Modelling challenges: Droughts-carbon cycle feedbacks

Observation-based data reveal a strengthening of (negative) correlation between yearly anomalies of land water availability and CO_2 growth rate: Not captured in climate models

Relevant for potential future abrupt increase in global mean temperature, CO_2 & fires





Article

Increasingly negative tropical water–interannual CO_2 growth rate coupling

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Open access

Check for updates

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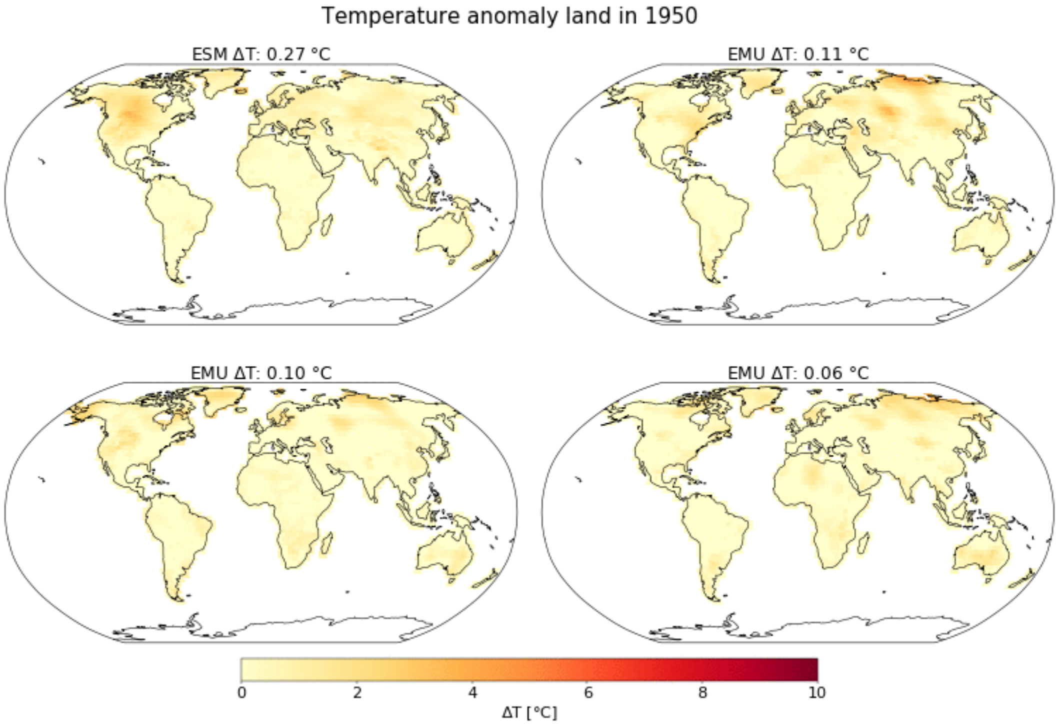
Terrestrial ecosystems have taken up about 32% of the total anthropogenic CO_2 emissions in the past six decades[1]. Large uncertainties in terrestrial carbon–climate feedbacks, however, make it difficult to predict how the land carbon sink will respond to future climate change[2]. Interannual variations in the atmospheric CO_2 growth rate (CGR) are dominated by land–atmosphere carbon fluxes in the tropics, providing an opportunity to explore land carbon–climate interactions[3–6]. It is thought that variations in CGR are largely controlled by temperature[7–10] but there is also evidence for a tight coupling between water availability and CGR[11]. Here, we use a record of global atmospheric CO_2, terrestrial water storage and precipitation data to investigate changes in the interannual relationship between tropical land climate conditions and CGR under a changing climate. We find that the interannual relationship between tropical water availability and CGR became increasingly negative during 1989–2018 compared to 1960–1989. This could be related to spatiotemporal changes in tropical water availability anomalies driven by shifts in El Niño/Southern Oscillation teleconnections, including declining spatial compensatory water effects[9]. We also demonstrate that most state-of-the-art coupled Earth System and Land Surface models do not reproduce the intensifying water–carbon coupling. Our results indicate that tropical water availability is increasingly controlling the interannual variability of the terrestrial carbon cycle and modulating tropical terrestrial carbon–climate feedbacks.

(Liu et al. 2023, Nature)

ESM emulators: Useful to explore tails & for fast assessments

A regional-scale ESM emulator coupled to integrated assessment models could help increase realism of developed scenarios & also be used for attribution *(see also Barnes et al.)*

MESMER emulator: Modular Earth System Model Emulator with spatially Resolved output



ERC PoC MESMER-X

(Beusch et al. 2020, ESD; Beusch et al 2022, GMD; Nath et al. 2022, ESD; Quilcaille et al. 2022, GRL)

Conclusions

- **Changes in climate extremes are an essential dimension of human-induced climate change:** All regions of the world are displaying observed changes in extremes, with increasing number of attribution studies on global and regional scale

- Attribution capabilities have been increasing in recent years. Some modelling challenges:
  - Heatwaves: Record-shattering events associated with land-atmosphere feedbacks
  - Droughts, heavy precipitation/severe convective storms, tropical cyclones
  - Global drought-carbon feedbacks

- New developments:
  - Using ESM emulators to speed up assessment and explore tails of distributions
  - Impact attribution: Spatially compound events and associated impacts on supply chains; attribution using combination of ESM and impact models

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