Drought-climate feedbacks: Model uncertainties and potential for surprises

(… and some other reflections on confronting models with obs)

Sonia I. Seneviratne, Laibao Liu, Dominik Schumacher, Svenja Seeber, Francesco Giardina, Lukas Gudmundsson, Martin Hirschi, Mathias Hauser, Felix Jäger, Ryan S. Padron, Jonas Schwaab and Kathrin Wehrli

ETH Zurich, Switzerland

Workshop on confronting Earth System Model trends with observations: The Good, the Bad, and the Ugly

US CLIVAR, NCAR, March 15, 2024

Confronting ESMs with observations:

- Observational uncertainties
- Separating sources of biases (forcing; thermodynamic vs dynamic biases)

Drought-climate feedbacks

- Relevant processes
- Drought trends in ESMs vs observations
- Potential biases in global drought-carbon feedbacks

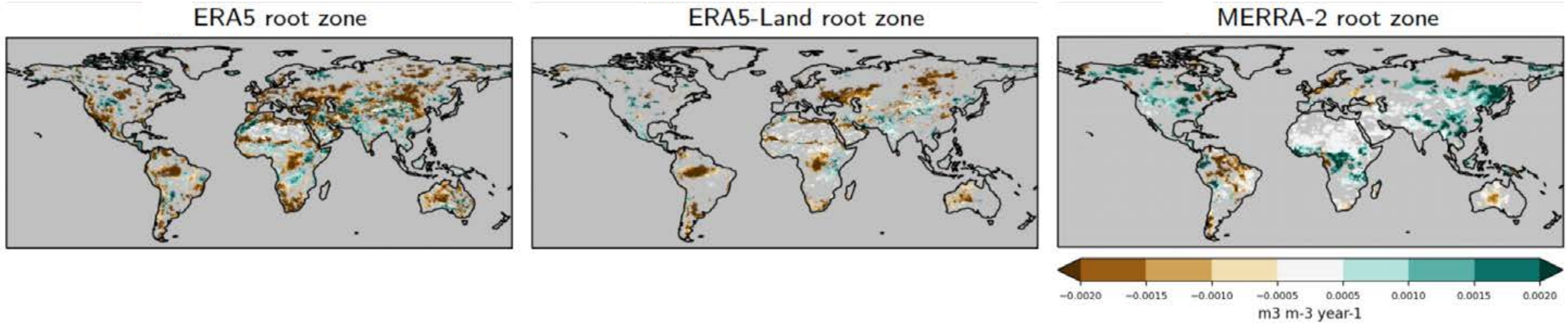
Some open questions

- Drought relevance for record-shattering heatwaves
- 2023 Record temperatures

Conclusions

Observational uncertainties

Drought trends (dry-season soil moisture), 2000-2020

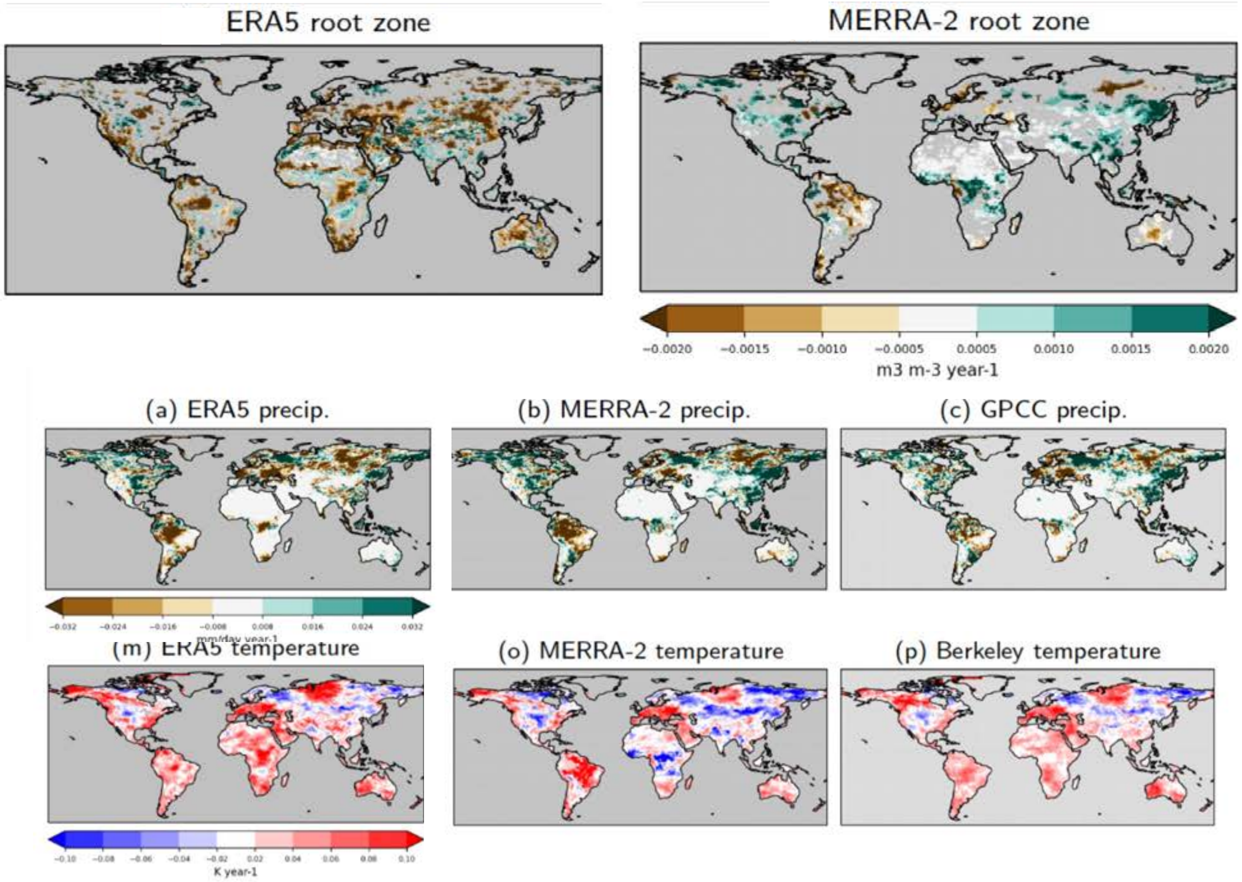


There are also large uncertainties in observational products!

(Hirschi et al, submitted to HESS)

Observational uncertainties

Drought trends (dry-season soil moisture), 2000-2020

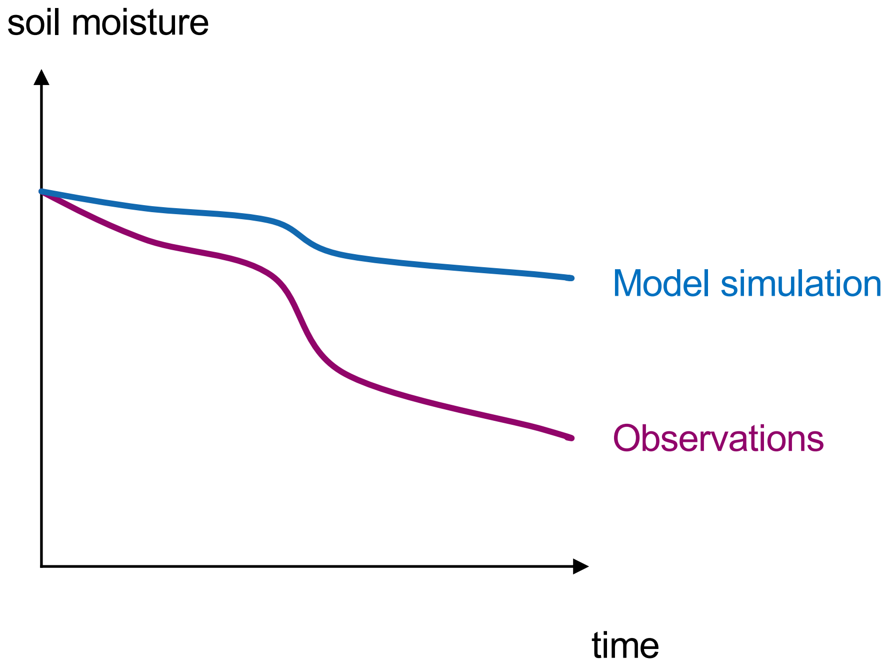


Comparison with ground observations suggest some biases in MERRA-2 product

(NB: 2-m temperatures are not assimilated in MERRA-2!)

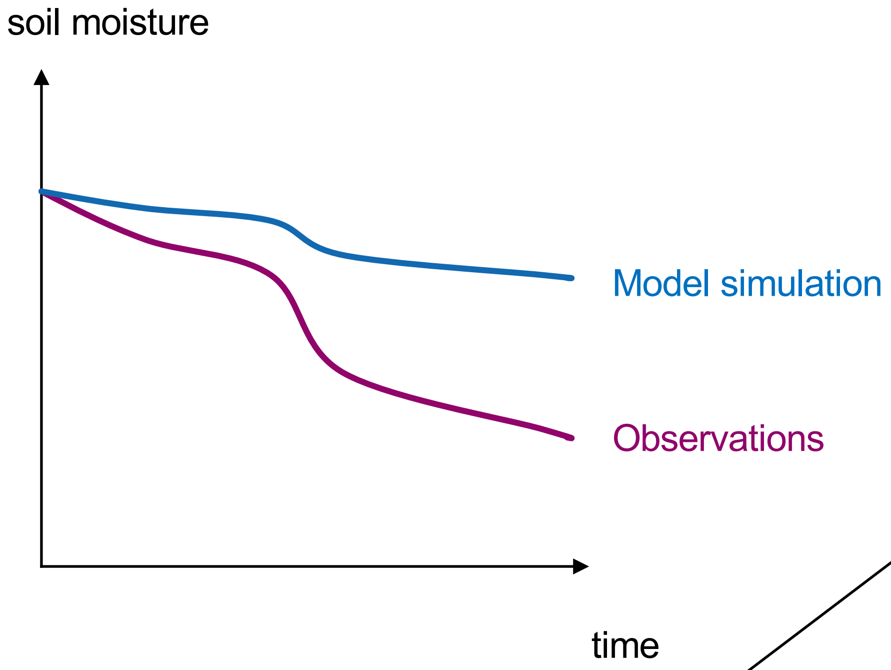
(Hirschi et al, submitted to HESS)

Separating sources of biases



Is the ESM consistent with observations?

Separating sources of biases

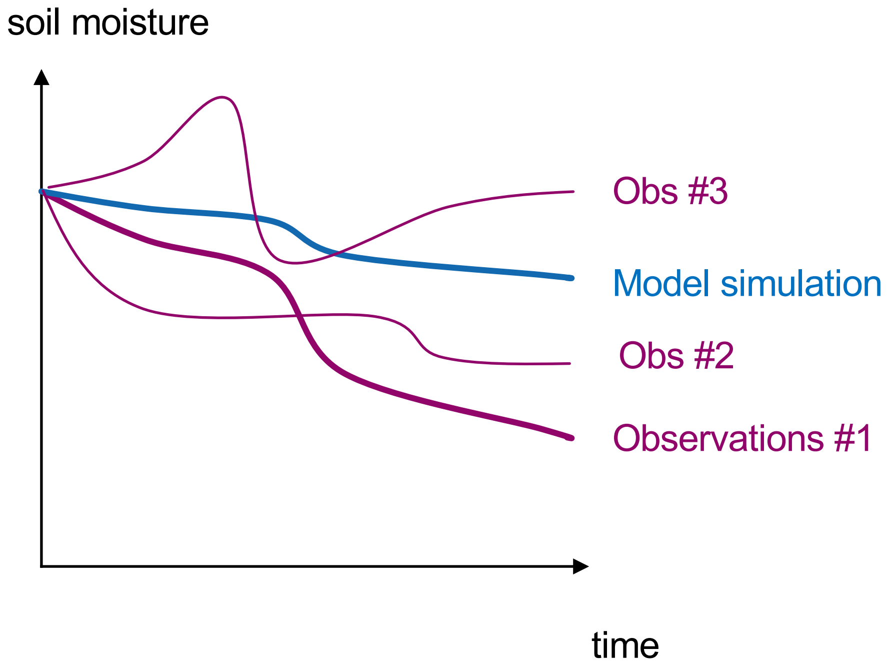


Is the ESM consistent with observations?

1) Consider observational spread
2) Consider model spread (several realizations)
3) Process-based evaluation of single components (e.g. dynamics vs thermodynamics, land vs atm vs ocean, extremes vs mean, forcing)

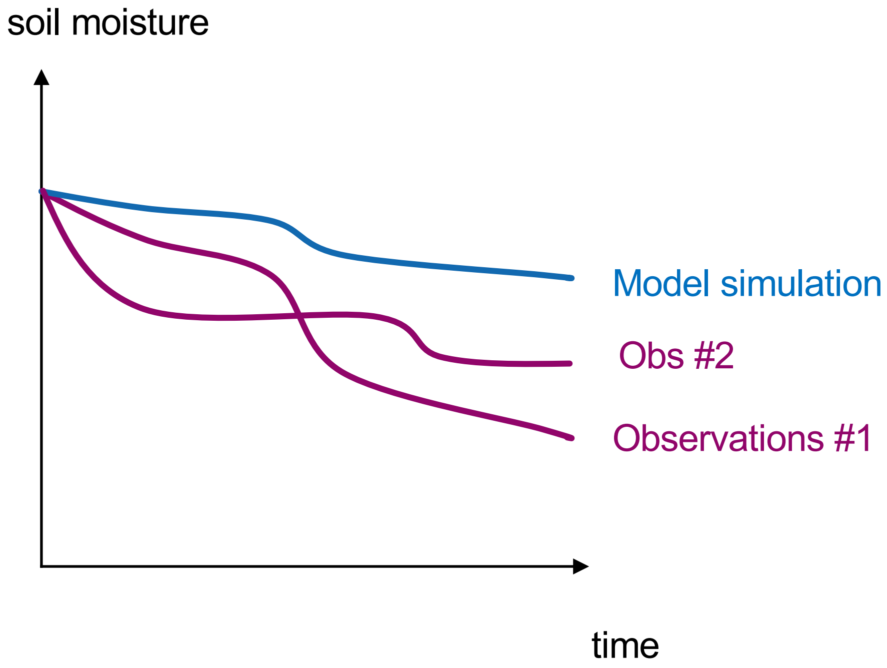
3-step evaluation

Separating sources of biases



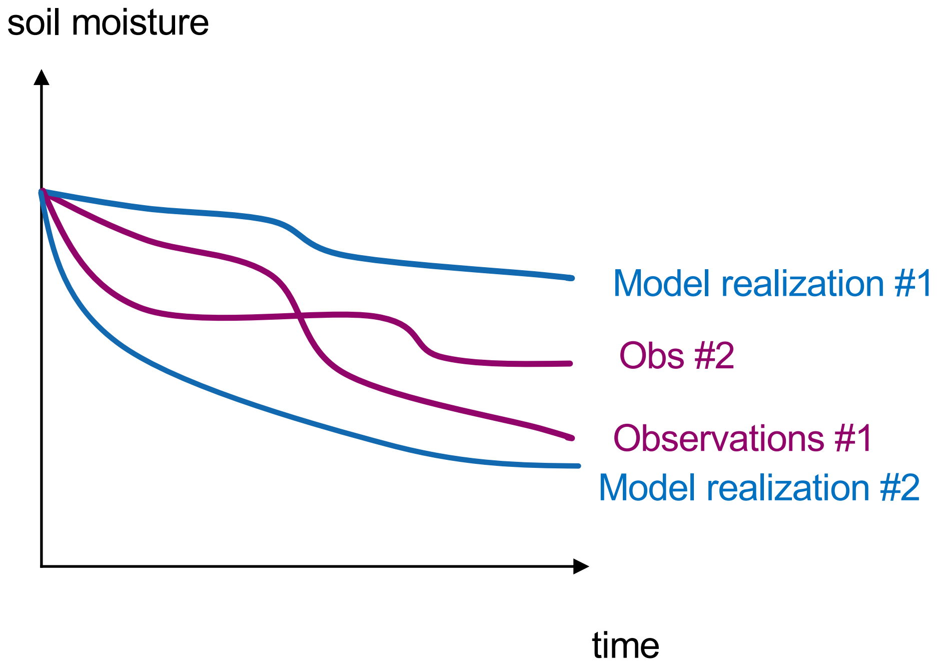
1) Need to consider **observational spread** …

Separating sources of biases



1) Need to consider **observational spread** *and possibly exclude some observational products with biases*

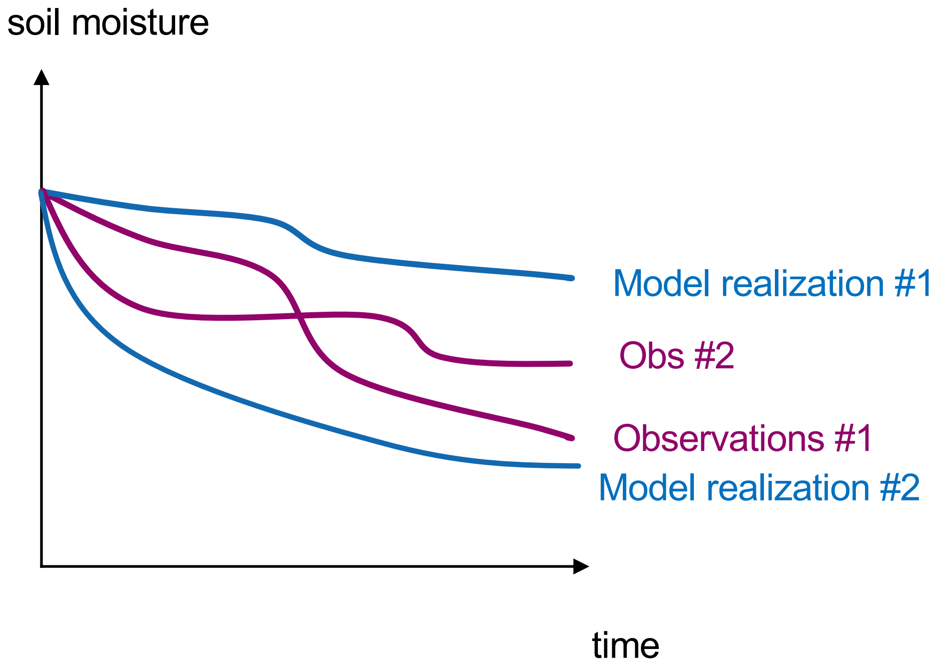
Separating sources of biases



1) Need to consider **observational spread** *and possibly exclude some observational products with biases*

2) Consider **multiple realisations from climate model** (not only single runs)
(Deser et al. 2012, Nature Climate Change)

Separating sources of biases

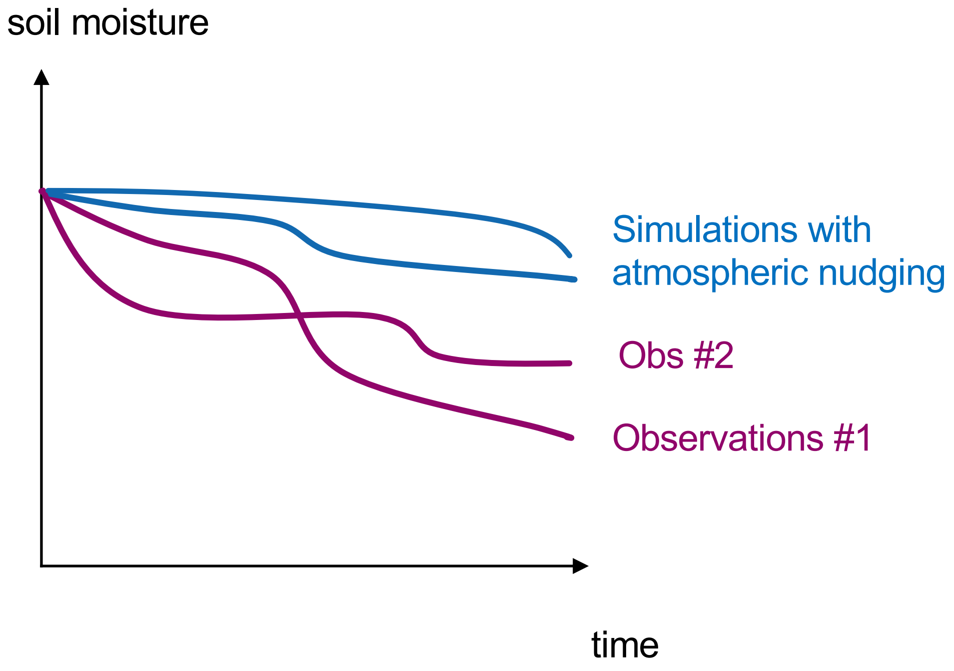


1) Need to consider **observational spread** *and possibly exclude some observational products with biases*

2) Consider **multiple realisations from climate model** (not only single runs)
(Deser et al. 2012, Nature Climate Change)

NB: The source for some of the model spread can be isolated and constrained (atmospheric dynamics)

Separating sources of biases



1) Need to consider **observational spread** *and possibly exclude some observational products with biases*

2) Consider **multiple realisations from climate model** (not only single runs)
(Deser et al. 2012, Nature Climate Change)

3) **Process-based evaluation of single ESM components** (some with obs constraints, others not)
(e.g. Wehrli et al. 2018, GRL)

Separating sources of biases: Dynamics vs thermodynamics

AGU100 ADVANCING EARTH AND SPACE SCIENCE

Geophysical Research Letters

RESEARCH LETTER
10.1029/2018GL079220

Assessing the Dynamic Versus Thermodynamic Origin of Climate Model Biases

Kathrin Wehrli[1], **Benoit P. Guillod**[1,2], **Mathias Hauser**[1], **Matthieu Leclair**[1], and **Sonia I. Seneviratne**[1]

[1]Institute for Atmospheric and Climate Science, Department of Environmental Systems Science, ETH Zurich, Zurich, Switzerland, [2]Institute for Environmental Decisions, Department of Environmental Systems Science, ETH Zurich, Zurich, Switzerland

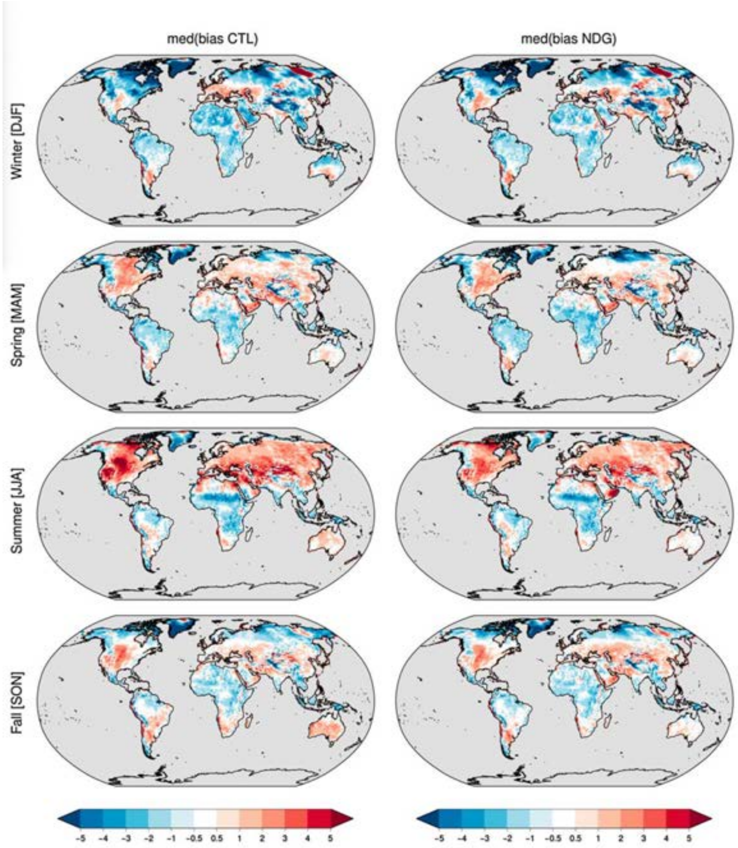
Key Points:
- Thermodynamical versus dynamical sources of biases can be identified using atmospheric nudging of horizontal winds in a climate model
- Atmospheric nudging improves simulated temperature and precipitation in CESM; however,

Wehrli et al. 2018, GRL

Separating sources of biases: Dynamics vs thermodynamics

Interactive atmosphere

Nudged winds



CESM 1.2

(comparison to CRU TS, 1982-2021; mean bias)

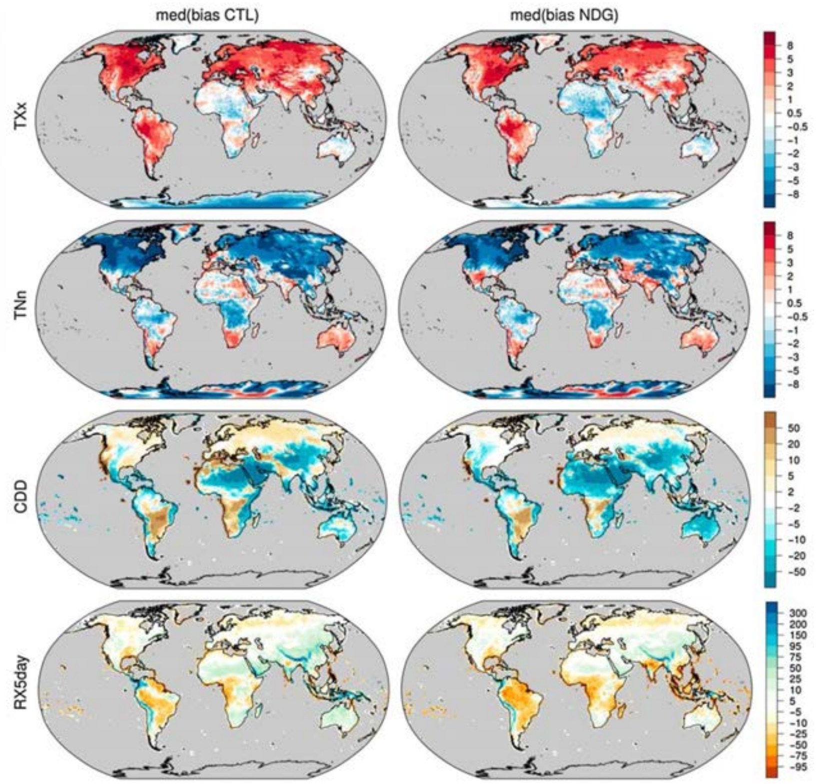
A large fraction of the biases remain, i.e. are of thermodynamic origin!

(Wehrli et al. 2018, GRL)

Separating sources of biases: Dynamics vs thermodynamics

Interactive atmosphere

Nudged winds



CESM 1.2

(comparison to ERA-interim (Txx, Tnn) and MERRA-2 (CDD, Rx5dday), 1982-2021; mean bias)

A large fraction of the biases remain, i.e. are of thermodynamic origin!

(Wehrli et al. 2018, GRL)

Separating sources of biases: Dynamics vs thermodynamics

EXTREMEX simulations: 2009-2015/2016; CESM, EC-EARTH, MIROC
Several set-ups, either with prescribed atmospheric winds, SST or soil moisture (contribution to climate extremes)
NB: New simulations with CESM2.1.2 and ERA5 atmospheric winds are currently on-going (D. Schumacher, ETH Zurich)

Earth Syst. Dynam., 13, 1167–1196, 2022
https://doi.org/10.5194/esd-13-1167-2022

Earth System Dynamics
Open Access
EGU

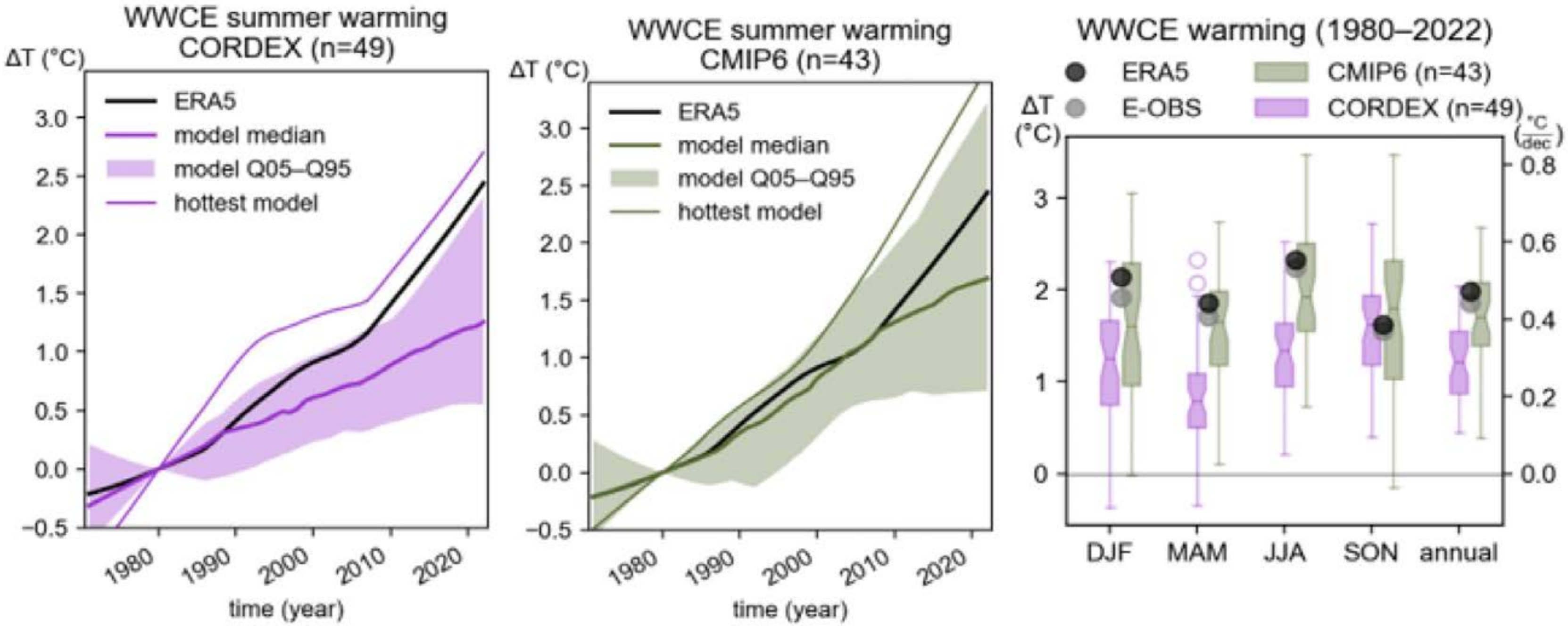
The ExtremeX global climate model experiment: investigating thermodynamic and dynamic processes contributing to weather and climate extremes

Kathrin Wehrli[1], Fei Luo[2,3], Mathias Hauser[1], Hideo Shiogama[4], Daisuke Tokuda[5], Hyungjun Kim[5,6,7], Dim Coumou[2,3], Wilhelm May[8], Philippe Le Sager[3], Frank Selten[3], Olivia Martius[9,10,11], Robert Vautard[12], and Sonia I. Seneviratne[1]

(Wehrli et al. 2022, ESD)

Separating sources of biases: Radiative forcing

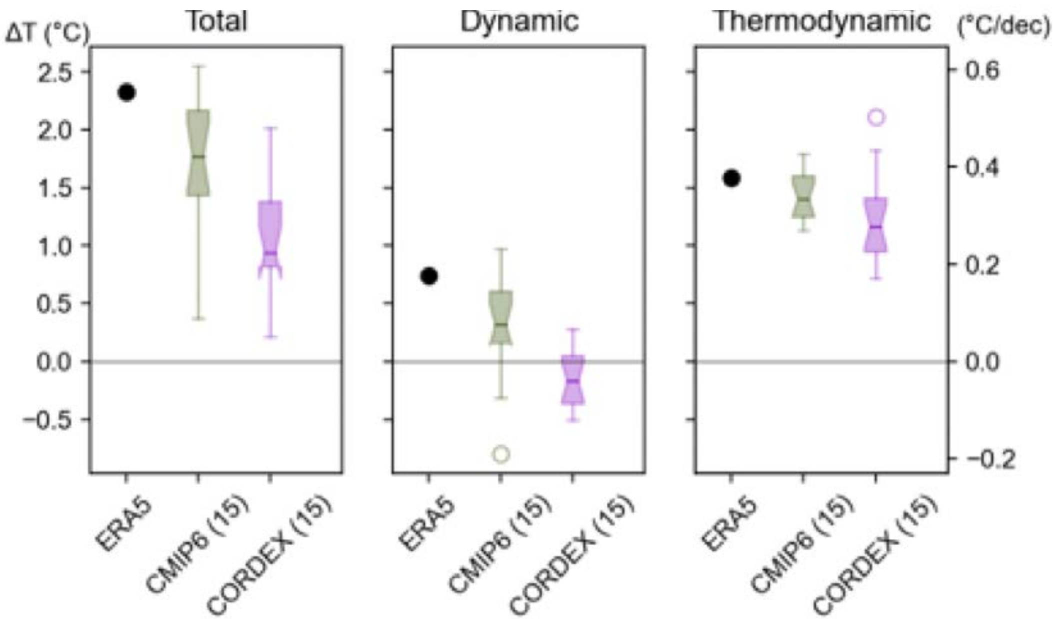
Temperature trends in Western West-Central Europe



(Schumacher et al., submitted; Preprint: https://www.researchsquare.com/article/rs-3314992/v1)

Separating sources of biases: Radiative forcing

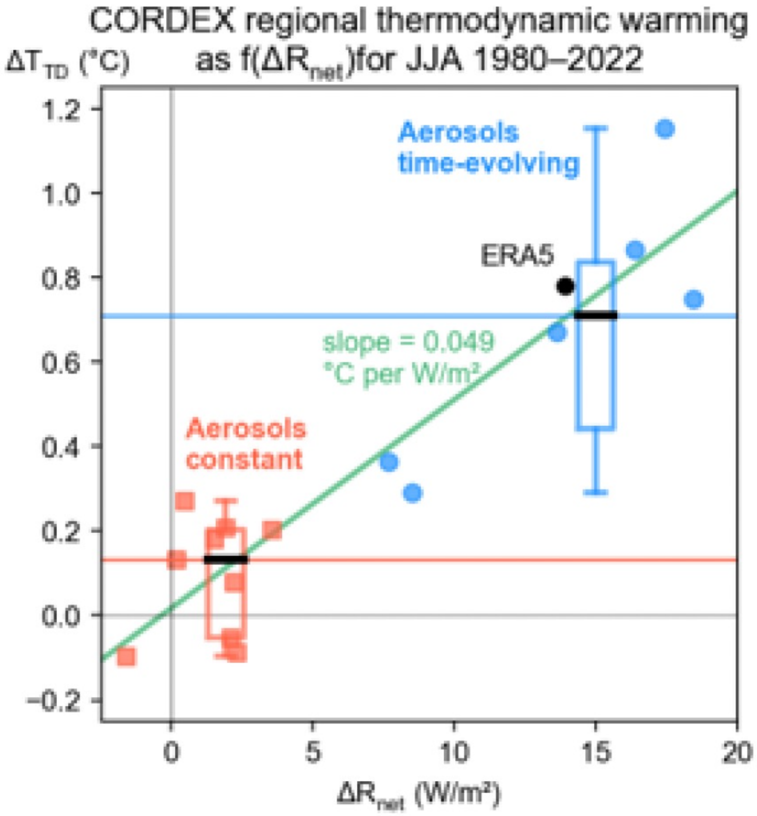
Temperature trends in Western West-Central Europe



Most of the observed warming is of thermodynamic origin (with some contribution of dynamic origin)

(Schumacher et al., submitted; Preprint: https://www.researchsquare.com/article/rs-3314992/v1)

Separating sources of biases: Radiative forcing



Constant aerosols in most of the CORDEX simulations: lead to substantial bias in temperature and radiation simulations! (important also for other regions!)

(Schumacher et al., submitted; Preprint: https://www.researchsquare.com/article/rs-3314992/v1)

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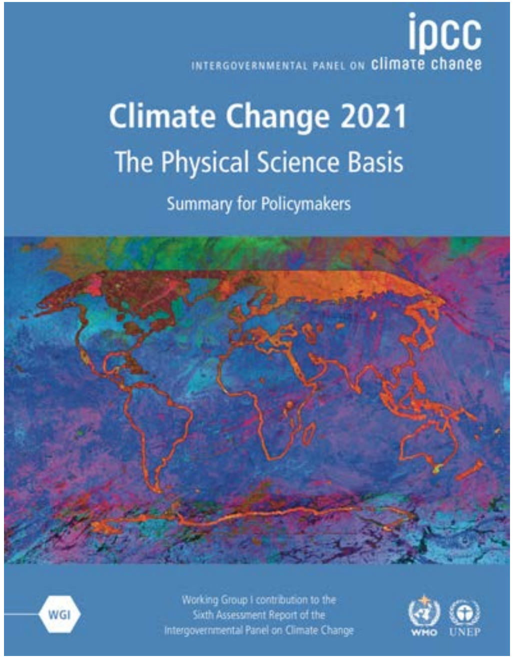
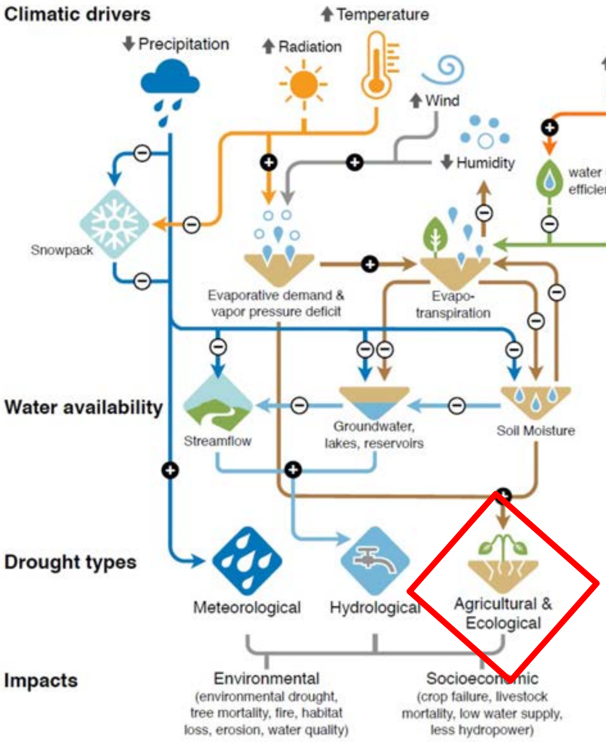
Conclusions

Drought types assessed in IPCC AR6

The IPCC AR6 distinguishes
3 drought types

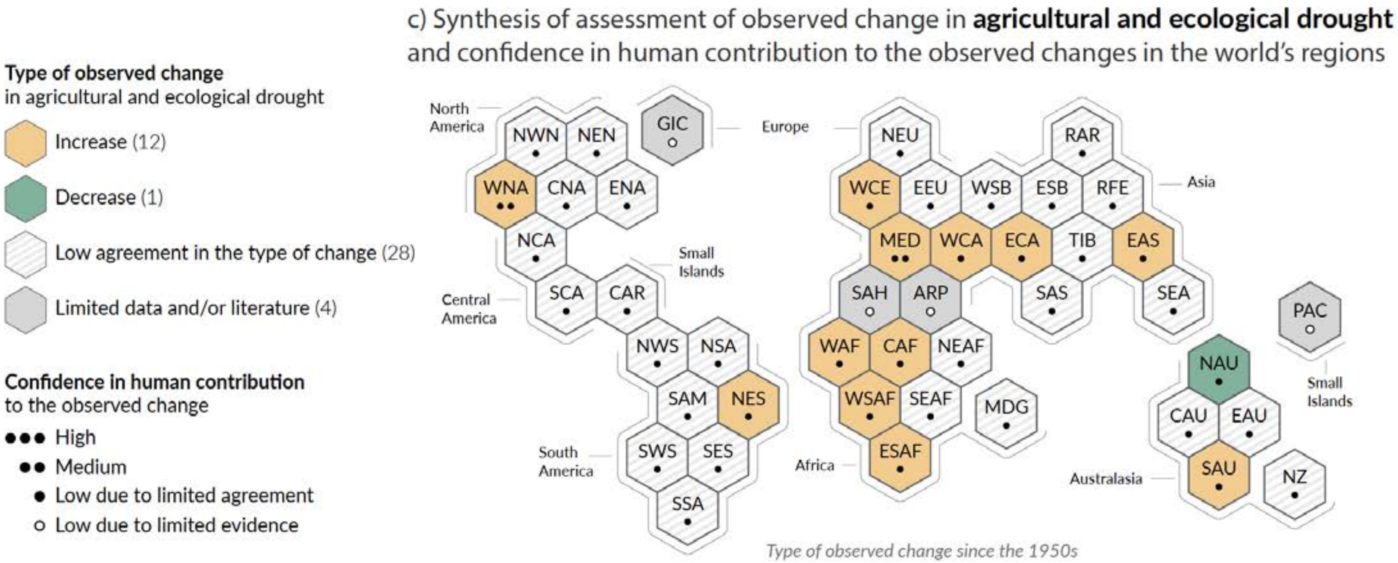




(IPCC AR6, Chapter 8; Douville et al. 2021)

IPCC assessment on historical changes in agroecological droughts

Regional changes in agricultural and ecological drought since 1950s (soil moisture, water-balance estimates, measures combining precipitation & atmospheric evaporative demand)

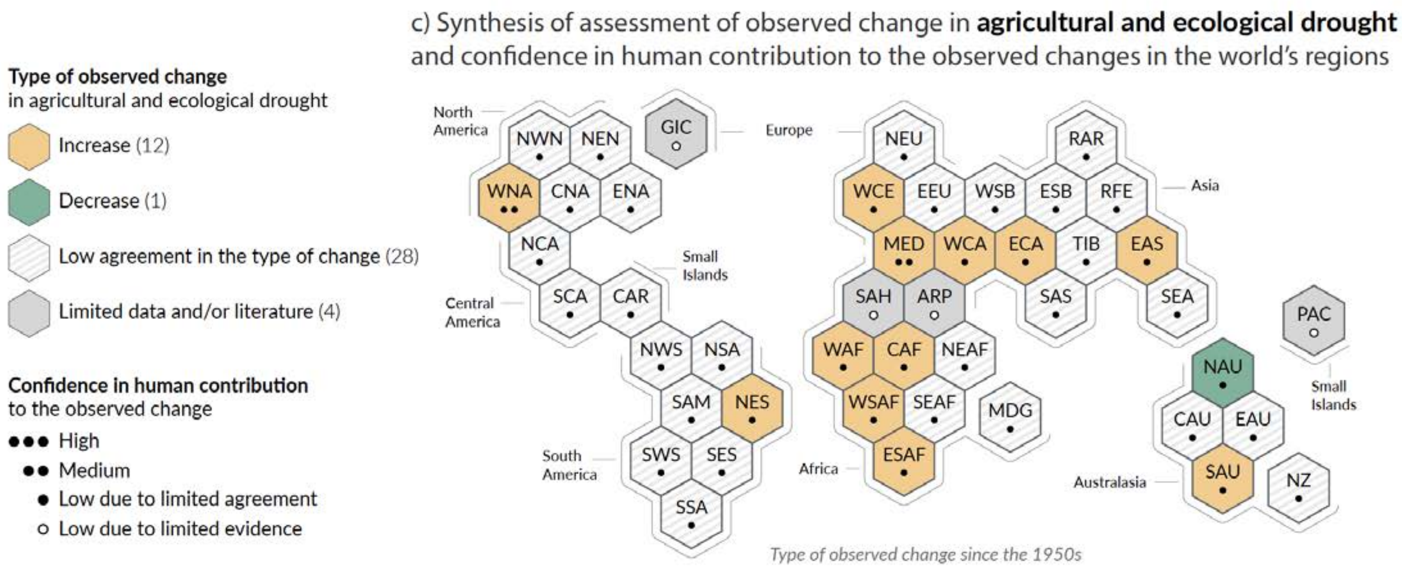


Dominant signal shows drying
Strong attributable signals in some regions (MED, WNA)

(IPCC AR6 SPM, Figure SPM.3; Based on Chapter 11, Seneviratne, Zhang et al. 2021)

IPCC assessment on historical changes in agroecological droughts

"**Human-induced climate change** has contributed to increases in **agricultural and ecological droughts** in some regions due to increased land evapotranspiration (*medium confidence*)"



Dominant signal shows drying
Strong attributable signals in some regions (MED, WNA)

(IPCC AR6 SPM, Figure SPM.3; Based on Chapter 11, Seneviratne, Zhang et al. 2021)

IPCC assessment on historical changes in extremes

Region and Drought Types		Observed Trends	Detection and Attribution; Event Attribution	Projections		
				+1.5°C	+2°C	+4°C
Greenland/ Iceland (GIC) *continued*	AGR ECOL	***Low confidence**:* ***Limited evidence**,* given **limited number of studies and limited data** (Walsh et al., 2020)	***Low confidence**: **Limited evidence*** because of lack of studies	***Low confidence**: **Limited evidence*** because of lack of studies (Walsh et al., 2020) and **inconsistent** changes in soil moisture in CMIP6 (11.SM)	***Low confidence**: **Limited evidence*** because of lack of studies (Walsh et al., 2020) and **inconsistent** changes in soil moisture in CMIP6 (11.SM)	***Low confidence**: **Limited evidence*** because of lack of studies (Walsh et al., 2020) and **inconsistent** changes in soil moisture in CMIP6 (11.SM)
	HYDR	***Low confidence**:* ***Limited evidence*** given **limited number of studies and limited data** (Walsh et al., 2020)	***Low confidence**: **Limited evidence*** because of **lack of studies**	***Low confidence**: **Limited evidence*** because of **lack of studies**	***Low confidence**: **Limited evidence*** because of **lack of studies**	***Low confidence**: **Limited evidence*** because of **lack of studies**
Mediter-ranean (MED)[10]	MET	***Low confidence**:* **Mixed signals.** Observed land precipitation trends show pronounced variability within the region, with magnitude and sign of trends in the path century depending on time period (Donat et al., 2014a; Stagge et al., 2017; Mathbout et al., 2018a; Zittis, 2018). There is *low confidence* in an increase of drought frequency and severity based on SPI (Spinoni et al., 2015; Gudmundsson and Seneviratne, 2016; MedECC, 2020; Peña-Angulo et al., 2020a; Driouech et al., 2021; Vicente-Serrano et al., 2021)	***Low confidence**:* **Mixed signals.** There are mixed signals within the region and *low confidence* in human influence on meteorological drought over MED (Kelley et al., 2015; Gudmundsson and Seneviratne, 2016; Knutson and Zeng, 2018; Wilcox et al., 2018)	***Medium confidence**:* **Increase.** With *medium confidence* CMIP5 and CMIP6 show a decline in winter and summer total precipitation and increase in number of CDD (percentage precipitation change per degree of local warming is *with high confidence* larger in June–July–August (JJA) than December–January–February (DJF) (Interactive Atlas, Cardell et al., 2020; Li et al., 2021; 11.SM). Also weak increase in meteorological drought based on SPI (Touma et al., 2015; L. Xu et al., 2019)	***Medium confidence**:* **Increase.** With *medium confidence* CMIP5 and CMIP6 show a decline in winter and summer total precipitation and increase in number of CDD (percentage precipitation change per degree of local warming is *with high confidence* larger in JJA than DJF) (Interactive Atlas, Cardell et al., 2020; Li et al., 2021; 11.SM). Also weak increase in meteorological drought based on SPI (Touma et al., 2015; L. Xu et al., 2019)	***High confidence**:* **Increase.** With *high confidence* CMIP5 and CMIP6 (and EURO-CORDEX) show a decline in winter and summer total precipitation and increase in number of CDD. Drought intensity and frequency increase with *high confidence*, particularly in the southern Mediterranean (11.SM; Interactive Atlas; Samuels et al., 2018; Cardell et al., 2020; Cook et al., 2020; Driouech et al., 2020; Spinoni et al., 2020; Coppola et al., 2021a; Li et al., 2021)
	AGR ECOL	***Medium confidence**:* **Increase.** Increases in probability and intensity of agricultural and ecological droughts based on soil moisture and water-balance deficits, but weakers signals in some studies (Greve et al., 2014; Hanel et al., 2018; García-Herrera et al., 2019; Moravec et al., 2019; Padrón et al., 2020; Markonis et al., 2021).	***Medium confidence**:* of attribution of **increasing** trend in ecological and agricultural drought, based on soil moisture and water-balance metrics (Mariotti et al., 2015; García-Herrera et al., 2019; Marvel et al., 2019; Padrón et al., 2020) García-Herrera et al. (2019): Attribution of the 2016–2017 drought in southwestern Europe to climate change based on NCEP trends in soil moisture for weather anologues to 2016–2017 event	***Medium confidence**:* Drought **increase** for pre-industrial and recent past baselines **Recent past baseline:** Decreasing soil water availability during drought events compared to 1971–2000, even when accounting for adaptation to mean conditions (Samaniego et al., 2018) Increasing drought duration and frequency compared to 1971–2000 (L. Xu et al., 2019)	***High confidence**:* Drought **increase** for pre-industrial and recent past baselines **Recent past baseline:** Decreasing soil water availability during drought events compared to 1971–2000, even when accounting for adaptation to mean conditions; about twice larger signal compared to response at +1.5°C (Samaniego et al., 2018)	***Very likely**:* **Drought increase** for pre-industrial and recent past baselines **Recent past baseline:** Based on projections at +3°C: Large decreasing soil water availability during drought events compared to 1971–2000, even when accounting for adaptation to mean conditions; more than three times larger signal compared to response at +1.5°C (Samaniego et al., 2018)

11

Weather and Climate Extreme Events in a Changing Climate

Coordinating Lead Authors:
Sonia I. Seneviratne (Switzerland), Xuebin Zhang (Canada)

Lead Authors:
Muhammad Adnan (Pakistan), Wafae Badi (Morocco), Claudine Dereczynski (Brazil), Alejandro Di Luca (Australia/Canada/Argentina), Subimal Ghosh (India), Iskhaq Iskandar (Indonesia), James Kossin (United States of America), Sophie Lewis (Australia), Friederike Otto (United Kingdom/Germany), Izidine Pinto (South Africa/Mozambique), Masaki Satoh (Japan), Sergio M. Vicente-Serrano (Spain), Michael Wehner (United States of America), Botao Zhou (China)

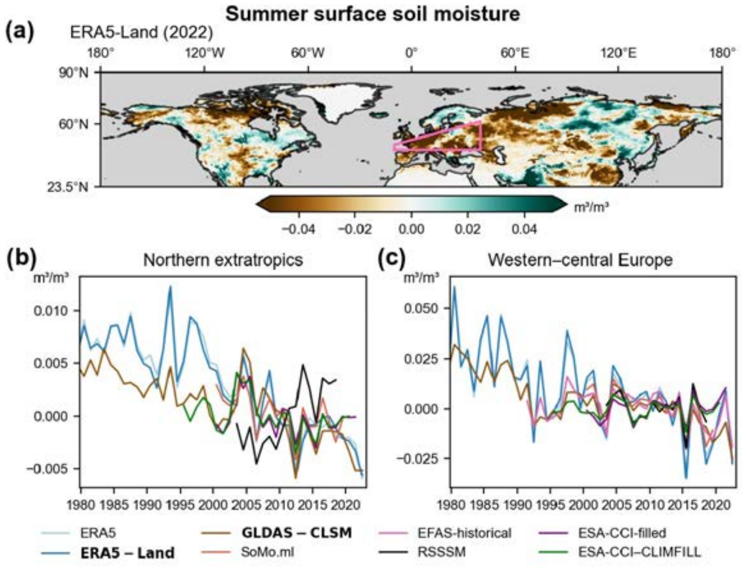
“Large tables” in Chapter 11, pages 1613-1705

(Seneviratne, Zhang, et al. 2021)

Attribution of drought trends in West-Central Europe

Detecting the human fingerprint in the summer 2022 western–central European soil drought

Dominik L. Schumacher[1], Mariam Zachariah[2], Friederike Otto[2], Clair Barnes[2], Sjoukje Philip[3], Sarah Kew[3], Maja Vahlberg[4], Roop Singh[4], Dorothy Heinrich[4], Julie Arrighi[4,5,6], Maarten van Aalst[4,6,7], Mathias Hauser[1], Martin Hirschi[1], Verena Bessenbacher[1,18], Lukas Gudmundsson[1], Hiroko K. Beaudoing[8,9], Matthew Rodell[8], Sihan Li[10], Wenchang Yang[11], Gabriel A. Vecchi[11,12], Luke J. Harrington[13], Flavio Lehner[14,15,17], Gianpaolo Balsamo[16], and Sonia I. Seneviratne[1]



(Schumacher et al. 2024, ESD)

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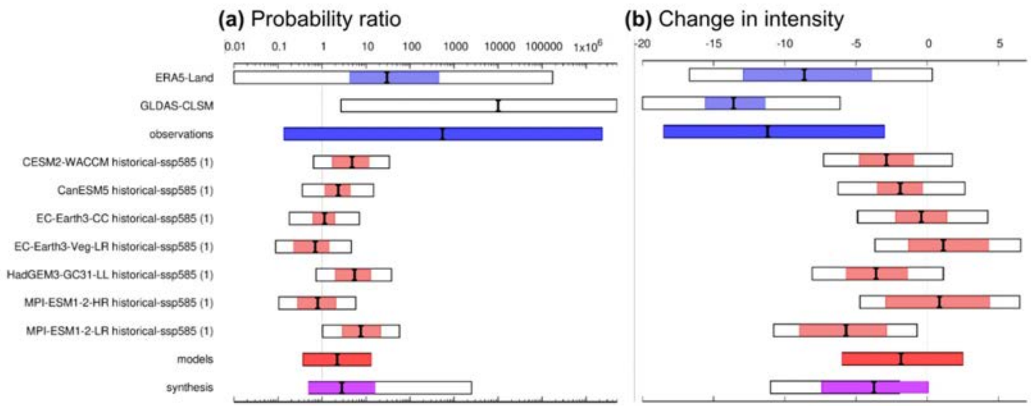
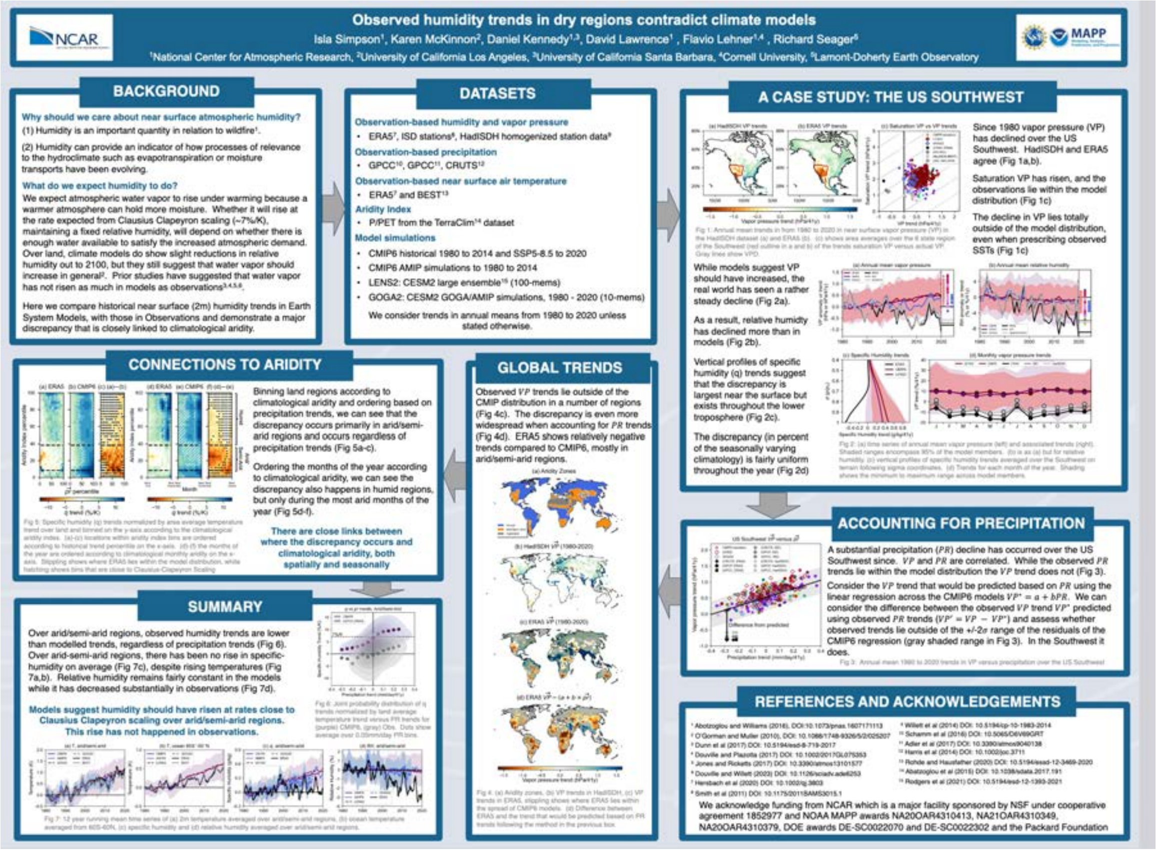


Figure 6. Synthesis for WCE root zone soil moisture. Synthesized **(a)** probability ratios and **(b)** intensity changes (%) when comparing the return period and magnitudes of the 2022 summer root zone soil moisture for the WCE region in the current climate and a 1.2 °C cooler climate. Note that while the employed observation-based products are restricted to 1950–2022, for models we make use of the additional available data for the statistical analysis (1850–2022).

NB: ESMs appear to underestimate the observed drying signal!

(Schumacher et al. 2024, ESD)

Droughts: Discrepancies between ESMs and observations



Is the ESM-obs discrepancy in atmospheric drying in West-Central Europe part of a global feature?

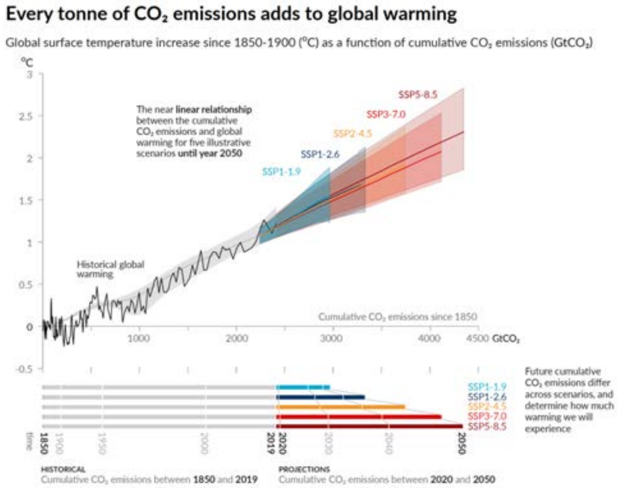
(See poster of Isla Simpson “Observed humidity trends in dry regions contradict climate models)

(see also: Douville and Piazzota 2017, GRL)

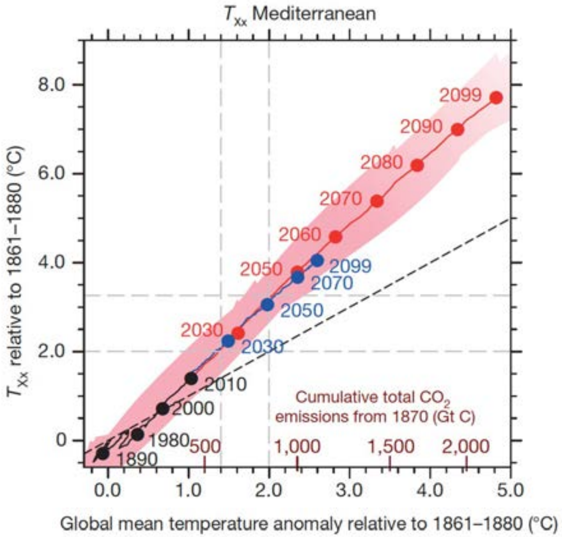
(Schumacher et al. 2024, ESD)

Could climate change turn worse than we expected?

- Yes, possibly
- There are uncertainties in climate models, and these increase when we move further away from known climate conditions
- **Models behave very linearly** and this is so far consistent with observations, but **what is the potential for tipping points**?
- Literature *(IPCC AR6, Armstrong MacKay et al. 2022, Science)* shows increasing risks of hitting tipping points with increasing global warming, with higher risks above 1.5°C-2°C



(IPCC AR6 WG1)



(Seneviratne et al. 2016, Nature)

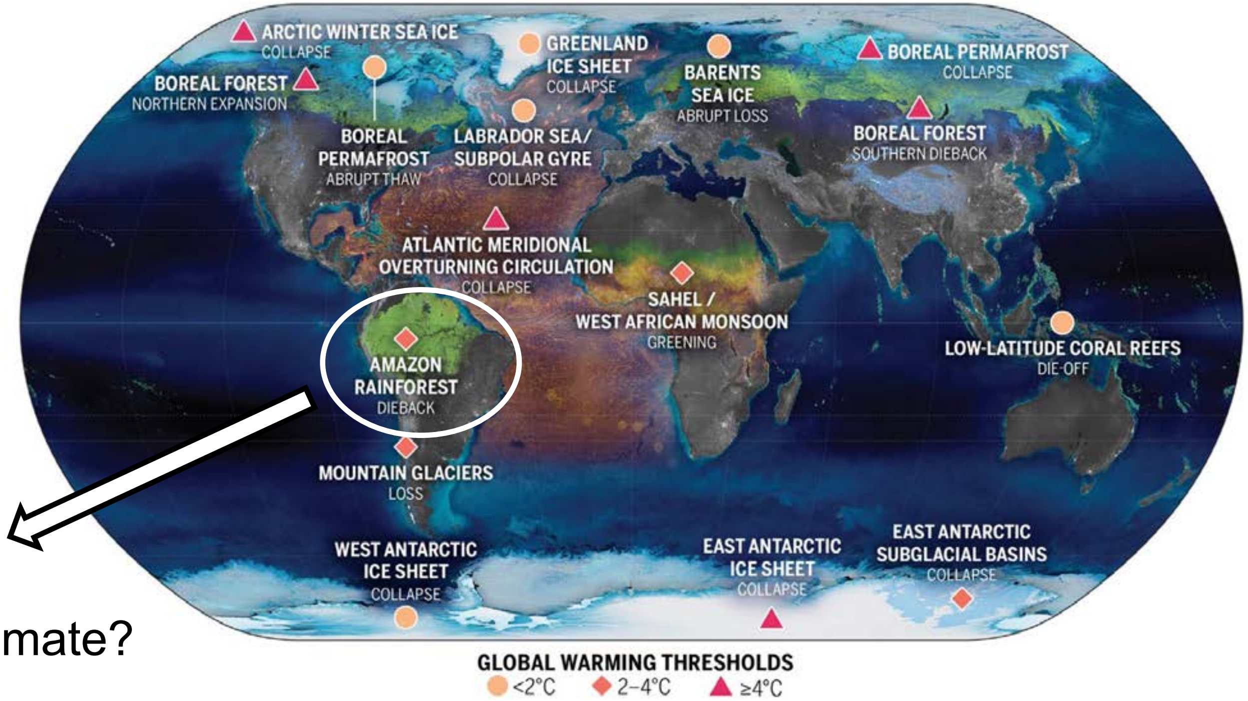
Could climate change turn worse than we expected?

RESEARCH ARTICLE SUMMARY

CLIMATE CHANGE

Exceeding 1.5°C global warming could trigger multiple climate tipping points

David I. Armstrong McKay*, Arie Staal, Jesse F. Abrams, Ricarda Winkelmann, Boris Sakschewski, Sina Loriani, Ingo Fetzer, Sarah E. Cornell, Johan Rockström, Timothy M. Lenton*



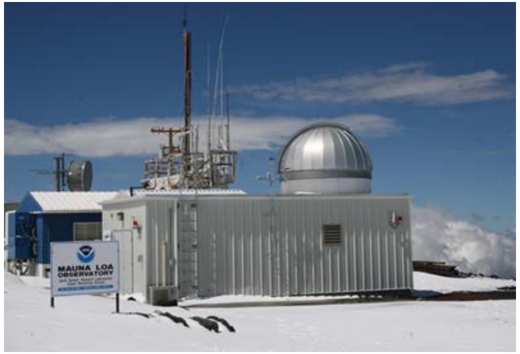
Maybe too optimistic estimate?

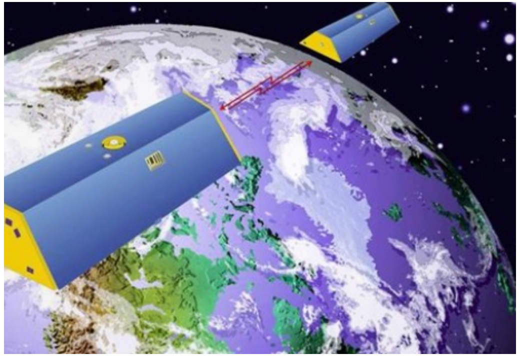
(Armstrong McKay et al. 2022, Science)

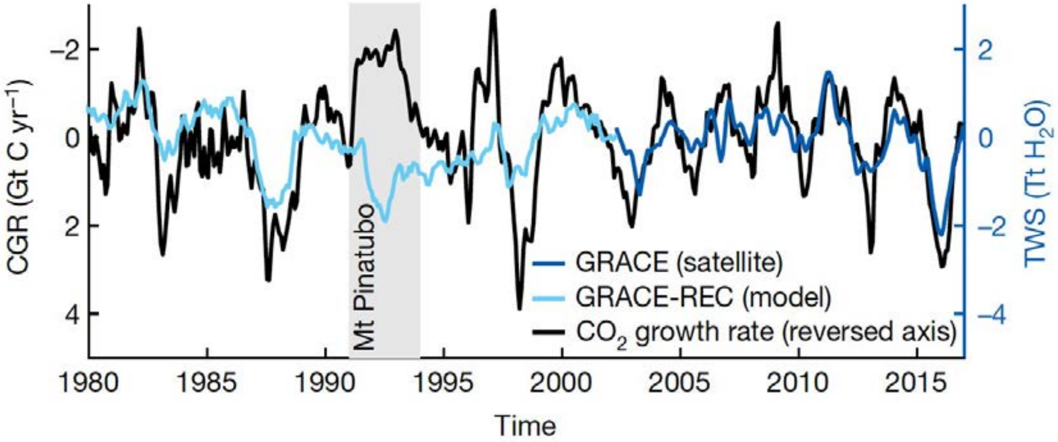
Effects of soil moisture/droughts on global carbon cycle

Comparing anomalies in global observations of:

- CO_2 growth rate from atmospheric observations
- Terrestrial water storage from GRACE satellites



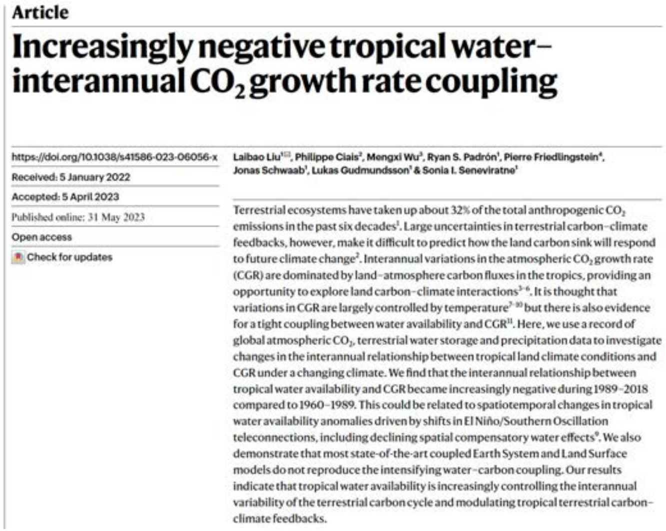




(Humphrey et al. 2018, Nature)

Could climate change turn worse than we expected?

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



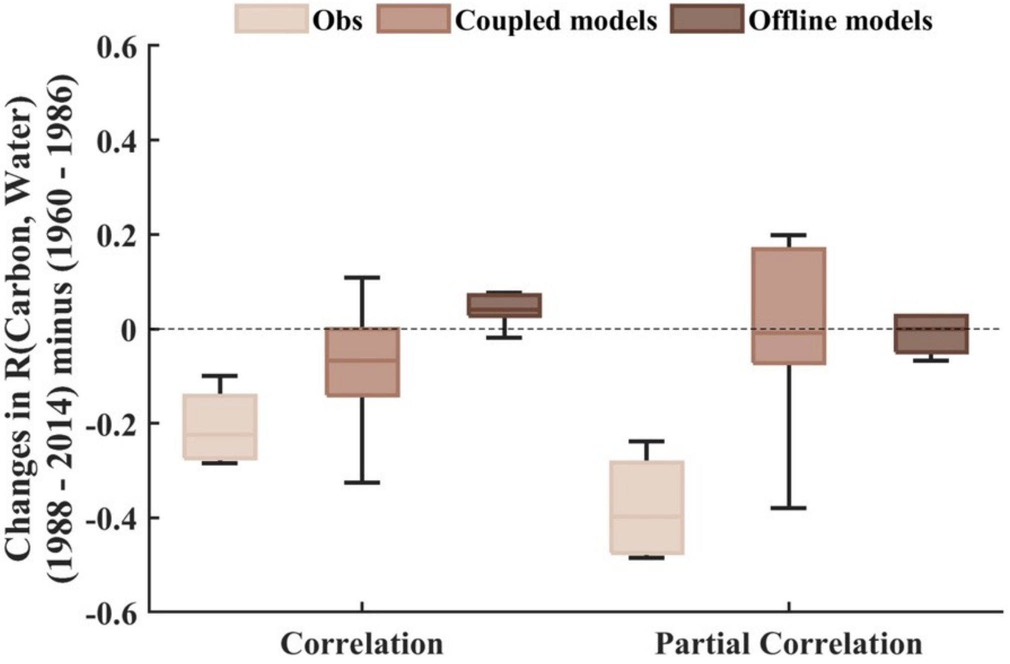
Article

Increasingly negative tropical water–interannual CO_2 growth rate coupling

https://doi.org/10.1038/s41586-023-06056-x
Received: 5 January 2022
Accepted: 5 April 2023
Published online: 31 May 2023
Open access
Check for updates

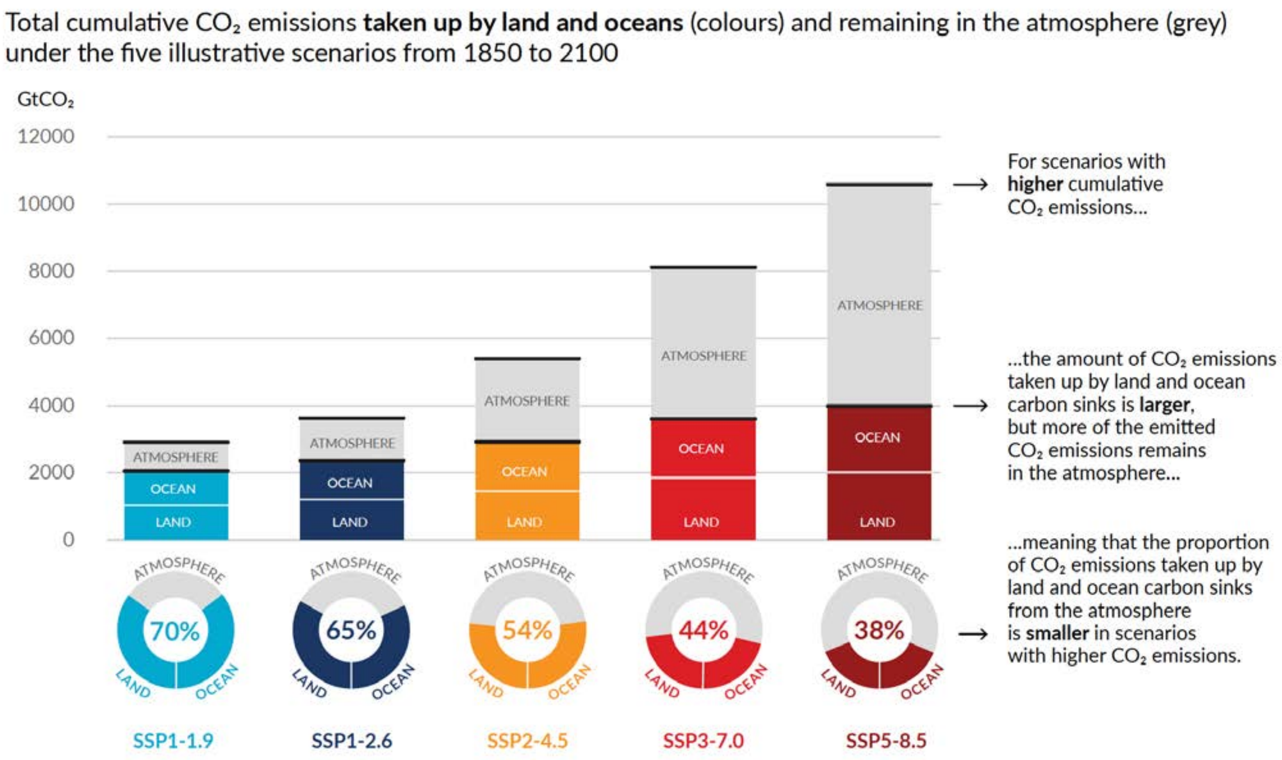
Laibao Liu[1]✉, Philippe Ciais[2], Mengxi Wu[3], Ryan S. Padrón[1], Pierre Friedlingstein[4], Jonas Schwaab[1], Lukas Gudmundsson[1] & Sonia I. Seneviratne[1]

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; see also Humphrey et al. 2018, Nature)

Could climate change turn worse than we expected?



Could the land carbon sink become even less effective with increasing global warming?

IPCC AR6, Figure SPM.7

Land-based carbon dioxide removal vs extremes

- Afforestation
- Bioenergy with carbon capture and storage

- How about extremes? (generally not included in integrated assessments models deriving emissions scenarios); could be too optimistic
  (see poster of Felix Jaeger; fire biases in ESMs: see Sanderson and Fisher, 2020)

Confronting ESMs with observations:

- Observational uncertainties
- Separating sources of biases (forcing; thermodynamic vs dynamic biases)

Drought-climate feedbacks

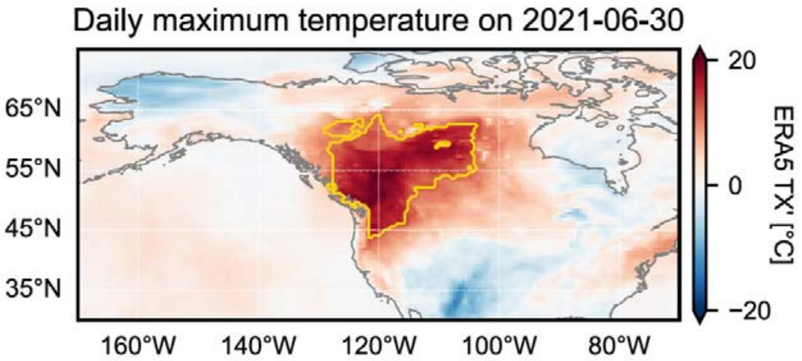
- Relevant processes
- Drought trends in ESMs vs observations
- Potential biases in global drought-carbon feedbacks

Some open questions

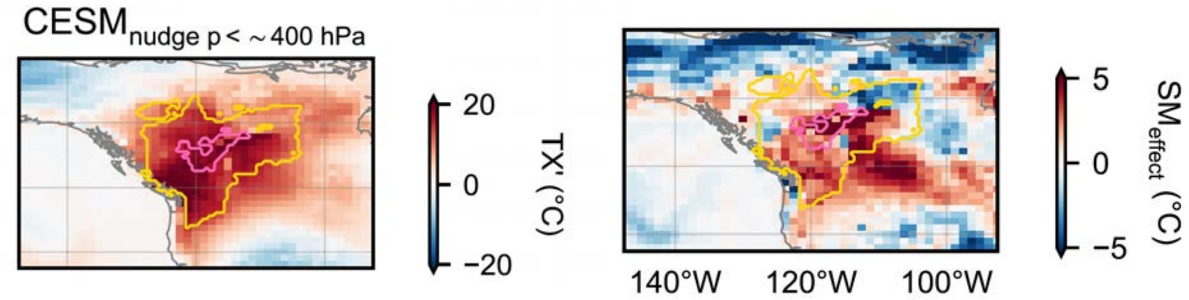
- Drought relevance for record-shattering heatwaves
- 2023 Record temperatures

Conclusions

2021 Pacific Northwest Heatwave: Role of initial dry soils



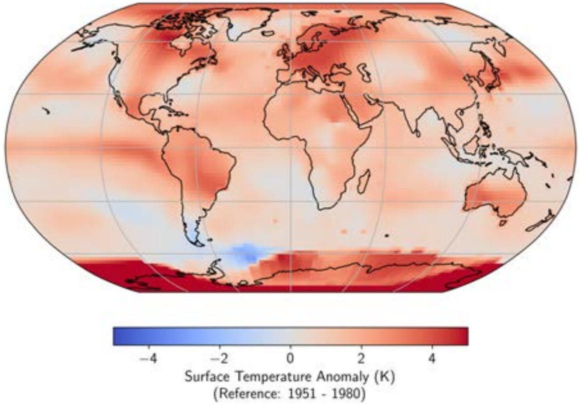
What does it imply for climate projections of heat extremes, in particular record-shattering heatwaves, if drought trends are underestimated in ESMs?



Soil moisture anomalies contributed up to 5ºC to the heatwave!

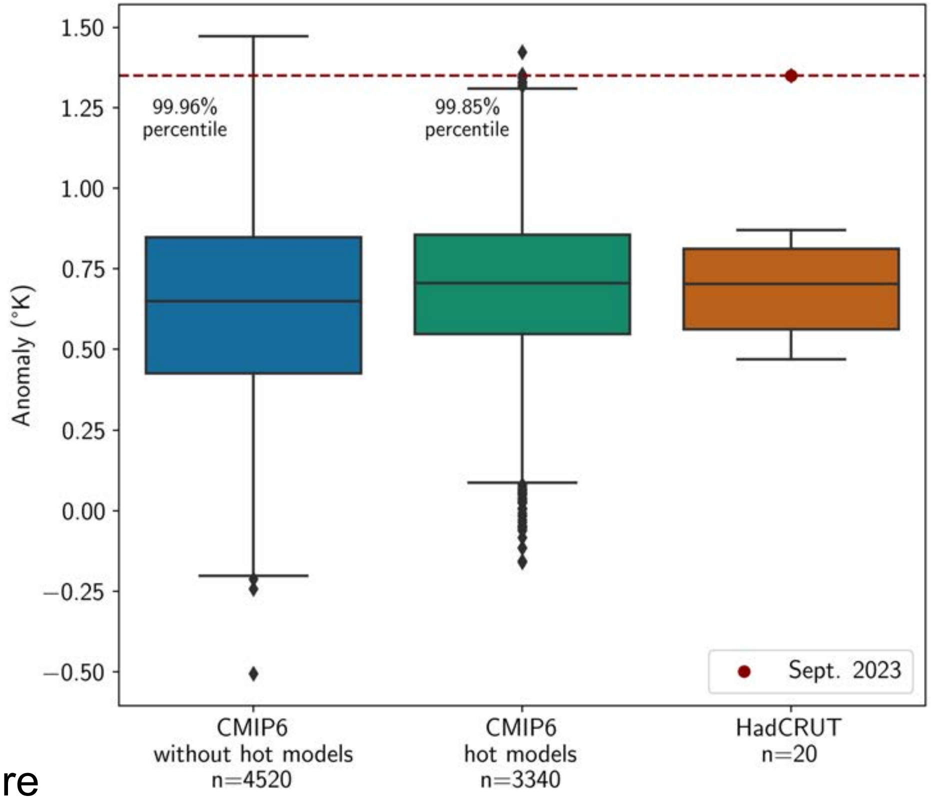
(Schumacher et al. 2022, Earth’s Future)

Is the September 2023 heat anomaly consistent with ESMs?



Data source:
GISTEMP v4

Clear anomaly in observations, very low probability in available ESMs, often 0% probability.
NB: “Hot models” do not capture the anomaly better & soil moisture-termperature feedbacks may have played a role



(Seeber et al., in preparation)

Conclusions

- **Confronting ESMs with observations requires consideration of several dimensions:**
  - Observational uncertainty
  - Internal climate variability in ESMs
  - Isolating sources of biases (e.g. thermodynamics vs dynamics, atmosphere vs land vs ocean, forcing):
    - Factorial experiments replacing some elements with observations or assessing potential spread can help identify the root causes for biases

- **Some biases in representation of droughts-climate feedbacks in ESMs:**
  - Implications for attribution and projections (also for heatwaves and global carbon cycle, including potential tipping points)
  - Need to better understand possible underlying causes (in particular land-atmosphere interactions)
  - Are the latest 2023-2024 observations consistent with ESMs?

Contact: sonia.seneviratne@ethz.ch