Critical Transitions in the Earth System

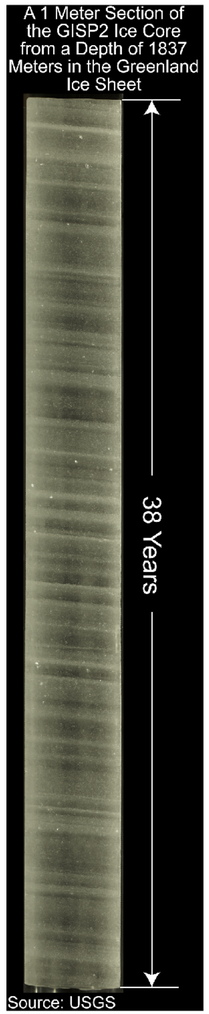
N. Boers, S. Bathiany, N. Bochow, M. Ben-Yami, L. Blaschke, M. Ghil, D. Nian, K. Riechers, T. Smith, T. Stocker

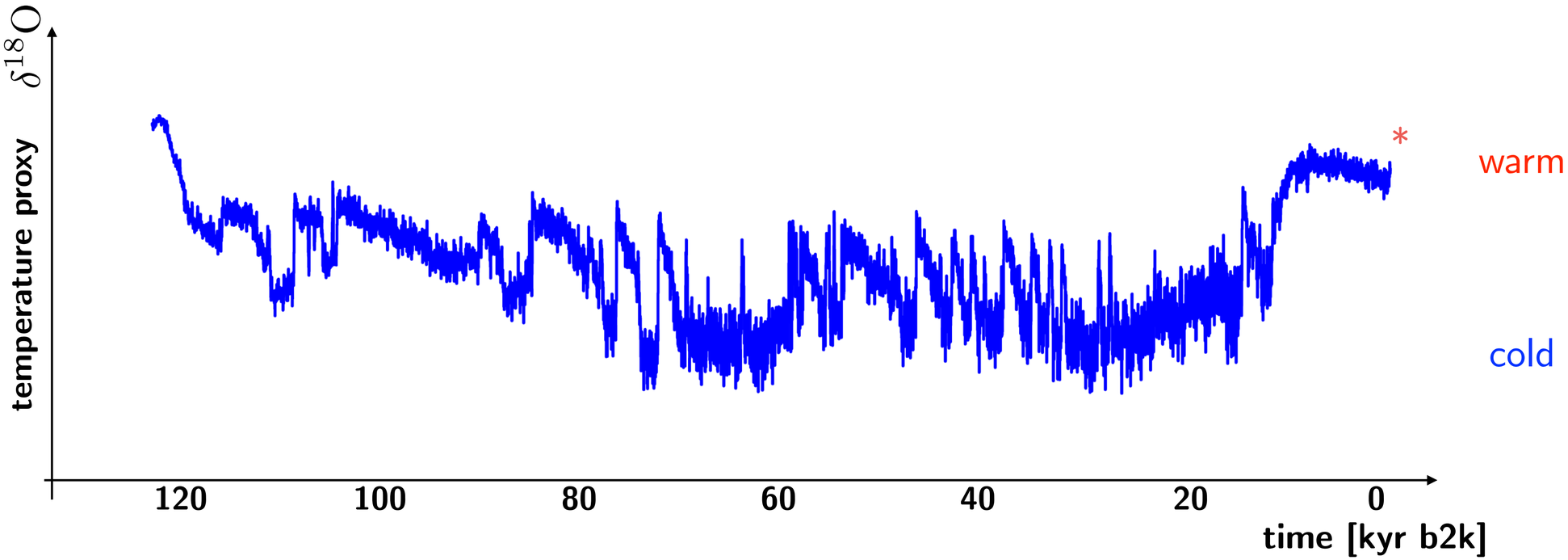
Tipping Point Workshop, IHP Paris, Oct 4 2023

Horizon 2020
European Union funding
for Research & Innovation

Critical transitions in the Earth system: paleoclimate evidence

Paleoclimate proxy records give the only empirical evidence for abrupt climate changes



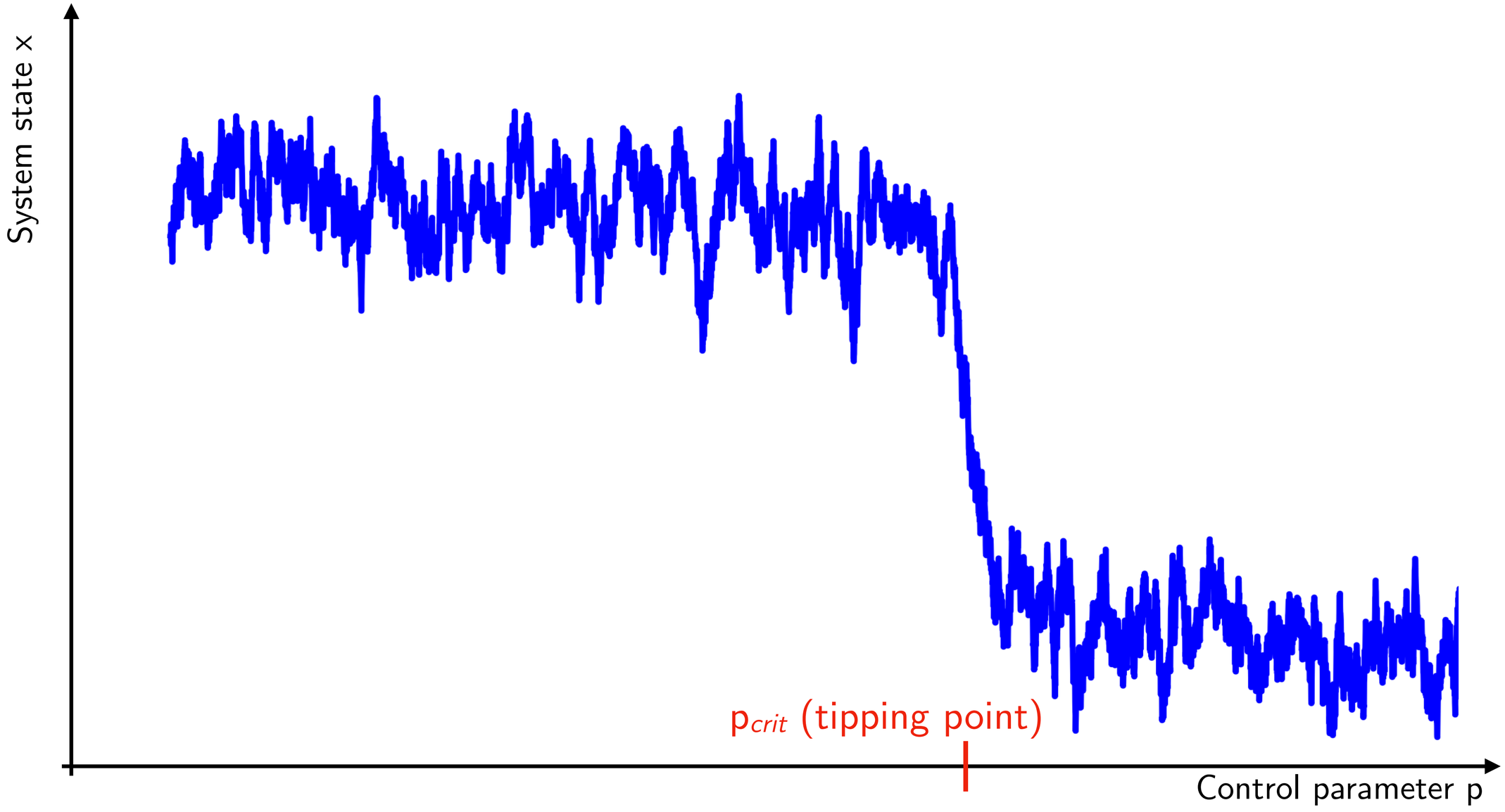


Dansgaard-Oeschger events - archetype of abrupt climate changes

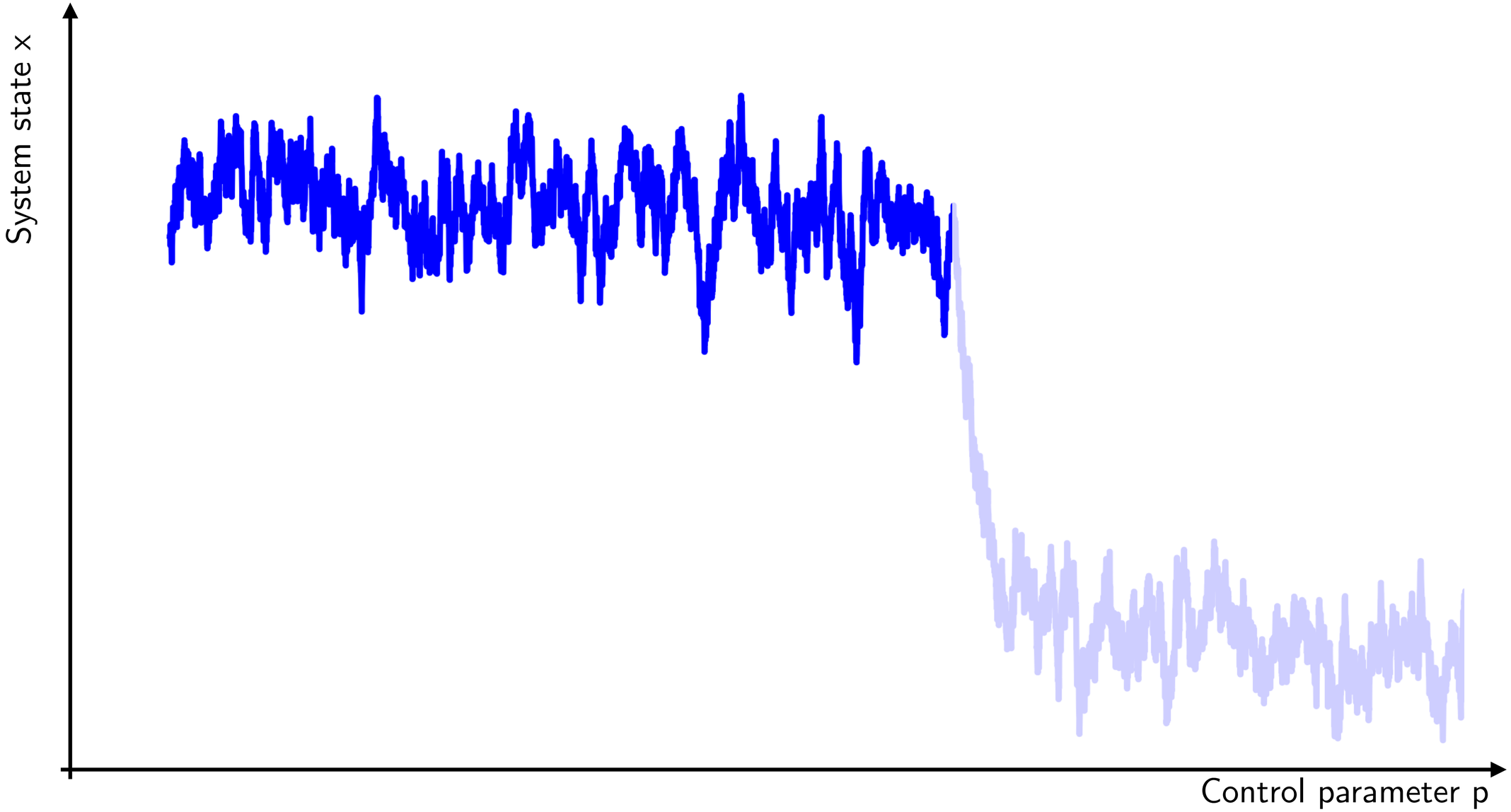
*Rapid 'temperature' jumps by **up to 16.5° within a few decades** during the last glacial ...*

Boers, Ghil, Stocker, ERL 2022

Critical transitions and ‘slowing down’



Critical transitions and ‘slowing down’



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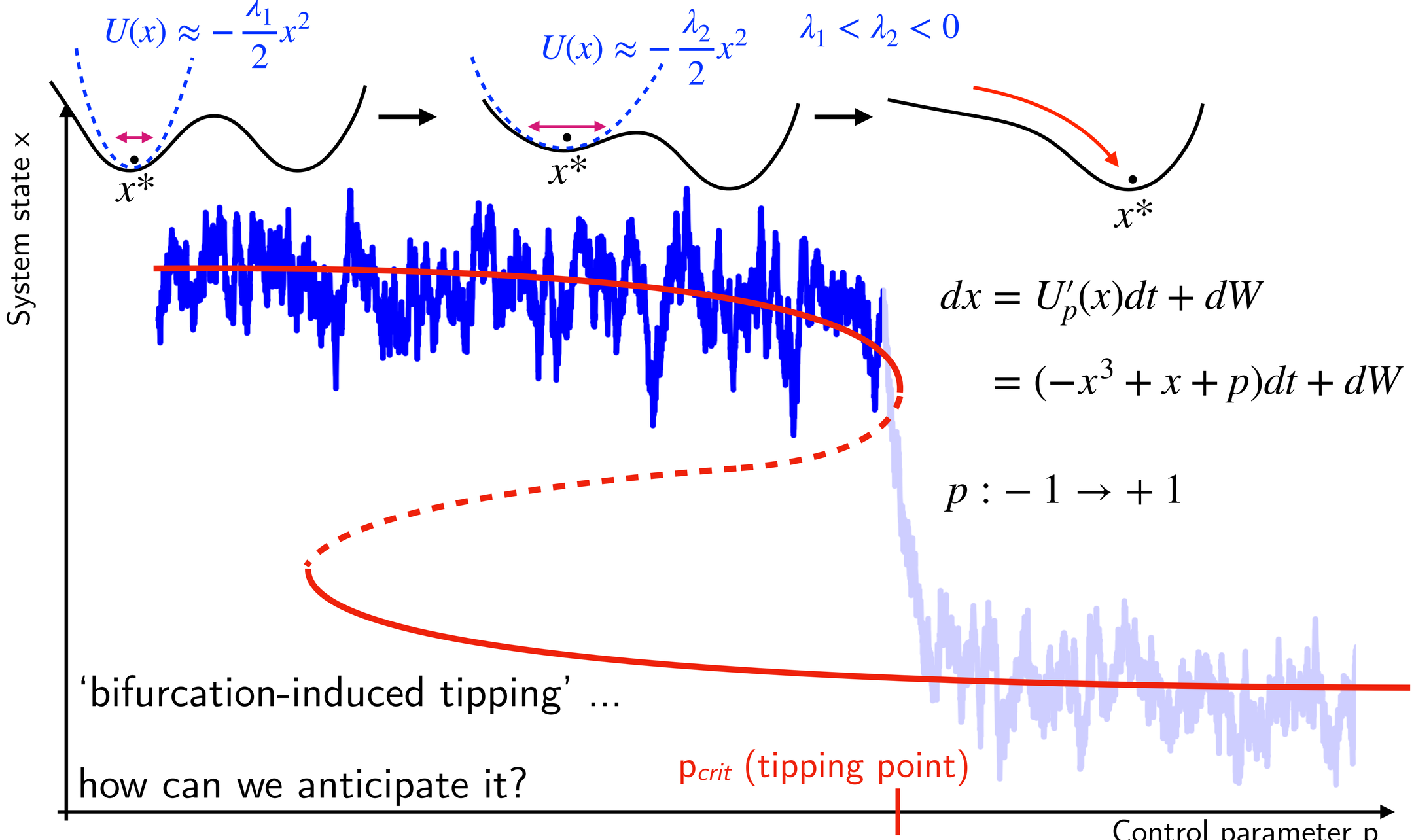

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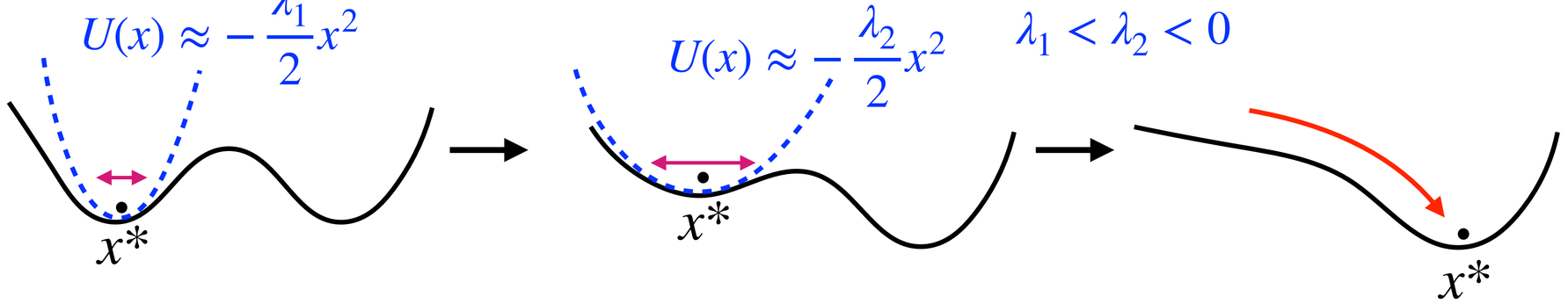


Linearization around x^* gives an Ornstein-Uhlenbeck process $dx \approx \lambda x dt + \sigma dW$; discretizing then gives an AR process $x_{n+1} = \alpha(1)x_n + \tilde{\sigma}\epsilon(t)$, $\epsilon(t) \sim \mathcal{N}(0,1)$ with

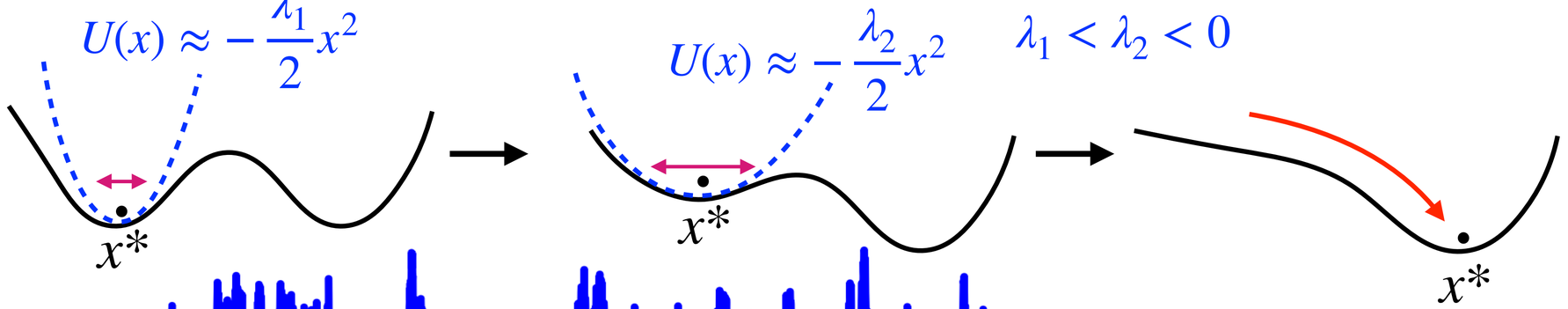
Variance	$\langle \Delta x^2 \rangle = \frac{\tilde{\sigma}^2}{1 - e^{2\lambda \Delta t}} = -\frac{\sigma^2}{2\lambda}$	$\xrightarrow{\lambda \to 0} +\infty$
Autocorrelation	$\alpha(n) = e^{n\lambda \Delta t}$	$\xrightarrow{\lambda \to 0} +1$

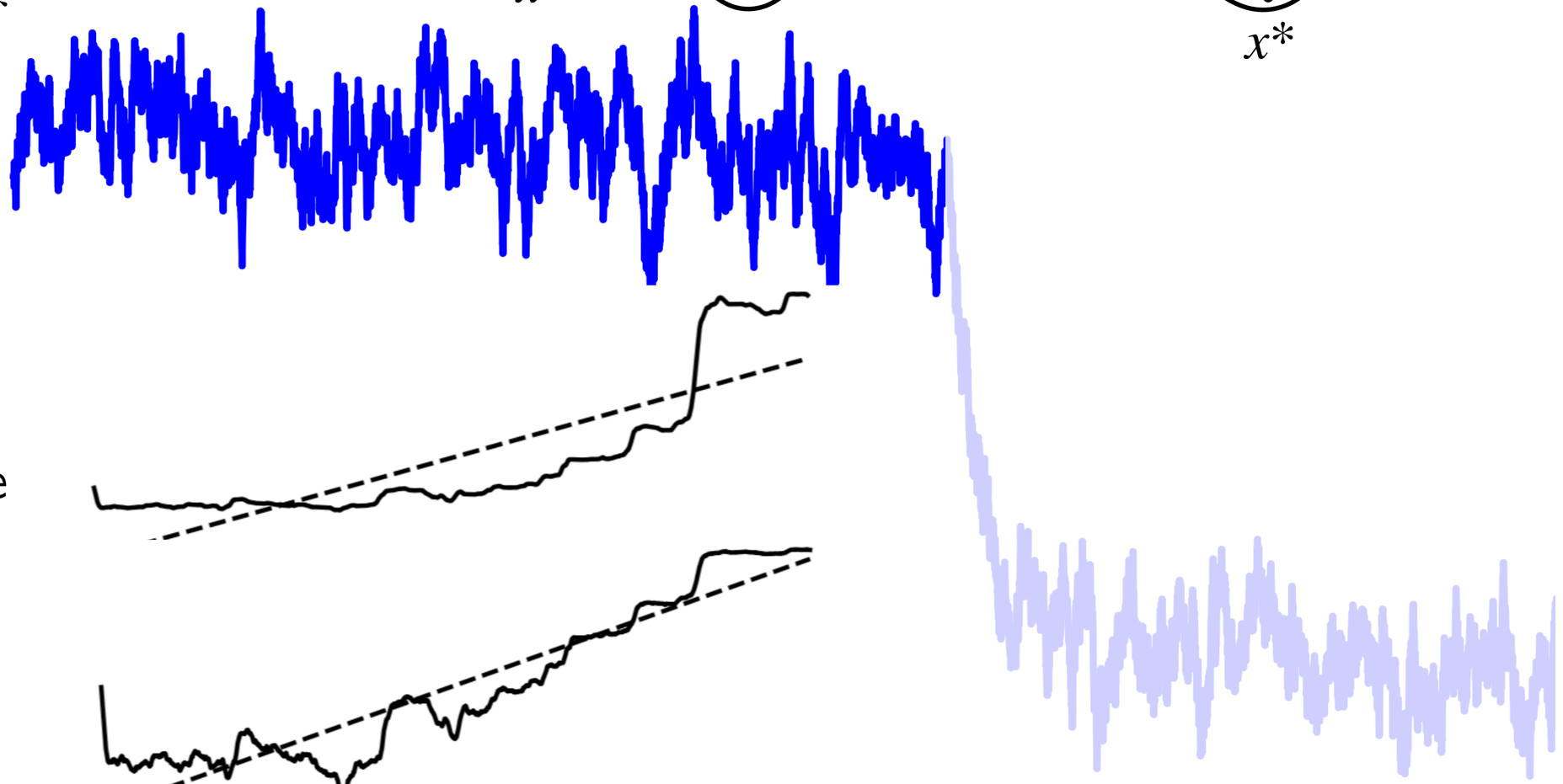
$$\tilde{\sigma}^2 = -\frac{\sigma^2}{2\lambda}(1 - e^{2\lambda \Delta t}) \approx \sigma^2 \Delta t$$

'Critical Slowing Down' **'Early-warning signs'**

Callen & Welton 1951; Kubo 1966; Dakos et al., 2008; Scheffer et al., 2009; Lenton et al., 2012

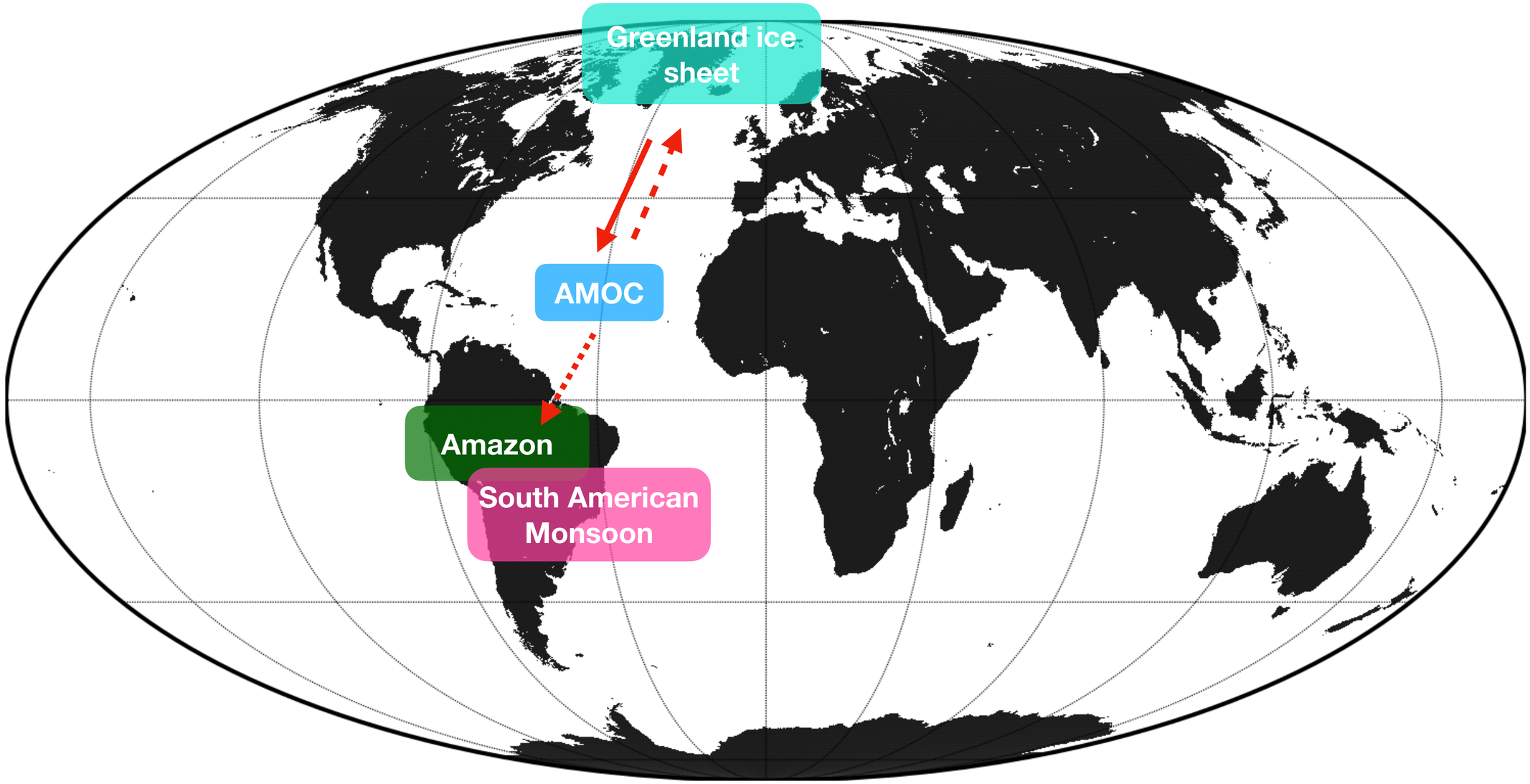
Critical transitions and 'slowing down'



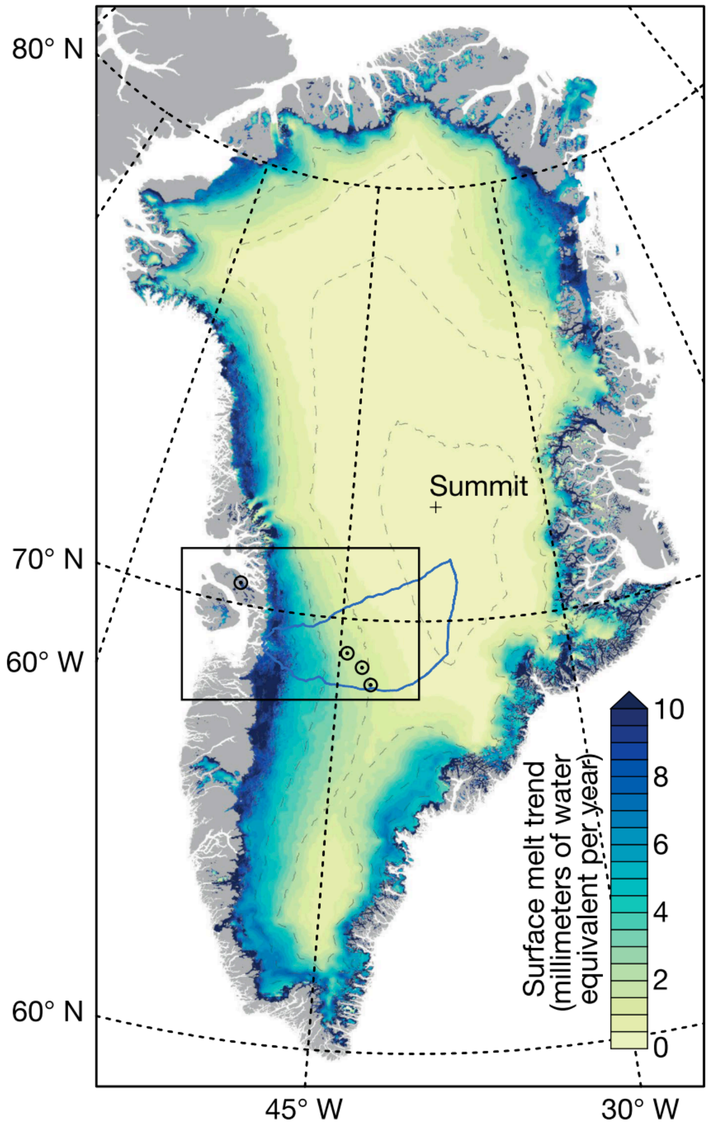


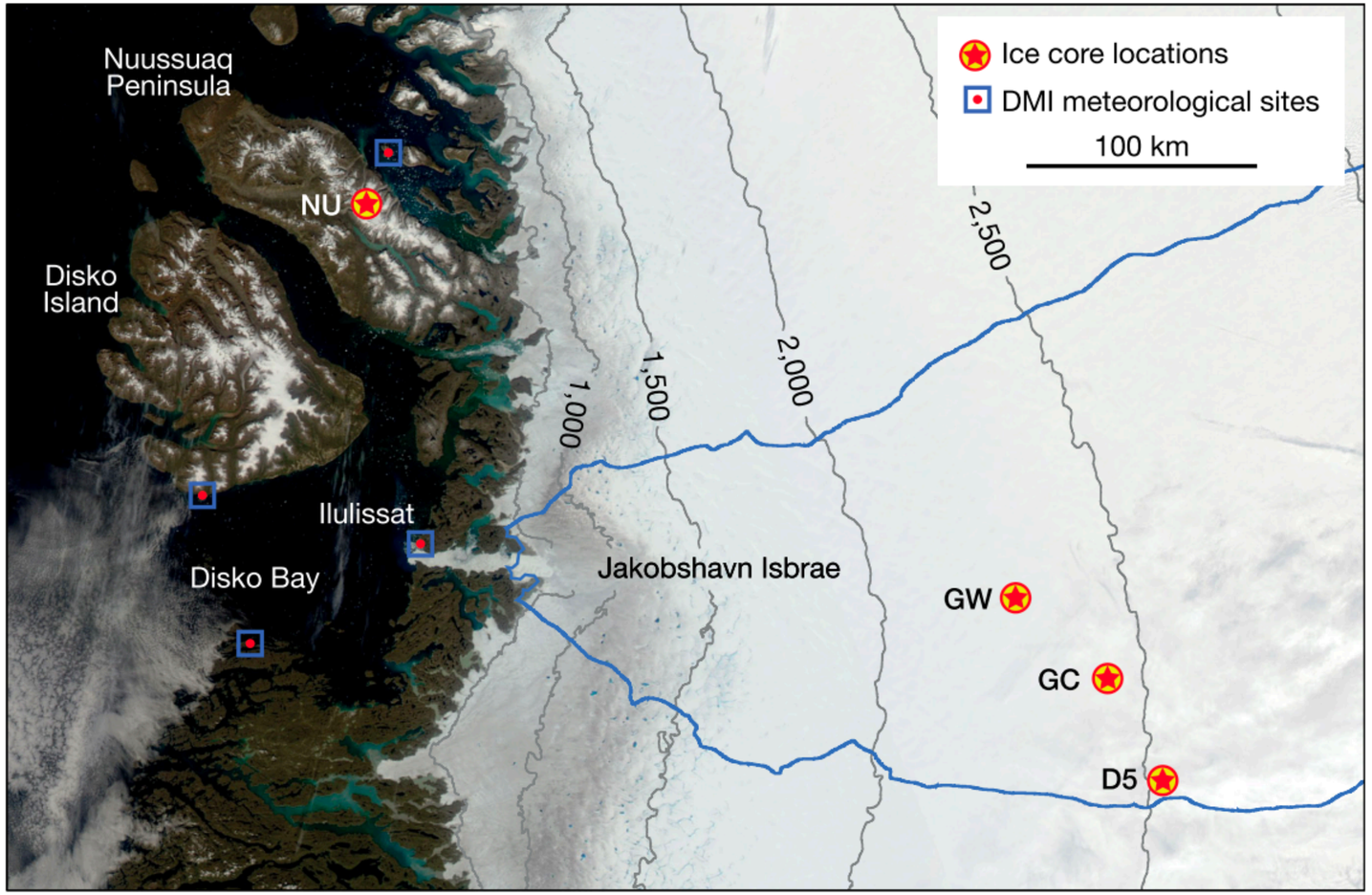
Callen & Welton 1951; Kubo 1966; Dakos et al., 2008; Scheffer et al., 2009; Lenton et al., 2012

Four key multistable, coupled Earth system components



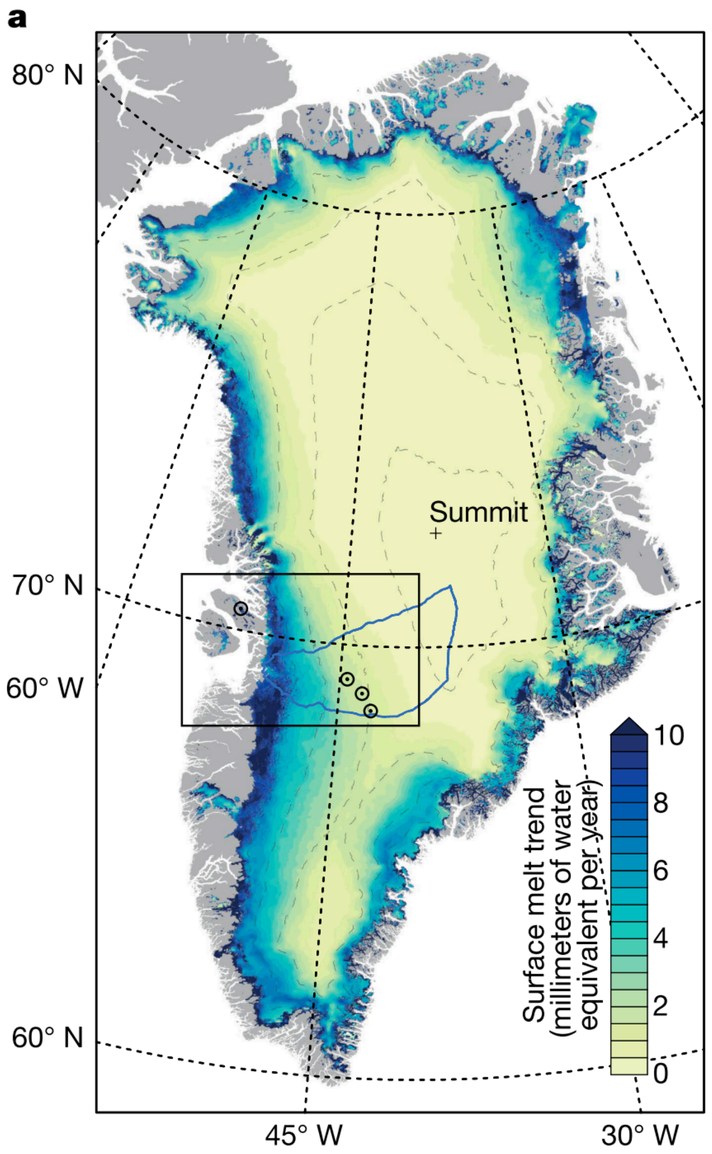
Central-Western Greenland Ice Sheet



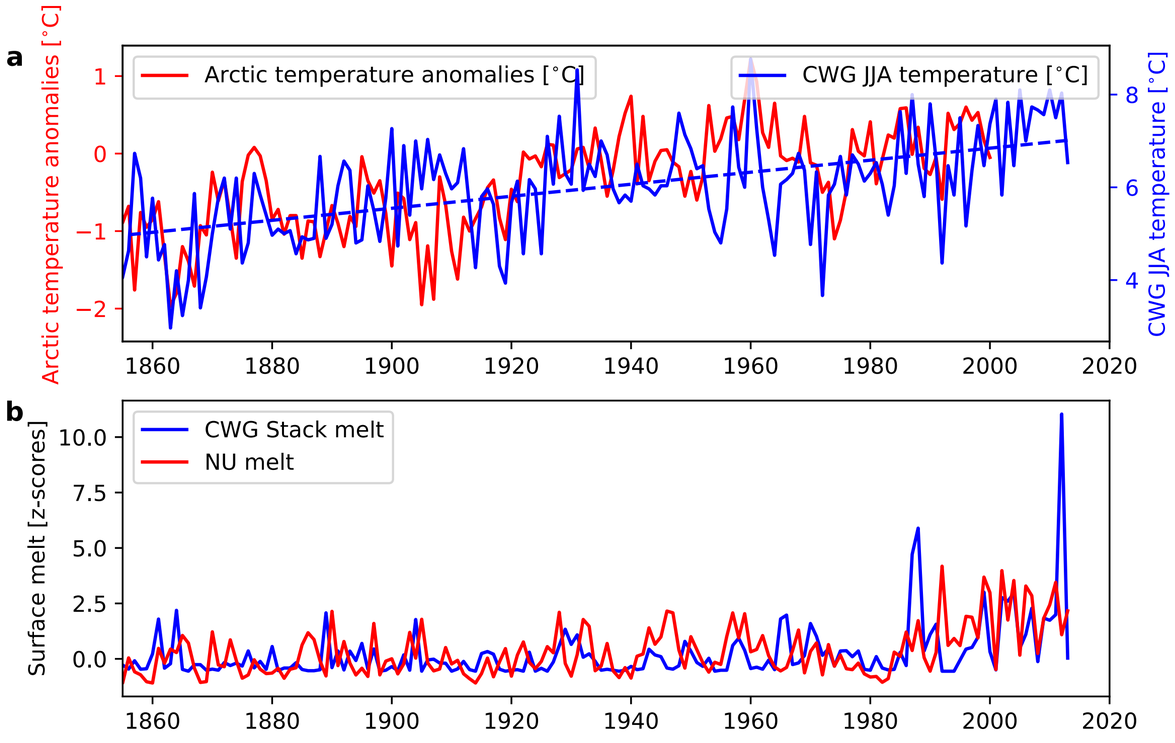


Trusel et al., Nature 2018

Central-Western Greenland Ice Sheet



Arctic and CW Greenland sea-level temperatures

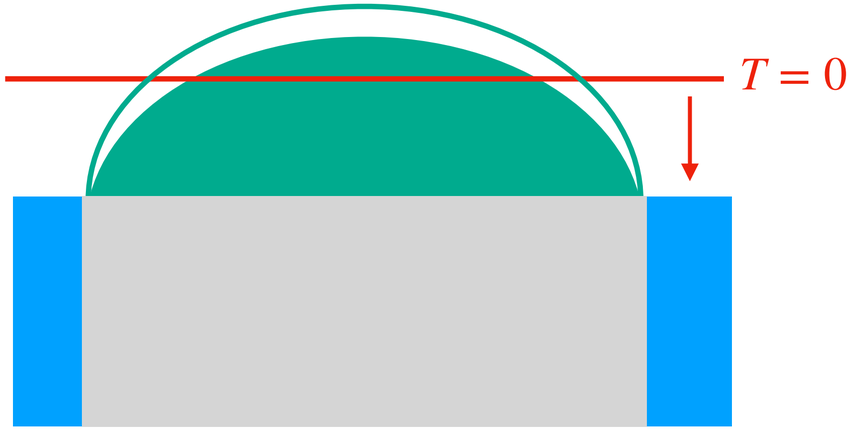


ice-core-derived melt rates from Jakobshavn drainage basin (>2000 m a.s.l.)

Trusel et al., Nature 2018; B & Rypdal, PNAS 2021

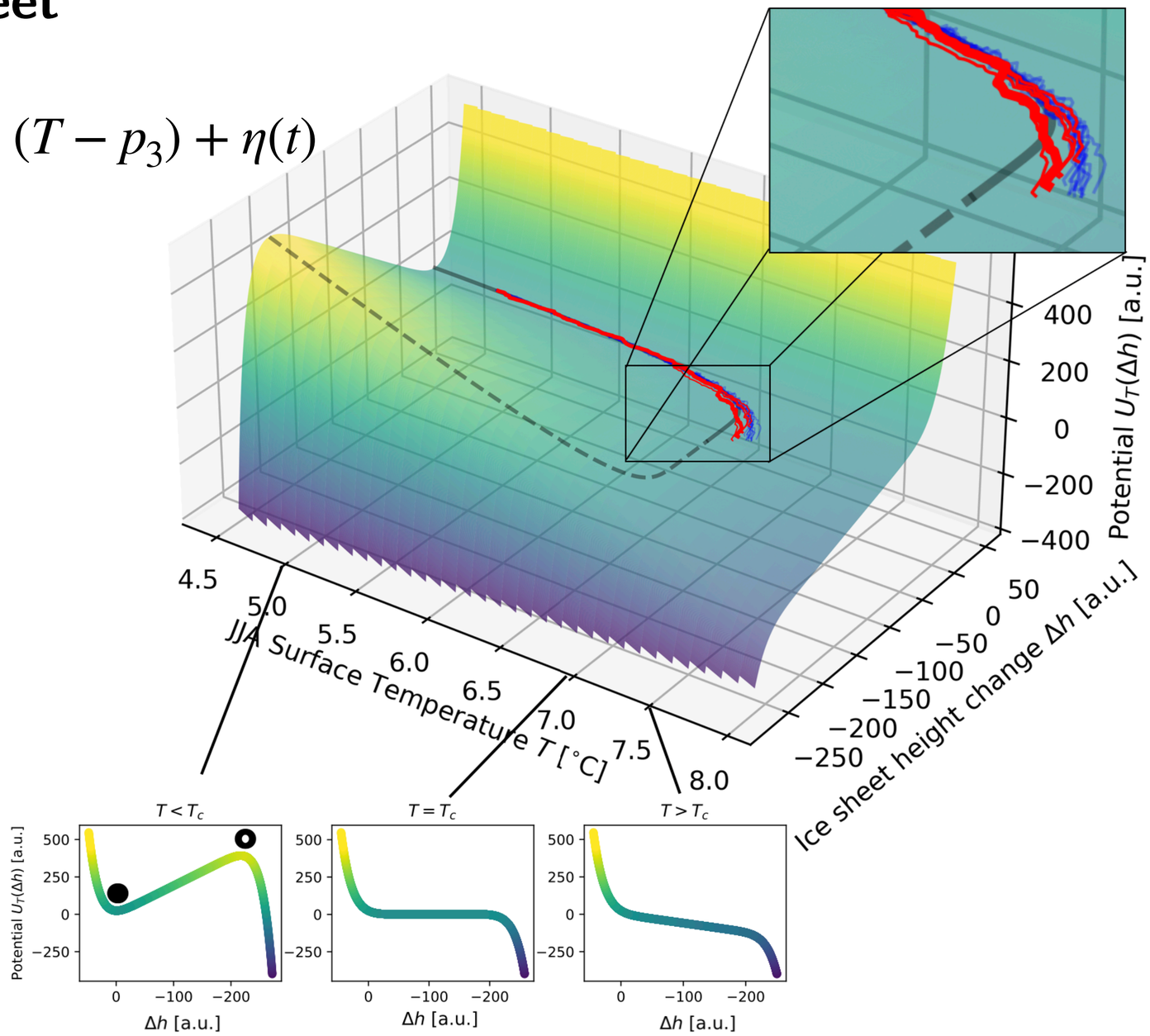
Central-Western Greenland Ice Sheet

$$C\frac{d\Delta h}{dt} = -p_0(\Delta h^8 - p_1) + p_2(\Delta h - p_1) - (T - p_3) + \eta(t)$$



+ feedbacks: MEF, albedo, snowline migration, outlet glacier thinning, firn-refreezing

— feedbacks: P-T feedback, changing circulation with decreasing height



Levermann & Winkelmann, TC 2016; B & Rypdal, PNAS 2021

Greenland Ice Sheet

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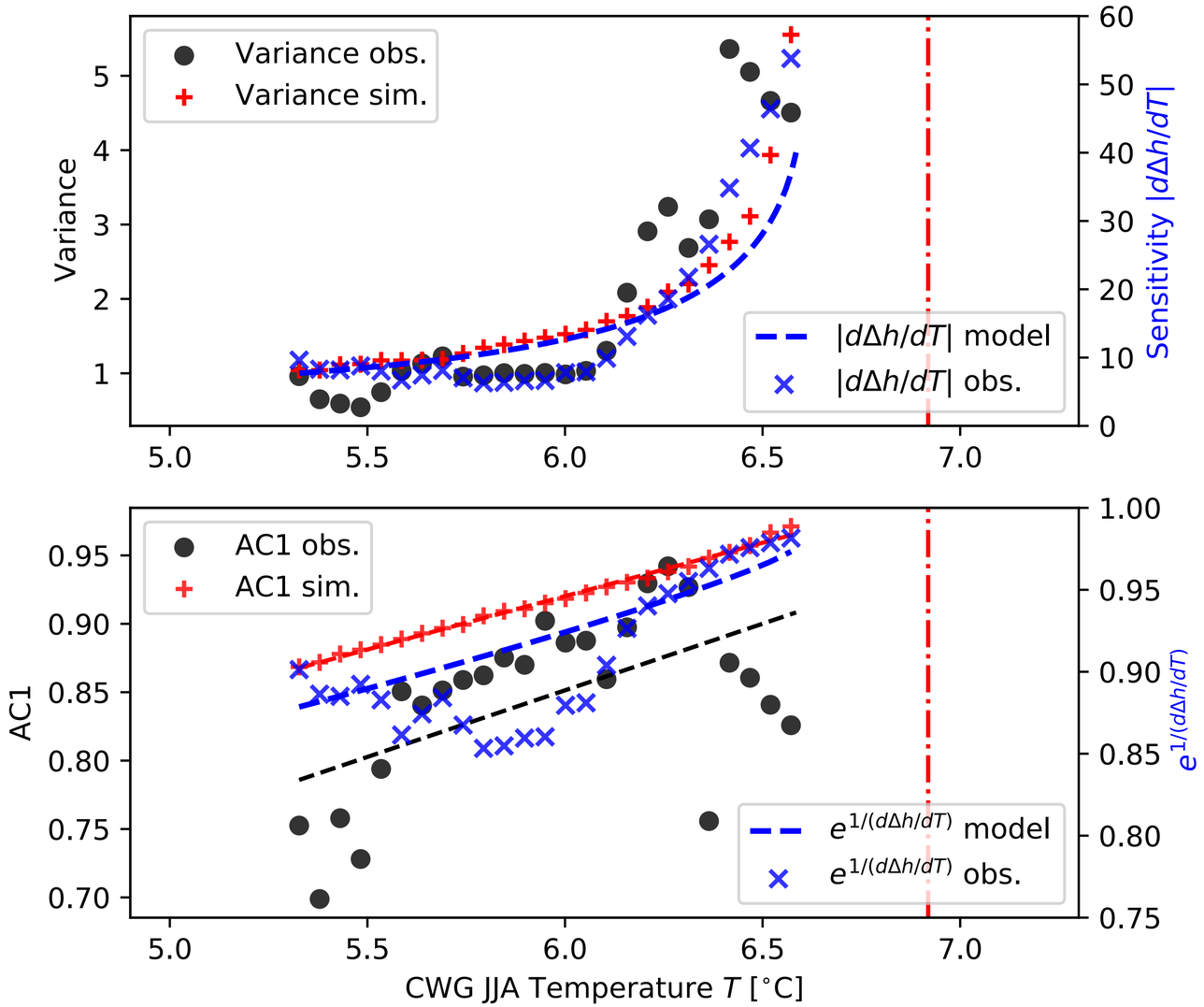
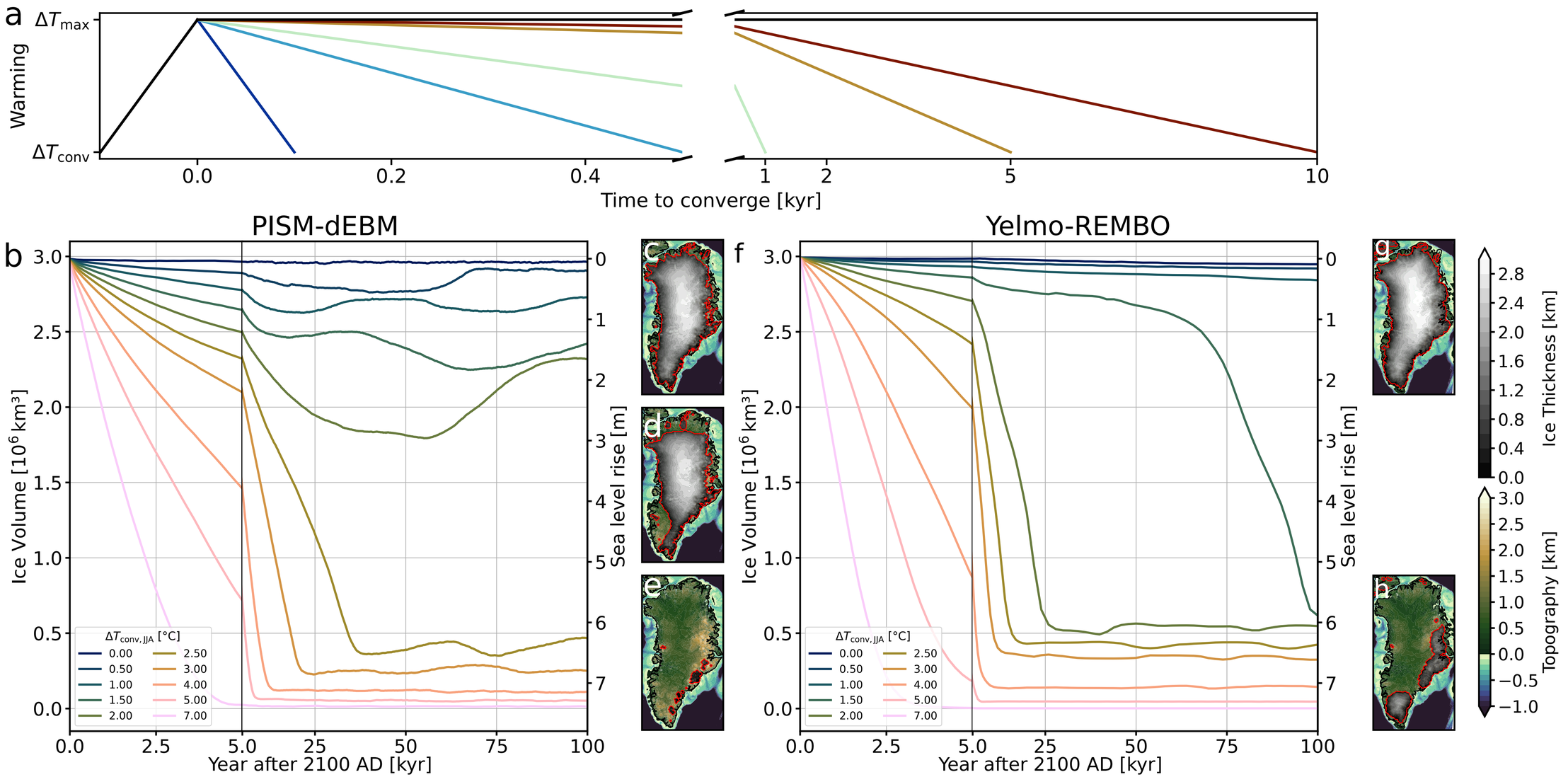


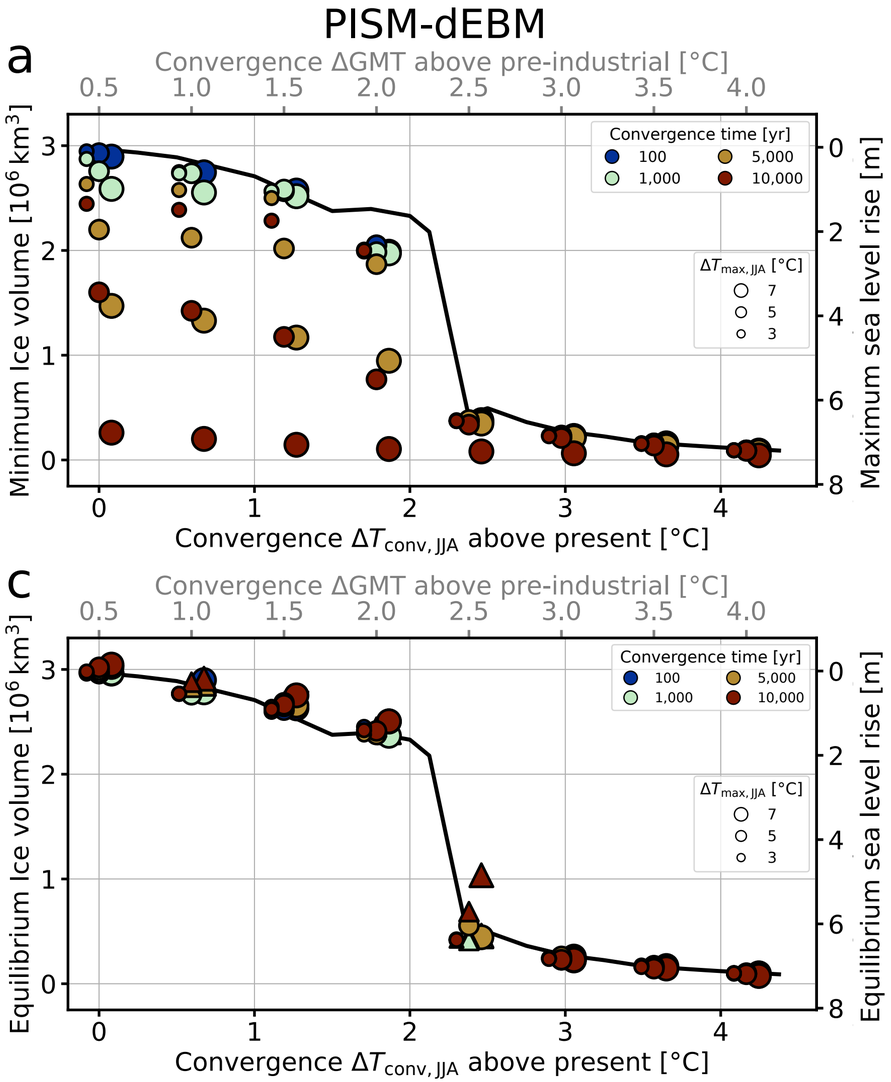
B & Rypdal, PNAS 2021

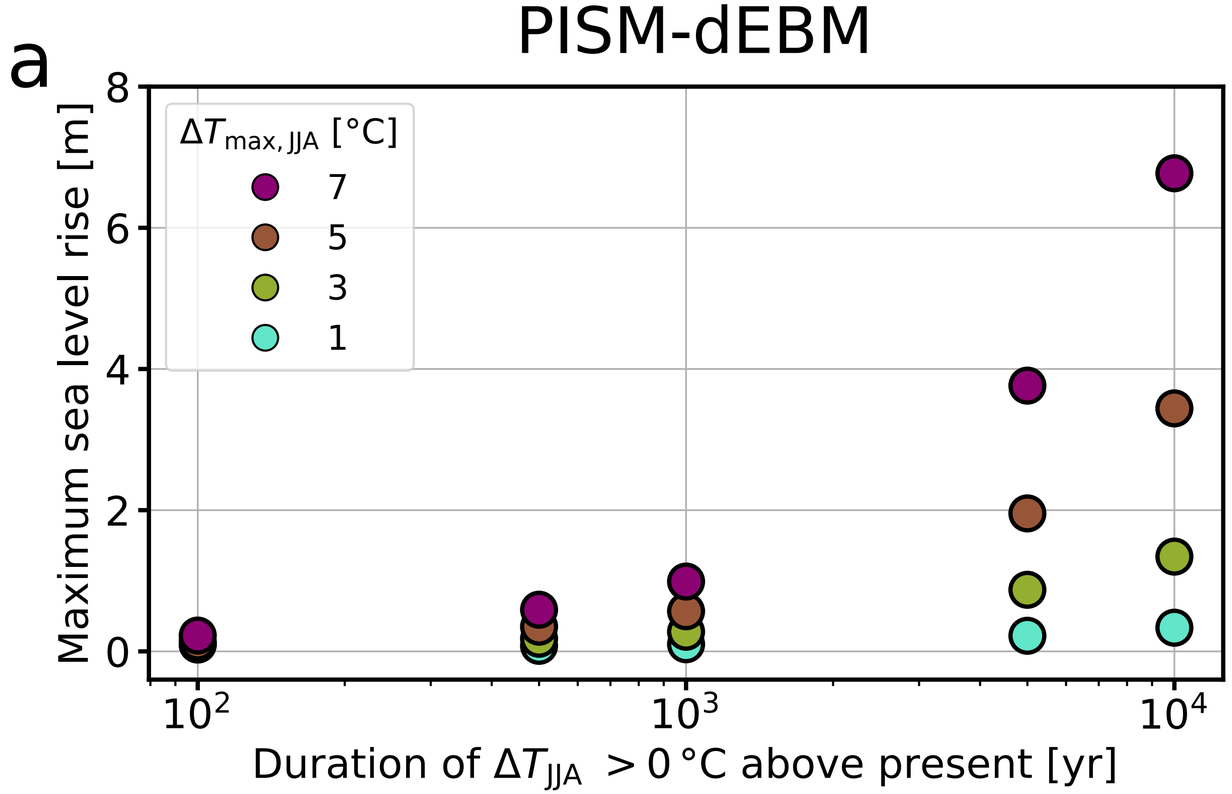
Greenland Ice Sheet



Bochow et al, Nature (in press)

Greenland Ice Sheet





Bochow et al, Nature (in press)

Remark: avoiding false positives

$$\langle \Delta x^2 \rangle = -\frac{\sigma^2}{2\lambda} \qquad \alpha(n) = e^{n\lambda\Delta t}$$

Variance $\langle \Delta x^2 \rangle$ and ACF $\alpha(\tau)$ can increase simply because the variance and ACF of the noise term η increase.

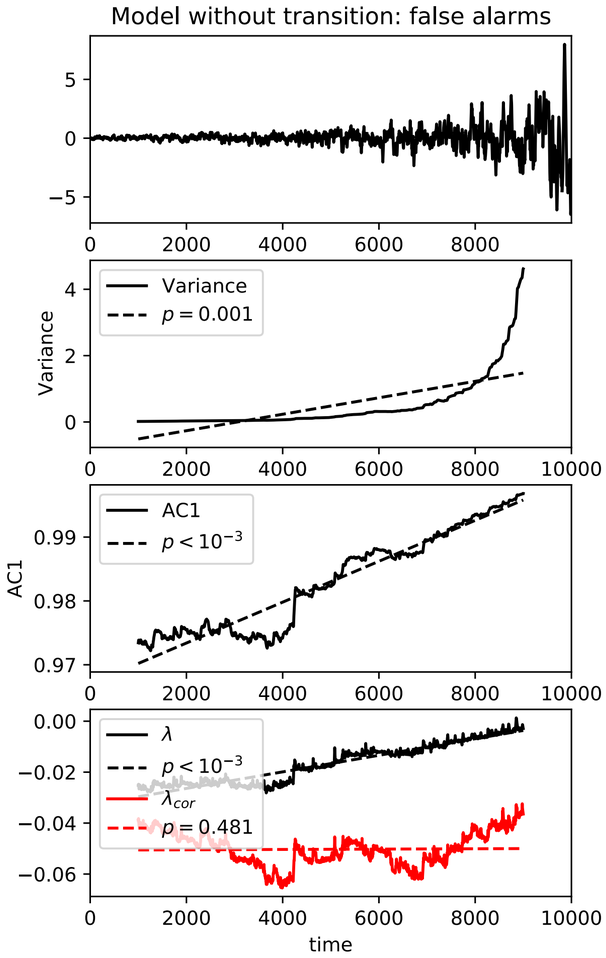
Estimate λ directly, and use it as EWS indicator? (Held & Kleinen, 2004)

$$\frac{d\Delta x}{dt} \approx \lambda \Delta x + \eta$$

Serial correlations of η bias the estimate for λ if obtained via LS assuming that η is white.

Instead, infer λ using Generalized Least Squares under the assumption of autocorrelated η:

$$\frac{d\Delta x}{dt} \approx \lambda_{cor} \Delta x + \eta^{a.c.}$$



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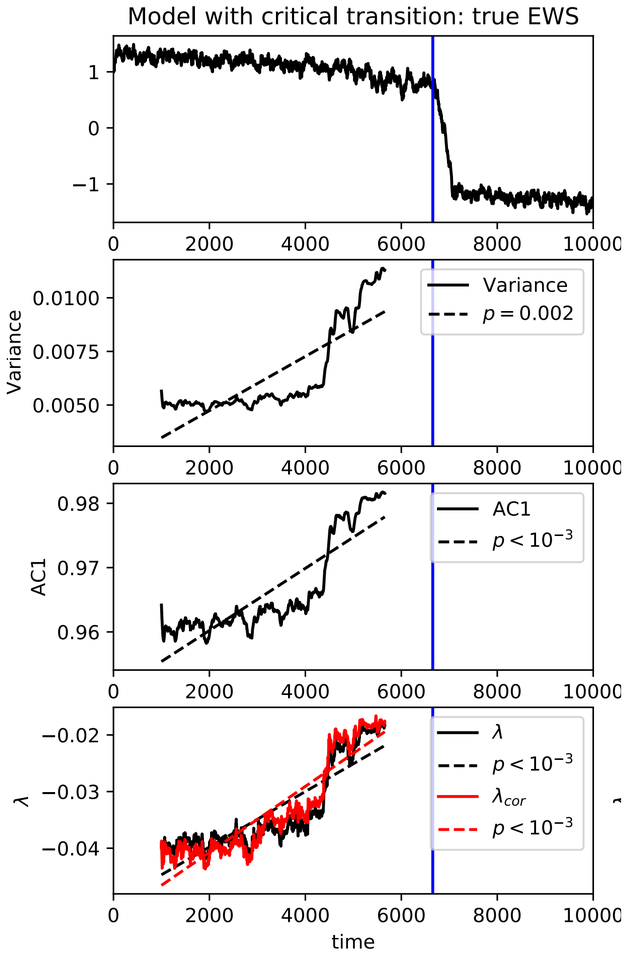
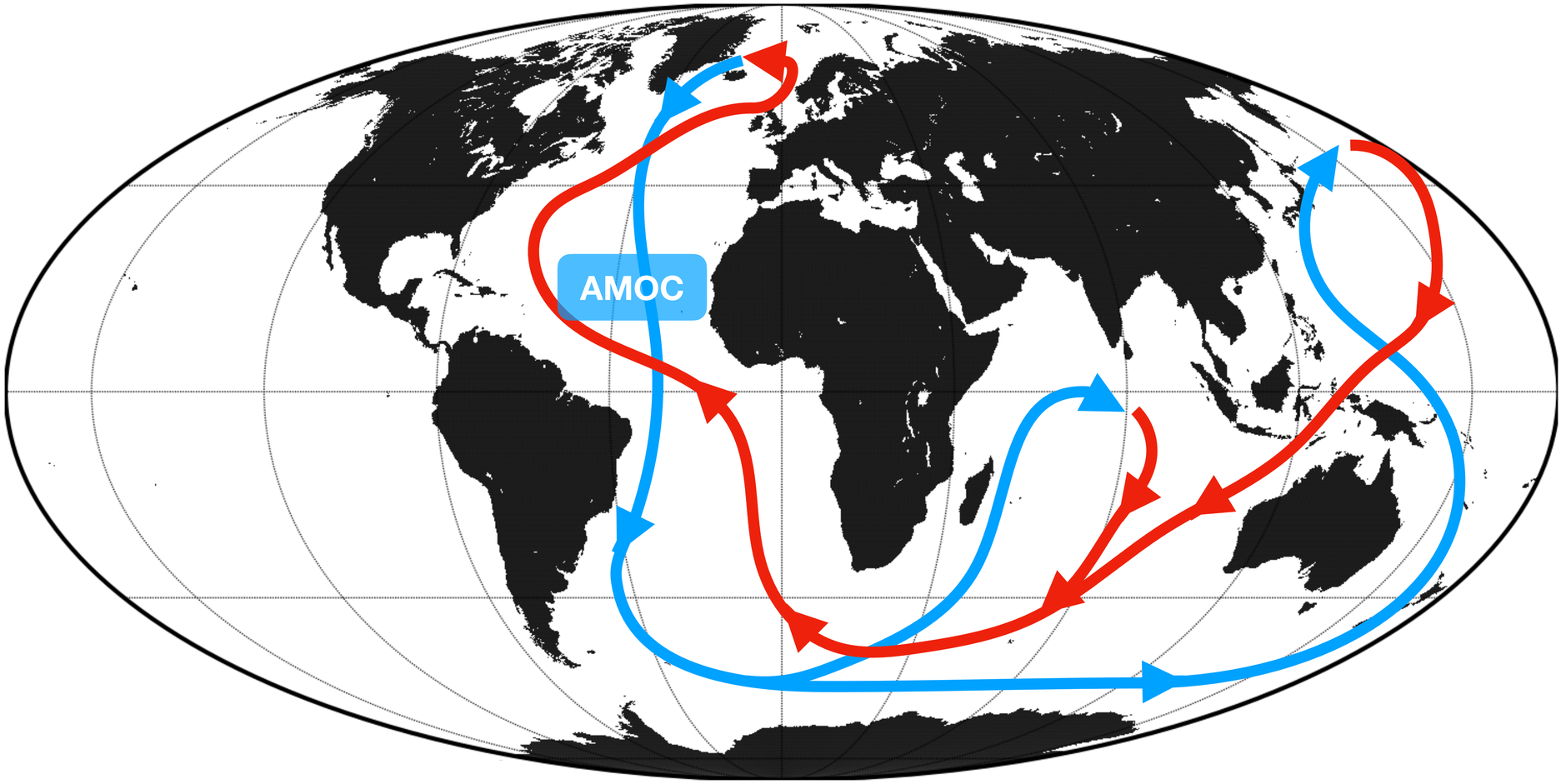


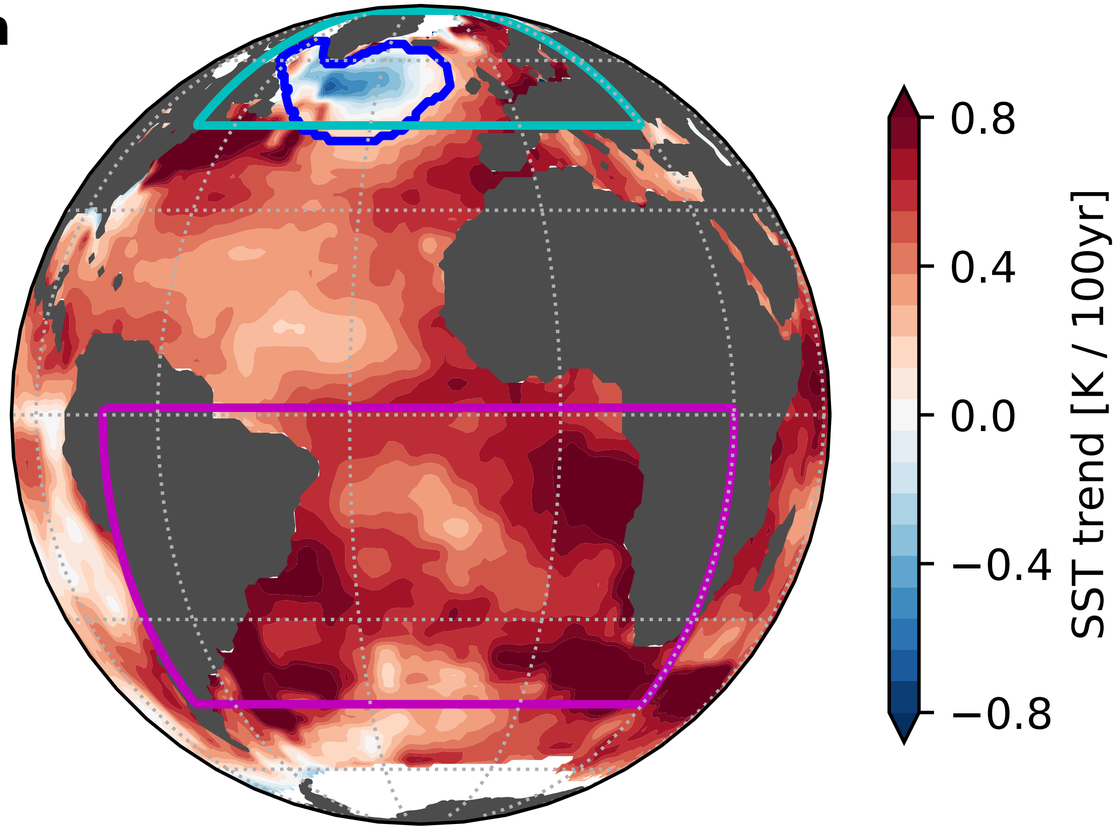
Atlantic Meridional Overturning Circulation



Atlantic Meridional Overturning Circulation

Sea-surface temperatures

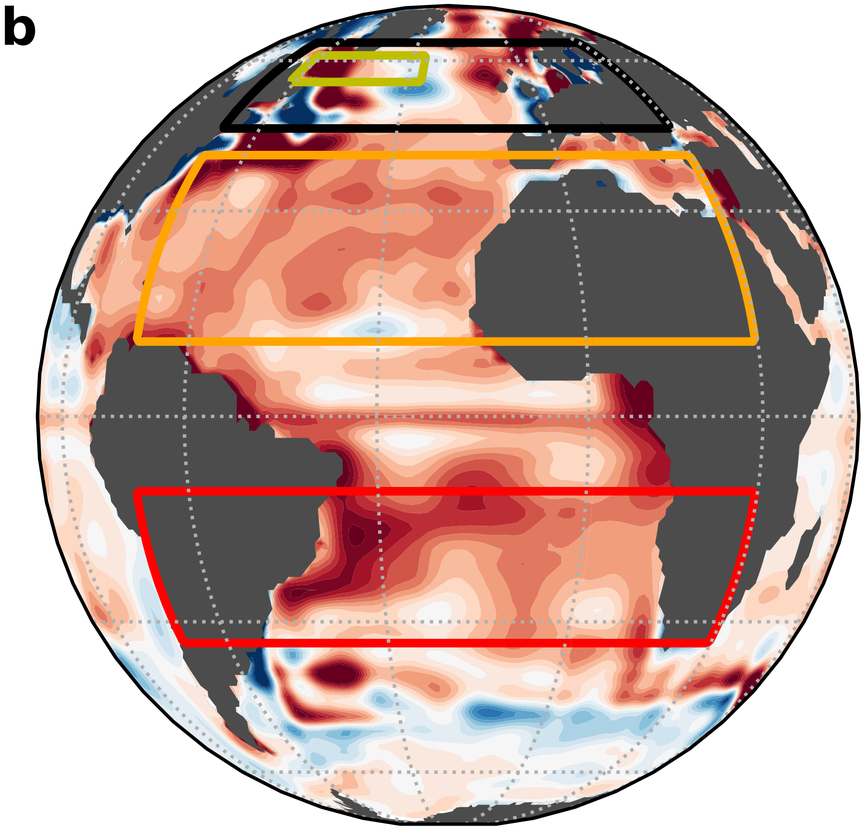
a

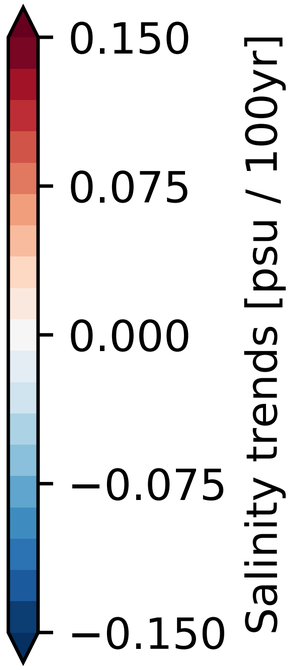


1870-present

Salinity

b



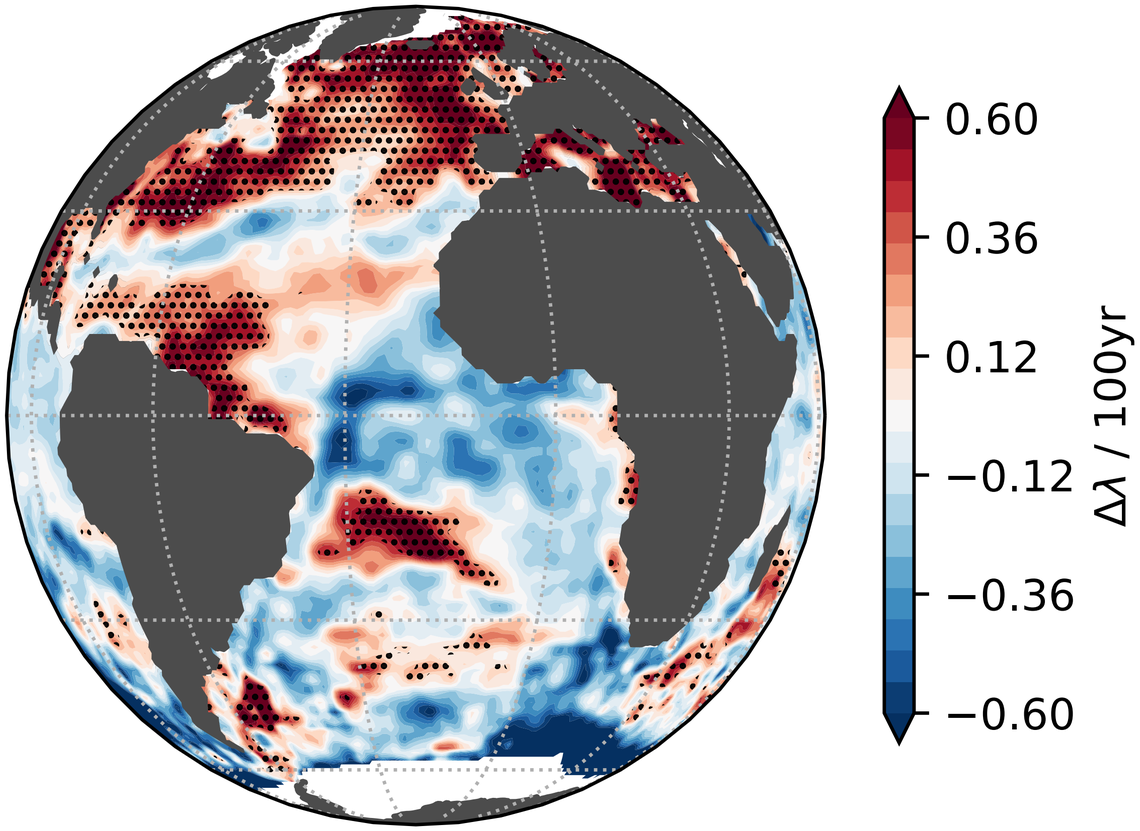


1900-present

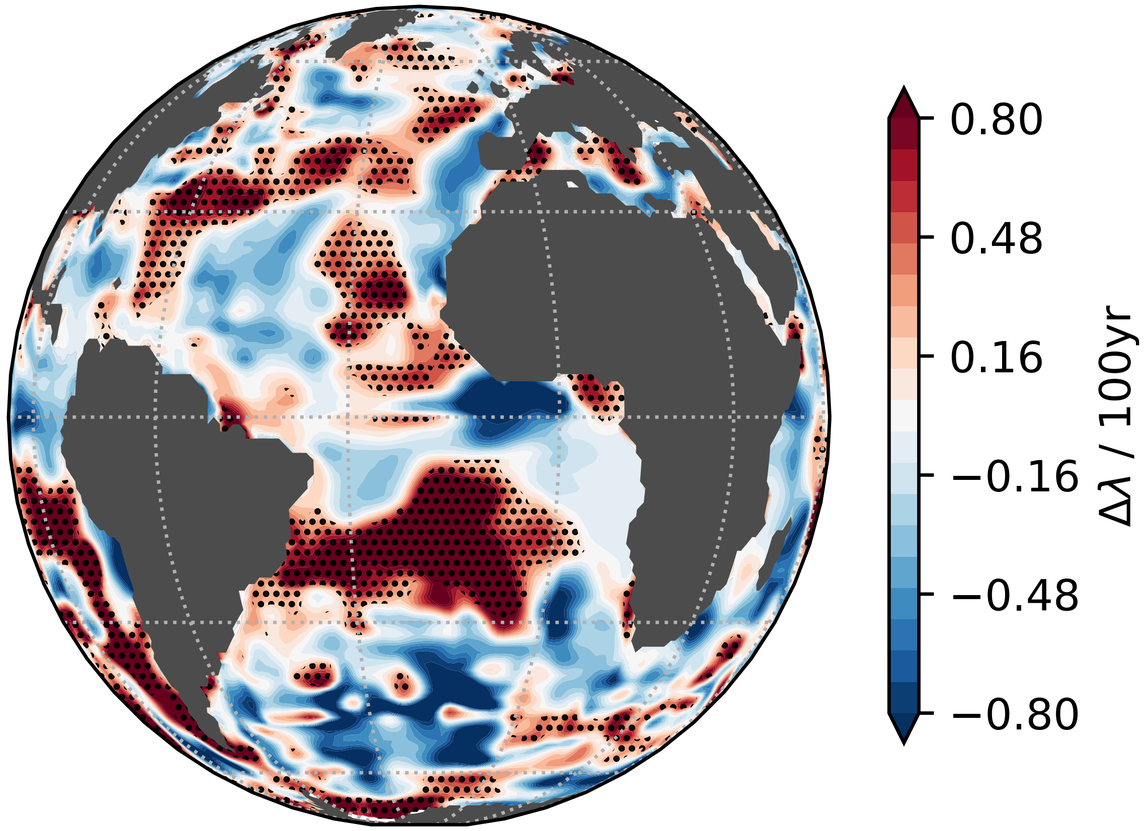
B, NCC 2021

Atlantic Meridional Overturning Circulation

Change in restoring rate λ



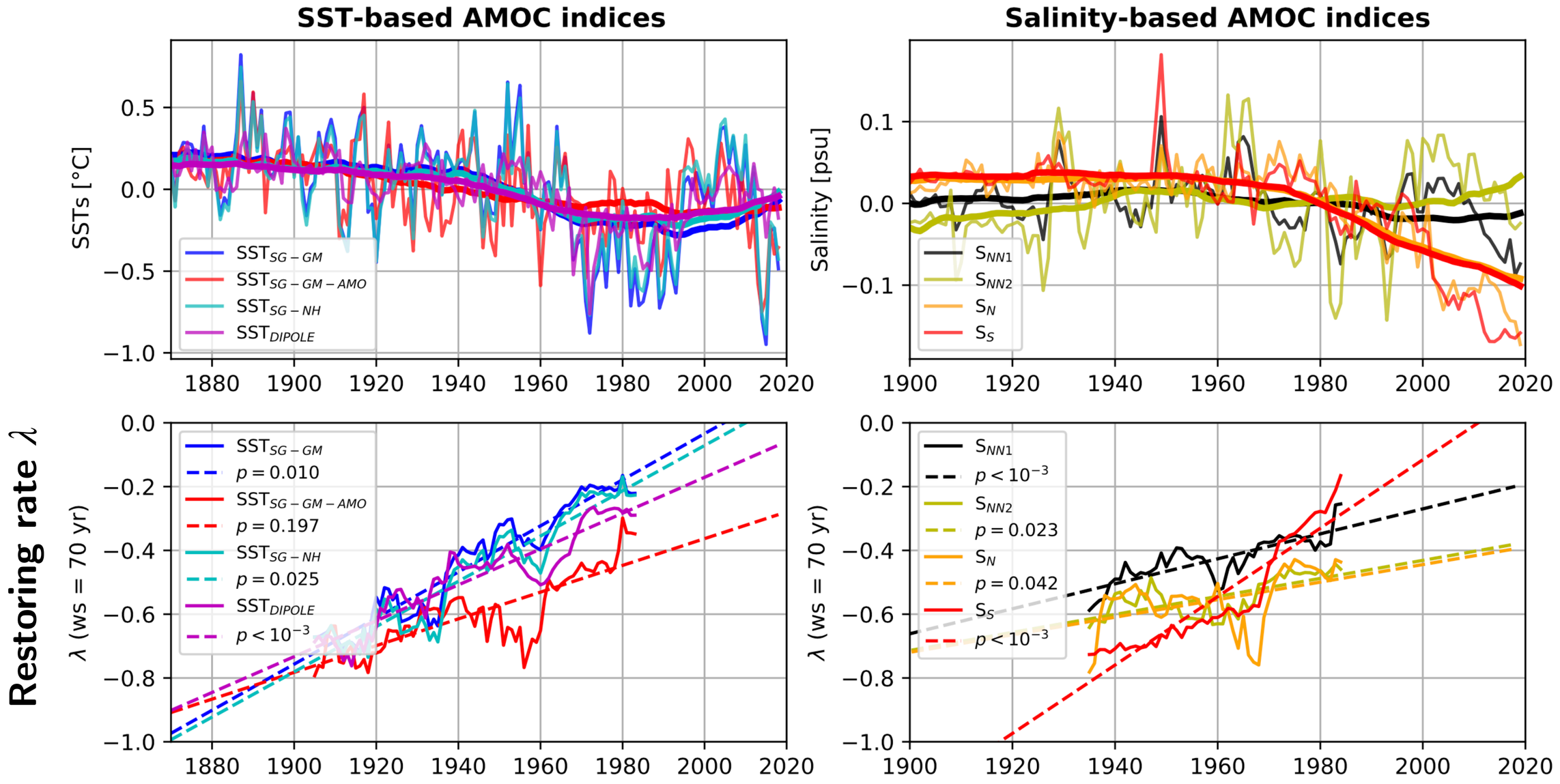
SSTs



Salinity

B, NCC 2021

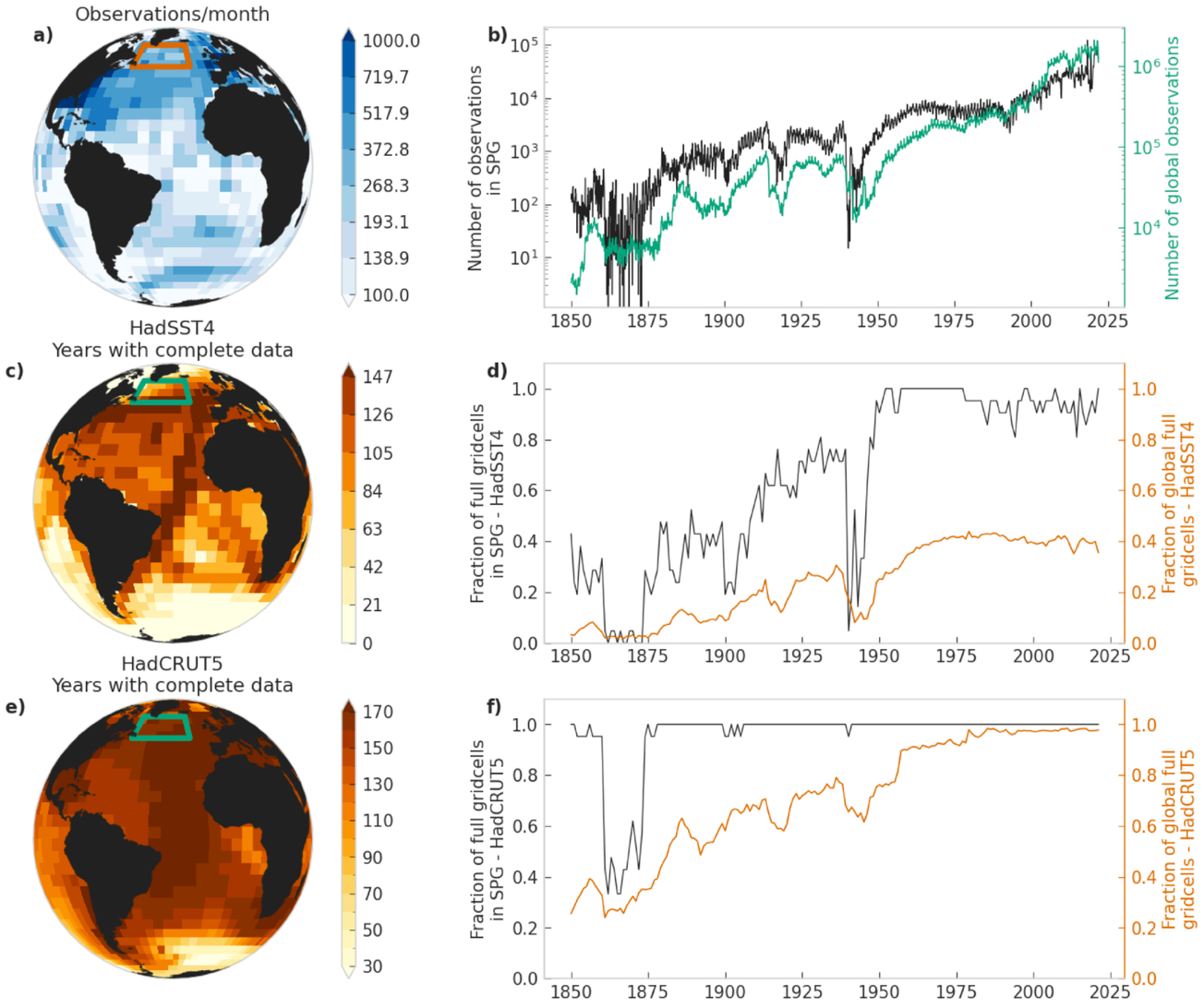
Atlantic Meridional Overturning Circulation



B, NCC 2021

Atlantic Meridional Overturning Circulation

BUT: Data is uncertain and coverage is highly non-stationary!



Ben-Yami et al., Nature Communications (accepted)

Atlantic Meridional Overturning Circulation

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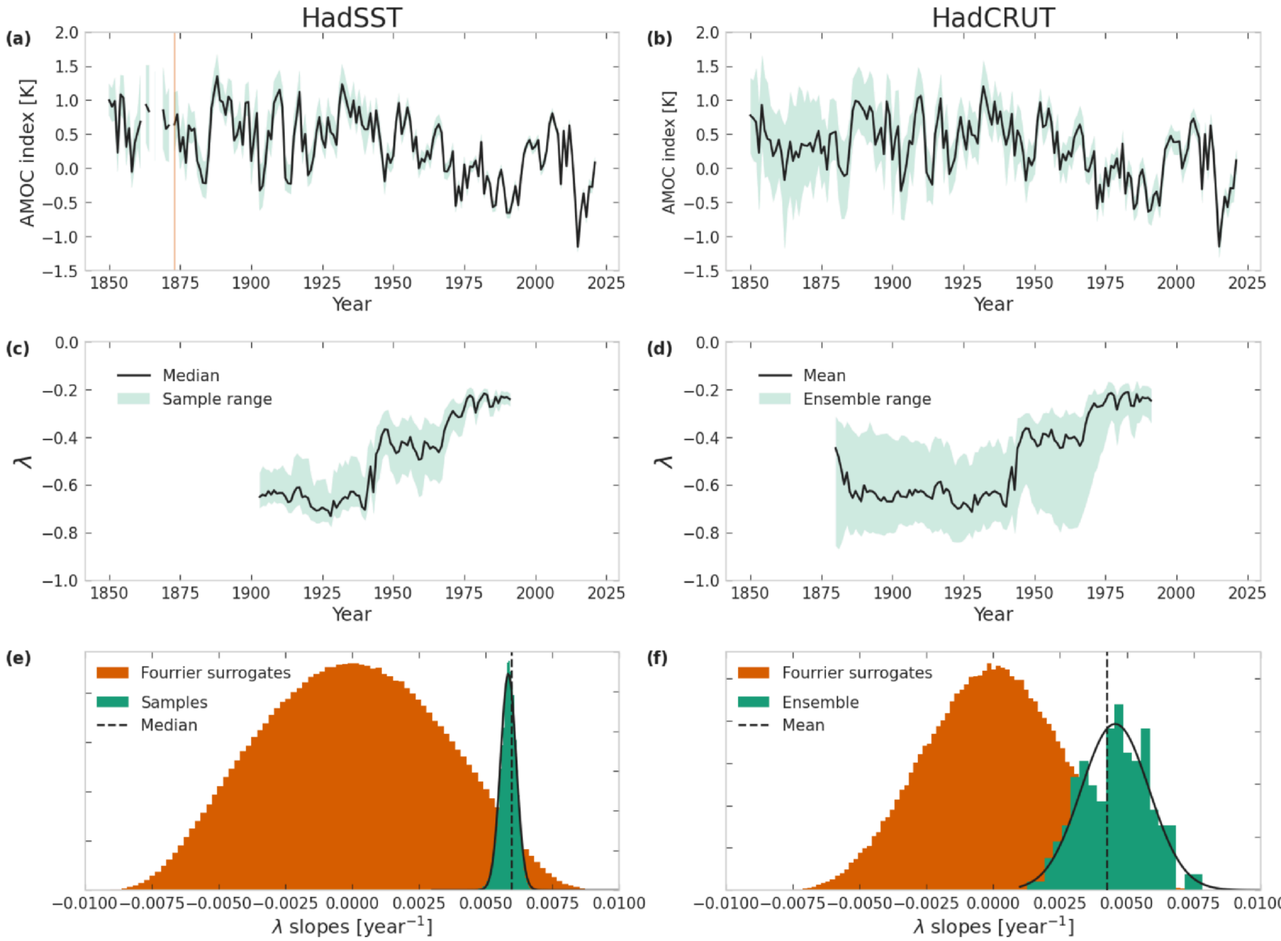

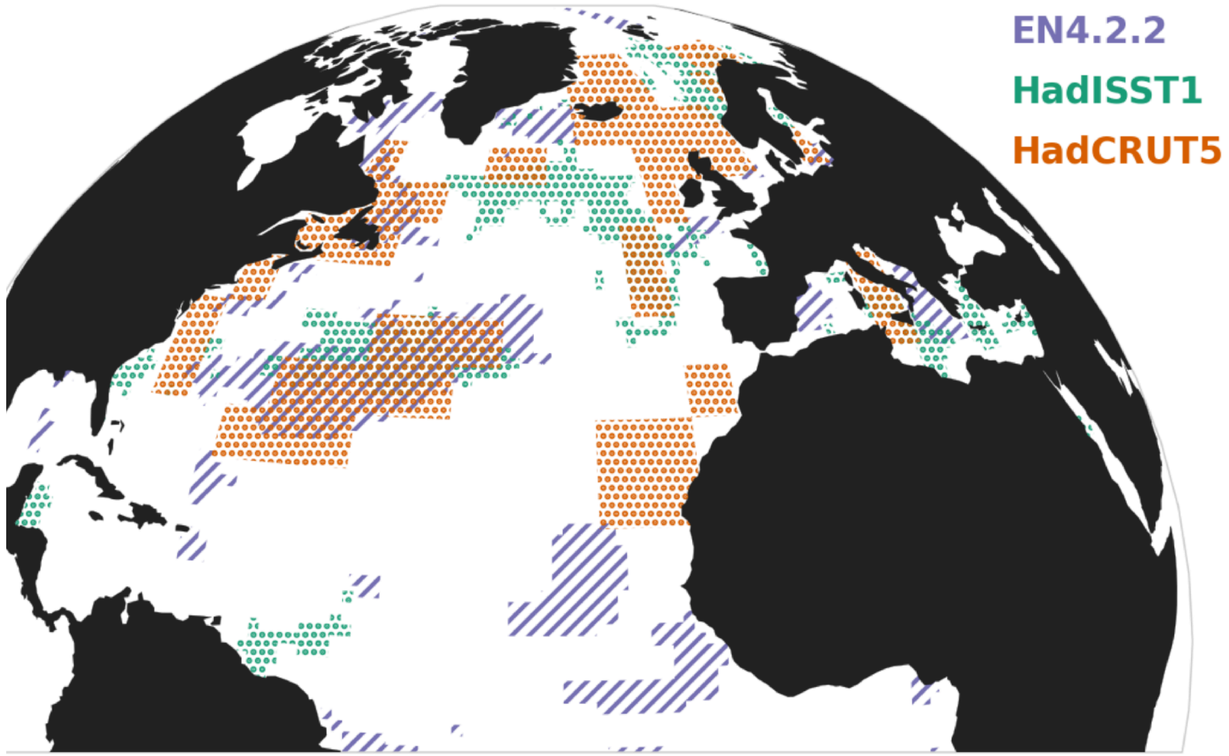

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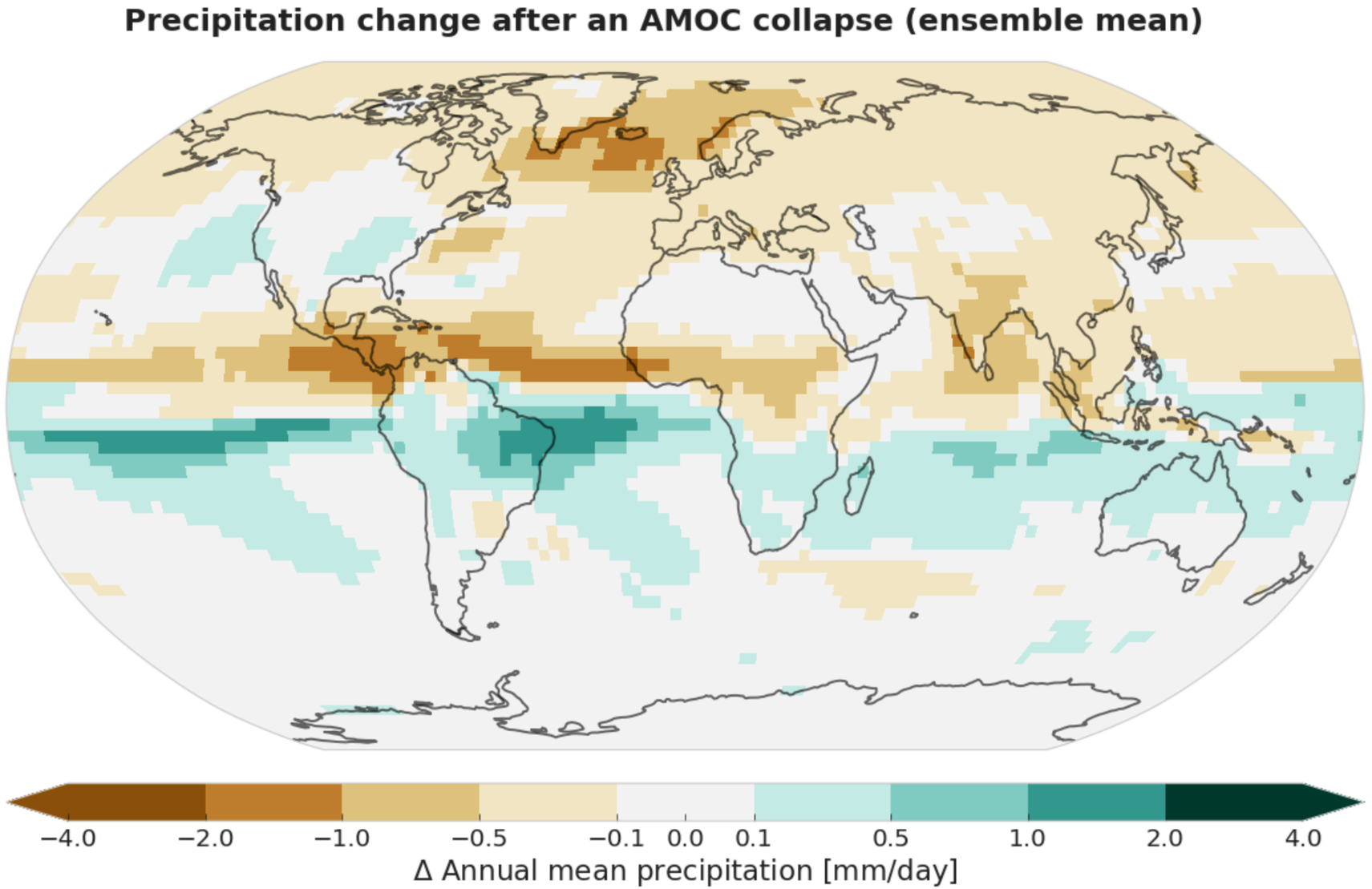
Atlantic Meridional Overturning Circulation

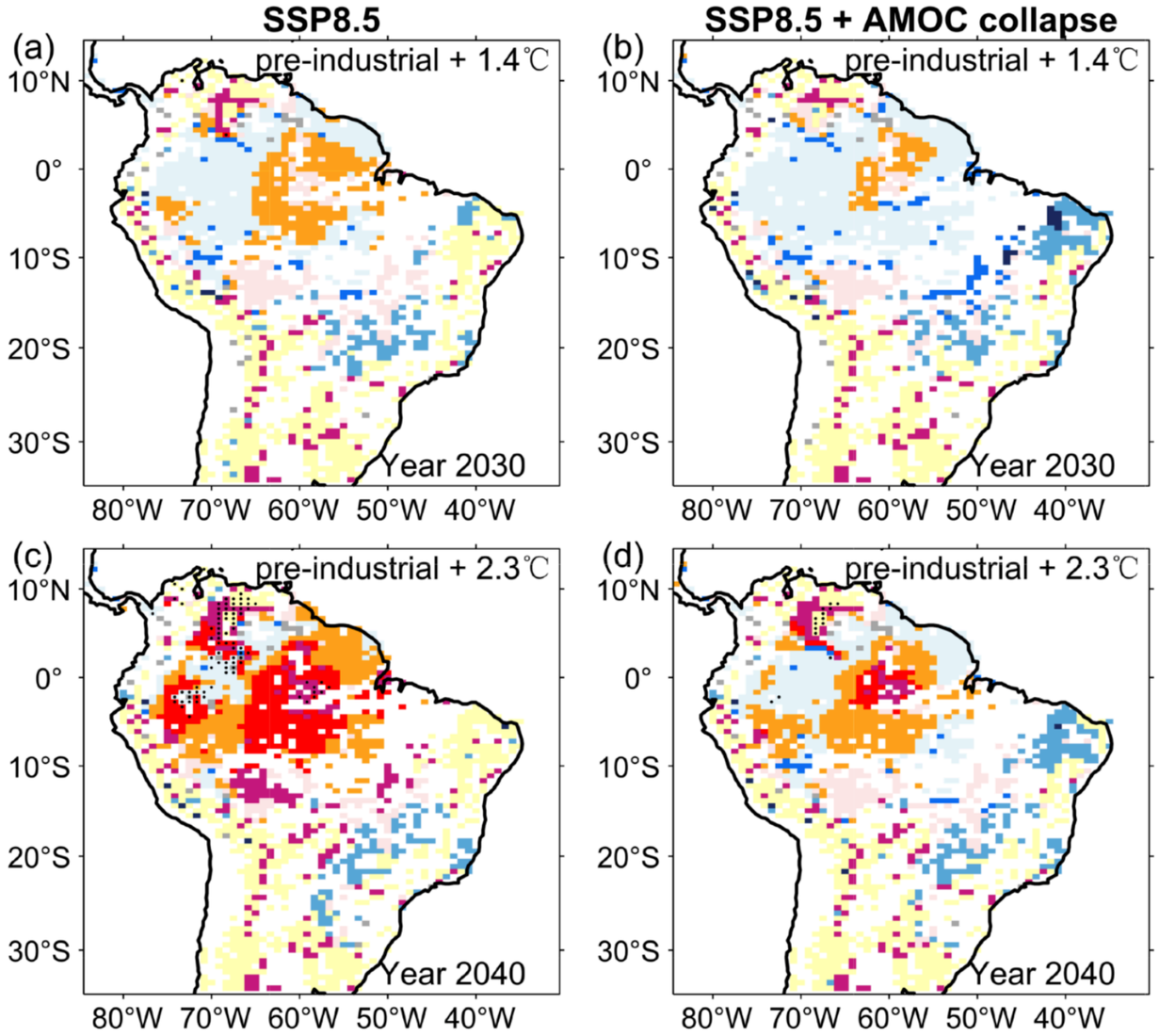
Impacts of collapse

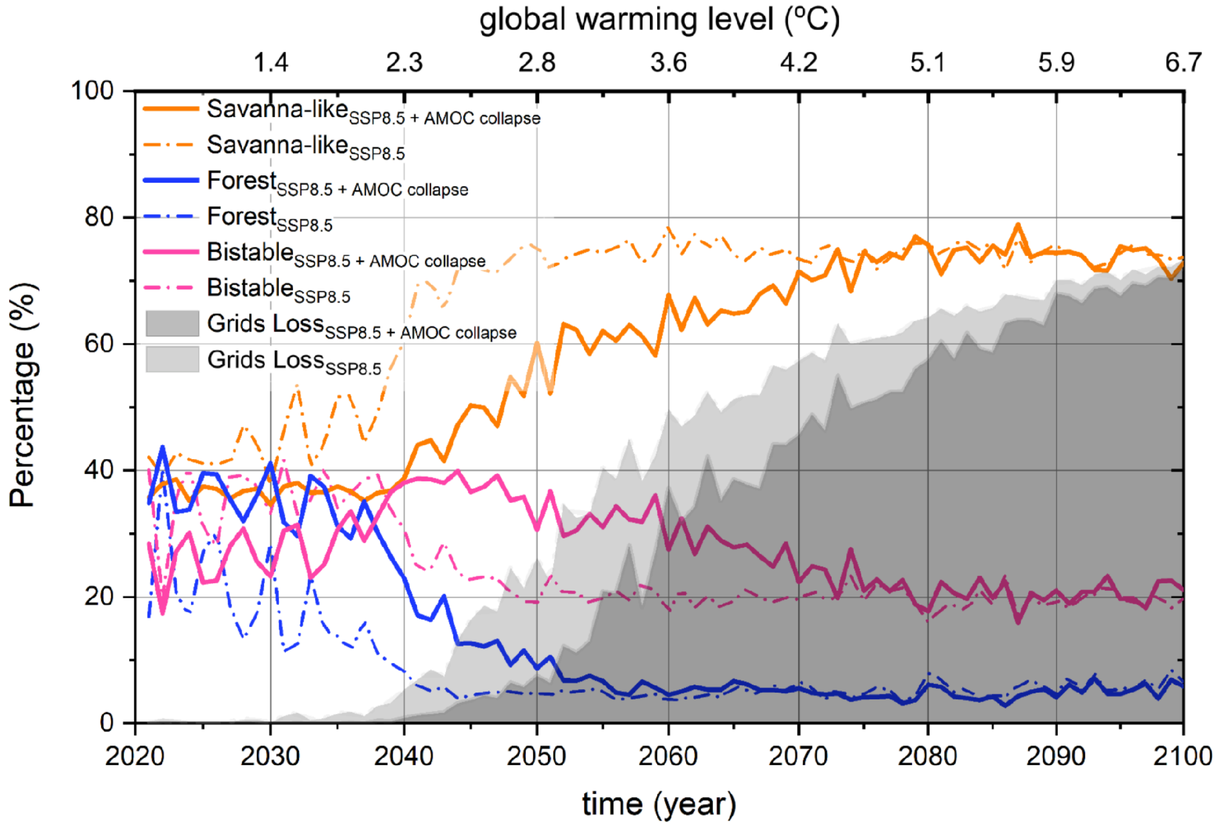


Ben-Yami et al., in revision

Atlantic Meridional Overturning Circulation

Impacts of collapse on Amazon: Offsets negative global warming impacts

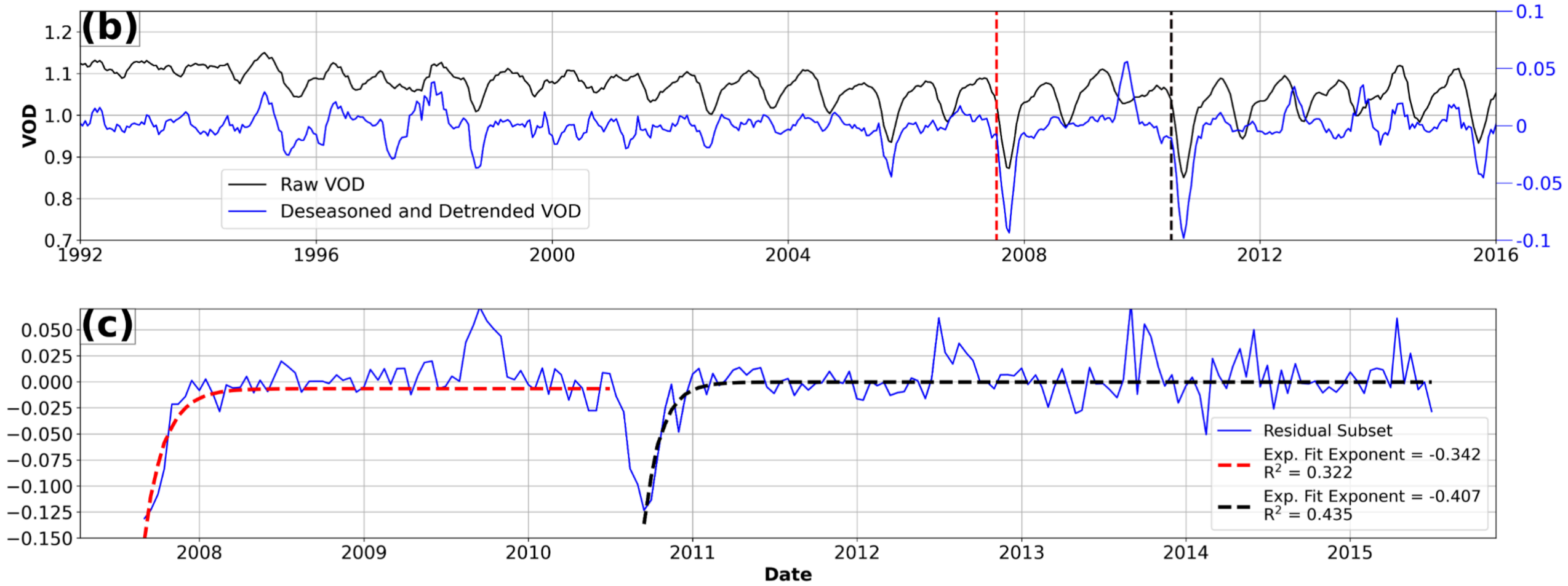




Nian et al., in revision

Empirical confirmation of CSD indicators for vegetation

Def. (Resilience): The ability of a system to recover from external perturbations



Smith, Traxl, B, NCC 2022

Empirical confirmation of CSD indicators for vegetation

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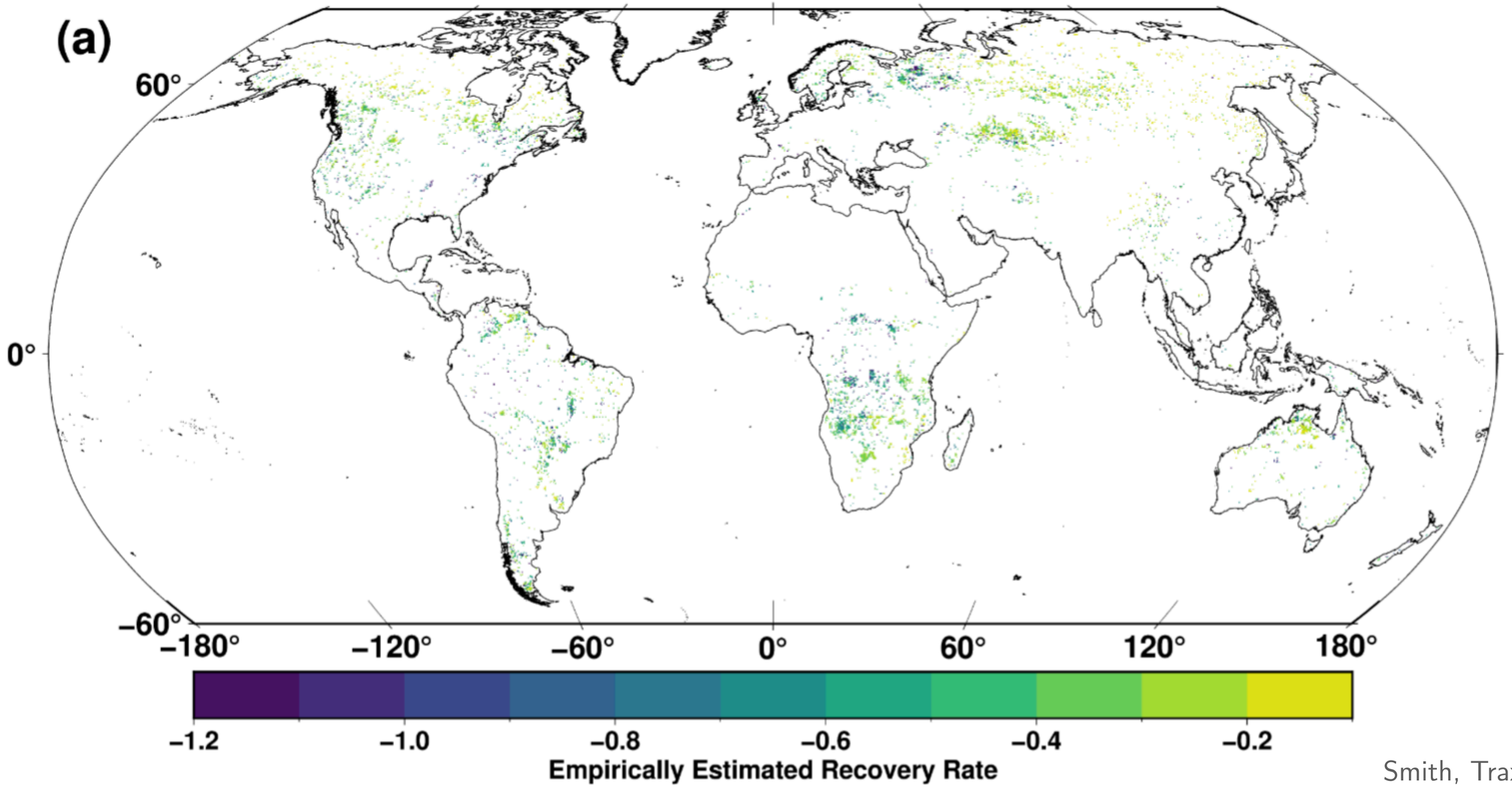
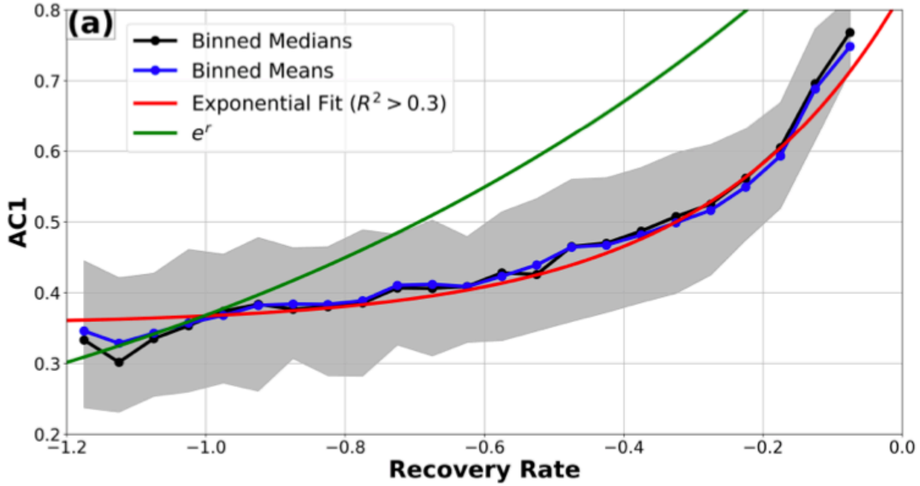


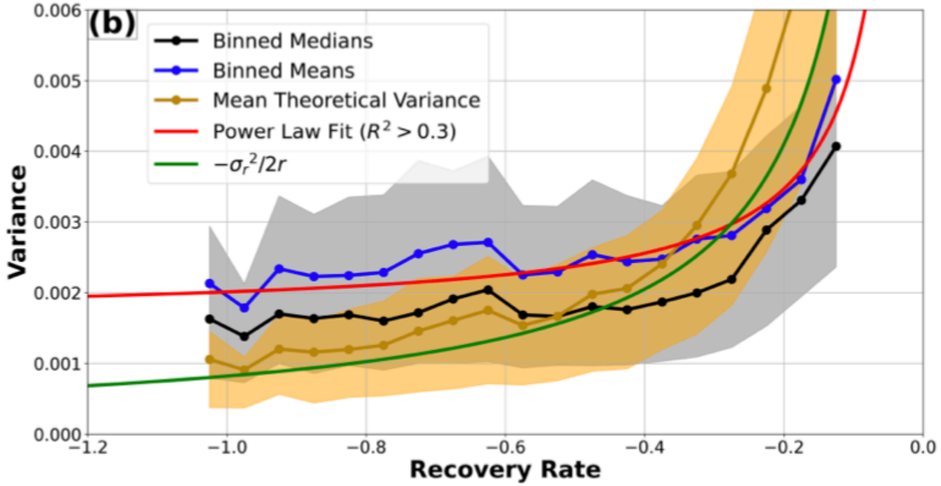
Smith, Traxl, B, NCC 2022

Empirical confirmation of CSD indicators for vegetation

$$\alpha(n) = e^{n\lambda\Delta t}$$



$$\langle \Delta x^2 \rangle = -\frac{\sigma^2}{2\lambda}$$

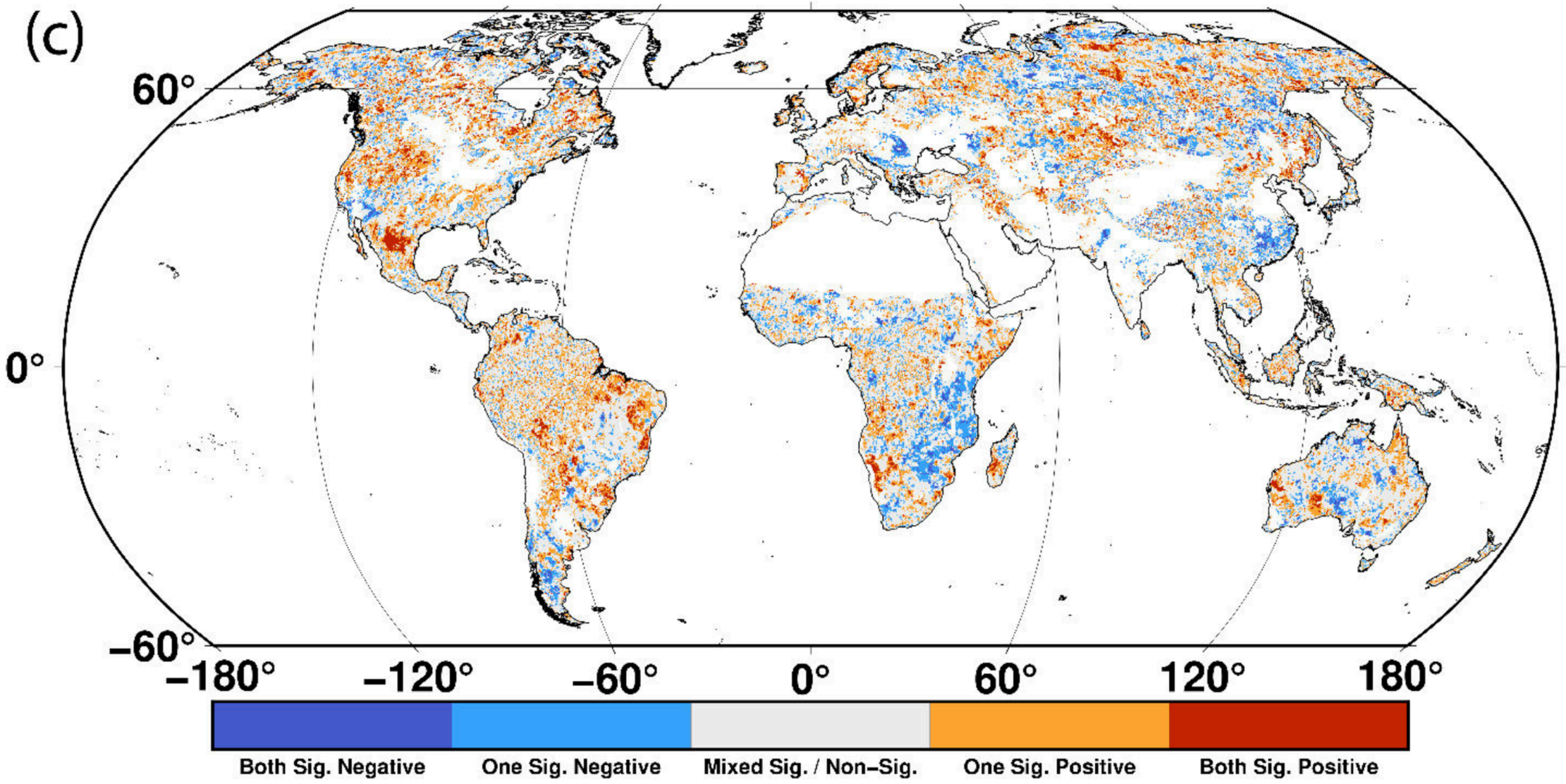


Empirical Confirmation of the FDT:

For vegetation it's (sort of) ok to use the natural variability to estimate the response to large external perturbations, and hence to quantify resilience!

Smith, Traxl, B, NCC 2022

Empirical confirmation of CSD indicators for vegetation



Smith, Traxl, B, NCC 2022

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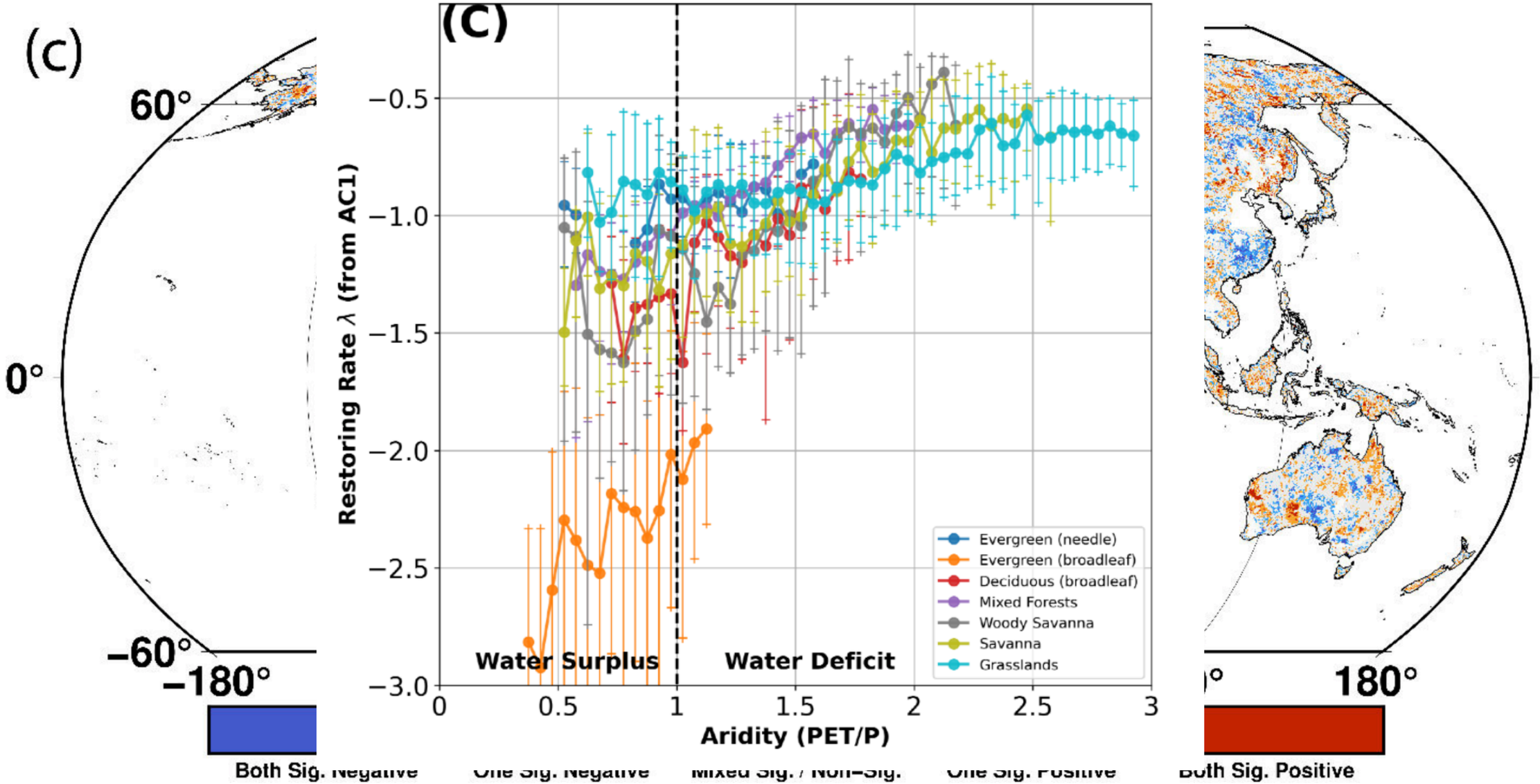


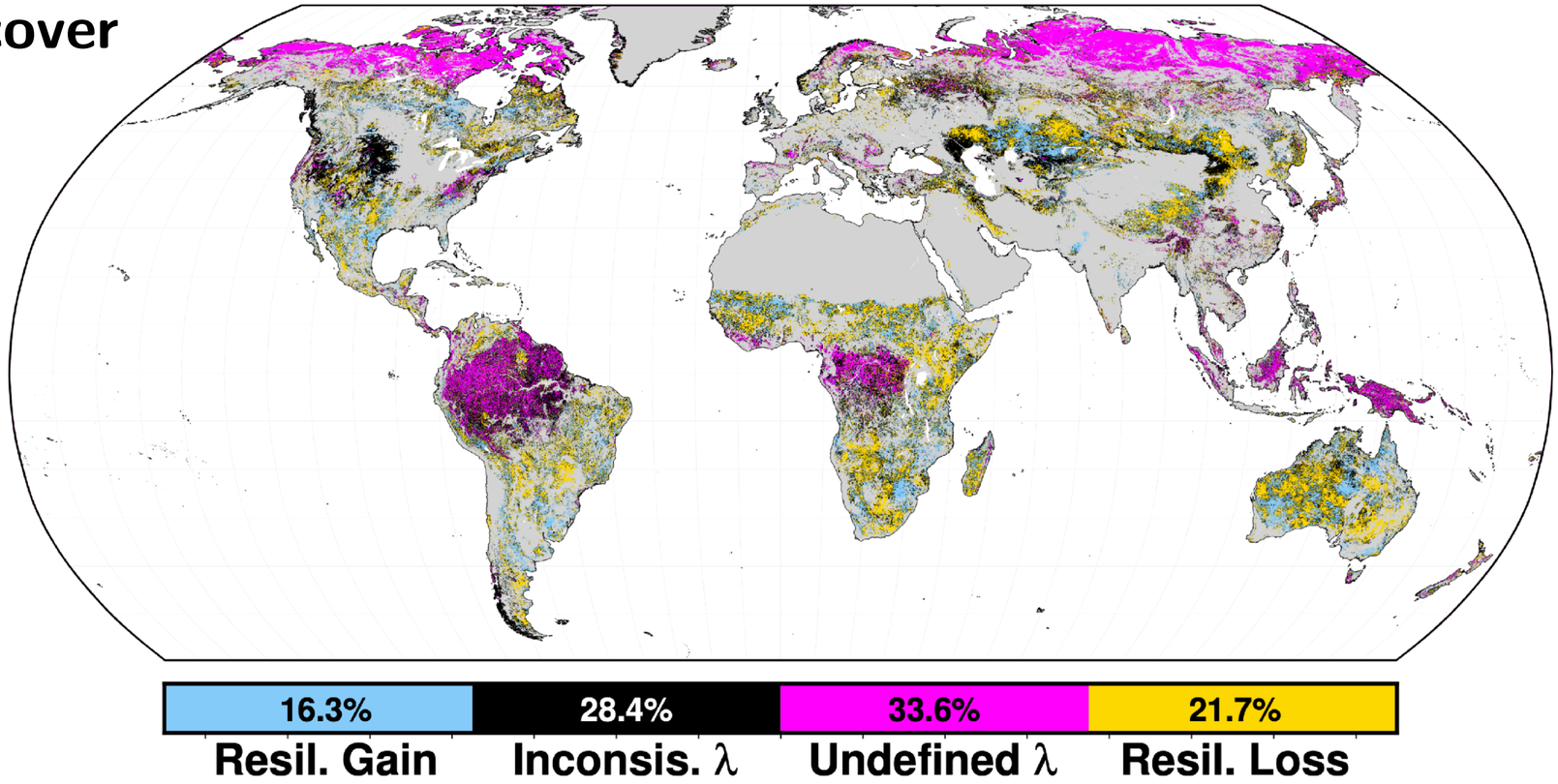
Smith, Traxl, B, NCC 2022; Smith & B, Nat. Comm's 2023

Empirical confirmation of CSD indicators for vegetation

CAUTION:

- **Merged multi-sensor datasets induce biases and should be a avoided**

- **Optical indices such as NDVI / EVI etc are problematic over dense vegetation cover**



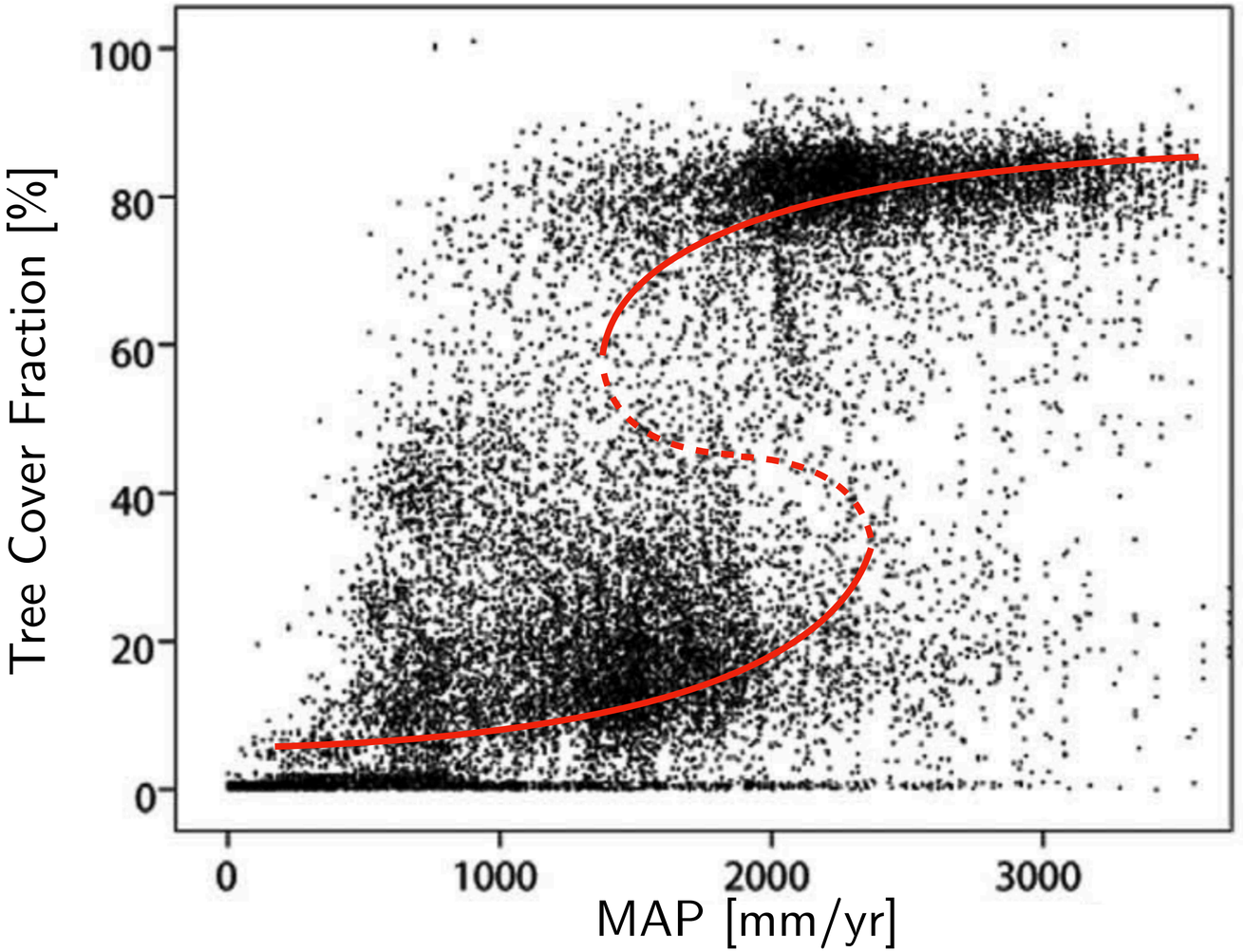
MODIS NDVI (single-sensor data)

Smith et al., ESD 2022; Smith & B, Nature Ecology & Evolution 2023

Amazon rainforest

Vegetation density (tree cover fraction) vs. mean annual precipitation (MAP):

Amazon ecosystem bistable for intermediate MAP regimes?



'space-for-time':

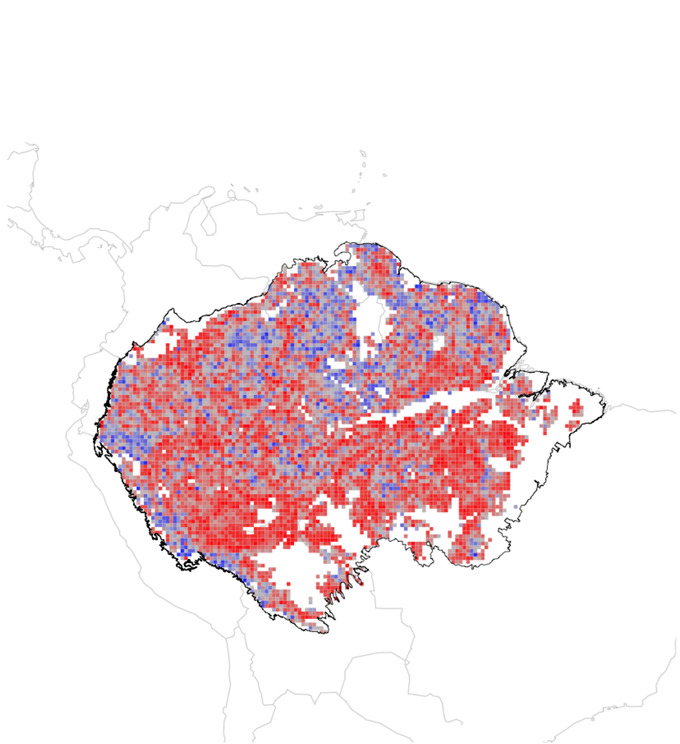
$$U_p(x) = -\frac{\sigma^2}{2}\log(\rho_p(x))$$

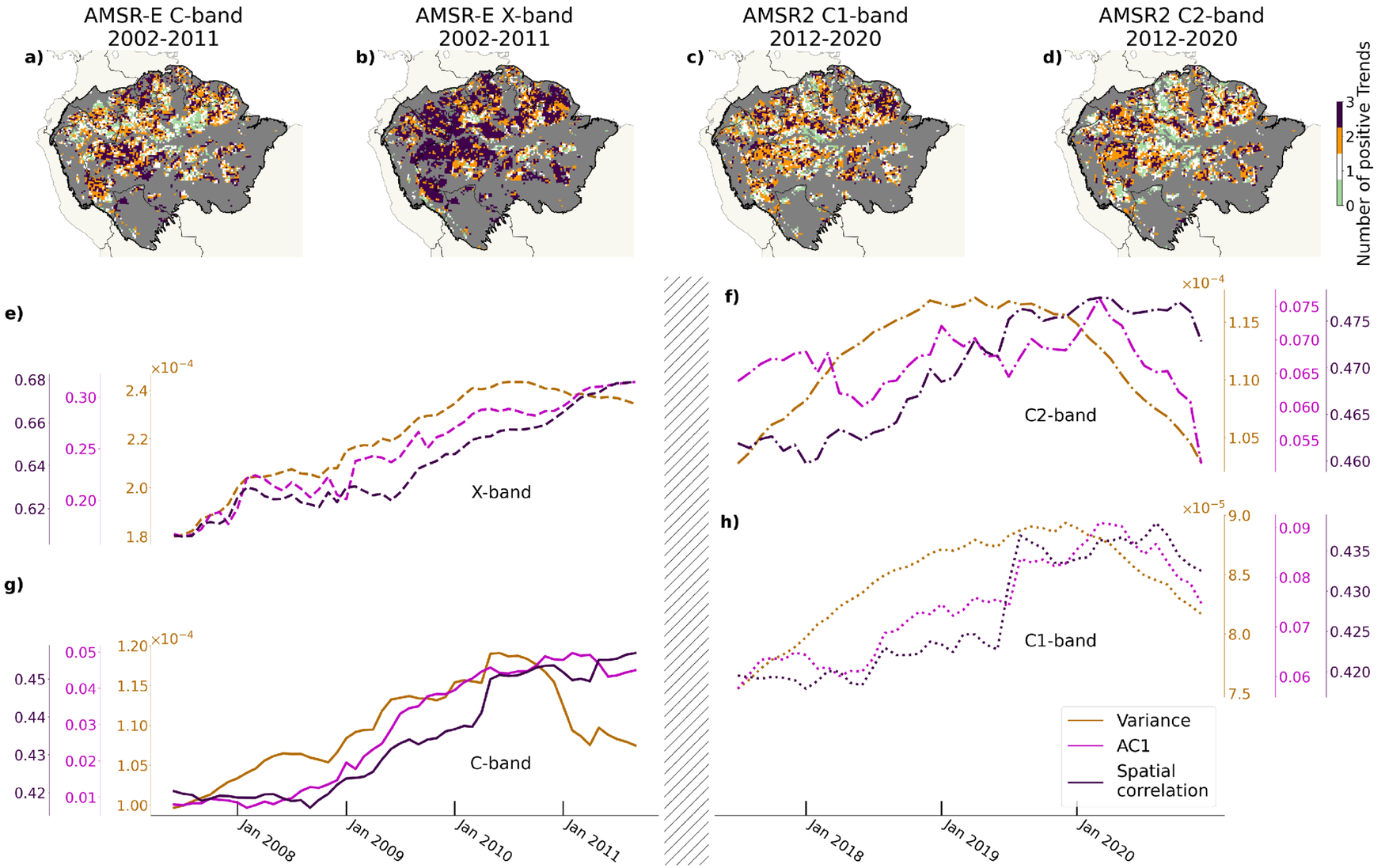
$$\dot{x} = U_p'(x) + \eta$$

Hirota et al., 2011

Amazon rainforest

Resilience loss confirmed from single-sensor VOD

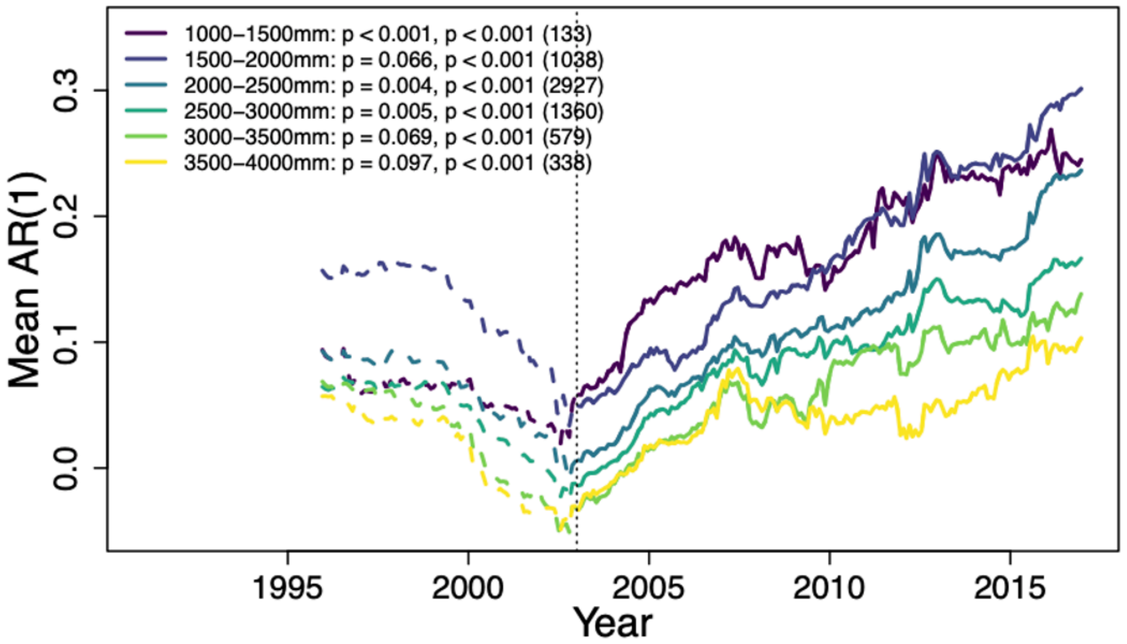




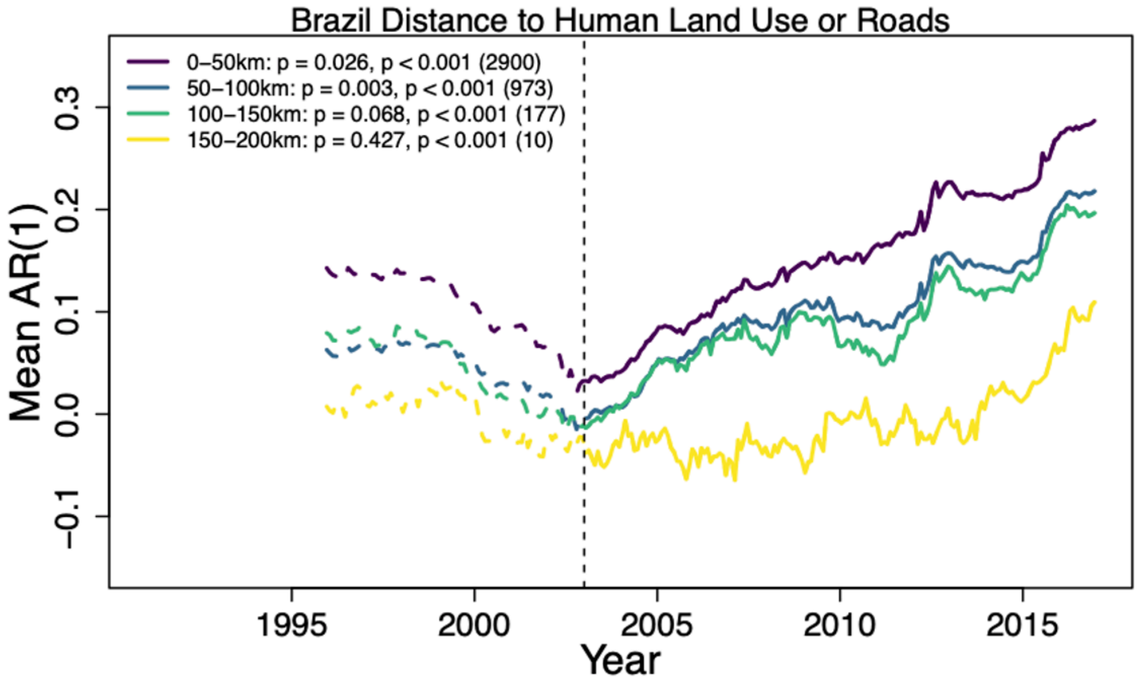
Boulton, Lenton, B, NCC 2022; Blaschke et al., in review

Amazon rainforest

role of mean annual precipitation



role of distance to human activity

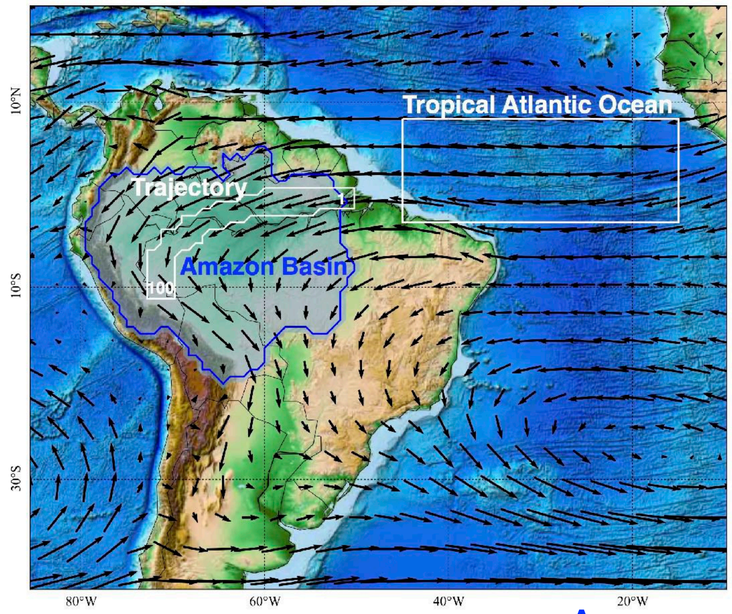


Resilience loss stronger in drier places and closer to human activity!

Boulton, Lenton, B, NCC 2022

Amazon rainforest & South American Monsoon

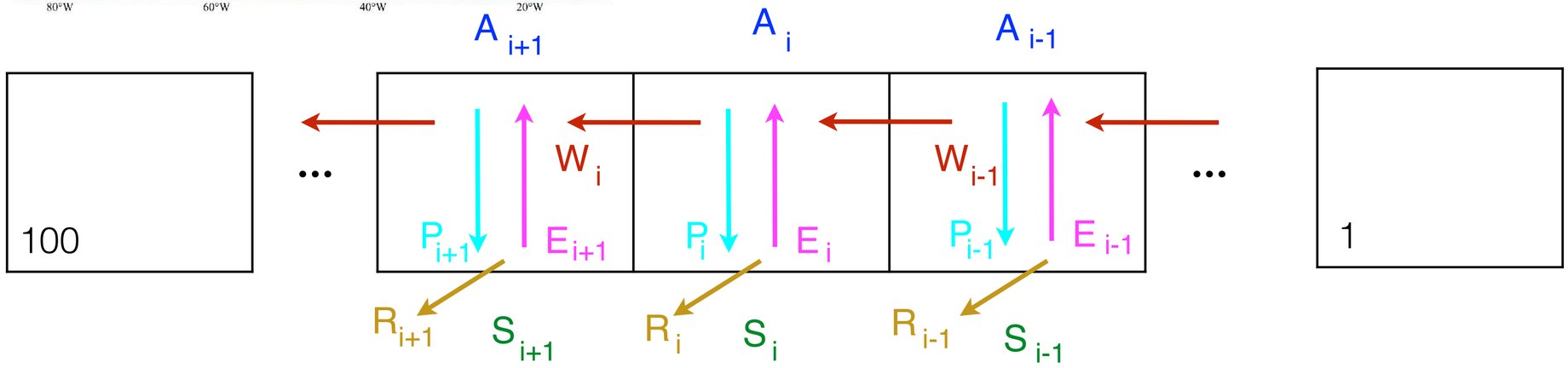
Via evapotranspiration and precipitation, the Amazon rainforest exchanges moisture with the atmosphere. Initial tree mortality or deforestation will reduce this moisture recycling!



$$\partial_t A_i = E_i - P_i + \frac{W_{i-1}A_{i-1} - W_i A_i}{l}$$

$$\partial_t S_i = P_i - E_i - R_i$$

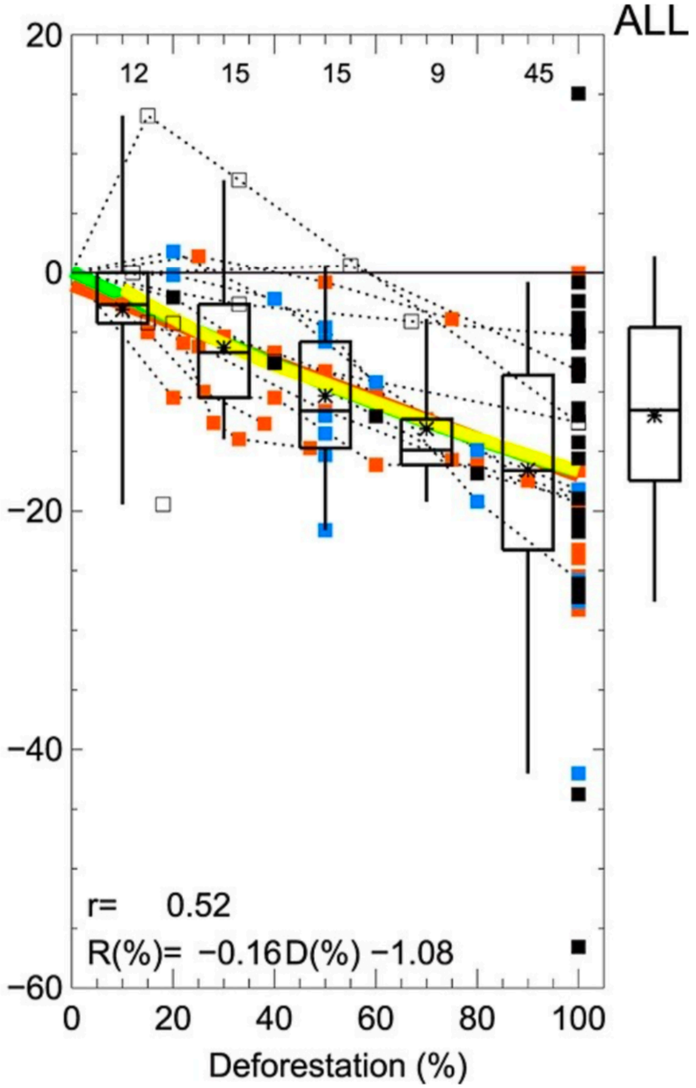
$$W_i = W_i^{trade} + W_i^{LH} \propto \overline{p_{Amazon}} - p_{coast}$$



B et al., 2017

Amazon rainforest & South American Monsoon: Impacts of Deforestation

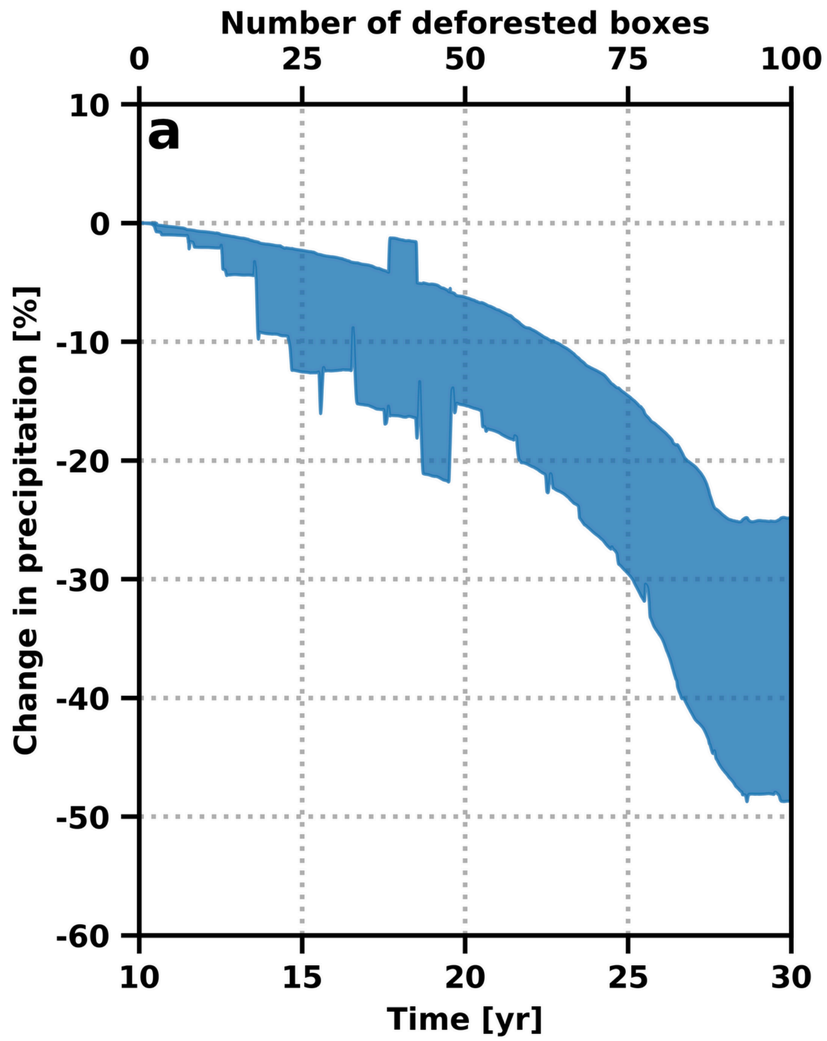
Simulating deforestation

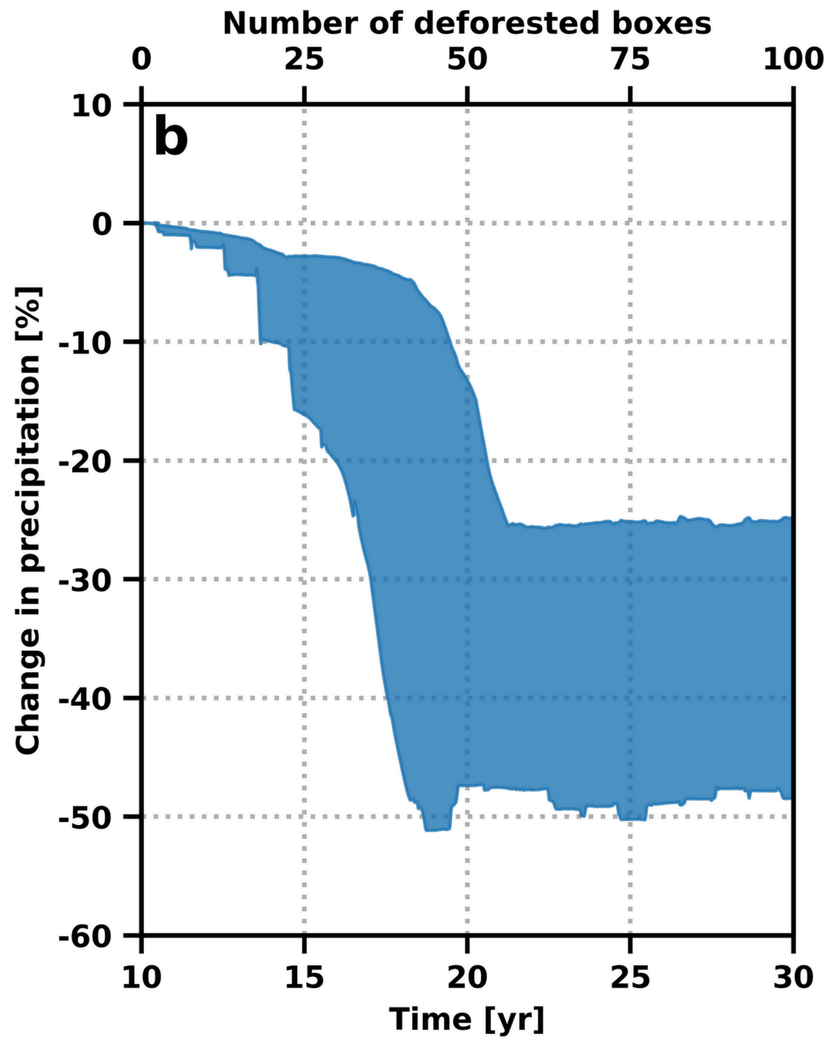


Spracklen & Garcia-Carreras 2015

Without vegetation feedback

With vegetation feedback

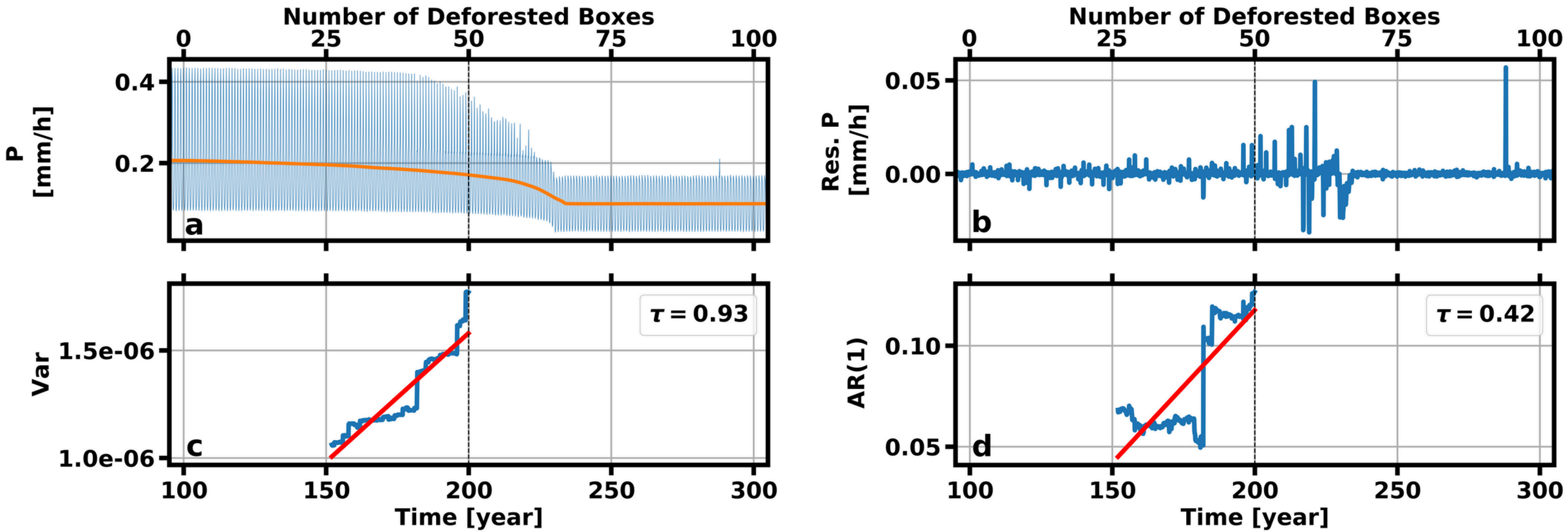




Bochow & B., Science Advances 2023

Amazon rainforest & South American Monsoon: Impacts of Deforestation

Statistical EWS in simulations



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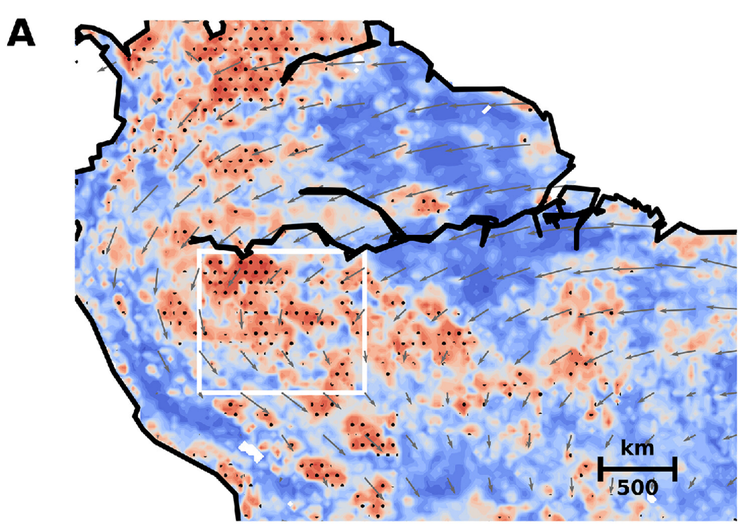
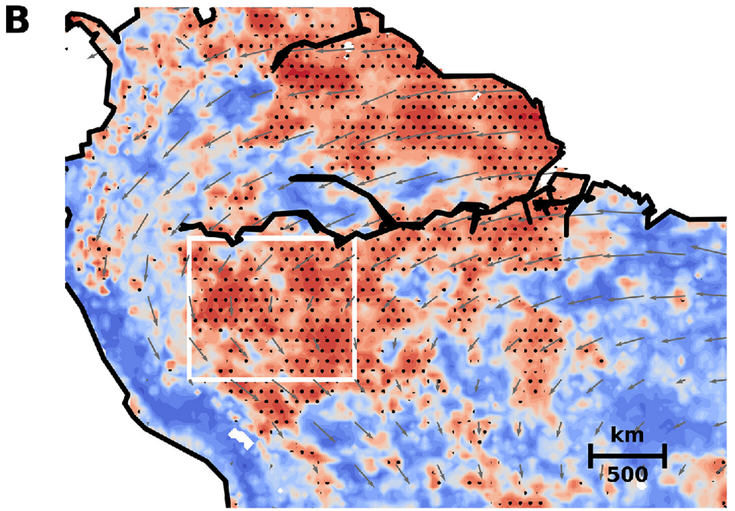
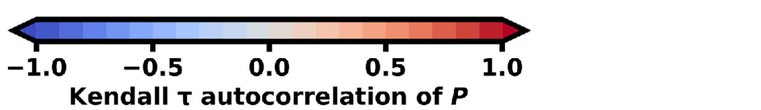
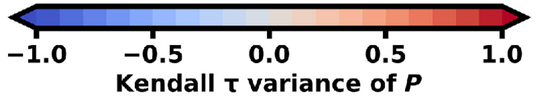
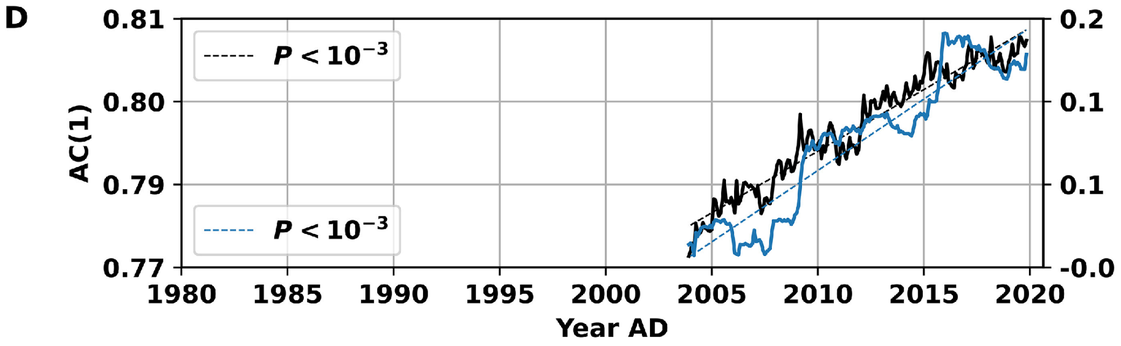
CSD in monthly rainfall rates (reanalysis and observations)

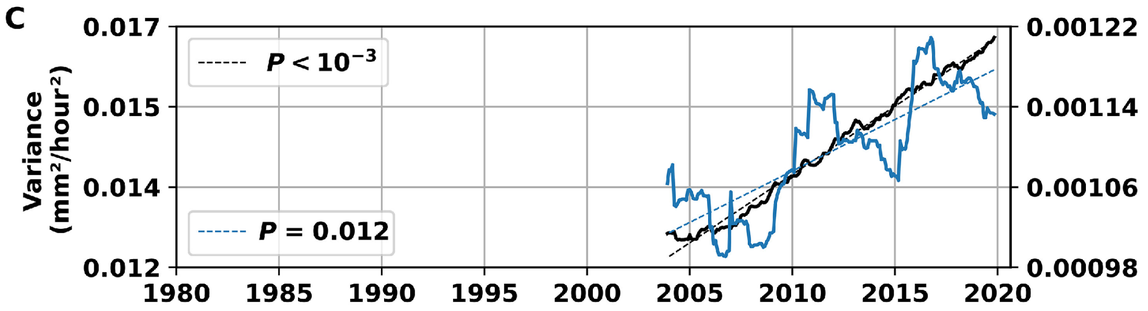












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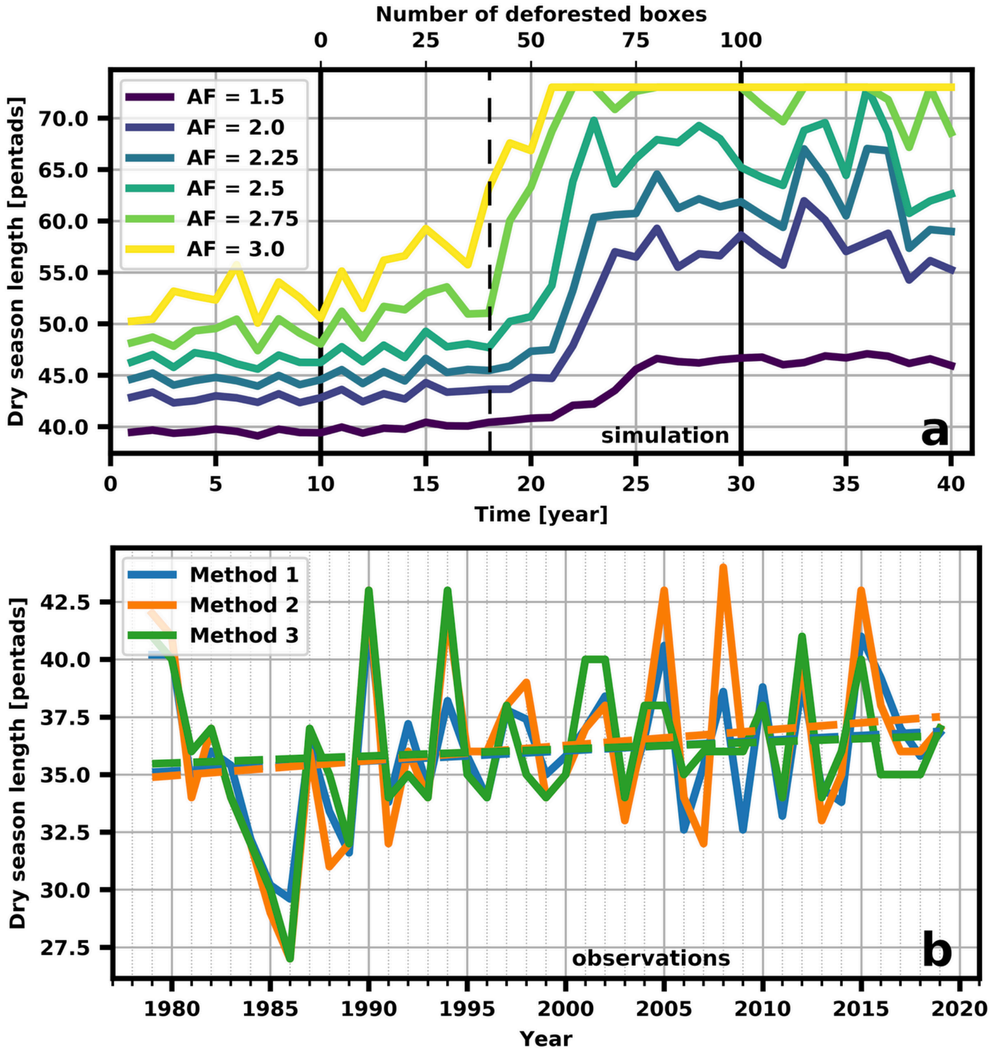
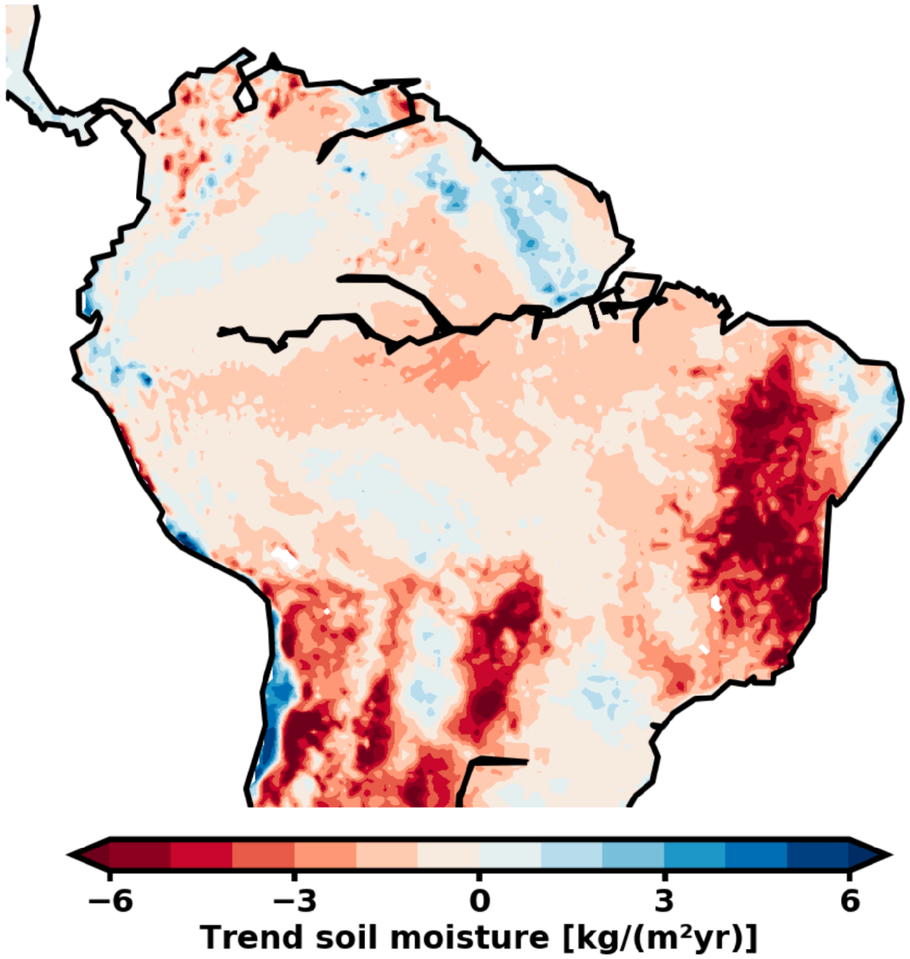
Physical EWS:

Increasing dry-season length



Decreasing Soil moisture



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Conclusions

- Paleoclimate records and theory suggest climate tipping events are possible
- Empirical data suggests that stability of some multistable Earth system components has been decreasing but uncertainties are too large to predict tipping times

BUT

- Observational records are short -> information on Tipping Elements is limited
- Climate models exhibit considerable spread and appear to be too stable -> Predictions of tipping points and their impacts uncertain

Outlook

ClimTip

Uncertainty-aware Quantification of climate tipping potential and climatic, ecological, and socioeconomic impacts (2024-2028)

- Improve representation of Tipping Elements in Earth System Models, e.g. using rare-event and CSD techniques
- Constrain position of critical forcing thresholds ("tipping points") to identify safe operating spaces
- High-resolution simulations of impacts of major tipping events on climate, ecosystems, biodiversity, society & economy

We'll have a TP conference at the IHP in 2025 :)

Thank you!

n.boers@tum.de

boers@pik-potsdam.de

This work has received funding from the VolkswagenStiftung and the European Union's Horizon 2020 research and innovation programme under grant agreement No. 820970