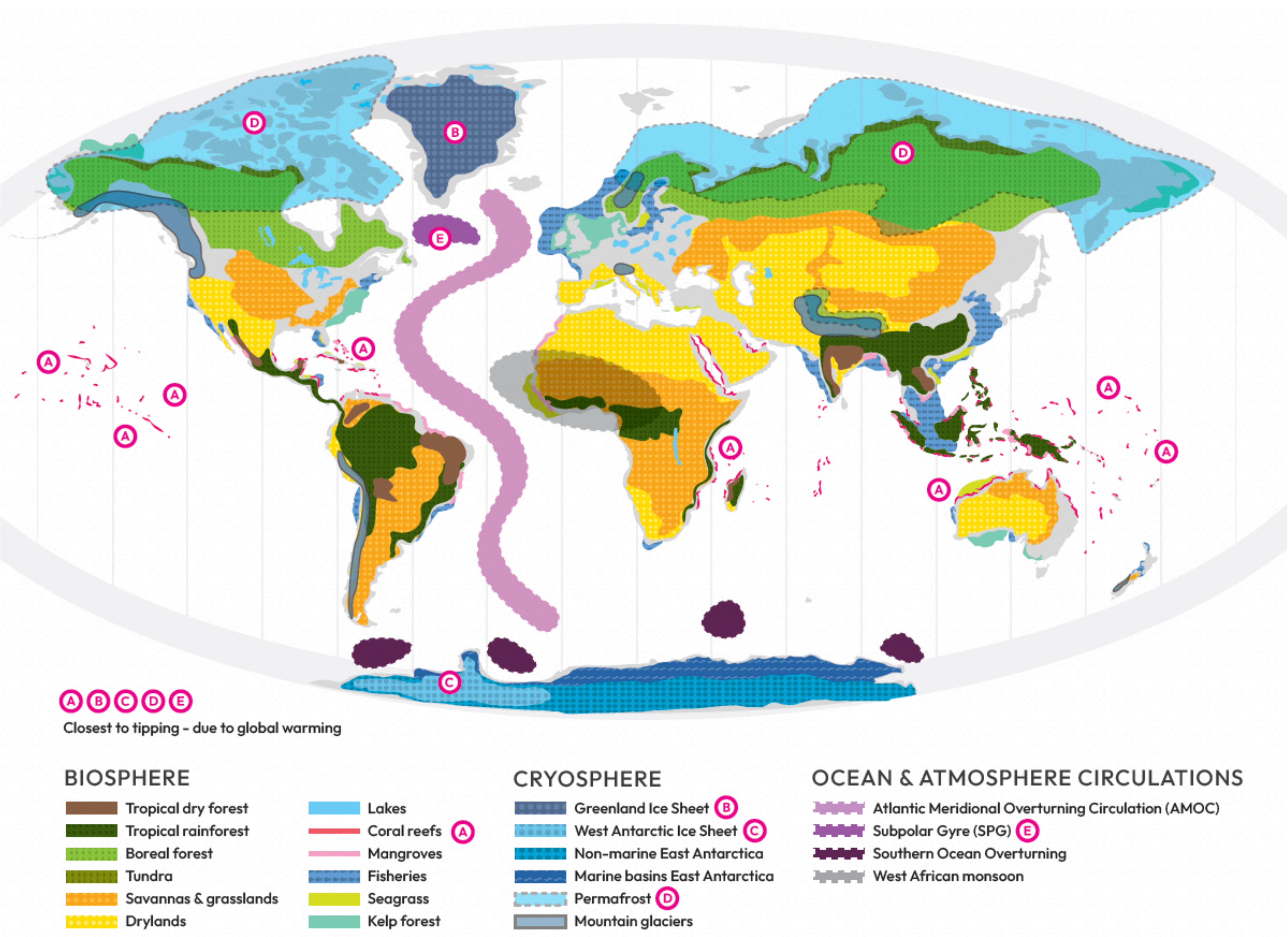
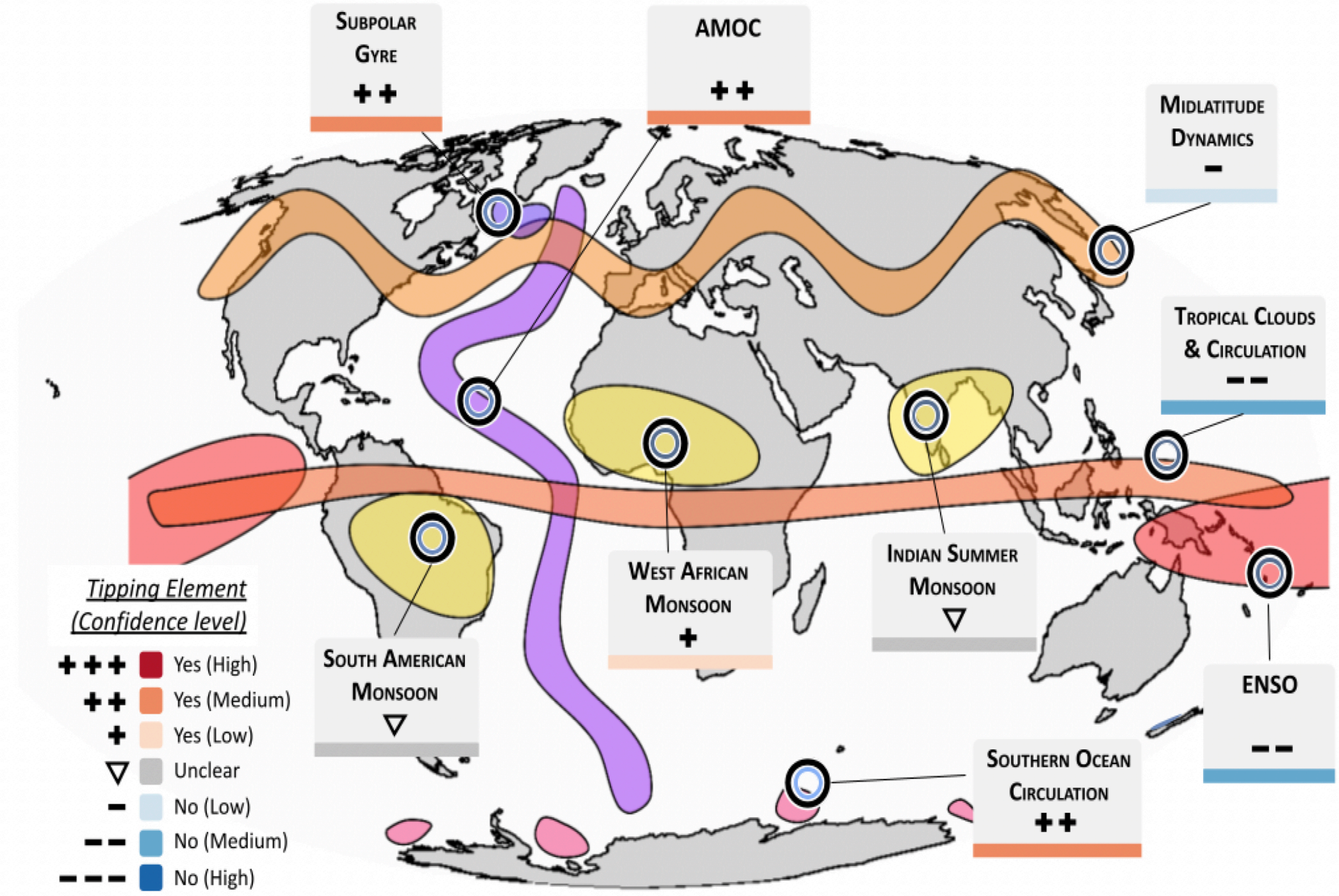
Tipping Behavior in the Climate System



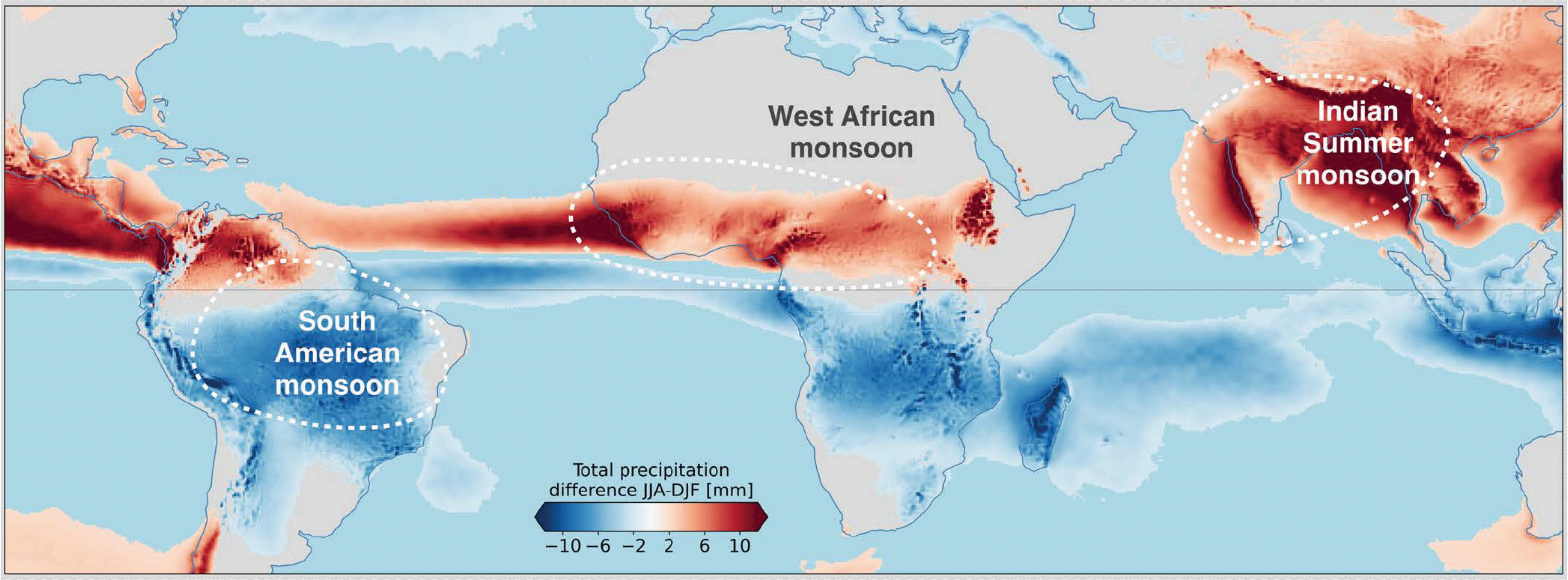
Henk Dijkstra,
Department of Physics,
Utrecht University, NL
&
DICAM,
University of Trento, IT

Tipping Elements: Atmosphere

Utrecht University

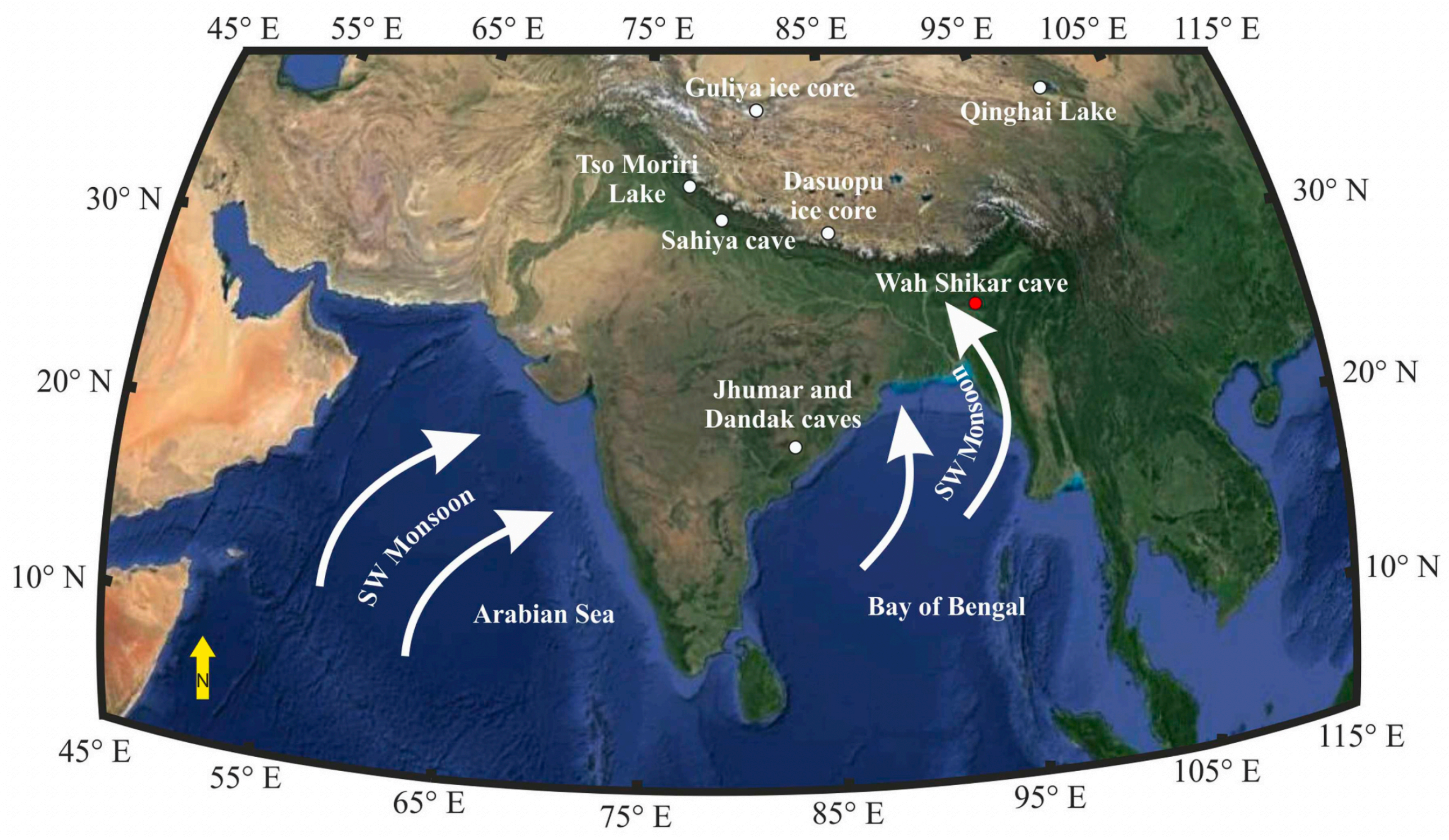


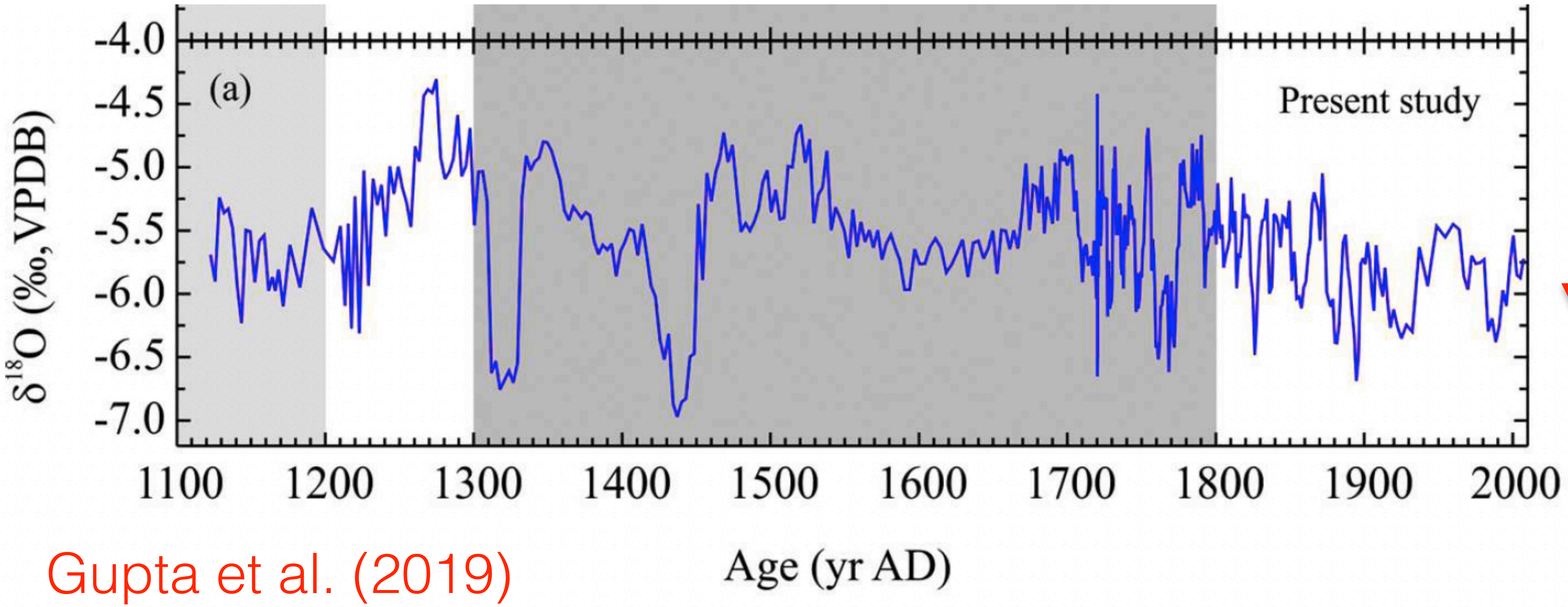
Indian Summer Monsoon



Tipping Behavior (?)

Cave record





More precipitation
(Stronger ISM)

Gupta et al. (2019)

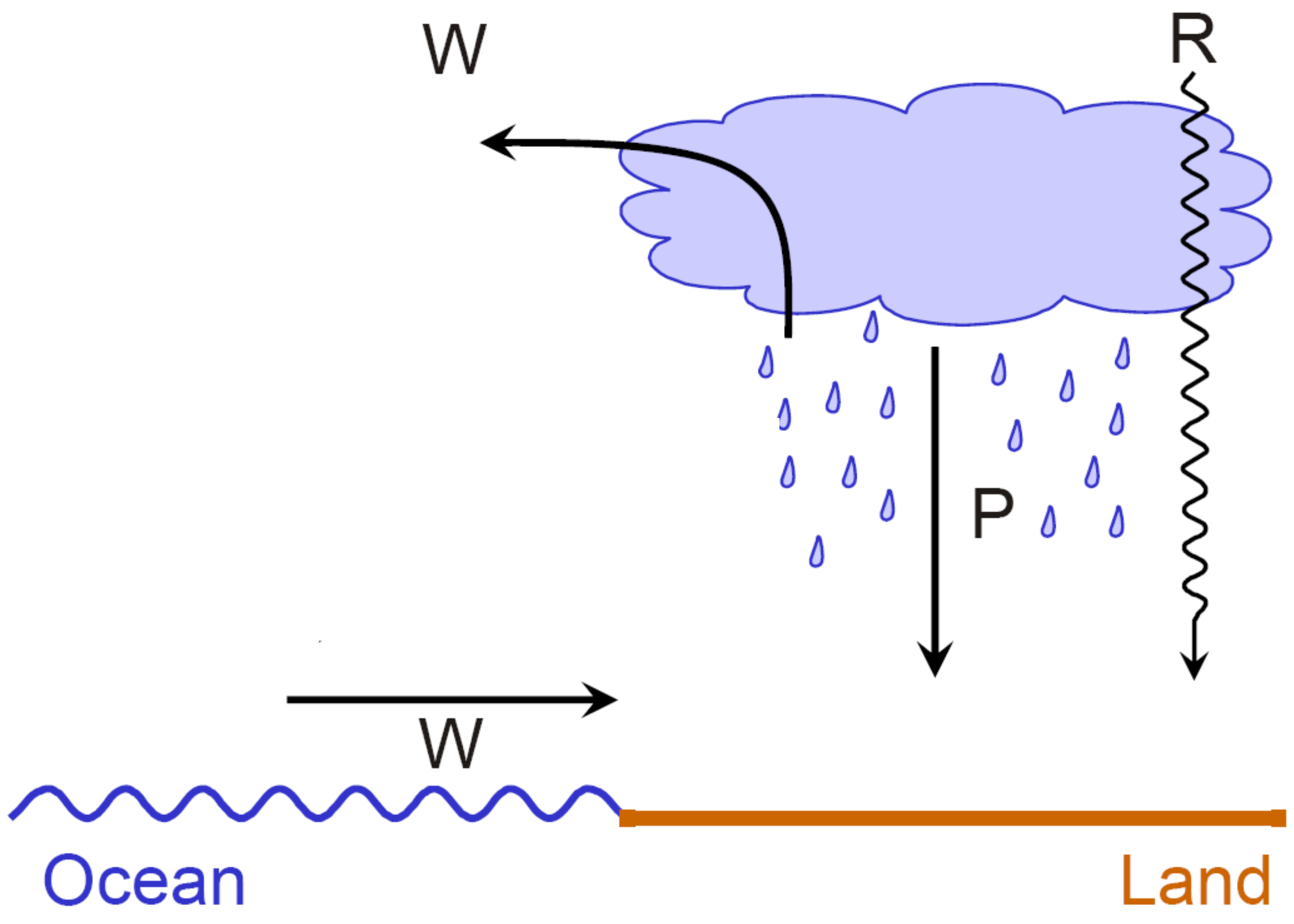
ISM Model

$$\frac{dq}{dt} = \frac{E - P + A_V}{\beta I_q}$$

$$E = C_E(T - T_{OC})(q_{sat} - q)$$

$$P = C_p q$$

$$A_V = (T - T_{OC})(C_{mo} q_{OC} - C_{ml} q)$$

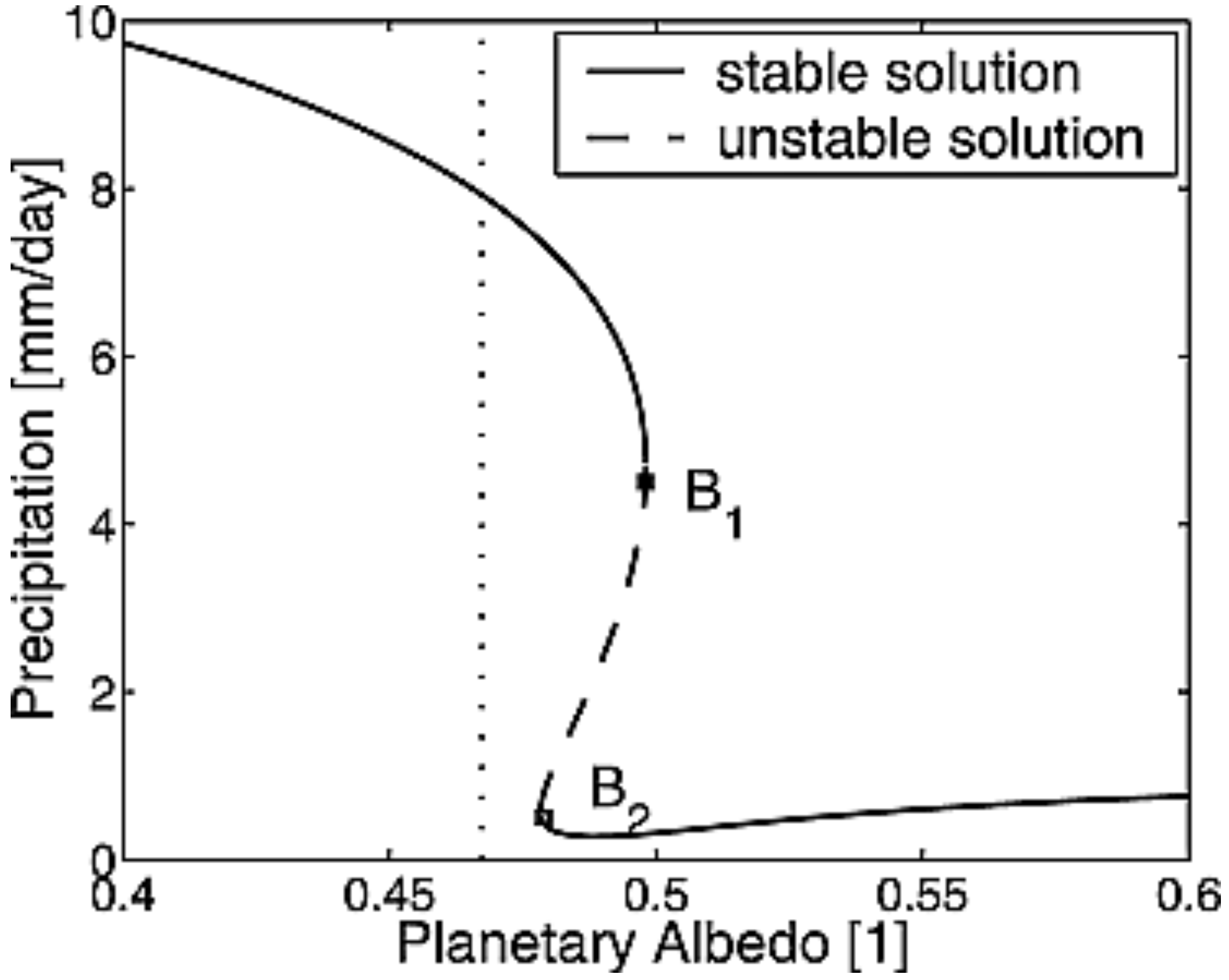


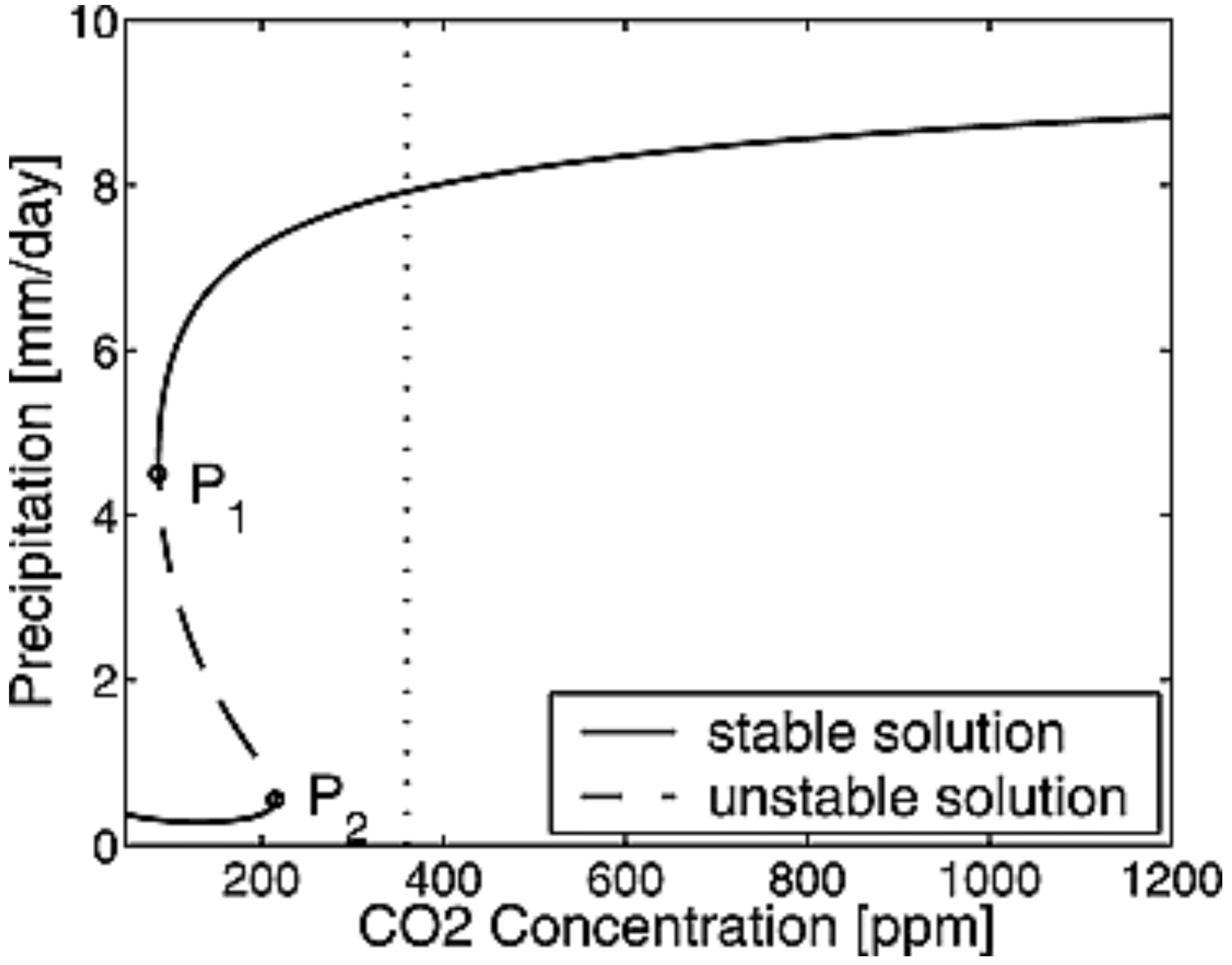
$$\frac{dT}{dt} = \frac{L(P - E) + F_{LW} + F_{SW}(1 - \alpha) + A_T}{\beta I_T}$$

$$F_{LW} = C_{L1} T + C_{L2}$$

$$A_T = C_H(T - T_{OC})(\theta_{OC} - \theta(q, T))$$

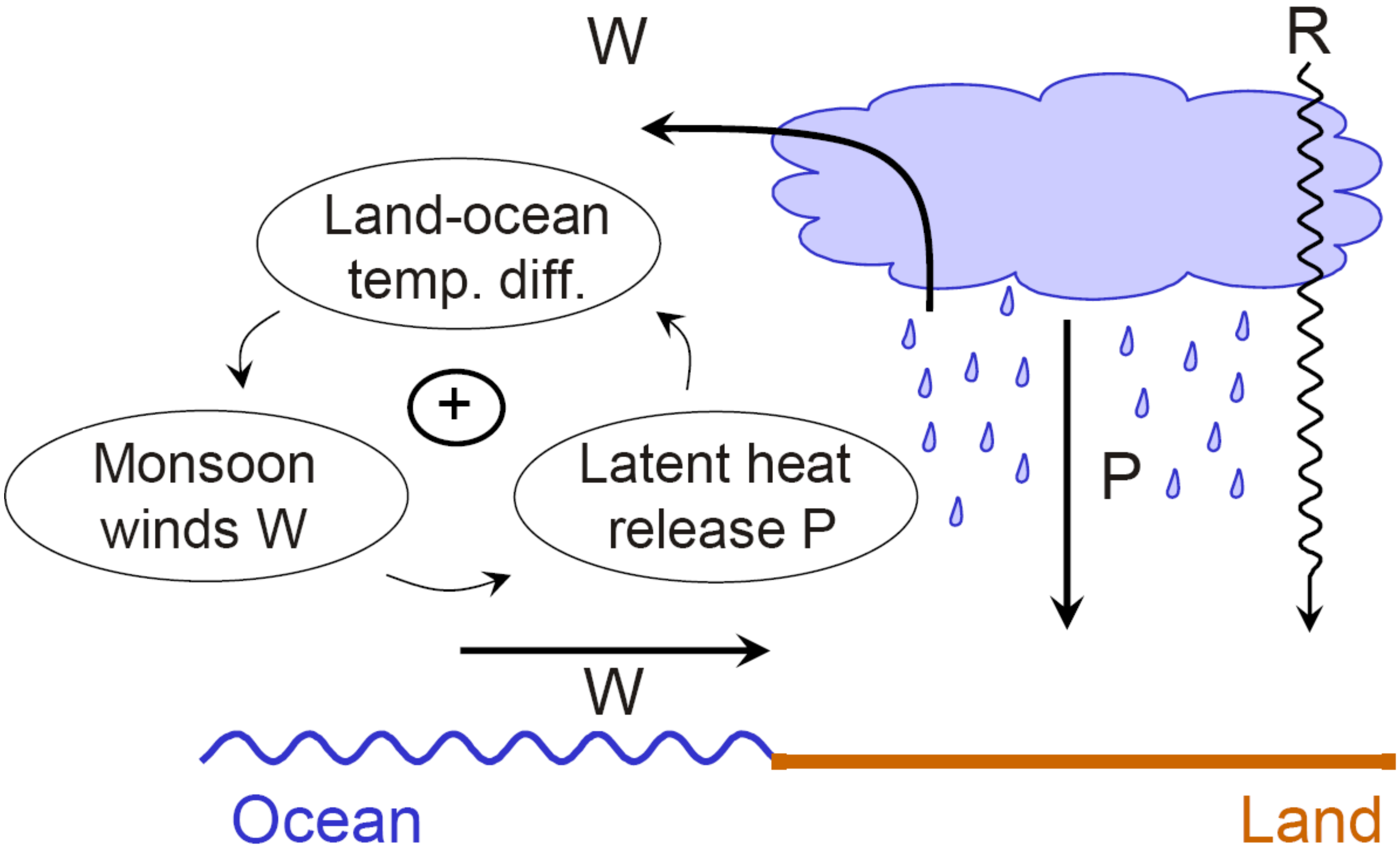
Bifurcation diagrams





Zickfeld et al. (2005)

Mechanism
Moisture-advection feedback



Slow-fast systems

$$\frac{d\mathbf{x}}{dt} = \mathbf{f}(\mathbf{x}, \mathbf{y}),$$

$$\frac{d\mathbf{y}}{dt} = \epsilon \mathbf{g}(\mathbf{x}, \mathbf{y}),$$

x: state vector

y: parameter vector (e.g. forcing)

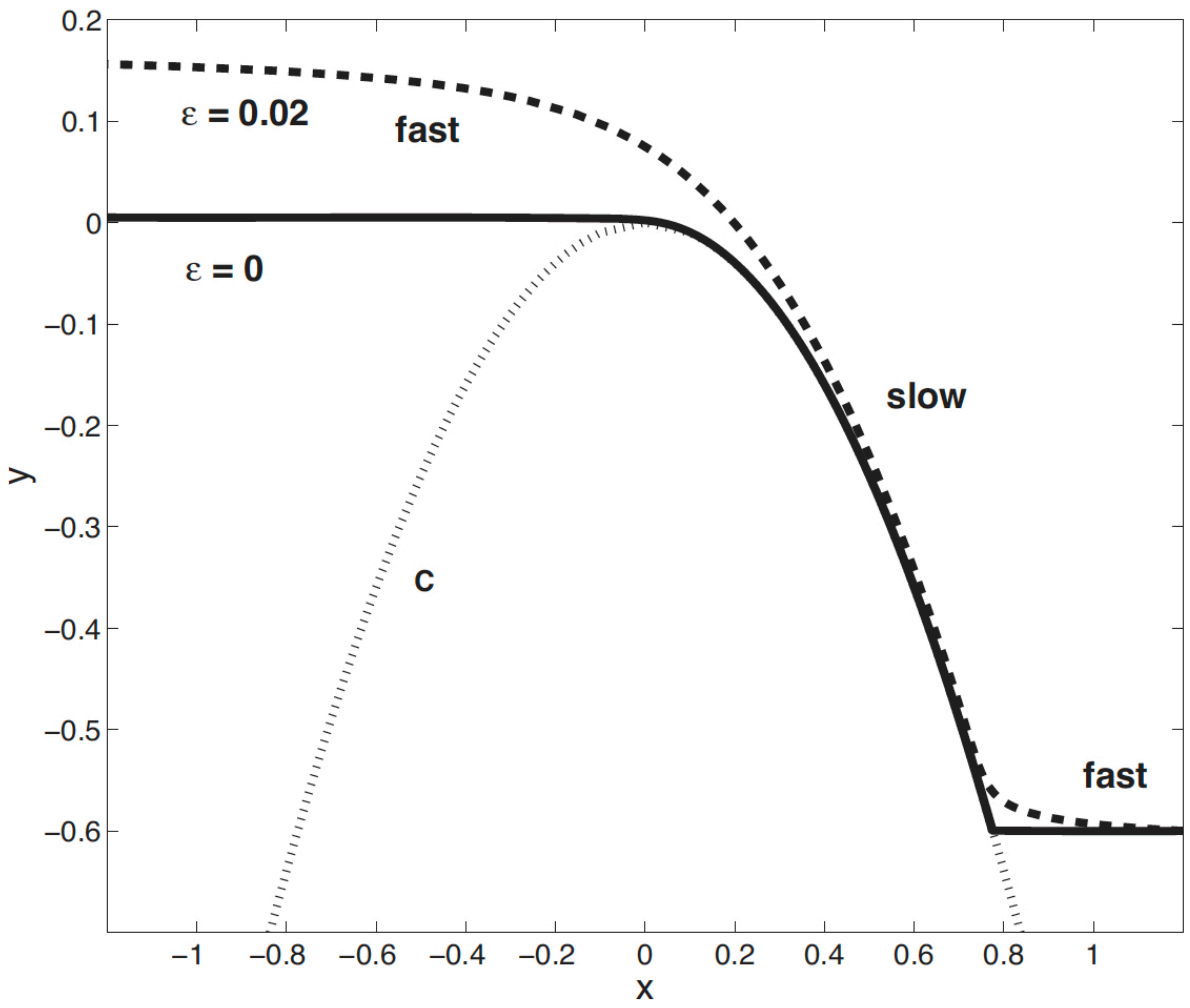
$$\tau = \epsilon t \quad \Rightarrow \quad \begin{aligned} \epsilon \frac{d\mathbf{x}}{d\tau} &= \mathbf{f}(\mathbf{x}, \mathbf{y}), \\ \frac{d\mathbf{y}}{d\tau} &= \mathbf{g}(\mathbf{x}, \mathbf{y}), \end{aligned}$$

$$\epsilon = 0 : \quad \left\{ C = \left\{(\mathbf{x}, \mathbf{y}) \in \mathbb{R}^{d+p} : \mathbf{f}(\mathbf{x}, \mathbf{y}) = 0\right\} \right.$$

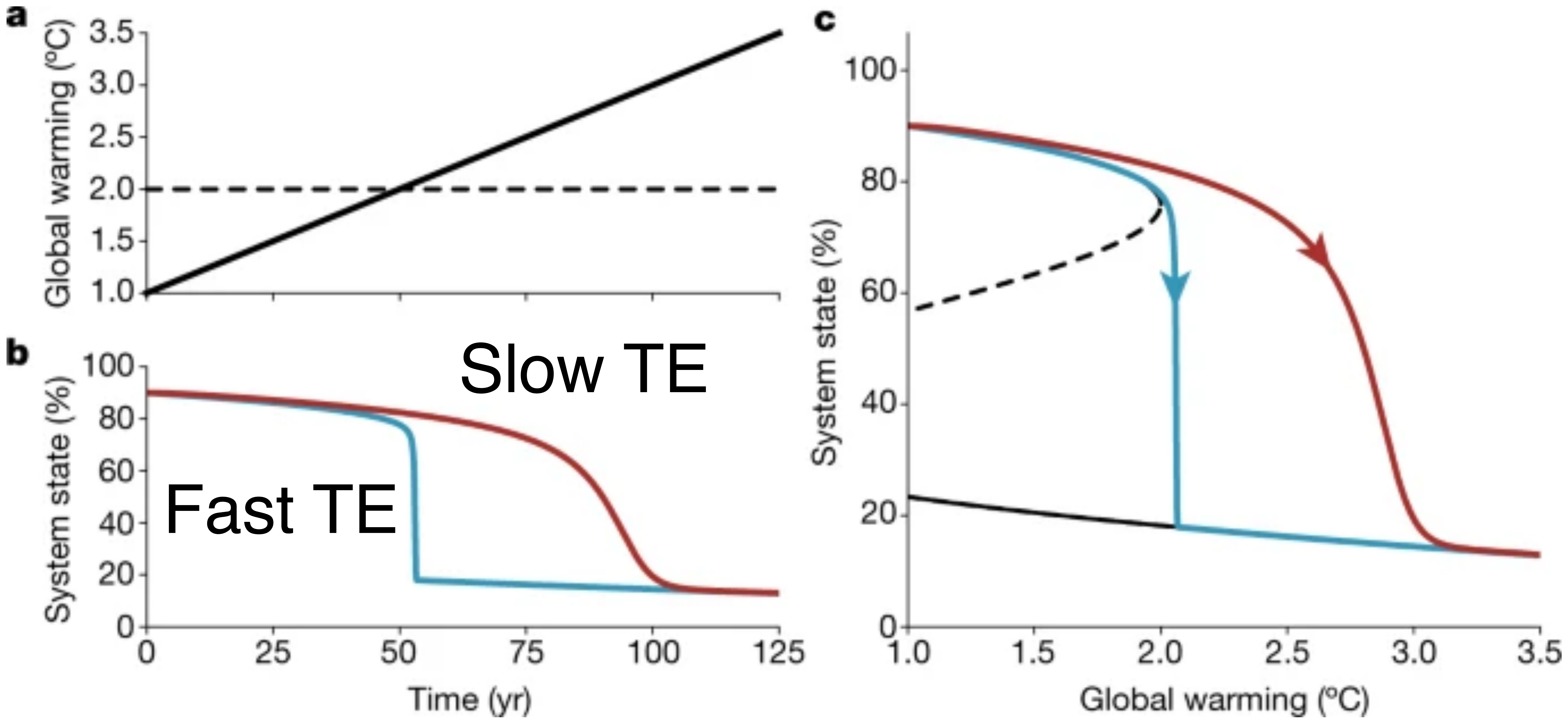
critical manifold

Slow-fast saddle-node bifurcation

$$\epsilon \frac{dx}{d\tau} = -y - x^2,$$
$$\frac{dy}{d\tau} = 1.$$

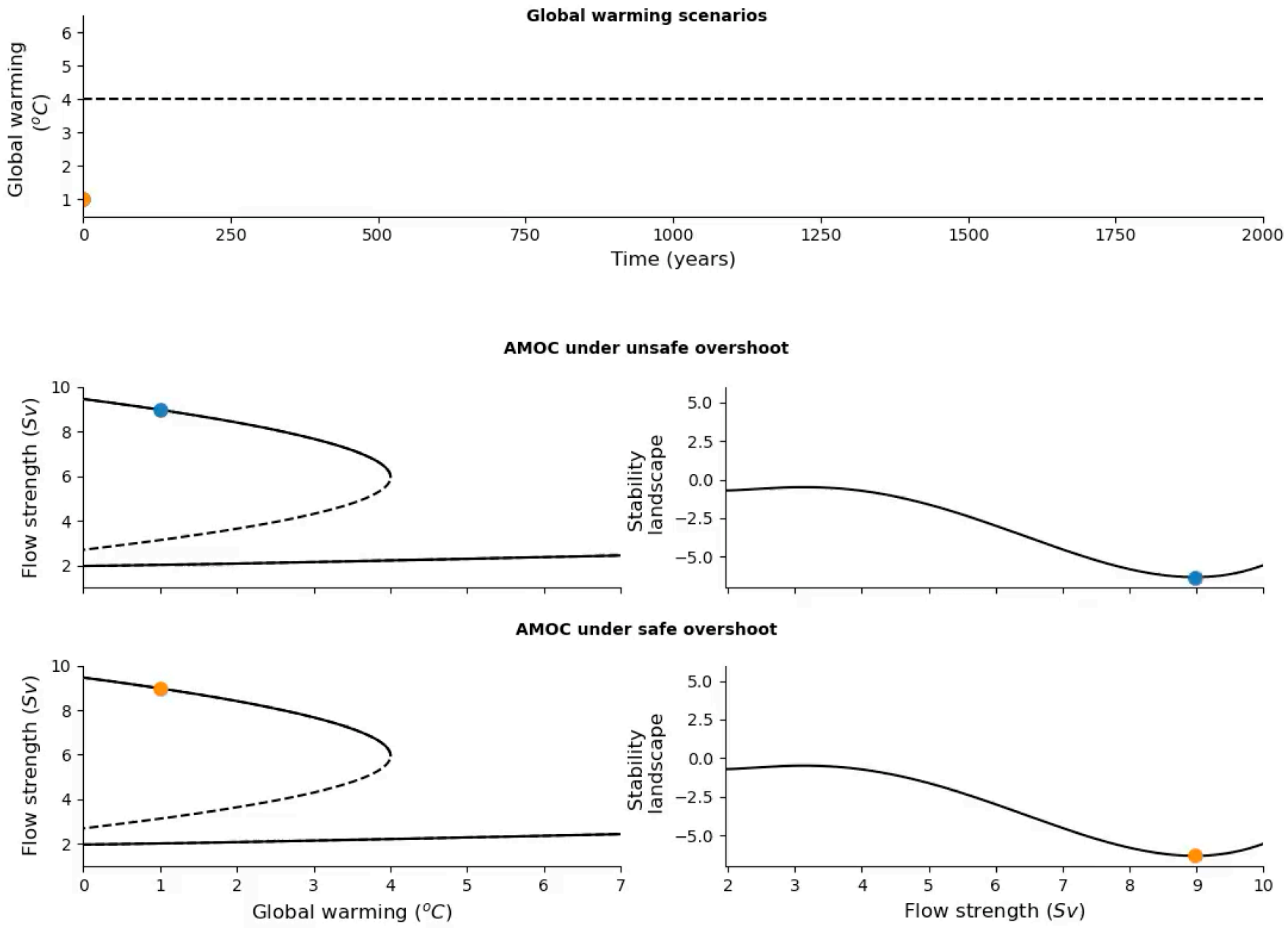


Overshoot phenomena



Ritchie et al. (2021)

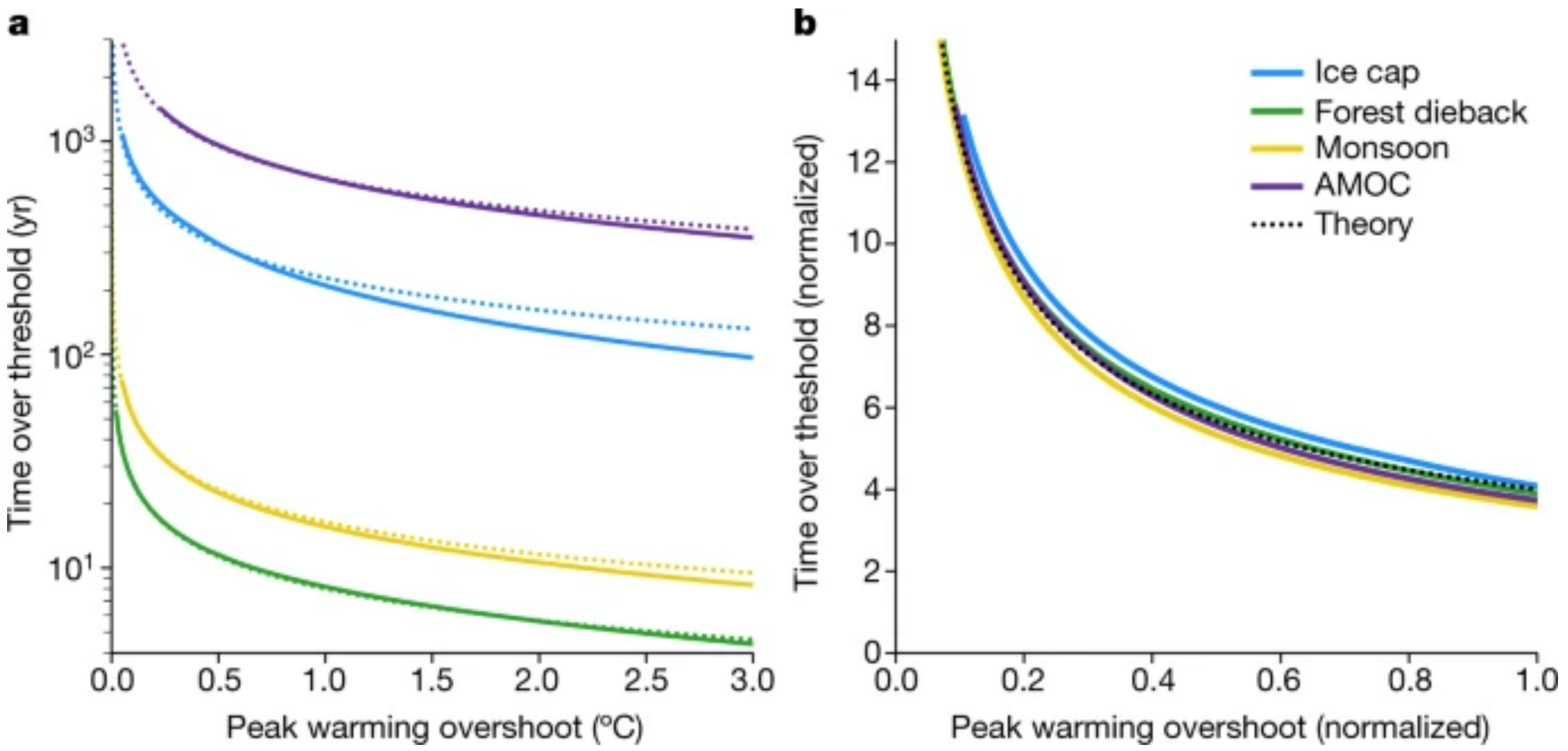
Safe vs unsafe overshoots



Video 2 : Illustration of overshooting a tipping point threshold in a model for the Atlantic Meridional Overturning Circulation (AMOC) as shown in Figure 2 of Ritchie et al. (2021). Valleys or wells in the stability landscapes represent stable states of the system and the ball indicates the current state the system resides in. As the tipping point threshold is approached the right-hand well becomes shallower before vanishing at the tipping point threshold. If the warming is reversed too slowly the ball transitions to the left. However, a sufficiently fast reversal and the right-hand well will reform in time to catch the ball and prevent tipping.

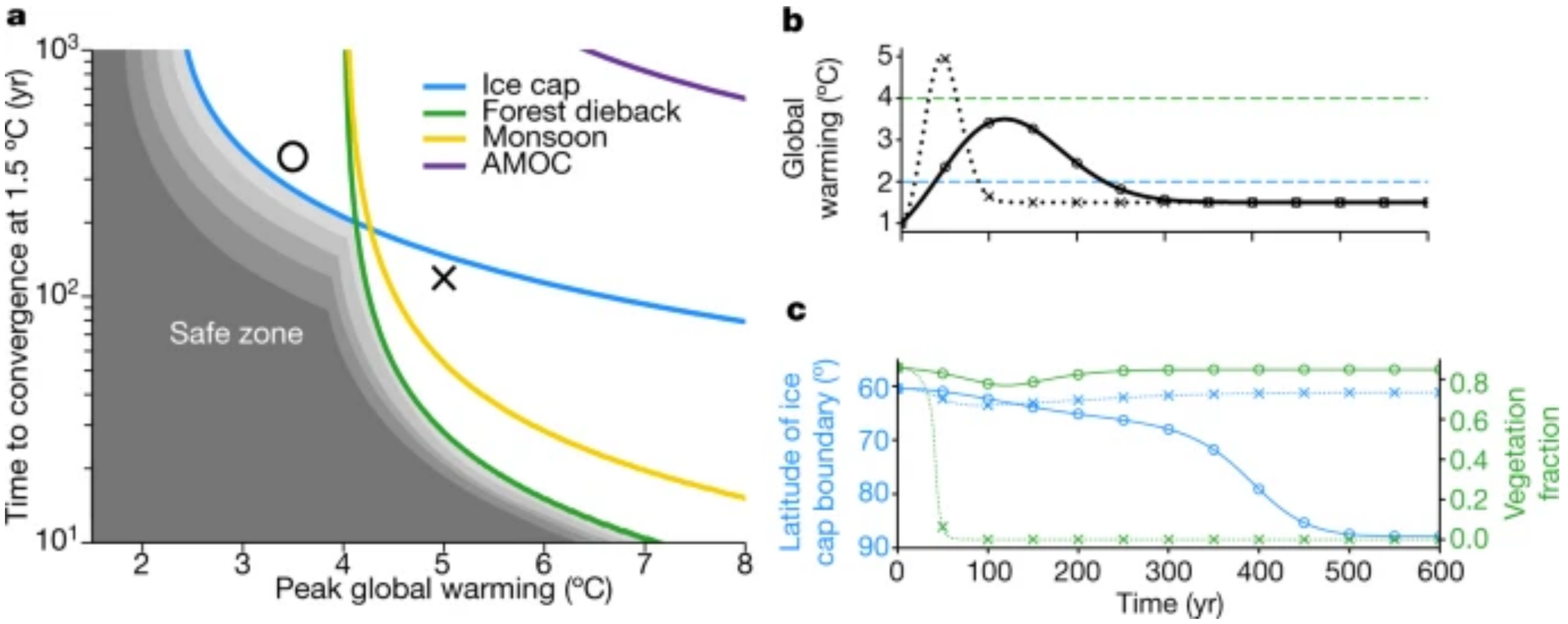
Ritchie et al. (2021)

Dependence on parameters



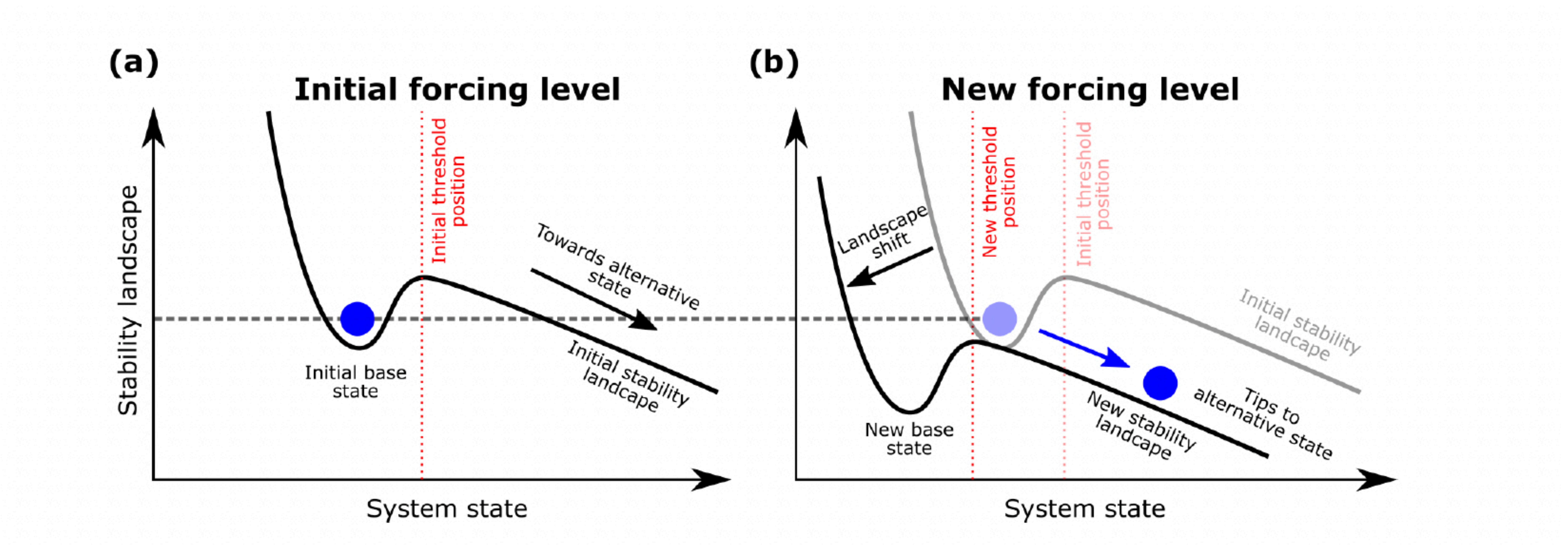
Ritchie et al. (2021)

Safe vs unsafe overshoots



Ritchie et al. (2021)

Rate induced tipping

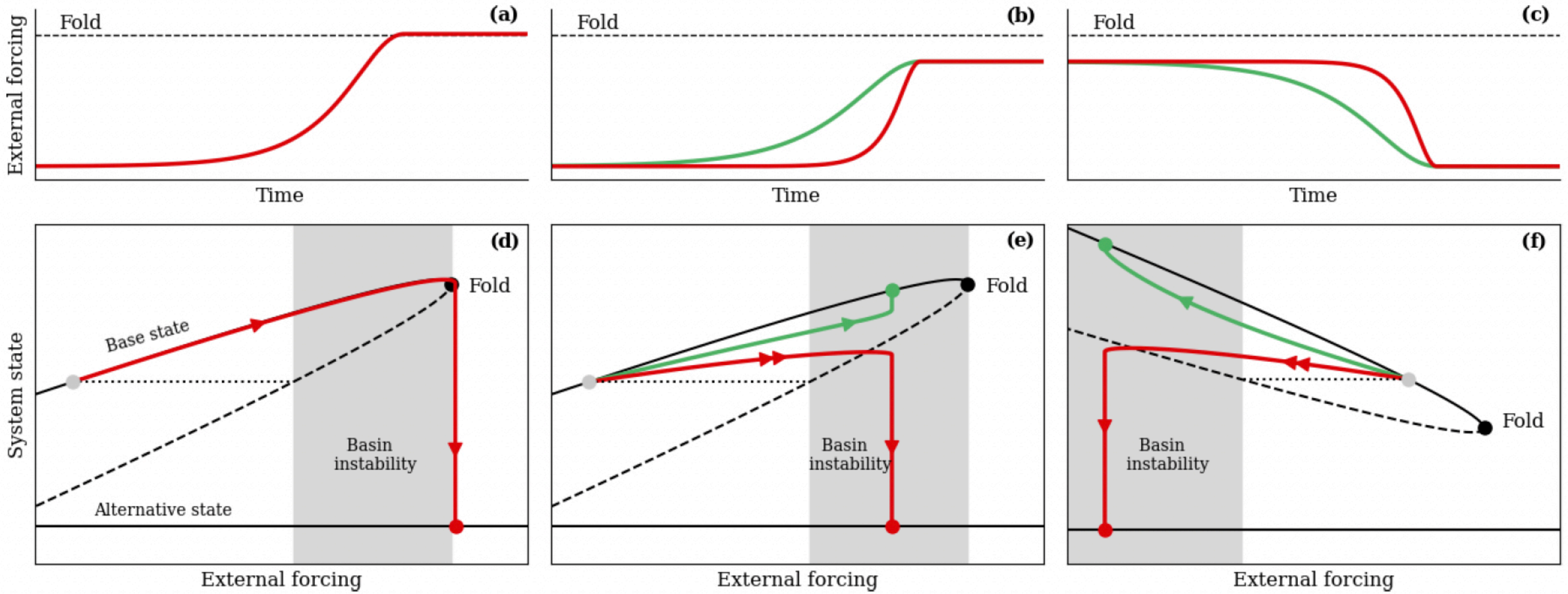


Rate of forcing changes slow: state will follow landscape and stay near equilibrium

Rate of forcing changes fast: state will tip

-> Critical rate for tipping

Rate induced tipping



Rate Induced Tipping

Bifurcation Tipping

Return Tipping

Ritchie et al. (2023)

AMOC collapse paper

SCIENCE ADVANCES | RESEARCH ARTICLE

OCEANOGRAPHY

van Westen *et al.*, *Sci. Adv.* **10**, eadk1189 (2024) 9 February 2024

Physics-based early warning signal shows that AMOC is on tipping course

René M. van Westen*, Michael Kliphuis, Henk A. Dijkstra

One of the most prominent climate tipping elements is the Atlantic meridional overturning circulation (AMOC), which can potentially collapse because of the input of fresh water in the North Atlantic. Although AMOC collapses have been induced in complex global climate models by strong freshwater forcing, the processes of an AMOC tipping event have so far not been investigated. Here, we show results of the first tipping event in the Community Earth System Model, including the large climate impacts of the collapse. Using these results, we develop a physics-based and observable early warning signal of AMOC tipping: the minimum of the AMOC-induced freshwater transport at the southern boundary of the Atlantic. Reanalysis products indicate that the present-day AMOC is on route to tipping. The early warning signal is a useful alternative to classical statistical ones, which, when applied to our simulated tipping event, turn out to be sensitive to the analyzed time interval before tipping.

Utrecht University

World News

The Washington Post
Democracy Dies in Darkness

Ocean system that moves heat gets closer to collapse, which could cause weather chaos, study says

By Seth Borenstein | AP
February 9, 2024 at 4:40 p.m. EST

Why this is one of the planetary shifts scientists are most worried about


By Sarah Kaplan

Updated February 9, 2024 at 3:10 p.m. EST | Published February 9, 2024 at 2:00 p.m. EST

Utrecht University

World News

World UK **Climate crisis** Ukraine Environment Science Global development Football Tech Business

Oceans

Atlantic Ocean circulation nearing 'devastating' tipping point, study finds

Collapse in system of currents that helps regulate global climate would be at such speed that adaptation would be impossible

Jonathan Watts
@jonathanwatts
Fri 9 Feb 2024 20.00 CET

The Guardian

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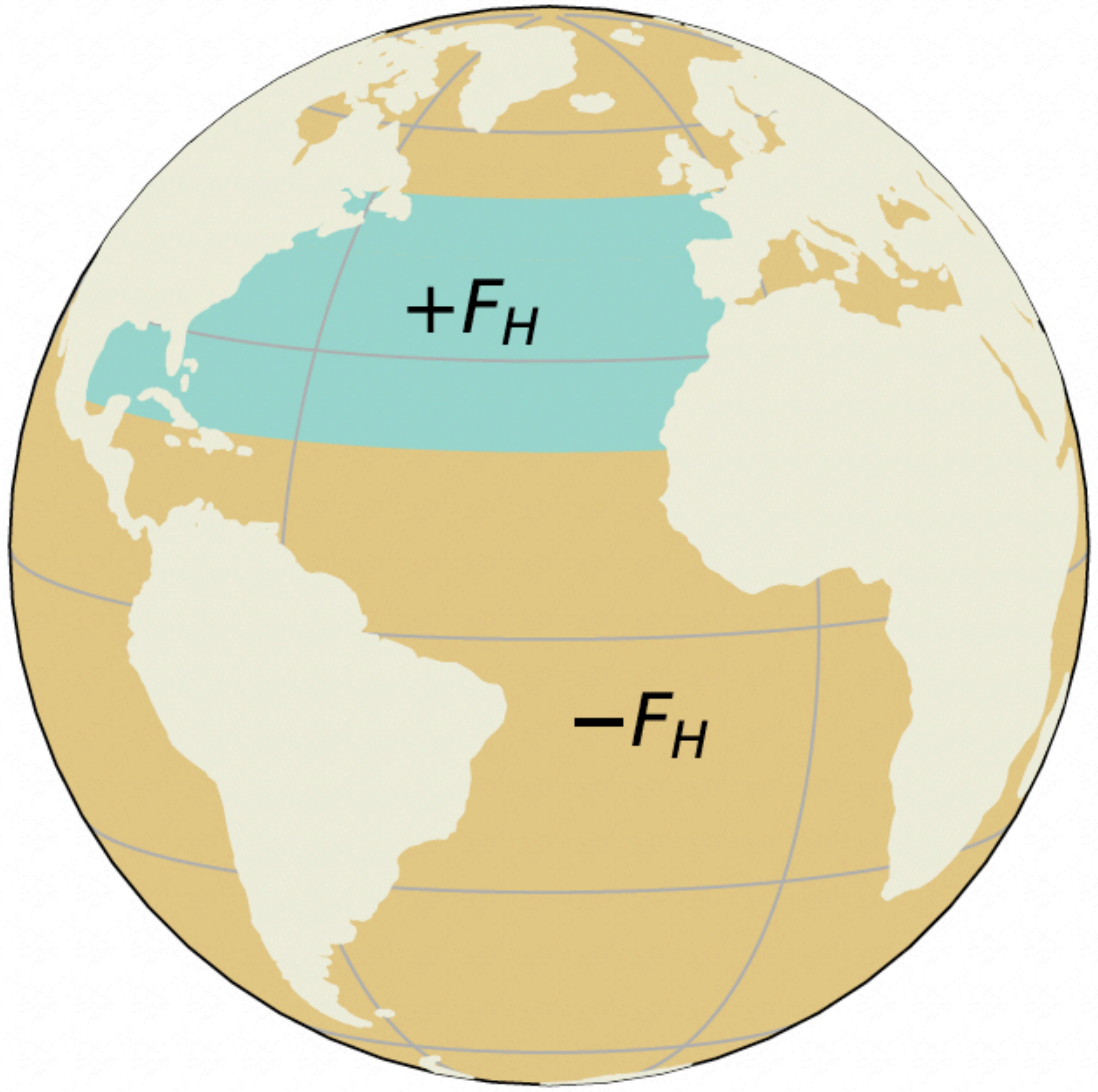
World / Climate

Critical Atlantic Ocean current system is showing early signs of collapse, prompting warning from scientists

By Laura Paddison, CNN
5 minute read · Published 2:00 PM EST, Fri February 9, 2024

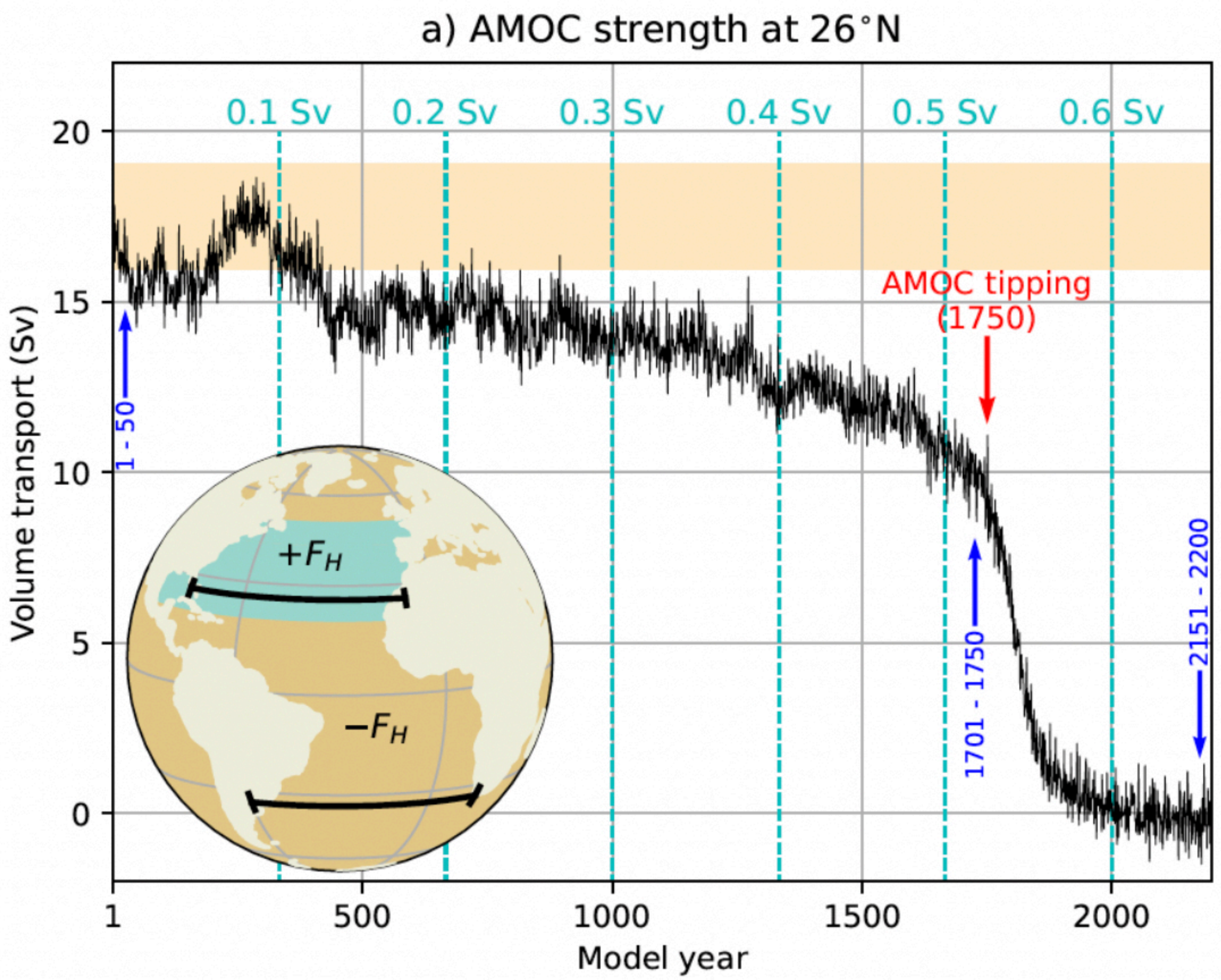
Recent UU-CESM1 Simulation



- CESM under pre-industrial (PI) conditions
  - Ocean resolution : 1°
  - Atmosphere resolution : 2°
  - Spin-up of 2,800 years
- $\dot{F}_H = 3 \times 10^{-4}$ Sv per year
  - Maximum in year 2,200: 0.66 Sv

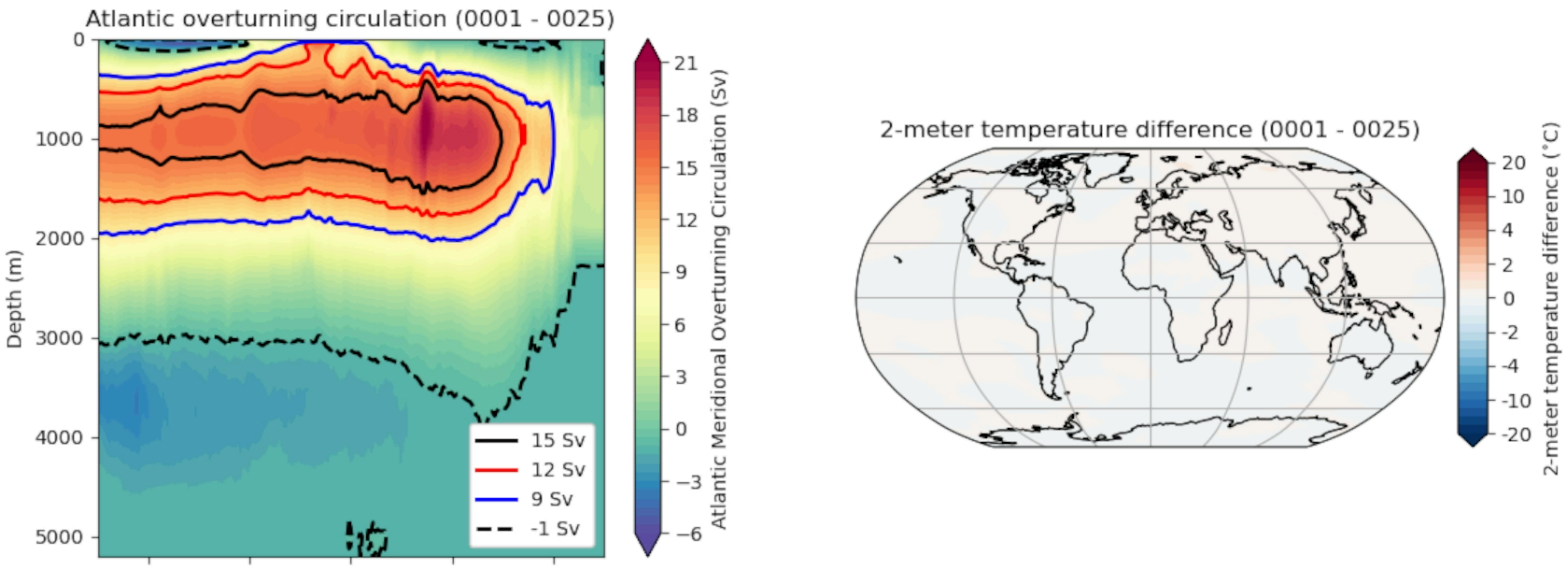
Van Westen et al. (2024)

Results: AMOC Collapse



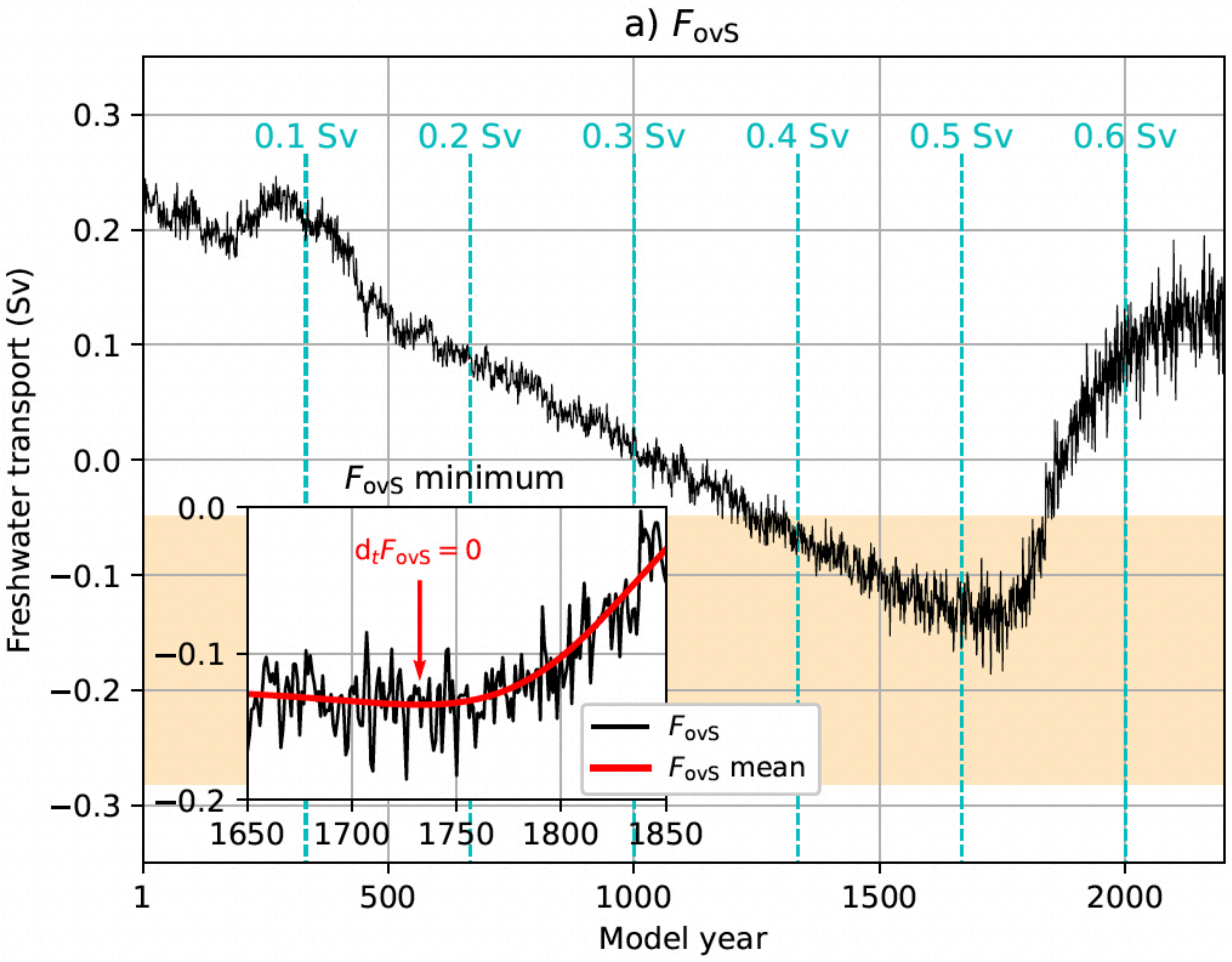
Van Westen et al. (2024)

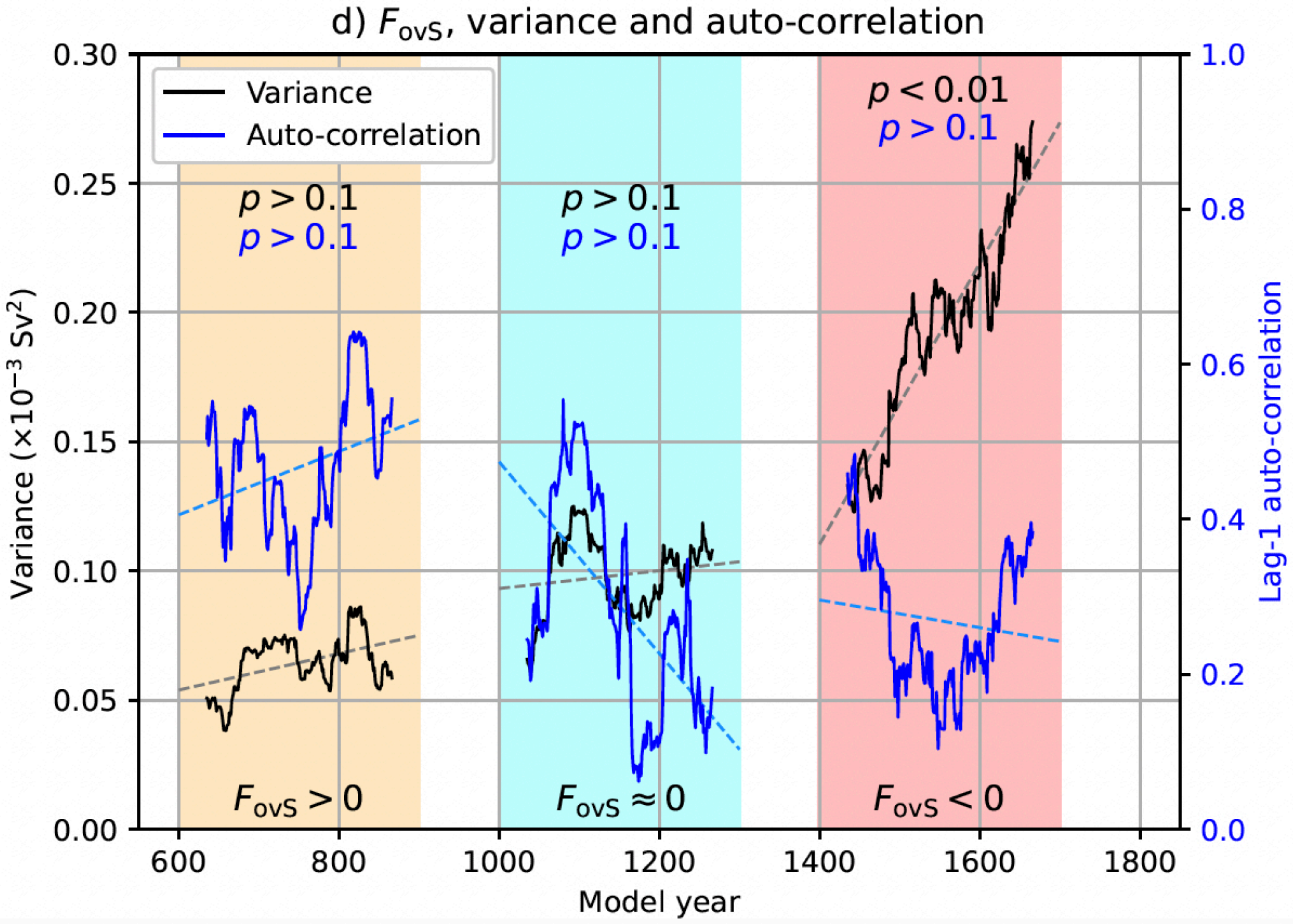
Impacts on Atmospheric Surface Temperature



Van Westen et al. (2024)

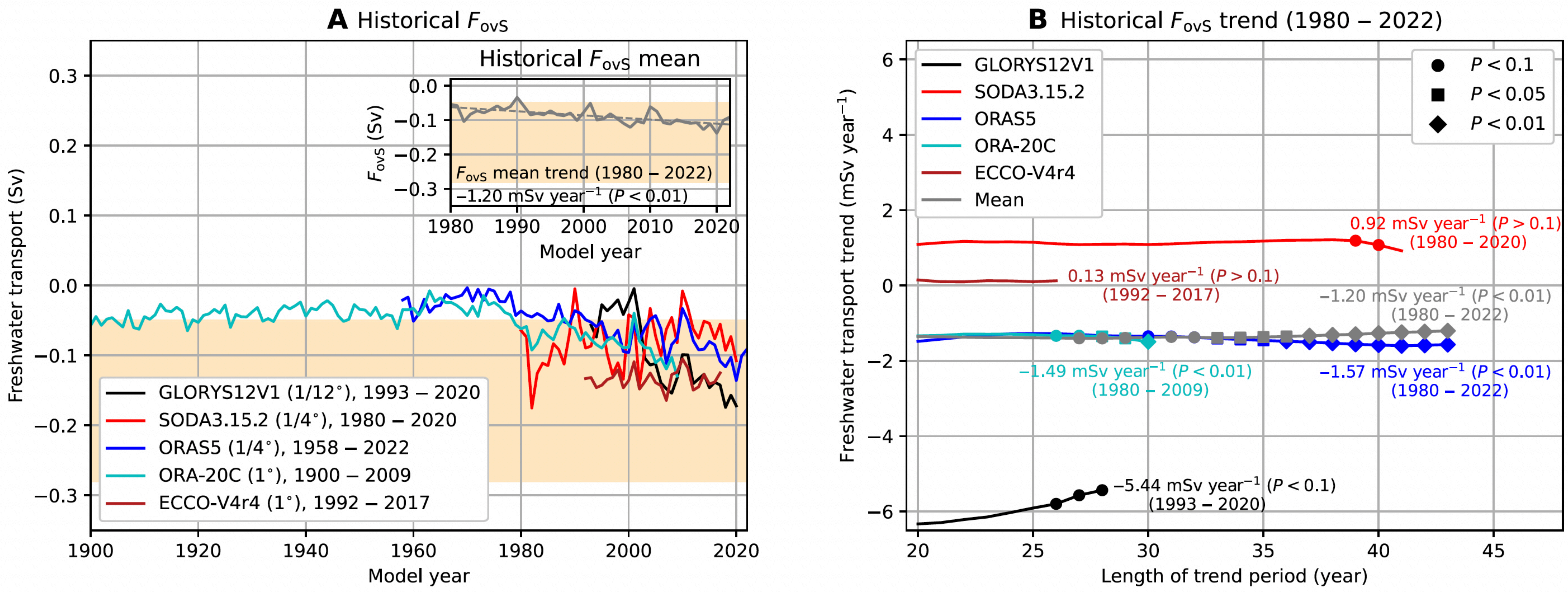
Novel early warning signal





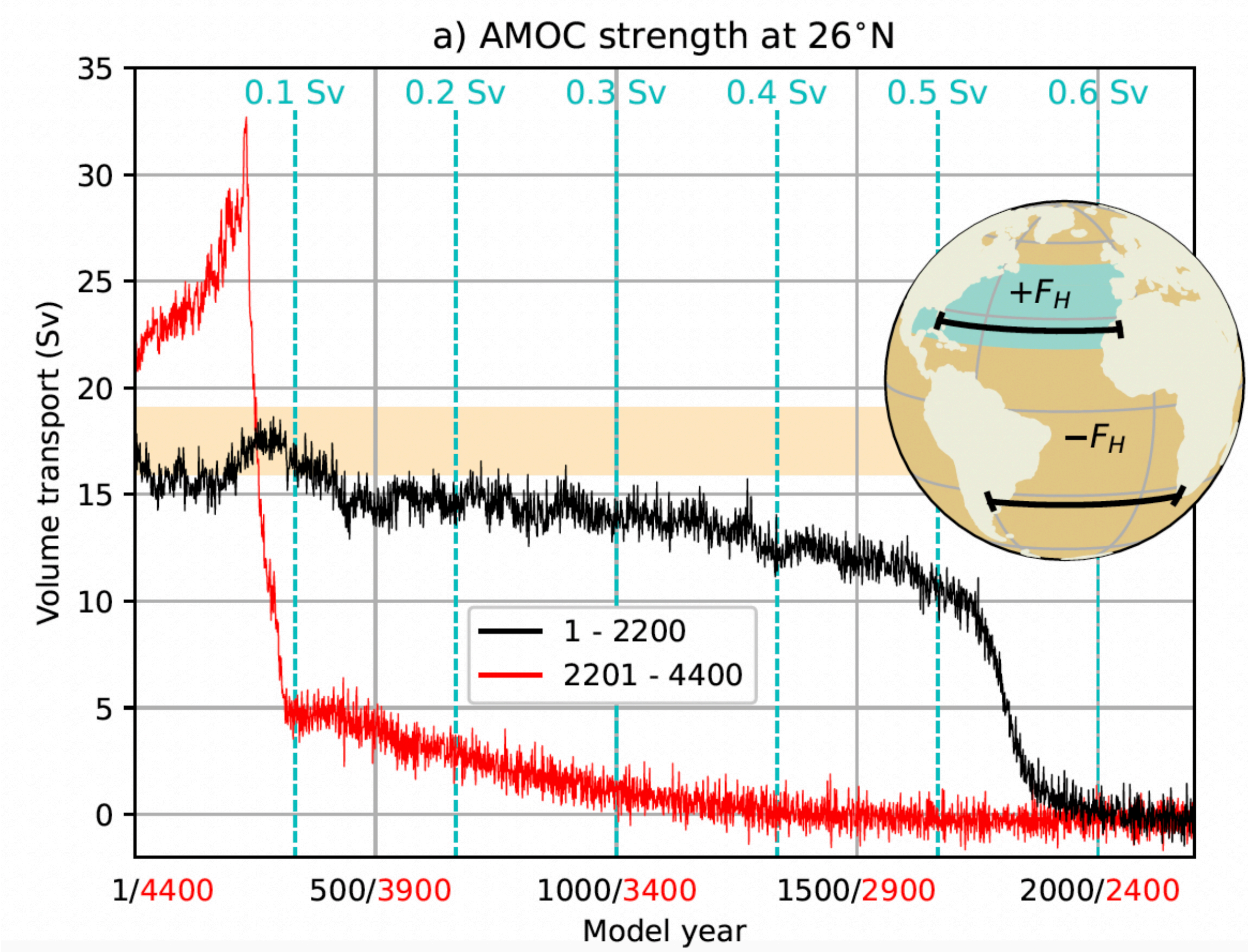
Van Westen et al. (2024)

AMOC on Tipping Course



Van Westen et al. (2024)

Reverse CESM Simulation



Van Westen & Dijkstra, GRL, in press (2023)

Exercises!