Tipping components of the climate system

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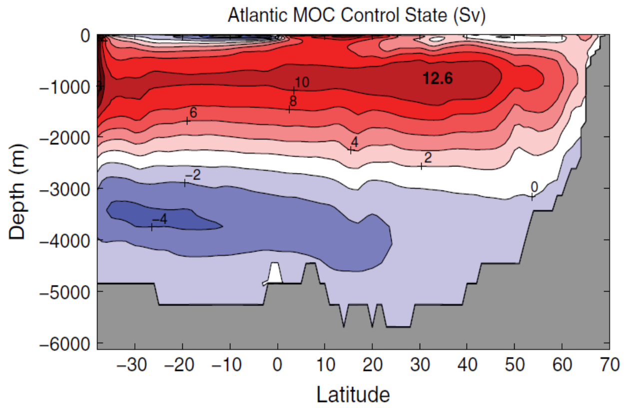
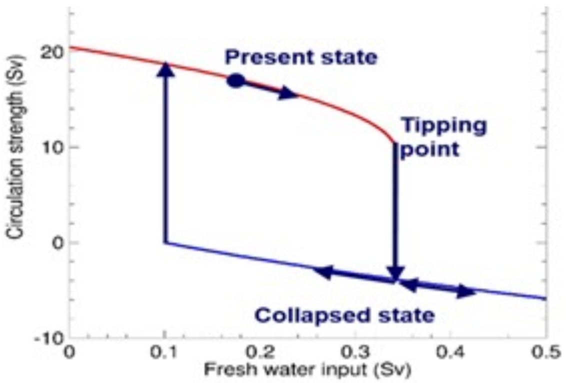
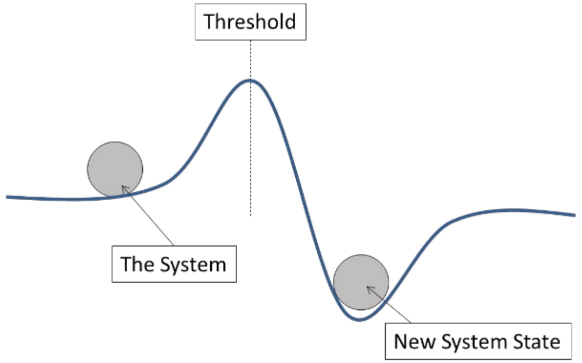
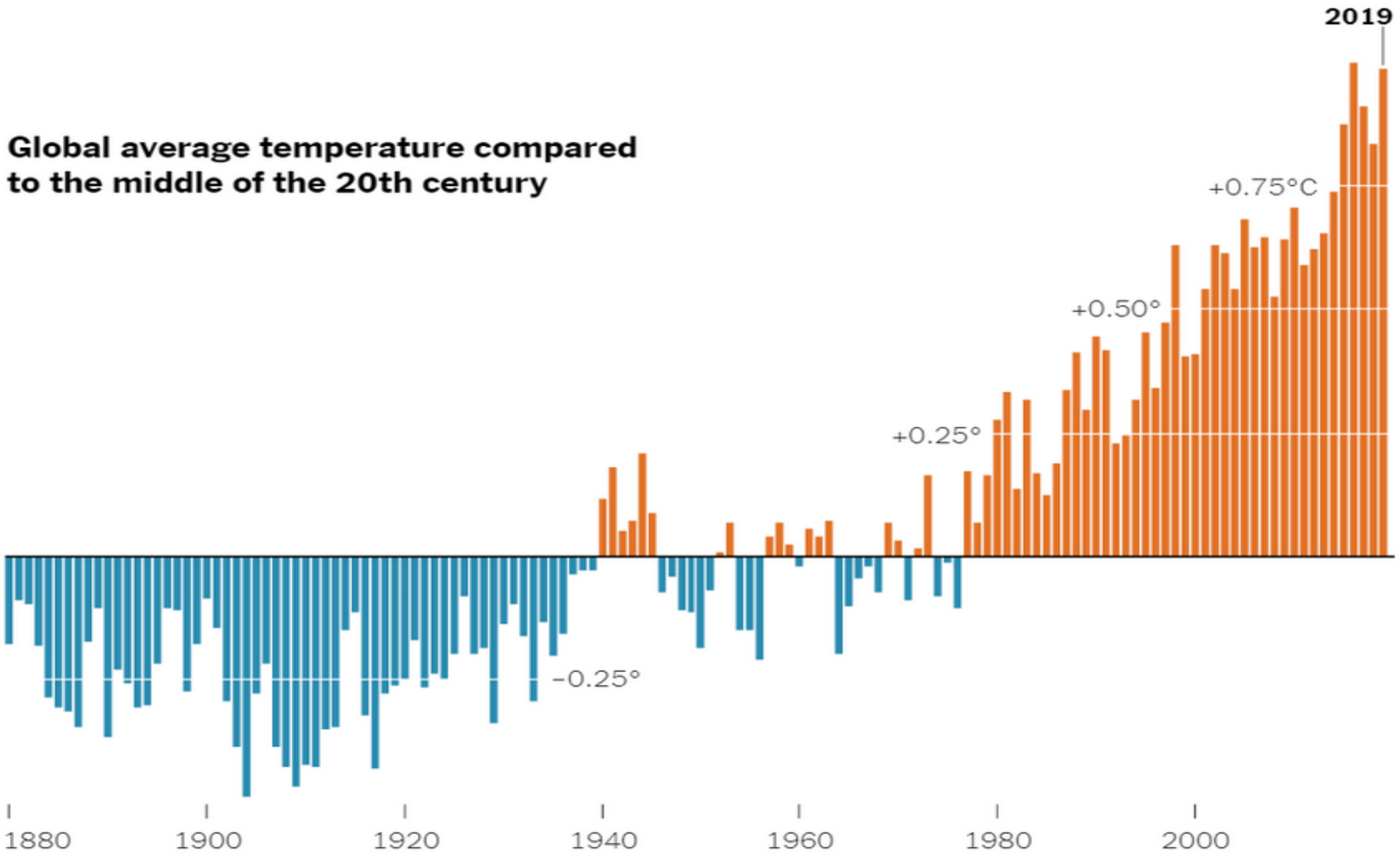




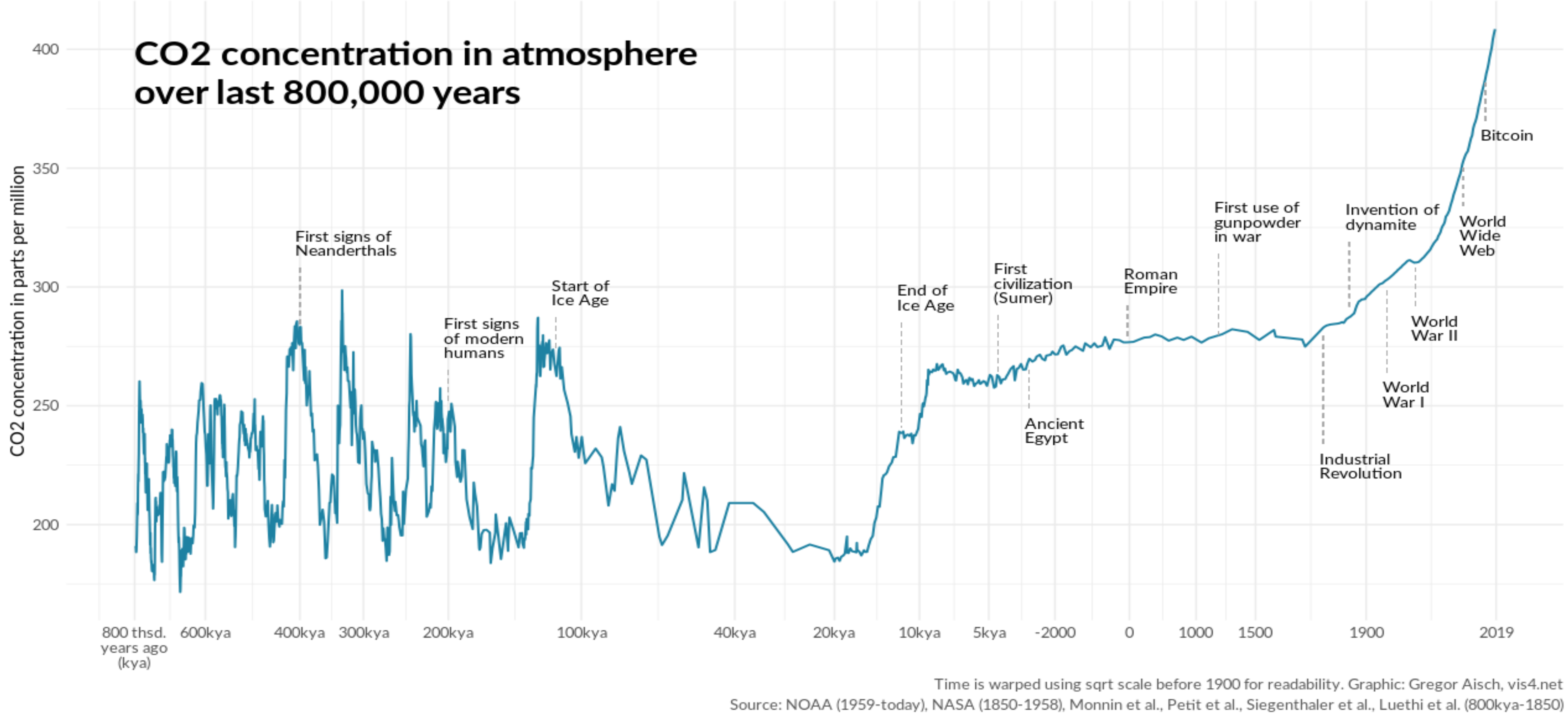


Global warming



- The Earth's surface is warming, due to human activity (greenhouse gases, e.g. CO_2).
- Should we be worried?

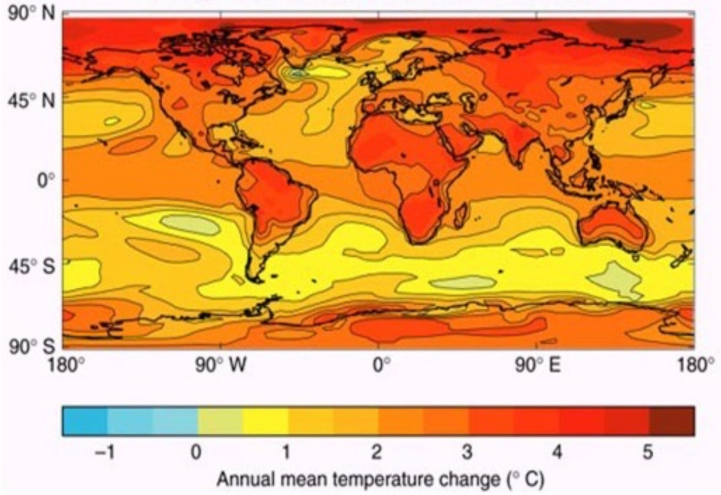
Evolution of atmospheric CO_2 concentration over the last 800.000 years



Evolutiion of atmospheric CO_2 concentration (ppmv) over the last 800.000 years, reconstructed based on a core in the Antarctic icesheet

- The increase of atmospheric CO_2 concentration in the last century is similar with that from glacial to interglacial transition.
- The growing rate is much higher than the natural one.
- Atmospheric CO_2 concentration is a climate parameter with global impact!

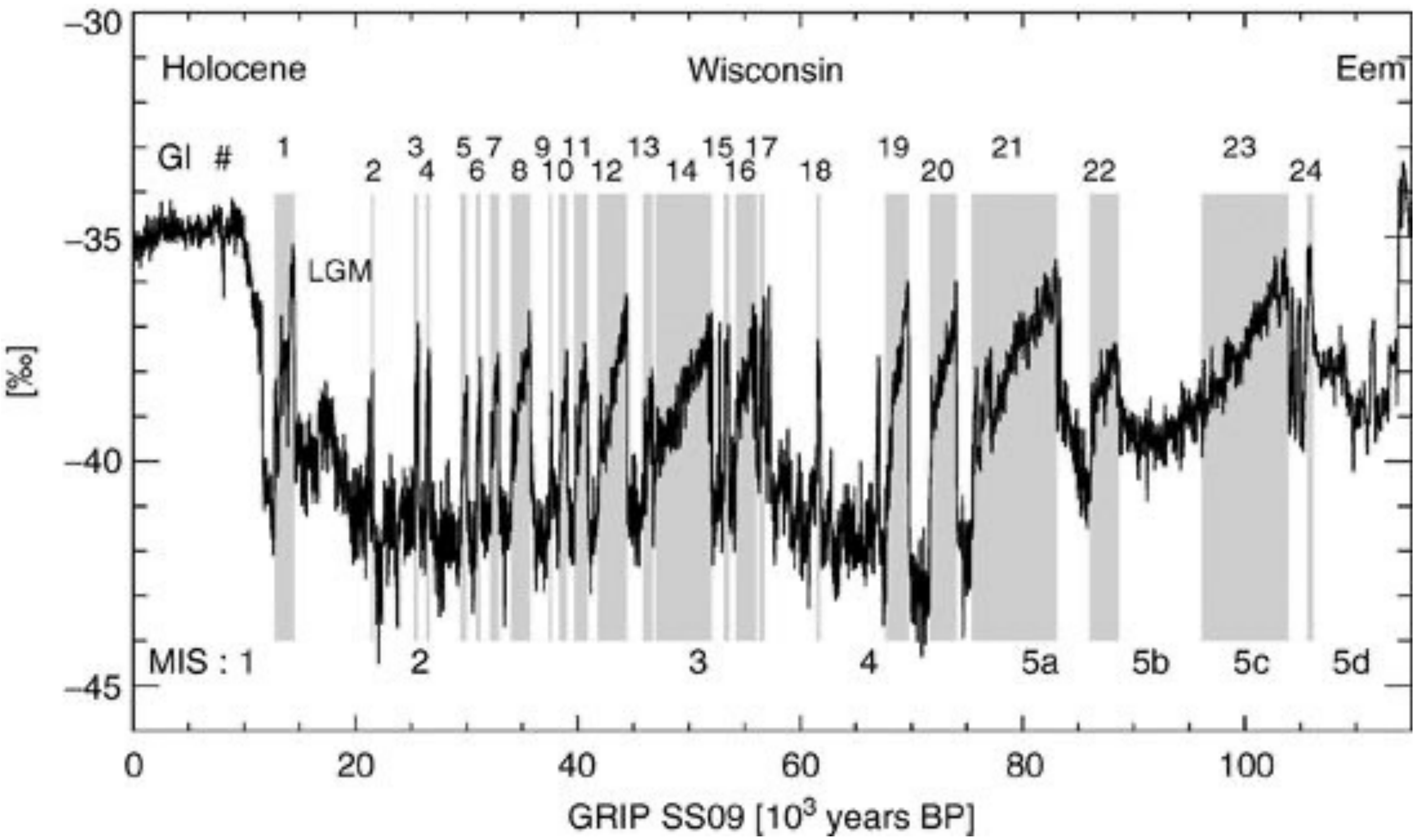
What types of climate changes one should expect in response to record CO_2 level?



- **Linear response**

- **Nonlinear response**
  - Extreme events
  - Any other type of nonlinear response?

Past abrupt climate changes



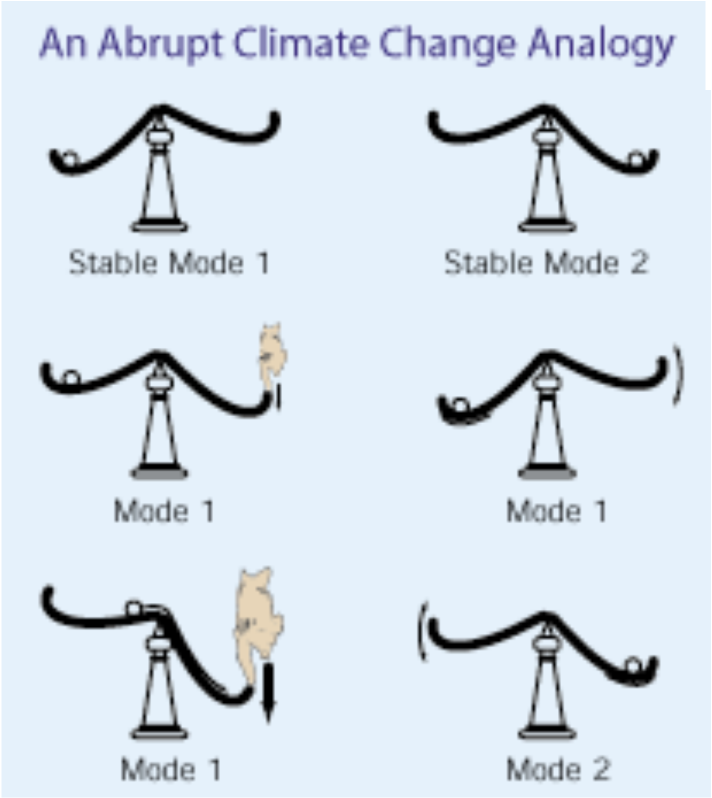
Oxygen isotopes ratio as a proxy for temperature above Greenland, derived from a core in this ice-sheet

- The abrupt warmings in Greenland (up to 10°C in a few years), known as Dansgaard-Oeschger events (marked with numbers in the figure above), represent the most spectacular abrupt climate changes of the last 120.000 years and a topic of intensive research.

Analogy for abrupt climate changes

Key properties of the system:

- it has two stable states;
- there are rapid transitions between states;
- the transitions proceed when the forcing exceeds a specific thereshold.



- There are components in the climate system which have these properties?

Tipping components of the climate system

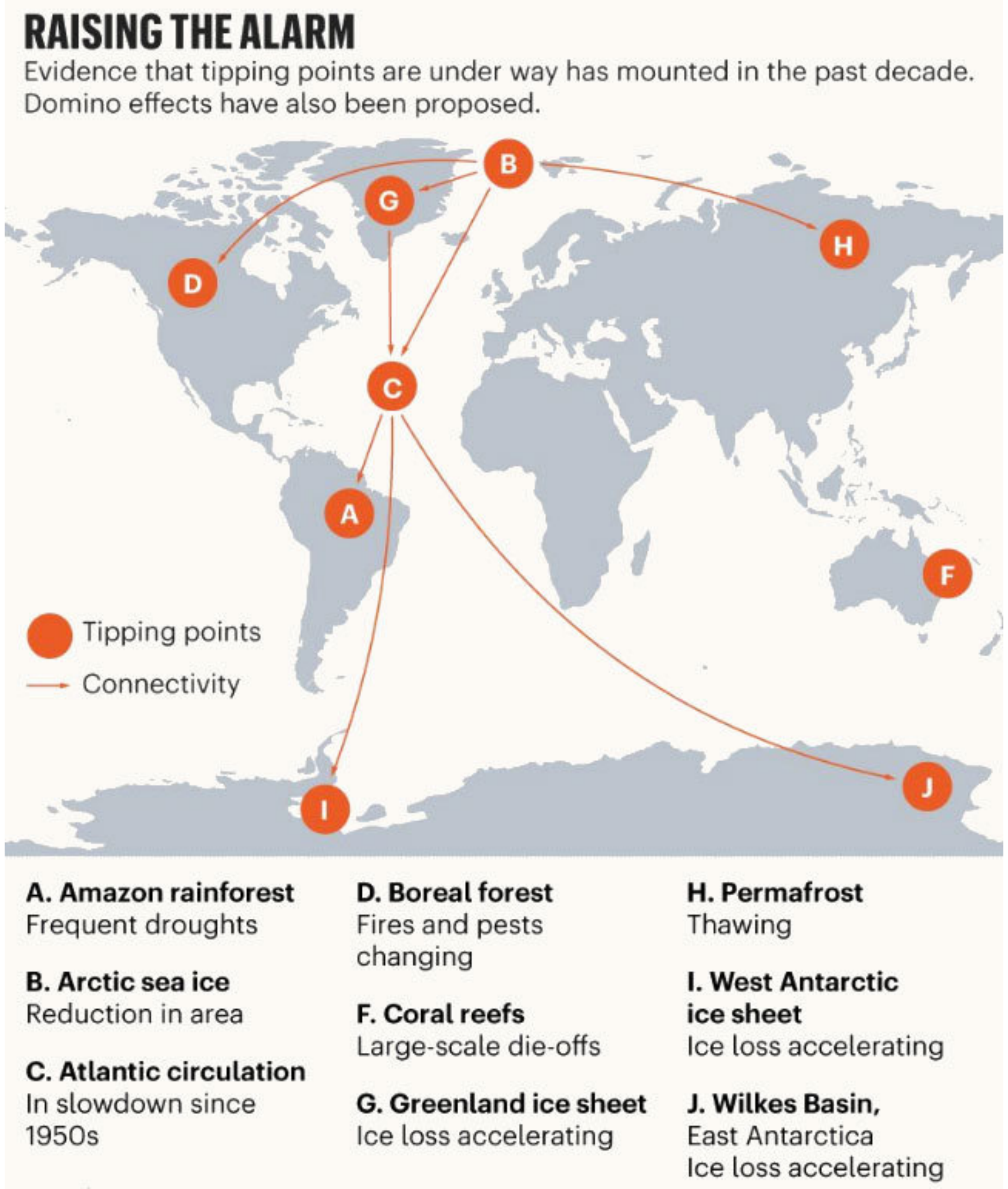
- **<u>Tipping components</u>**

- parts of the climate system which can suffer irreversible (and rapid) transitions between two distinct states;

- are associated with high climatic risk, due to their rapid irreversible transitions and potential disrupting impact on the society;

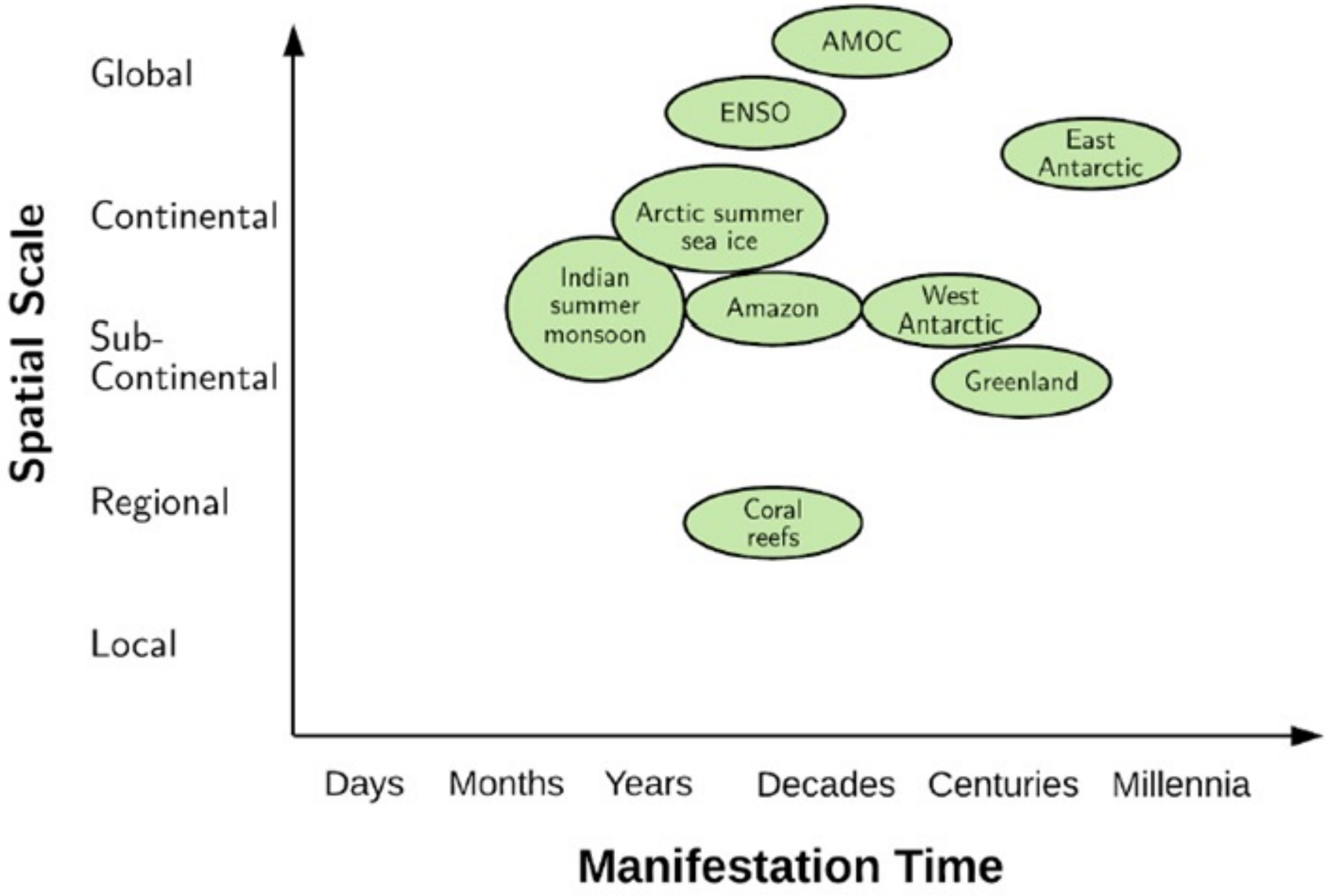
- among them, the **Atlantic Meridional Overturning Circulation (AMOC)** is one connected with several other tipping components.

Lenton et al. (2019)



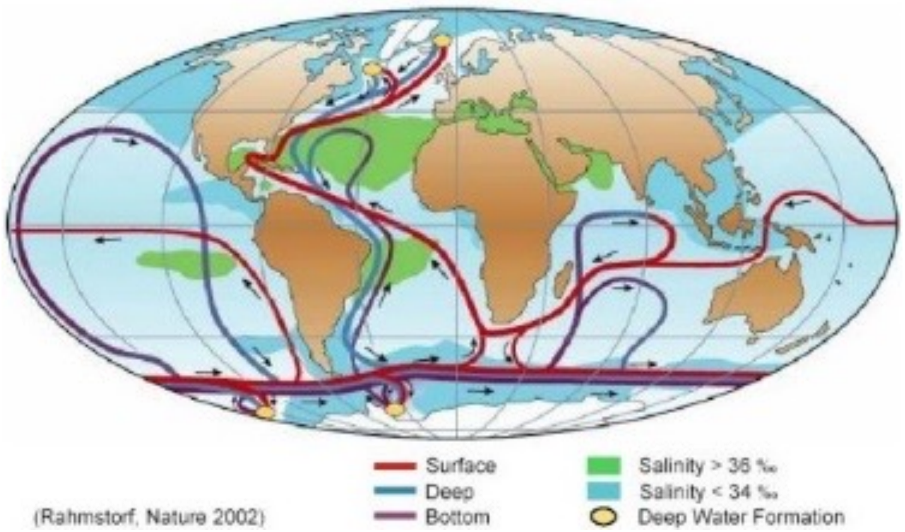
Tipping components of the climate system

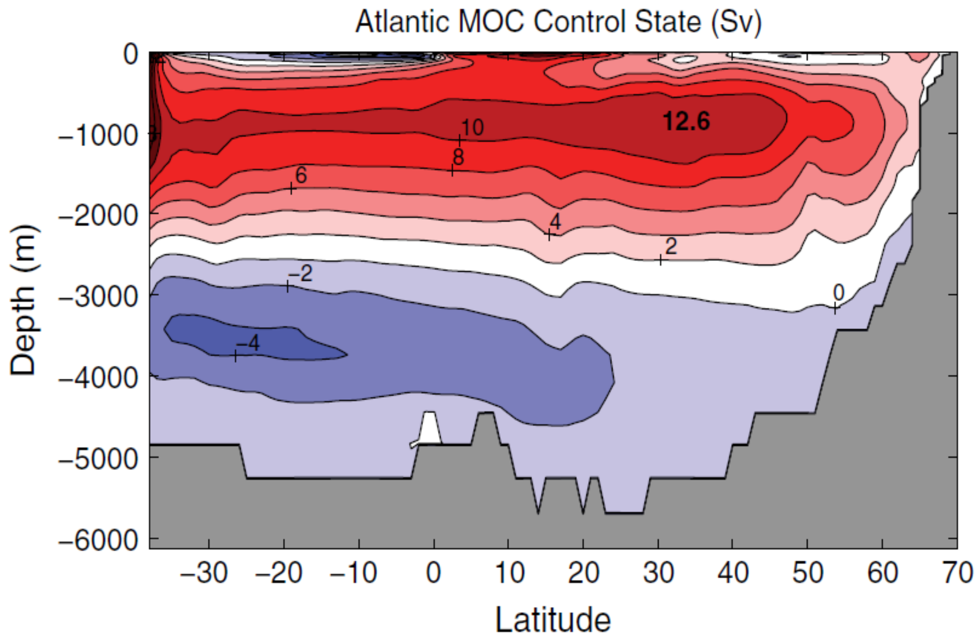
- Among the tipping components, AMOC has the largest spatial impact.
- It has also a relatively short characteristic time scale.



Winkelmann et al. (2019)

Thermohaline circulation

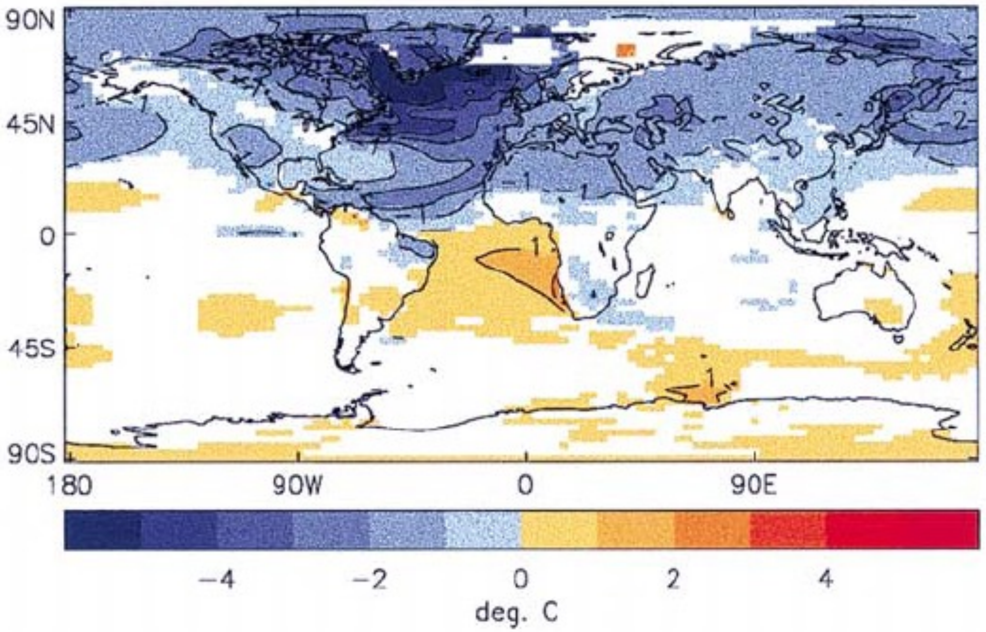




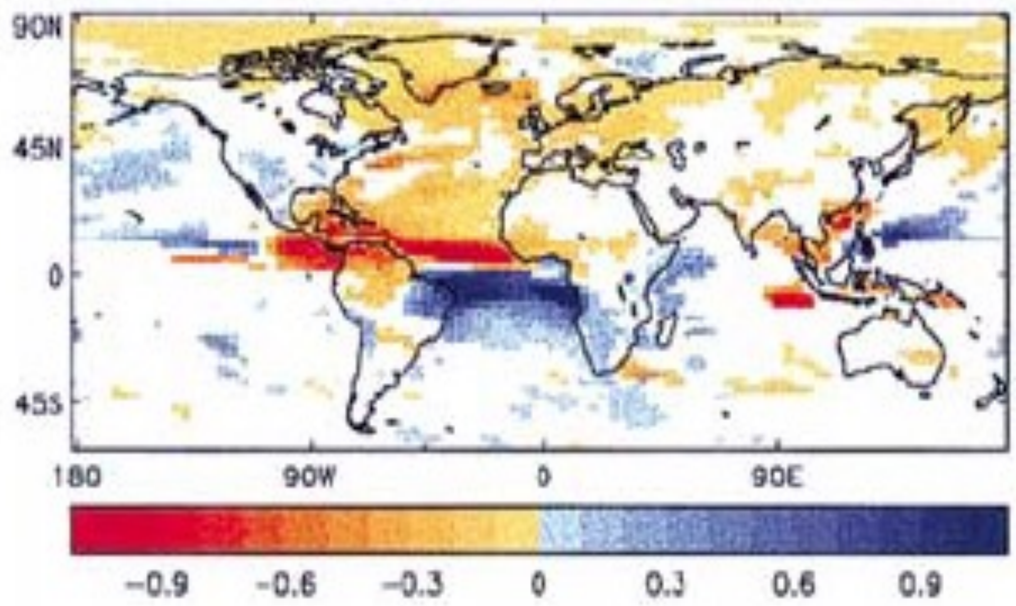
- Thermohaline circulation (THC) – the part of the global ocean circulation, which is driven by water density differences.
- Ocean density increases with decreasing temperature and with growing salinity.
- In Atlantic, salty and warm waters are advected poleward. At mid and high latitudes they are losing heat to atmosphere. Consequently, in North Atlantic the surface waters became very dense.
- In North Atlantic the surface water density is higher than at depth and therefore oceanic convection forms. The descending motion is compensated by upwelling in South Atlantic and a meridional cell forms in this basin.

Why investigating AMOC?

Surface temperature anomaly



Precipitation rate anomaly



Surface temperature (°C) and precipitation rate (m/year) anomalies induced by an AMOC shutdown (Vellinga and Wood 2002)

AMOC is of significant interest because:

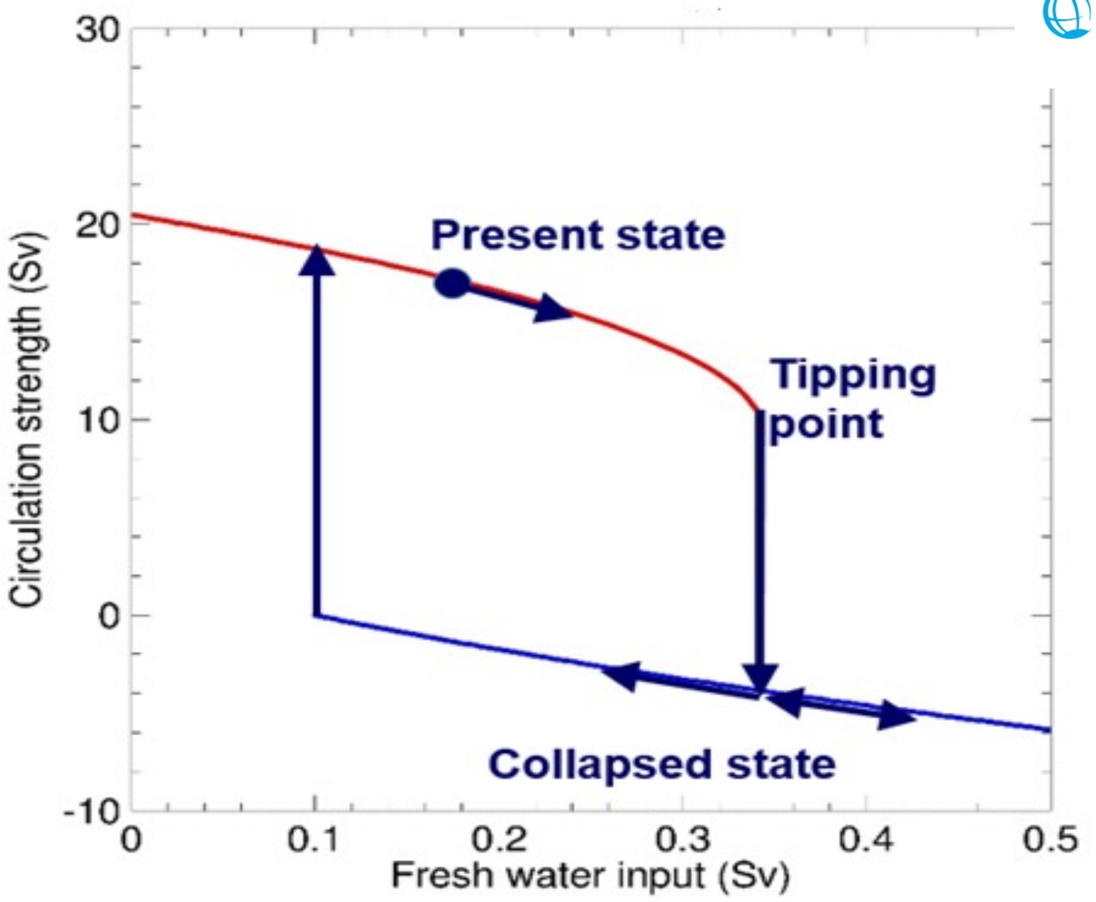
- has a worldwide heterogeneous climate impact (e.g. is warming the North Western Europe and provides a mild climate);
- it played a central role in most abrupt climate changes of the last 120.000 years;
- theoretical studies show that is has a nonlinear dynamics and it can suffer rapid jumps between two distinct states;
- could be affected by freshwaters resulting from ice melting in Arctic and North Atlantic, under global warming.

The hysteresis property of AMOC

- The AMOC stability is synthesized in its hysteresis diagram.

- The hysteresis diagram is constructed with a General Circulation Model in which freshwater in North Atlantic is increased and decreased slowly.

- The definitory characteristics of the diagram:
  - two stable states;
  - two tipping points;
  - Irreversible (rapid) transitions between states, after tipping points;
  - two stability regimes: monostable and bistable.



AMOC hysteresis behavior in response to freshwater forcing

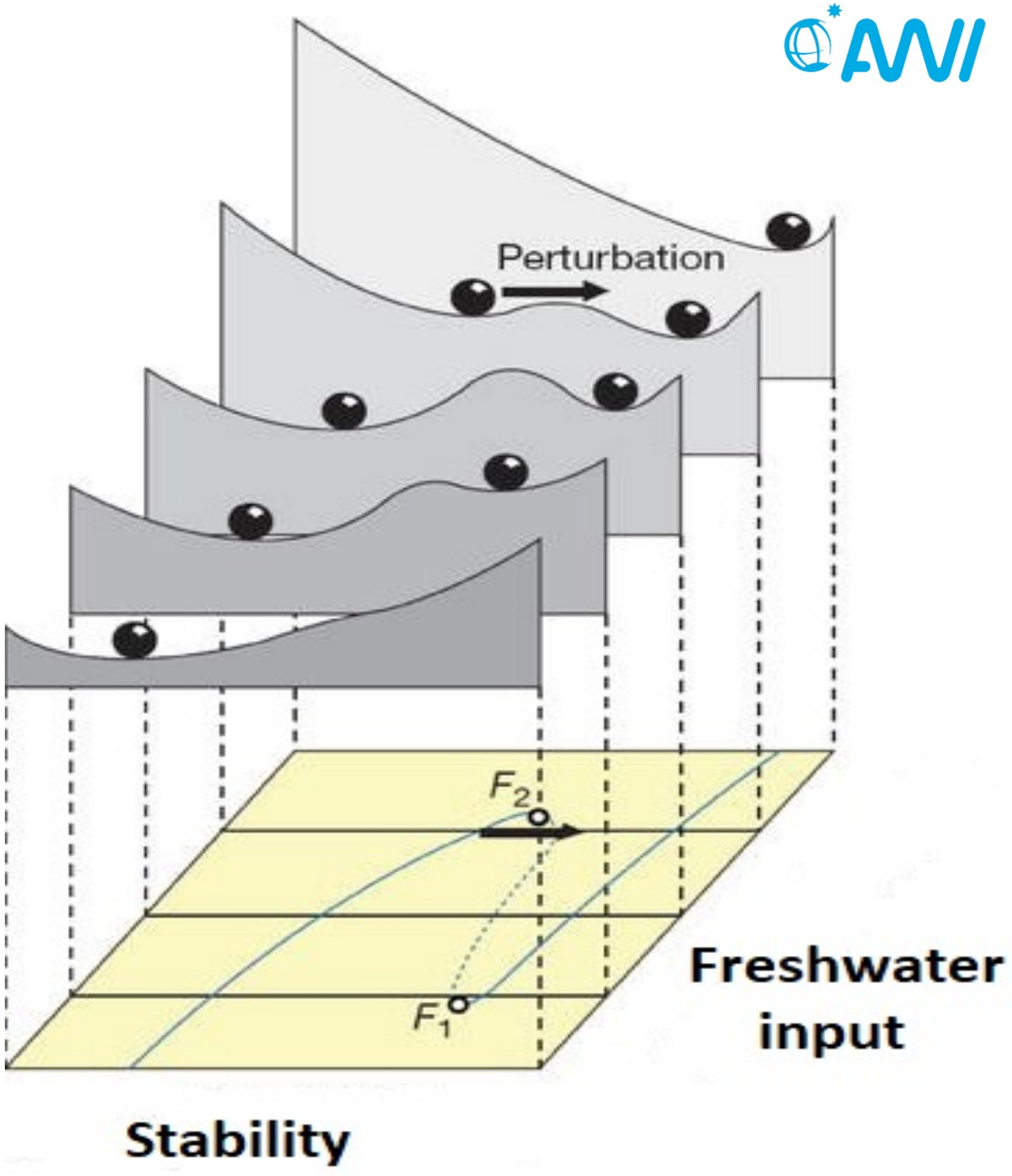
AMOC stability

- As is observed in figure, as the freshwater input increases, the monostable regime is transformed in a bistable one, which includes rapid transitions between distinct states.

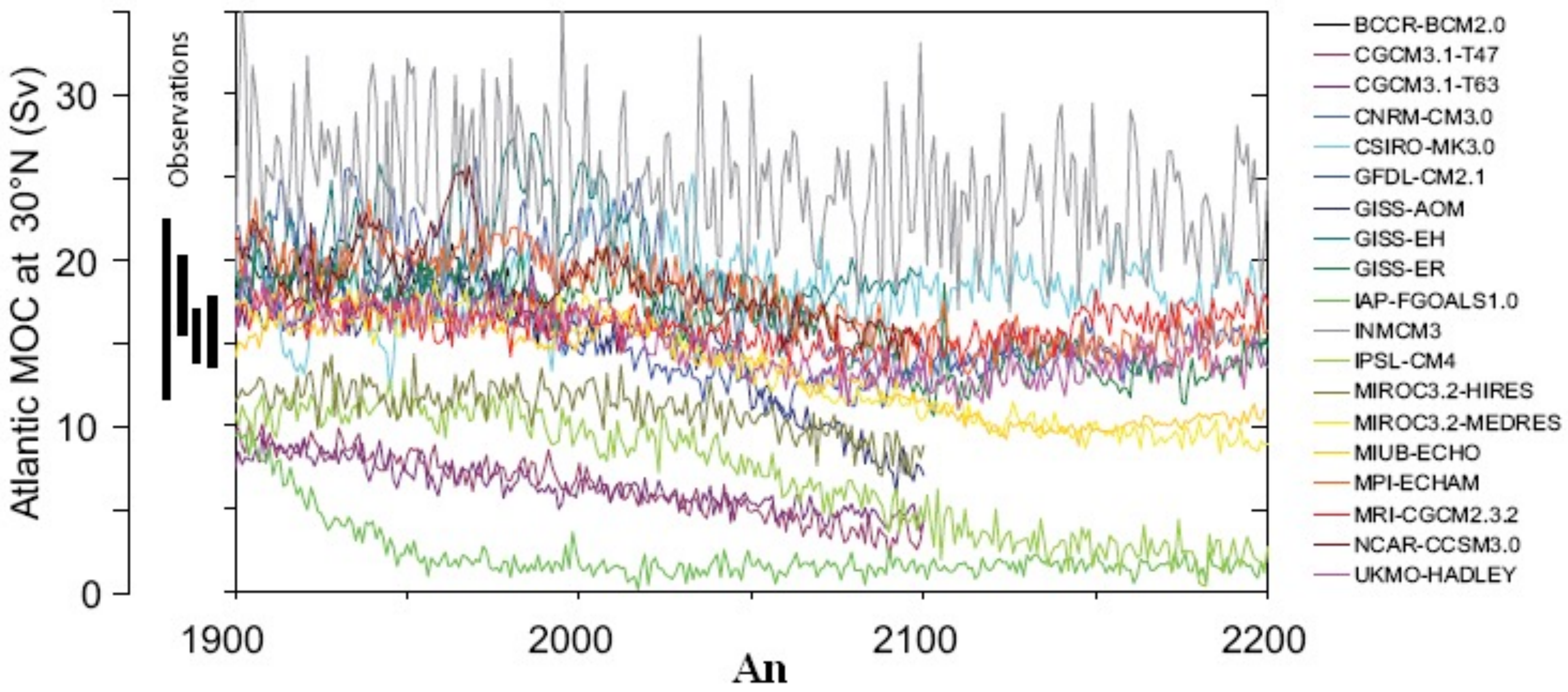
- Further, if the increase of freshwater continues, then the bistable regime is transformed in another monostable regime.

- Currently, AMOC is in a monostable or in a bistable regime?

- If it is in the bistable regime, how far it is from the tipping point?



What climate models indicate about future AMOC evolution?

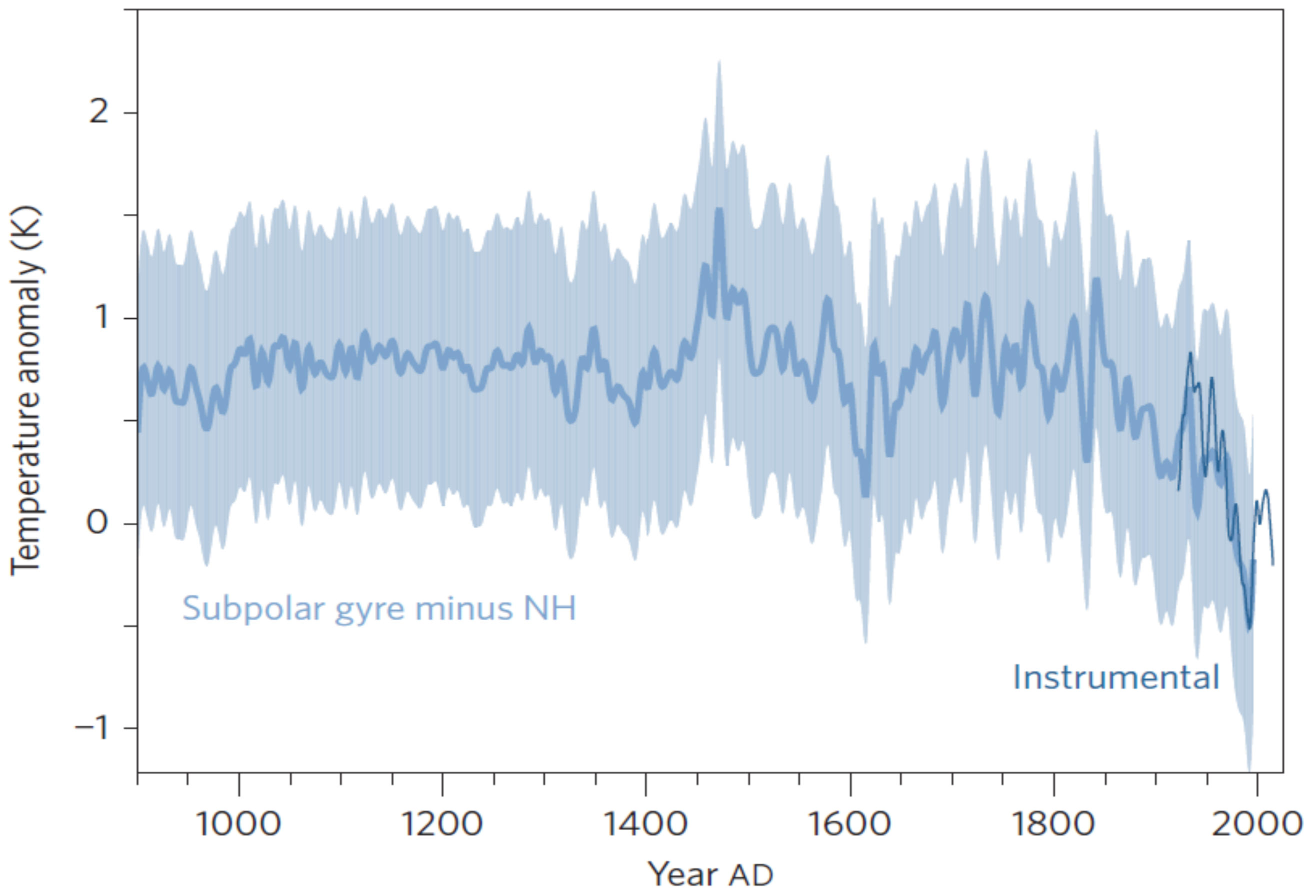


AMOC projections performed with different GCMs (IPCC 2013)

- Most of the models show a gradual AMOC weakening over the 21^{st} century.
- However, the significant quantitative differences between models point to large uncertainties regarding the AMOC fate in a warming world.

What is data indicating about the present AMOC state?

- Direct measurements on AMOC are available only for about the last 15 years. It is to short to emphasize a potential centennial scale weakening.
- However, an AMOC reconstructions based on proxy data indicate that in the last decades it reached the lowest level in the last millennium.
- How could we investigate how far/close is AMOC from the tipping point?



AMOC reconstruction for the past millennium

Rahmstorf et al. (2015)

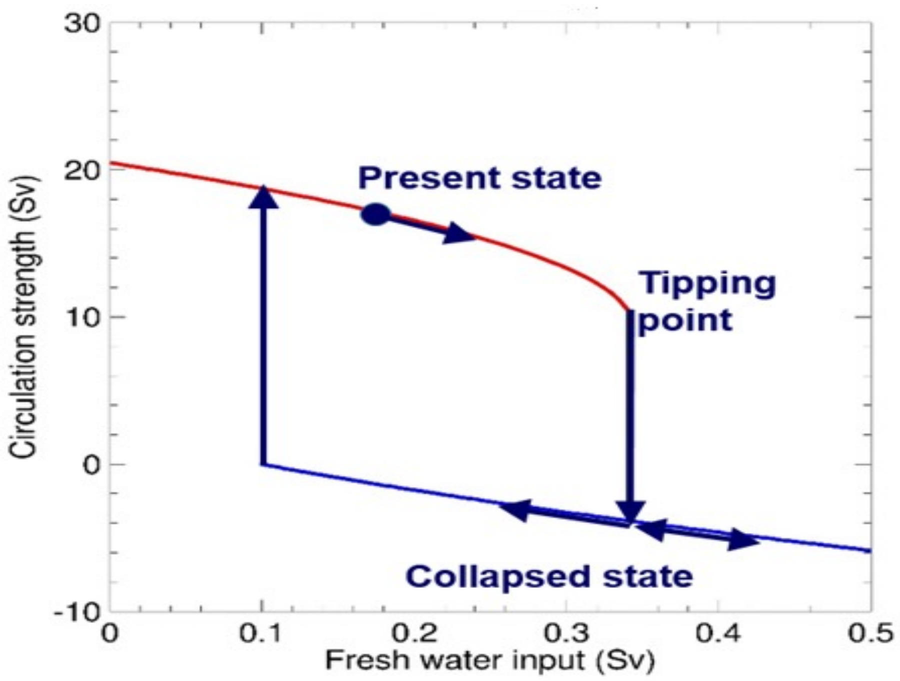
Tipping component/point - definitions

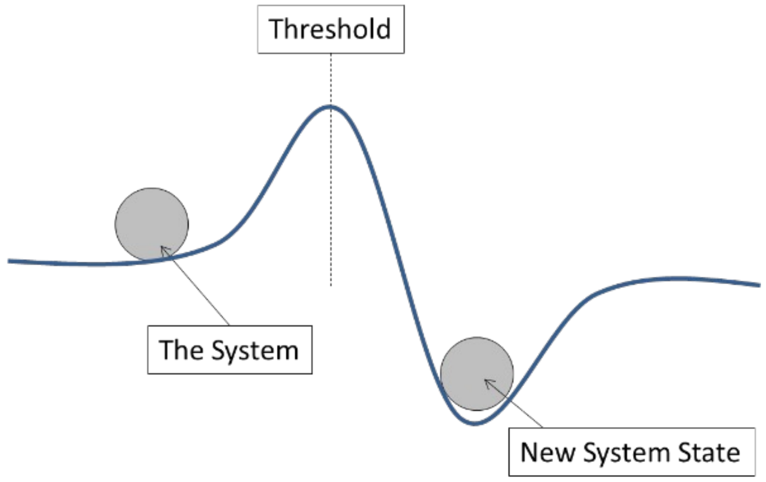
- **Tipping component - large-scale subsystem of the Earth system that can be switched by small perturbations into a qualitatively different state.**
  (these must be at least sub-continental in scale - length scale of order ~1,000 km).

- The phrase 'tipping point' captures the colloquial notion that '**little things can make a big difference**', that is, at a particular moment in time, a small change can have large, long-term consequences for a system.

- **Tipping point – threshold value of a parameter, which when it is exceeded, the system which it characterizes suffers a nonlinear qualitative change of its state, driven by internal feedbacks, which inevitably lead to a qualitatively different state.**

- Human-induced climate change could push several large-scale 'tipping climatic components' (e.g. AMOC, Greenland icesheet, Indian monsoon) over their tipping points.

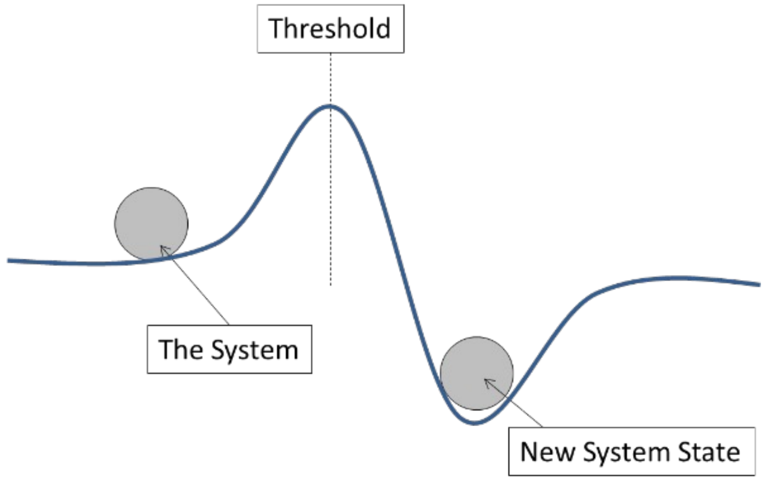




Generality of typing components/points

- It is becoming increasingly clear that many complex systems have **critical thresholds**—so-called **tipping points** — at which the system shifts abruptly from one state to another:
  – Medicine - spontaneous systemic failures such as asthma attacks or epileptic seizures;
  – Global finance - markets crashes;
  – Earth system - abrupt shifts in ocean circulation
  – Biology - catastrophic shifts in fish populations

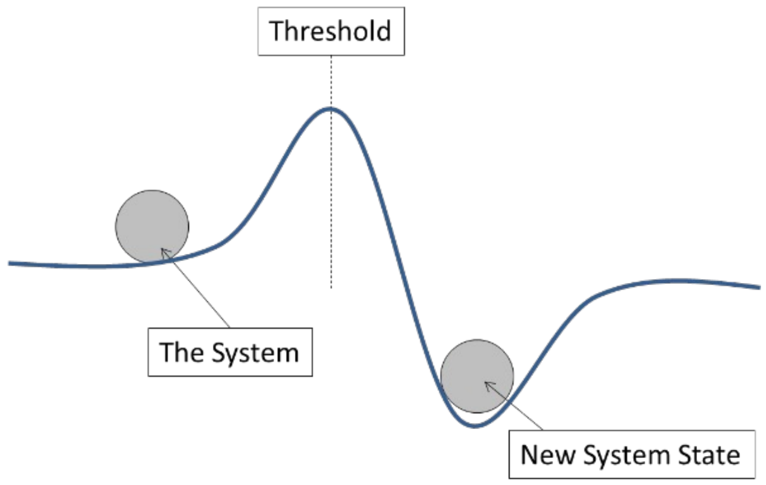
- Could the approachings of tipping points be anticipated?



Early warning signals (EWS)

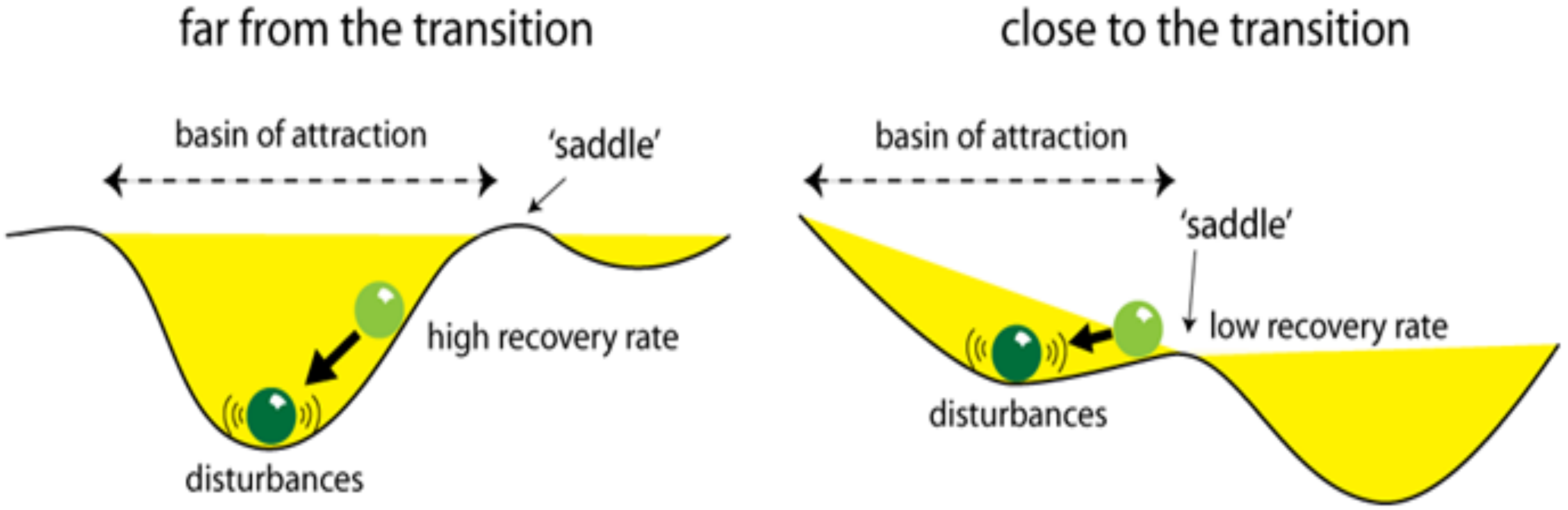
- Although predicting such critical points before they are reached is extremely difficult, work in different scientific fields is now suggesting the existence of generic **early-warning signals** that may indicate, for a wide class of systems, if a critical threshold is approached.

- Early warning can take several forms:
    - knowledge that an event could occur;
    - qualitative assessment that it is becoming more likely;
    - forecast of its timing.



Critical slowing down

- The most important clues that have been suggested as indicators of whether a system is getting close to a critical threshold are related to a phenomenon known in dynamical systems theory as **critical slowing down**.
- When a system approaches a bifurcation point where its current state becomes unstable, and it switches to some other state, one can expect to see it becoming more sluggish in its response to small perturbations.



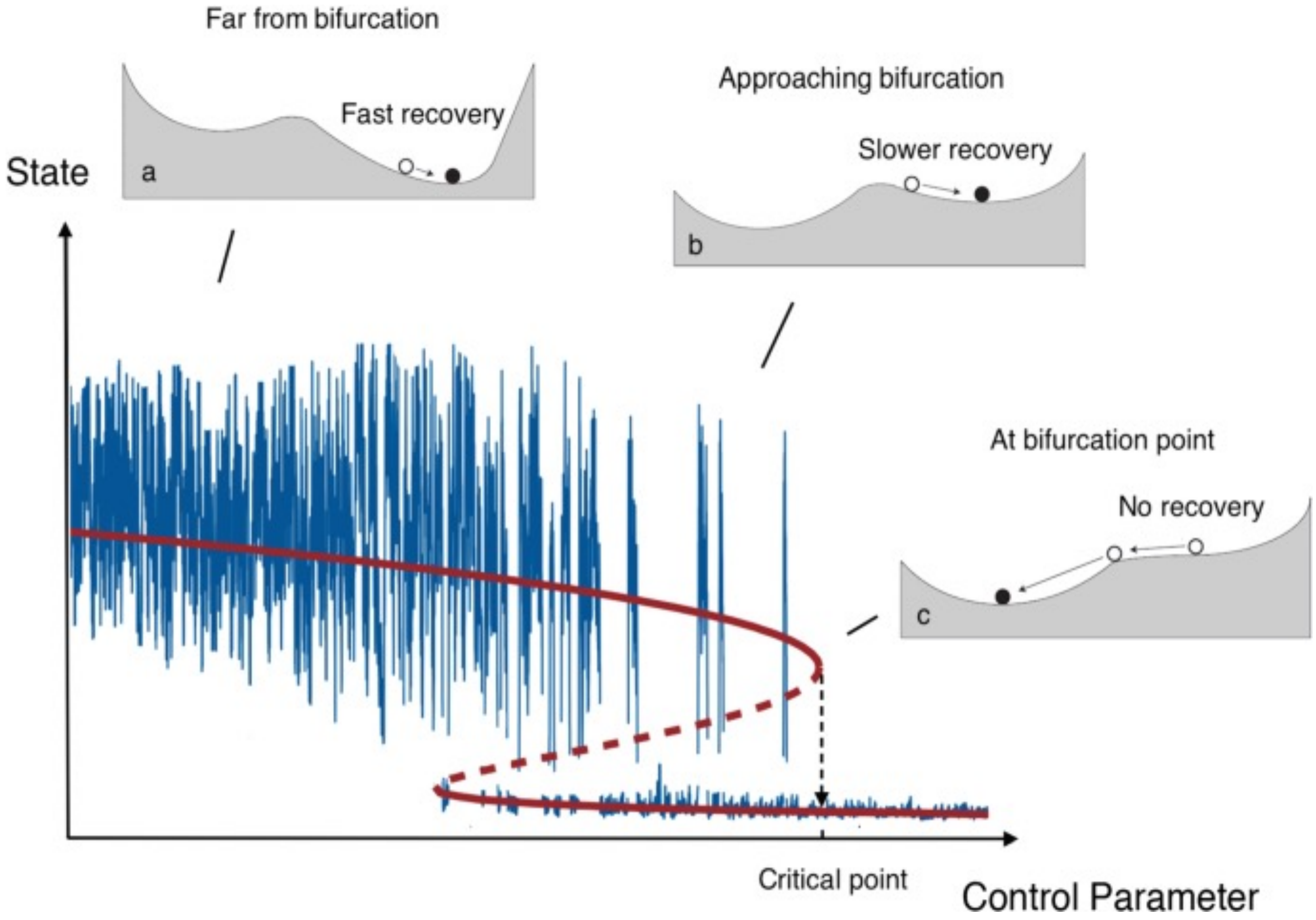
- Mathematically, for systems that are gradually approaching a bifurcation point in their equilibrium solutions, the leading eigenvalue tends towards zero, indicating a tendency towards infinitely slow recovery from perturbations.
- This phenomenon — termed 'critical slowing down' in dynamical systems theory — has only recently been applied to climate dynamics.

Critical slowing down

- Analyzes of various models shows that such slowing down typically starts far from the bifurcation point, and that **recovery rates decrease smoothly to zero as the critical point is approached.**

- Slowing down causes the intrinsic rates of change in a system to decrease, and therefore the state of the system at any given moment should become more like its past state. This increase in memory can be measured in a variety of ways.

- How one could detect a decrease of the recovery rate and an increase in memory?



Increasing variance and autocorrelation as EWS of critical transitions

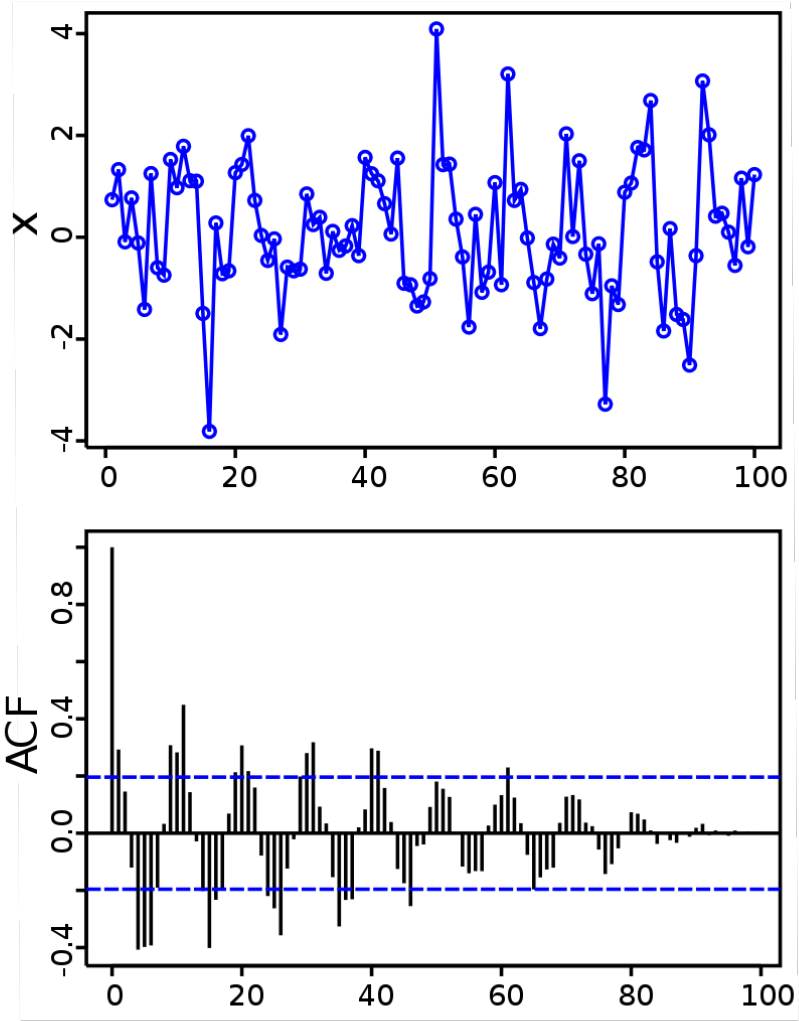
- **Variance** - measures how far a set of numbers is spread out from their average value:

$$Var(X) = \frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2$$

- **Autocorrelation** - the correlation of a time series with a delayed copy of itself, as a function of lag.
- The correlation of a time series with a one-time step delayed copy of itself it is named **lag-1 autocorrelation**.
- It is a measure of the **memory** contained in the time series.

$$r_k = \frac{\sum_{i=1}^{N-k}(X_i - \bar{X})(X_{i+k} - \bar{X})}{\sum_{i=1}^{N}(X_i - \bar{X})^2}$$

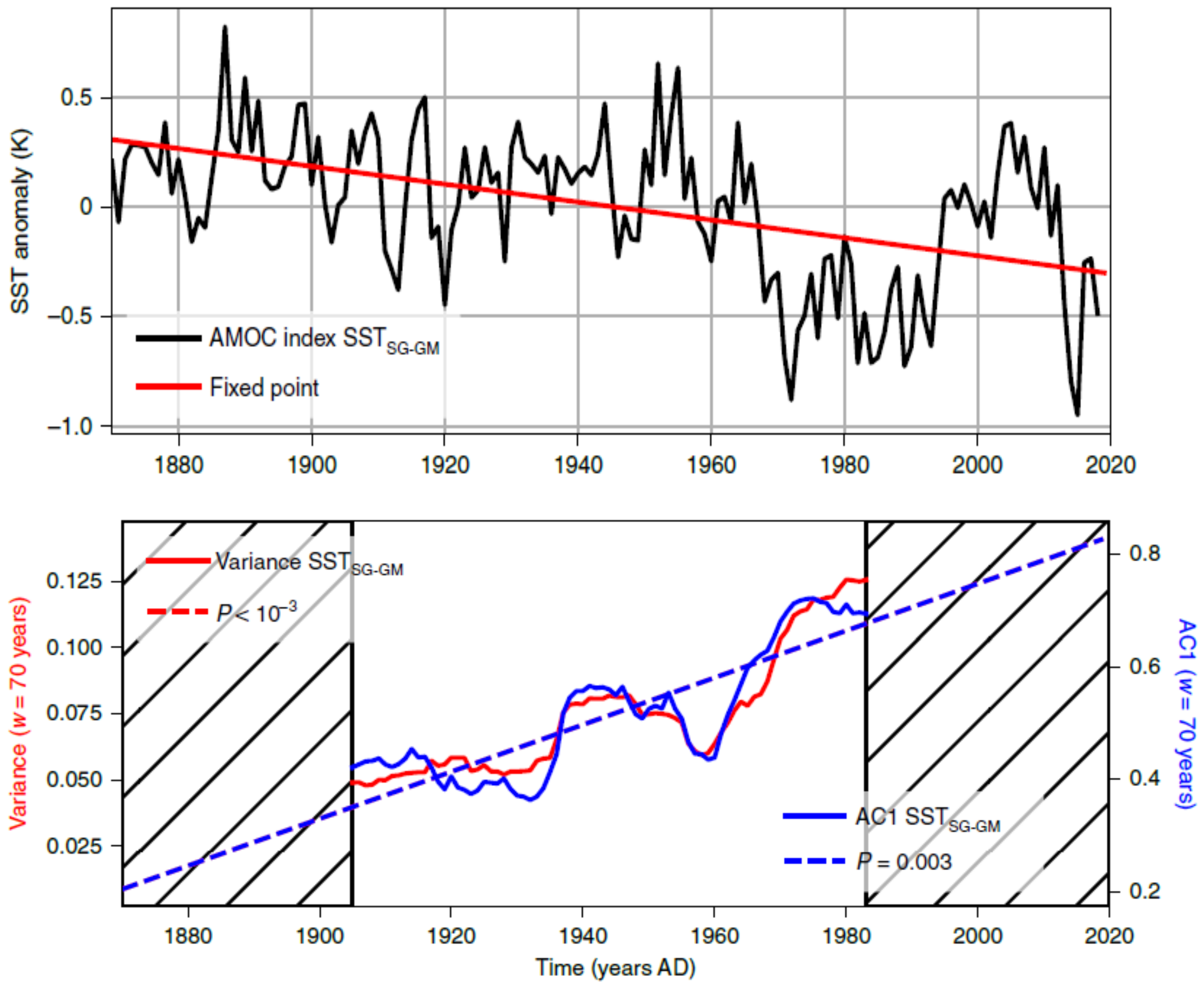
$$r_k \in [-1,1]$$



A time series (top) and its autocorrelation function (bottom).

Example of application of EWS to observed AMOC variability

- EWS are computed for an AMOC index constructed based on observational data (top panel)
- Variance and autocorrelation are increasing toward present, indicating that AMOC is approaching a tipping point



Summary

- There are several tipping components in the climate system, some of them connected to each other; they could generate a cascade of nonlinear irreversible transitions.

- Tipping component - large-scale subsystem of the Earth system that can be switched by small perturbations into a qualitatively different state.

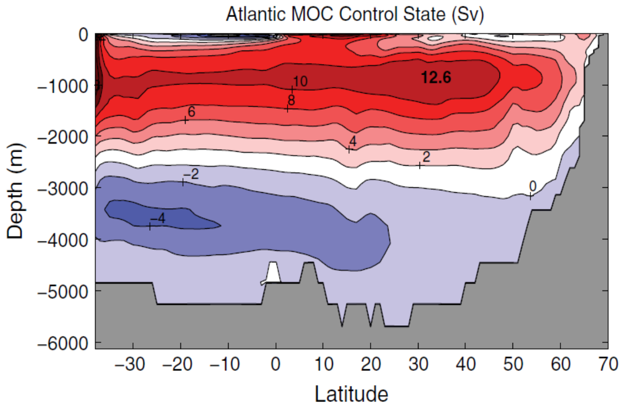
- Climate change could manifest as nonlinear irreversible (and rapid) variations, generated by responses of tipping components to anthropogenic forcing.

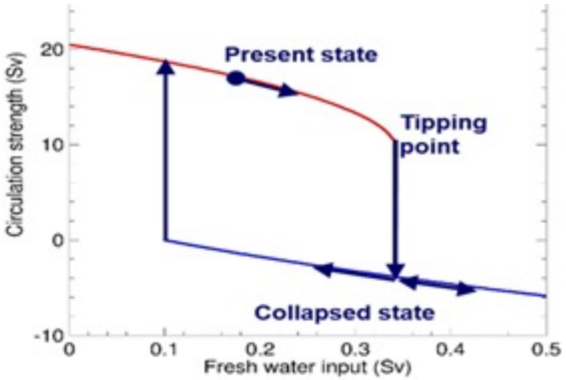
- AMOC is one of the climatic tipping components, with quasi-global impact; recent observations study indicates that it is approaching a tipping point.

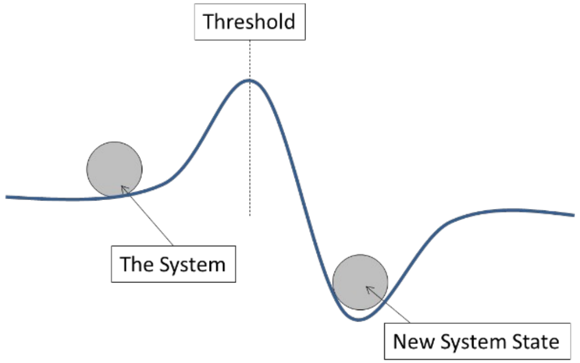
- A key question is how far are the climatic tipping components from their critical points?

- The approach of a tipping point is in principle signaled by critical slowing down, which could be detected by, for example, increasing variance and autocorrelation (as early warning signals).

Looking forward for questions …

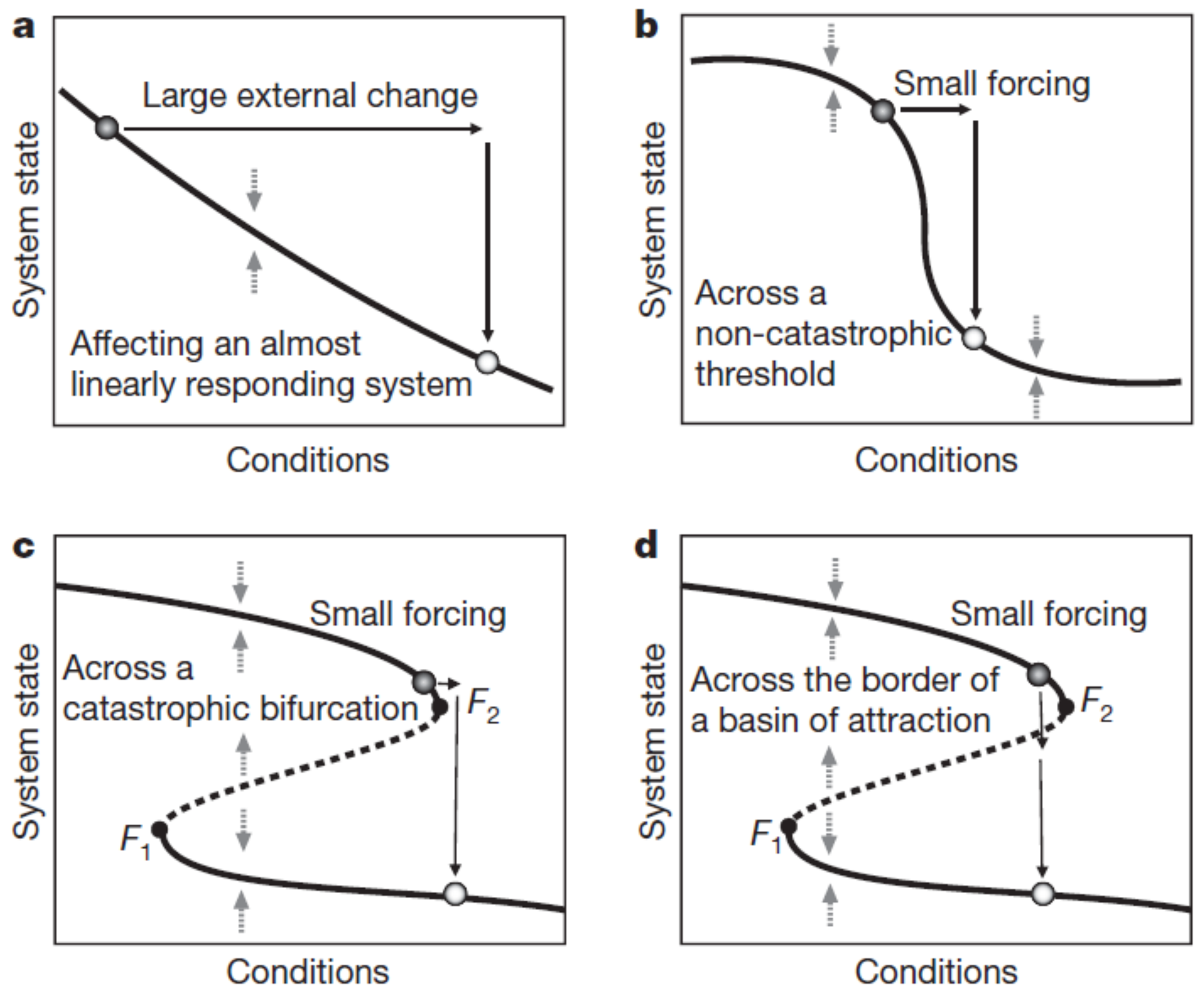






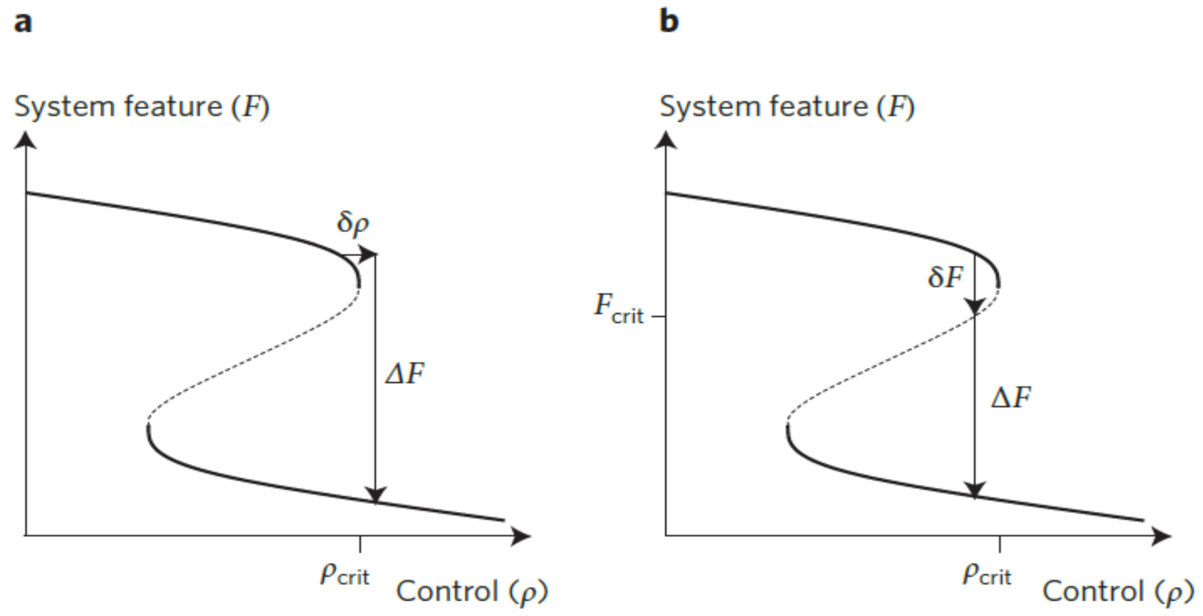
Types of forcing -> response relationships

- A system can respond in different ways to changes in conditions (external forcing; e.g. increasing temperature).



a) a linear response to forcing; the amplitude of change is linearly linked (comparable) with the amplitude of response;
b) a non-linear response to forcing; a relatively small change in forcing results in a relatively large response;
c) a tiny change in forcing may cause a large shift in response through a fold bifurcation, through which the system “jumps” to a very different state;
d) a small perturbation may also cause a large shift in response by driving the system across the boundary between the attraction basins.

Types of critical transitions



- Three types of critical transitions can be emphasized:
- **1) Bifurcation** (panel a) - where a small change in forcing ($\delta\rho$) past a critical threshold ρ_{crit} causes a large, nonlinear change in system state (ΔF);
- **2) Noise-induced transition** (panel b)- where internal short-term variability (δF) passing an unstable steady state F_{crit} causes a large, nonlinear change in system state (ΔF) without any change in forcing control (ρ) - are fundamentally unpredictable;
- **3) Rate-induced transition** – (panel b) where a fast change in the forcing moves the boundary of the attractor.

An example of critical slowing down

- To see why the rate of recovery rate after a small perturbation will be reduced and will approach zero when a system moves towards a catastrophic bifurcation point, consider the following simple dynamical system, where γ is a positive scaling factor and a and b are parameters:

$$\frac{dx}{dt} = \gamma(x-a)(x-b)$$

- It can easily be seen that this model has two equilibria (at equilibria dx/dt=0), $\overline{x_1} = a$ and $\overline{x_2} = b$, of which one is stable and the other is unstable. If the value of parameter a equals that of b, the equilibria collide and exchange stability (in a transcritical bifurcation).
- Assuming that $\overline{x_1}$ is the stable equilibrium, we can now study what happens if the state of the equilibrium is perturbed slightly ($\mathrm{x} = \overline{x_1} + \varepsilon$):

$$\frac{d(\overline{x_1}+\varepsilon)}{dt} = f(\overline{x_1}+\varepsilon)$$

- Here f(x) is the right hand side of the first equation of this slide. Linearizing this equation using a first-order Taylor expansion yields:

$$\frac{d(\overline{x_1}+\varepsilon)}{dt} = f(\overline{x_1}+\varepsilon) \approx f(\overline{x_1}) + \left.\frac{\partial f}{\partial x}\right|_{\overline{x_1}} \varepsilon$$

An example of critical slowing down

- The previous equation simplifies to:

$$\frac{d(\overline{x_1})}{dt} + \frac{d\varepsilon}{dt} = f(\overline{x_1}) + \frac{d\varepsilon}{dt} = f(\overline{x_1}) + \left.\frac{\partial f}{\partial x}\right|_{\overline{x_1}} \varepsilon \Rightarrow \frac{d\varepsilon}{dt} = \lambda_1 \varepsilon \qquad \frac{d\varepsilon}{\varepsilon} = \lambda_1 dt \Rightarrow \boldsymbol{\varepsilon} = \boldsymbol{e^{\lambda_1 t}}$$

- With eigenvalues λ_1 and λ_2 in this case, we have:

$$\lambda_1 = \left.\frac{\partial f}{\partial x}\right|_a = -\gamma(b-a)$$

- And for the other equilibrium:

$$\lambda_2 = \left.\frac{\partial f}{\partial x}\right|_b = \gamma(b-a)$$

- If b>a then the first equilibrium has a negative eigenvalue, λ_1, and is thus stable (as the perturbation goes exponentially to zero).
- **It is easy to see from the two relations above that at the bifurcation (b=a) the recovery rates λ_1 and λ_2 are both zero and perturbations will not recover.**
- Farther away from the bifurcation, the recovery rate in this model is linearly dependent on the size of the basin of attraction (b-a). For more realistic models, this is not necessarily true but the relation is still monotonic and is often nearly linear.