Universiteit Utrecht

[Faculty of Science
Physics and Astronomy]

Palaeoclimate variability

Can the past tell us about the future?

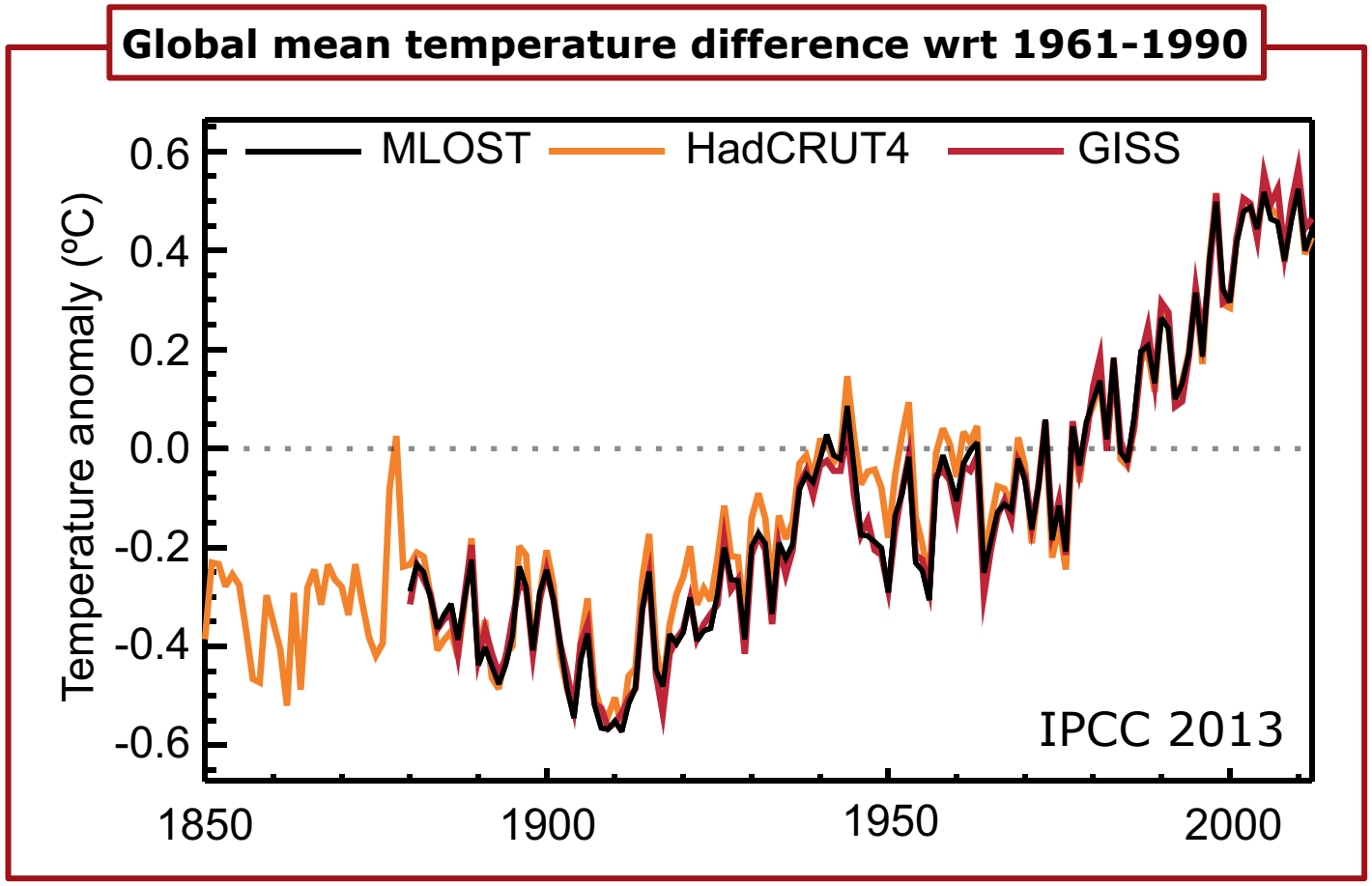
Anna von der Heydt

Institute for Marine and Atmospheric Research,
Utrecht University, The Netherlands.

NETHERLANDS EARTH SYSTEM SCIENCE CENTRE

How hot will the Earth be in 2100?

Will temperatures rise steadily or can we expect sudden accelerations?



… and after 2100?

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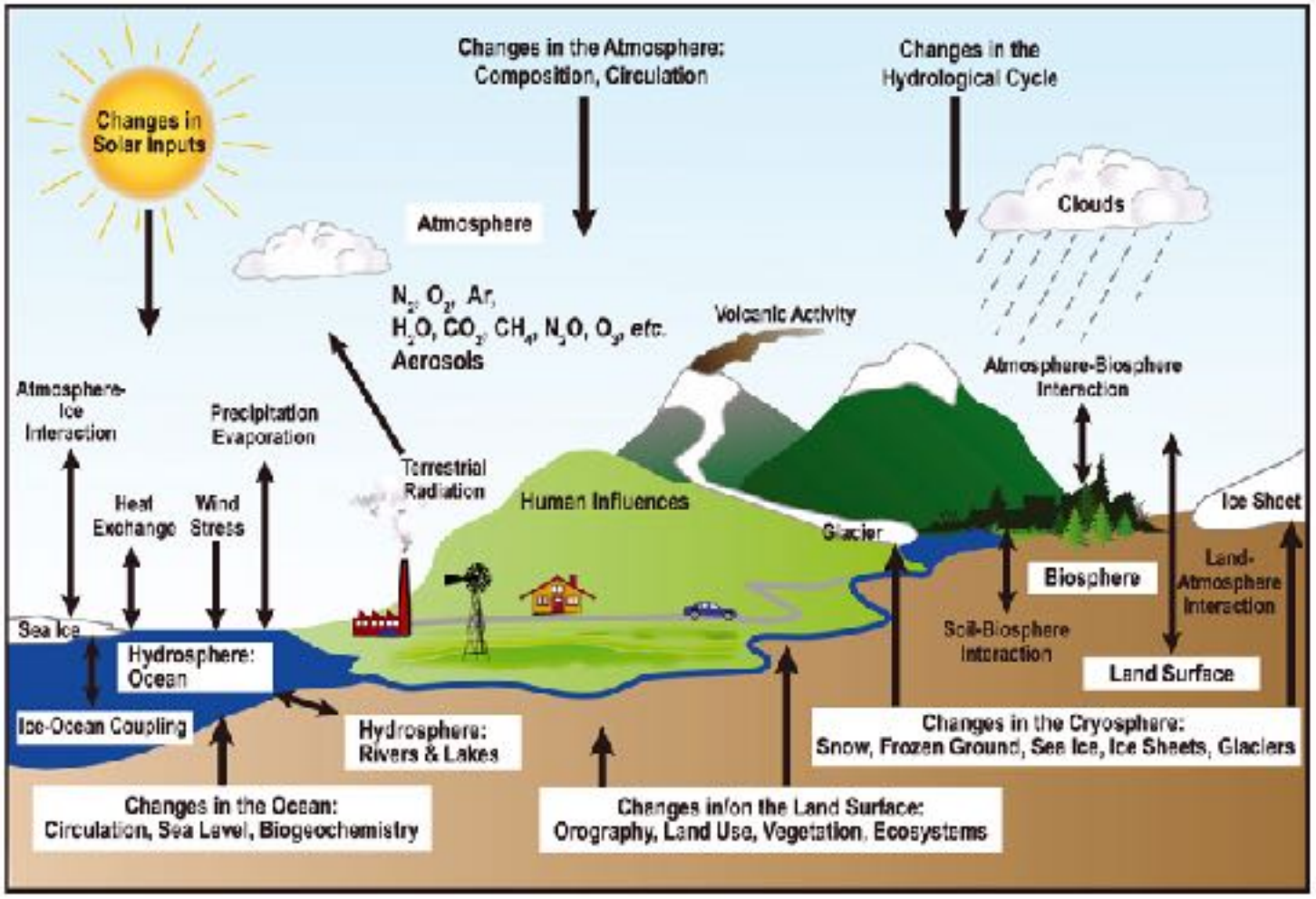
IMAU

Complex Climate System



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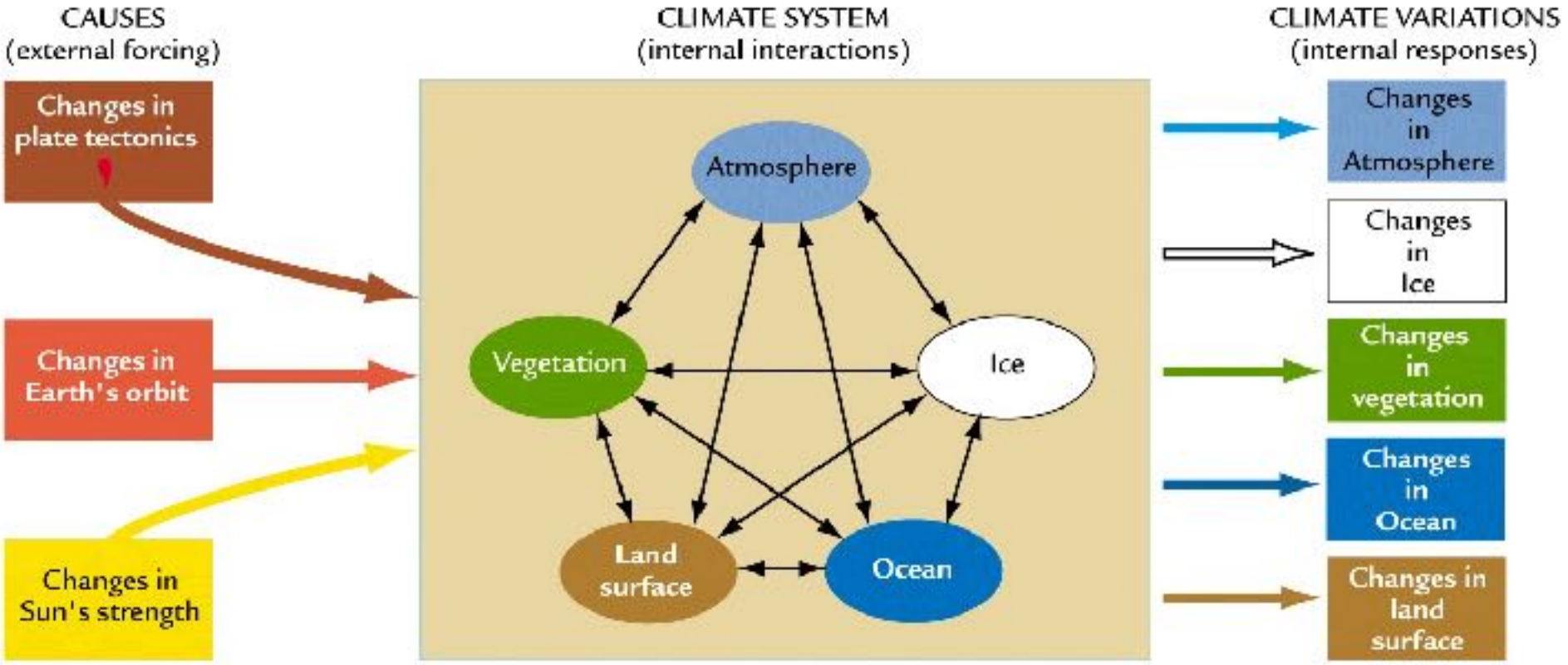
Complex Climate System



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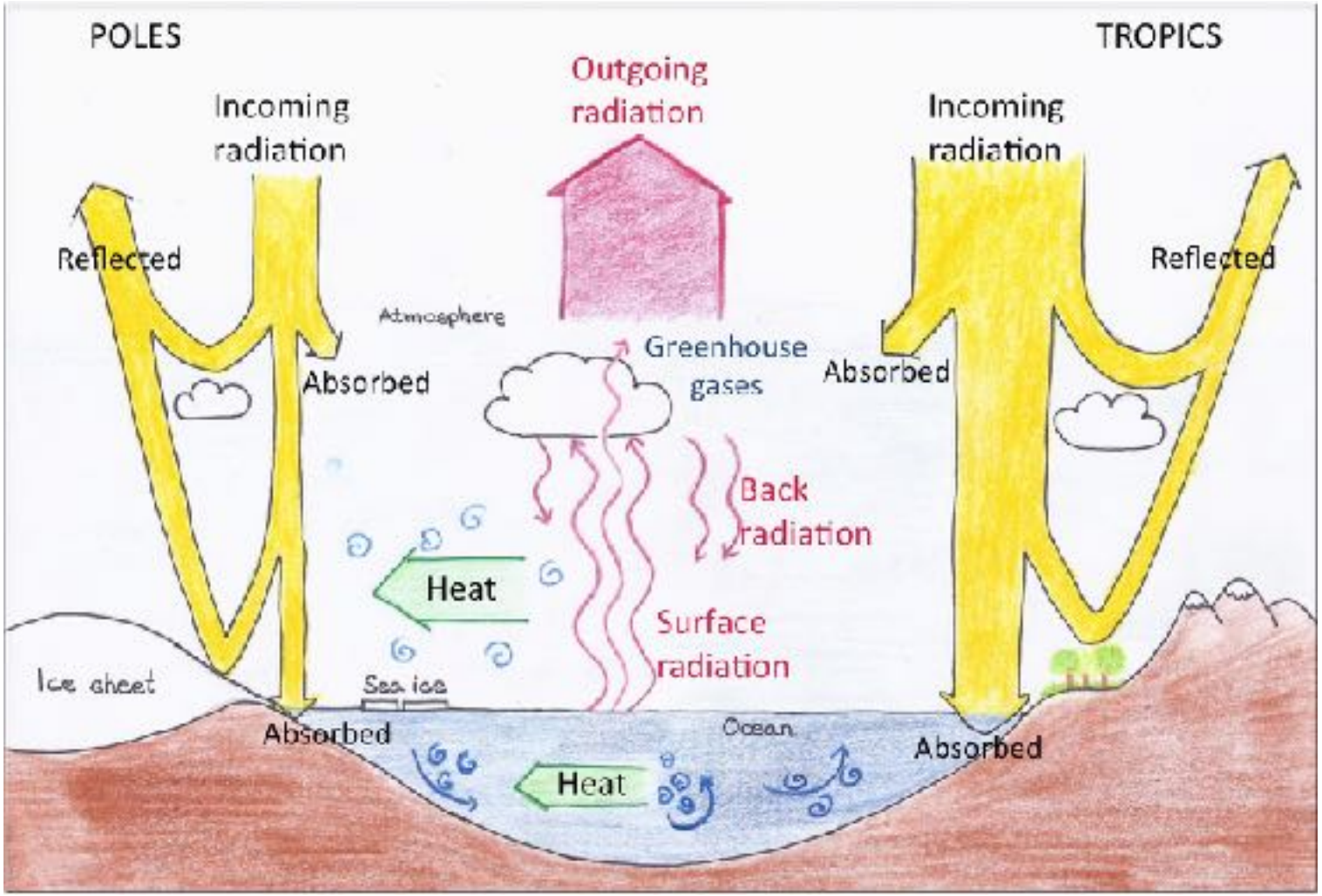
Energy balance of the Earth



Physical climate system = mostly fluids!

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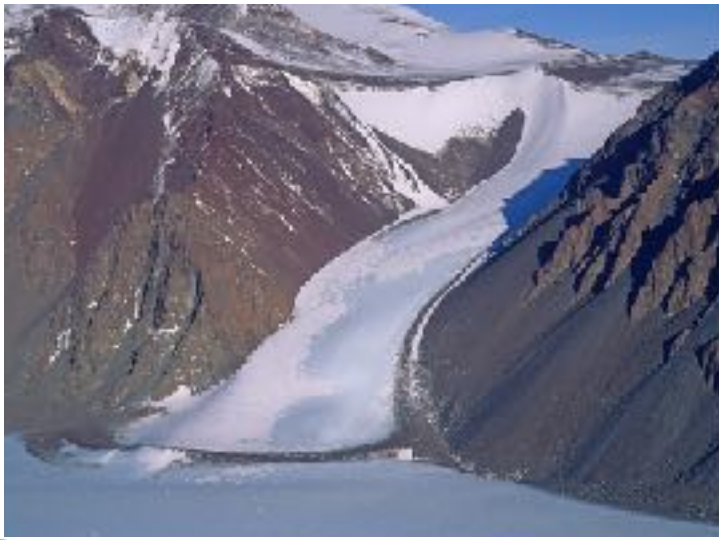
Fluids....

Air

Foam

Water



Ice

Granular media

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… can show complex patterns

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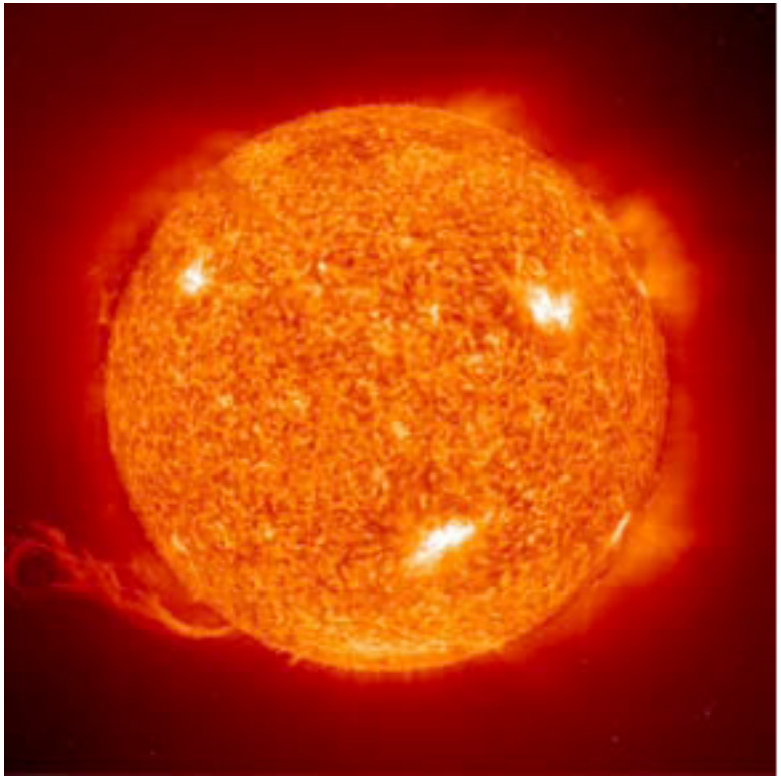
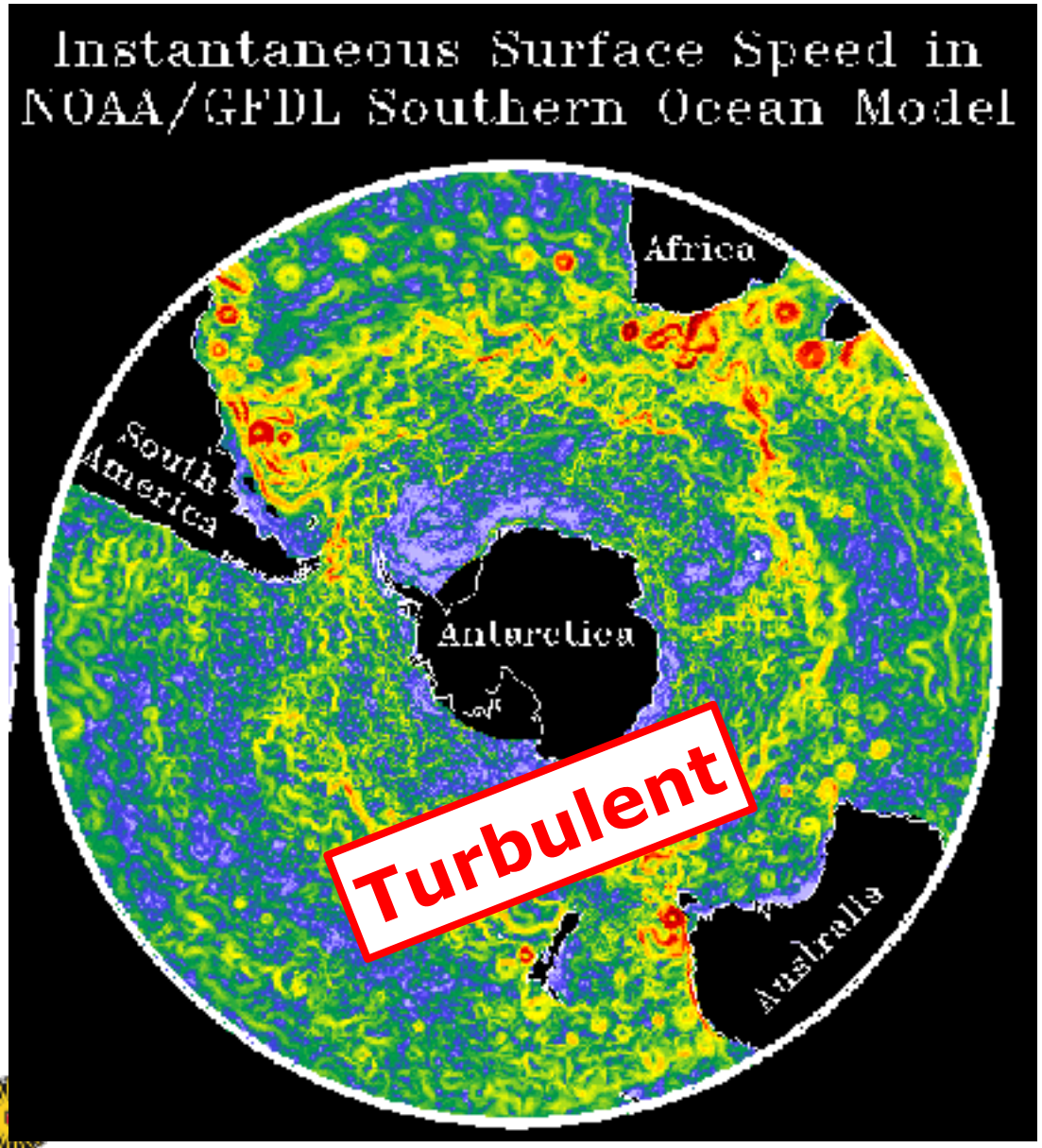
Motion in fluids occurs on

- Length scales of **mm** till **10.000 km**
- Time scales of **seconds** till **years**

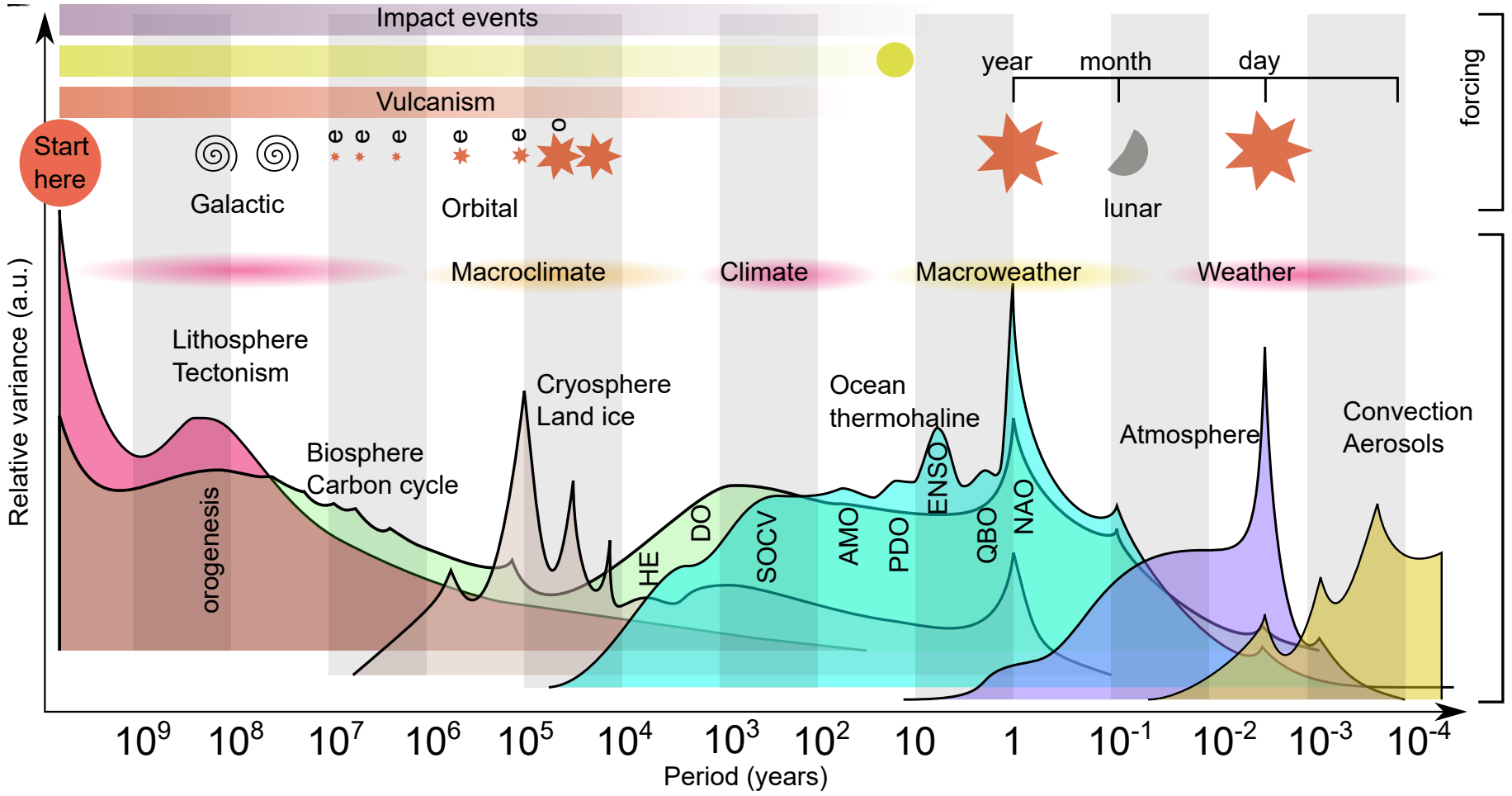


Fluid flows can become...



- unstable
- chaotic
- unpredictable?

Climate variability



Von der Heydt et al (2020) https://eartharxiv.org/repository/view/219/

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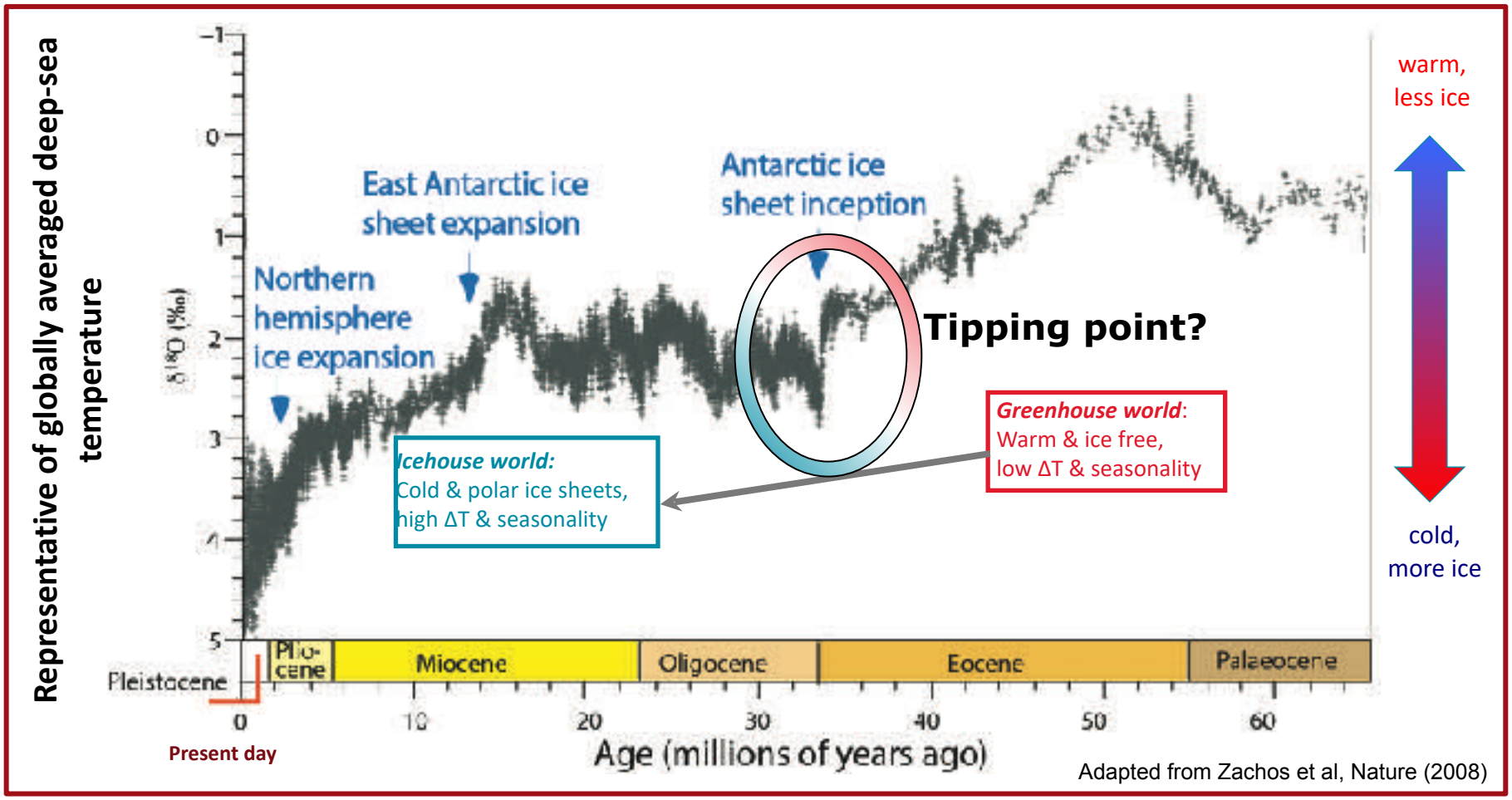
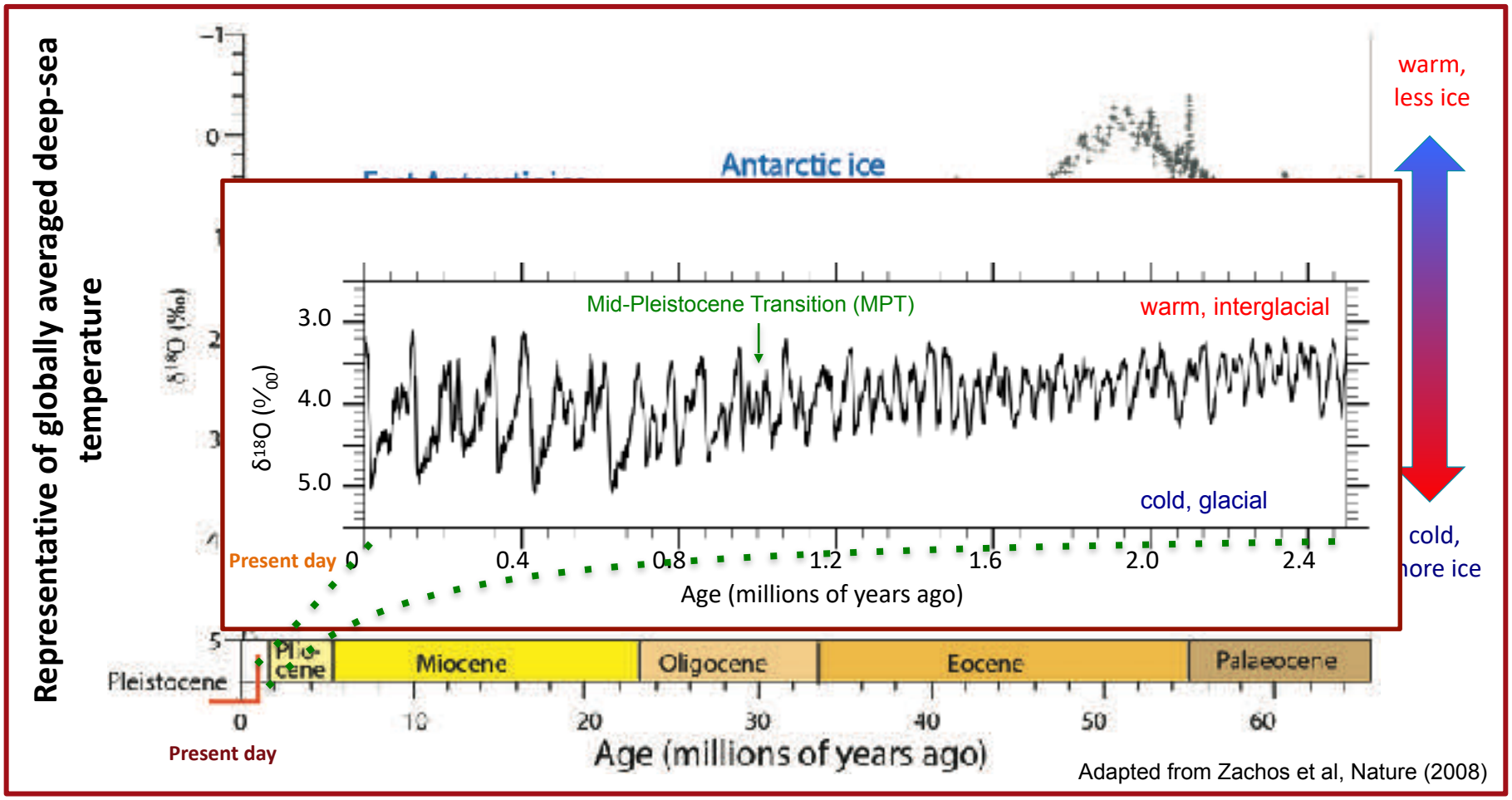
Climate on Earth - last 65 Myr

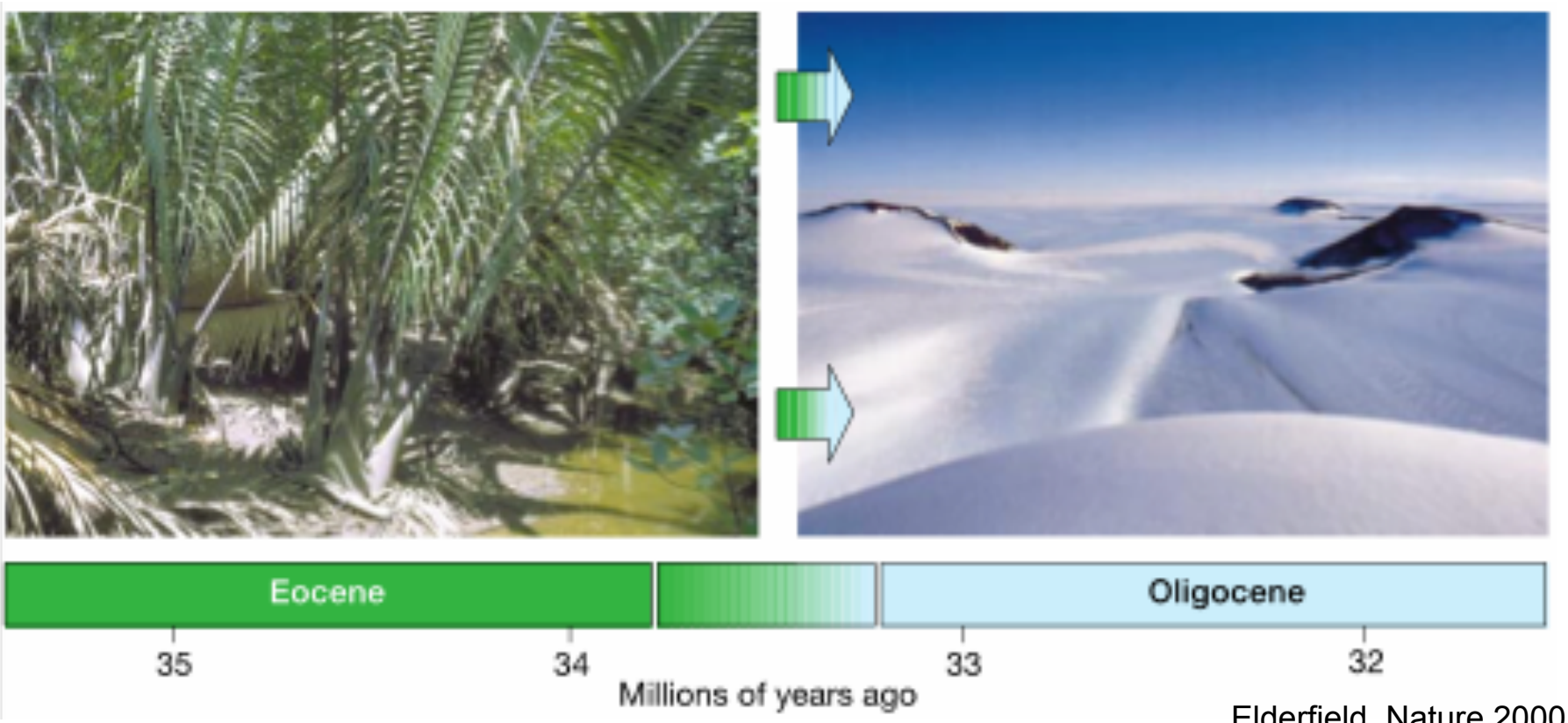


Climate on Earth - last 65 Myr

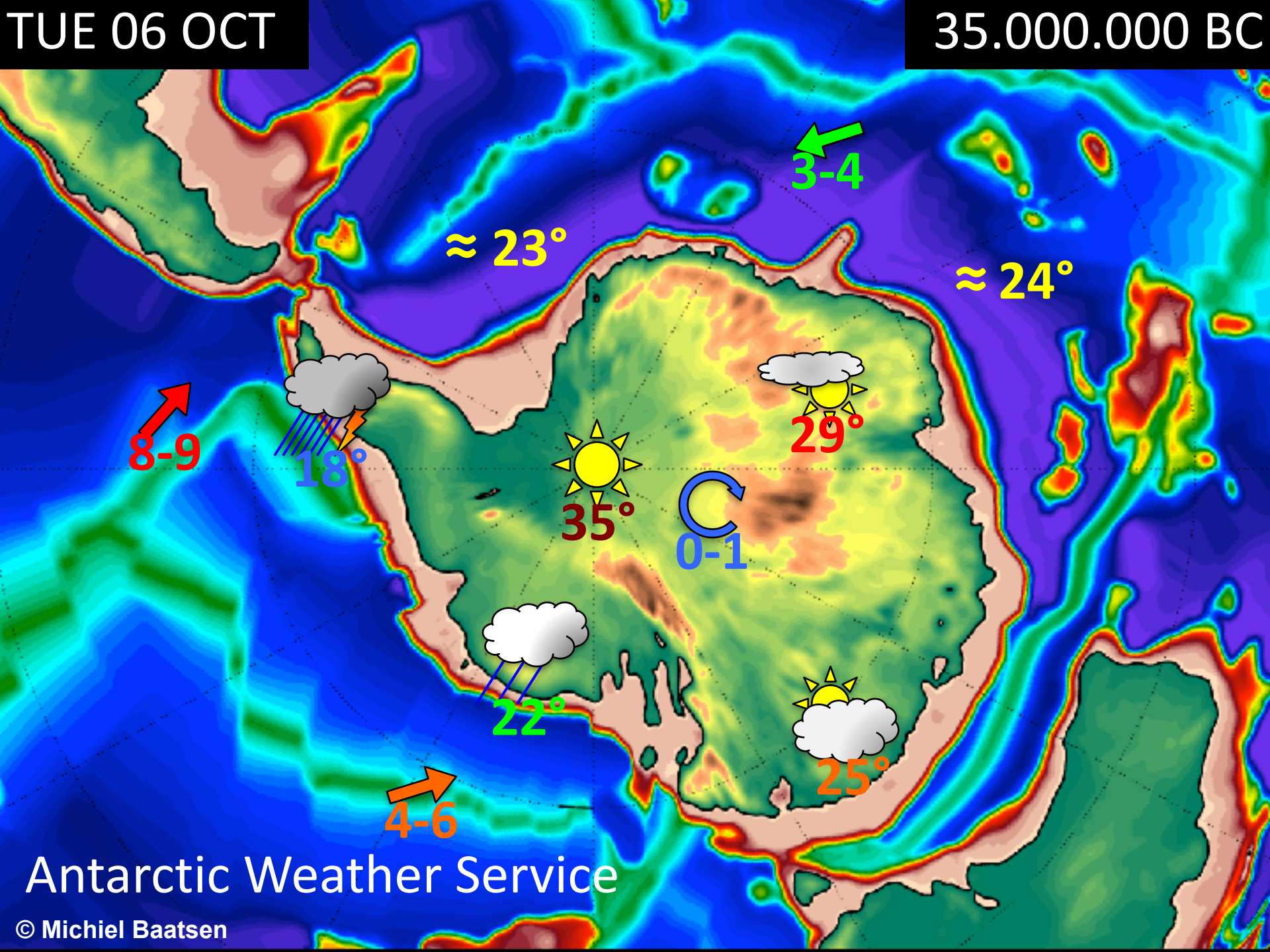


Adapted from Zachos et al, Nature (2008)

Antarctica 34 myr ago: tipping point?

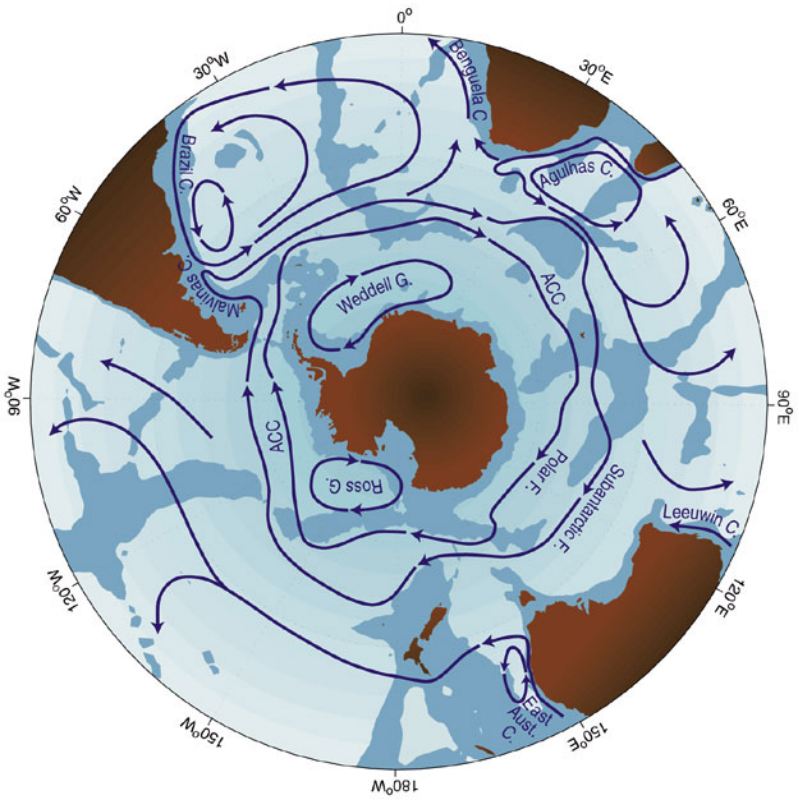


Elderfield, Nature 2000

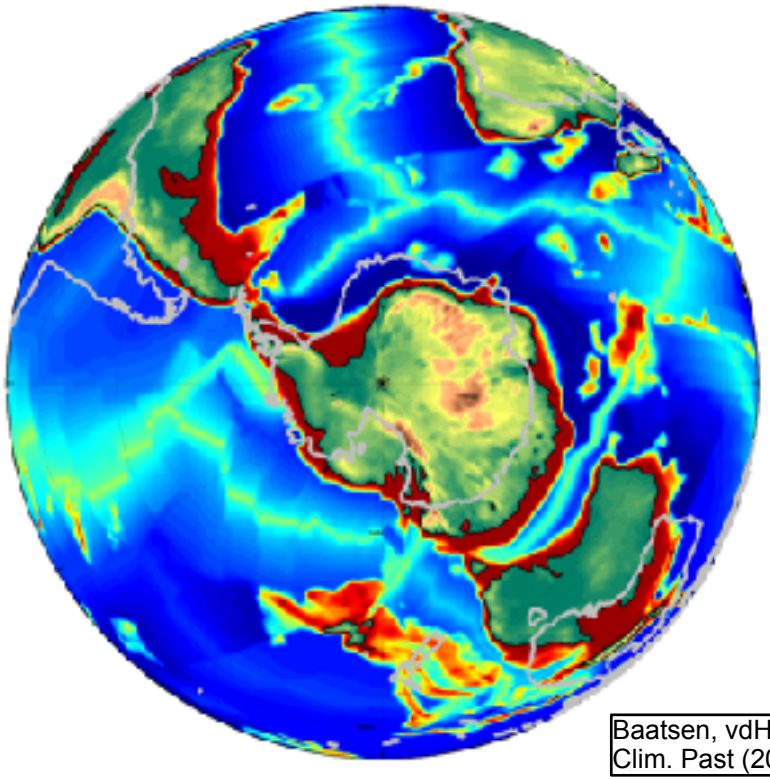

TUE 06 OCT
35.000.000 BC
3-4
≈ 23°
≈ 24°
8-9
18°
29°
35°
0-1
22°
25°
4-6
Antarctic Weather Service
© Michiel Baatsen

Antarctic glaciation: Why end of Eocene?

Present day Southern Ocean circulation



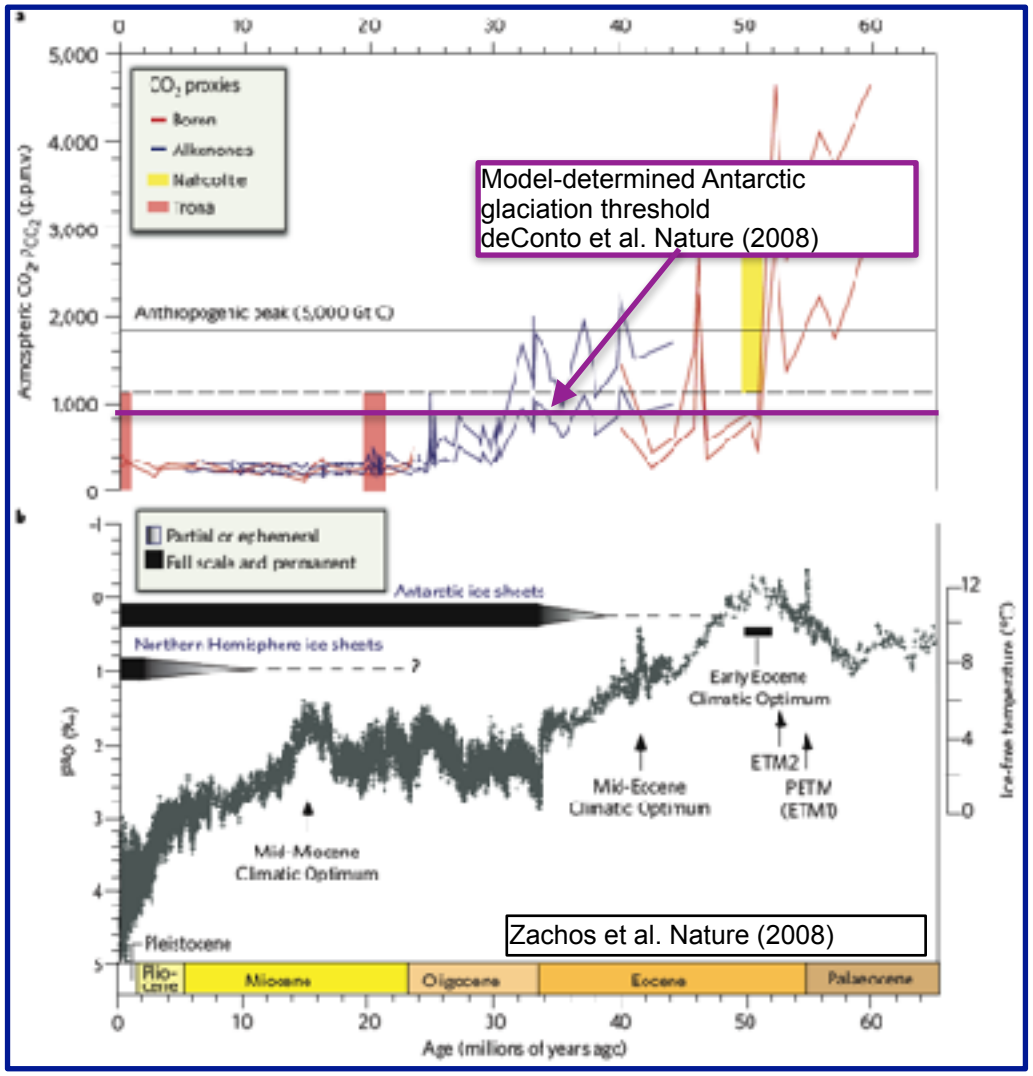
Late Eocene reconstructed topography



Baatsen, vdH et al., Clim. Past (2016)

Oldest hypothesis (Kennett 1977):
The opening of SO gateways has been crucial within the processes leading to the glaciation of Antarctica.

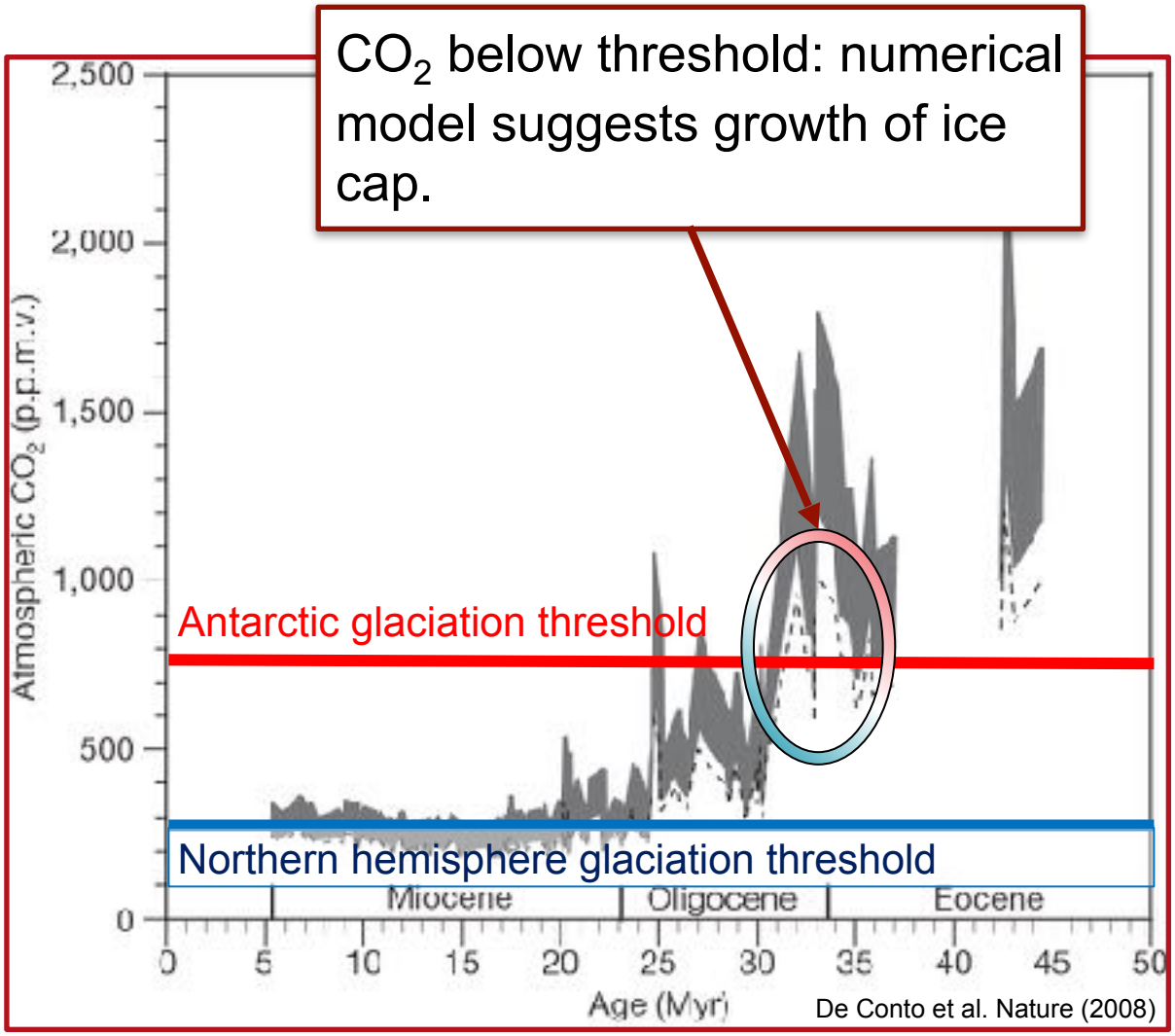
Antarctic glaciation: Why end of Eocene?



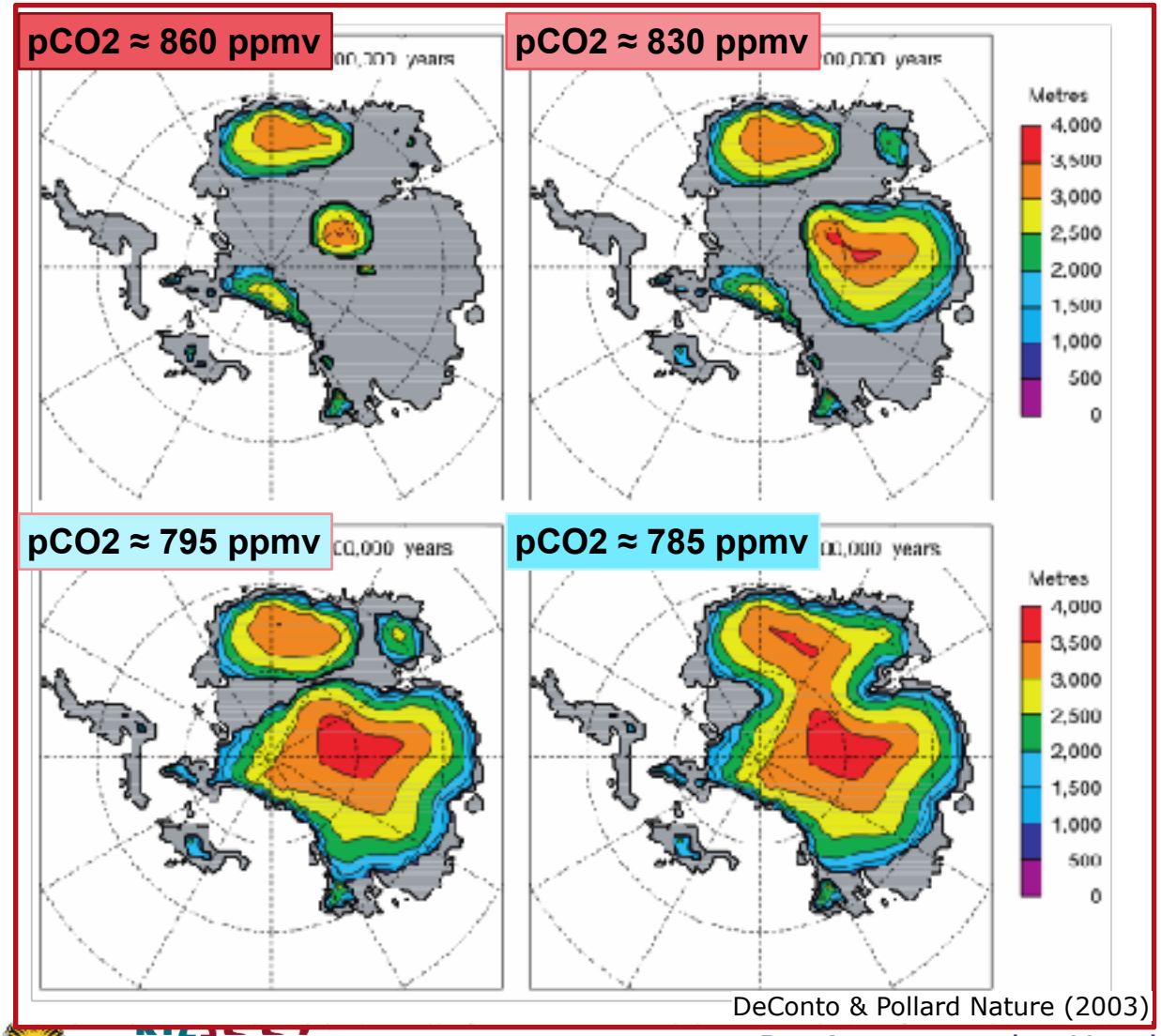
Hypothesis 2:

A critical threshold in atmospheric CO_2 was reached allowing rapid ice sheet growth on Antarctica.

Decreasing CO_2 — Tipping?



Decreasing CO_2

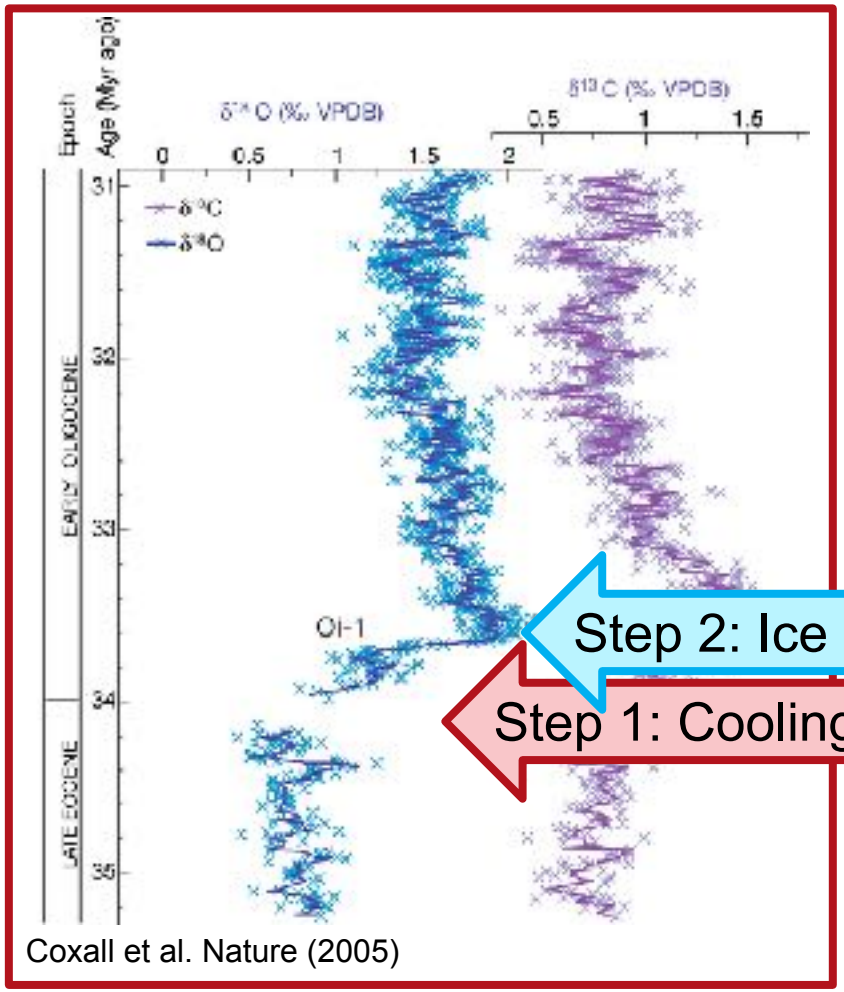


DeConto & Pollard Nature (2003)

Feedback processes:

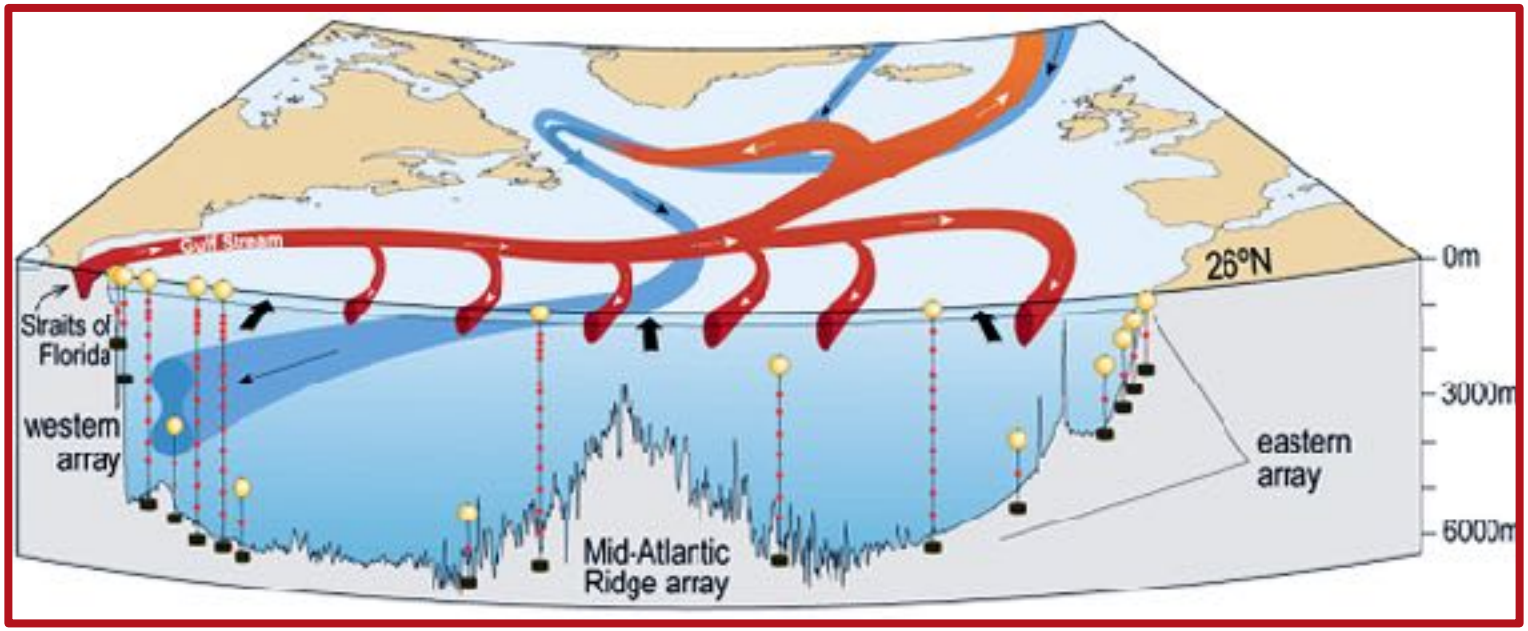
- Mass balance – height
- Merging of ice caps

2-step transition - other options for tipping



Coxall et al. Nature (2005)

Ocean circulation



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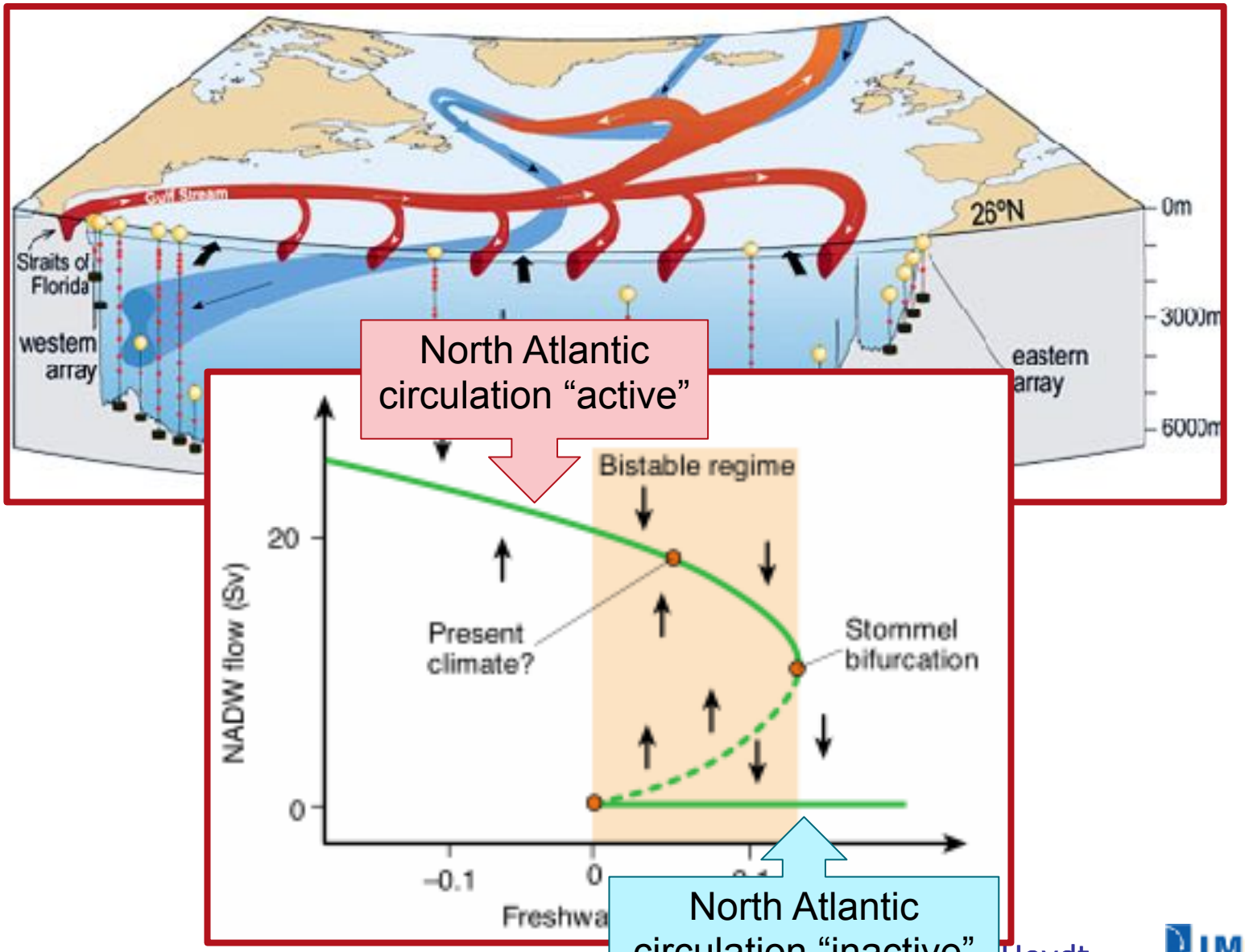
Ocean circulation

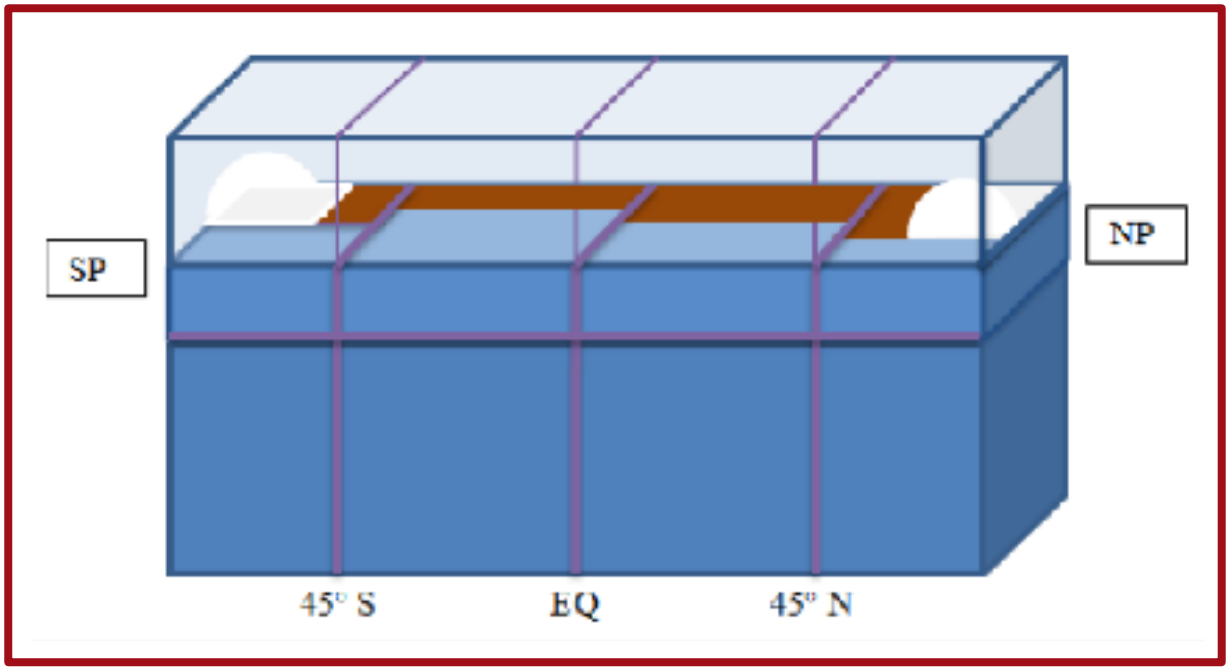


Heydt

Conceptual climate model

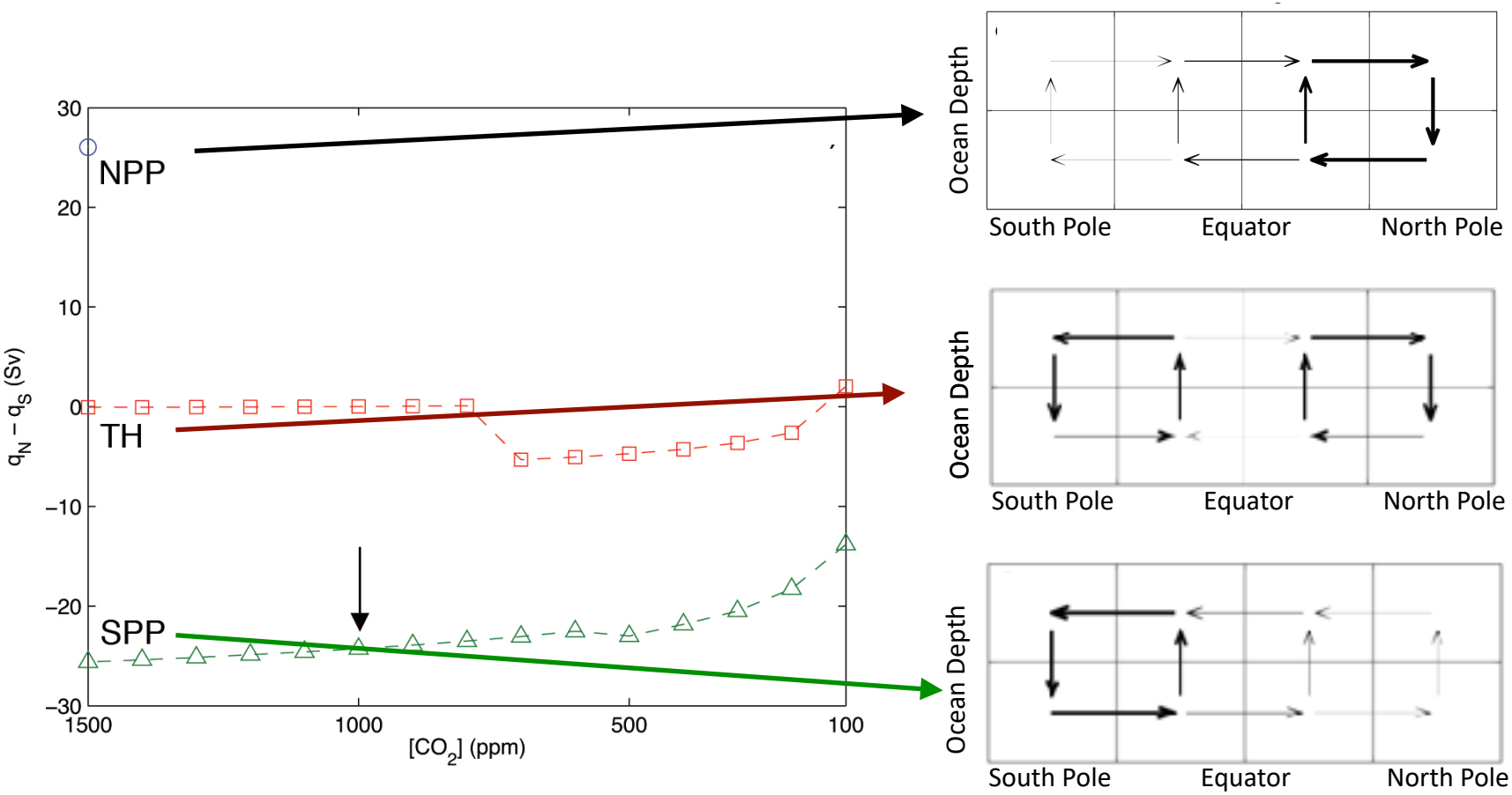
Simple Earth System model: Gildor & Tziperman 2000, 2001, 2002

- ★ Atmosphere,
- ★ Ocean,
- ★ Land ice,
- ★ Oxygen isotopes.



- ★ Land/ocean fraction adapted to Eocene values.
- ★ Optional: Ocean biogeochemistry & dynamic atmospheric pCO_2.

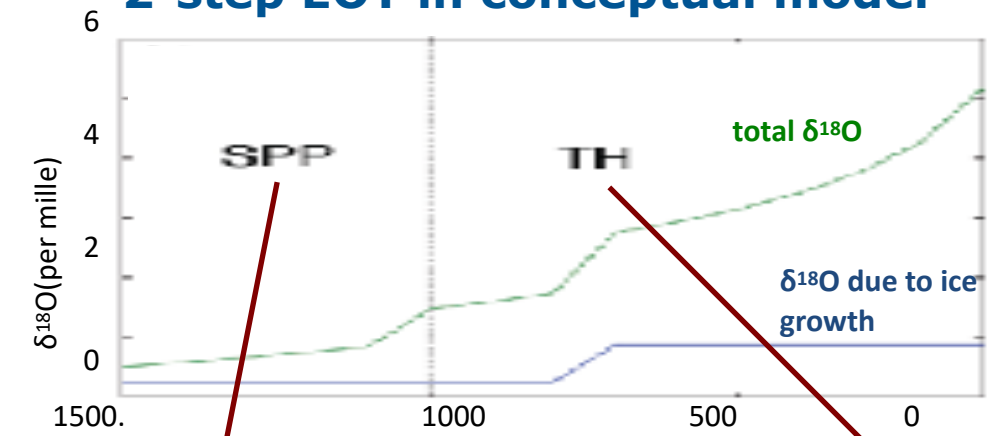
Multiple Ocean Circulation States

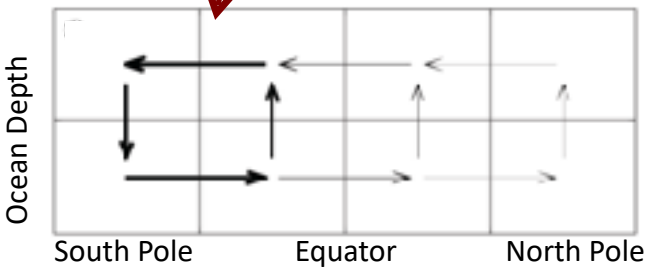


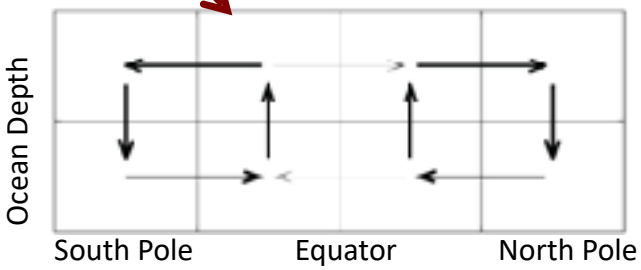
Tigchelaar, vdH, Dijkstra, Clim. Past (2011)

Antarctic glaciation: Why end of Eocene?

2-step EOT in conceptual model







- Two-step $\delta^{18}O$ increase across Eocene-Oligocene boundary can be explained by:
  - **First step** in $\delta^{18}O$ due to transition in ocean circulation pattern from SPP to TH.
  - **Second step in** $\delta^{18}O$ due to ice growth on Antarctica

Tigchelaar, vdH, Dijkstra, Clim. Past (2011)

Hypothesis 2b:
A change in global ocean circulation caused step 1, reduced CO_2 and brought ice sheet closer to critical transition.

Combination of 2 hypotheses?

nature geoscience

ARTICLES

PUBLISHED ONLINE: 30 JANUARY 2017 | DOI: 10.1038/NGEO2888

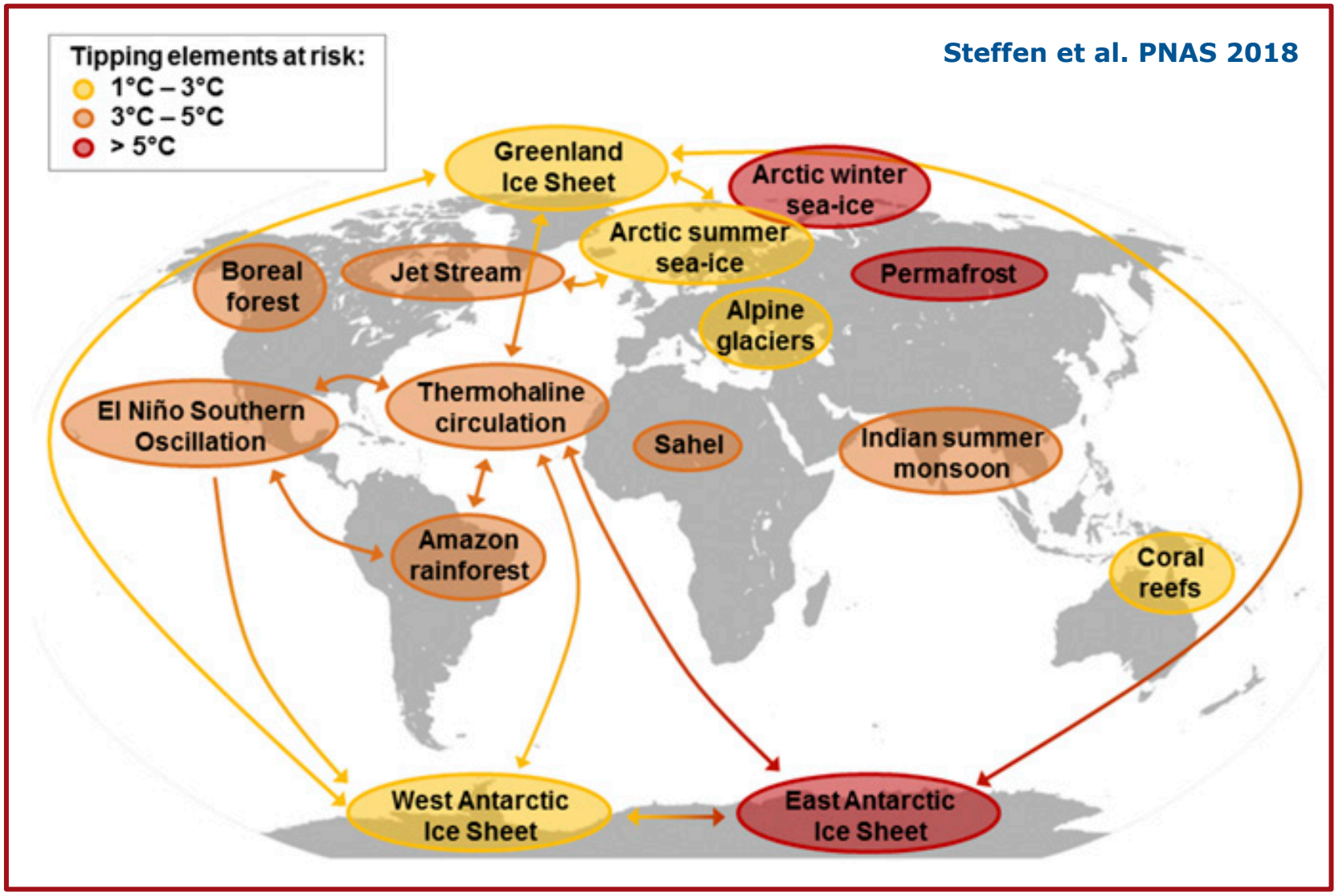
Enhanced weathering and CO_2 drawdown caused by latest Eocene strengthening of the Atlantic meridional overturning circulation

Geneviève Elsworth[1]*, Eric Galbraith[1,2,3], Galen Halverson[1] and Simon Yang[4]

On timescales significantly greater than 10^5 years, atmospheric p_{CO_2} is controlled by the rate of mantle outgassing relative to the set-point of the silicate weathering feedback. The weathering set-point has been shown to depend on the distribution and characteristics of rocks exposed at the Earth's surface, vegetation types and topography. Here we argue that large-scale climate impacts caused by changes in ocean circulation can also modify the weathering set-point and show evidence suggesting that this played a role in the establishment of the Antarctic ice sheet at the Eocene–Oligocene boundary. In our simulations, tectonic deepening of the Drake Passage causes freshening and stratification of the Southern Ocean, strengthening the Atlantic meridional overturning circulation and consequently raising temperatures and intensifying rainfall over land. These simulated changes are consistent with late Eocene tectonic reconstructions that show Drake Passage deepening, and with sediment records that reveal Southern Ocean stratification, the emergence of North Atlantic Deep Water, and a hemispherically asymmetric temperature change. These factors would have driven intensified silicate weathering and can thereby explain the drawdown of carbon dioxide that has been linked with Antarctic ice sheet growth. We suggest that this mechanism illustrates another way in which ocean–atmosphere climate dynamics can introduce nonlinear threshold behaviour through interaction with the geologic carbon cycle.

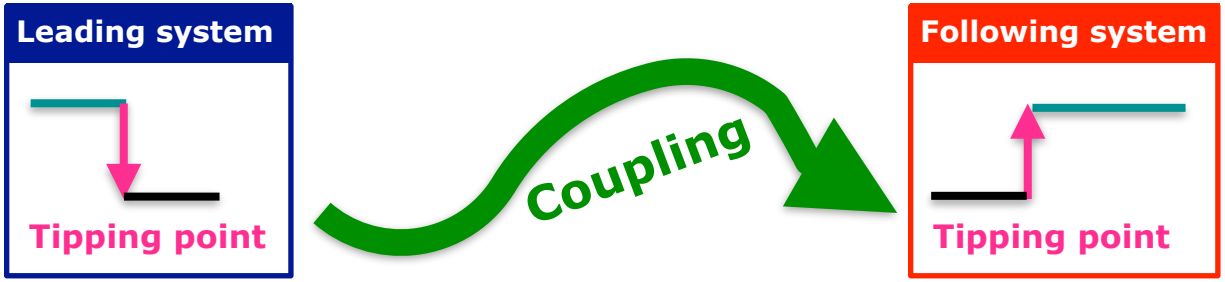
Potential for "cascading tipping" mechanism?

Potential tipping elements in the Earth System

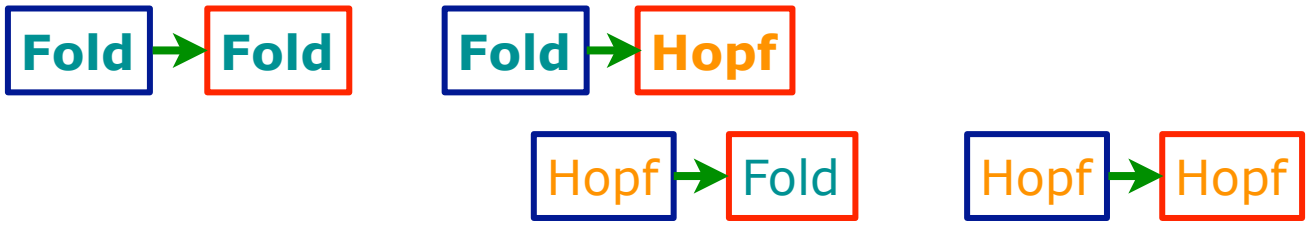


Cascading Tipping: concept

- Ingredients:



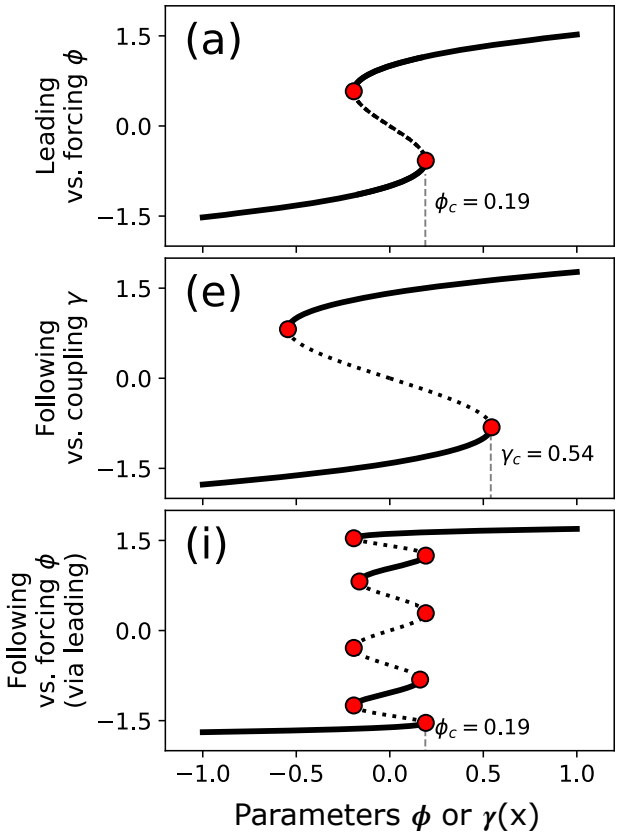
- Simplest tipping points:
  - ★ Back-to-back saddle node (bistable systems).
  - ★ Hopf bifurcation (stationary - oscillatory transition).
- Combine simple tipping points by dependency of forcing parameter in following system on the state of the leading system.

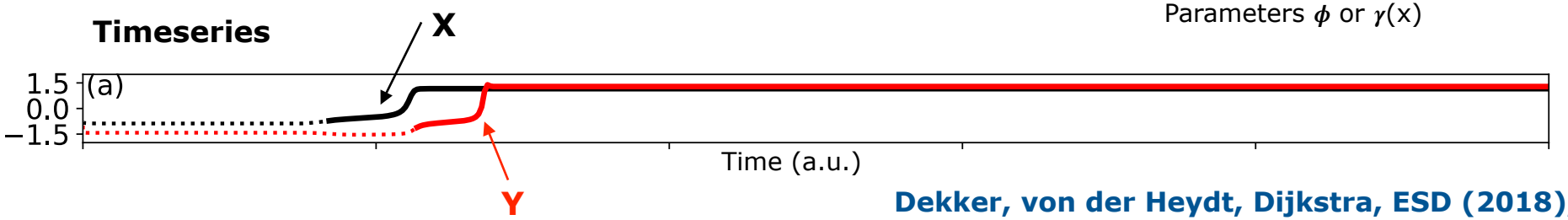


Fold-fold cascade

- Leading system X = slow-fast system
  - ★ Forced by slow parameter change (ϕ)
- Following system Y = slow-fast system
  - ★ linear coupling $\gamma(x)=\gamma_1 + \gamma_2 x$
  - ★ tipping in x ➙ tipping in y

$$\begin{cases} \dfrac{dx}{dt} = a_1 x^3 + a_2 x + \phi \\ \dfrac{dy}{dt} = b_1 y^3 + b_2 y + \gamma(x) \end{cases}$$

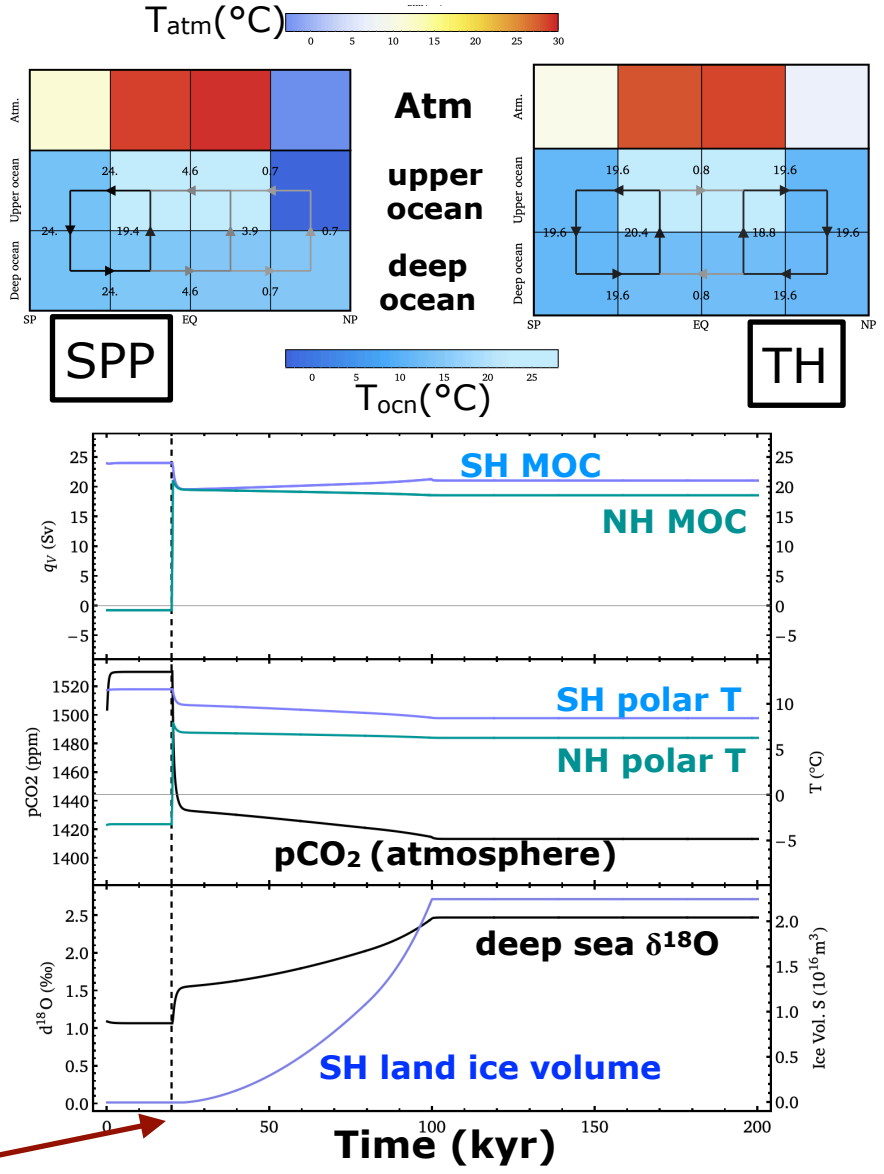




Dekker, von der Heydt, Dijkstra, ESD (2018), doi:10.5194/esd-9-1243-2018

Cascading: MOC - Antarctic ice sheet

- Leading (bistable) system: global meridional overturning circulation (MOC).
- MOC transition SPP→TH leads to:
  - ★ cooling deep ocean
  - ★ enhanced atmospheric CO_2 drawdown (vertical mixing)
- Following (bistable) system: Antarctic ice sheet
  - ★ Ice sheet inception depends on atmospheric CO_2.

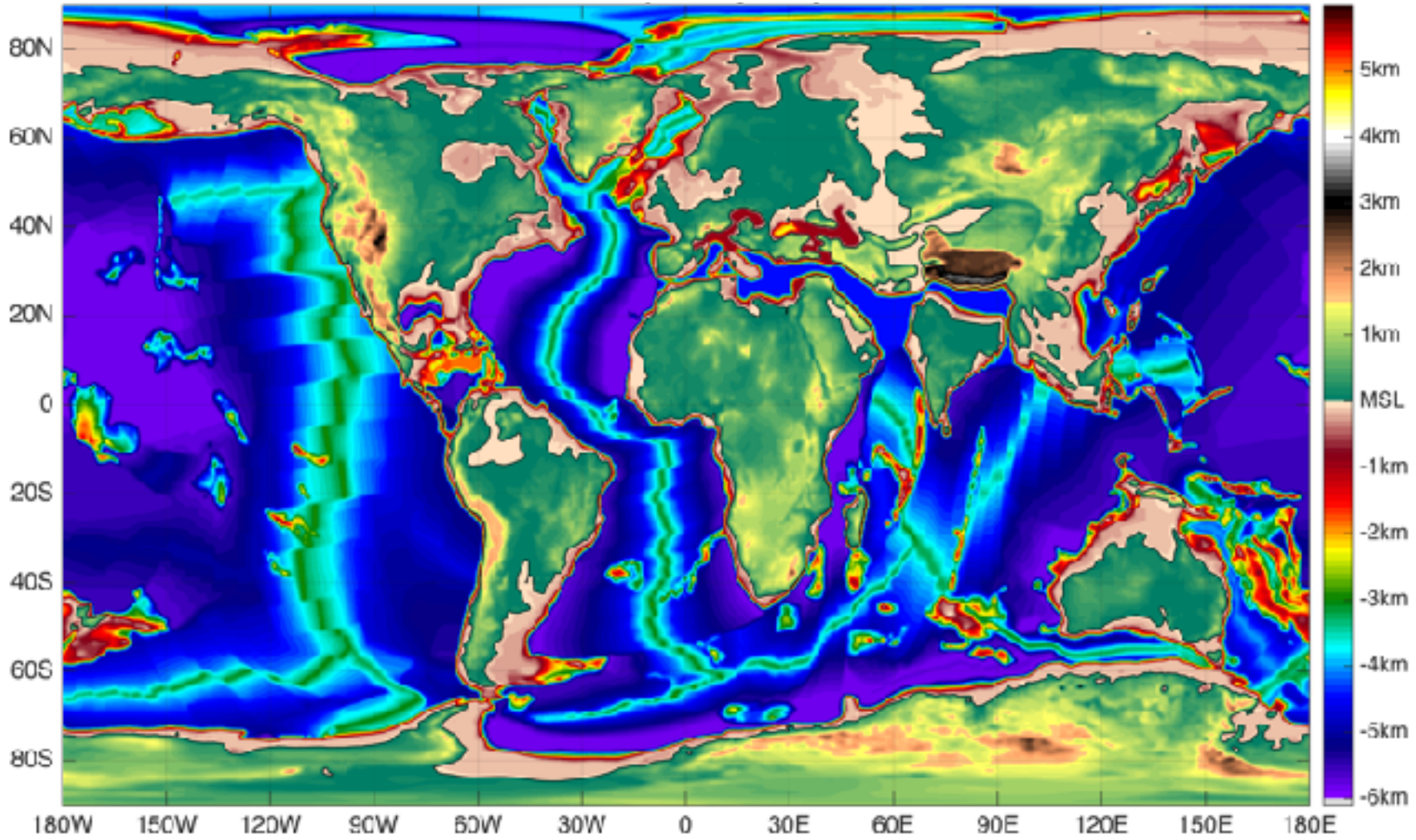


Figures by M. Clemenkowff (2019)

induced MOC transition

Ocean circulation 35 myr ago

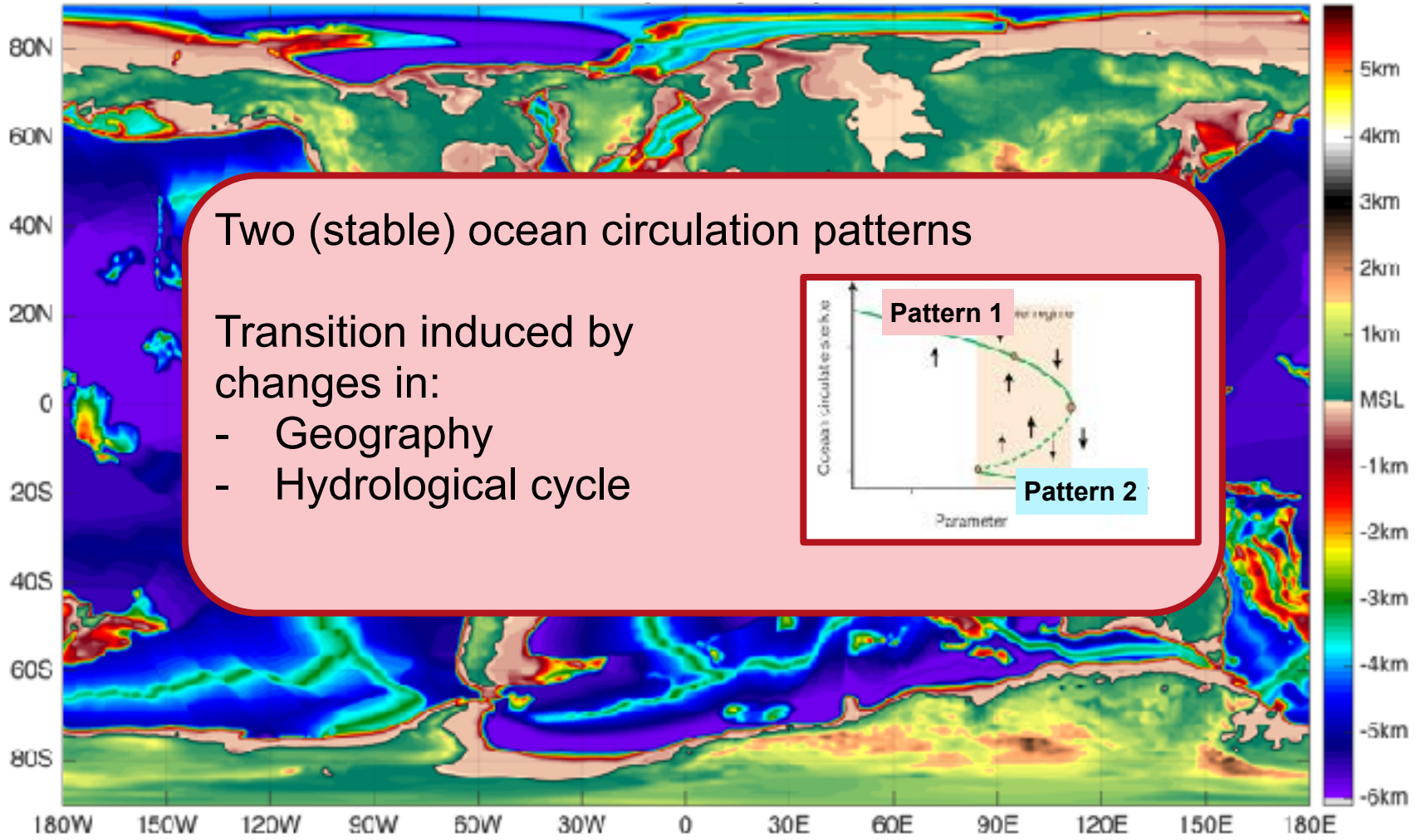
Late Eocene geography



Baatsen, vdHeydt et al. Clim. Past (2016)

Ocean circulation 35 myr ago

Late Eocene geography



Two (stable) ocean circulation patterns

Transition induced by changes in:
- Geography
- Hydrological cycle

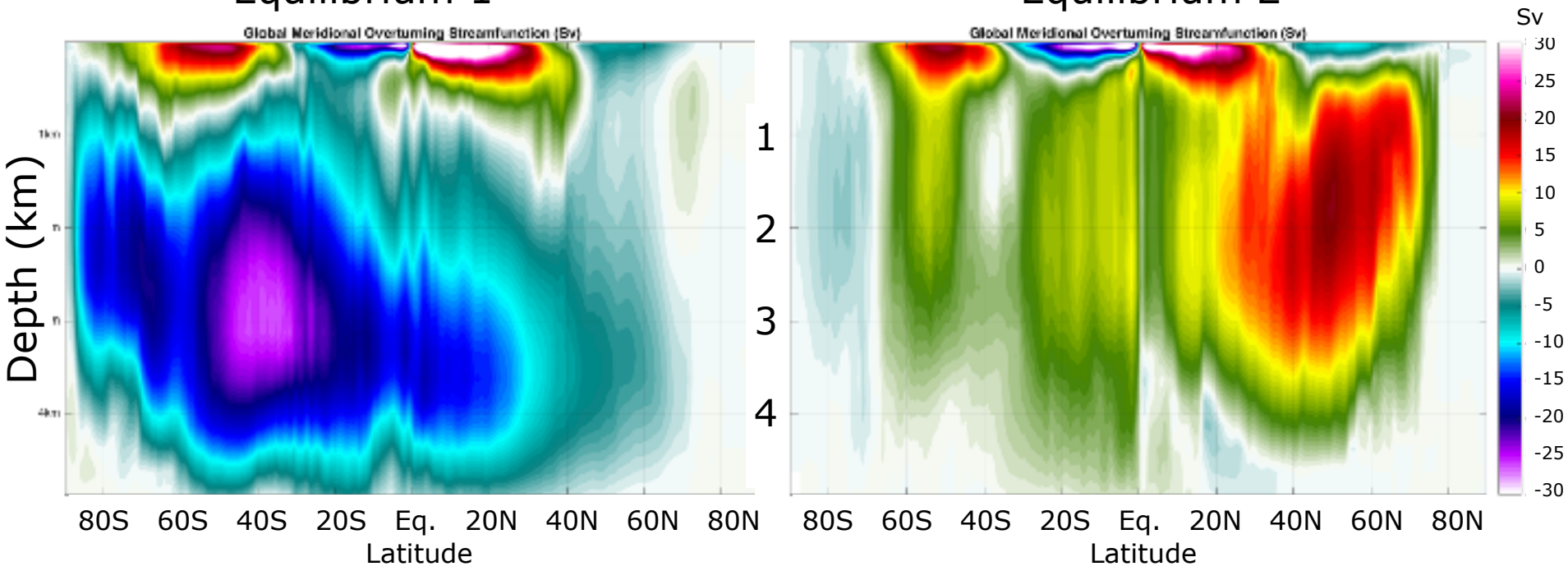
Baatsen, vdHeydt et al. Clim. Past (2016)

Eocene: PMOC - Multiple equilibria

Global meridional overturning circulation [Sv]

Equilibrium 1

Equilibrium 2



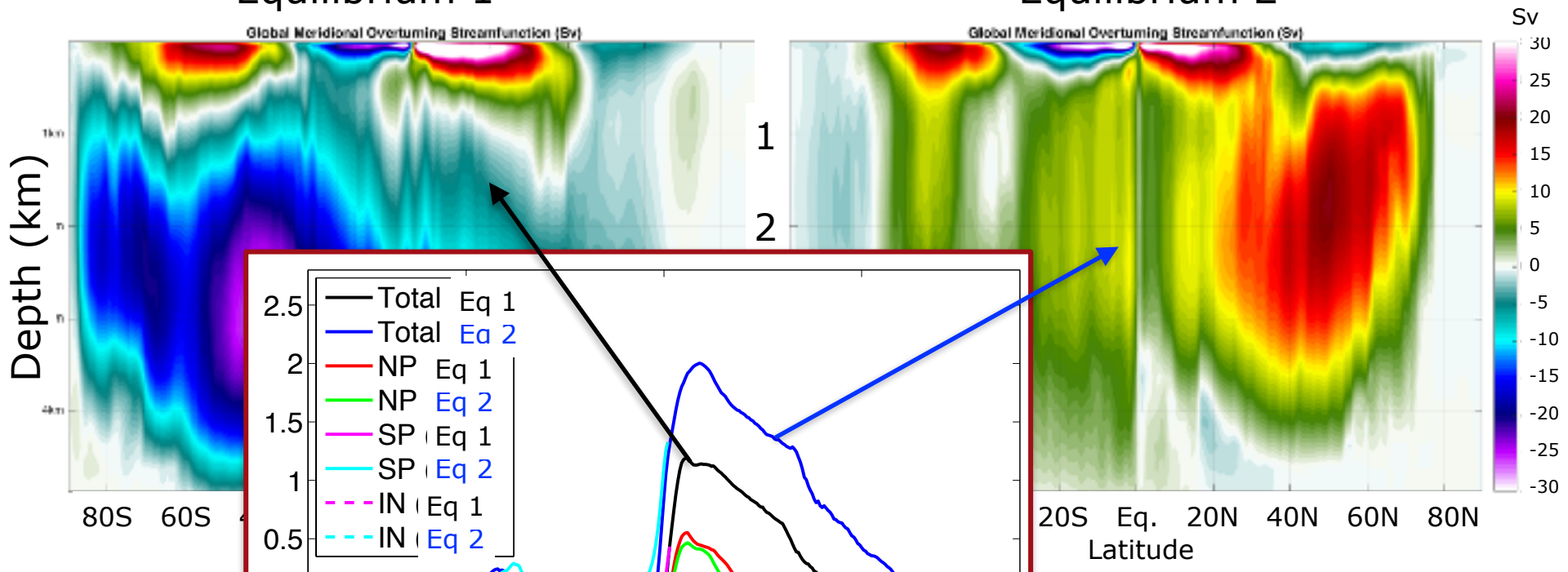
Baatsen, vdH et al., Global Planet. Change. (2018)

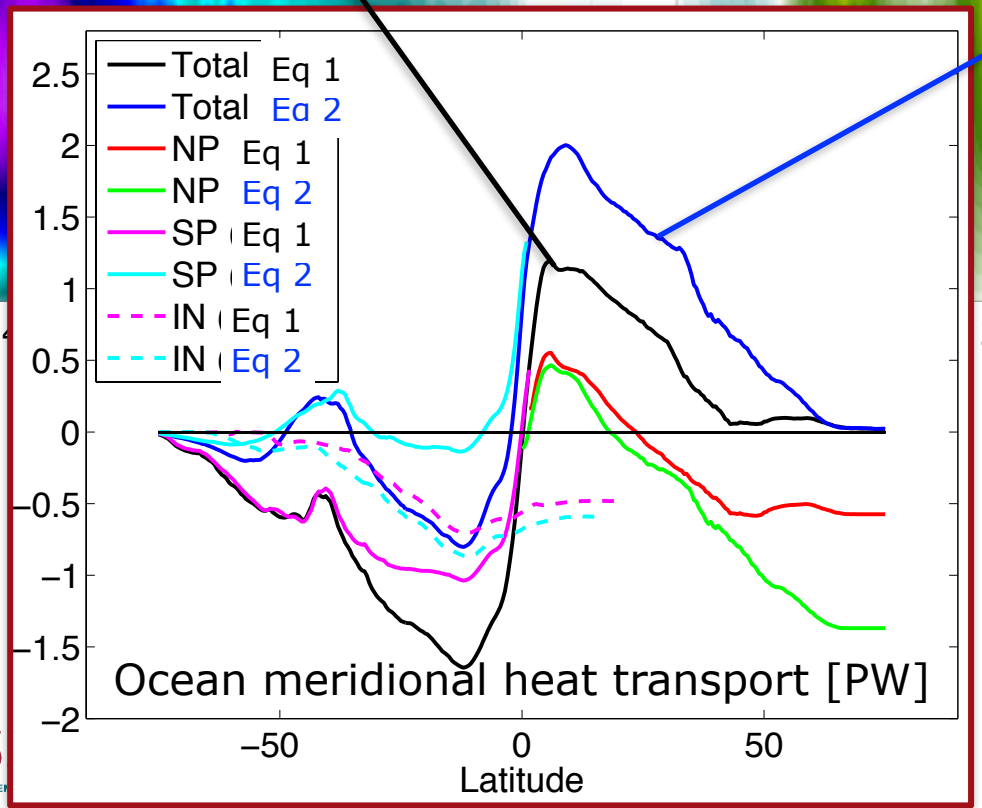
Eocene: PMOC - Multiple equilibria

Global meridional overturning circulation [Sv]

Equilibrium 1

Equilibrium 2

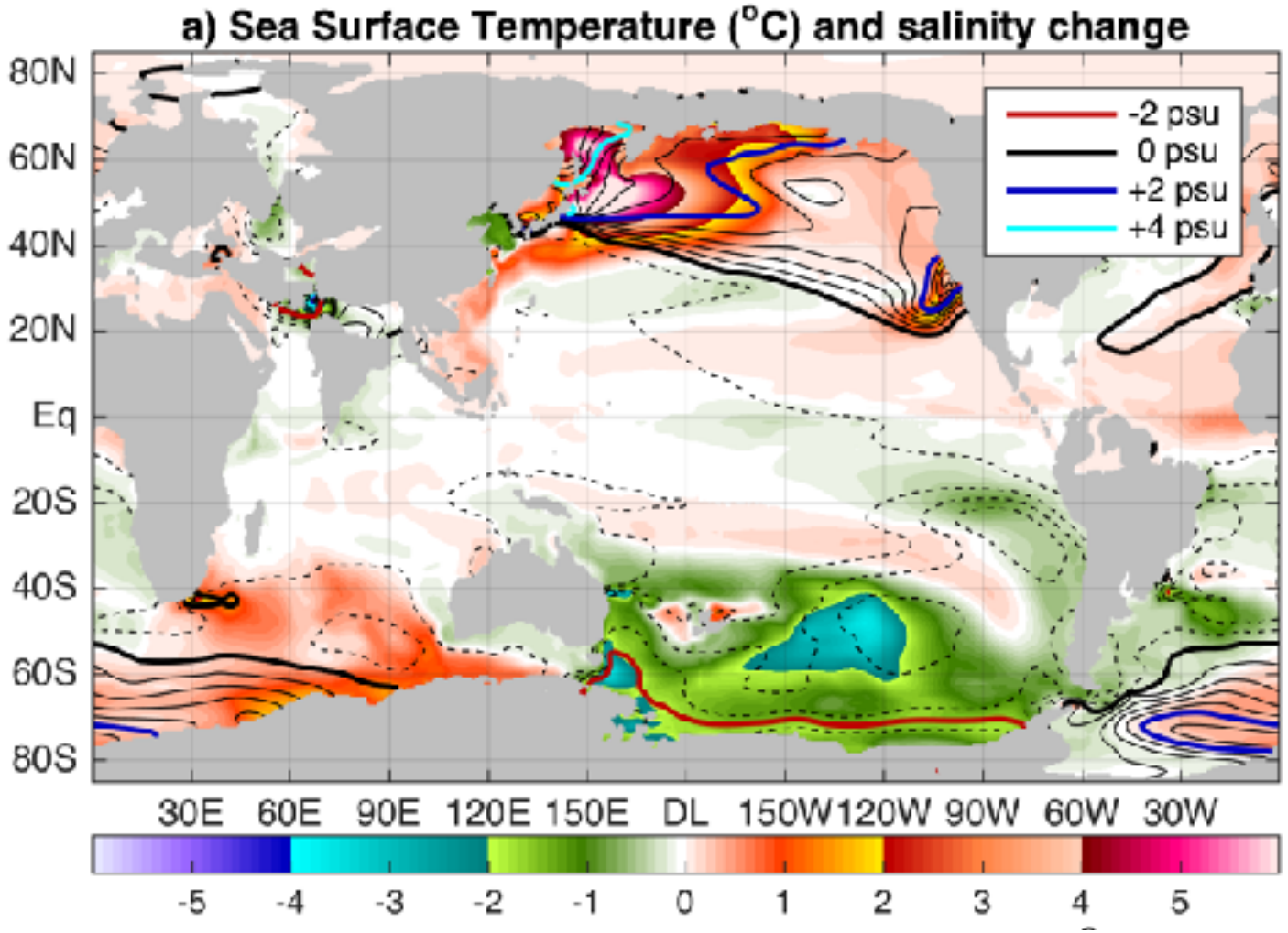




Baatsen, vdH et al., Global Planet. Change. (2018)

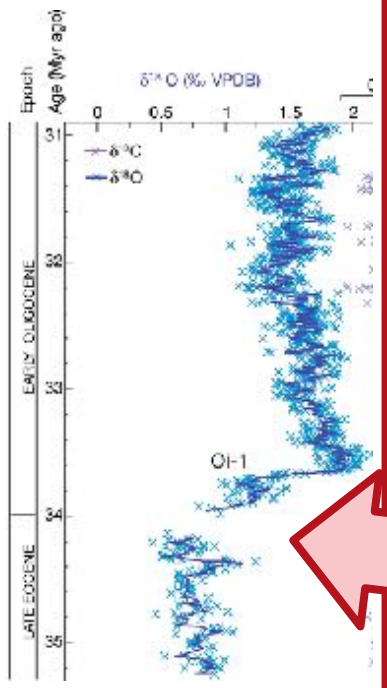
Eocene geography: Sea surface response

NH sinking (MOC 2) - SH sinking (MOC 1)

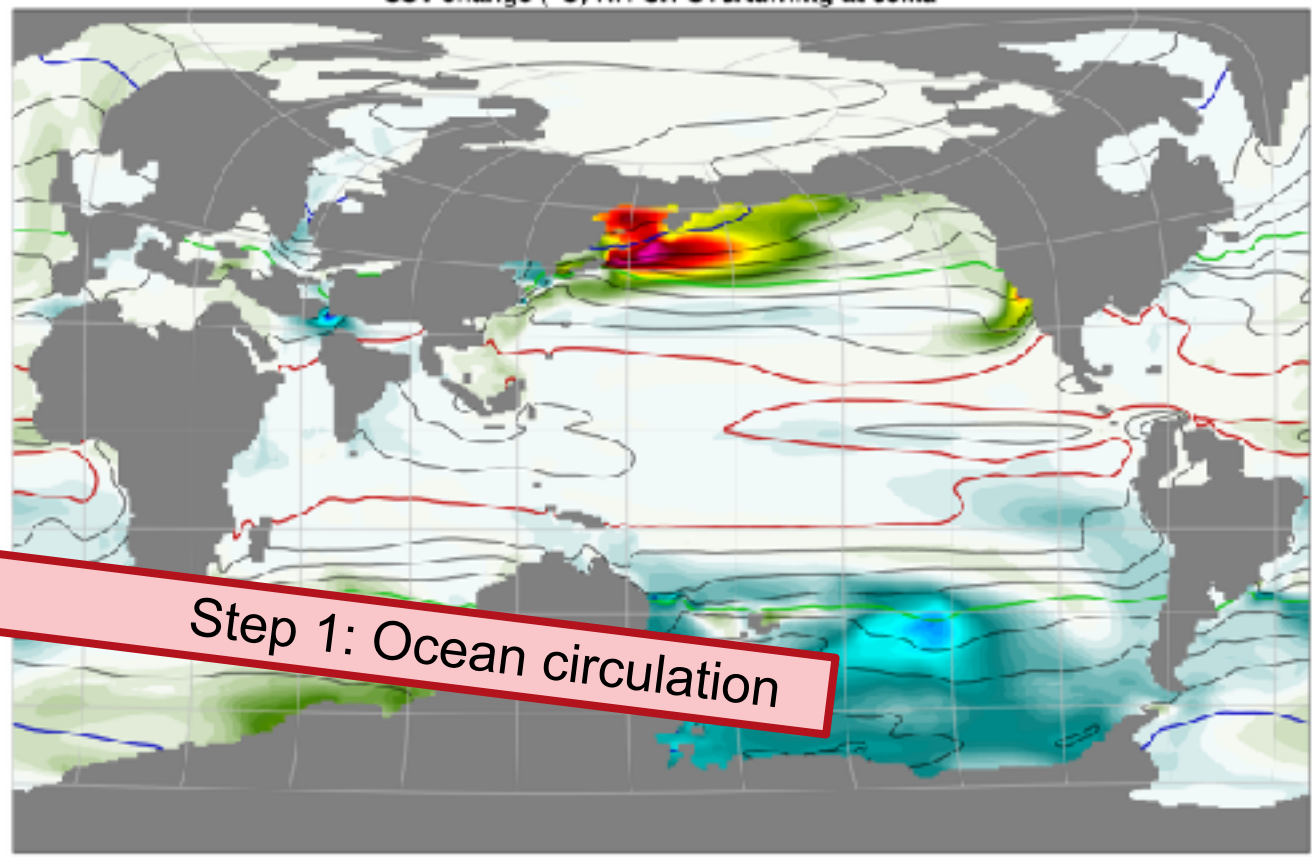


Baatsen, vdH et al., Global Planet. Change. (2018)

Ocean circulation 35 myr ago



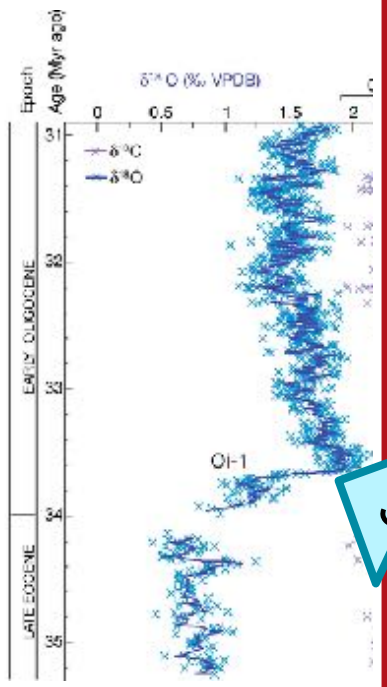
Coxall et al. Nature (2005)



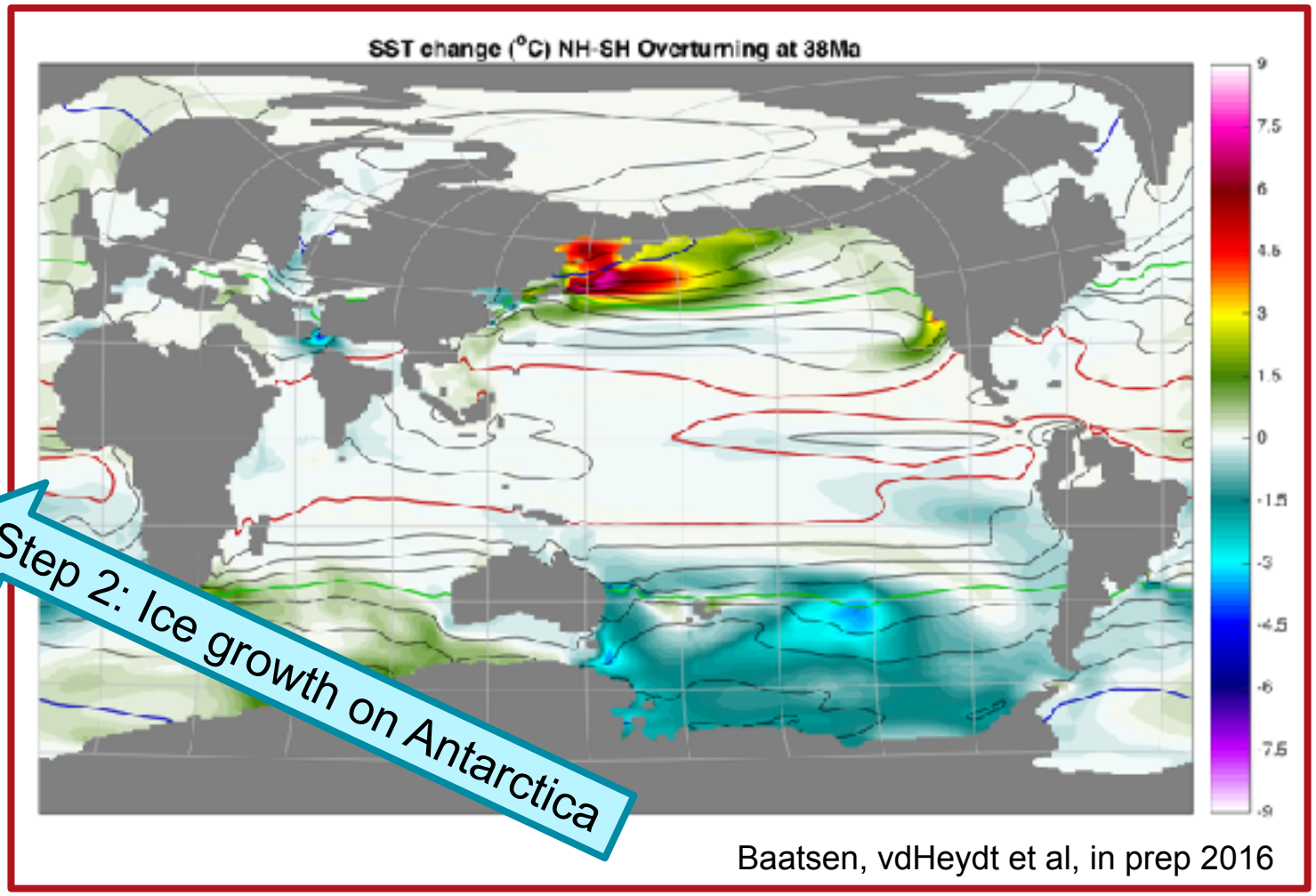
Step 1: Ocean circulation

Baatsen, vdHeydt et al, in prep 2016

Ocean circulation 35 myr ago



Coxall et al. Nature (2005)



Step 2: Ice growth on Antarctica

Baatsen, vdHeydt et al, in prep 2016

Conclusions

- Several tipping elements in climate subsystems have been identified. A **directional coupling** provides the possibility of **cascading tipping**.
- The **Eocene-Oligocene transition**
  - ★ is characterised major ice buildup on Antarctica, changes in the carbon cycle and ocean circulation reorganisation.
  - ★ in **two steps** may be explained by cascading tipping of 1. MOC and 2. land ice, coupled via atmospheric CO_2 (conceptual model).
- Eocene continental geometry:
  - ★ Potential for multiple equilibria of the **Pacific MOC** (3D ocean model).
  - ★ Extreme seasonality & Antarctic summer-monsoon climate inhibits ice growth in Antarctic interior (coupled climate model).
  - ★ Mild, less extreme coastal regions may allow for (regional) glaciers to develop (coupled climate model).

Thanks: www.pastearth.net