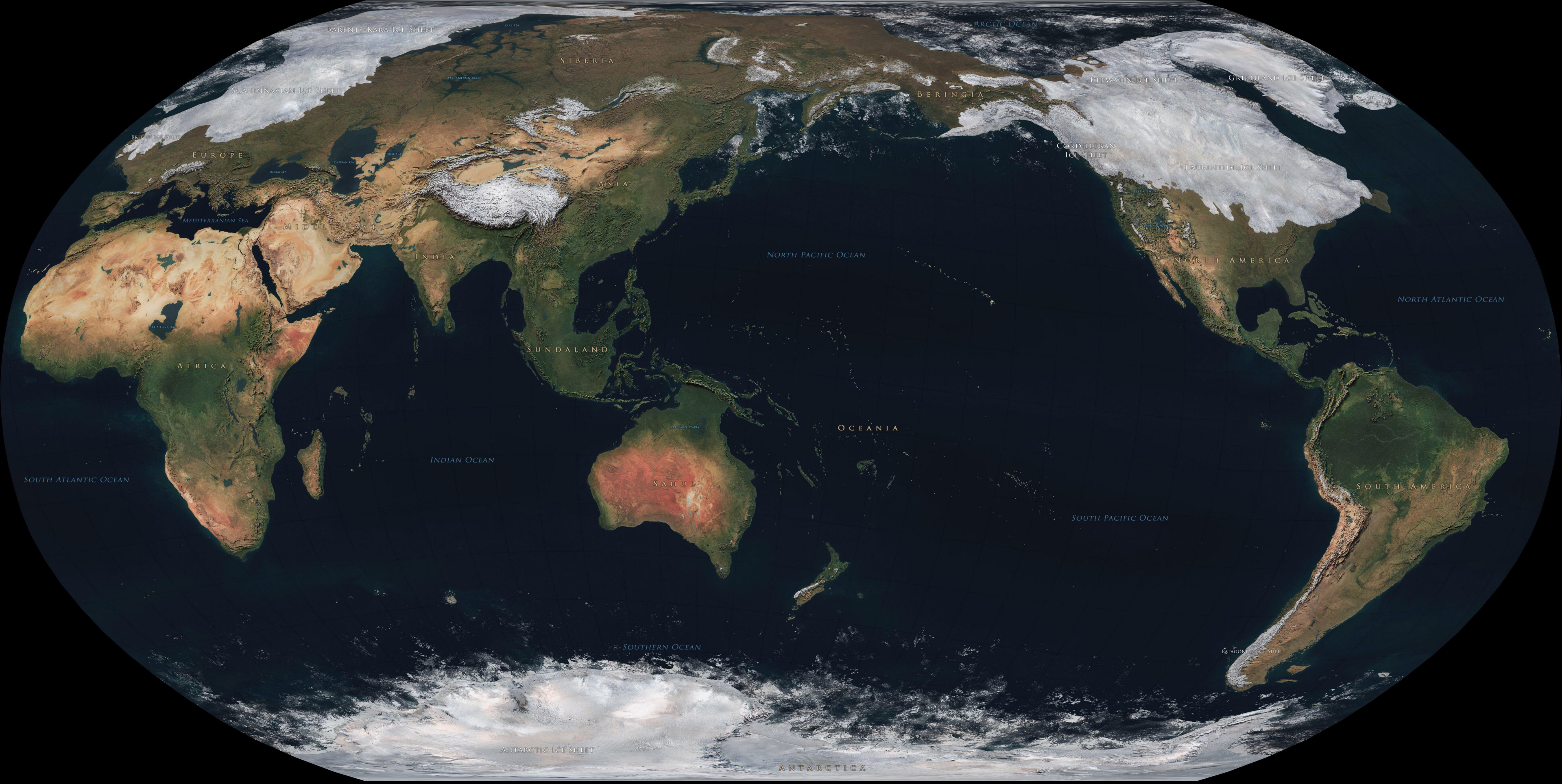


Glaciation and Climate Change

John Noble
Earth 203, UCSC
October 30, 2008
(Updated)

Motivation and significance

- Better understand:
  - natural variability in the climate system
  - climate periodicity
  - climate thresholds & tipping points

- Develop references:
  - to compare our current climate and its rate of change

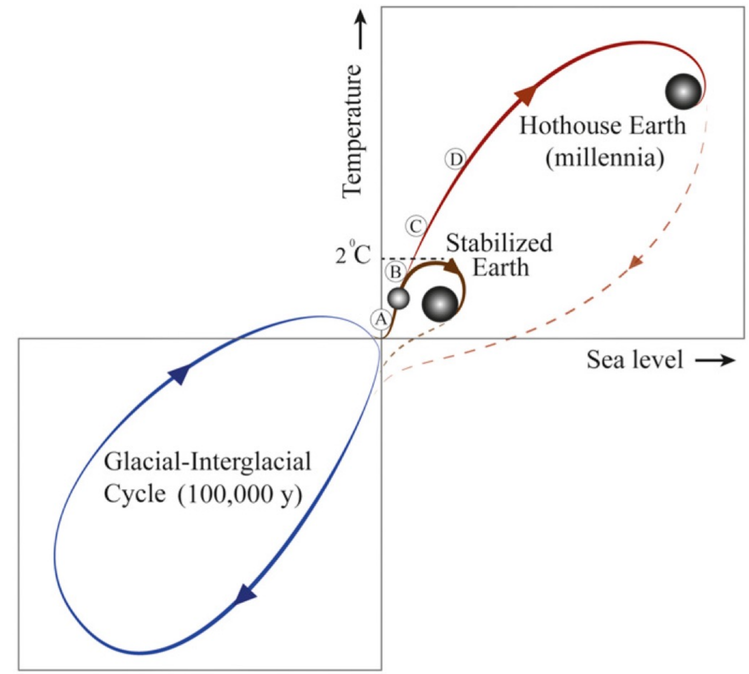


Fig. 1. A schematic illustration of possible future pathways of the climate against the background of the typical glacial–interglacial cycles (*Lower Left*). The interglacial state of the Earth System is at the top of the glacial–interglacial cycle, while the glacial state is at the bottom. Sea level follows temperature change relatively slowly through thermal expansion and the melting of glaciers and ice caps. The horizontal line in the middle of the figure represents the preindustrial temperature level, and the current position of the Earth System is shown by the small sphere on the red line close to the divergence between the Stabilized Earth and Hothouse Earth pathways. The proposed planetary threshold at ~2 °C above the preindustrial level is also shown. The letters along the Stabilized Earth/Hothouse Earth pathways represent four time periods in Earth's recent past that may give insights into positions along these pathways (*SI Appendix*): A, Mid-Holocene; B, Eemian; C, Mid-Pliocene; and D, Mid-Miocene. Their positions on the pathway are approximate only. Their temperature ranges relative to preindustrial are given in *SI Appendix*, Table S1.

(Steffen *et al.* 2018)

Major glaciation periods

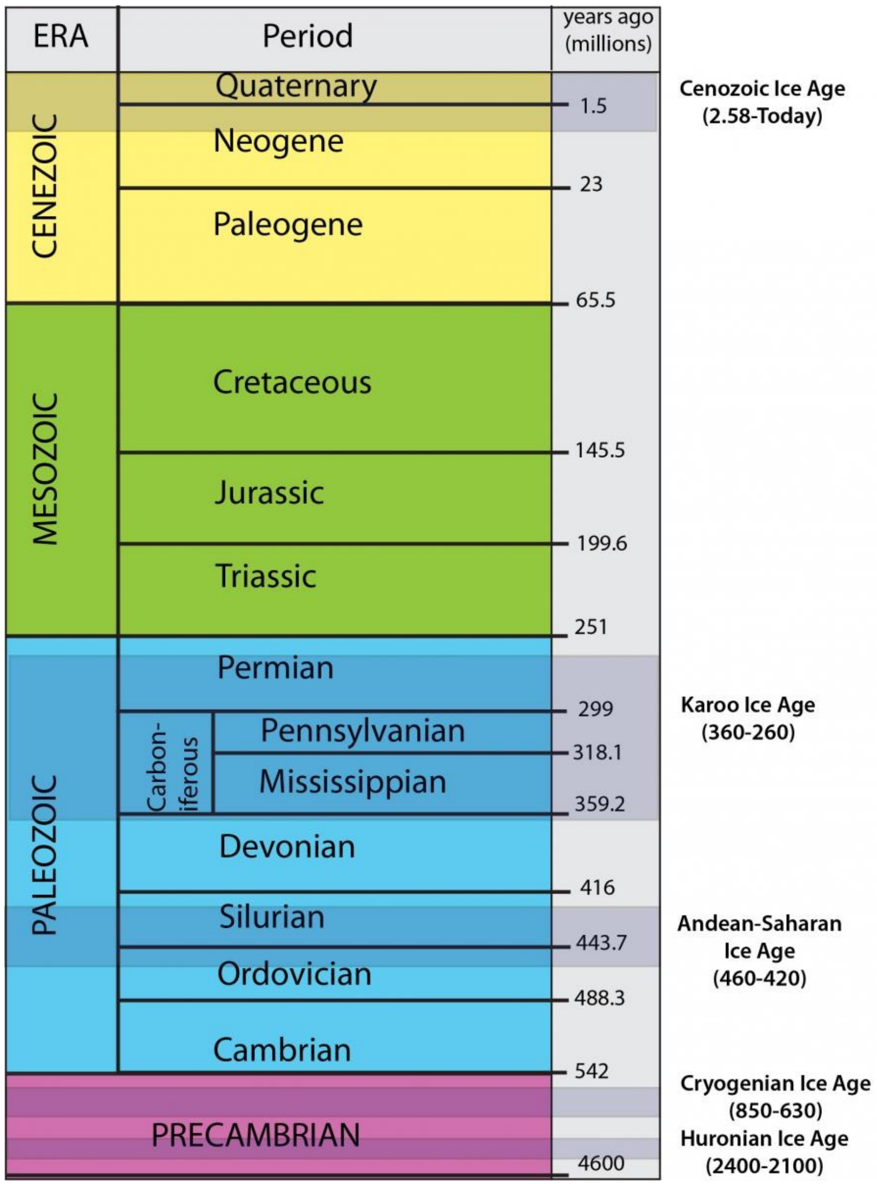
1. Huronian, 2.7 to 2.3 Ga
2. Cryogenian 850635 Ma
   - Snowball Earth hypothesis, followed by Cambrian explosion
3. Andean-Saharan, 460430 Ma
   - Late Ordovician and the Silurian period.
4. Karoo, 350 to 260 Ma
   - Carboniferous and early Permian Periods
5. Quaternary, 2.5 Ma to present

(Bradley 1999, Ruddiman 2008, IPCC WG1 2007)

Possible future pathways of the climate against the background of the typical glacial interglacial cycles. Time periods that may give insights into positions along these pathways:

A) Mid-Holocene (~67 ka)
B) Eemian (~125 ka)
C) Mid-Pliocene (~34 Ma)
D) Mid-Miocene (~1517 Ma)

(Steffen *et al.* 2018)



Glaciation timeline

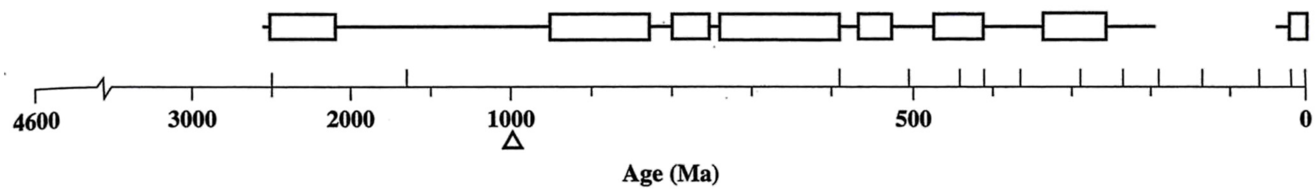
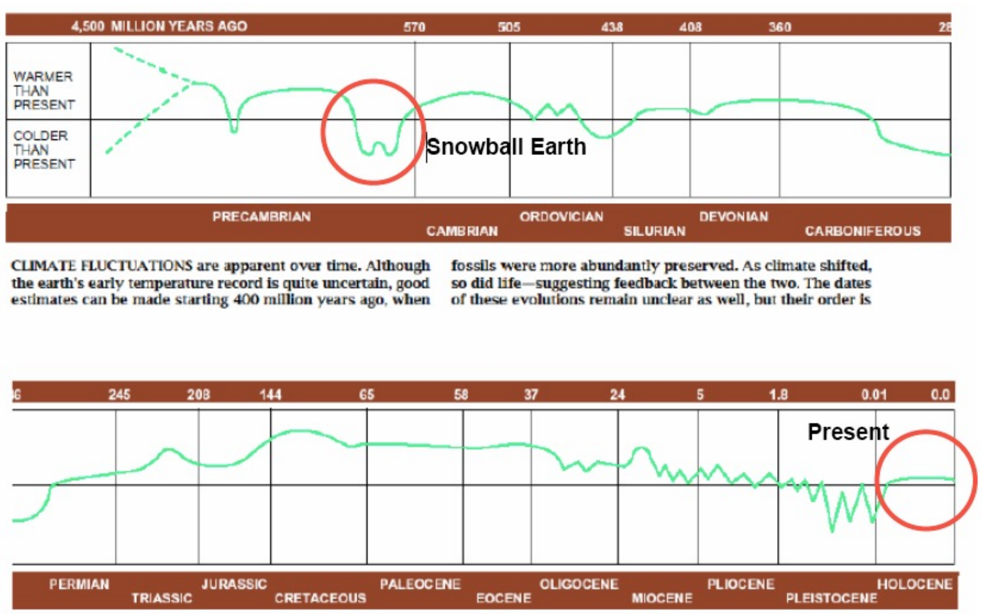
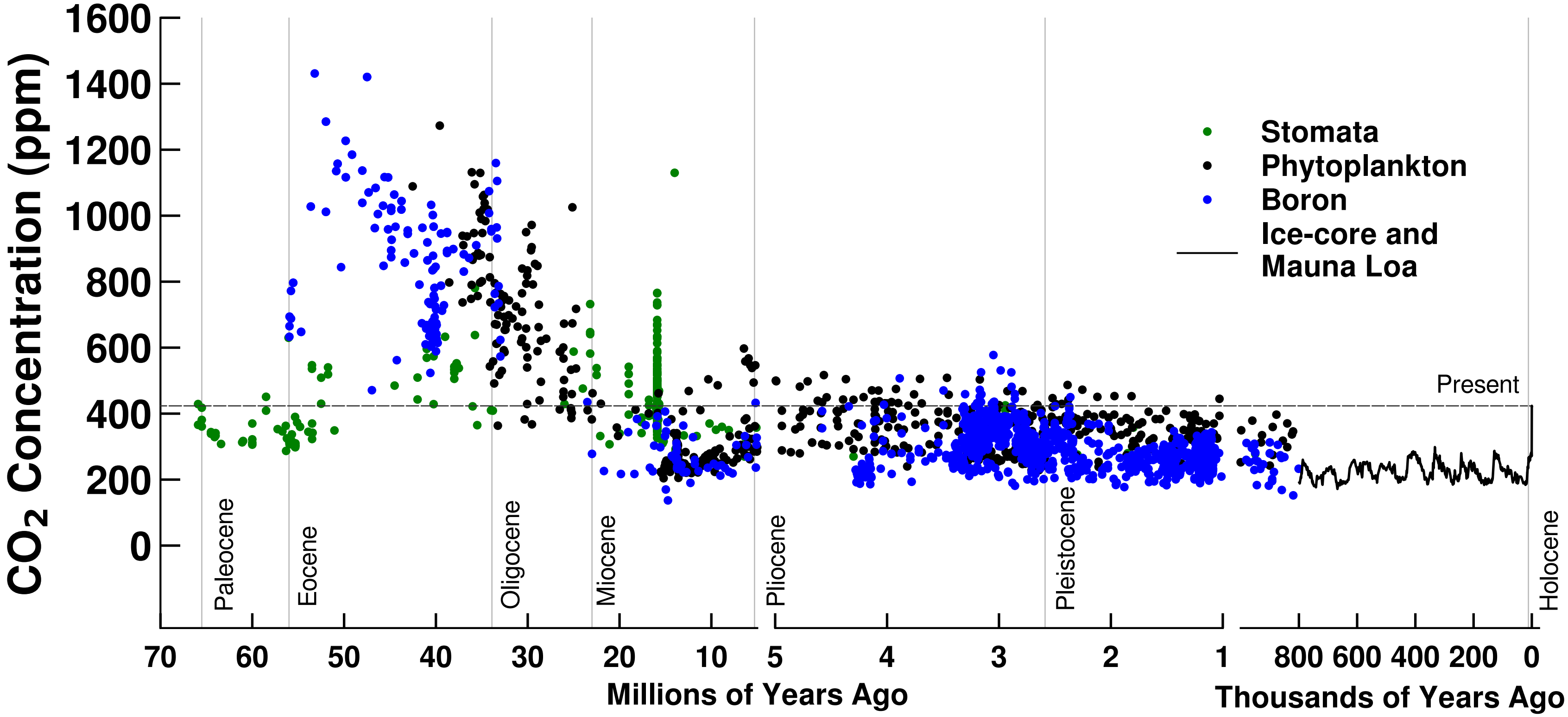


Figure 19.2. Timeline of ice ages. Boxes correspond to times in Earth's history during which widespread glaciation occurred, based on geologic data from a number of locations around the globe. Other times when at least some year-round ice was present on Earth are marked with the horizontal lines. Blanks characterize episodes when Earth had little or no year-round ice anywhere. Times are marked in millions of years before present: Thus, "1,000 Ma" is a billion years ago. From Barron (1992).



70,000,000-year history of atmospheric CO_2



(Keeling 2024)

Glaciation causes

Changes in and interplay of:

- Solar output
- Earth's orbital parameters (Milankovitch cycles)
- Distribution of continents
  ⇒ Affects albedo and ocean circulation
- Atmospheric composition
- Meteorite impacts
- Orbital dynamics of the Earth-Moon system
- Volcanic activity

N.B.

- Glaciation progression from 40,000–100,000 years ago is not fully accounted for by orbital cycles.

- Uncertain if CO_2 is responding to, or forcing, temperature.

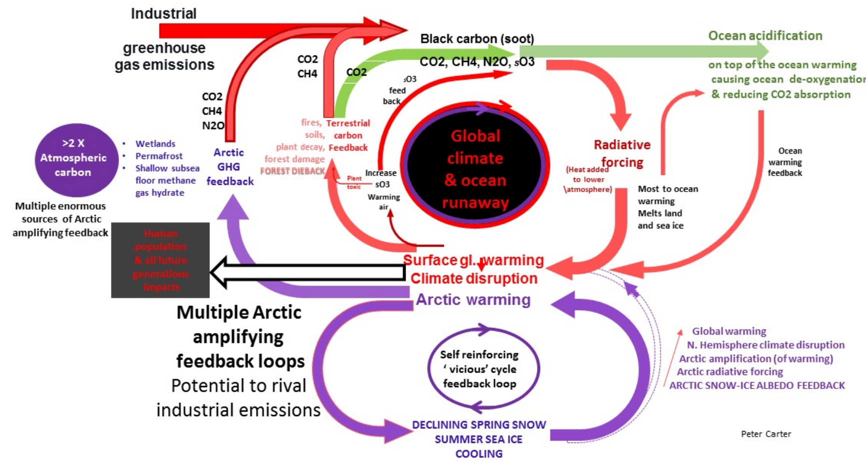
Feedback mechanisms & tipping points

Positive feedbacks may amplify small perturbations. A series of small changes may push the system into a different state.

- Changes in Earth's atmospheric composition may alter the climate, while climate change itself can change the atmospheric composition (*e.g.* by changing the rate at which weathering removes CO_2).

- Ice sheet cover increases albedo, causing cooling, which supports further ice sheet growth. Albedo is proportional to continental ice cover.

- Continental position partially determines ocean circulation.



(Carter 2019)

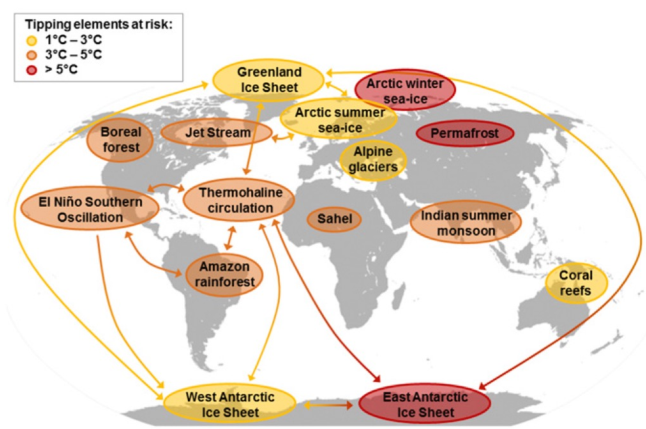


Fig. 3. Global map of potential tipping cascades. The individual tipping elements are color- coded according to estimated thresholds in global average surface temperature (tipping points) (12, 34). Arrows show the potential interactions among the tipping elements based on expert elicitation that could generate cascades. Note that, although the risk for tipping (loss of) the East Antarctic Ice Sheet is proposed at >5 °C, some marine-based sectors in East Antarctica may be vulnerable at lower temperatures (35–38).

(Steffen *et al.* 2018)

Evidence and proxies

Marine record

- Preserves all past glaciations

Land-based

- Less complete since successive glaciations may destroy previous evidence

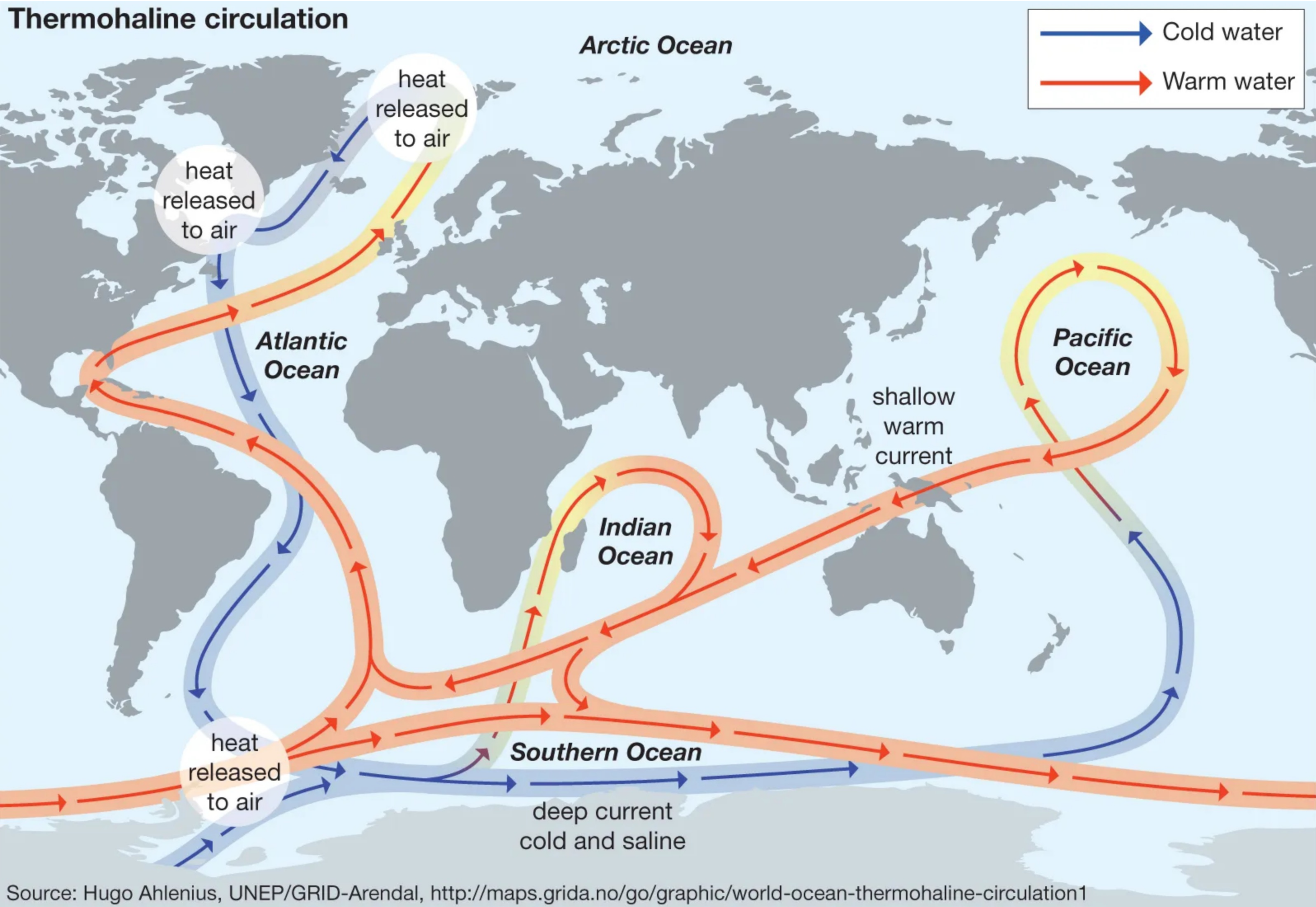
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

Proxies for temperature and precipitation

- Ocean cores
  - Infer temperature data 450 Ma
- Ice cores
  - Infer temperature data 800 Ma
- Lake cores
  - Infer temperature data from millions yr BP
- Pollen
  - 10,000–2,000,000 yr BP
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

Pleistocene

- Geological processes and atmospheric chemistry are “modern”.
- Detailed climate records have been constructed.
  Onset:
  - Continental landmasses at high latitudes
  - Low atmospheric CO_2
- Pattern:
  - Long spans of continental glaciation (40,000–100,000 yr)
  - Short interglacials (10,000–20,000 yr)



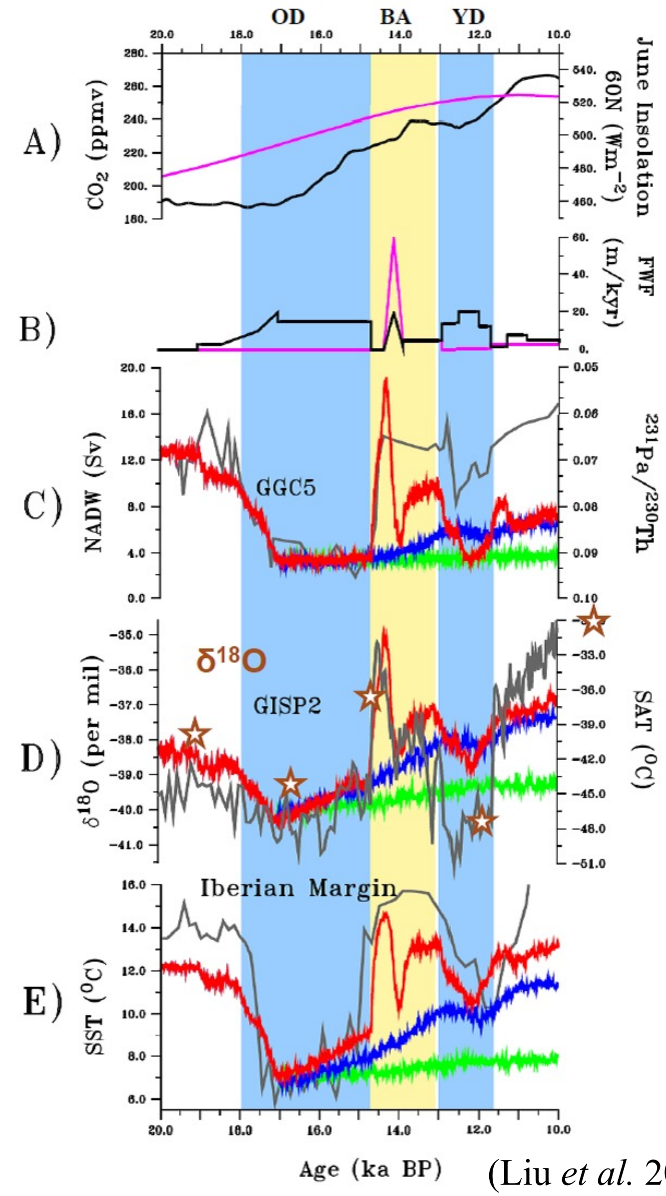
Thermohaline circulation

Source: Hugo Ahlenius, UNEP/GRID-Arendal, http://maps.grida.no/go/graphic/world-ocean-thermohaline-circulation1

Younger Dryas (Early Holocene)

- Striking episode of climate variability
  - Lasted 1000 years, then warmed rapidly (decades).
  - Occurred during glacial retreat.
  - Evidence from pollen and ice core records.

- Hypothesized that massive influx of glacial meltwater diluted north Atlantic
  - Freshwater is less dense than salty.
  - Changed Thermohaline circulation and north Atlantic heat pump.



(Liu *et al.* 2012)

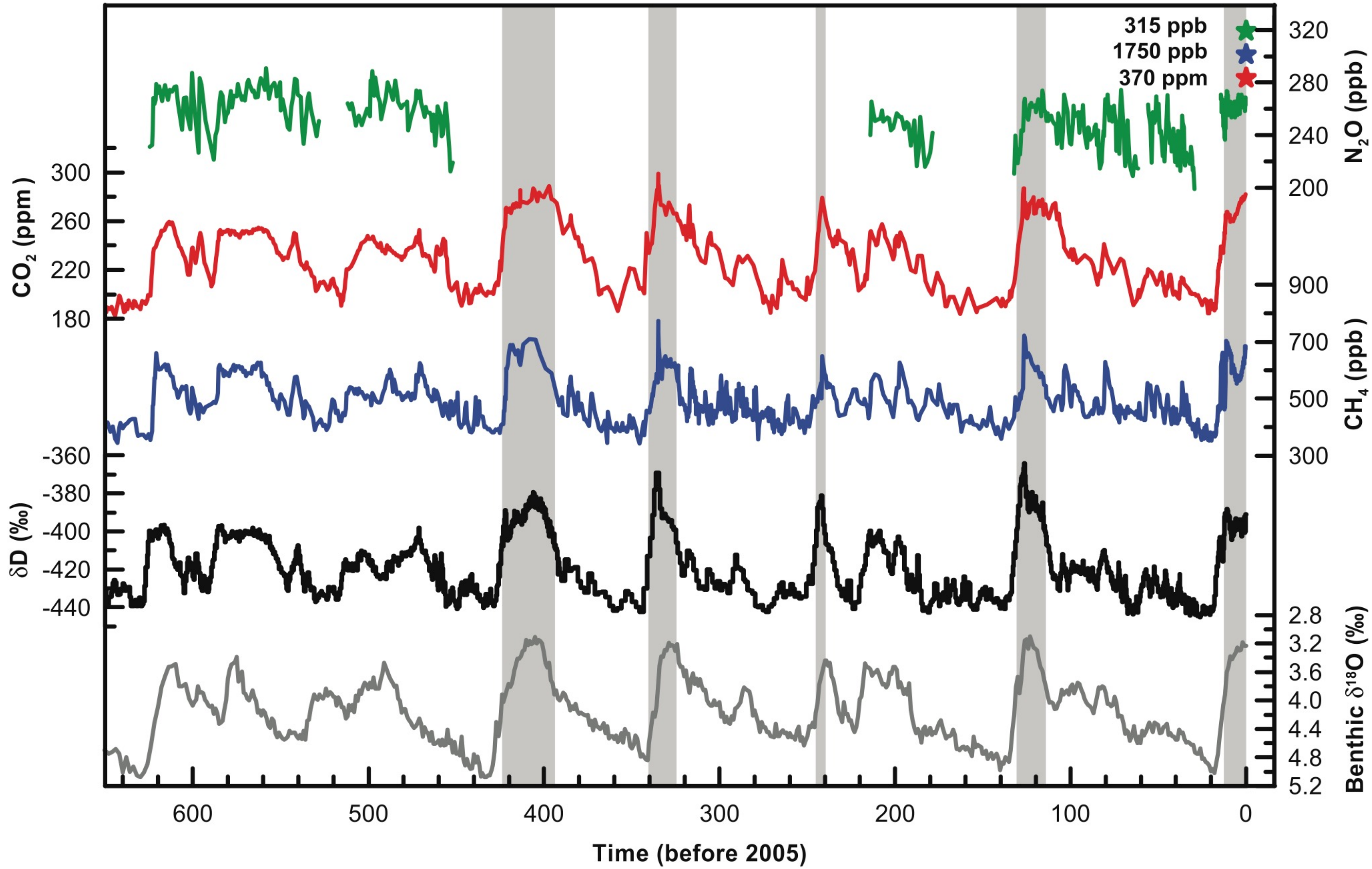
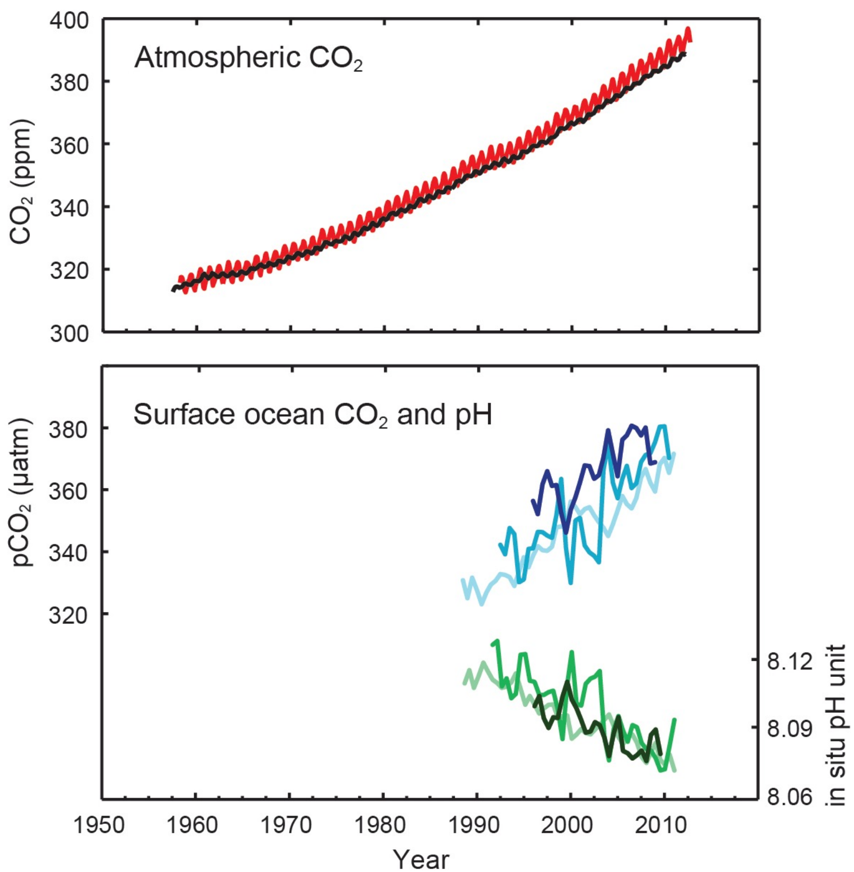


Figure 6.3. *Variations of deuterium (δD; black), a proxy for local temperature, and the atmospheric concentrations of the greenhouse gases CO_2 (red), CH_4 (blue), and nitrous oxide (N_2O; green) derived from air trapped within ice cores from Antarctica and from recent atmospheric measurements (Petit et al., 1999; Indermühle et al., 2000; EPICA community members, 2004; Spahni et al., 2005; Siegenthaler et al., 2005a,b). The shading indicates the last interglacial warm periods. Interglacial periods also existed prior to 450 ka, but these were apparently colder than the typical interglacials of the latest Quaternary. The length of the current interglacial is not unusual in the context of the last 650 kyr. The stack of 57 globally distributed benthic $\delta^{18}O$ marine records (dark grey), a proxy for global ice volume fluctuations (Lisiecki and Raymo, 2005), is displayed for comparison with the ice core data. Downward trends in the benthic $\delta^{18}O$ curve reflect increasing ice volumes on land. Note that the shaded vertical bars are based on the ice core age model (EPICA community members, 2004), and that the marine record is plotted on its original time scale based on tuning to the orbital parameters (Lisiecki and Raymo, 2005). The stars and labels indicate atmospheric concentrations at year 2000.*

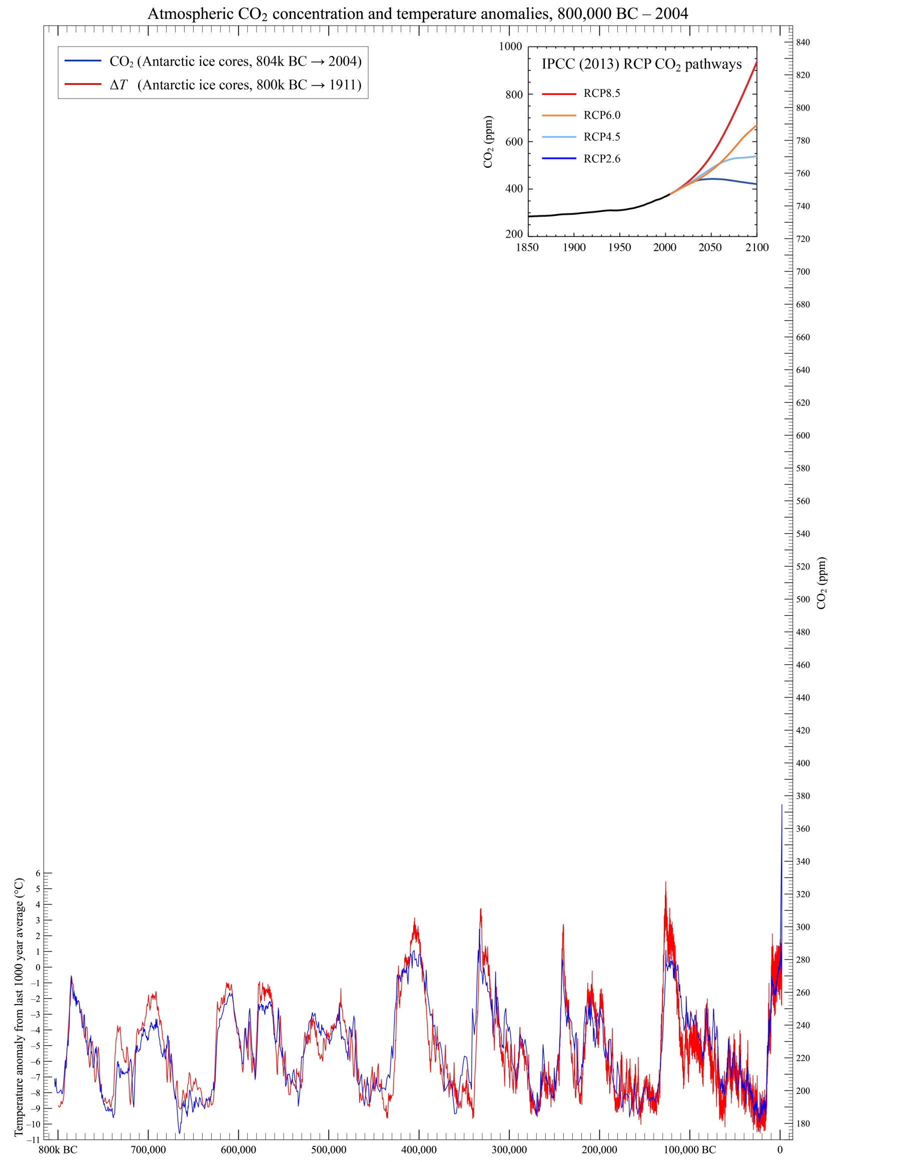
(IPCC 2007)

Ocean pH and atmospheric CO_2 & temperature records

It is very likely that the current atmospheric concentrations of CO_2 (379 ppm) and CH_4 (1,774 ppb) exceed by far the natural range of the last 650 kyr (IPCC WG1 2007).



(IPCC 2013)



(Noble 2024)

Climate stabilization

Steffen *et al.* explore the risk that self-reinforcing feedbacks could push the Earth System toward a planetary threshold.

If crossed:

- **stabilization of the climate at intermediate temperature rises may be impossible**
- **continued warming on a Hothouse Earth pathway** (higher global average temperature than any interglacial in the past 1.2 million years and to sea levels significantly higher than at any time in the Holocene).

Steffen *et al.* suggest that 2^{o} C warming (globally and annually averaged) could activate important tipping elements, raising the temperature further to activate other tipping elements in a domino-like cascade that could take the Earth System to even higher temperatures (Tipping Cascades).

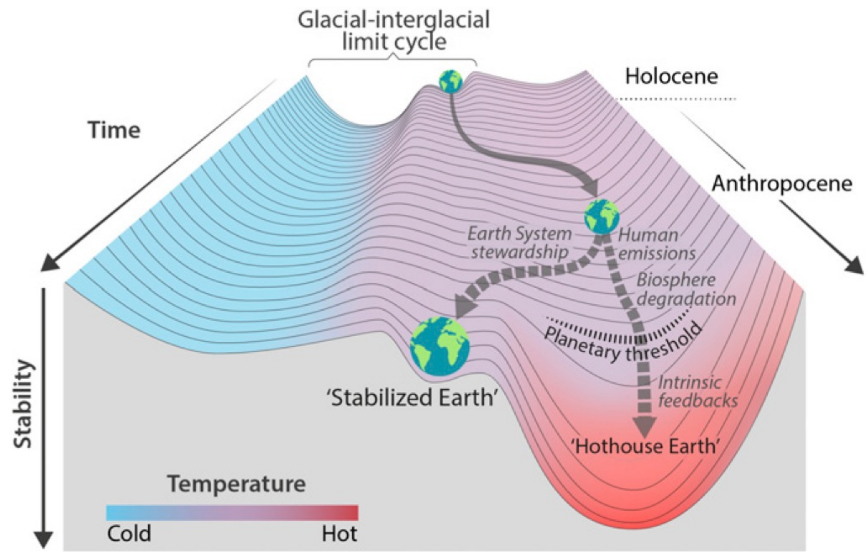


Fig. 2. Stability landscape showing the pathway of the Earth System out of the Holocene and thus, out of the glacial–interglacial limit cycle to its present position in the hotter Anthropocene. The fork in the road in Fig. 1 is shown here as the two divergent pathways of the Earth System in the future (broken arrows). Currently, the Earth System is on a Hothouse Earth pathway driven by human emissions of greenhouse gases and biosphere degradation toward a planetary threshold at ~2 °C (horizontal broken line at 2 °C in Fig. 1), beyond which the system follows an essentially irreversible pathway driven by intrinsic biogeophysical feedbacks. The other pathway leads to Stabilized Earth, a pathway of Earth System stewardship guided by human-created feedbacks to a quasistable, human-maintained basin of attraction. "Stability" (vertical axis) is defined here as the inverse of the potential energy of the system. Systems in a highly stable state (deep valley) have low potential energy, and considerable energy is required to move them out of this stable state. Systems in an unstable state (top of a hill) have high potential energy, and they require only a little additional energy to push them off the hill and down toward a valley of lower potential energy.

(Steffen *et al.* 2018)

References

Bradley, R.S., 1999: Paleoclimatology: reconstructing climates of the Quaternary. Elsevier.

Carter, P., 2019: climateemergencyinstitute.com

IPCC, 2007: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge Univ. Press.

IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge Univ. Press.

Keeling, C.D., 2024: Keeling CO_2 dataset. keelingcurve.ucsd.edu.

Liu, Z., 2012: Younger Dryas cooling and the Greenland climate response to CO_2. *PNAS*, **109**, 11101–11104.

Noble, J., 2024: Visualization of atmospheric CO_2 datasets (software development). jnoble.org/climate.

Ruddiman, W., 2001: Earth's Climate: Past and Future. Macmillan.

Steffen *et al*., 2018: Trajectories of the Earth system in the Anthropocene, *PNAS*, **115**