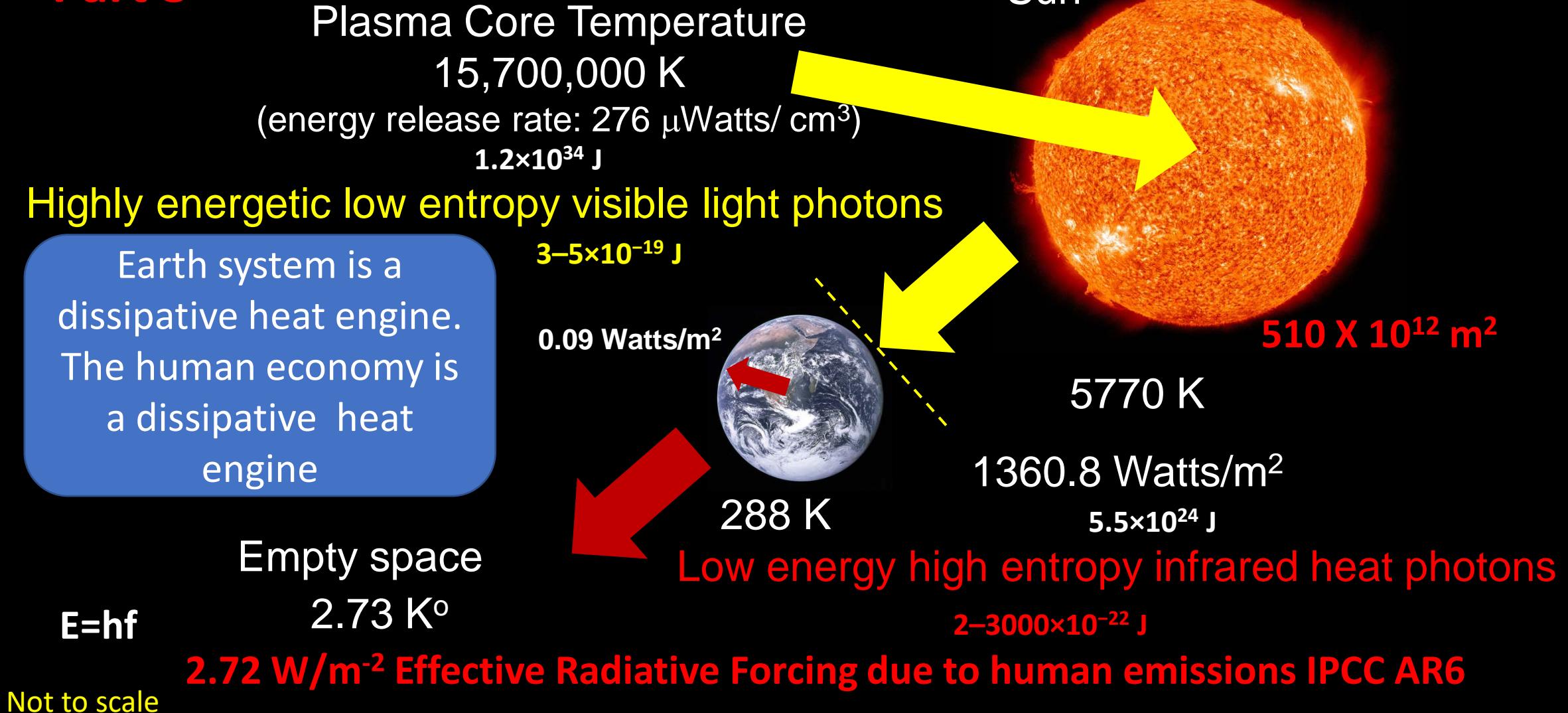


An Engineer's perspective on the Human condition the evolution of civilization

Part 3



The entire history of the evolution of our environment

- Part 1 The evolution of the universe the first 9.3 billion years
 - Where did we come from
 - What are the laws
- Part 2 The evolution of Earth the next 4.5 billion years
 - Brief history of Earth, right up to the Cenozoic
- Part 3 The evolution of civilization, the Anthropocene
 - Current extinction event, the Holocene extinction
 - Climate change
- Part 4 The evolution of our possible futures
 - Economics (and our environment)
- Part 5 The evolution of our possible futures
 - Energy (and our environment)
- Part 6 solution space and discussion

<https://www.youtube.com/watch?v=L0zlwdAPS4s>
Euan Nisbet. Climate in Deep Time: From the Archean to the Ice Ages

Cliff notes version of Charles Langmuir and Wally Broecker's "How to Build a Habitable Planet" or Paolo Saraceno, "Beyond the Stars" also Stanley and Luczaj "Earth System History" and Lunine "Earth".

What we've learned

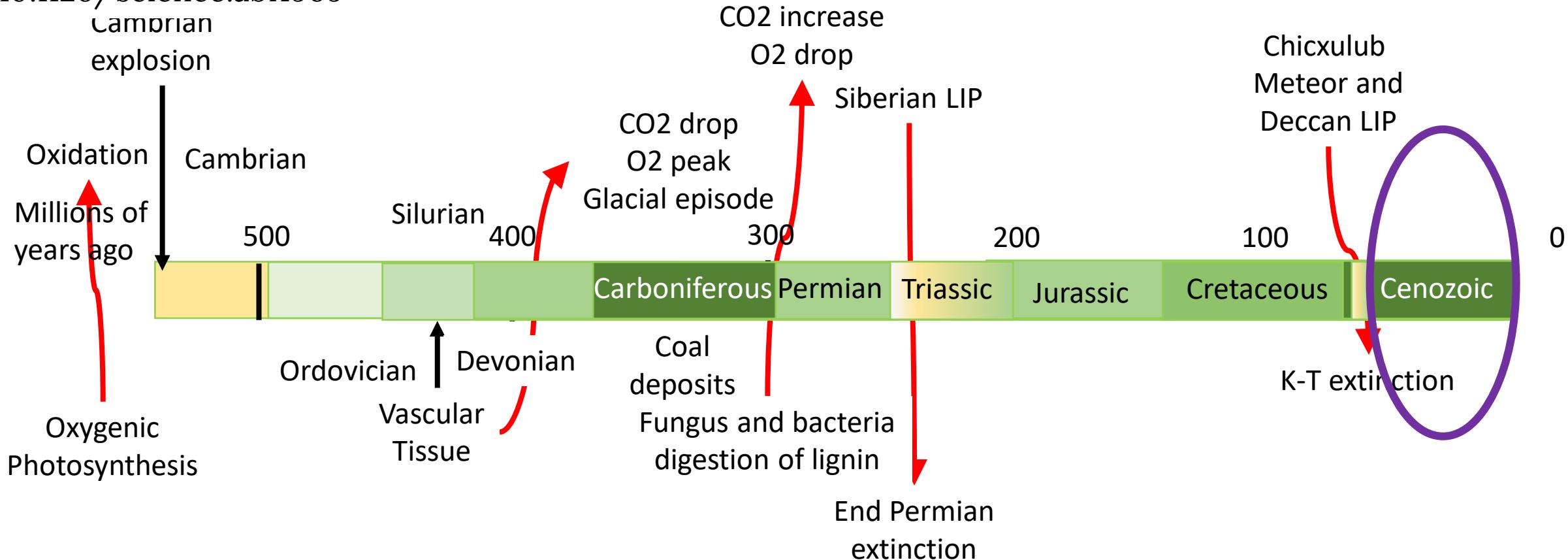
- We are emitting carbon dioxide 10 times faster into the atmosphere than the most extreme event during the Phanerozoic, and the worst extinction event of all time.
- Including other green house gases and accounting for the faint young sun, our annual emissions have more than 30 times the global warming potential.
- We are burning about 1,000,000 years of sequestered carbon every year.
- **What could possibly go wrong?**

Mónica R. Carvalho *et al.* 2021. Extinction at the end-Cretaceous and the origin of modern Neotropical rainforests. *Science* 372 (6537): 63–68; doi: 10.1126/science.abf1969

Environment

<http://www.largeigneousprovinces.org/>

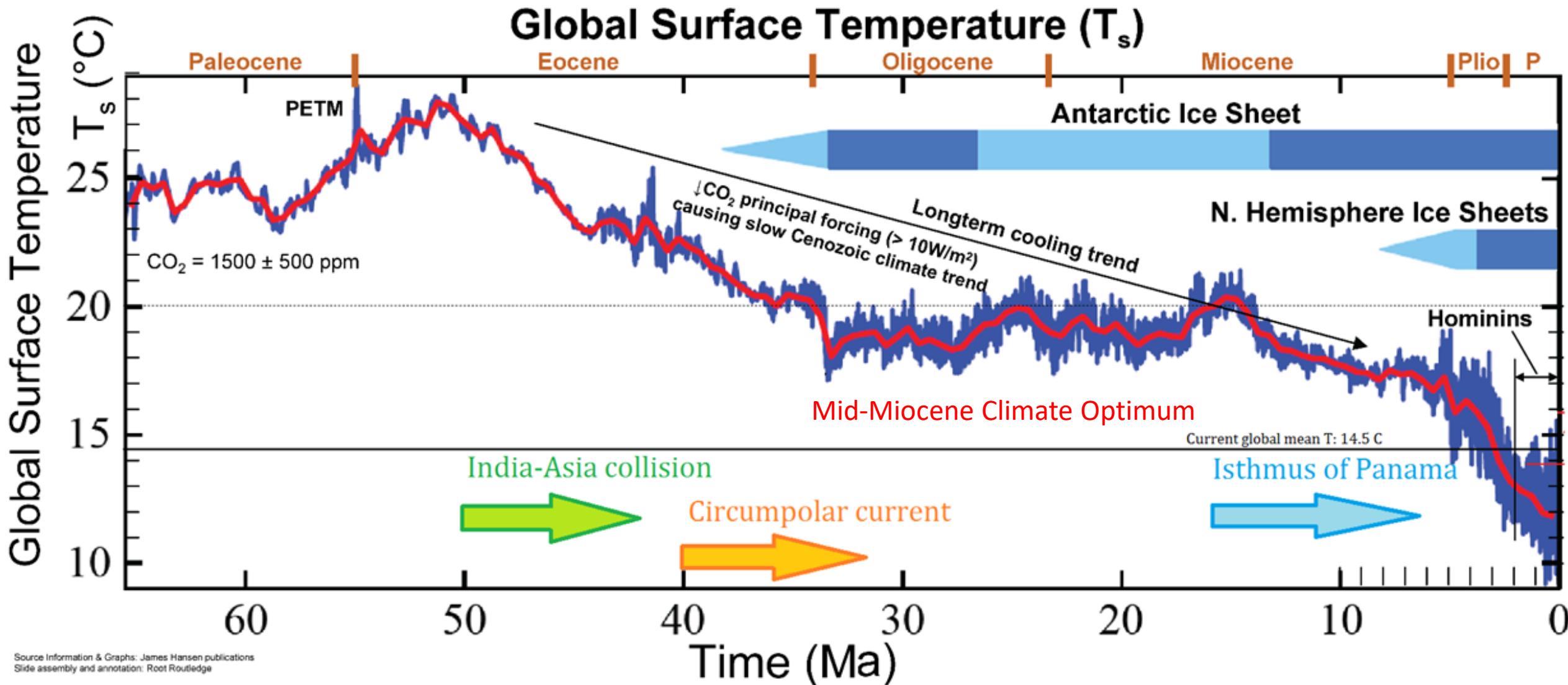
Large igneous Province



Life

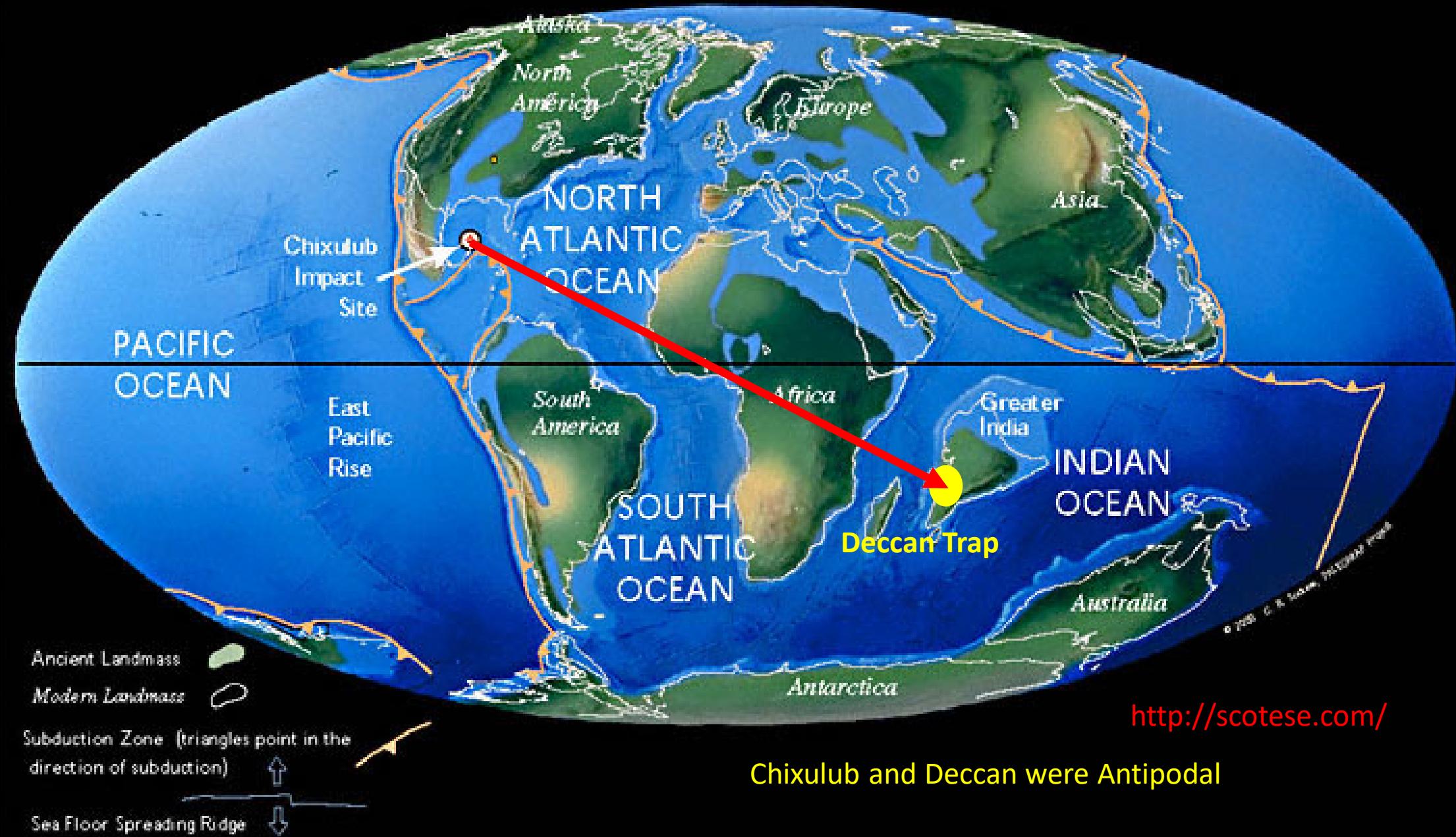
Phanerozoic

<https://www.youtube.com/watch?v=Stv-a96foIE>

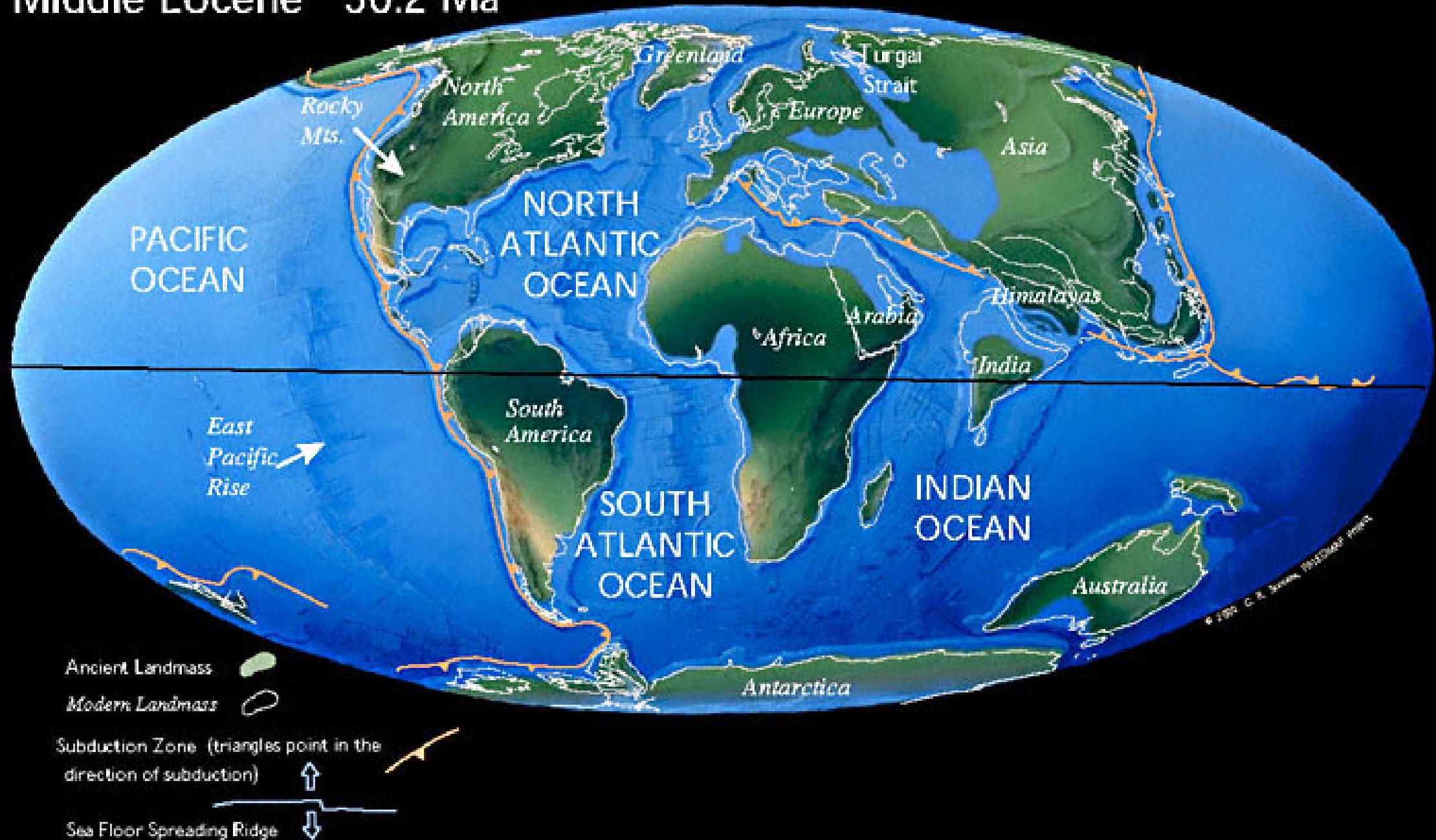


Source Information & Graphs: James Hansen publications
Slide assembly and annotation: Root Routledge

K/T Boundary 66 Ma



Middle Eocene 50.2 Ma



Middle Miocene 14 Ma



Last Glacial Maximum 18,000 years ago



Ancient Landmass



Modern Landmass

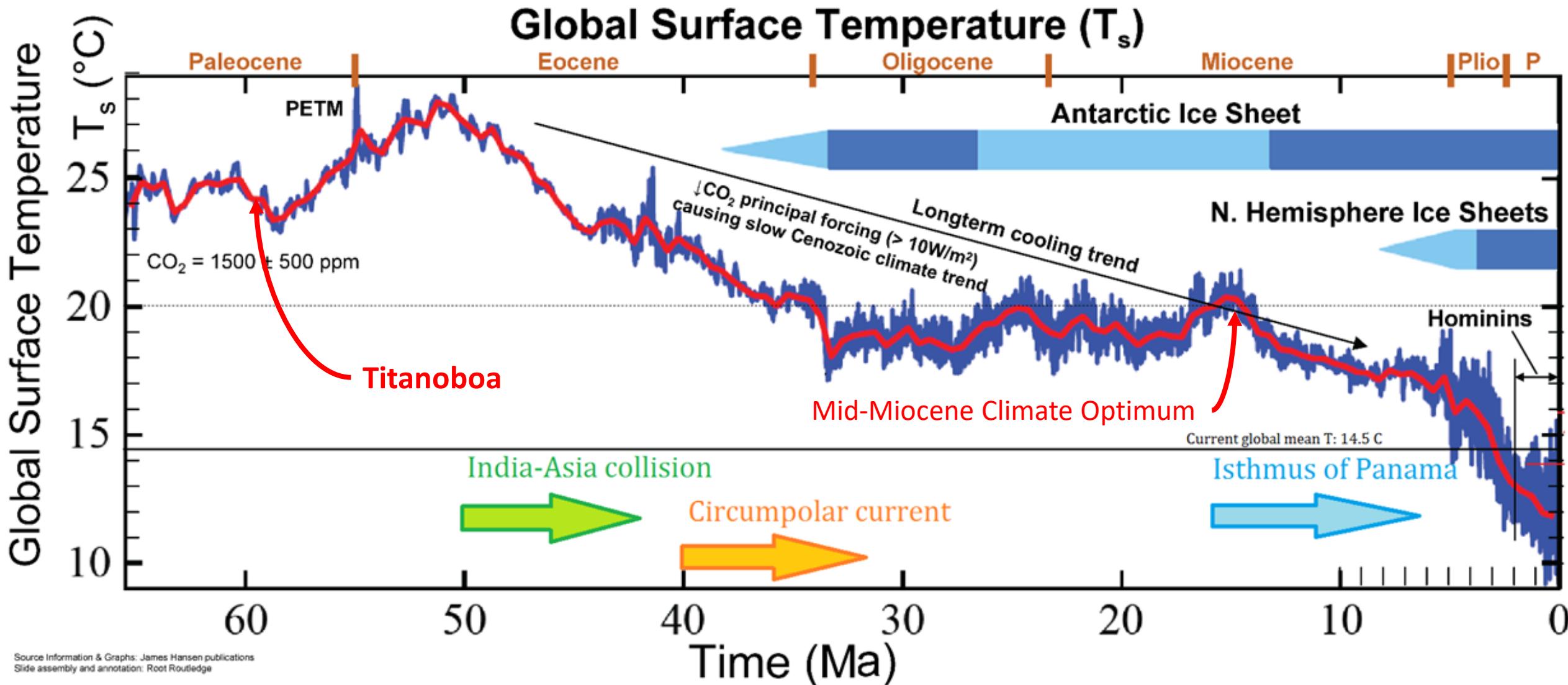


Subduction Zone (triangles point in the direction of subduction)



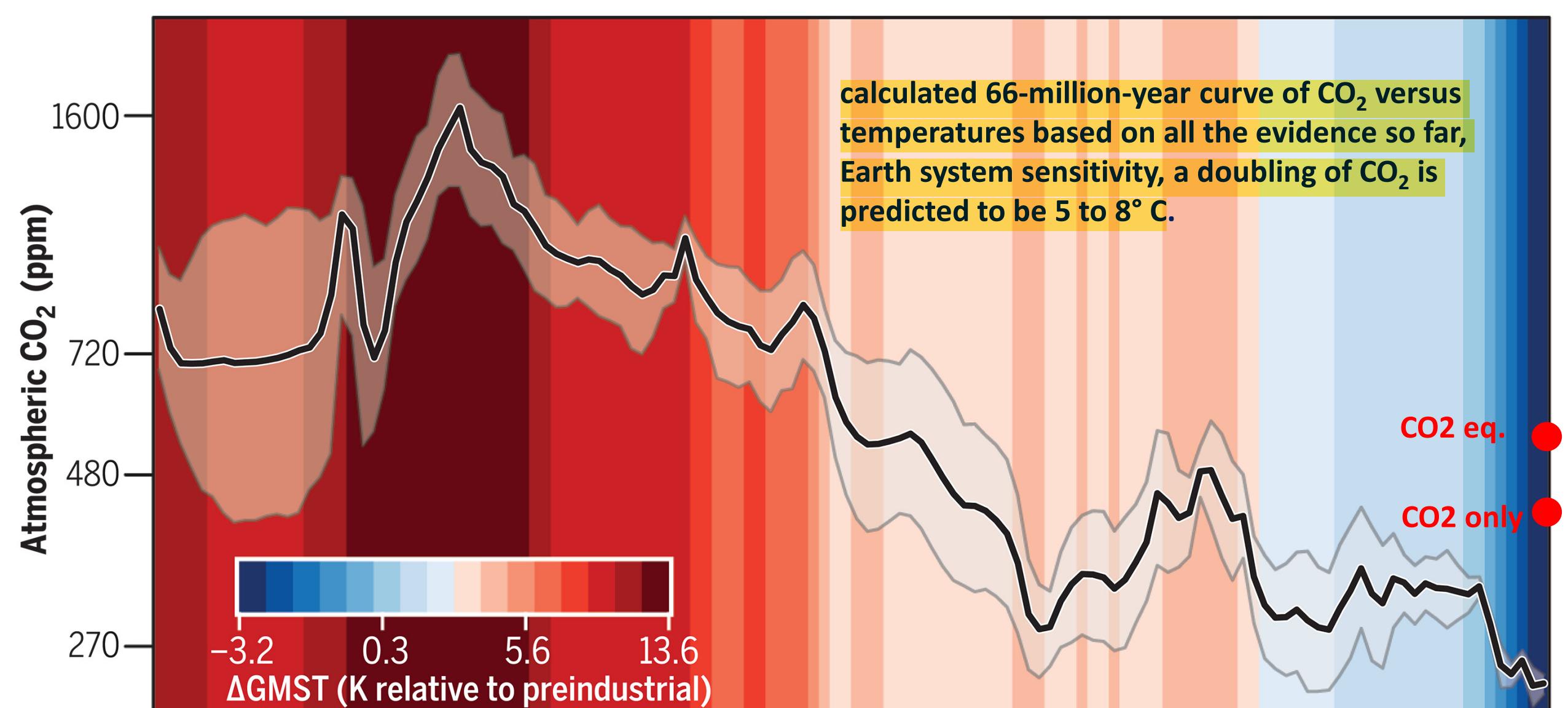
Sea Floor Spreading Ridge





Source Information & Graphs: James Hansen publications
Slide assembly and annotation: Root Routledge

Thomas Westerhold, et al., An astronomically dated record of Earth's climate and its predictability over the last 66 million Years, Science 369 (6509), 1383-1387. <https://doi.org/10.1126/science.aba6853>

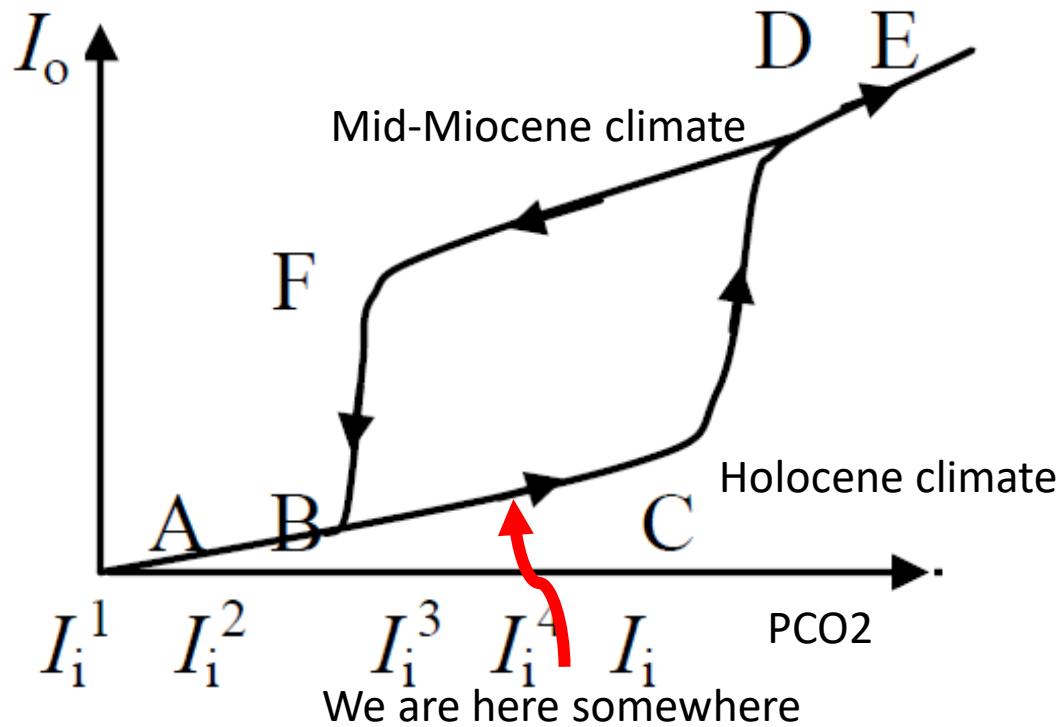


The Cenozoic CO₂ Proxy Integration Project (CenCO2PIP) Consortium, Toward a Cenozoic history of atmospheric CO₂ Science, 8 December, 2023, <https://doi.org/10.1126/science.ad5177>

Millions of years before present

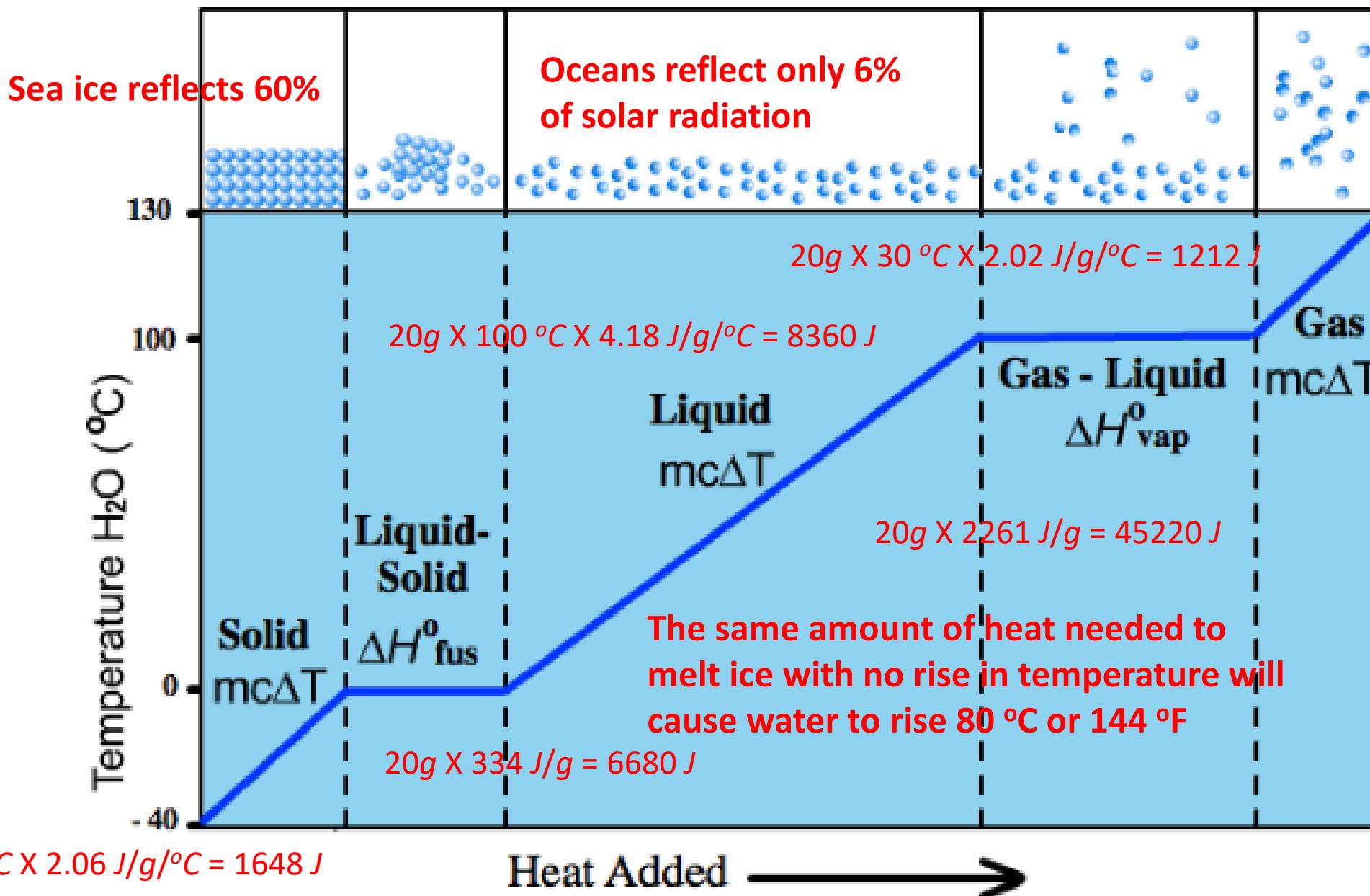
temperature

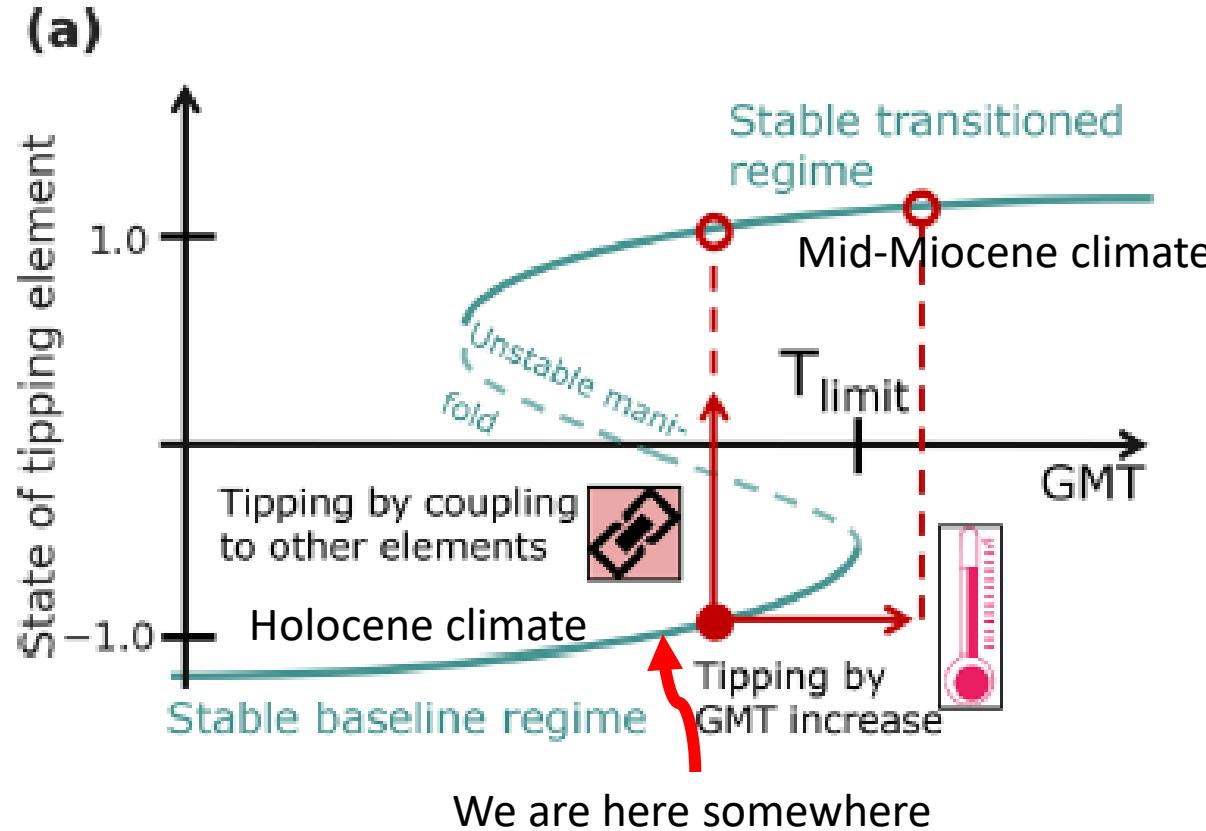
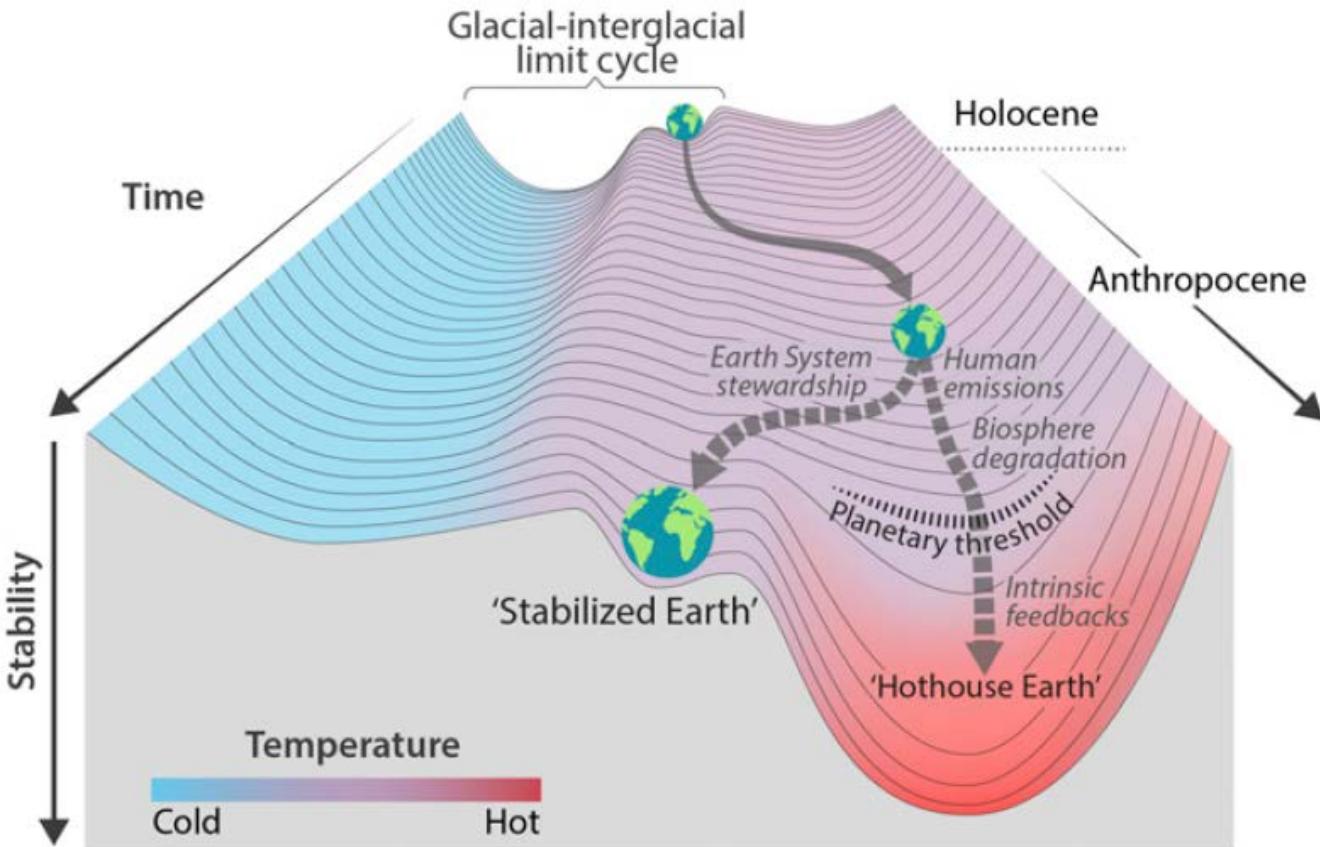
Climate is bistable



Phase Change Diagram for Water (H_2O)

(What amount of heat is required to warm 20 grams of ice from -40°C to steam 130°C at 1 atm?)

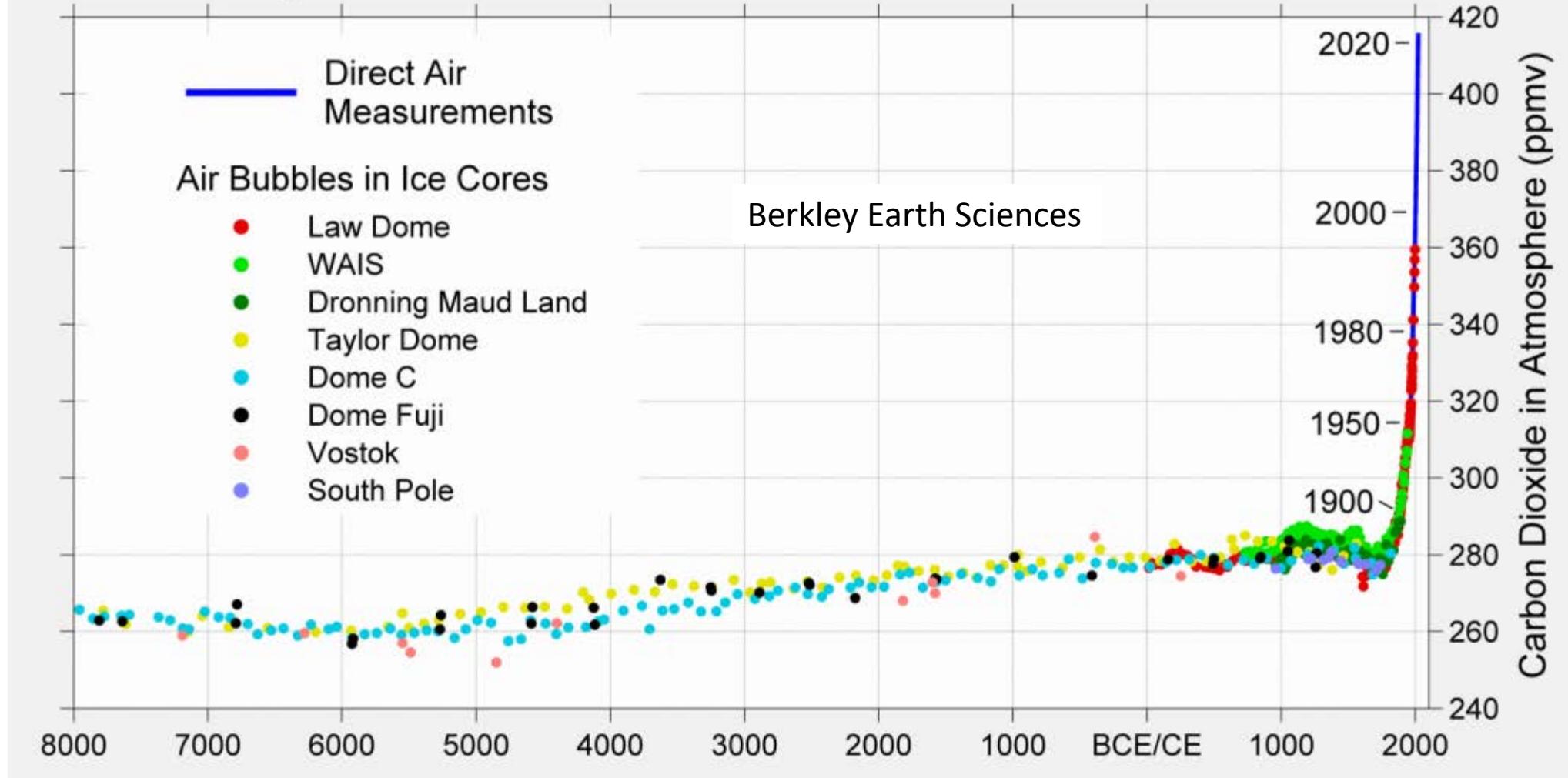




Will Steffen, Johan Rockström, Katherine Richardson, Timothy M. Lenton, Carl Folke, Diana Liverman, Colin P. Summerhayes, Anthony D. Barnosky, Sarah E. Cornell, Michel Crucifix, Jonathan F. Donges, Ingo Fetzer, Steven J. Lade, Marten Scheffer, Ricarda Winkelmann, and Hans Joachim Schellnhuber, Trajectories of the Earth System in the Anthropocene, PNAS, www.pnas.org/cgi/doi/10.1073/pnas.1810141115

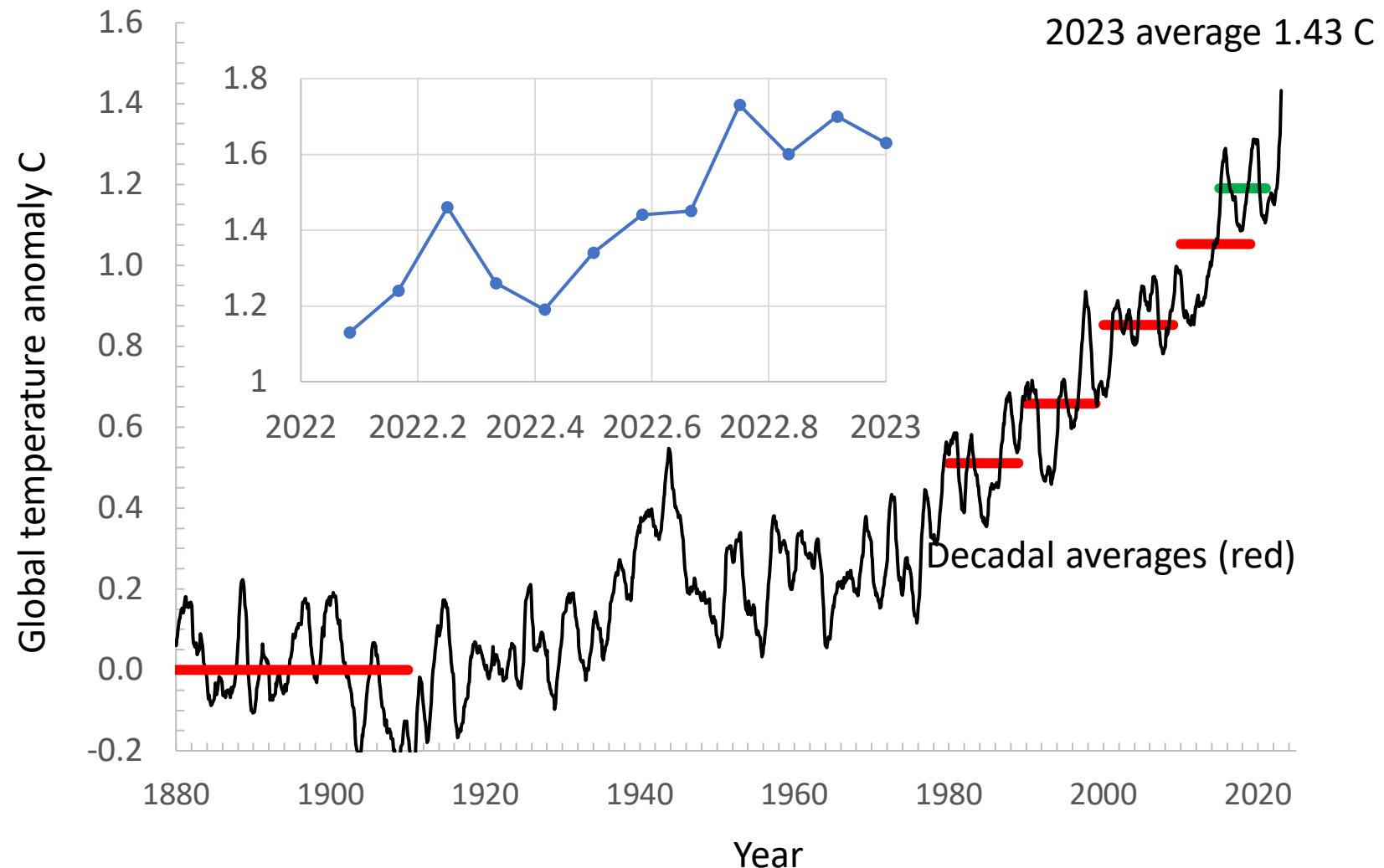
N. Wunderling et al.: Interacting tipping elements increase risk of climate domino effects under global warming, Earth Syst. Dynam., 12, 601–619, 2021, <https://doi.org/10.5194/esd-12-601-2021>

10,000 Years of Carbon Dioxide



<https://berkeleyearth.org/dv/10000-years-of-carbon-dioxide/#:~:text=10%2C000%20Years%20of%20Carbon%20Dioxide.%20A%20graph%20reflecting,would%20reach%20double%20the%20preindustrial%20by%20~2075.%20>

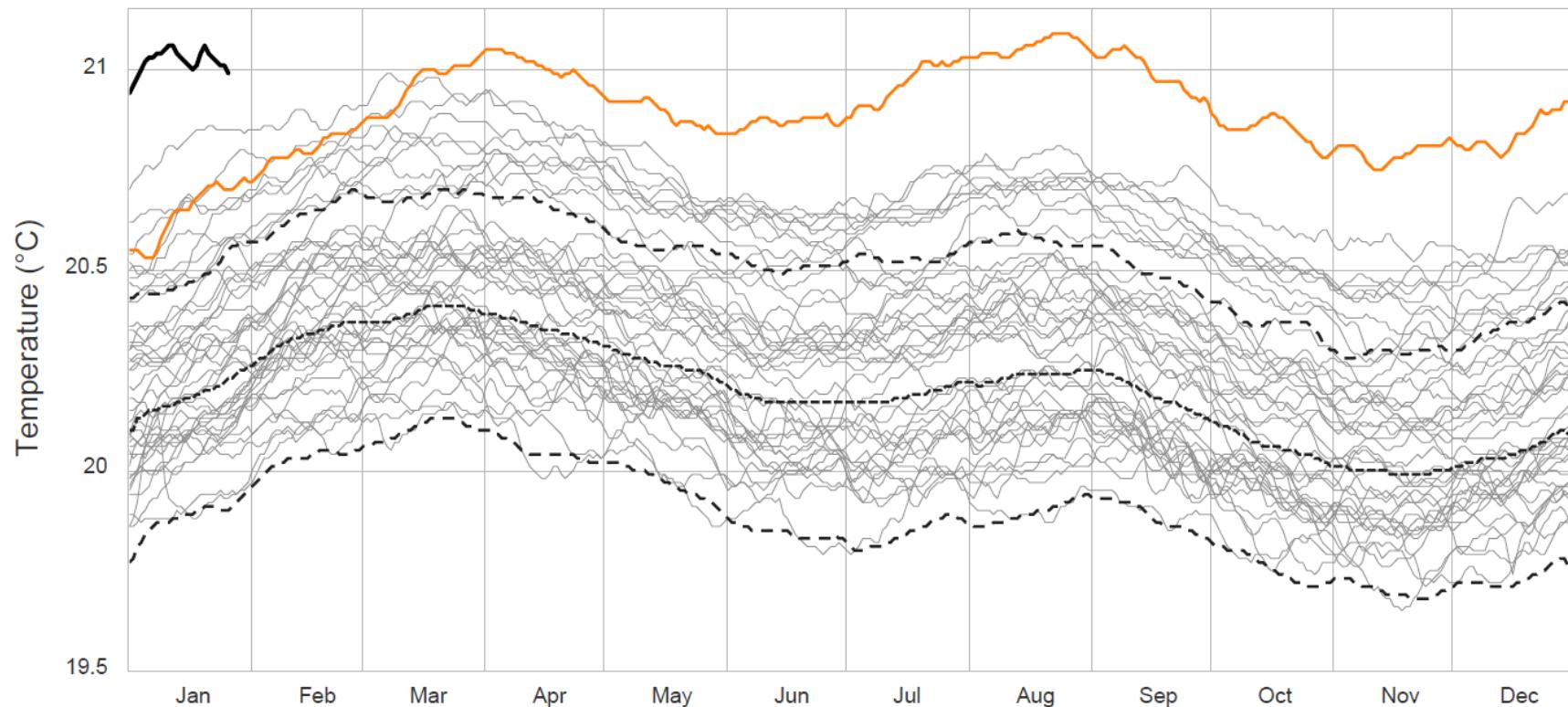
NASA/GISS Global temperature anomaly since 1880 up to December, 2023
Relative to the 1880-1910 average



Source: https://data.giss.nasa.gov/gistemp/tabledata_v4/GLB.Ts+dSST.txt

Daily Sea Surface Temperature, World (60°S-60°N, 0-360°E)

Dataset: NOAA OISST V2.1 | Image Credit: ClimateReanalyzer.org, Climate Change Institute, University of Maine

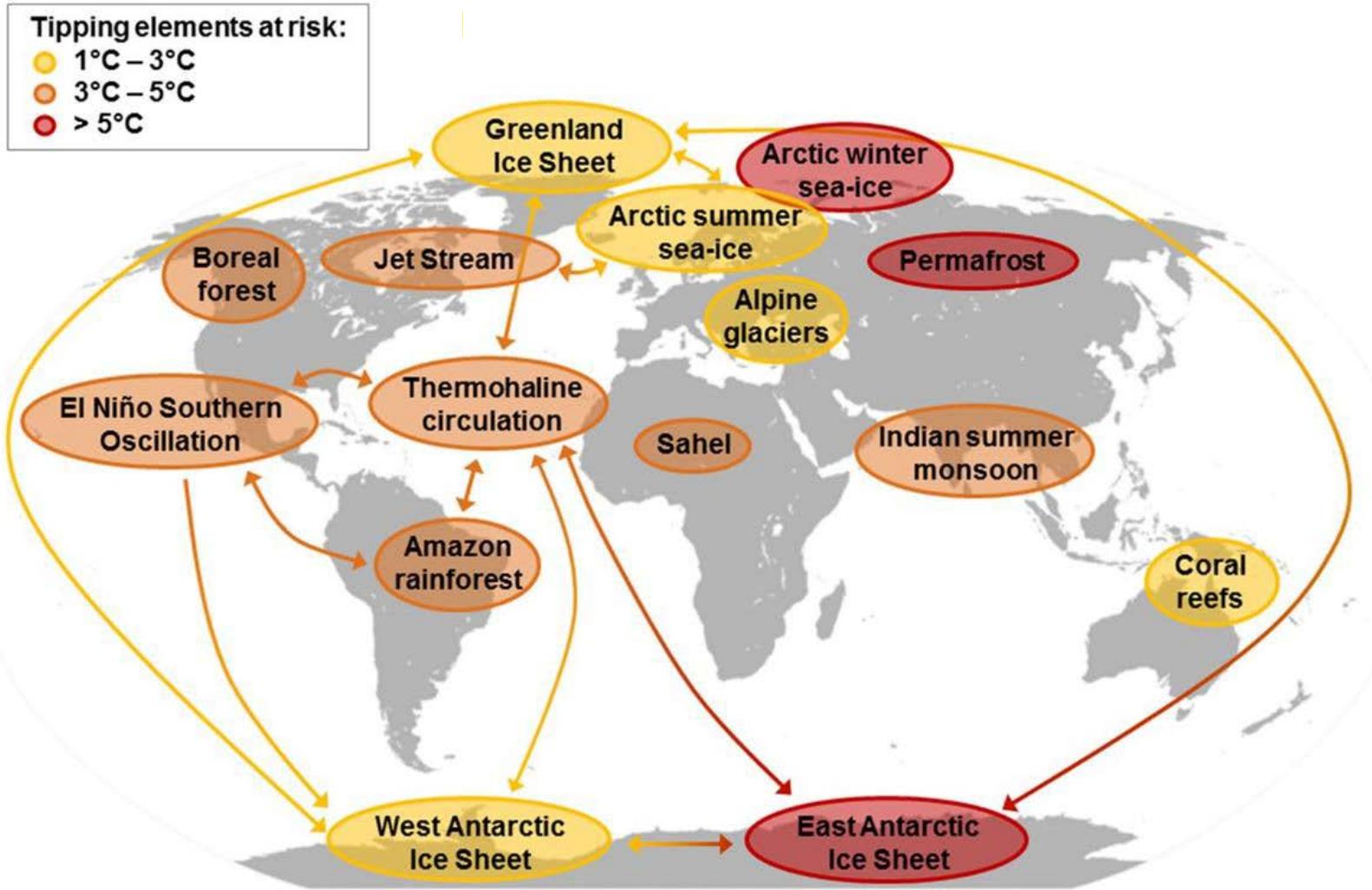


Cheng, L., Abraham, J., Trenberth, K.E. et al. New Record Ocean Temperatures and Related Climate Indicators in 2023. *Adv. Atmos. Sci.* (2024). <https://doi.org/10.1007/s00376-024-3378-5>

Tipping points

- Tropical coral reefs are most likely already committed to extinction 1.5 (1.0-2.0) K [McKay].
- Arctic sea ice may disappear seasonally before 2035 [Guarino] 1.7 (1.3-2) K [McKay] adding 1,000 billion tons of additional atmospheric carbon dioxide to the radiation budget
- which according to Jansen et al. may be the trigger for abrupt climate change globally [Jansen] similar to the D-O events shown in the figure. And this ice sheet may disappear even during the winter [Polyakov].
- Greenland ice sheet may have already passed a tipping point [King] [Sasgen] 1.6 (0.8-3.2) K [McKay]. Losing 279 Gtonnes ice per year from entire perimeter [AGU-G, 2021] Jason Box, Nov. 2 2021.
<https://www.youtube.com/watch?v=vunM3Z1BA8M>
- at 2 K warming, the West Antarctic Ice sheet is also passed an unrecoverable tipping point [Garbe] 1.6 (1.0-2.5) K [McKay].
 - Thwaites glacier ice shelf may go within a decade [AGU-WA, 2021]
- Earth's ability to absorb human-caused carbon emissions could be reduced from 57% to 42% within decades [Duffy]
<https://www.youtube.com/watch?v=Yi6zFY7tMn8>

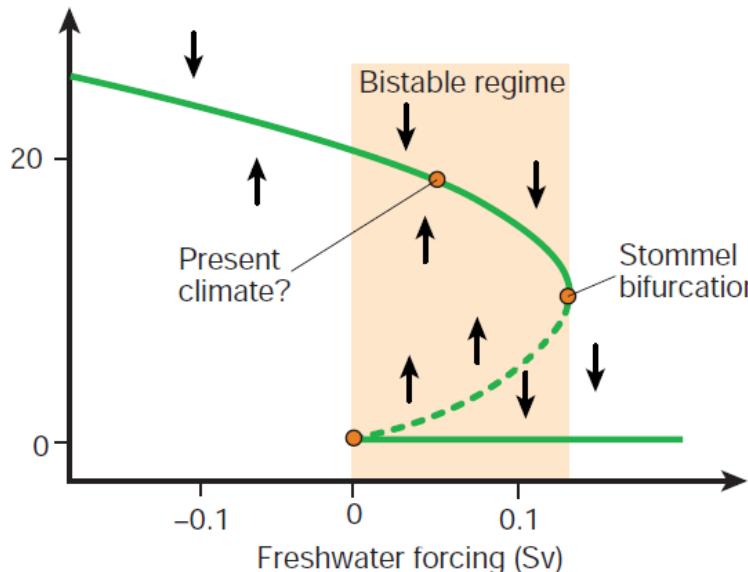
Atlantic Merid. Overturn. Circulation (AMOC)
 Amazon Forest Dieback (AFDB)
 Boreal Forest Dieback (BFDB)
 Arctic Permafrost Thaw (APFT)
 West African Monsoon (WAM)
 Permanent El Nino (ENSO)
 East Antarctic land-based Ice Sheet (EAIS)
 Arctic Winter Sea Ice (AWSI)
 Alpine glaciers
 Jet Stream Instability (JSI)
 Indian Summer Monsoon (ISM)
 Marine Methane Hydrates
 Marine Bio Pump Weakening
 Carbon Sink Weakening



David I. Armstrong McKay, Arie Staal, Sarah Cornell, Timothy M. Lenton, Ingo Fetzer, Climate Tipping Points: Can they trigger a Global Cascade? EGU Session: ITS3.1/NP1.2 Tipping Points in the Earth System - 6/5/20

Will Steffen, Johan Rockström, Katherine Richardson, Timothy M. Lenton, Carl Folke, Diana Liverman, Colin P. Summerhayes, Anthony D. Barnosky, Sarah E. Cornell, Michel Crucifix, Jonathan F. Donges, Ingo Fetzer, Steven J. Lade, Marten Scheffer, Ricarda Winkelmann, and Hans Joachim Schellnhuber, Trajectories of the Earth System in the Anthropocene, PNAS, www.pnas.org/cgi/doi/10.1073/pnas.1810141115

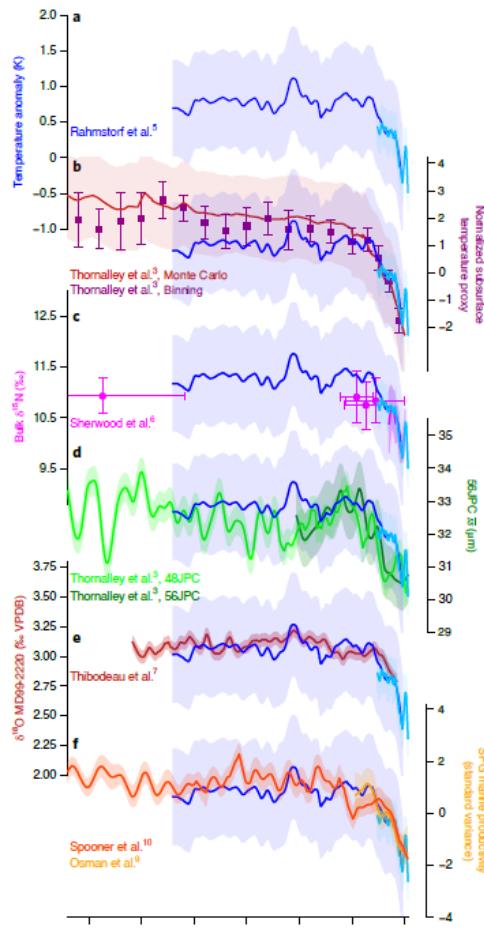
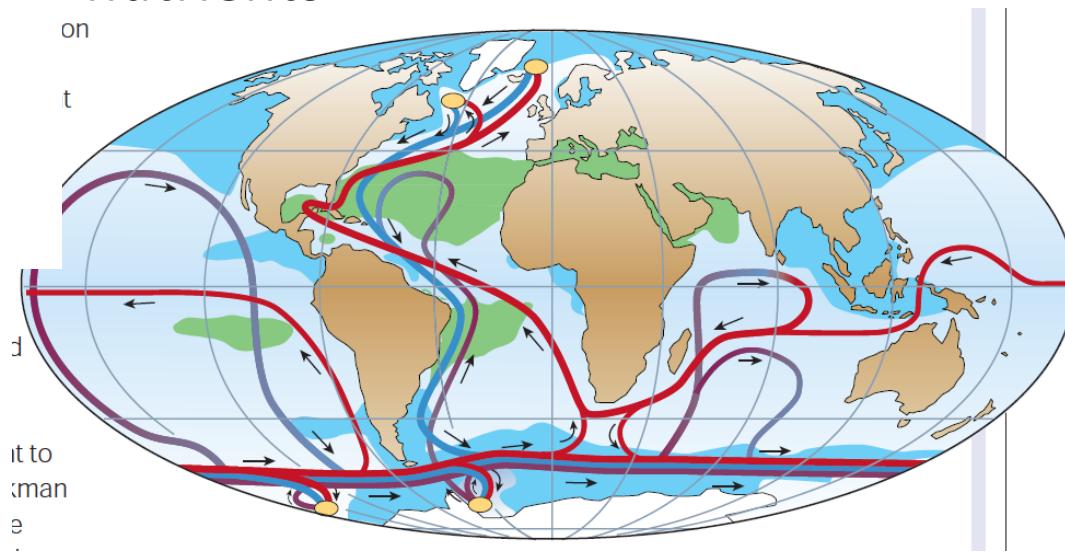
North Atlantic Flow



Ditlevsen, P., Ditlevsen, S. Warning of a forthcoming collapse of the Atlantic meridional overturning circulation. Nat Commun 14, 4254 (2023). <https://doi.org/10.1038/s41467-023-39810-w>

AMOC part of the Ocean

Thermohaline conveyor current circulates oxygen, heat and nutrients



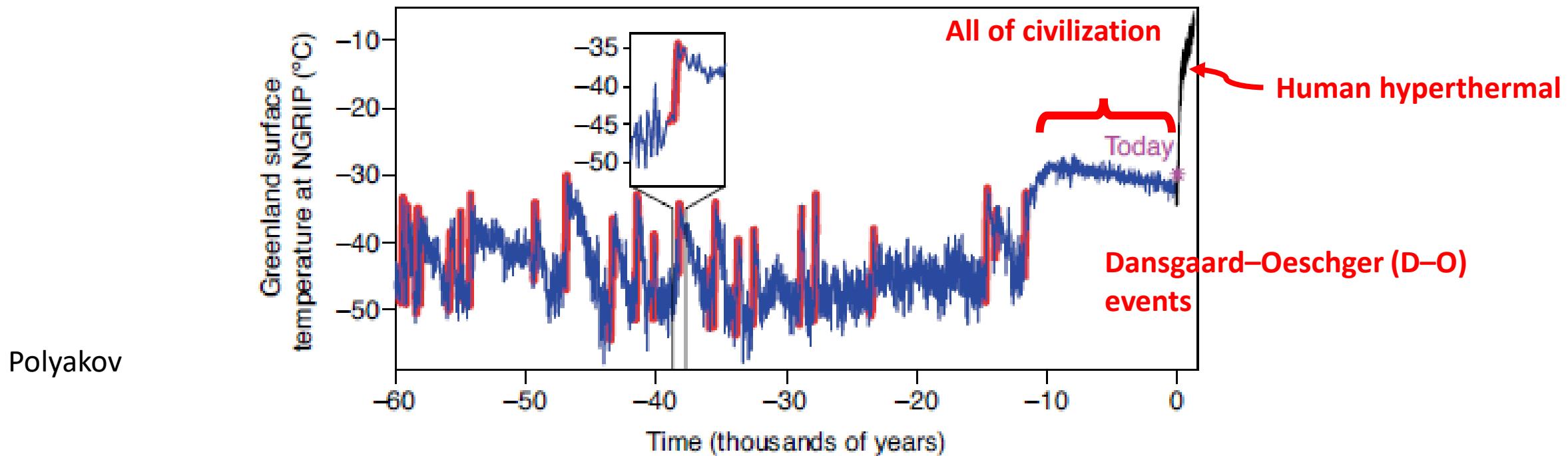
<https://www.livescience.com/planet-earth/climate-change/gulf-stream-current-could-collapse-in-2025-plunging-earth-into-climate-chaos-we-were-actually-bewildered>

Stefan Rahmstorf, Ocean circulation and climate during the past 120,000 years, Nature review article September 2002, Vol 419, <https://doi.org/10.1038/nature01090>

L. Caesar, G. D. McCarthy, D. J. R. Thornalley, N. Cahill and S. Rahmstorf, Current Atlantic Meridional Overturning Circulation weakest in last millennium, Nature Geoscience, March 2021, Vol 14, <https://doi.org/10.1038/s41561-021-00699-z>

Prof. Stefan Rahmstorf at the Exeter 'Tipping Points' Conference, 12 September 2022, <https://www.youtube.com/watch?v=XI-Xd-z2qkw>

Civilization has never experienced a dramatic climate shift but the biosphere has survived many [Jansen]



“...climate during the last 10,000 years of the post-Ice Age present, the Holocene, has been uniquely stable, almost surreally flat, compared to the jagged instabilities of the Pleistocene.”

“Without the warming of the earth with the end of the Pleistocene, the transition to food production and the entire subsequent course of human civilization could never have unfolded.”

John L. Brooke, Climate Change and the Course of Human History, A Rough Journey, Cambridge, 2014 [p. 102, and 129]

<https://www.youtube.com/watch?v=VEqKSpQLKrg>

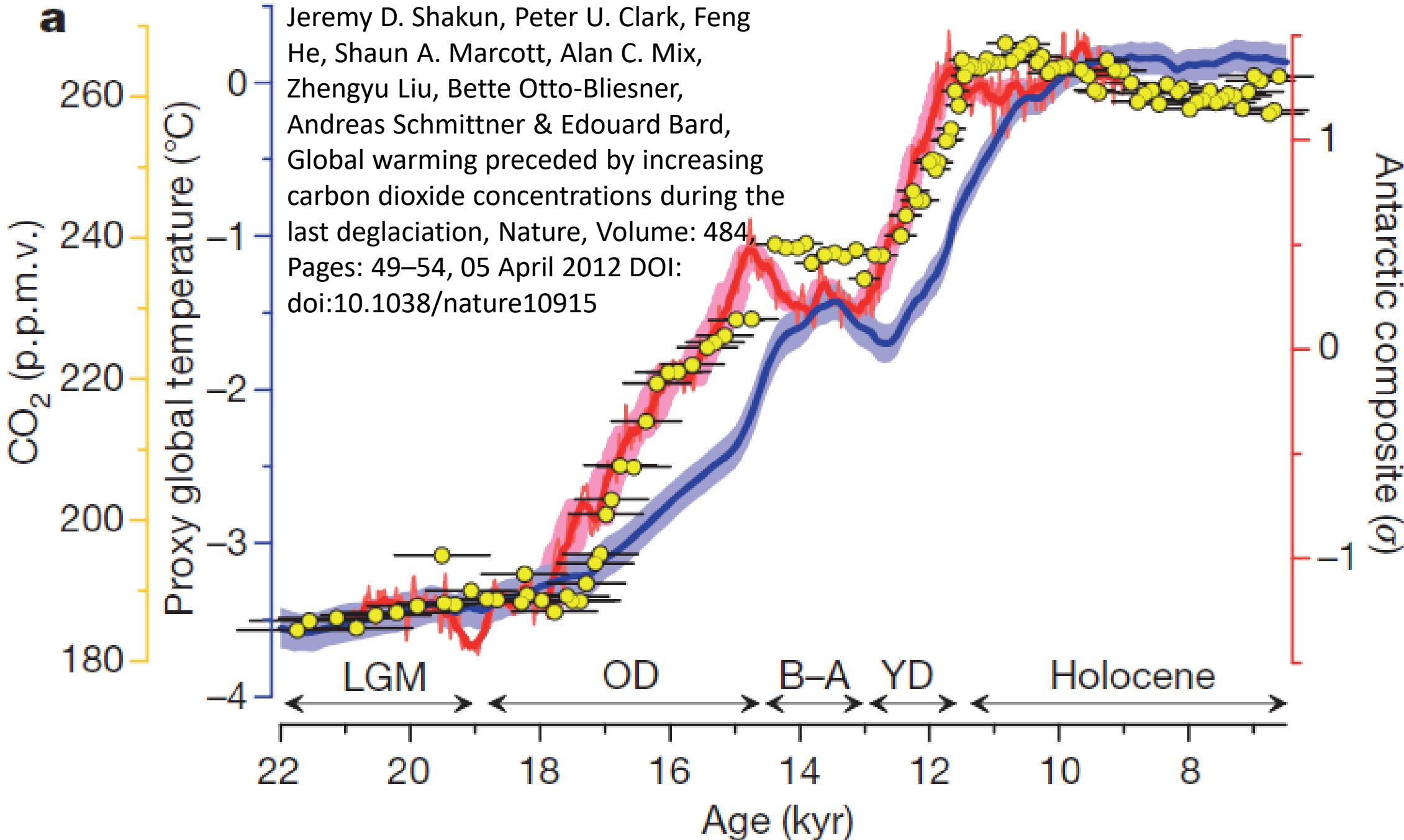
David Graeber, David Wengrow, The Dawn of Everything: A New History of Humanity Hardcover – November 9, 2021

Human population growth and leverage

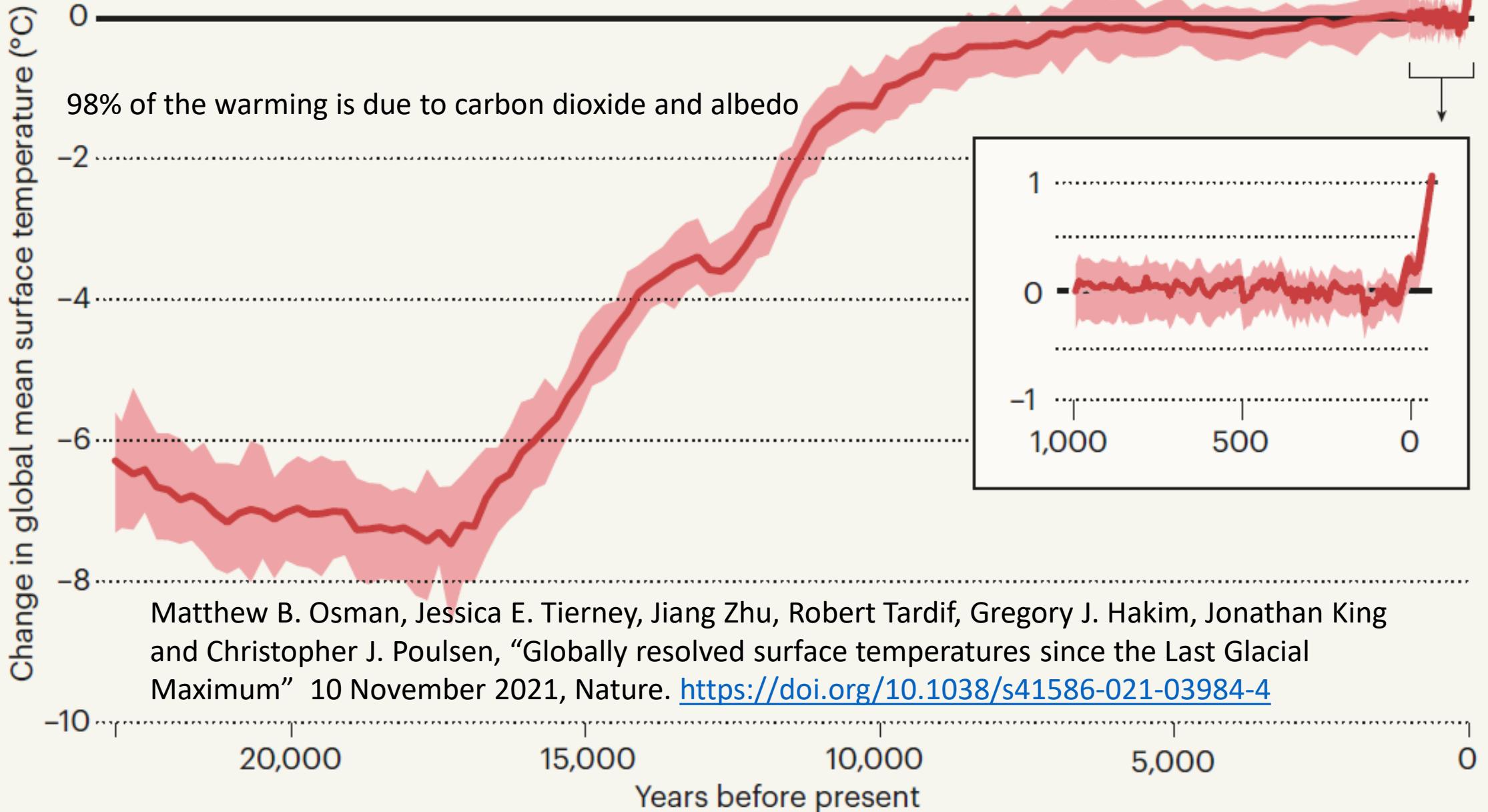
- Pre-AG growth 0.01% per year, using stone tools and fire, 5 GJ/year/capita
- post-Ag growth 0.1% per year. 20 GJ/year/capita
- Post fossil fuels growth is on the order of 1.4% per year. 80 GJ/year/capita
- Growth is all about energy flows. Data from [Desjardins] and [Millward-Hopkins].
- Hunting and gathering is resilient but not efficient.

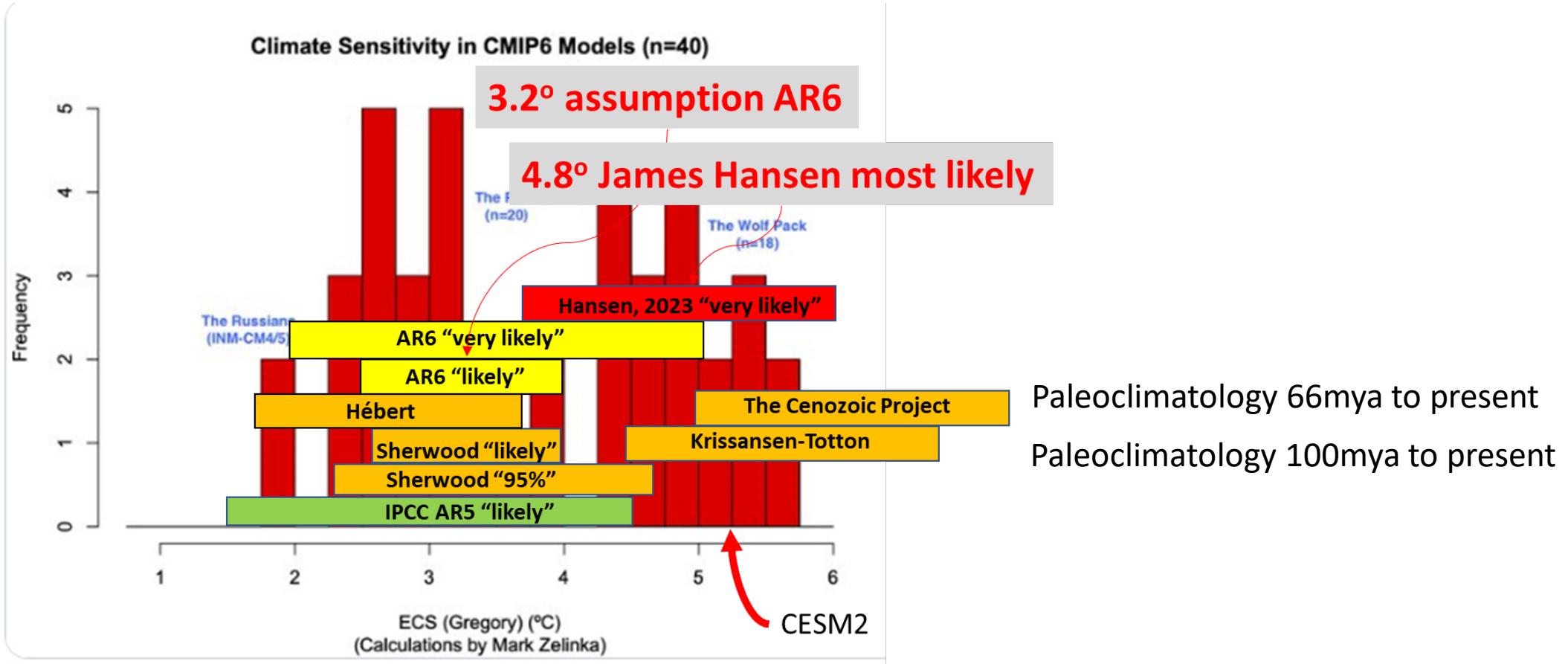
[Desjardins] Jeff Desjardins, Animation: Human Population Growth Over All of History, January 31, 2018, <https://www.visualcapitalist.com/animation-population-growth-history/>

Joel Millward-Hopkins, Julia K. Steinberger, Narasimha D. Rao, Yannick Oswald, Providing decent living with minimum energy: A global scenario, Global Environmental Change, 2020, <https://doi.org/10.1016/j.gloenvcha.2020.102168>



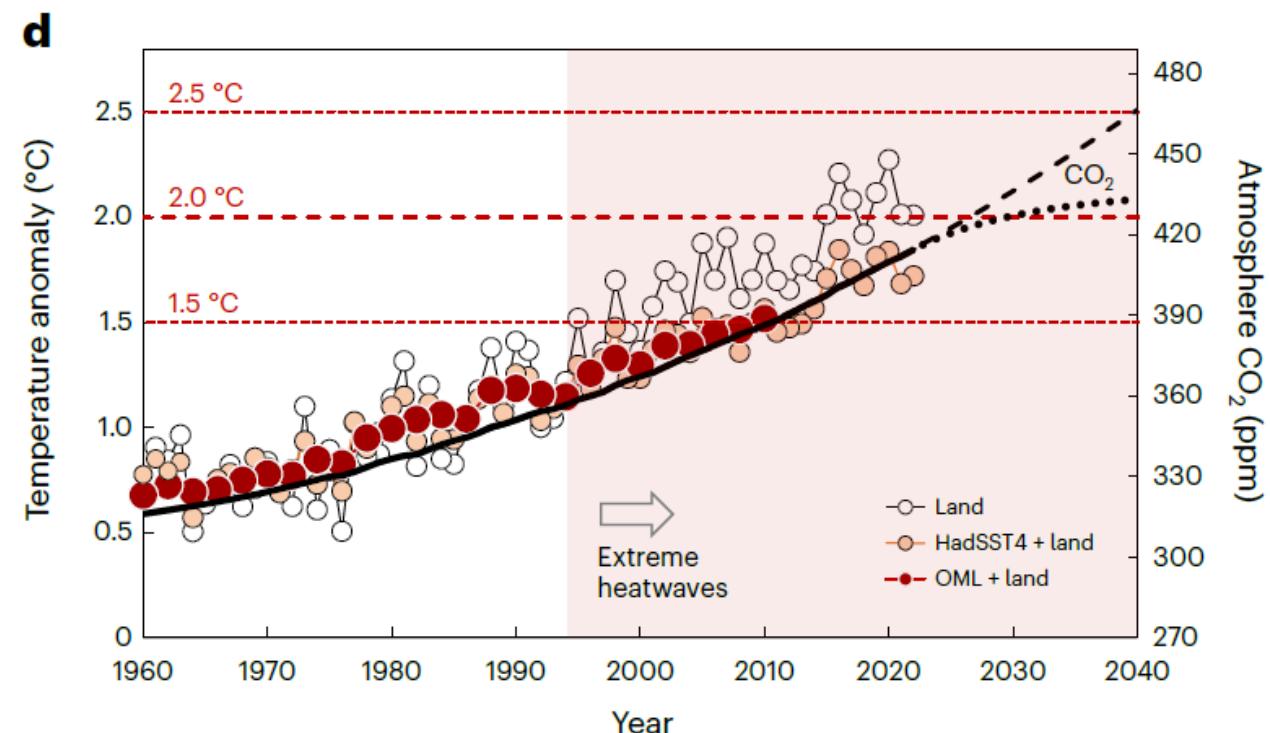
1.2 °C above pre-industrial climate currently with 1.1 °C committed warming





James E Hansen, Makiko Sato, Leon Simons, Larissa S Nazarenko, Isabelle Sangha, Pushker Kharecha, James C Zachos, Karina von Schuckmann, Norman G Loeb, Matthew B Osman, Qinjian Jin, George Tselioudis, Eunbi Jeong, Andrew Lacis, Reto Ruedy, Gary Russell, Junji Cao, Jing Li, Global warming in the pipeline, Oxford Open Climate Change, Volume 3, Issue 1, 2023, kgad008, <https://doi.org/10.1093/oxfclm/kgad008>

More recent (5 February 2024) evidence supporting a higher ECS.



Hotter land temperatures, together with the earlier onset of industrial-era warming, indicate that global warming was already **1.7 ± 0.1 °C above pre-industrial levels by 2020**. Our result is 0.5 °C higher than IPCC estimates, with **2 °C global warming projected by the late 2020s**, nearly two decades earlier than expected.

McCulloch, M.T., Winter, A., Sherman, C.E. et al. 300 years of sclerosponge thermometry shows global warming has exceeded 1.5 °C. Nat. Clim. Chang. (2024). <https://doi.org/10.1038/s41558-023-01919-7>

Deng, W. Ocean warming and warning. Nat. Clim. Chang. 14, 118–119 (2024). <https://doi.org/10.1038/s41558-023-01921-z>

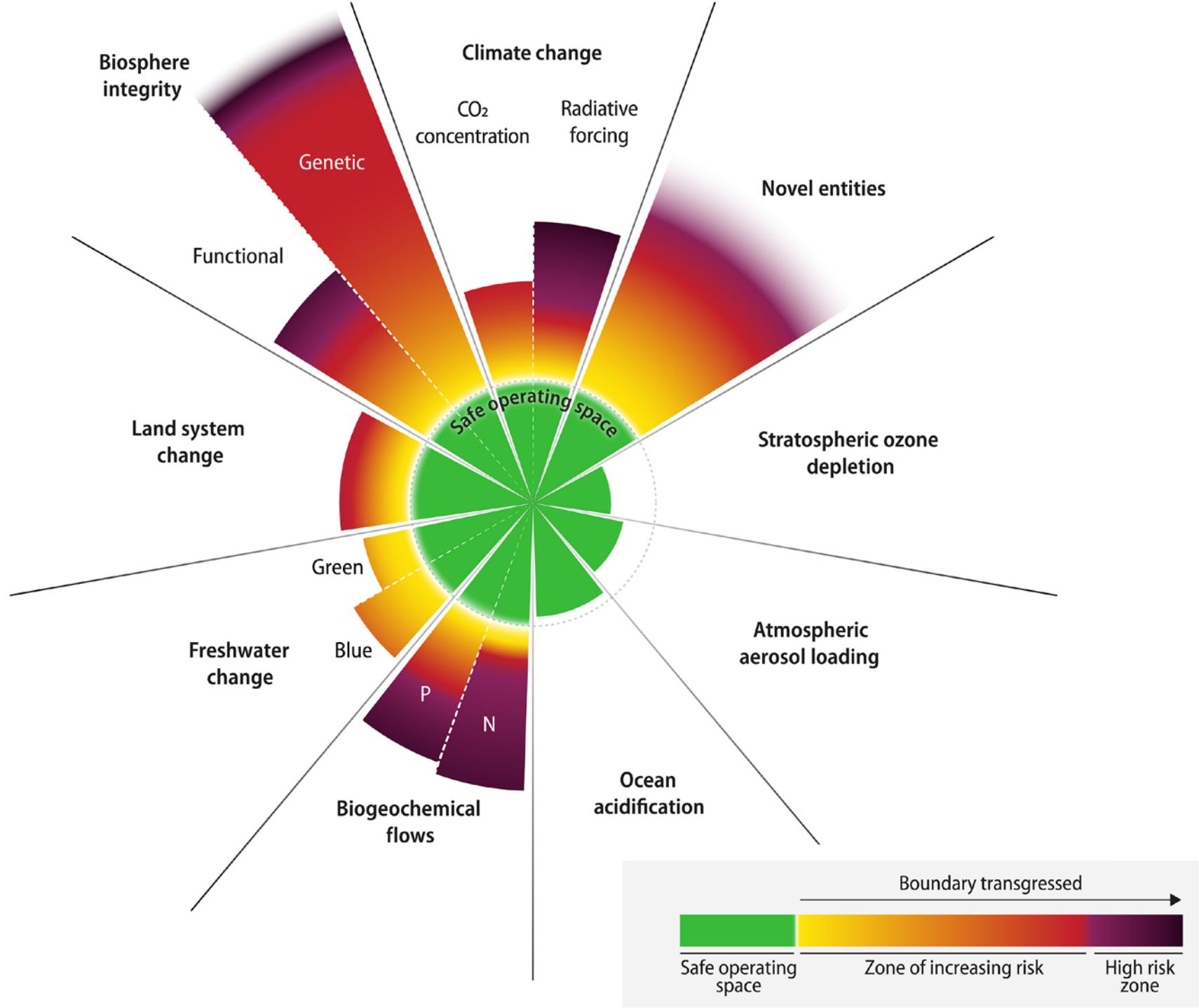
Civilization has never experienced a dramatic climate shift but the biosphere has survived many. And yet...

88 civilizations collapsed between 3000 BCE and 1000 CE [Kemp] because of abrupt climate change, overshoot and depletion of resources, increasing reliance on complexity and the diminishing returns of technology, and inequality and establishment of an oligarchy. All of these stresses are in play currently.

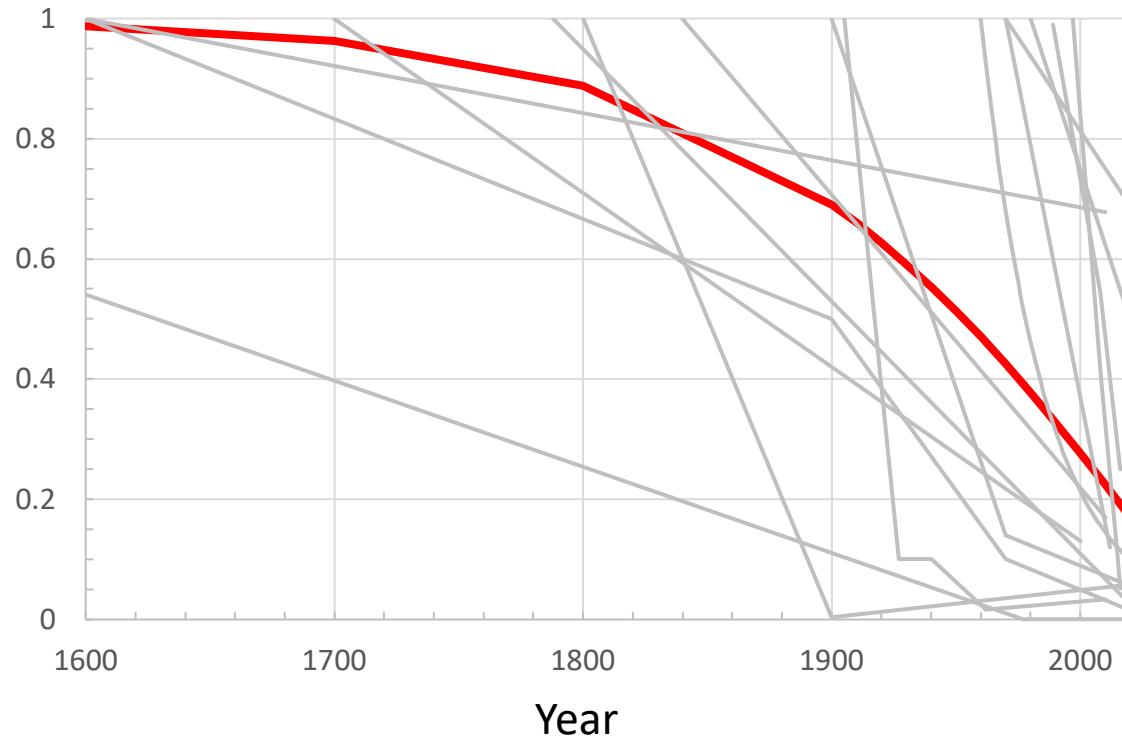
[Kemp] Luke Kemp <https://www.bbc.com/future/article/20190218-the-lifespans-of-ancient-civilisations-compared> and <https://www.bbc.com/future/article/20190218-are-we-on-the-road-to-civilisation-collapse>

Megadrought and Collapse: From Early Agriculture to Angkor Illustrated Edition by Harvey Weiss (Editor)

[Jansen] Eystein Jansen, Jens Hesselbjerg Christensen, Trond Dokken, Kerim H. Nisancioglu, Bo M. Vinther, Emilie Capron , Chuncheng Guo, Mari F. Jensen, Peter L. Langen, Rasmus A. Pedersen, Shuting Yang, Mats Bentsen, Helle A. Kjær, Henrik Sadatzki, Evangeline Sessford and Martin Stendel, Past perspectives on the present era of abrupt Arctic climate change, Nature Climate Change, Vol. 10, August 2020, <https://doi.org/10.1038/s41558-020-0860-7>



Biomass of Wild Mammals is in freefall



Wild mammal biomass [Bar-On] [WWF]
The grey curves show populations of
mammals including elephants, whales,
rhino and kakapo as well as other
evidence of the decline of life on Earth...

**Only 17% of wild
mammal biomass**

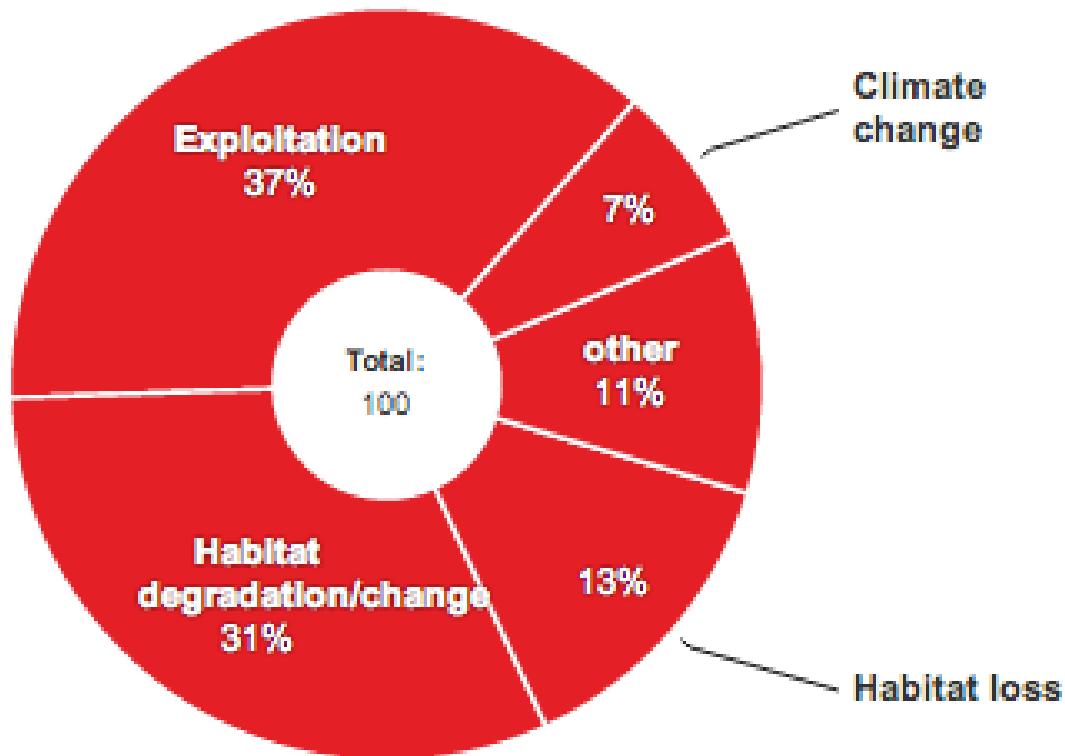
[Bar-On] Yinon M. Bar-On, Rob Phillips, and Ron Milo, The biomass distribution on Earth, PNAS, April 13, 2018, www.pnas.org/cgi/doi/10.1073/pnas.1711842115

[WWF] https://wwf.panda.org/knowledge_hub/all_publications/living_planet_report_2018/
[IPBES] Summary IPBES https://www.youtube.com/watch?v=l_lwdyctOEM

Anthropogenic stressors on biosphere

Causes of wildlife declines globally

WWF's 'Living Planet Index' categorises the causes of wildlife declines based on analysis of 3,430 species' populations



SOURCE: WWF

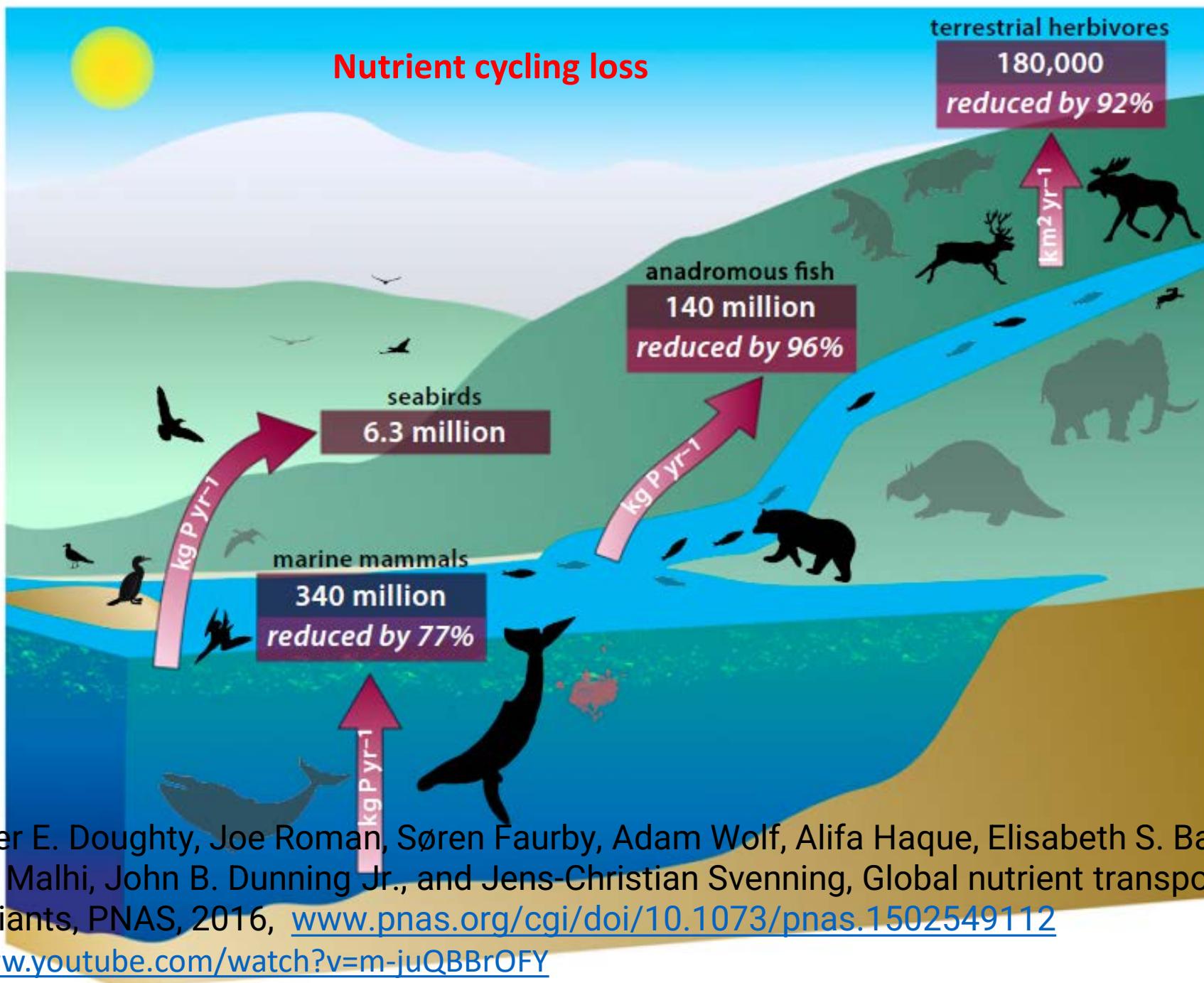
https://wwf.panda.org/knowledge_hub/all_publications/living_planet_report_2018/

we might solve global warming and still destroy life on the planet

Earth habitability at risk

- Mean extinction rate of mammals during Cenozoic is **0.25** extinctions per species per million years.
- The mean extinction rate during the last 126,000 years for all mammals **is 0.46**, largely attributed to human activity.
- The mean extinction rate over the last 500 years is **28** extinctions per species per million years or 100 times the Cenozoic background rate [Andermann]

T. Andermann, S. Faurby, S. T. Turvey, A. Antonelli, D. Silvestro, The past and future human impact on mammalian diversity. Sci. Adv. 6, eabb2313 (2020). <https://doi.org/10.1126/sciadv.eabb2313>

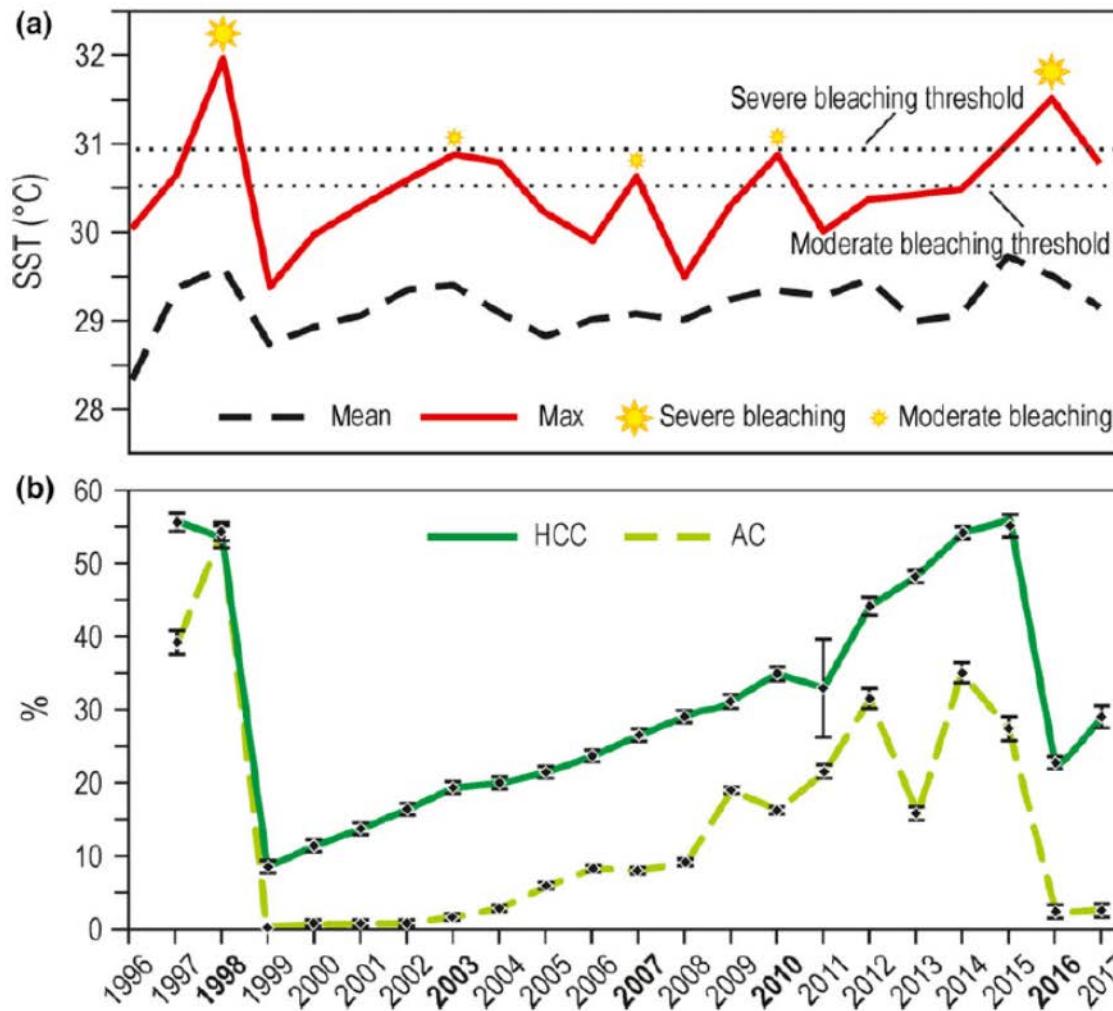


Christopher E. Doughty, Joe Roman, Søren Faurby, Adam Wolf, Alifa Haque, Elisabeth S. Bakker, Yadvinder Malhi, John B. Dunning Jr., and Jens-Christian Svenning, Global nutrient transport in a world of giants, PNAS, 2016, www.pnas.org/cgi/doi/10.1073/pnas.1502549112
<https://www.youtube.com/watch?v=m-juQBBBrOFY>

Coral Reefs – canaries in our coal mine

- IPCC SR15: at 1.5 degrees C 70-90% of tropical corals are dead. At 2 degrees C 99% are dead.
- NASA: “*At 1.5 degrees, ...tropical coral reefs stand a chance of adapting and reversing a portion of their die-off in the last half of the century. But at 2 degrees, the chance of recovery vanishes. Tropical corals are virtually wiped out by the year 2100.*” <https://climate.nasa.gov/news/2458/why-a-half-degree-temperature-rise-is-a-big-deal/>
- Extreme marine heat waves
<https://www.newscientist.com/article/2306423-extreme-marine-heatwaves-are-now-normal-for-the-worlds-oceans/>
- <https://scitechdaily.com/up-to-95-of-ocean-surface-climates-may-disappear-by-2100-due-to-climate-change/>

Coral Reef extinction – a nonlinear phenomenon



1.1 degrees C increase is already booked:

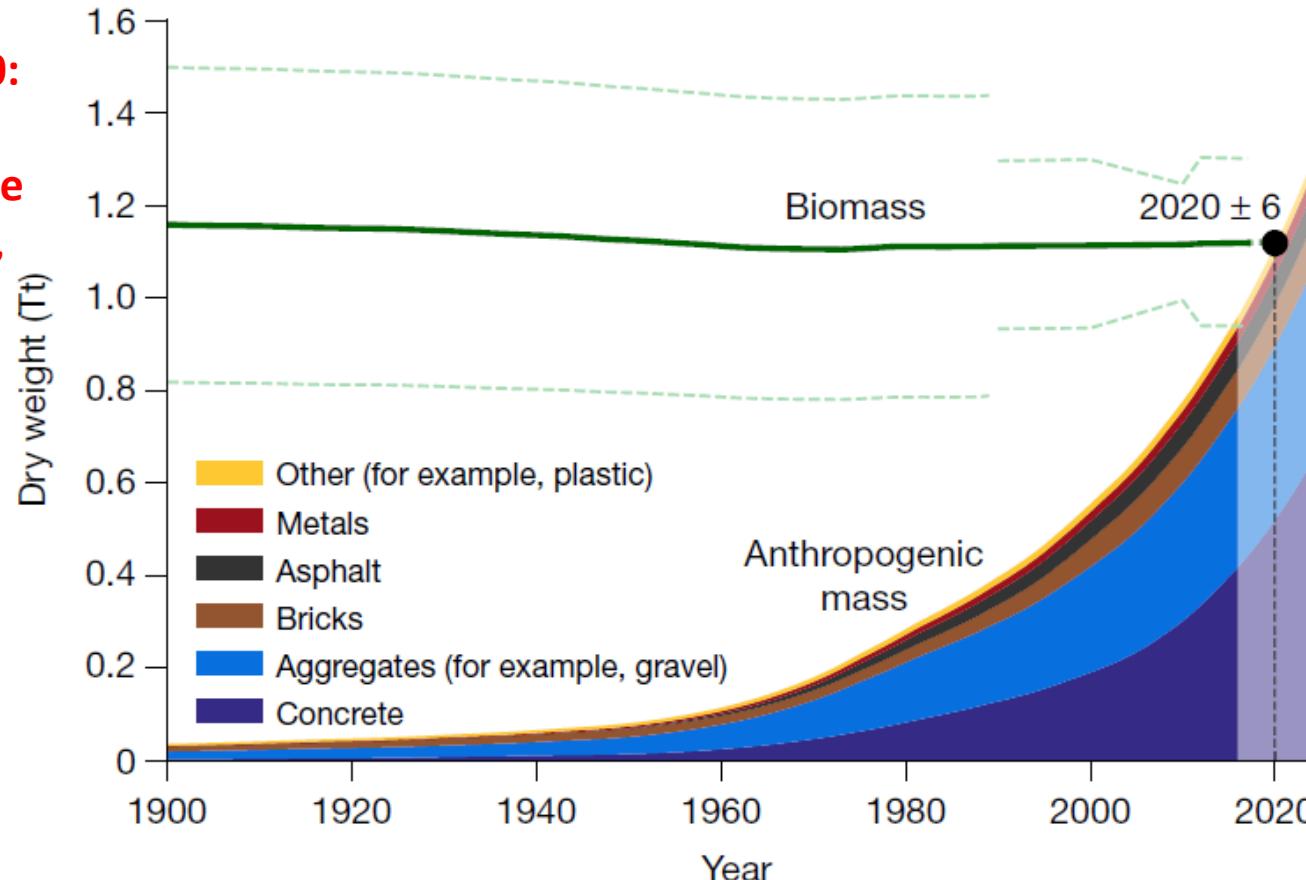
Chen Zhou, Mark D. Zelinka, Andrew E. Dessler and Minghuai Wang, Greater committed warming after accounting for the pattern effect, *Nature Climate change*, 2021, <https://doi.org/10.1038/s41558-020-00955-x>

See also: Marc Salzmann (2016), Global warming without global mean precipitation increase?, *Science Advance*, <https://doi.org/10.1126/sciadv.1501572>

Monica Montefalcone, Carla Morri, Carlo Nike Bianchi, 2018. Long-term change in bioconstruction potential of Maldivian coral reefs following extreme climate anomalies, *Global Change Biology*, 24: 5629-5641, <https://doi.org/10.1111/gcb.14439>

Dry mass of human stuff now exceeds dry mass of all life on Earth [Elhacham] waste not included!

We were warned in 1970:
silent spring, peak oil,
population bomb, climate
change, limits to growth,
small is beautiful



All of our stuff is far from thermodynamic equilibrium and requires energy to maintain; more stuff creates a requirement for more energy in the future.

Emily Elhacham, Liad Ben-Uri, Jonathan Grozovski, Yinon M. Bar-On & Ron Milo, Global human-made mass exceeds all living biomass, Nature, 2020, <https://doi.org/10.1038/s41586-020-3010-5>

Timothy J. Garrett, Matheus Grasselli, Stephen Keen, Past world economic production constrains current energy demands: Persistent scaling with implications for economic growth and climate change mitigation, PlosOne, August, 2020, <https://doi.org/10.1371/journal.pone.0237672>

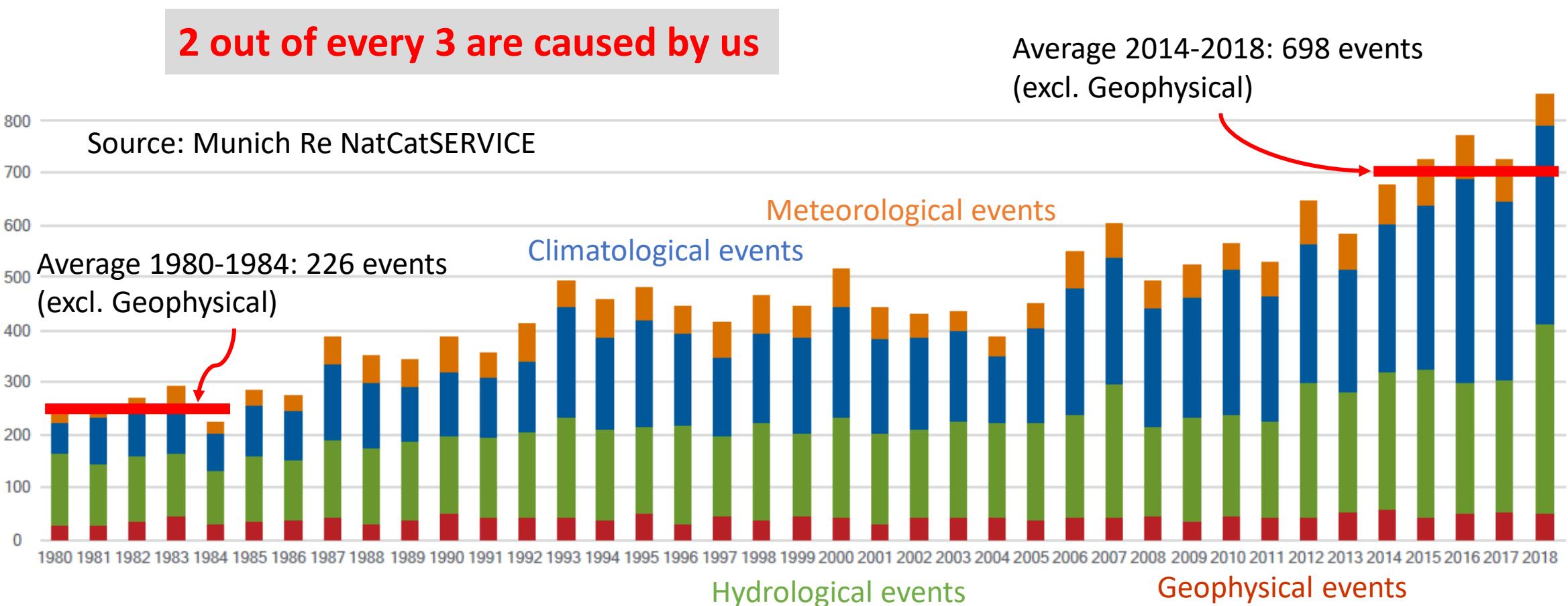
Earth Biosphere being replace by our stuff

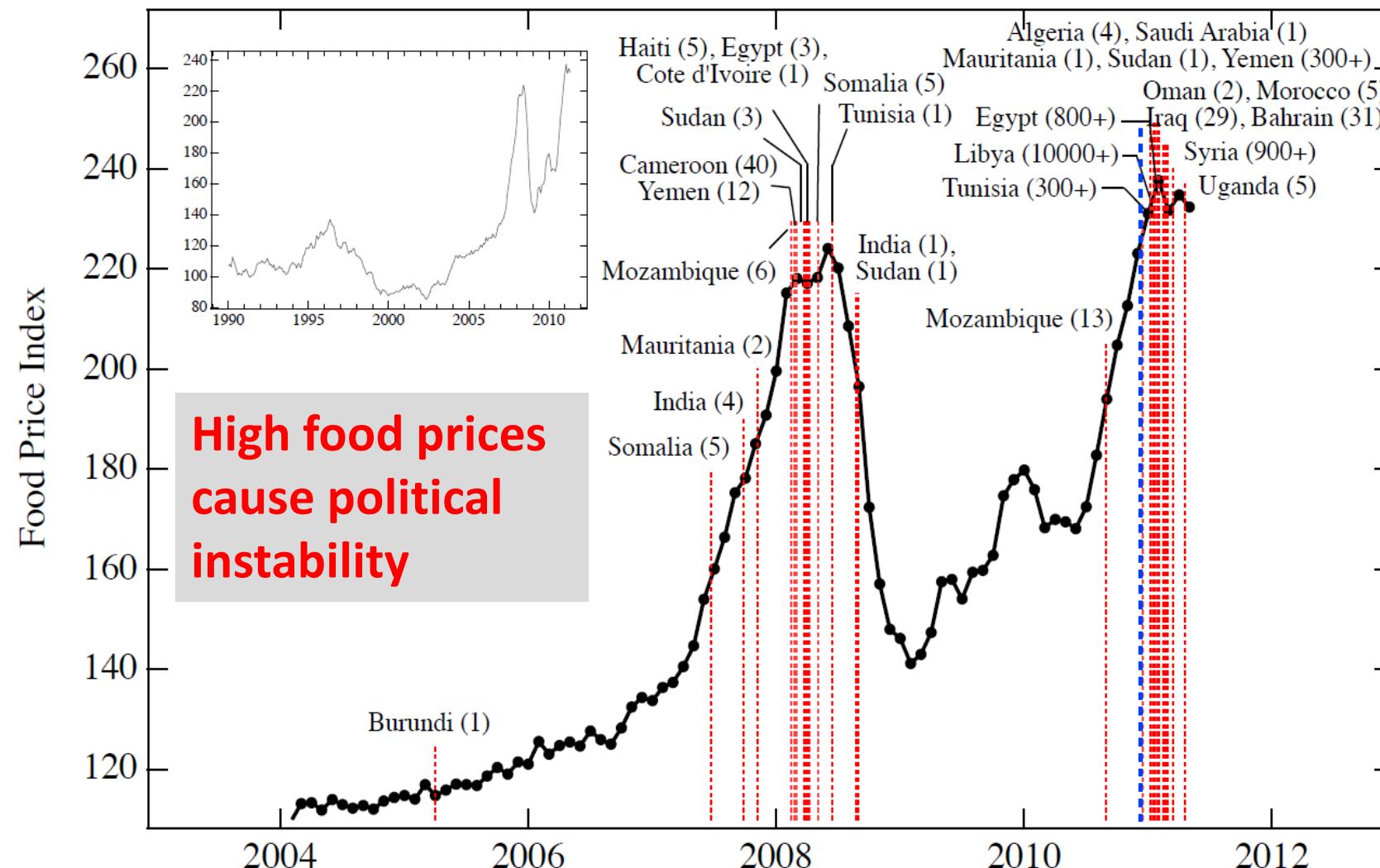
- Human stuff doubling every 20 years
- Global mass of produced plastic greater than the overall mass of all terrestrial and marine mammals combined
- Since the first agricultural revolution, 12,000 years ago, humanity has halved the mass of plants from 2 Teratonnes to 1 Tt replacing forests, wetlands and prairies with 0.01 Tt domesticated crops.
- All new anthropogenic mass will become waste. In the next 20 years, we will produce as much waste as from the last 110 years together.
- Most of what we have now has been built in the last couple of decades, since the 1960s, and is becoming end-of-life, so we are really facing huge, huge waste flows.

Stephanie Pappas, December 9, 2020, scientific American, Human-Made Stuff Now Outweighs All Life on Earth
The sheer scale of buildings, infrastructure and other anthropogenic objects underscores our impact on the planet,
<https://www.scientificamerican.com/article/human-made-stuff-now-outweighs-all-life-on-earth/>

climate related events have already been increasing: 300% in 40 years.

The red bars are the Geophysical events including Earthquake, tsunami, volcanic activity. The Orange bars are the Meteorological events including Tropical storm, extratropical storm, convective storm, local storm events. The Blue bars are Climatological events including Extreme temperature, drought, wildfire. The Green bars are the Hydrological events including Flood, mud slides. All data is for worldwide events.





M. Lagi, K.Z. Bertrand, Y. Bar-Yam, The Food Crises and Political Instability in North Africa and the Middle East.
arXiv:1108.2455 (August 10, 2011). <http://necsi.edu/research/social/foodcrises.html>

The probability that all four maize-exporting countries (US, Brazil, Argentina, Ukraine), have simultaneous production losses in any year, today virtually zero,

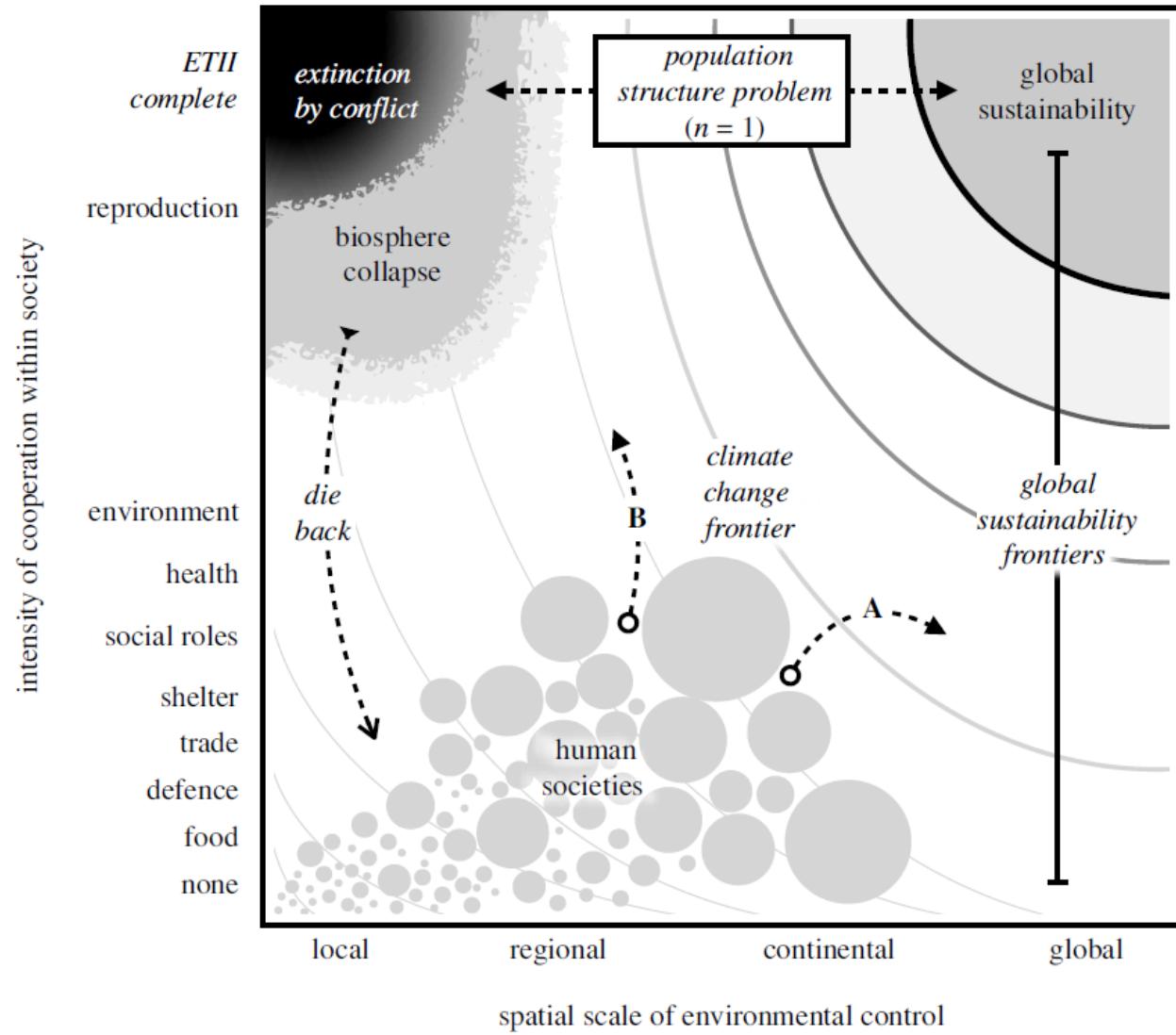
- *2 °C warming*: over any twenty year period is an 88% probability, a manageable disaster
- *4 °C warming*: near certainty once every three years. an unmanageable catastrophe

Civilization requires agriculture
and a stable climate

Michelle Tigchelaar, David S. Battisti, Rosamond L. Naylor, and Deepak K. Ray, Future warming increases probability of globally synchronized maize production shocks, PNAS, 2018, www.pnas.org/cgi/doi/10.1073/pnas.1718031115



<https://eos.org/articles/even-tardigrades-will-feel-the-heat-of-climate-change>



- how human evolution has operated in the context of environmental resources,
- how human evolution has contributed to the multiple global environmental crises, and
- how global environmental limits might change the outcomes of human evolution in the future.

Waring TM, Wood ZT, Szathmáry E. Characteristic processes of human evolution caused the Anthropocene and may obstruct its global solutions. Phil. Trans. R. Soc. B 379: 20220259. January, 2024,
<https://doi.org/10.1098/rstb.2022.0259>

What we may have learned in Part 3

- The climate is in a bistable state
- We are close to tipping the climate into a 5-degree warmer mid-Miocene climate but do not know how close
- Civilization depends on agriculture and agriculture depends on a stable climate
- We are warming the climate too fast for the biosphere and civilization to adapt
- The Holocene extinction event is underway
- The planet is not in peril. We cannot save the Earth. Earth does not need saving. The Earth is not in trouble
- We are.

The entire history of the evolution of our environment

- Part 1 The evolution of the universe the first 9.3 billion years
 - Where did we come from
 - What are the laws
- Part 2 The evolution of Earth the next 4.5 billion years
 - Brief history of Earth, right up to the Cenozoic
- Part 3 The evolution of civilization, the Anthropocene
 - Current extinction event, the Holocene extinction
 - Climate change
- Part 4 The evolution of our possible futures
 - Economics (and our environment)
- Part 5 The evolution of our possible futures
 - Energy (and our environment)
- Part 6 solution space and discussion

Cliff notes version of Charles Langmuir and Wally Broecker's "How to Build a Habitable Planet" or Paolo Saraceno, "Beyond the Stars" also Stanley and Luczaj "Earth System History" and Lunine "Earth".

An Engineer's perspective on the Human condition the evolution of possible futures - economics

Part 4

