



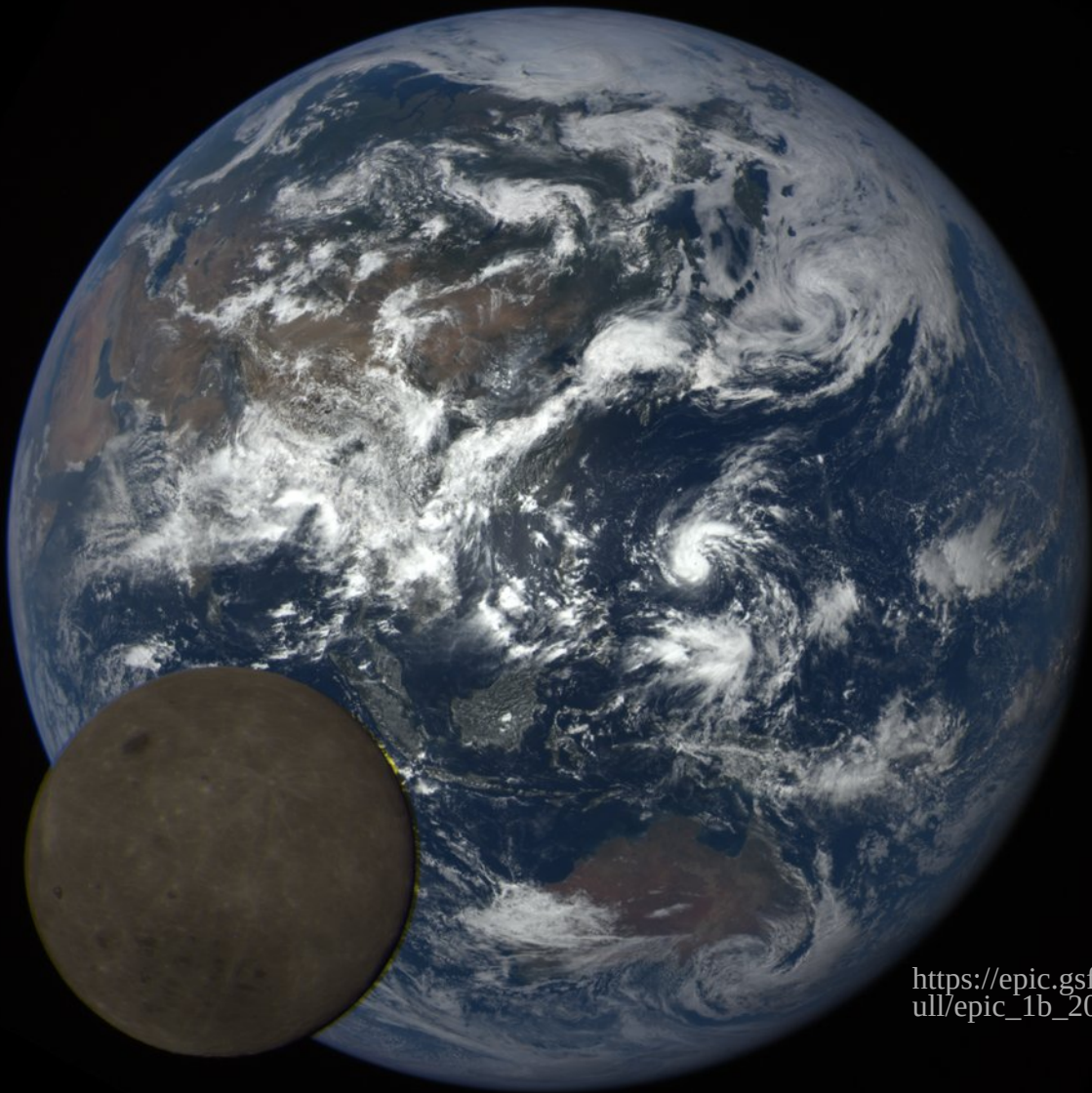
Global warming - physicist's perspective

01 – an overview of the problem

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https://epic.gsfc.nasa.gov/epic-galleries/2016/lunar_transit/full/epic_1b_20160705044720_01.png



ΔQ_s



ΔQ_c



T1

>

T2

>

T3

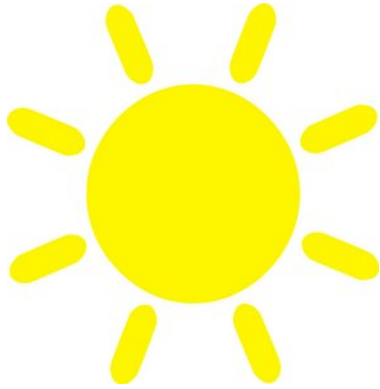
THE EARTH is illuminated by shortwave SOLAR radiation, which is partially absorbed (ΔQ_s) and partially reflected (not shown).

In (quasi) equilibrium energy of absorbed radiation ΔQ_s is balanced by emission of EARTH's radiation ΔQ_c in thermal infrared.

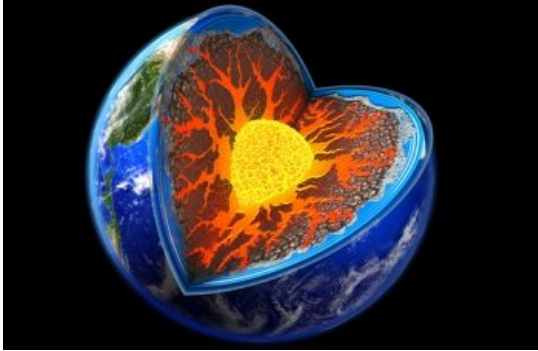
Heating $\Delta Q_s > \Delta Q_c \rightarrow$ positive imbalance.

Cooling $\Delta Q_s < \Delta Q_c \rightarrow$ negative imbalance.

**Radiative forcing: change of radiation fluxes
(from a certain reference state)**



$\sim 340 \text{ W/m}^2$ (160 W/m^2)



$\sim 0.1 \text{ W/m}^2 \ll 160 \text{ W/m}^2$



$\sim 0.04 \text{ W/m}^2 \ll 160 \text{ W/m}^2$

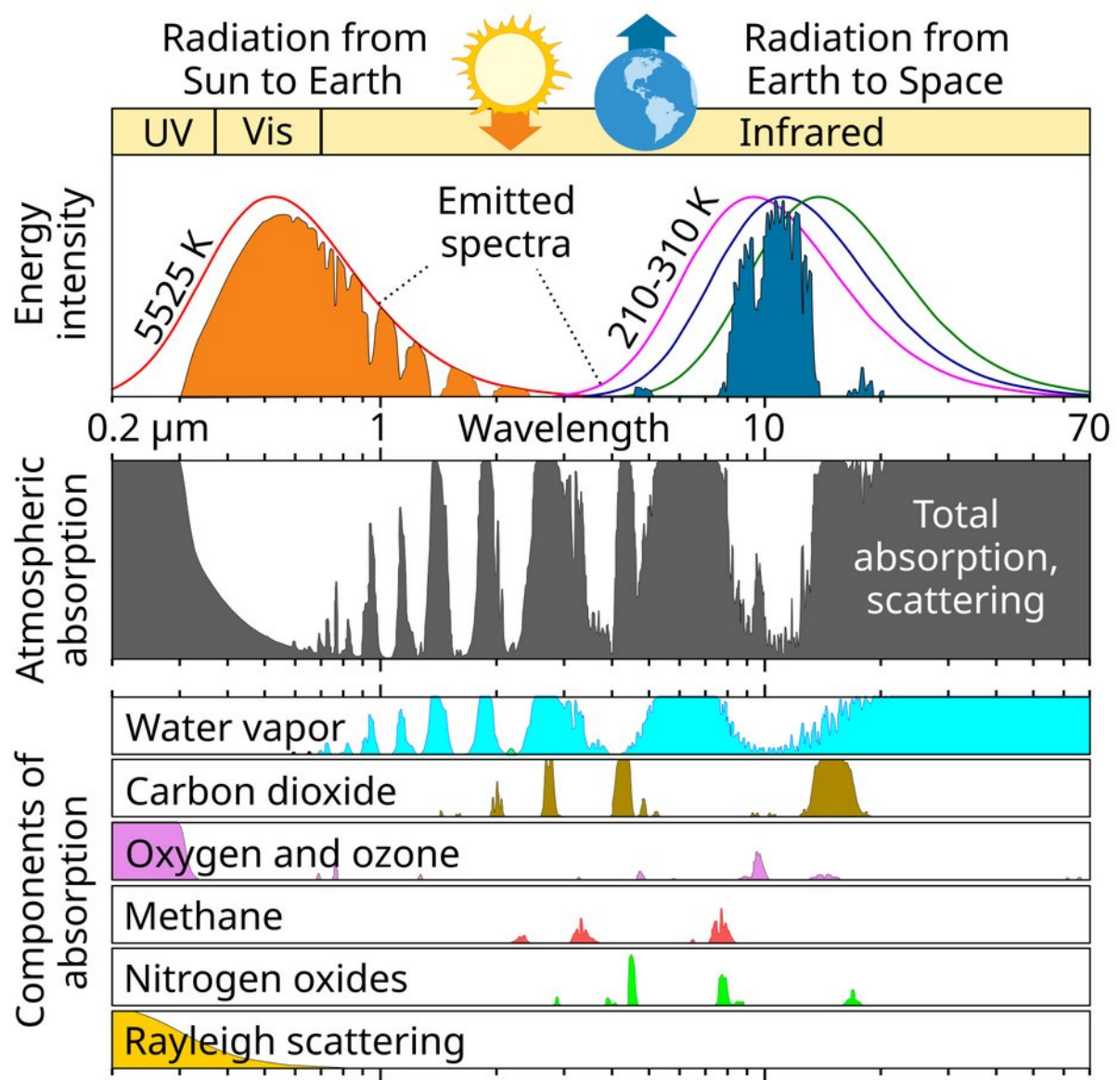
ENERGY IN THE CLIMATE SYSTEM

1. Solar energy flux = $\frac{1}{4}$ of Solar constant
 $\frac{1}{4} * 1362 \text{W/m}^2 \approx 341 \text{W/m}^2$.
2. Earth's surface albedo, mean ≈ 0.3 , highly variable, from 0.9 (fresh snow) to 0.07 (clean ocean).
3. Geothermal energy flux $\approx 0.092 \text{W/m}^2$.
4. Heat flux from fossil fuel combustion $\approx 0.04 \text{W/m}^2$.

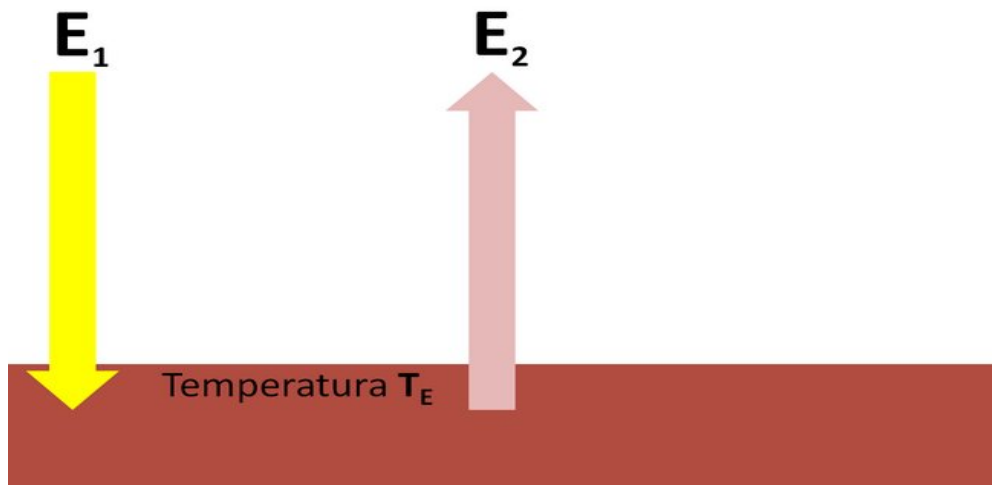
BASIC PROPERTIES OF THE CLIMATE SYSTEM

1. Air: surface pressure $\approx 1000 \text{hPa}$ (10m of water),
 $c_p = 1004 \text{J/kg} \cdot \text{K}$.
2. Water: global average depth $\approx 3000 \text{m}$, $c_w = 4192 \text{J/kg} \cdot \text{K}$.
3. Ground – only a shallow layer responding to radiative fluxes.
4. Greenhouse gases: H_2O , CO_2 , CH_4 , O_3 , many others.

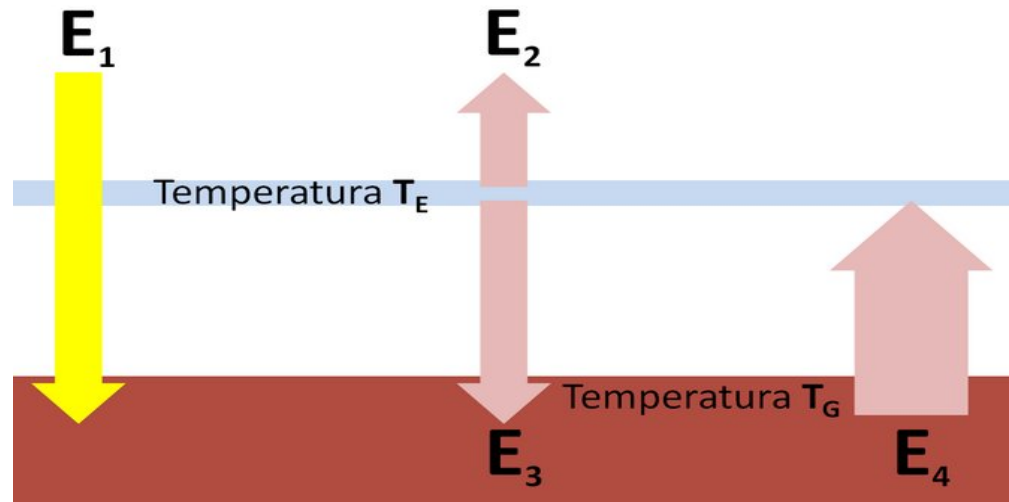
Radiative transfer of energy through the atmosphere and greenhouse gases.



Greenhouse effect: a principle

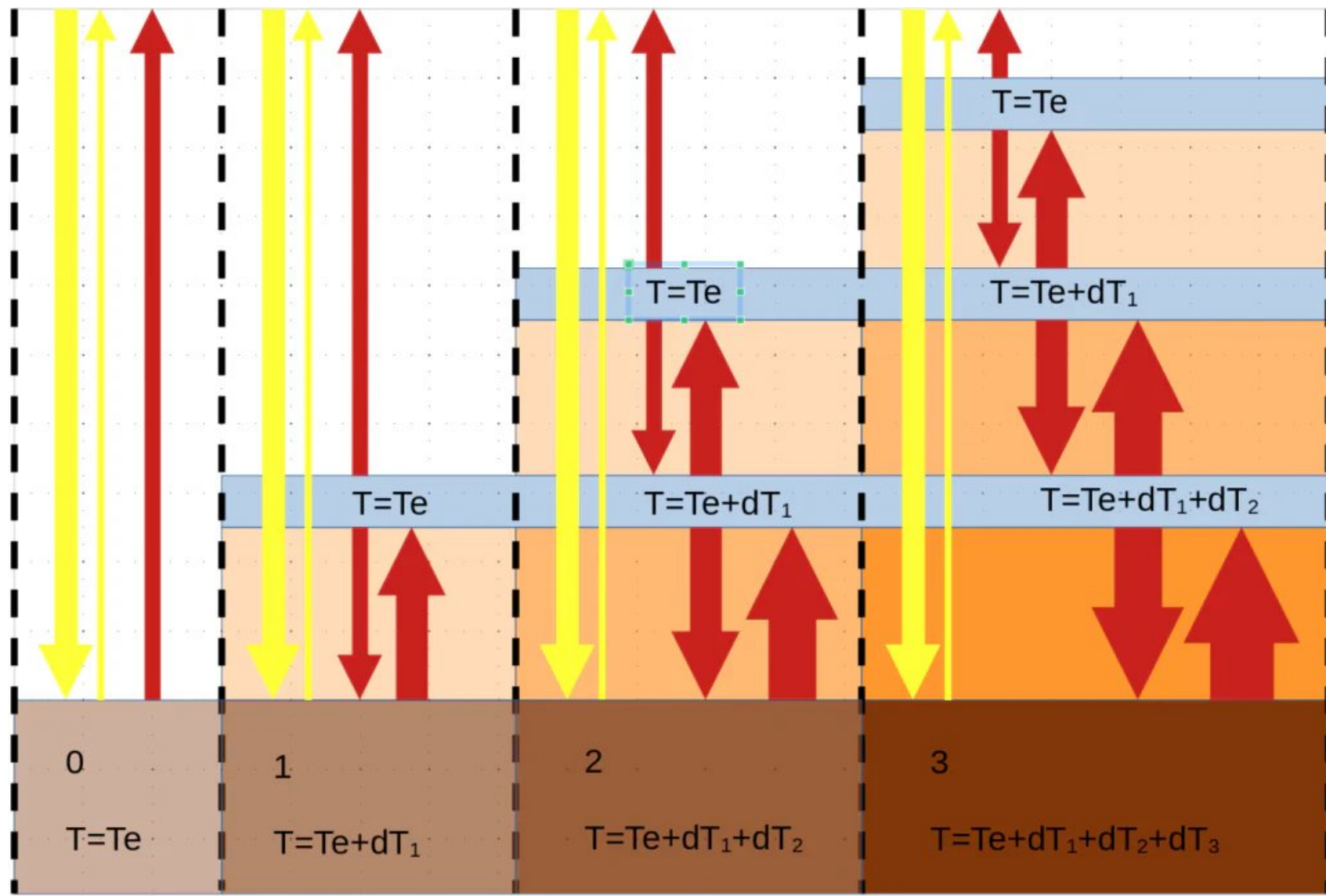


$$E_1 = E_2$$

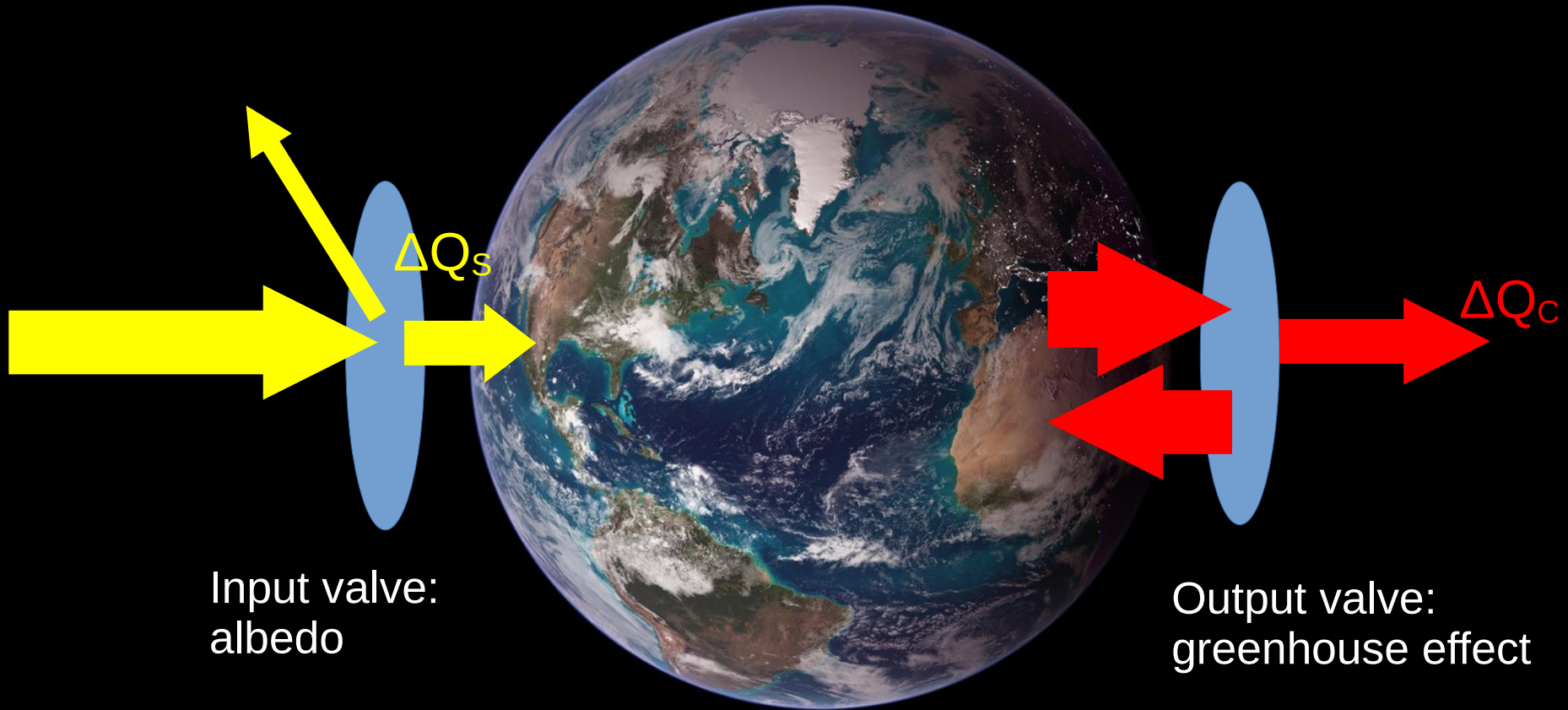


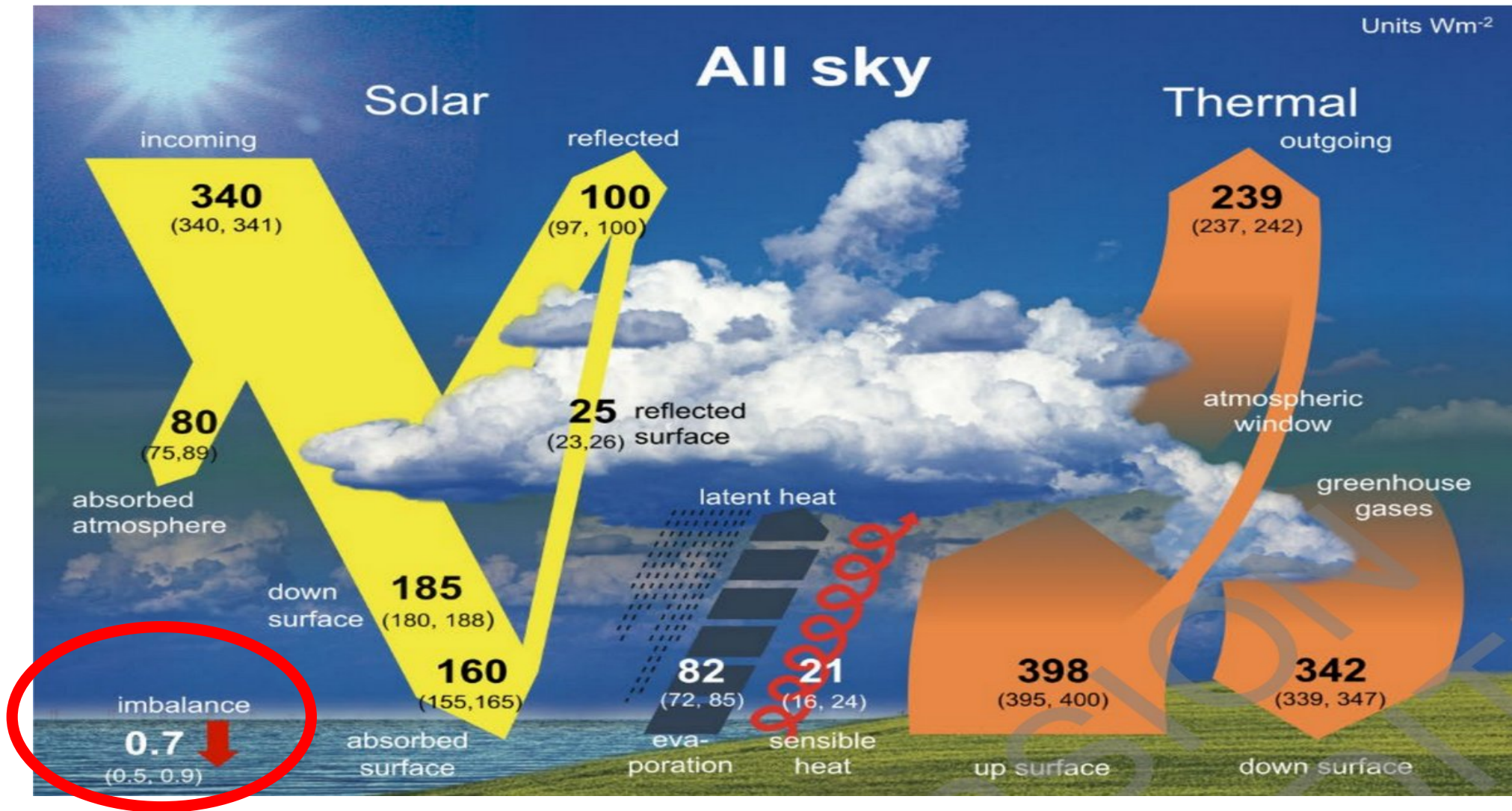
$$E_1 = E_2 = E_3$$

$$E_4 = E_1 + E_3$$

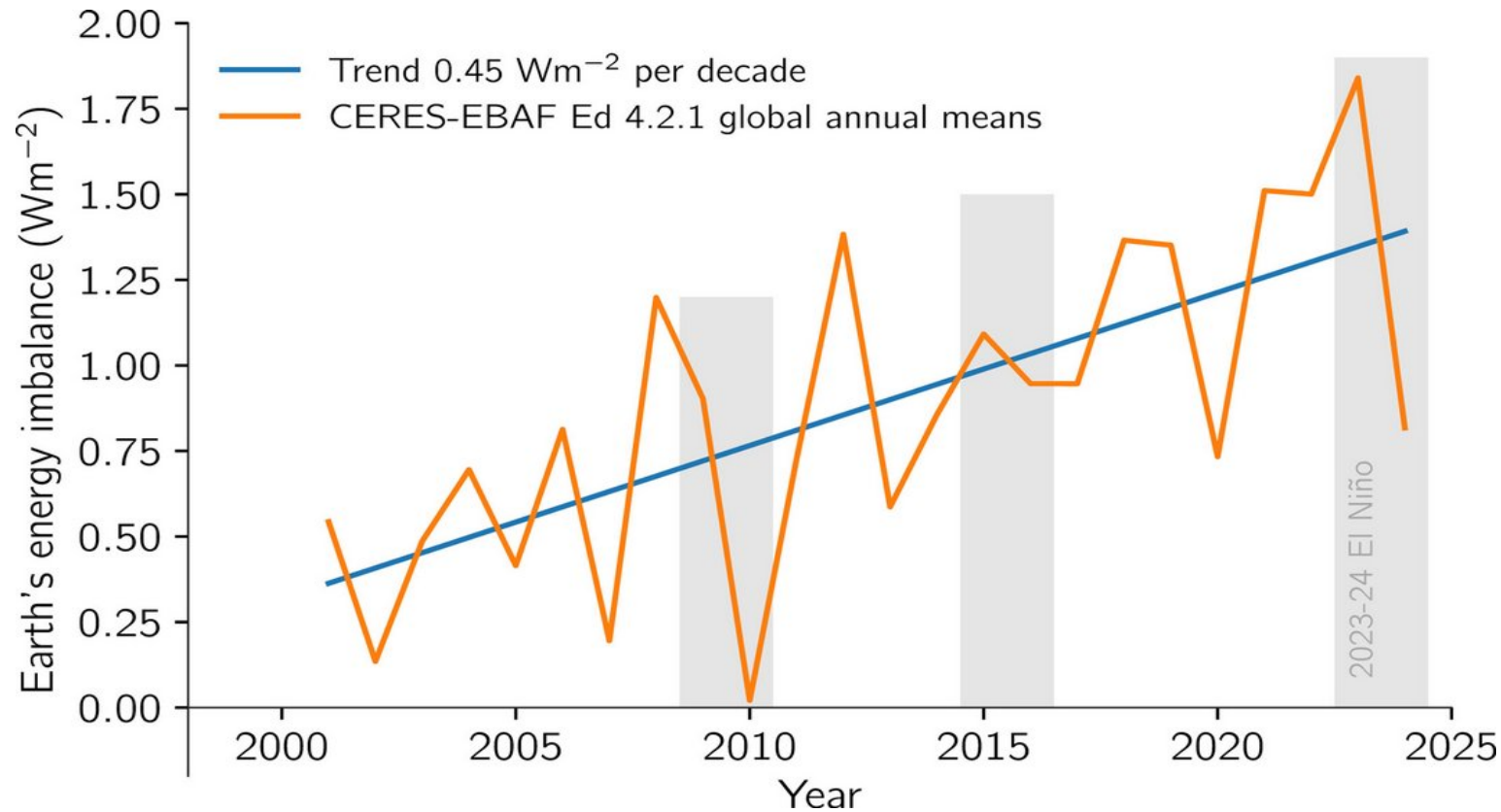


Earth climate system temperature depends the balance of ΔQ_s and ΔQ_c





Energy balance of climate system. Units: W/m^2 .



AGU Advances

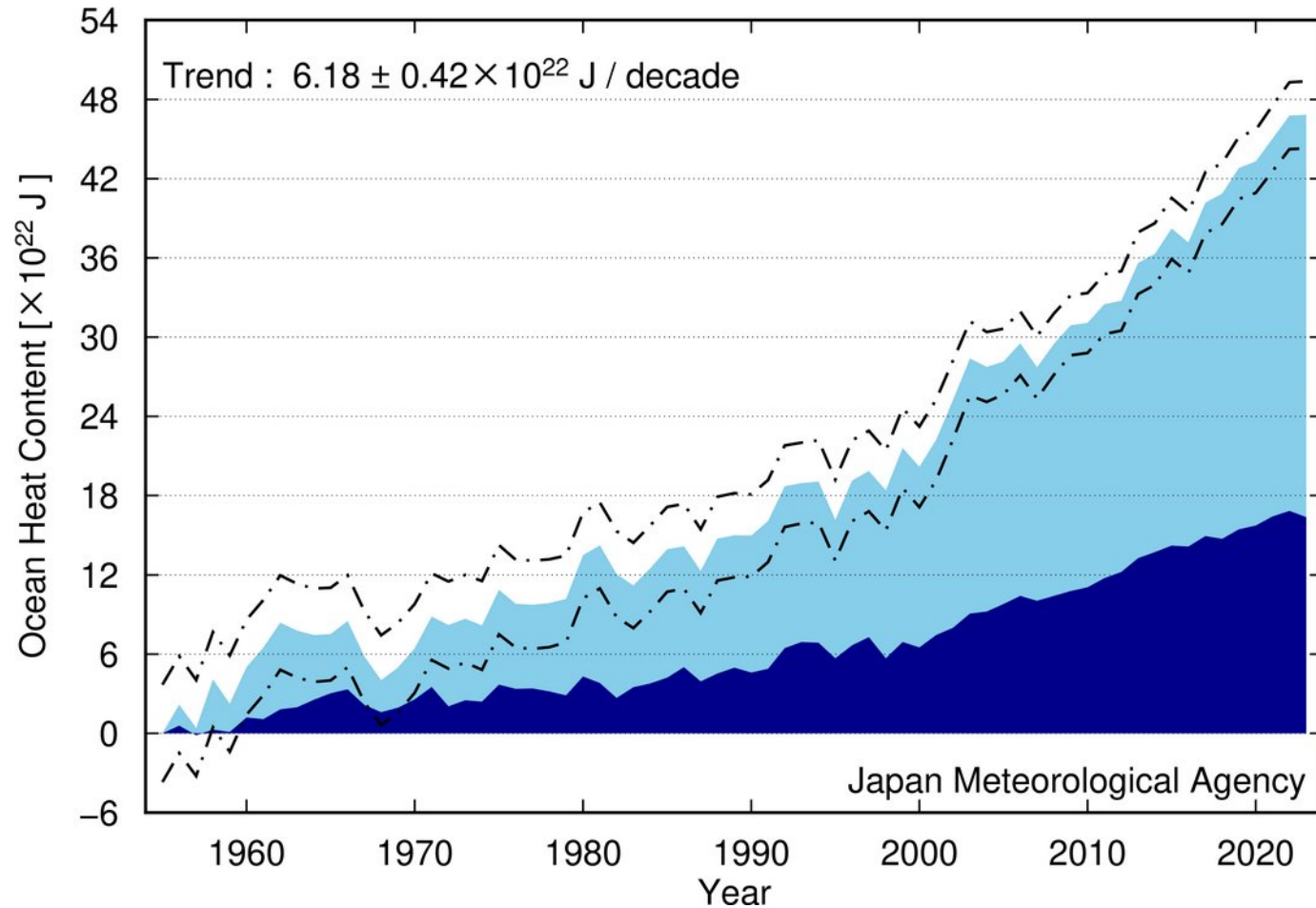
Commentary | [Open Access](#) | [CC BY](#)

Earth's Energy Imbalance More Than Doubled in Recent Decades

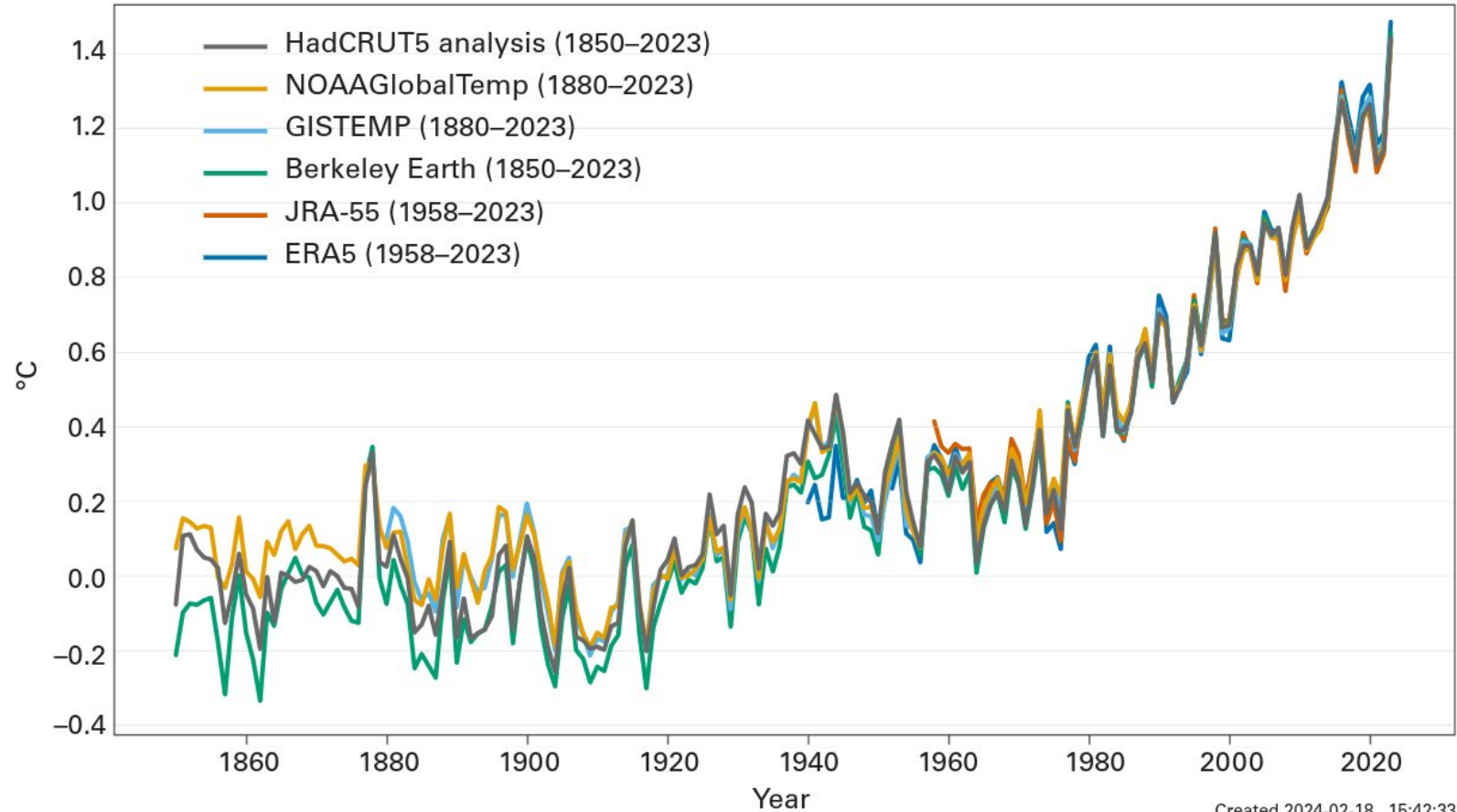
Thorsten Mauritsen  Yoko Tsushima, Benoit Meyssignac, Norman G. Loeb, Maria Hakuba, Peter Pilewskie, Jason Cole, Kentaro Suzuki, Thomas P. Ackerman, Richard P. Allan ... [See all authors](#)

First published: 10 May 2025 | <https://doi.org/10.1029/2024AV001636> | Citations: 3

Ocean heat content increases. 96% of the energy imbalance ends in the ocean.



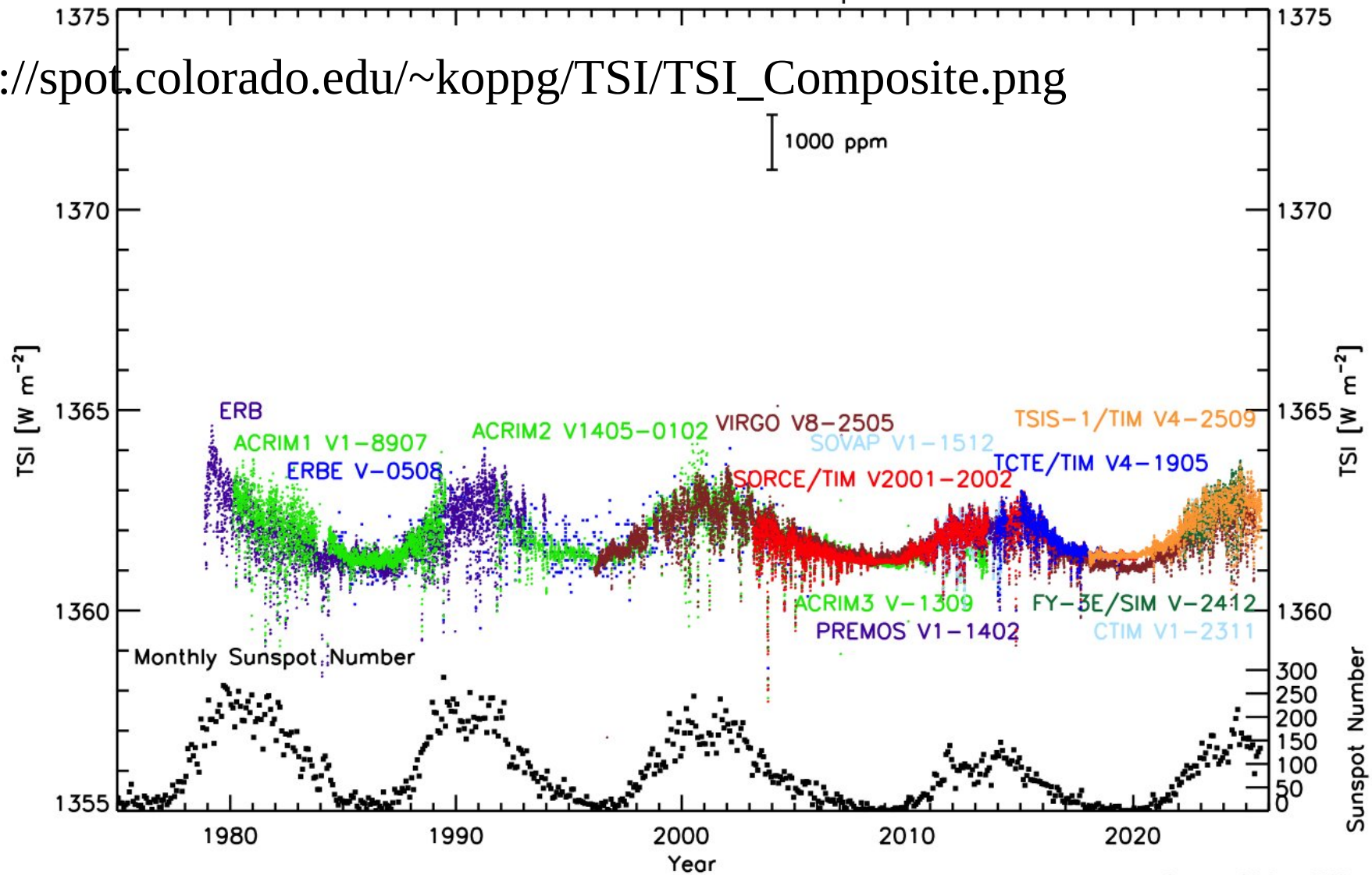
Positive energy balance – temperature of the air at the surface increases.



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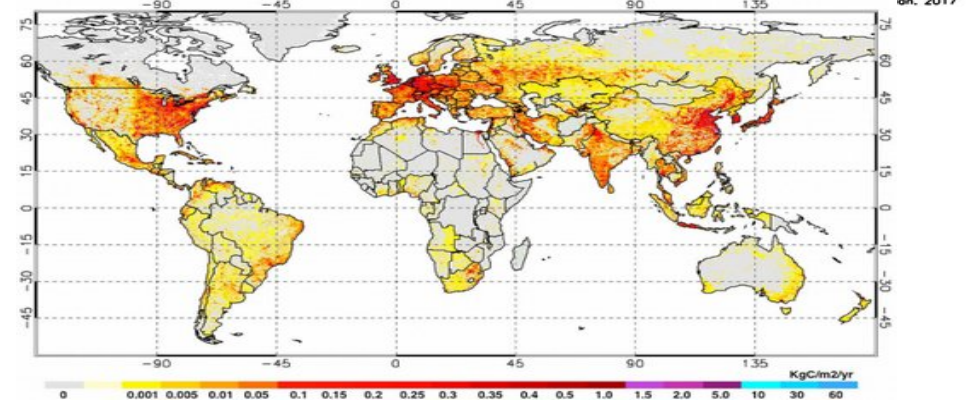
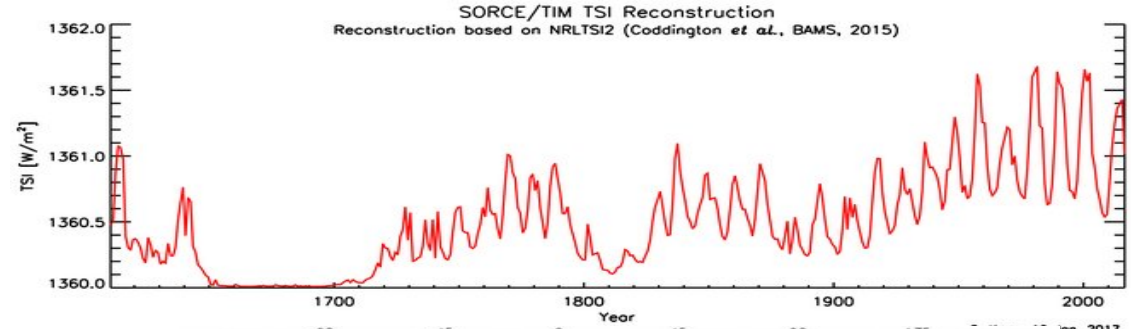
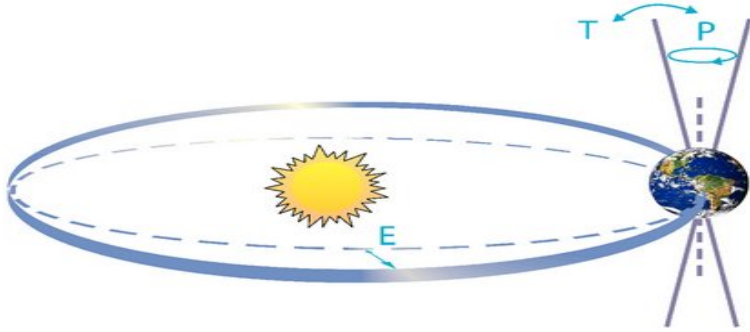
Total Solar Irradiance Composite

https://spot.colorado.edu/~koppg/TSI/TSI_Composite.png



Forcings and feedbacks in climate system.

Climate **forcings** are the **initial drivers** of a climate shift.



Forcings and feedbacks in climate system.

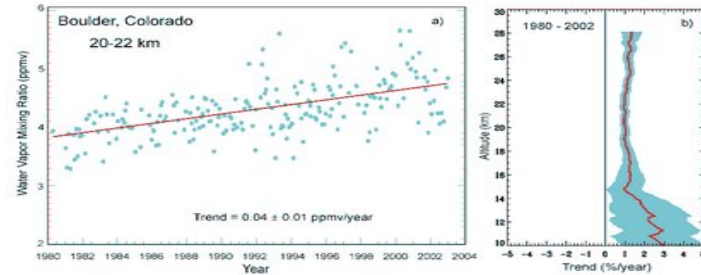
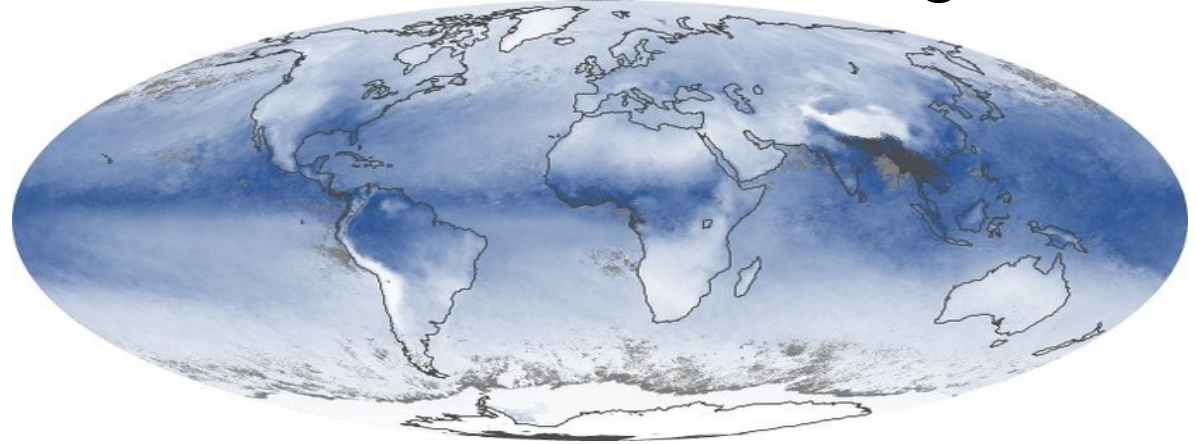
Climate **feedbacks** are processes that **change** as a result of a **change in forcing**, and **cause additional climate change**.



1979 SSM/I Composite Data

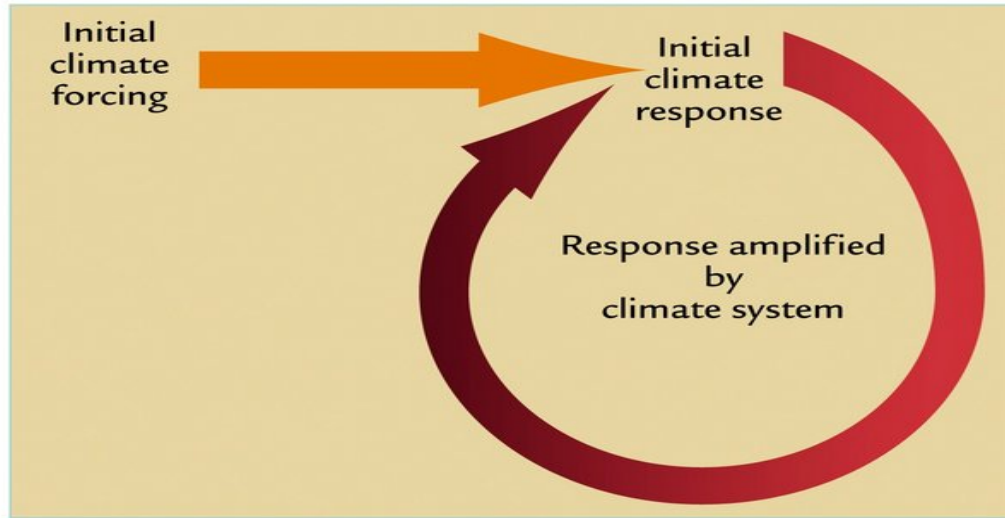


2003 SSM/I Composite Data

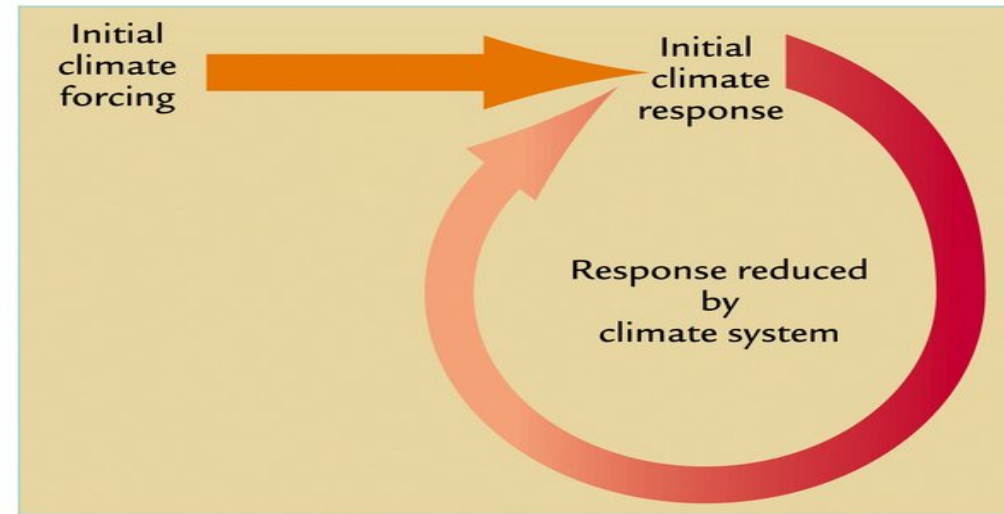


Feedbacks can be positive or negative.

Positive feedbacks, when exceeding thresholds, may lead to rapid climate changes.

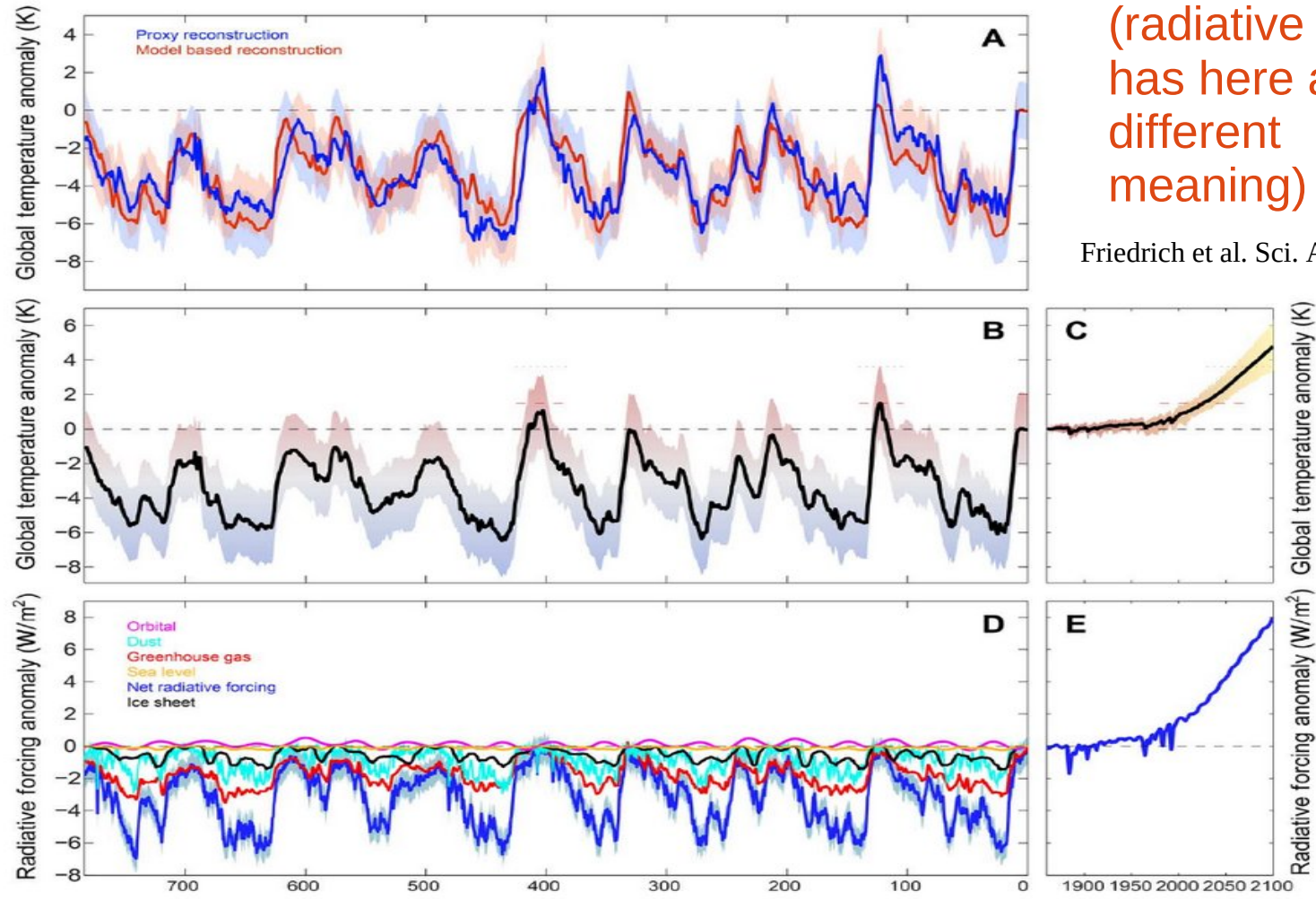


A Positive feedback



B Negative feedback

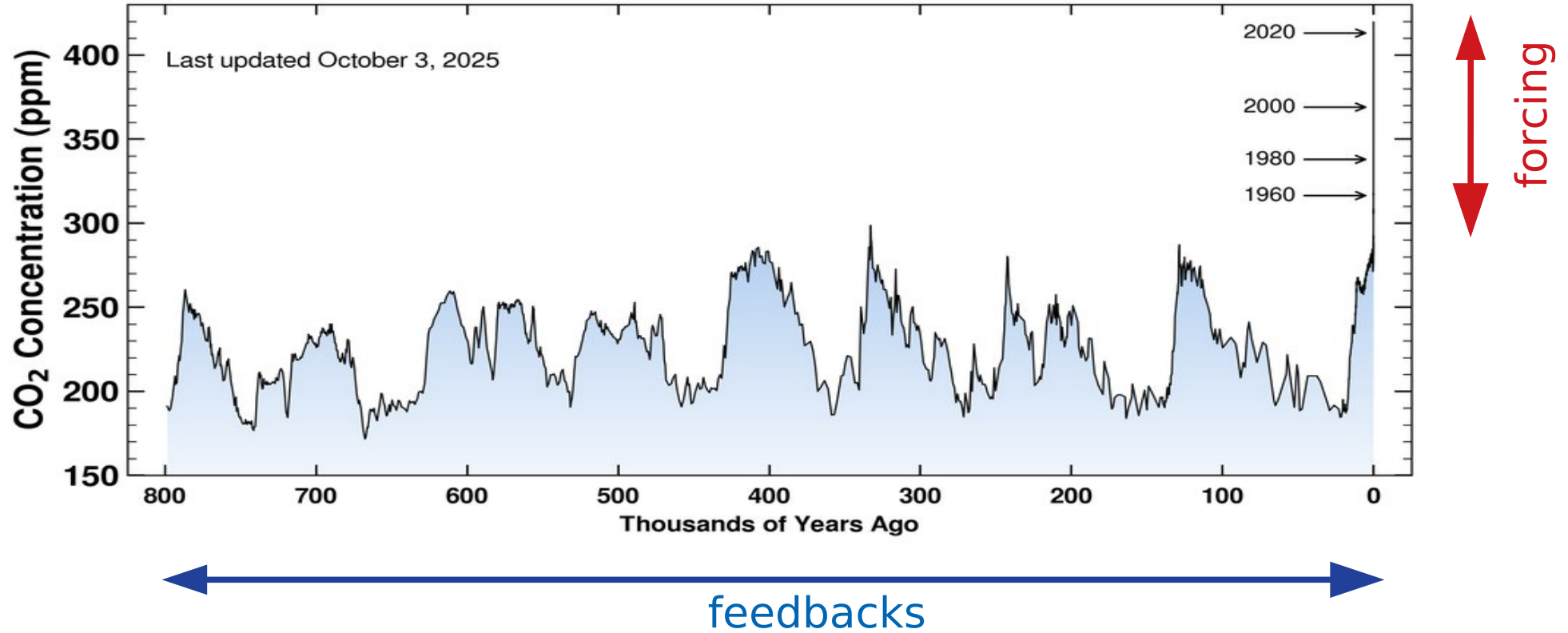
Orbital forcing and system feedbacks in the course of ice ages lead to remarkable radiative effects



(radiative forcing
has here a
different
meaning)

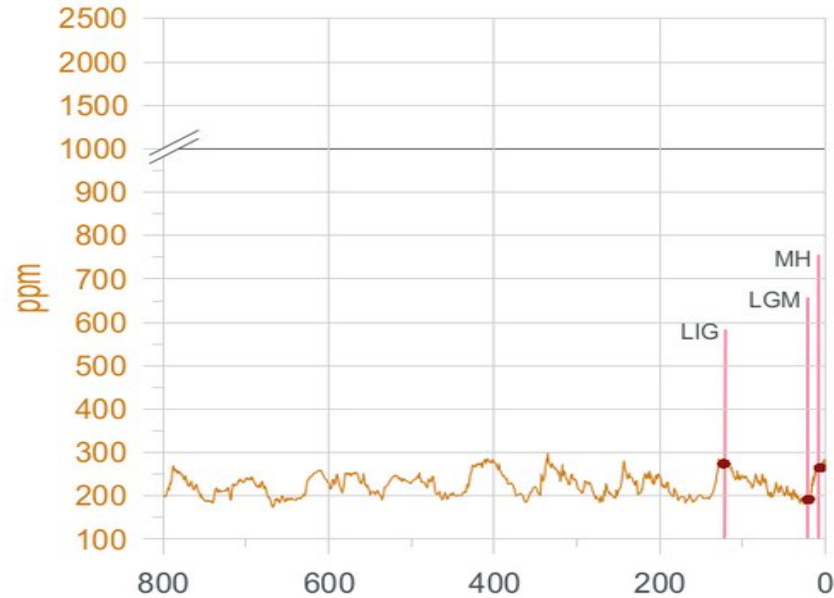
Friedrich et al. Sci. Adv. 2016; 2 : e1501923

CO₂: feedback and forcing.

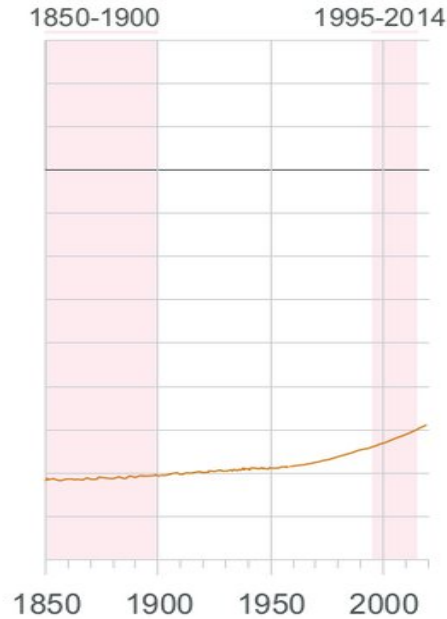


Paleoclimatic data of the past 800,000 years

(a) Atmospheric CO₂ concentration



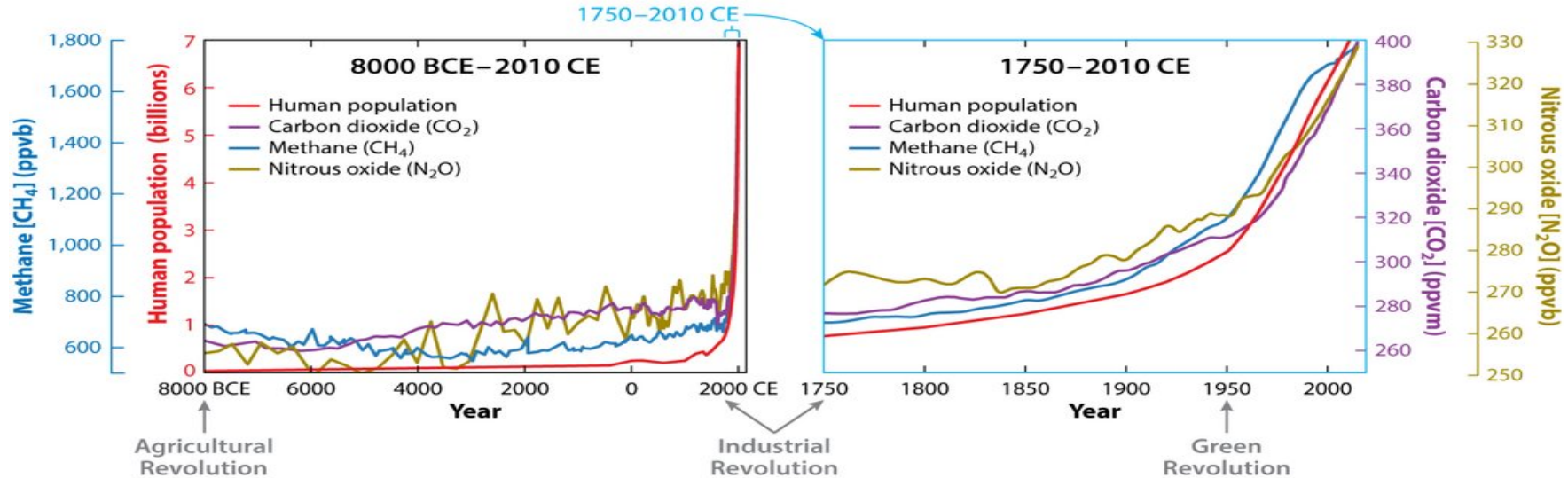
Data since 1850



Climate Model Projections

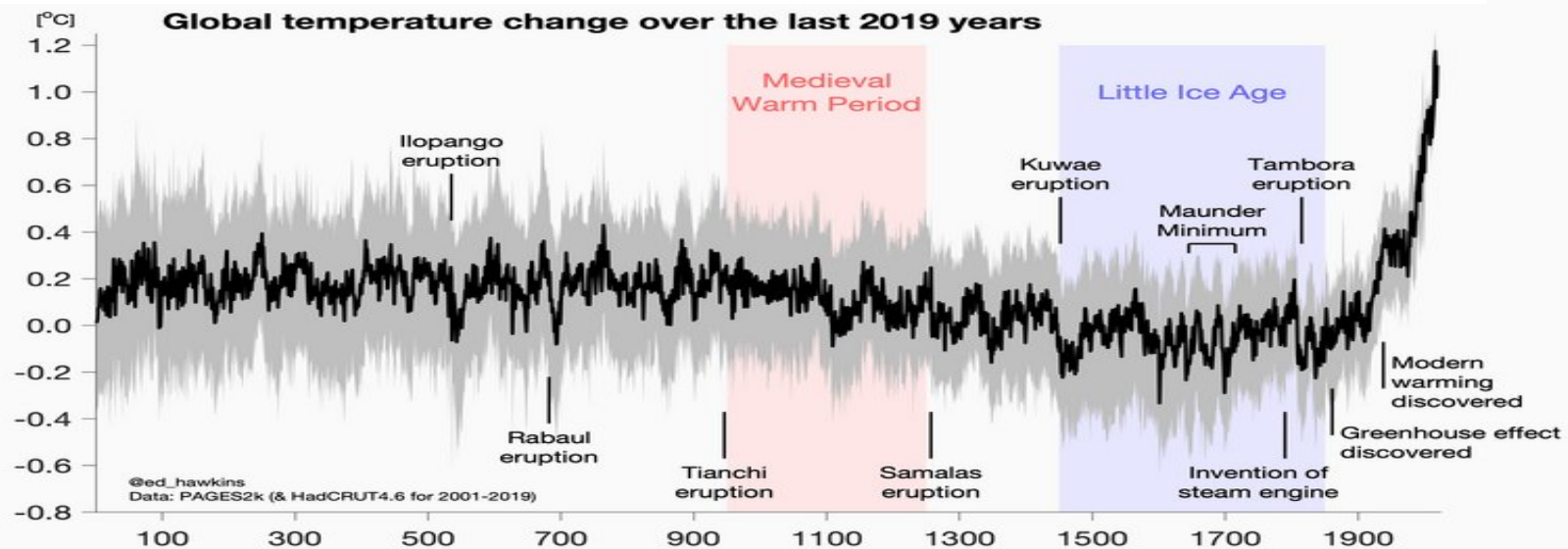
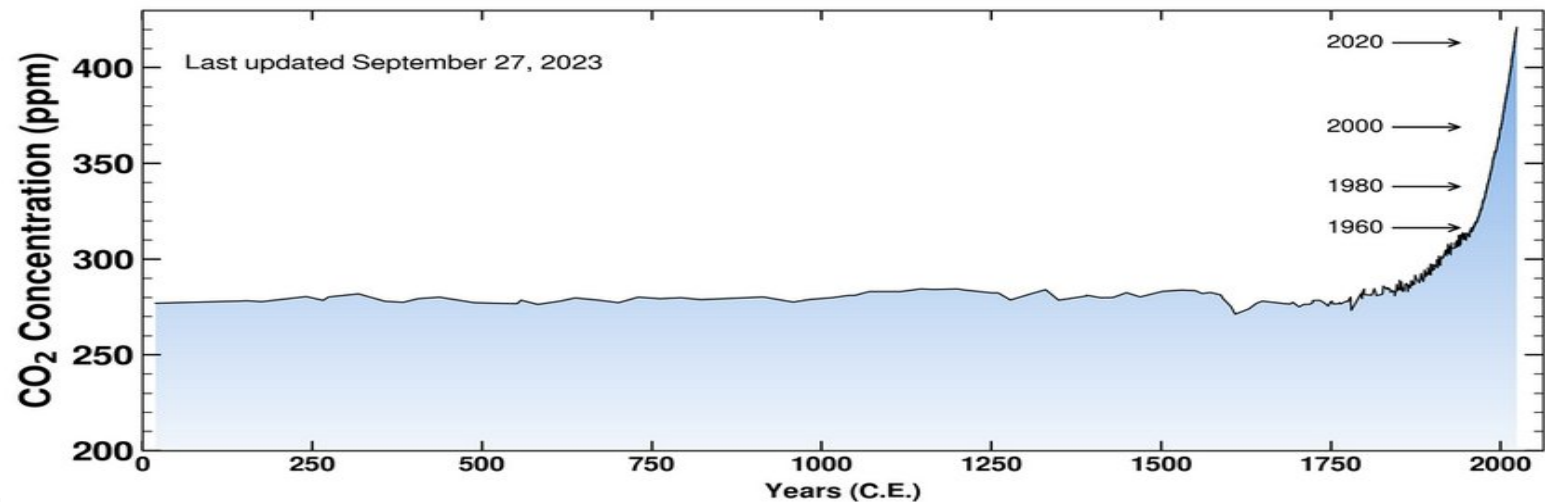


Evolution of human population and greenhouse gases over the past 10,000 years



The abrupt and simultaneous upward trajectories of human population and greenhouse gases after the start of the Industrial Revolution (~1750), and the distinct acceleration after the start of the Green Revolution (~1950), show that the Human System has become the primary driver of these gases and the changes in the Earth System.

Adapted from Fu & Li (2016), CC-BY, <https://doi.org/10.1093/nsr/nww094>.



Observed warming is driven by emissions from human activities, with greenhouse gas warming partly masked by aerosol cooling

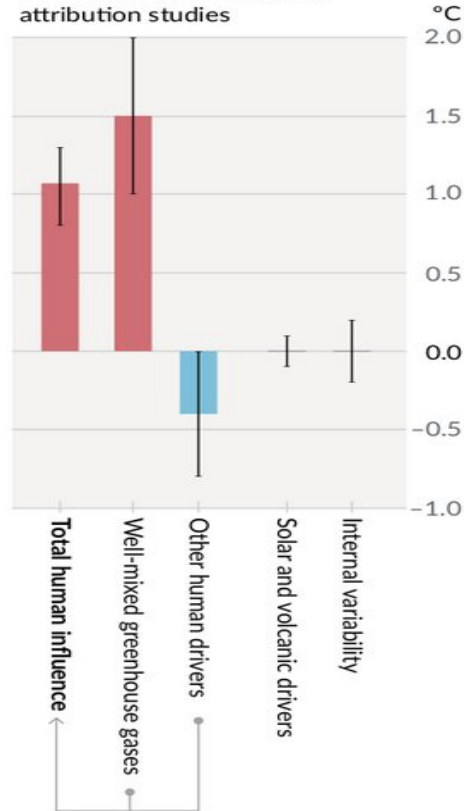
Observed warming

(a) Observed warming 2010–2019 relative to 1850–1900

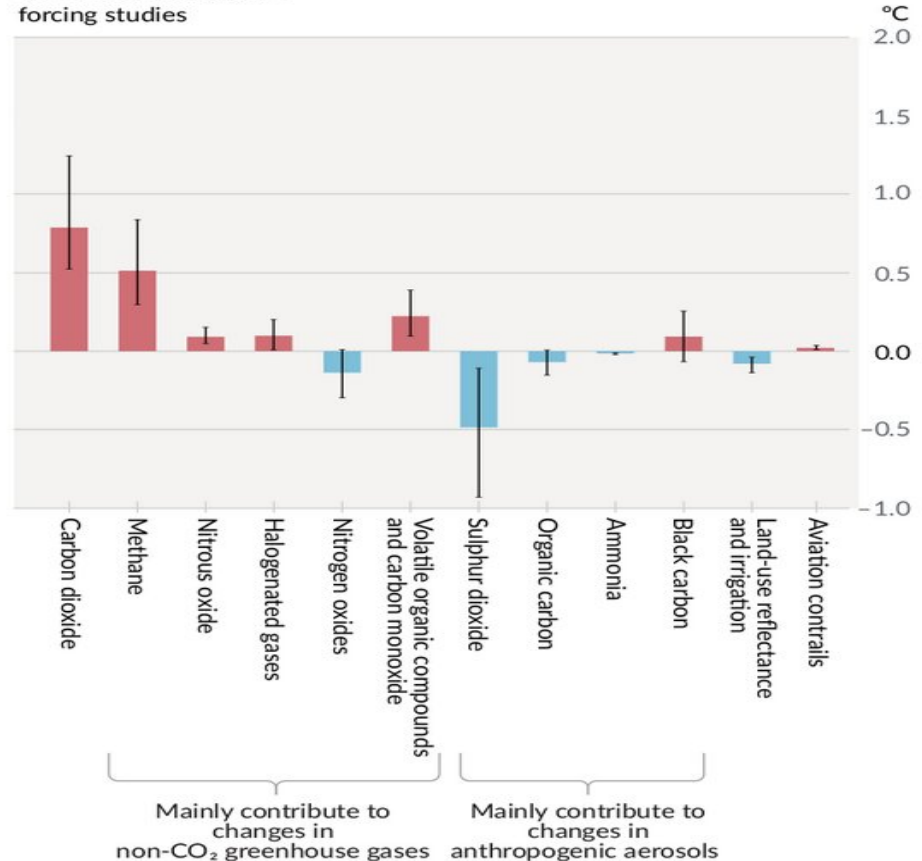


Contributions to warming based on two complementary approaches

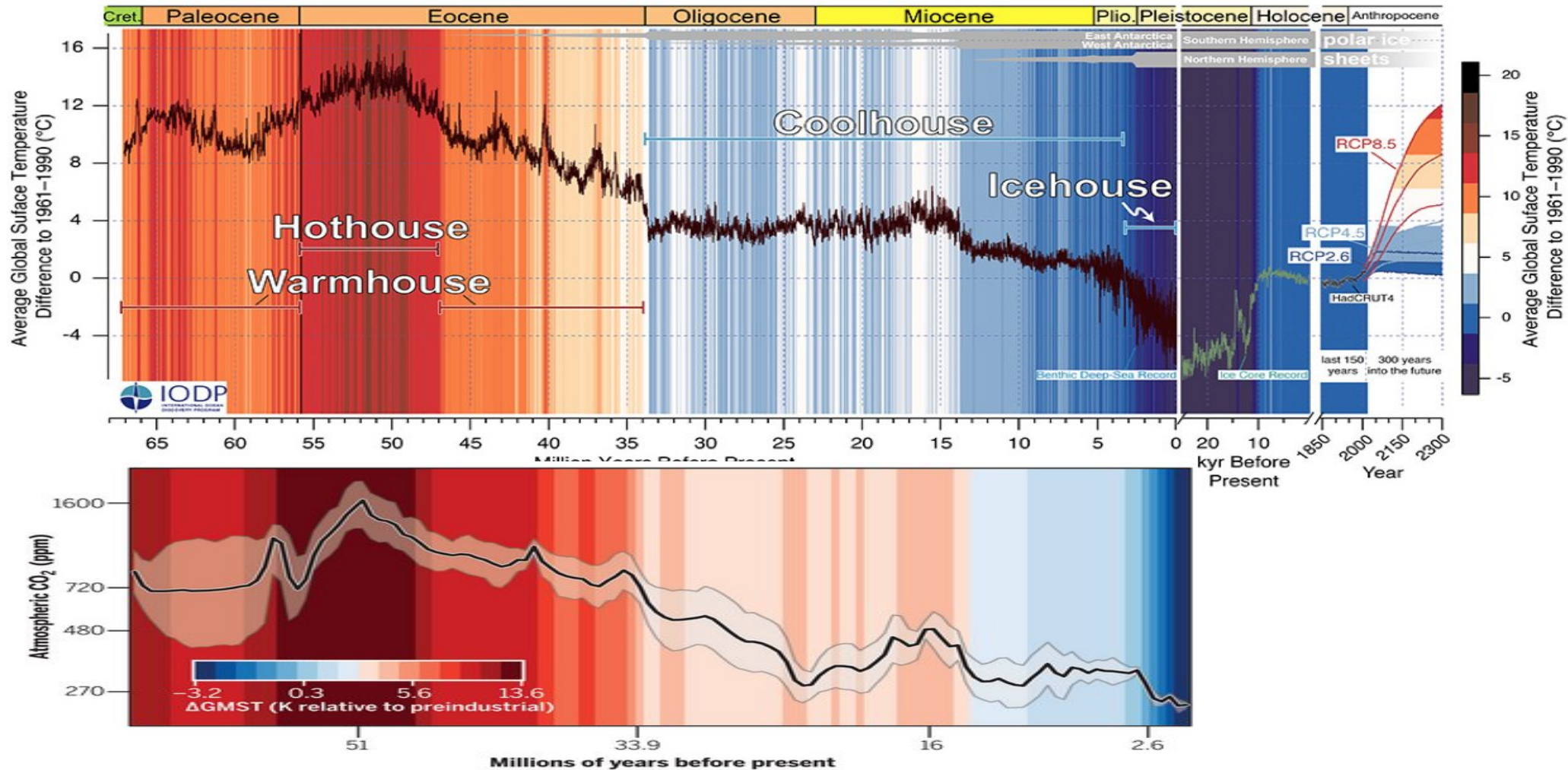
(b) Aggregated contributions to 2010–2019 warming relative to 1850–1900, assessed from attribution studies



(c) Contributions to 2010–2019 warming relative to 1850–1900, assessed from radiative forcing studies



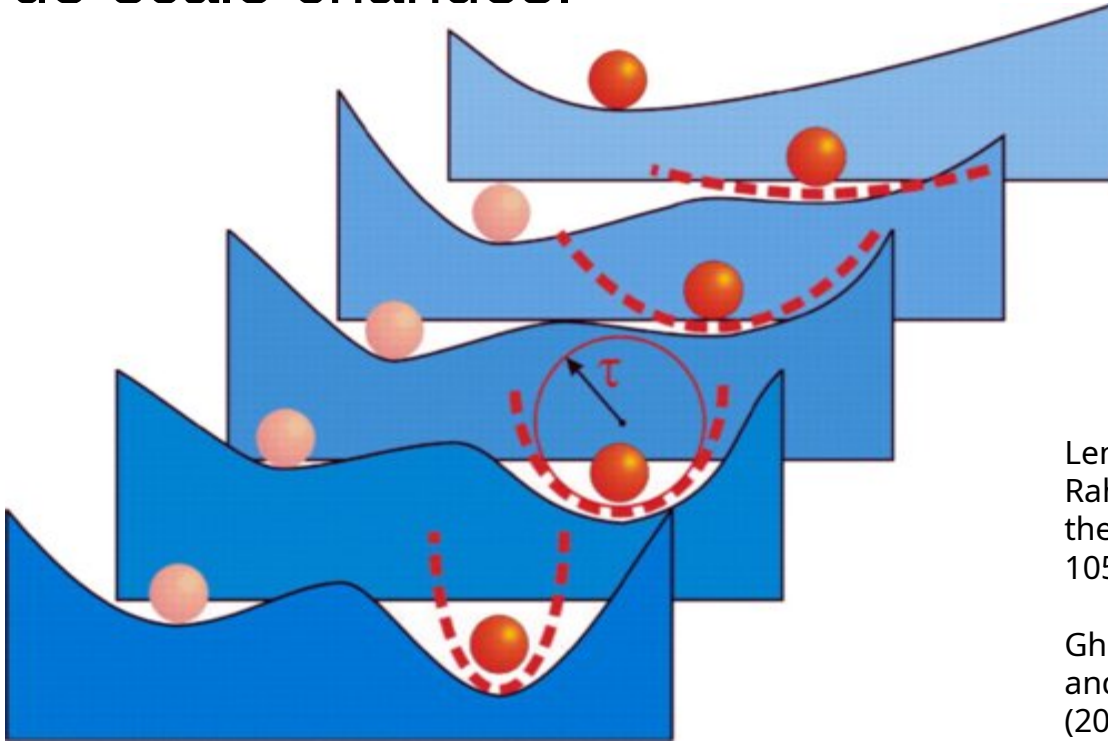
Very past and and near future climate



Tipping points.

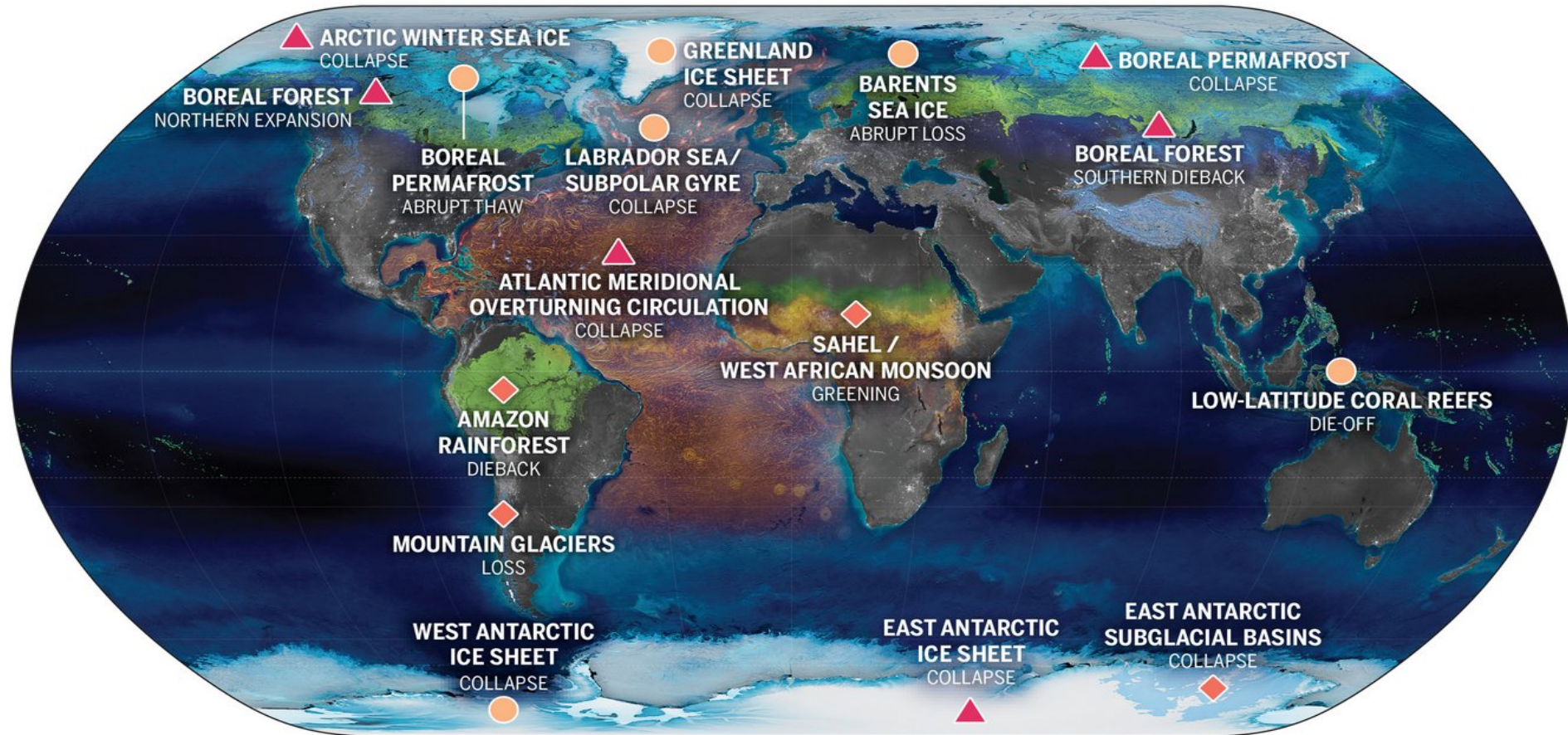
Passing a tipping point leads to the change of the state of the system.

Crossing multiple tipping points could lead to irreversible large-scale changes.

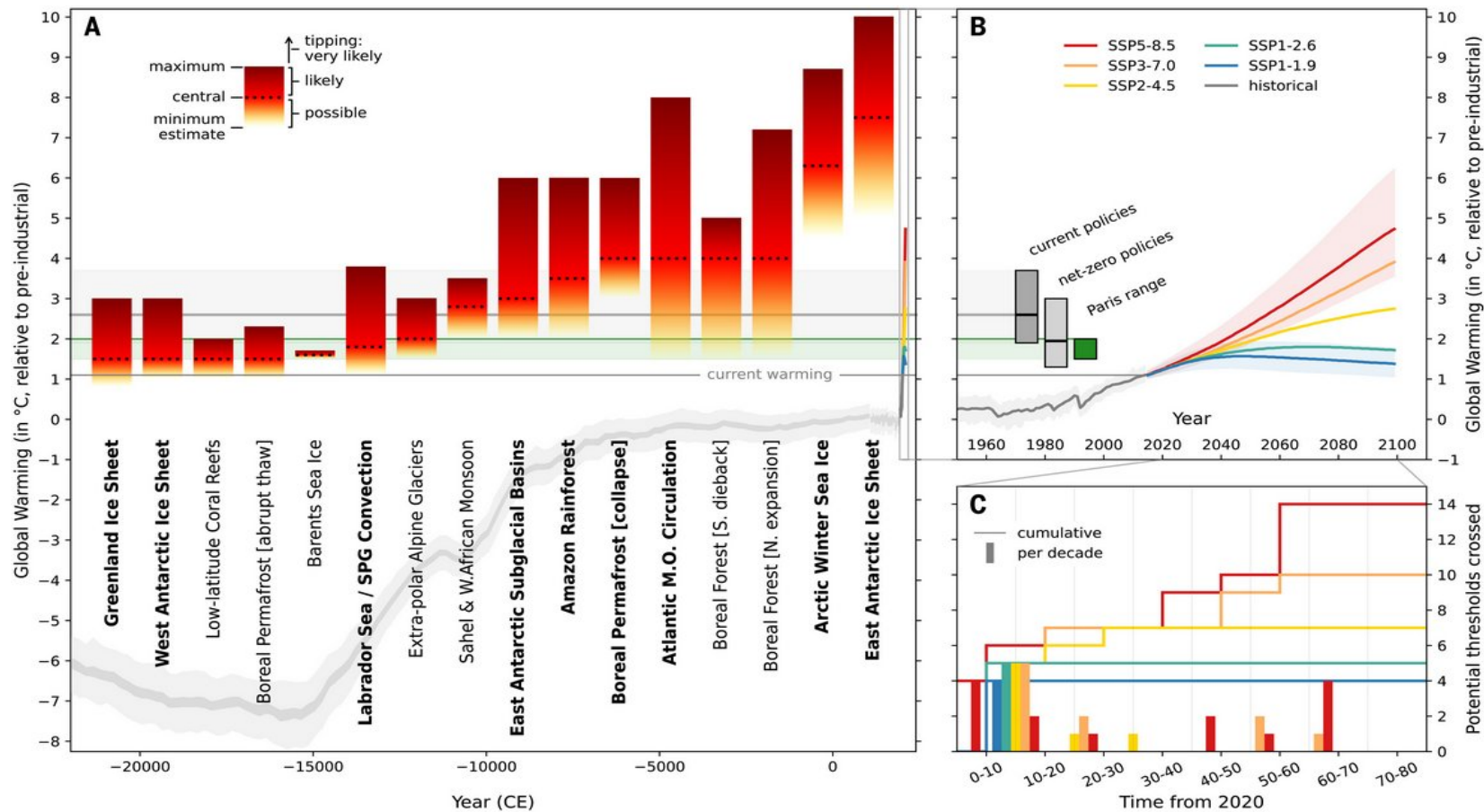


Lenton, T. M., H. Held, E. Kriegler, J. W. Hall, W. Lucht, S. Rahmstorf, and H. J. Schellnhuber, Tipping elements in the Earth's climate system, *Proc. Natl. Acad. Sci. U.S.A.* 105, 1786–1793 (2008).

Ghil, M., V. Lucarini, The physics of climate variability and climate change, *Rev. Mod. Phys.* 92, 035002 (2020).



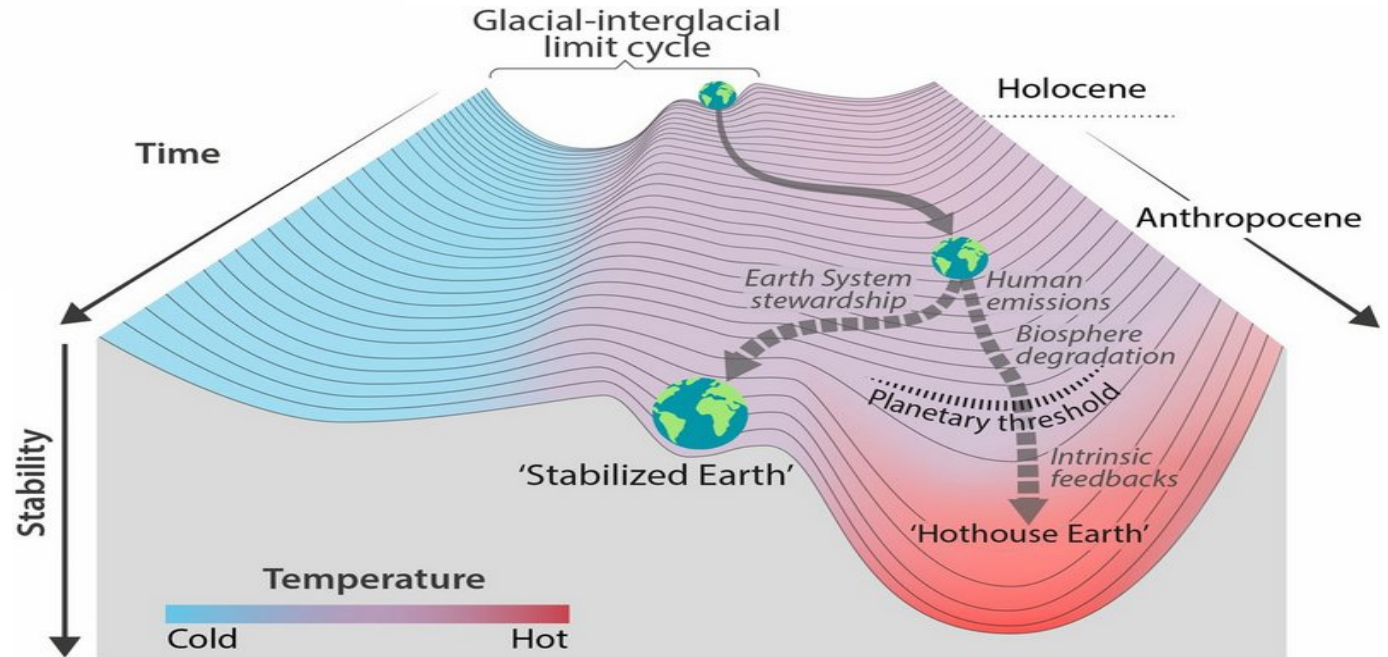
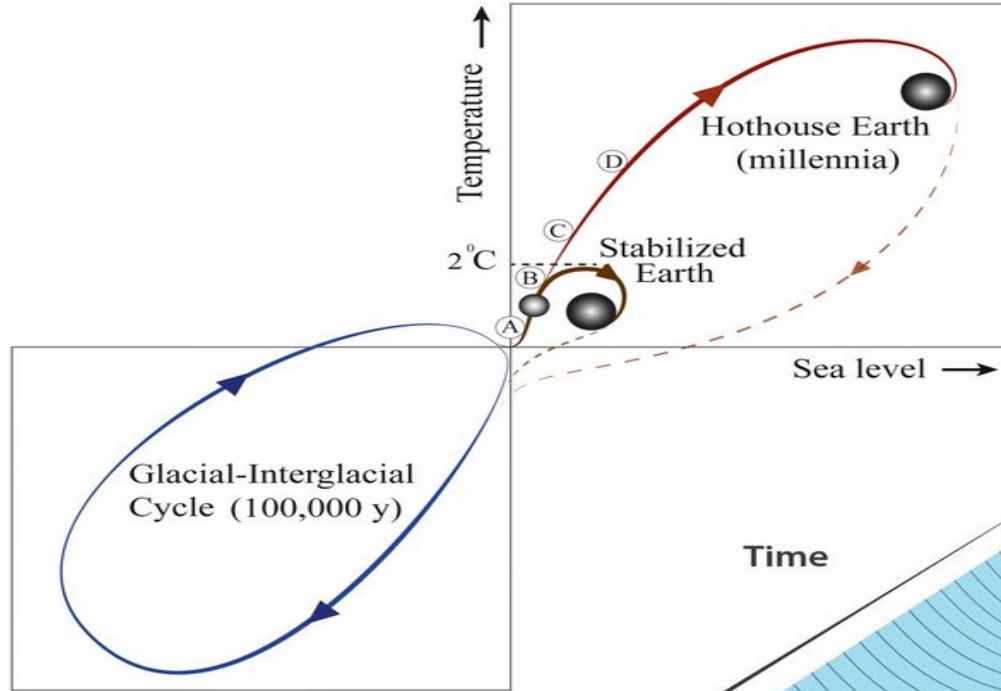
GLOBAL WARMING THRESHOLDS
● <2°C ◆ 2–4°C ▲ ≥4°C



Global warming threshold estimates for global core and regional impact climate tipping elements.

Tipping elements (A) relative to IPCC SSP projections and likely future scenarios given current policies and targets (B) and how many thresholds may be crossed per Shared Socioeconomic Pathways (SSP) projection (C).

Stability of the Earth
climate system
endangered
due to tipping points
cascade crossings?



Steffen et al., PNAS
August 14, 2018 115 (33)
8252-8259;
<https://doi.org/10.1073/pnas.1810141115>

Roger R. Revelle and Hans E. Suess,

“Carbon Dioxide Exchange Between Atmosphere and Ocean and the Question of an Increase of Atmospheric CO₂ during the Past Decades,”

Tellus IX (1957), pp. 19-20.

“Thus human beings are now carrying out a large scale geophysical experiment of a kind that could not have happened in the past nor be reproduced in the future. Within a few centuries we are returning to the atmosphere and oceans the concentrated organic carbon stored in sedimentary rocks over hundreds of millions of years....”

SIXTY THREE YEARS AFTER
WE FACE THE FOLLOWING QUESTION:

Can we gain control on this experiment?

200 years of climate physics

- almost 200 years since term “greenhouse effect” was introduced and Earth's energy balance was considered a main driver of climate,
- almost 150 years from first measurements of properties of greenhouse gases,
- more than 100 years from the first calculations of temperature effect of CO₂ doubling,
- over 55 years from formulation of first modern radiative transfer / circulation models,
- over 25 years from successive applications of global climate models...
- we talk and deliver the message but it is not enough to avoid catastrophe.