Life on our planet

Nick Barton

Caroline Muller

Outline of the climate discussion:

I) INTRO: HISTORY OF CLIMATE

Chronology from 4.5 billion years ago

II) KEY PROCESSES THAT SHAPE CLIMATE: OVERVIEW

II.1) Top-Of-Atmosphere (TOA) energy balance

II.2) Surface temperatures: Greenhouse effect

III) HOW THESE PROCESSES SHAPED PAST CLIMATES

III.1) Faint sun paradox (~4.5 By)

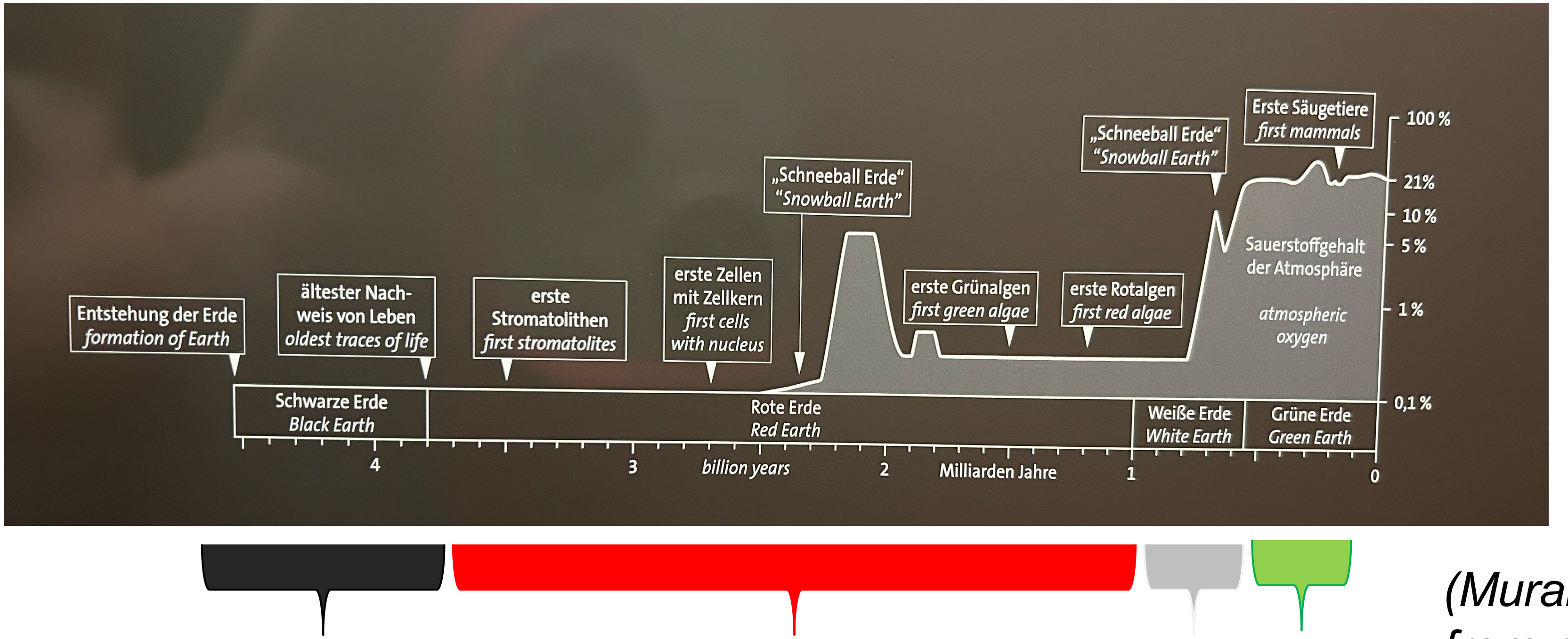
III.2) Snowball Earth (~2.5 By & .6 By)

III.3) Equable climate (~65 My)

III.4) Ice ages (~1 My)

IV) RECENT CLIMATE CHANGE

1) INTRO:
HISTORY OF CLIMATE



(Mural fresco from museum)

1) Black Earth

Earth formation -> oxygen release = 4.5By -> 3.5By

2) Red Earth

oxygen release -> cooling = 3.5By -> 1By

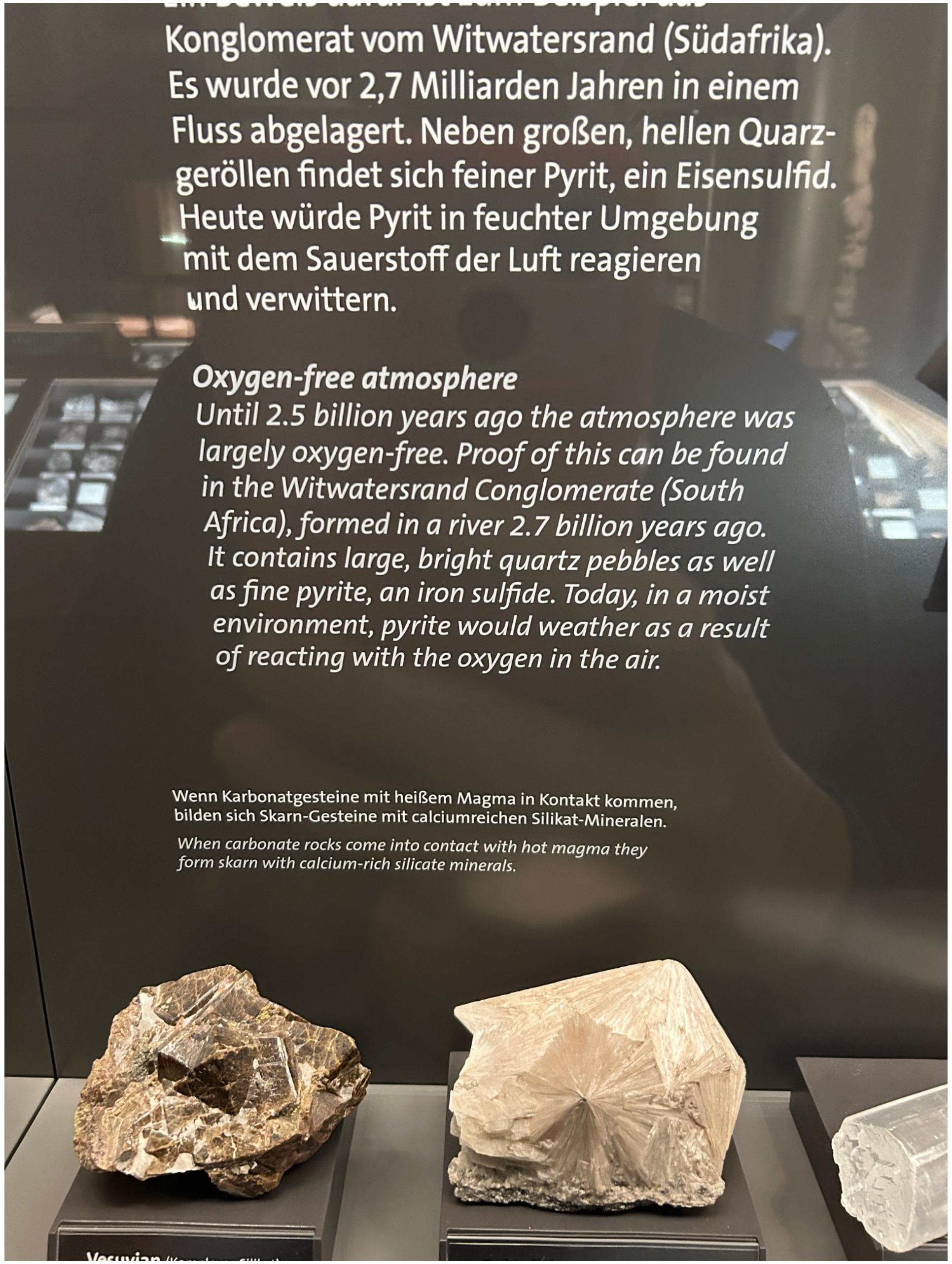
3) White Earth

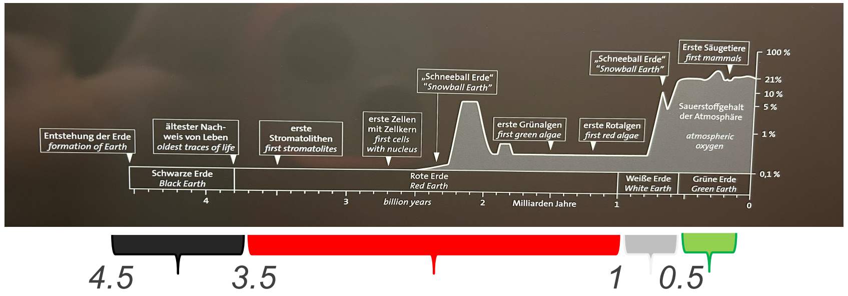
cooler/wetter climate -> peaked oxygen = 1By -> 500My

4) Green Earth

peaked oxygen -> present = 500My -> 0

1) Black Earth



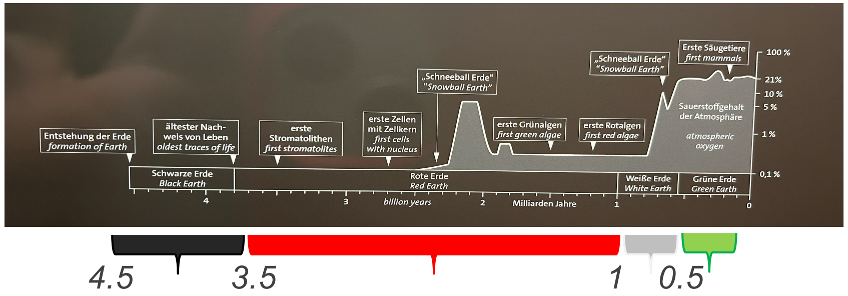


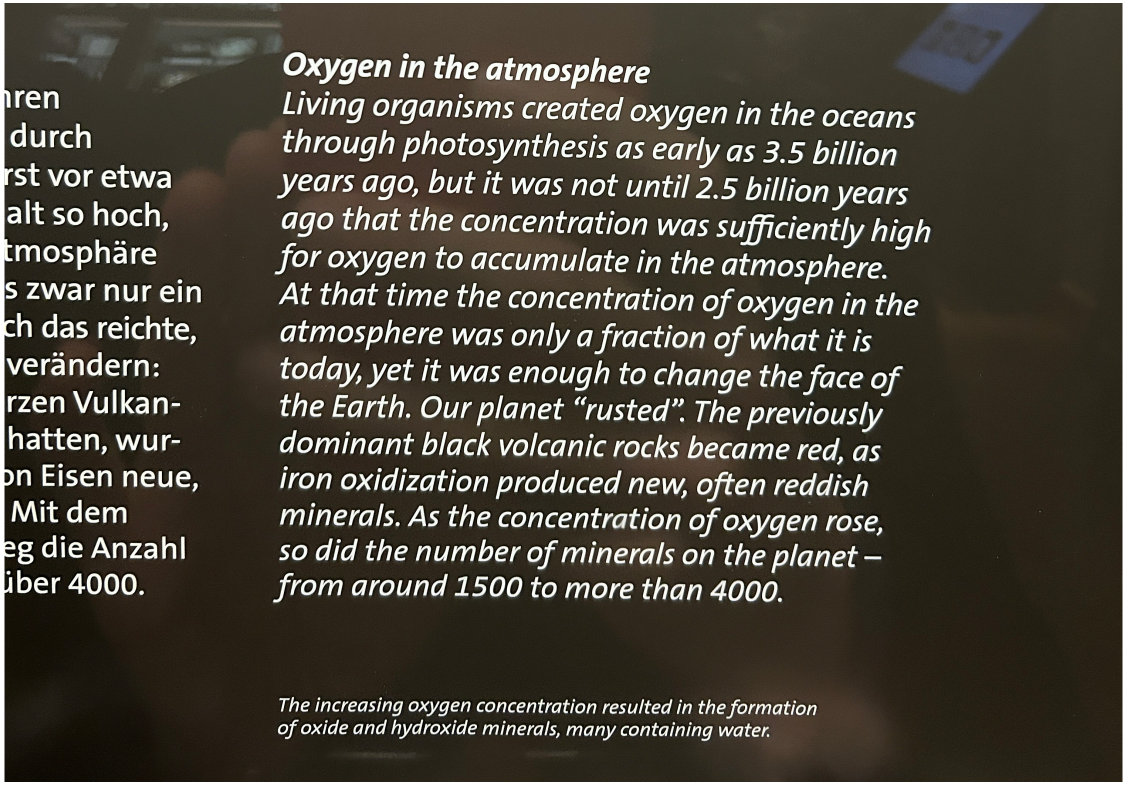
Until 3.5By, **oxygen free**

Even until 2.5 still largely oxygen free

Evidence: Can find quartz pebbles and other rocks that would weather in a moist/oxygen-rich environment

2) Red Earth





⇒ **Increase in Oxygen**
from ~3.5 By

⇒ Still lower than today's oxygen layer, but enough to "rust" rocks

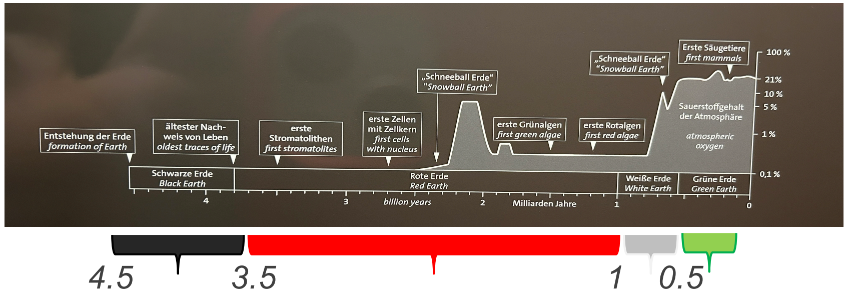
⇒ Iron **oxidization** -> red minerals

⇒ First **snowball earth**
~ 2.4 to 2 By?

Possible causes and triggers of snowball Earth:

- Great Oxidation Event: One theory: increase in atmospheric **oxygen** => **reduced greenhouse warming** => global cooling and glaciation
- **Reduced tectonic** activity: Another hypothesis: reduced volcanic and tectonic activity => massive **drop in greenhouse gases** => glaciation

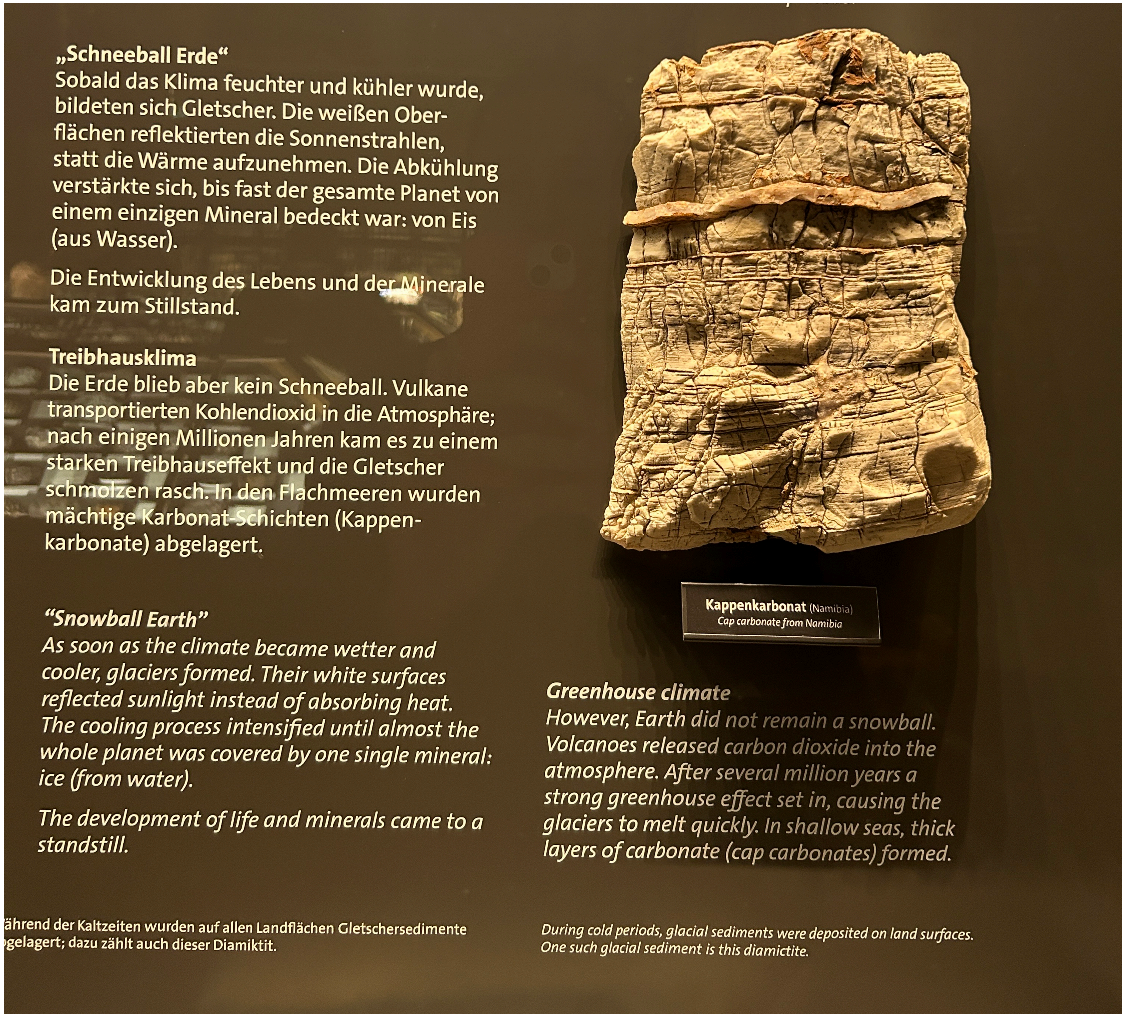
3) White Earth



⇒ Increase in Oxygen, decreased CO2, methane

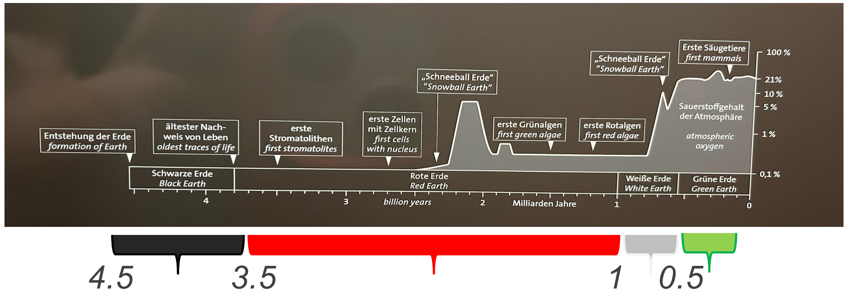
⇒ **colder climate**

⇒ Ice caps / Snowball earth



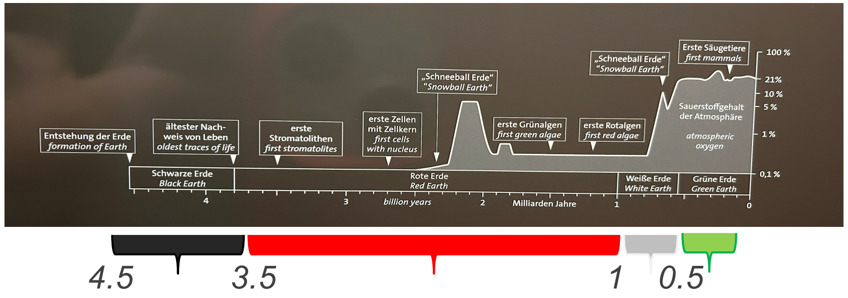
Artist's view of snowball earth

4) Green Earth



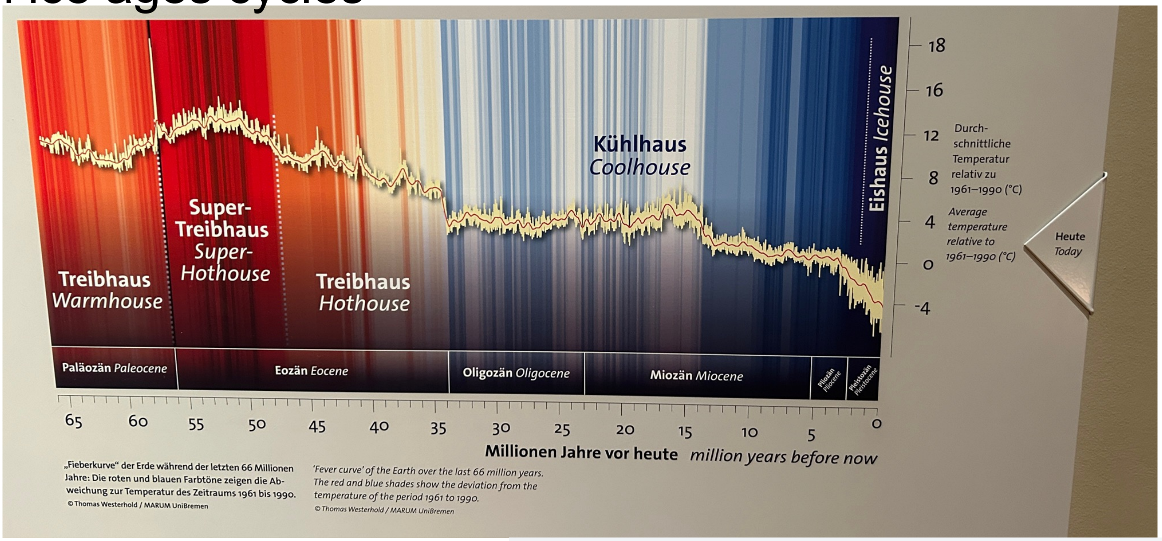
End of snowball earth, **life thrives**

4) Green Earth

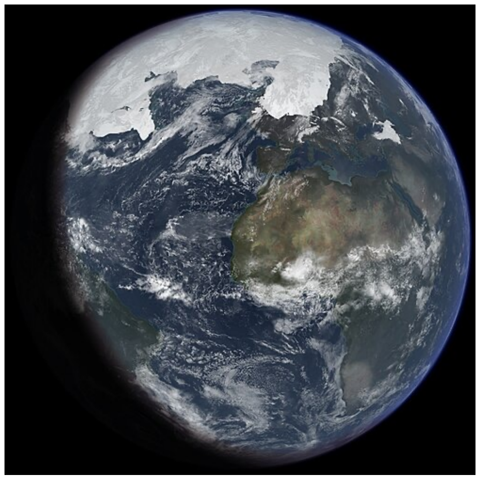


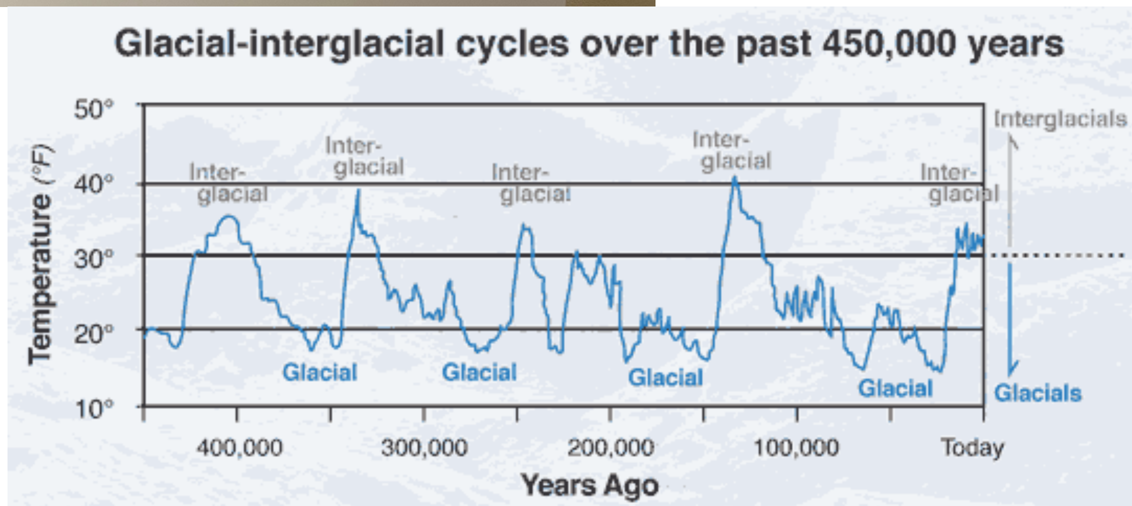
Very recent climate :

Warm Paleocene/Eocene (65-35 My)
Earth cooled down, ice sheets formed (35My – 3My),
then ice ages cycles

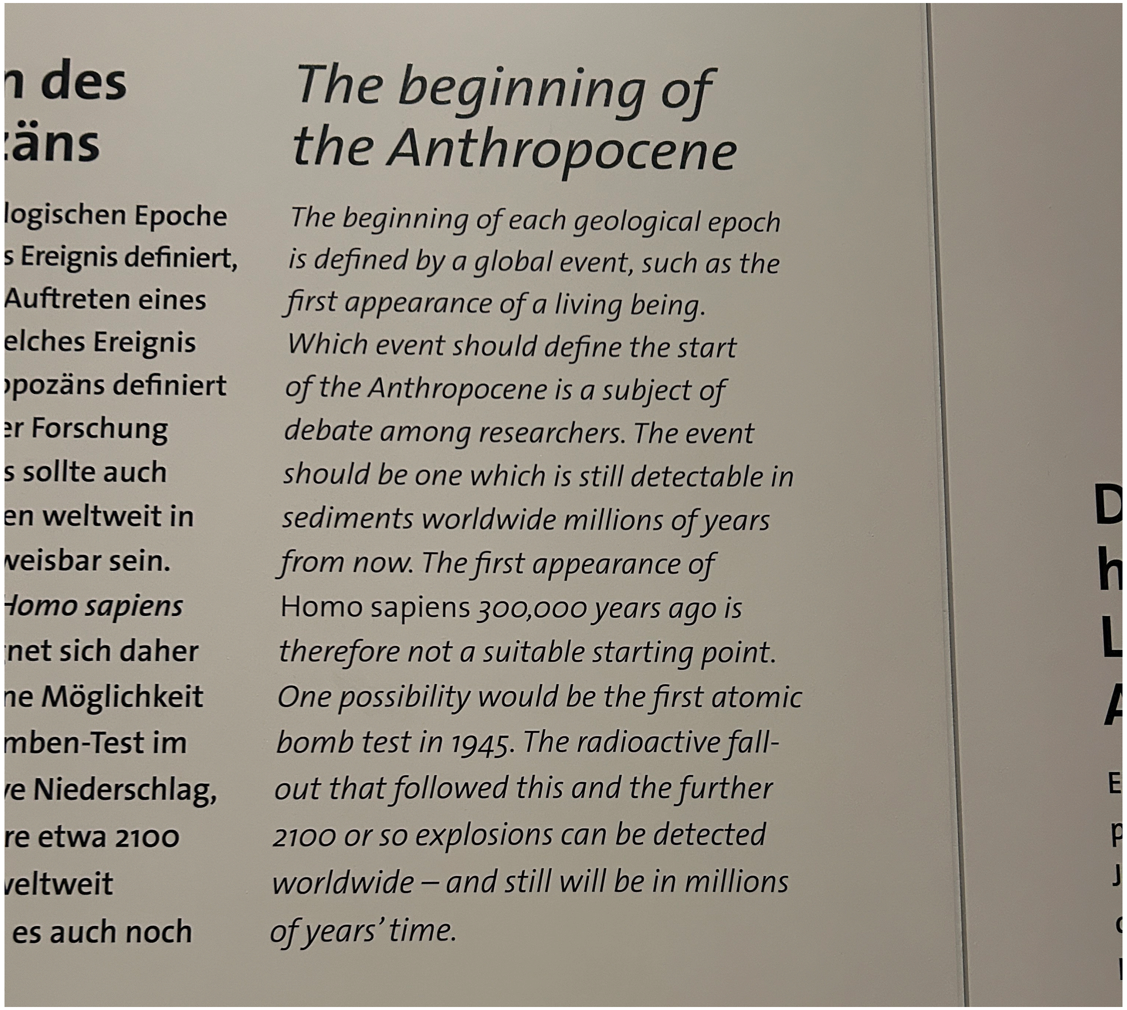


Ice age:
Cooling Tsfc
Expansion of continental and polar ice caps





Modern climate: **Anthropocene**?



Proposed geological epoch characterized by significant human impact on Earth's geology, ecosystems, and atmosphere

Outline of the climate discussion:

I) INTRO: HISTORY OF CLIMATE

Chronology from 4.5 billion years ago

II) KEY PROCESSES THAT SHAPE CLIMATE: OVERVIEW

II.1) Top-Of-Atmosphere (TOA) energy balance

II.2) Surface temperatures: Greenhouse effect

III) HOW THESE PROCESSES SHAPED PAST CLIMATES

III.1) Faint sun paradox (~4.5 By)

III.2) Snowball Earth (~2.5 By & .6 By)

III.3) Equable climate (~65 My)

III.4) Ice ages (~1 My)

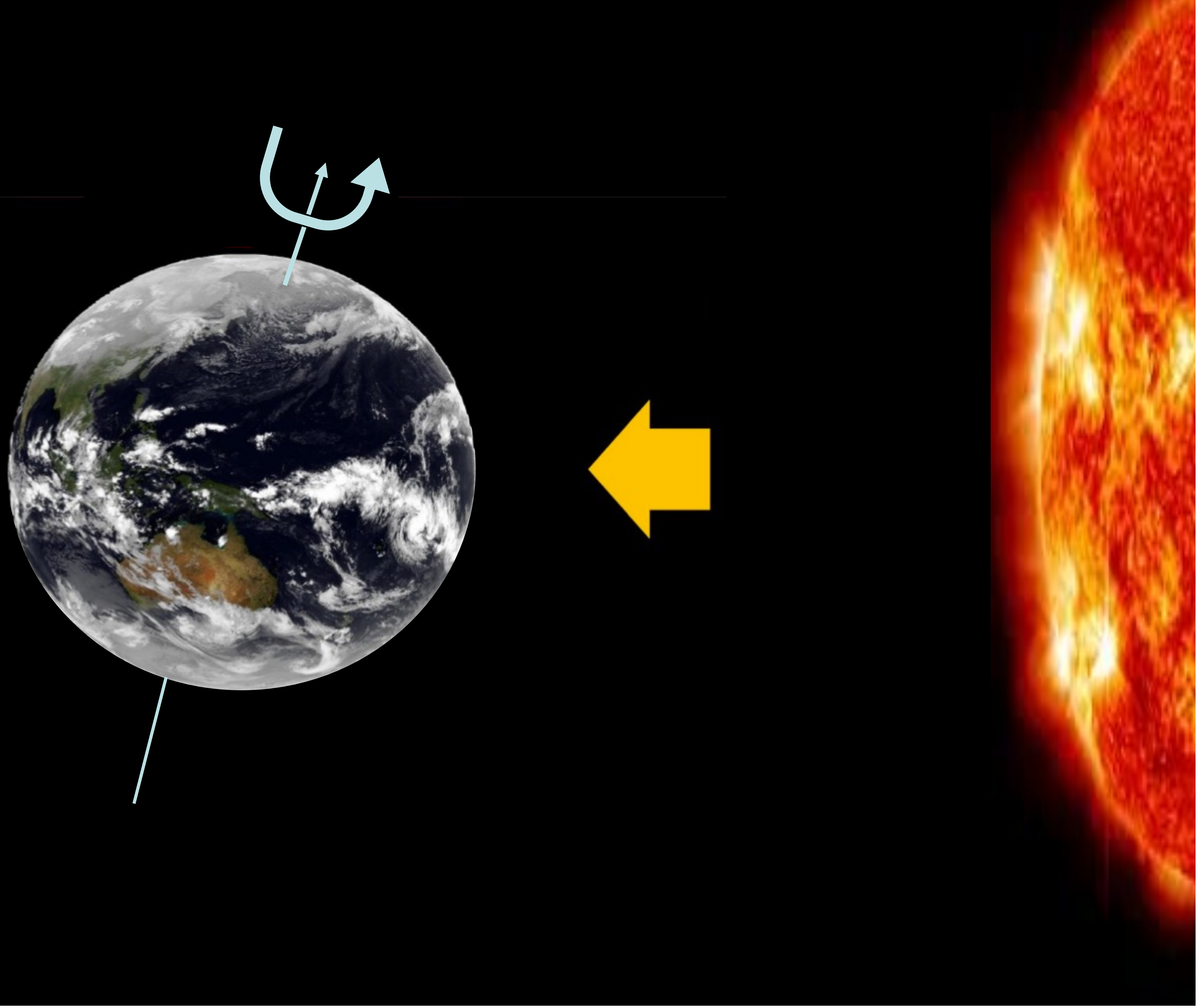
IV) RECENT CLIMATE CHANGE

II.1) TOA ENERGY BALANCE

-Global mean

-Latitudinal distribution

Important driver for atmospheric dynamics:
Solar forcing



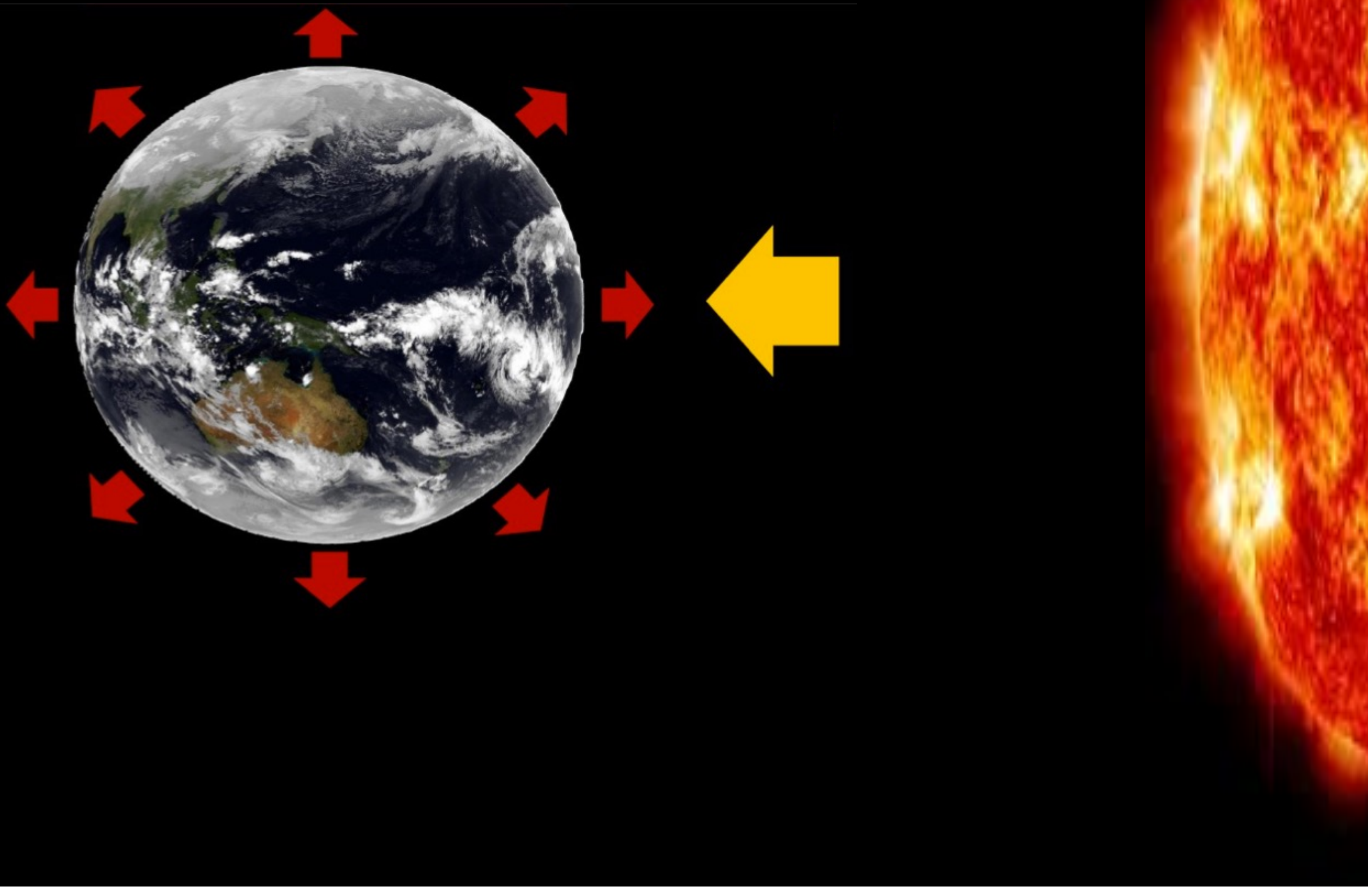
Solar forcing

Energy balance at the top of the atmosphere:

- Earth receives solar visible radiation from the sun
- Earth emits infrared radiation to space

Outgoing infrared radiation
Depends on temperature

Incoming visible radiation



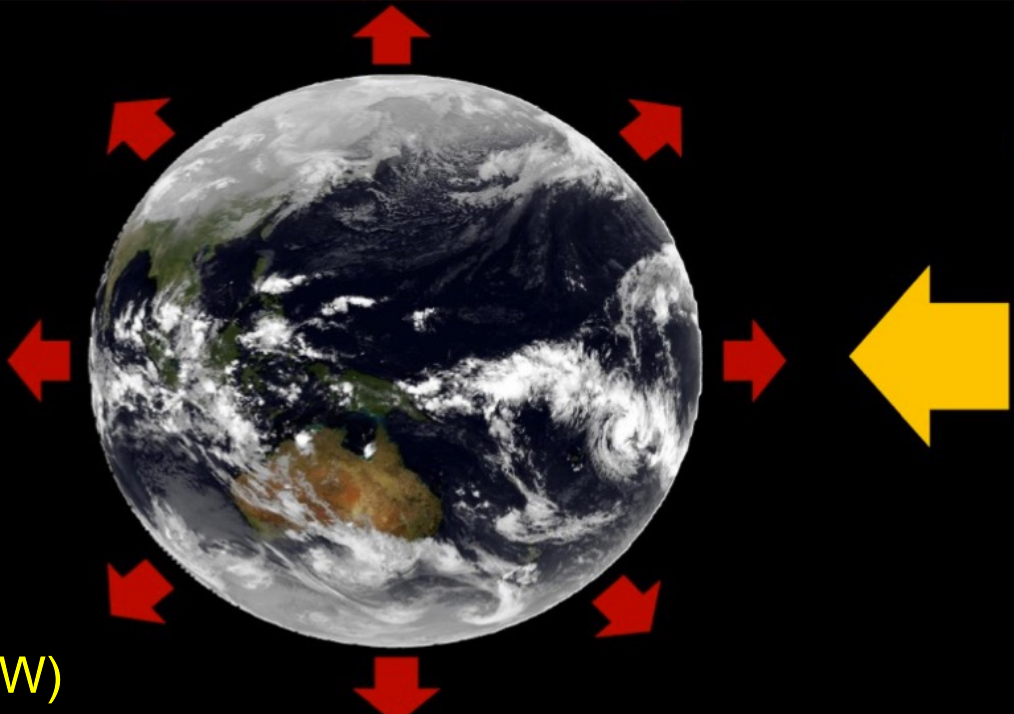
Solar forcing

Energy balance at the top of the atmosphere:

- Earth receives solar visible radiation from the sun
- Earth emits infrared radiation to space

Outgoing infrared radiation
Depends on temperature

Incoming visible radiation



Shortwave (SW)

Longwave (LW)

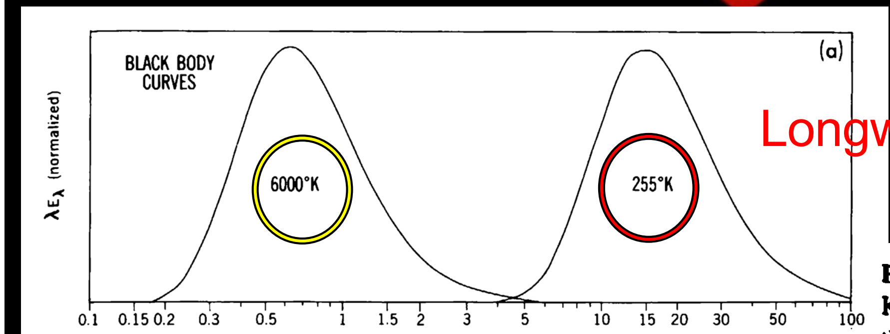


FIGURE 6.2. Black body curves for the solar radiation (assumed to have a temperature of 6000 K) and the terrestrial radiation (assumed to have a temperature of 255 K) (a); absorption spectra for

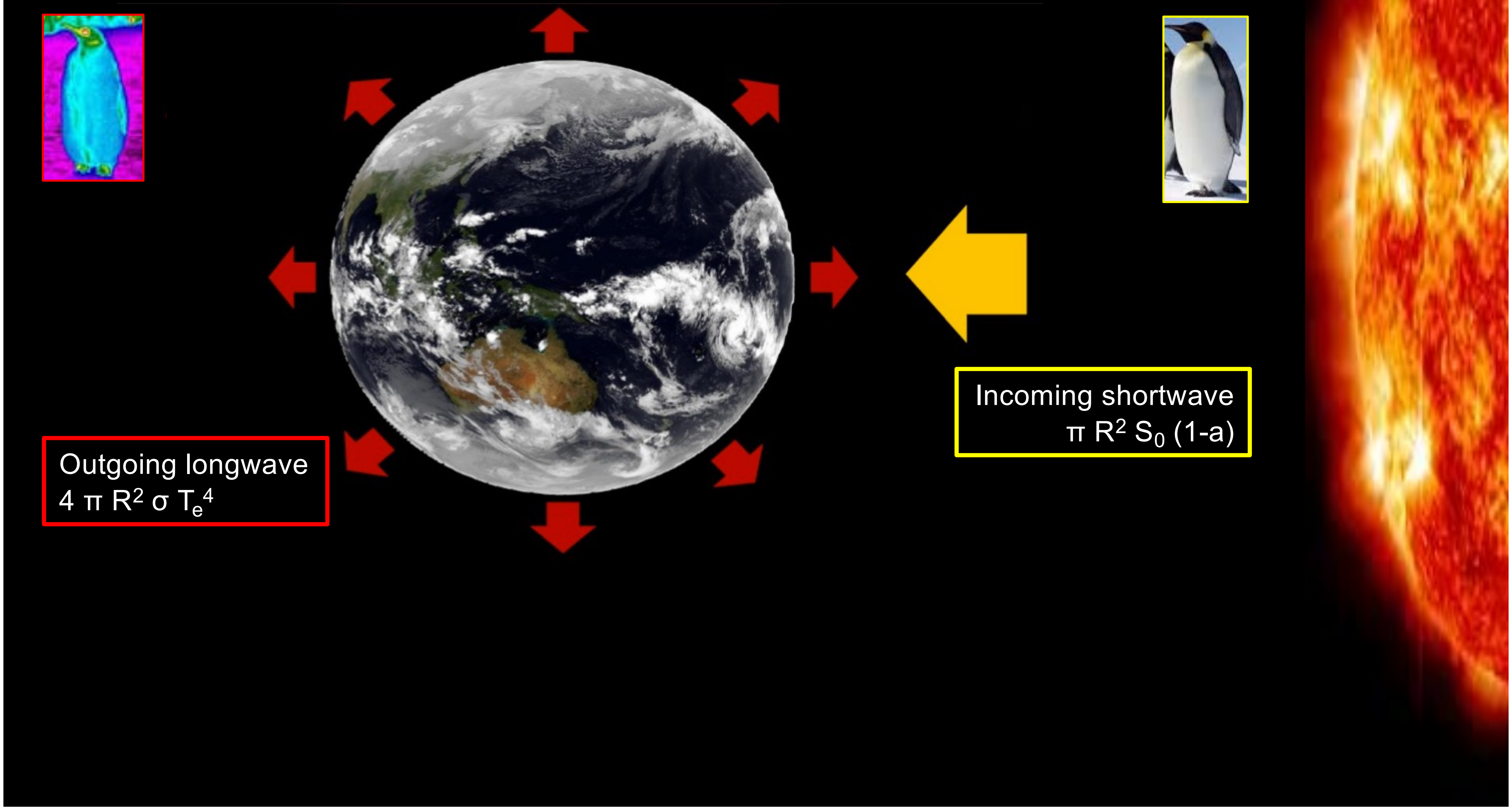
Solar forcing

Energy balance at the top of the atmosphere:

- Earth receives solar visible radiation from the sun
- Earth emits infrared radiation to space

Outgoing infrared radiation
Depends on temperature

Incoming visible radiation



TOA ENERGY BALANCE:

Outgoing longwave
$4 \pi R^2 \sigma T_e^4$

Incoming shortwave
$\pi R^2 S_0 (1-a)$

SW in from sun – LW out from planet = Energy balance TOA

If Earth temperatures are ~ stable => SW in = LW out
=> Determines Earth emission temperature

Remark:
This is a 1D view (one value received, one value emitted)

But
- incoming solar radiation S_0,
- emission temperature Te,
- albedo a

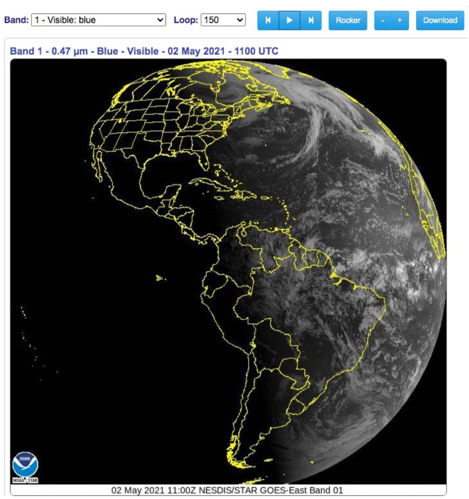
are *not* uniformly distributed on Earth

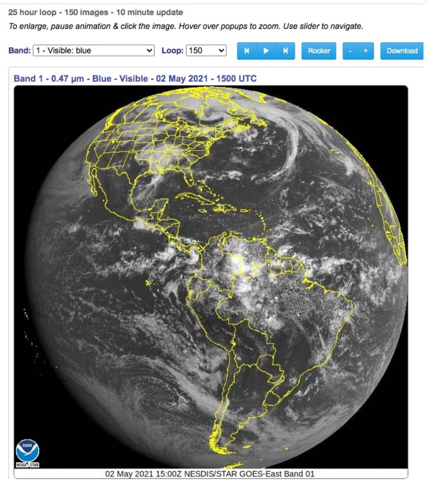
Latitudinal distribution in our current climate ?

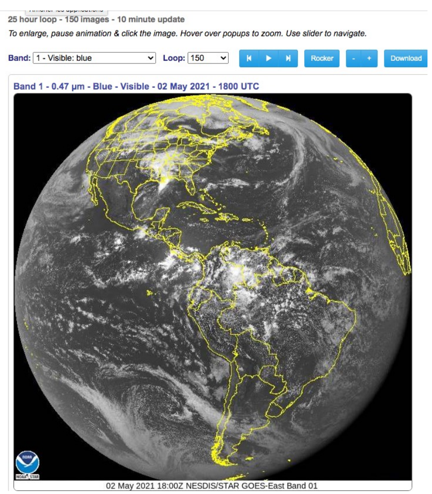
Latitudinal distribution of TOA energy budget & ocean/atmosphere energy transport

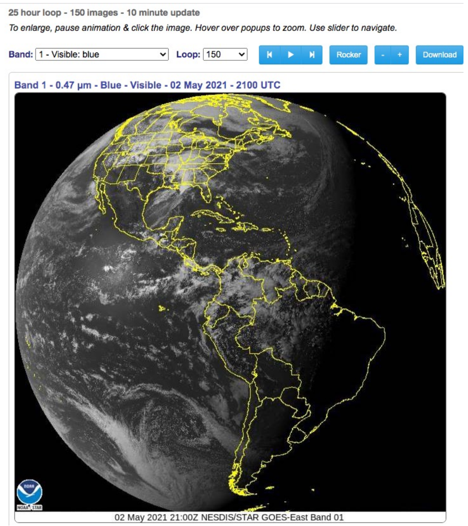
GOES satellite imagery May 2nd @ 11,15,18,21 UTC

Shortwave, or visible

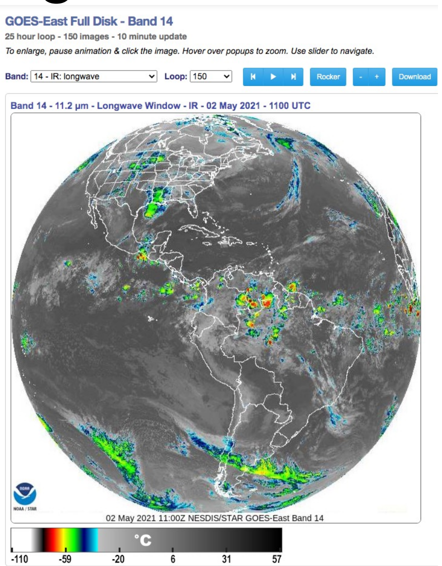


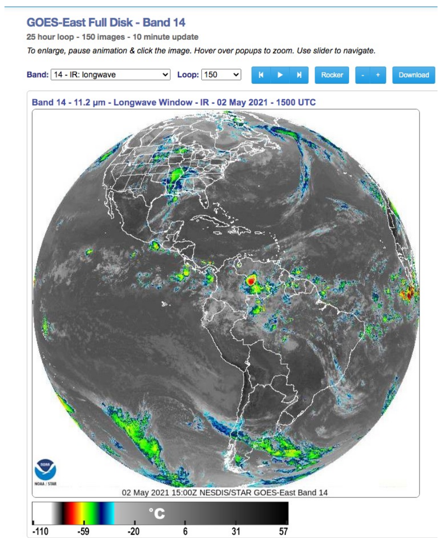


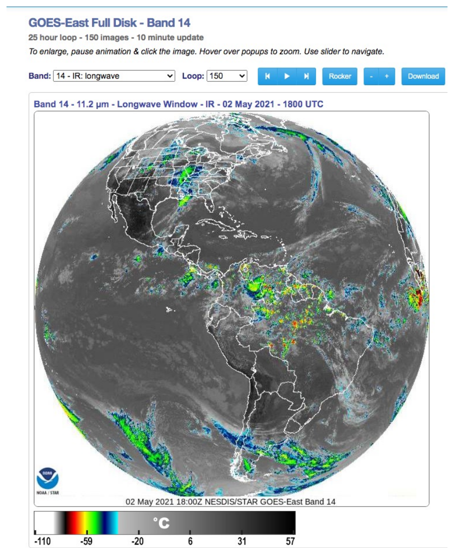


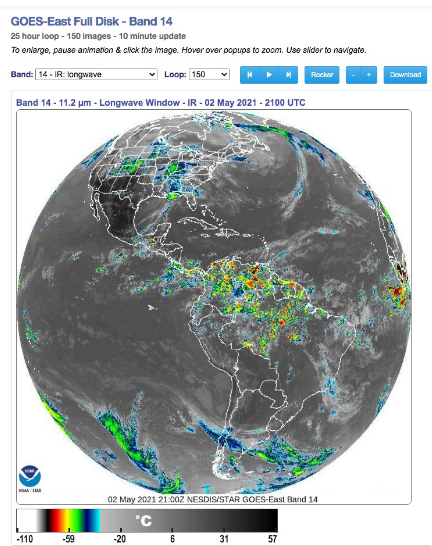


Longwave, or infrared (emission temperature)



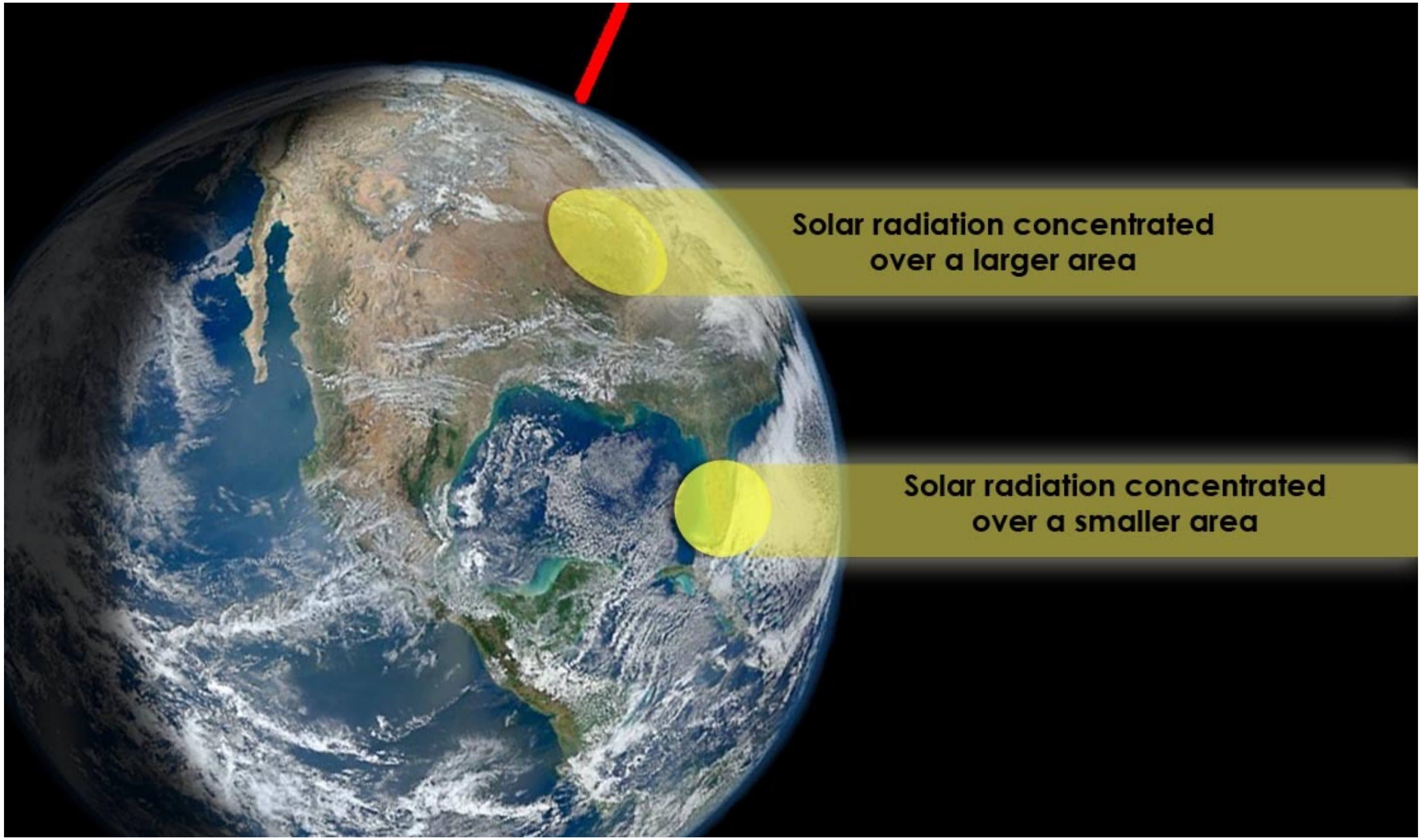






Solar forcing: latitudinal distribution

More received near the equator
Less at high latitude



Solar forcing: latitudinal/seasonal distribution

⇒ *On average, more received at the equator*

⇒ Sharp gradient in winter hemisphere

⇒ Weak gradient toward the summer pole

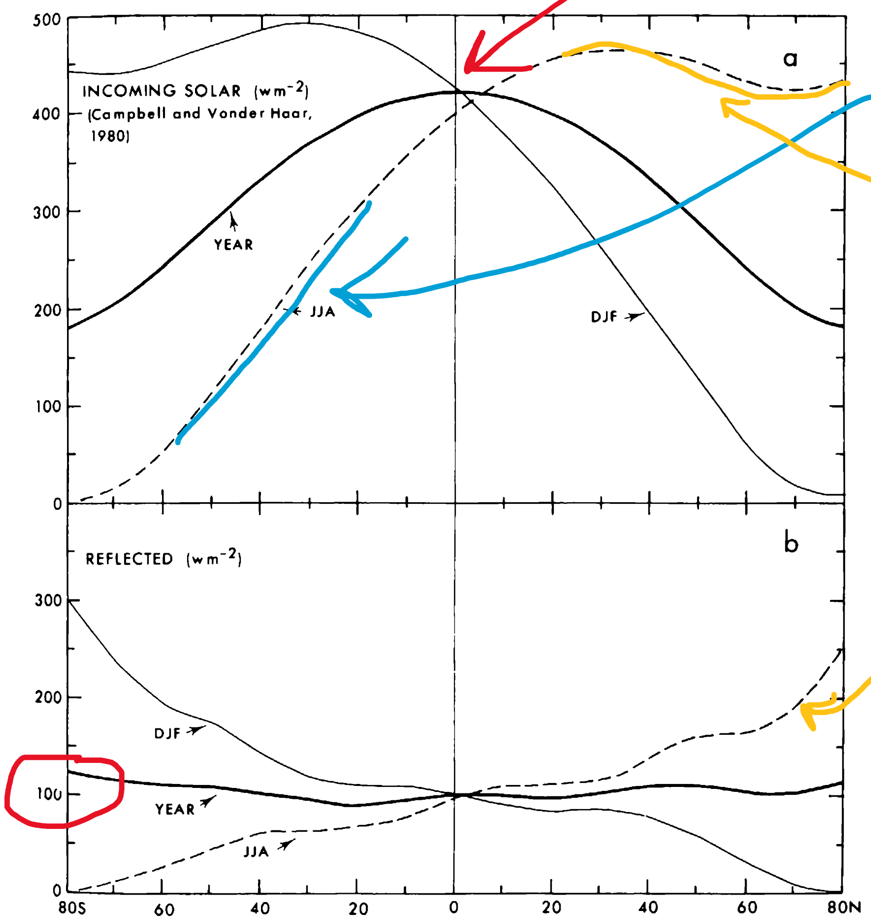


FIGURE 6.13. Meridional profiles of the zonal-mean incoming (a) and reflected solar radiation (b) at the top of the atmosphere in W m^{-2} for annual, DJF, and JJA mean conditions (based on data from Campbell and Vonder Haar, 1980). No corrections were made to insure global radiation balance.

⇒ Large fraction reflected

⇒ Especially at high latitudes where albedo is large (due to large angle of incidence of incoming radiation and ice/snow)

⇒ *Remark: In summer, more received at the pole than at the equator!*

Energy transport by the atmosphere and the ocean

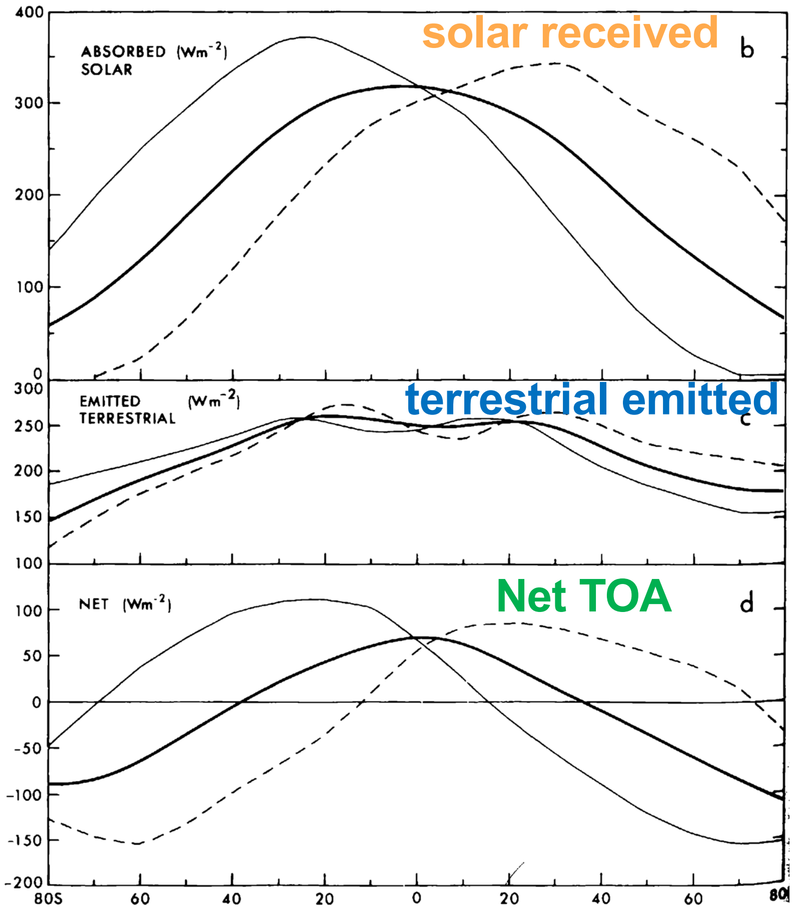


FIGURE 6.14. Meridional profiles of the zonal-mean albedo (a), absorbed solar radiation (b), emitted terrestrial radiation (c), and net radiation (d) at the top of the atmosphere for annual, DJF, and JJA mean conditions (based on data from Campbell and Vonder Haar, 1980). No correction were made for global radiation balance.

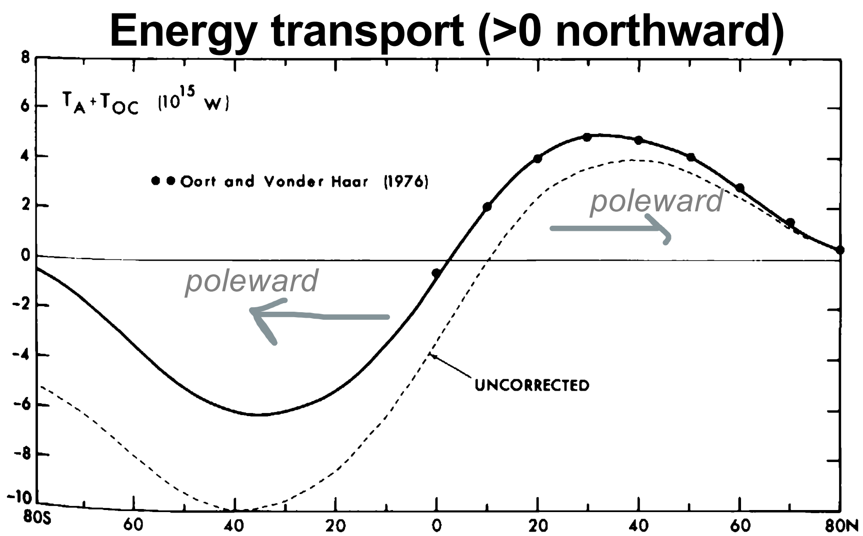


FIGURE 6.15. Meridional profiles of the annual transport of energy by the atmosphere and oceans in 10^{15} W calculated from radiation requirements. The dashed curve is obtained from uncorrected data starting the integration at the North Pole, and the solid curve from the same data after correction for global balance (see Table 6.2) (after Oort and Peixoto, 1983).

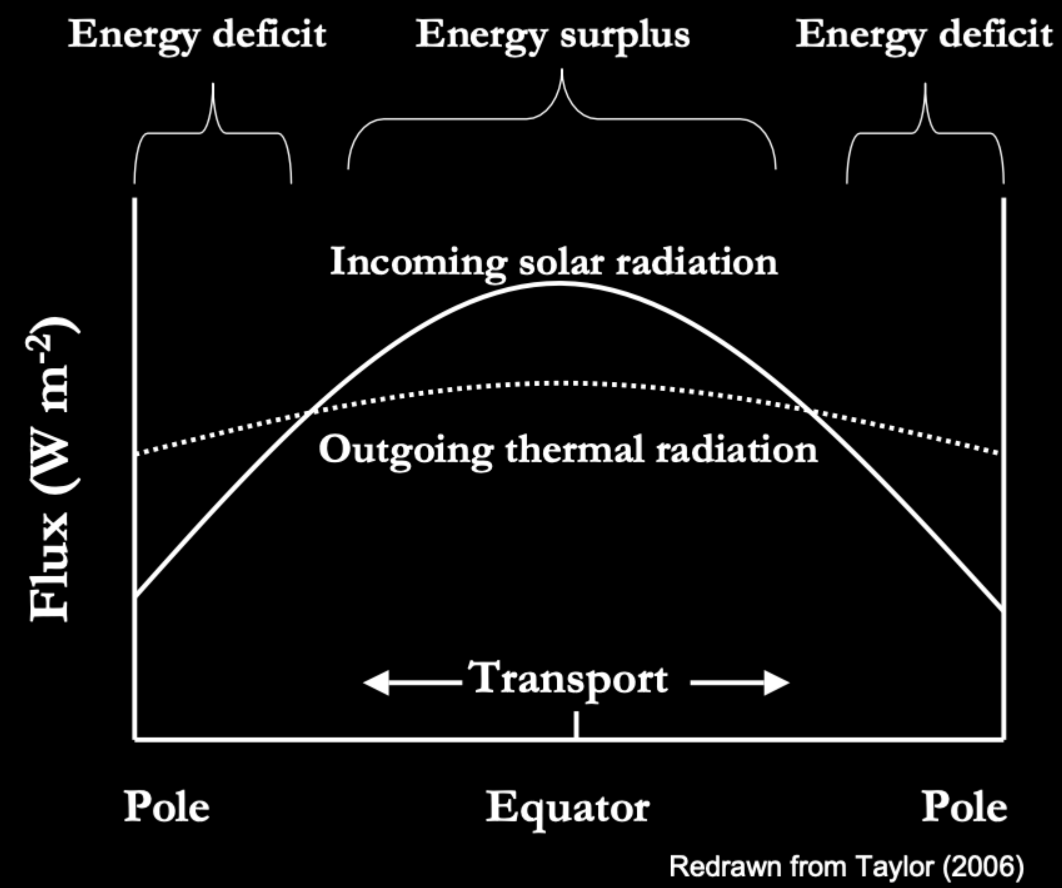
⇒ Net TOA = solar received – terrestrial emitted

⇒ Requires **energy transport**

⇒ Total **poleward energy transport** by **atmosphere+ocean** system needed to maintain the observed temperature structure

⇒ Almost N/S symmetry
(slight cross equatorial N->S transport)

⇒ Schematically :



Taylor, FW (2006) Elementary Climate Physics. Oxford University Press

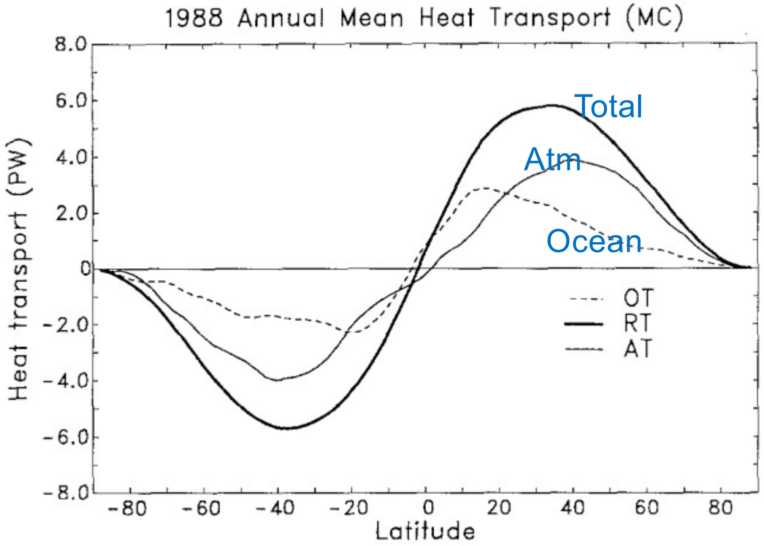
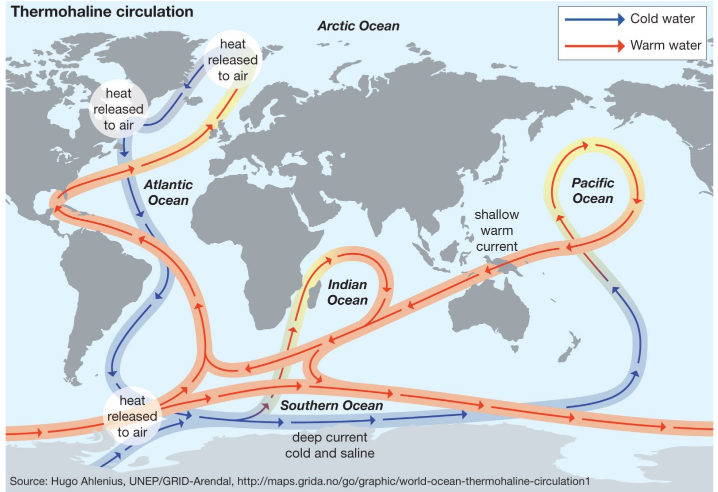


Fig. 16. The top-of-the-atmosphere required northward heat transport from satellite radiation measurements *RT*, the estimated atmospheric transports *AT*, and the ocean transports *OT* computed as a residual, for 1988 in PW

Ocean overturning circulation



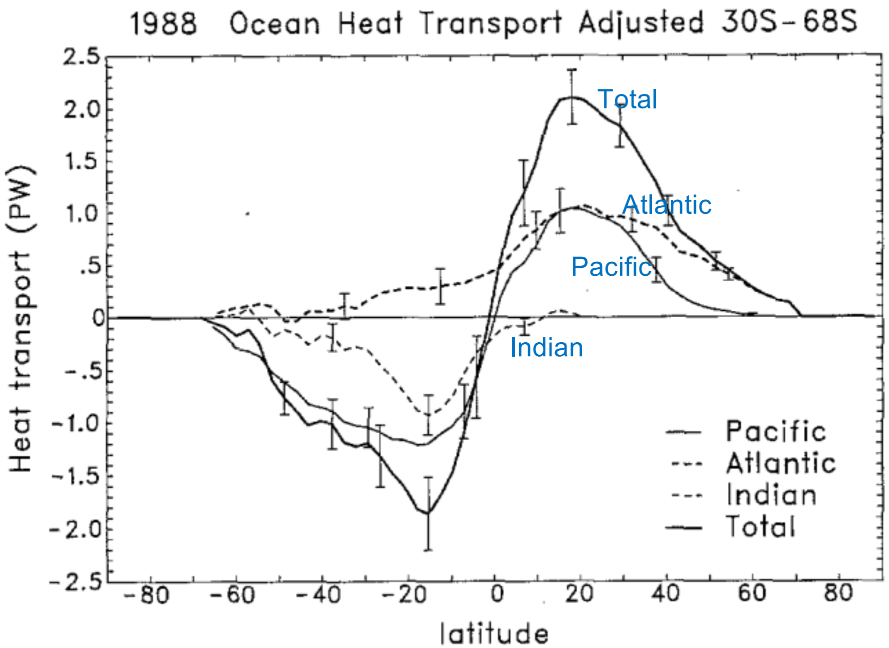
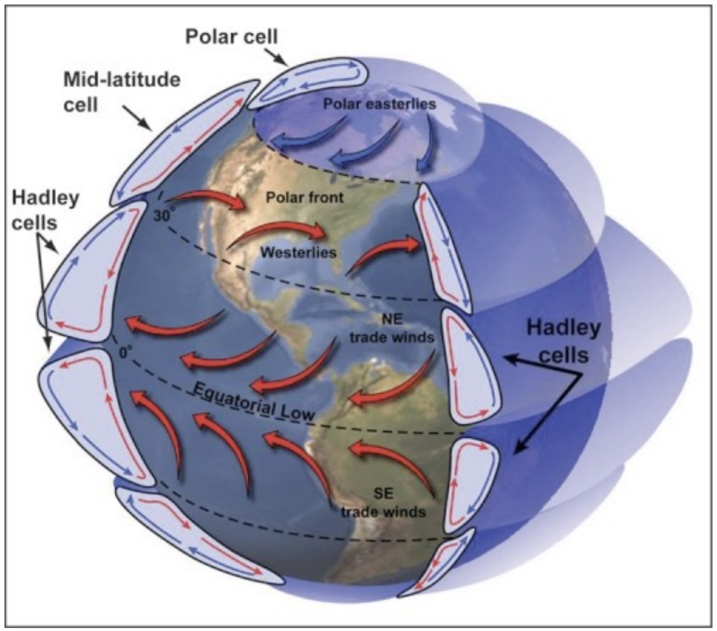


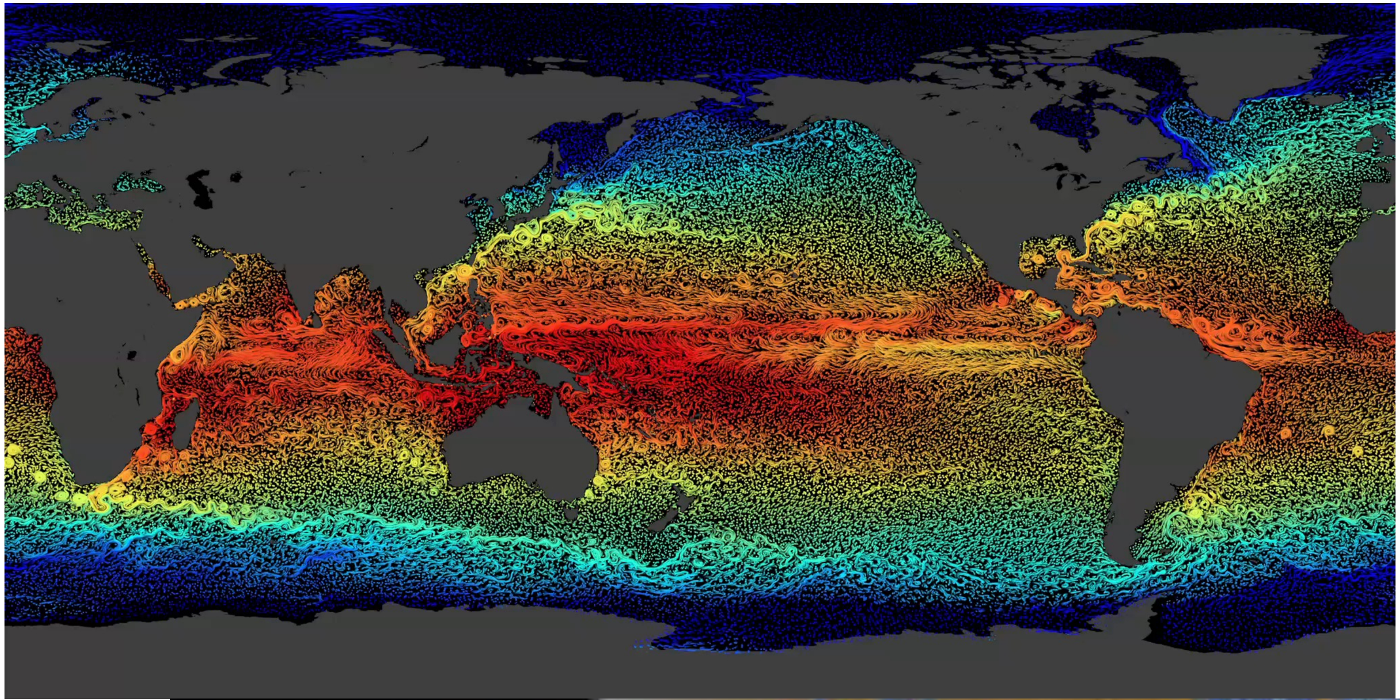
Fig. 17. The poleward ocean heat transports in each ocean basin and summed over all oceans (*total*), as computed from the net flux through the ocean surface, integrated from 65°N and adjusted south of 30°S, for 1988 in PW. As this calculation does not account for the Indonesian throughflow, the Pacific and Indian ocean contributions should be combined

Atmospheric cells

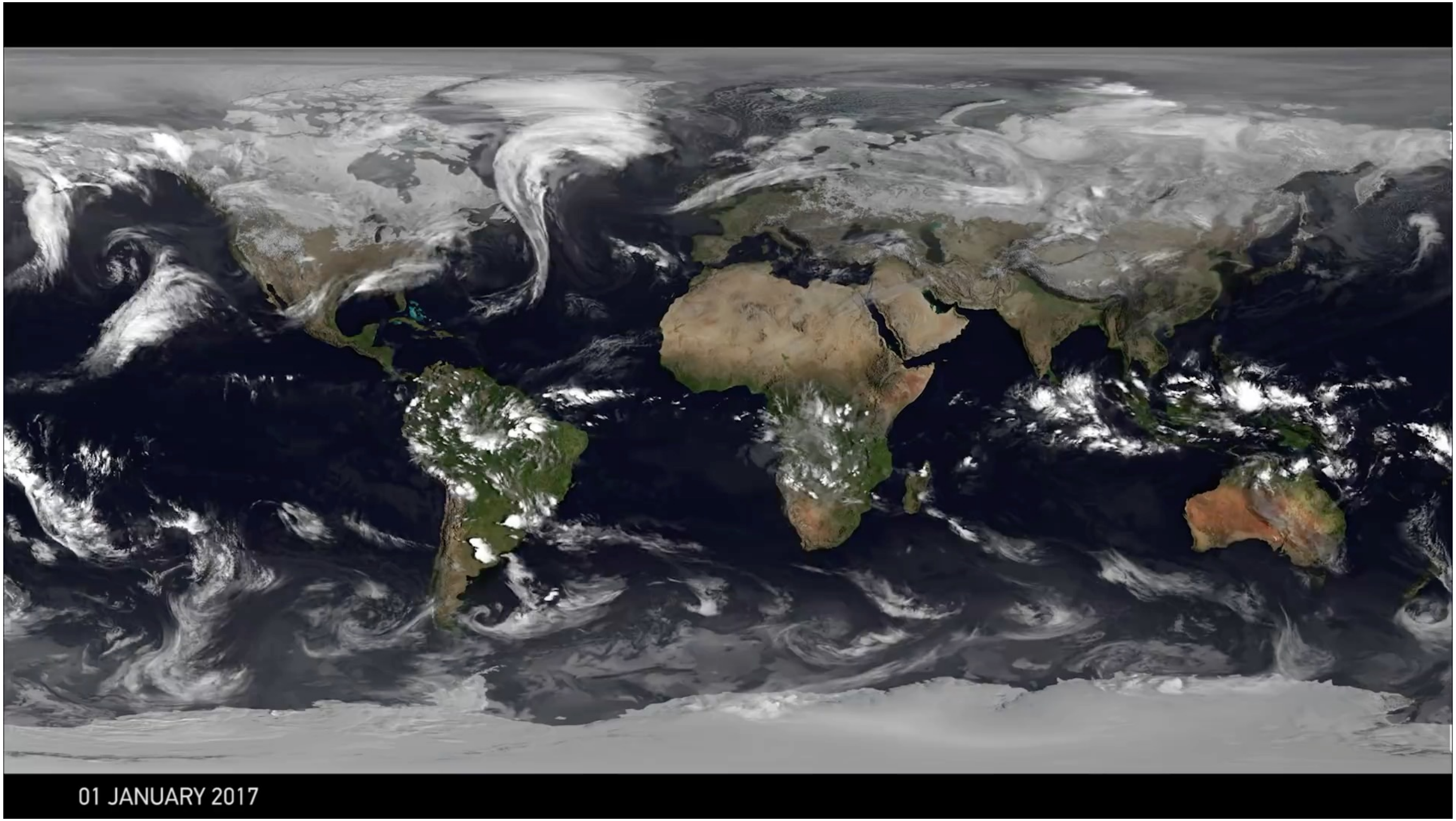


Trenberth Solomon 94

Ocean circulation redistributes energy



Atmospheric circulation redistributes energy



Impact of land

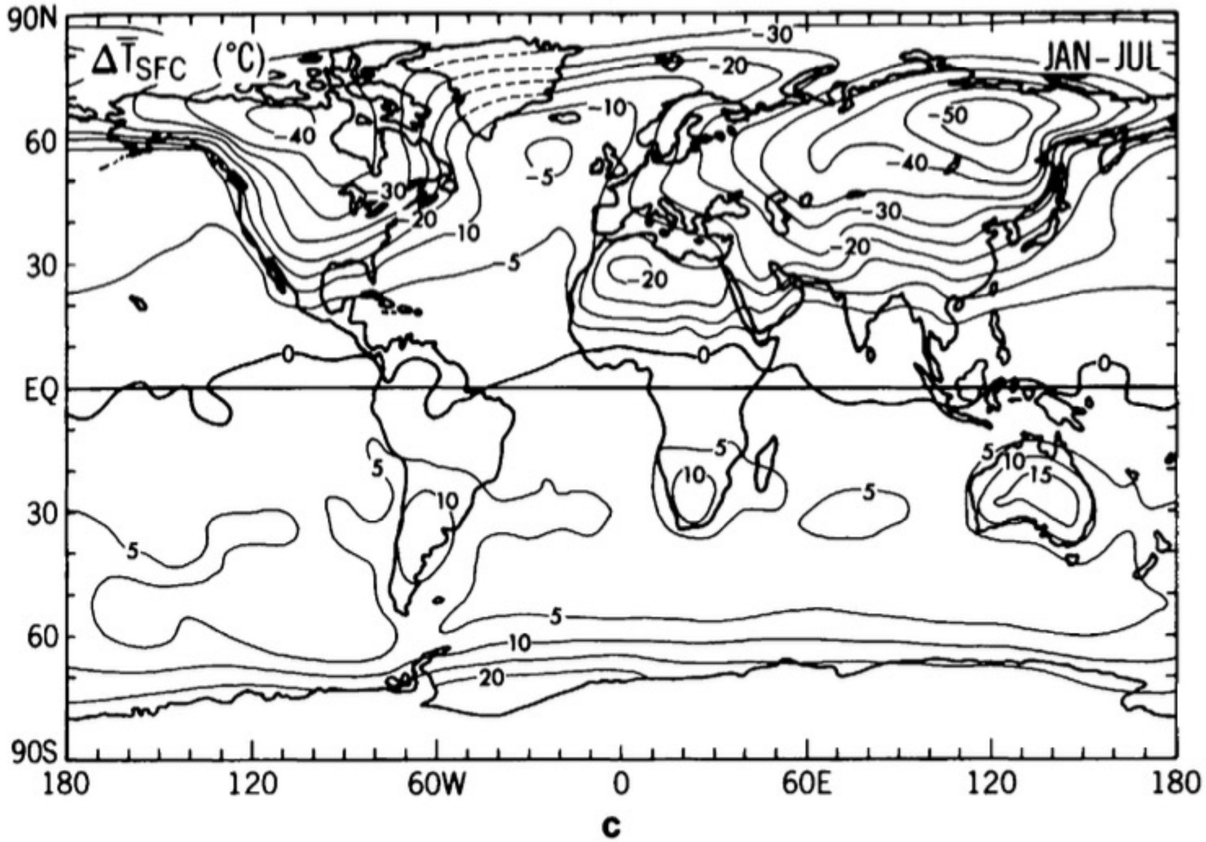


FIGURE 7.4. Horizontal distributions of the surface air temperature (in °C) for January (a) and July (b) after National Climatic Data Center (1987), and for the January–July difference (c) based on the 1963–73 analyses in Oort (1983).

Conclusions II.1) TOA energy balance

⇒ TOA energy balance between **SW received** from the sun and **LW emitted** to space

⇒ To leading order, this determines the mean **emission temperature** of our planet T_e

⇒ The SW received and LW emitted also **depend on latitude**, and are closely **linked to ocean/atmosphere energy transport**

⇒ In our current climate, more SW received in the tropics, less at higher latitudes => poleward energy transport by geophysical fluids (ocean+atmosphere)

Outline of the climate discussion:

I) INTRO: HISTORY OF CLIMATE

Chronology from 4.5 billion years ago

II) KEY PROCESSES THAT SHAPE CLIMATE: OVERVIEW

II.1) Top-Of-Atmosphere (TOA) energy balance

II.2) Surface temperatures: Greenhouse effect

III) HOW THESE PROCESSES SHAPED PAST CLIMATES

III.1) Faint sun paradox (~4.5 By)

III.2) Snowball Earth (~2.5 By & .6 By)

III.3) Equable climate (~65 My)

III.4) Ice ages (~1 My)

IV) RECENT CLIMATE CHANGE

T near surface and tropopause (~10-15 km altitude)

Tropopause

Near surface

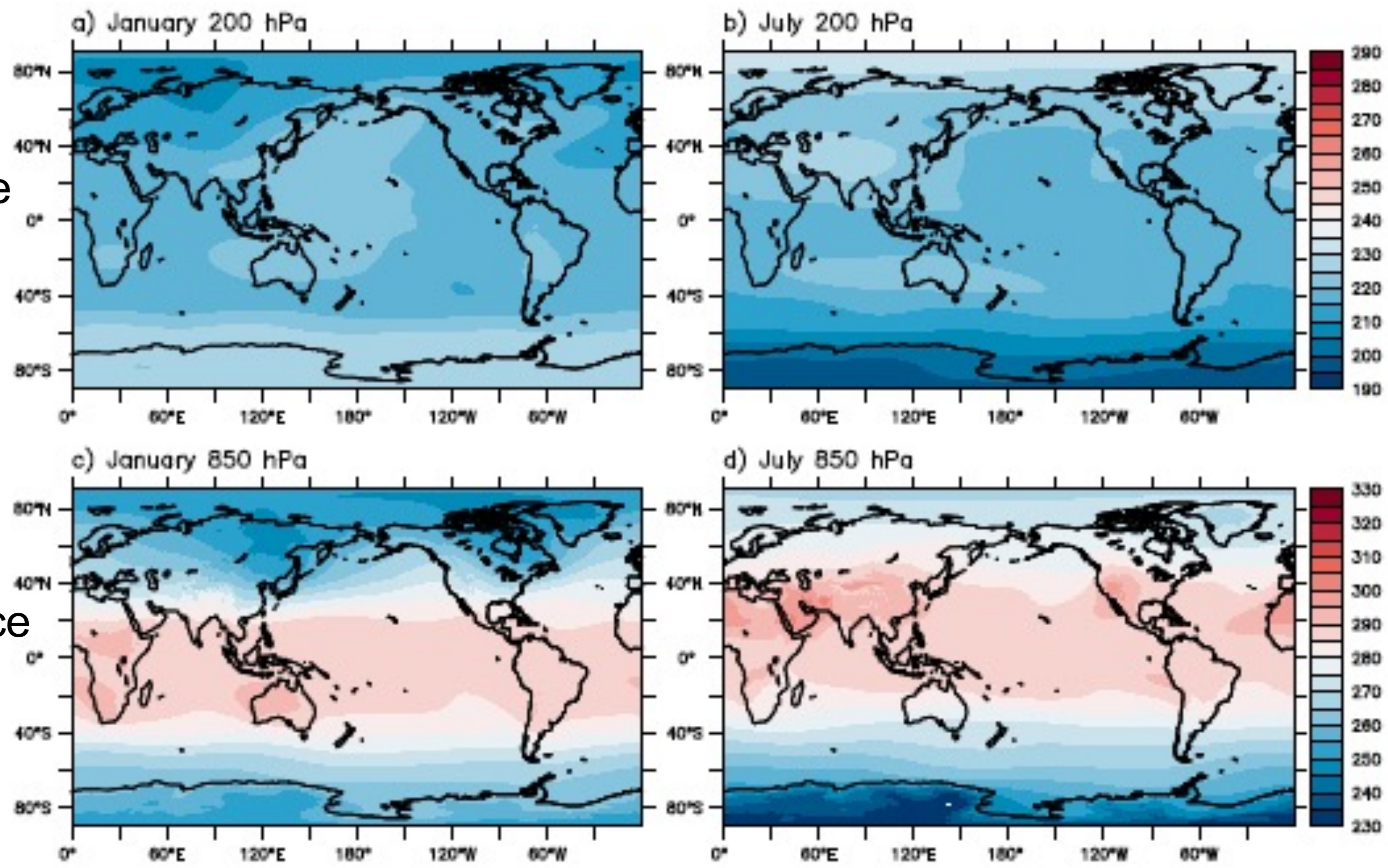


Figure 2.1. *Climatology of temperature (unit : K) at (upper panels) 200 hPa and (lower panels) 850 hPa in a),c) January and b),d) July. Source : ERA5 reanalysis from 1979 to 2020.*

Greenhouse effect

common experience: the sky

Figure 1.1. *A nightsky reminds us that the atmosphere is mostly transparent to visible light, while a sunset (in the Harbour of La Rochelle, France) serves to highlight that the interaction of the atmosphere with solar radiation will be an issue to consider. (Photo credit : R. Plougonven)*

Solar forcing: atmospheric absorption

Top of the atmosphere received: ~1360W/m2

100W light bulb

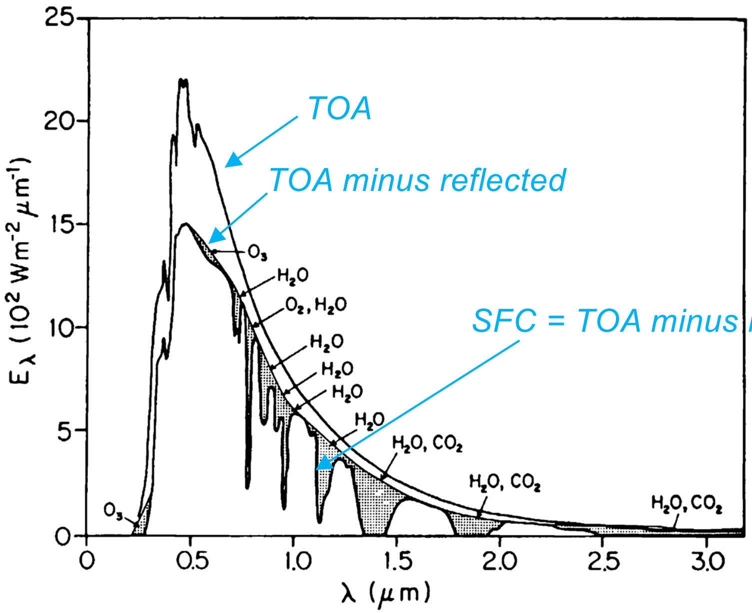


FIGURE 6.1. Spectral distribution of solar irradiation at the top of the atmosphere and at sea level for average atmospheric conditions for the sun at zenith. The shaded areas represent absorption by various atmospheric gases. The unshaded area between the two curves represents the portion of the solar energy backscattered by the air, water vapor, dust, and aerosols and reflected by clouds. For the curve at the top of the atmosphere the integral $\int_0^\infty E_\lambda \, d\lambda \simeq 1360$ W m^{-2} represents the solar constant (adapted from Gast, 1965).

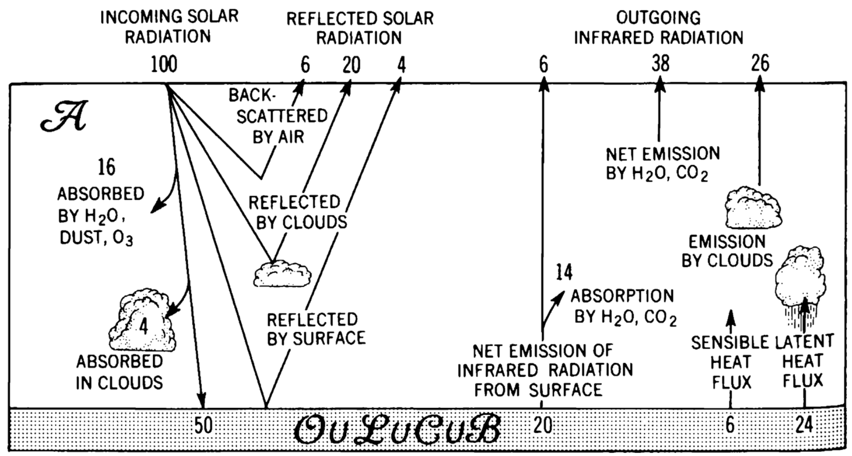
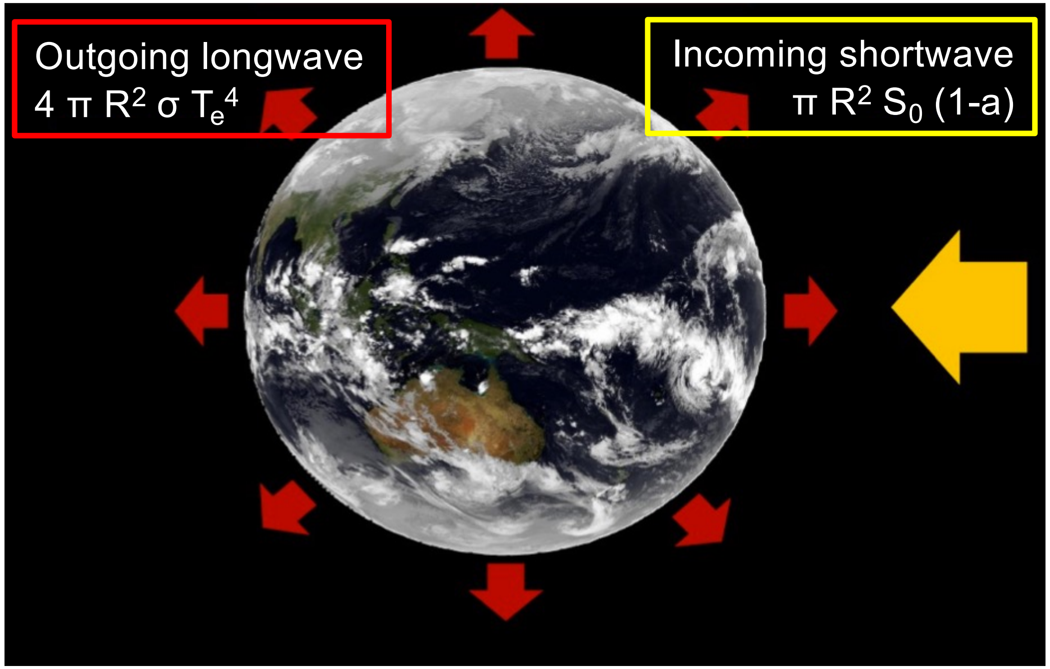
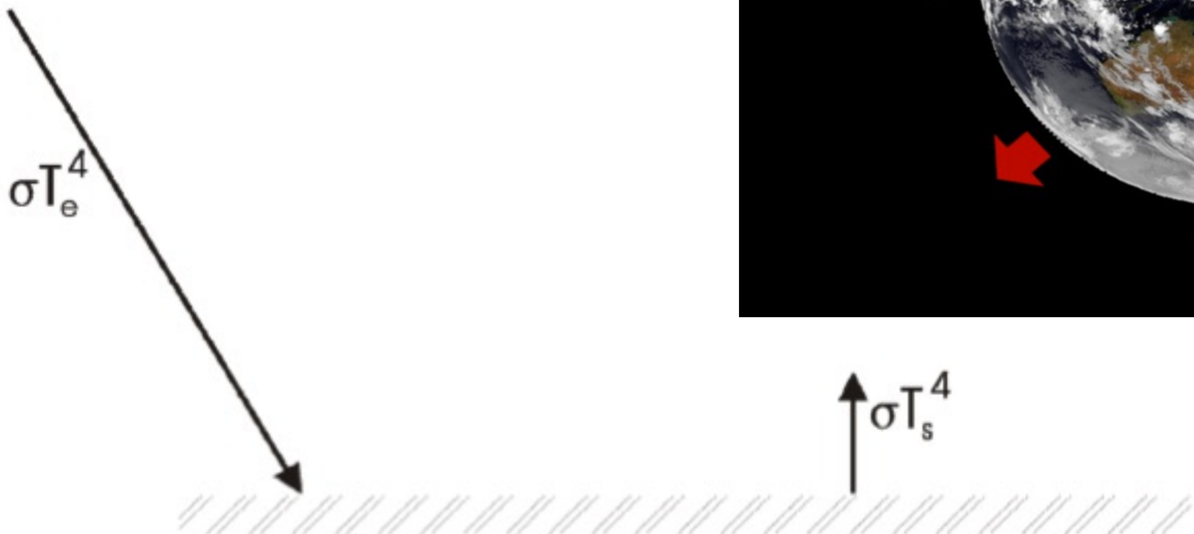


FIGURE 6.3. Schematic diagram of the global radiation budget in the climatic system. A value of 100 units is assigned to the incoming flux of solar energy.

Greenhouse effect of atmosphere

Radiative Equilibrium:



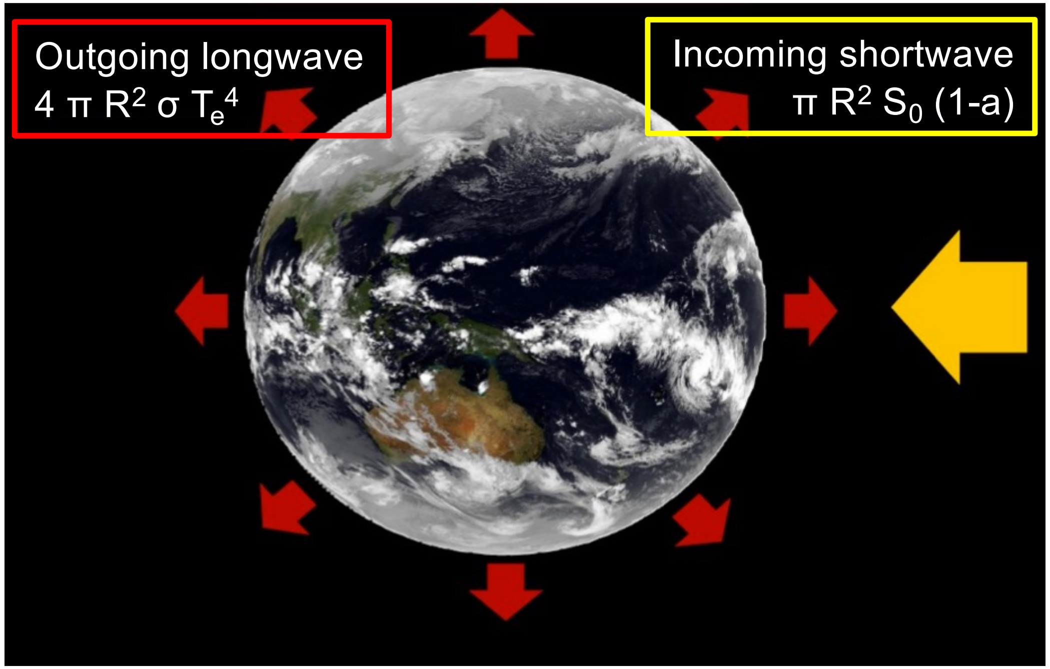


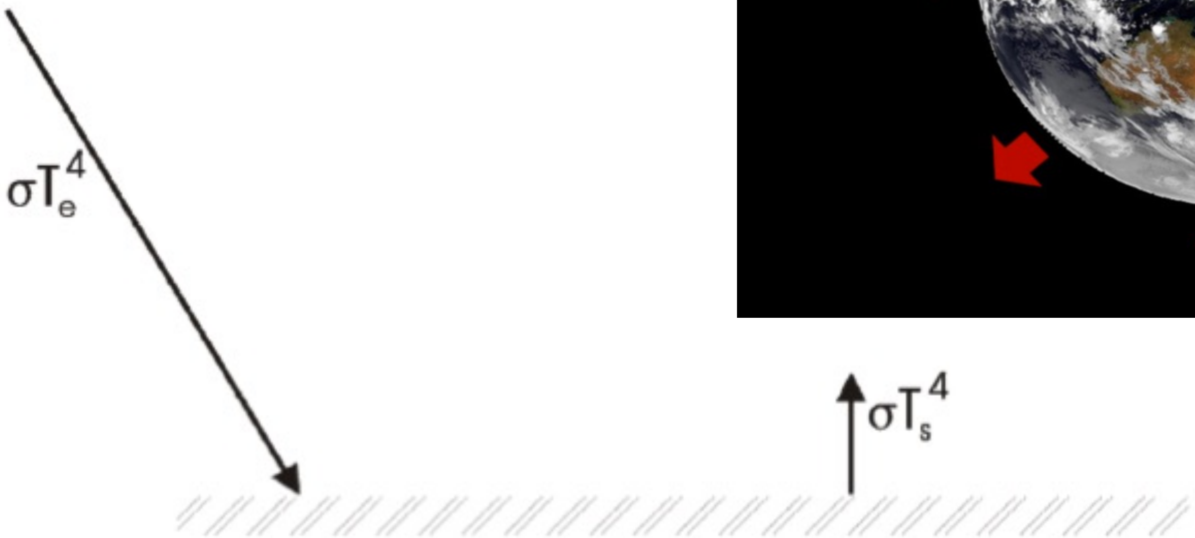
TOA: $\sigma T_e^4 = S_0 (1-a) / 4$

($\sigma \sim 5.6 \times 10^{-8}$ J s^{-1} m^{-2} K^{-4}
Stefan-Boltzmann constant;
S_0~1340 W/m^2 incoming solar
a~0.3 albedo)

Greenhouse effect of atmosphere

Radiative Equilibrium:





TOA: $\sigma T_e^4 = S_0 (1-a) / 4$

Earth => $T_e = T_s$ = 255K = −18° C !!

Observed average surface temperature = 288K = 15° C…

Greenhouse effect of atmosphere

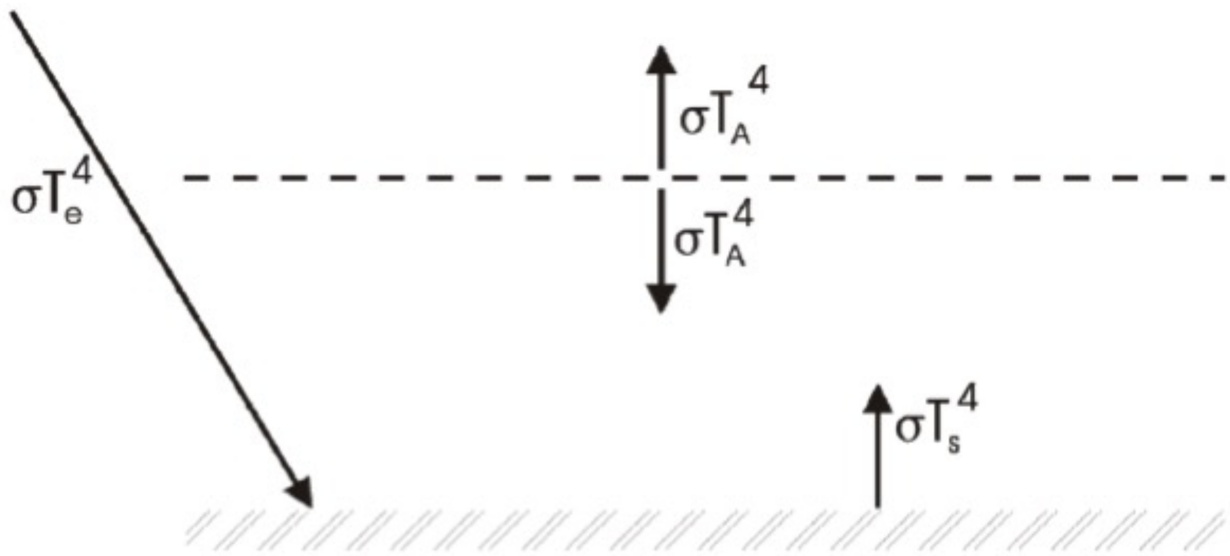
Radiative Equilibrium:

One-Layer Model

Transparent to solar radiation

Opaque to infrared radiation

Blackbody emission from surface and each layer



Courtesy Kerry Emanuel

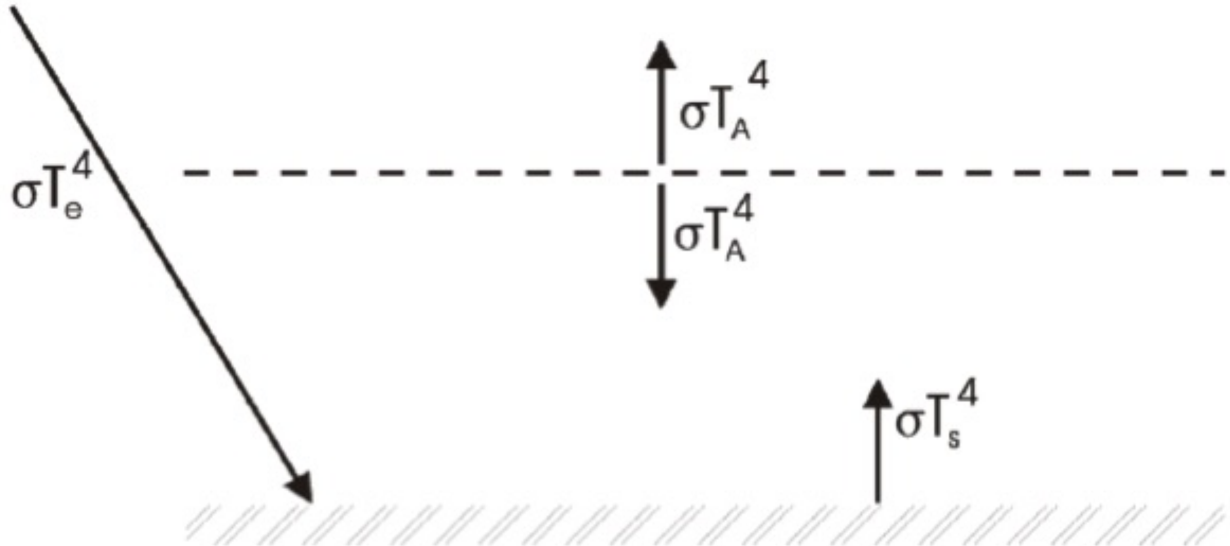
TOA: $\sigma T_e^4 = S_0 (1\text{-}a) / 4$

Greenhouse effect of atmosphere

Radiative Equilibrium:

One-Layer Model

Transparent to solar radiation
Opaque to infrared radiation
Blackbody emission from surface and each layer



Courtesy Kerry Emanuel

TOA: $\sigma T_e^4 = S_0 (1\text{-}a) / 4$

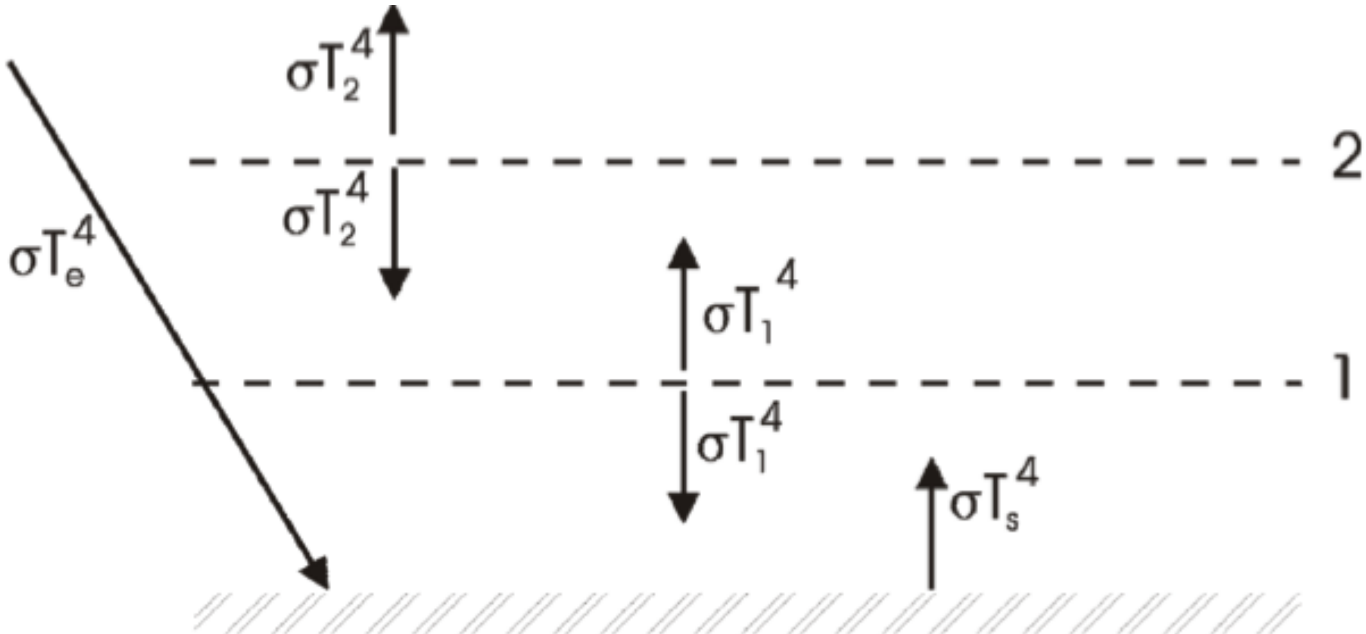
Level 1: $2 \sigma T_A^4 = \sigma T_s^4$

Surface: $\sigma T_s^4 = \sigma T_e^4 + \sigma T_A^4$

$\Rightarrow T_A^4 = T_e^4$ and $T_s^4 = 2 T_e^4 \Rightarrow T_s = 2^{1/4} T_e = 303$ K

Greenhouse effect of atmosphere

Radiative Equilibrium:
Two-Layer Model



TOA: $\sigma T_e^4 = S_0 (1\text{-}a) / 4$

Courtesy Kerry Emanuel

Level 2: $2\sigma T_2^4 = \sigma T_1^4$

Level 1: $2\sigma T_1^4 = \sigma T_s^4 + \sigma T_2^4$

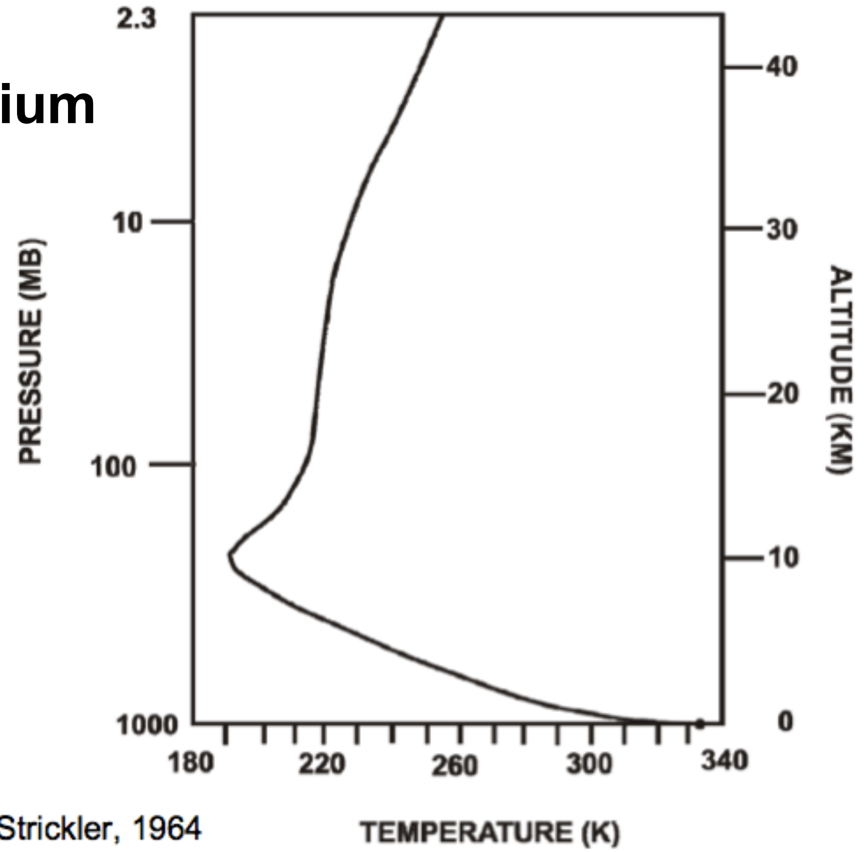
Surface: $\sigma T_s^4 = \sigma T_e^4 + \sigma T_1^4$

=> $T_s = 3^{1/4}\, T_e$

Greenhouse effect of atmosphere

Radiative Equilibrium:

Full calculation of Radiative Equilibrium



After Manabe and Strickler, 1964

Physics Nobel laureate 2021

⇒ Too warm at the surface, too cold aloft

⇒ Unstable to convection (air movement)

⇒ Realistic equilibrium is called radiative-convective equilibrium (radiation destabilizes, convection stabilizes)

⇒ CO_2 forcing increases greenhouse warming

Remark: T beyond the tropopause

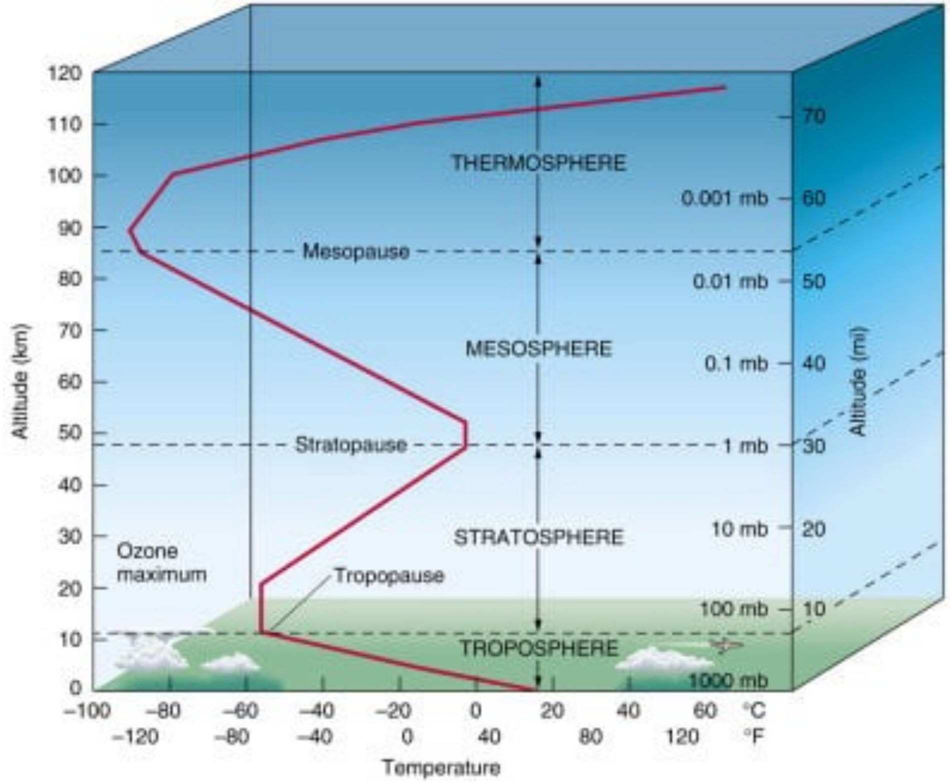


Figure 1.6. *(left) Felix Baumgartner just before his famous jump, 14 October 2012, from 38 960 m altitude above New Mexico, U.S.A. (right) The atmosphere seen from the Internation Space Station.*

Conclusions II.2) Surface temperatures and the greenhouse effect

⇒ How it works

-Incoming solar energy: The Earth's atmosphere is mostly transparent to incoming sunlight. The Earth's surface absorbs this energy and warms up.
-Outgoing infrared radiation: The warm surface then releases energy back into the atmosphere as infrared radiation, or heat.
-Trapping the heat: Greenhouse gases in the atmosphere absorb this outgoing infrared radiation and prevent it from escaping into space.
-Warming the planet: The gases re-radiate some of this heat back toward the Earth's surface, warming the planet.

⇒ Main greenhouse gases

-Water vapor (H20) : The most abundant greenhouse gas.
-Carbon dioxide (CO_2) : A major contributor, with levels increased by human activities.
-Methane (CH_4) : A powerful greenhouse gas.
...

Outline of the climate discussion:

I) INTRO: HISTORY OF CLIMATE

Chronology from 4.5 billion years ago

II) KEY PROCESSES THAT SHAPE CLIMATE: OVERVIEW

II.1) Top-Of-Atmosphere (TOA) energy balance

II.2) Surface temperatures: Greenhouse effect

III) HOW THESE PROCESSES SHAPED PAST CLIMATES

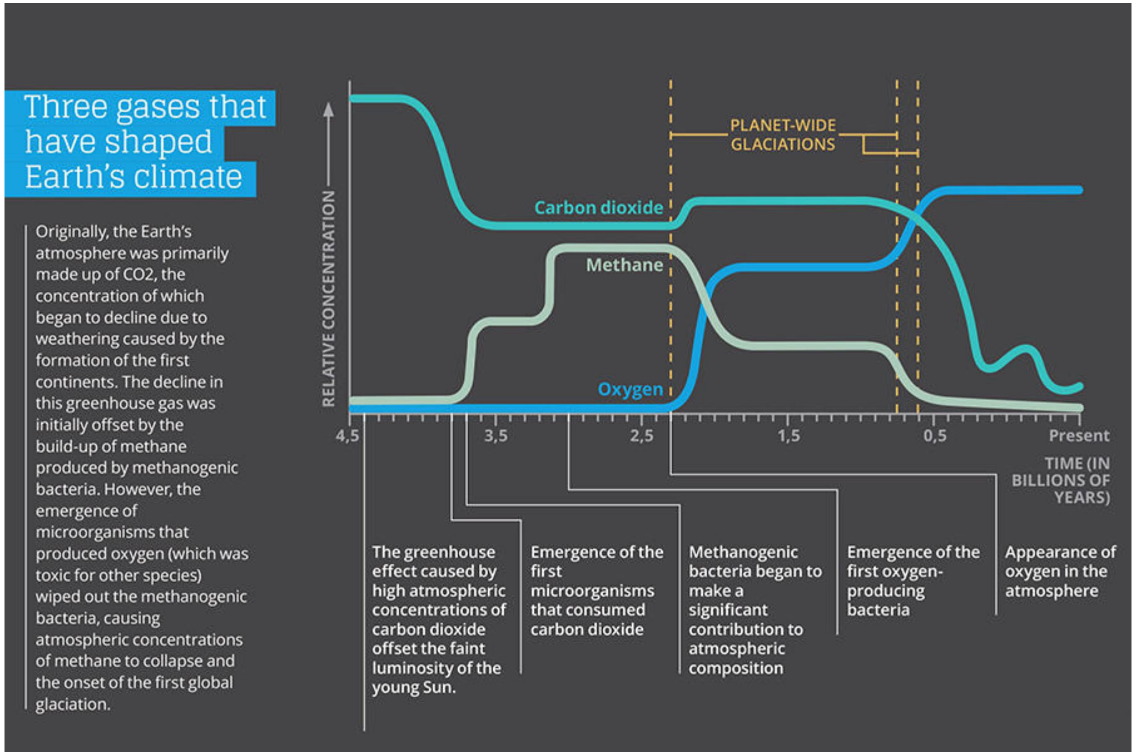
III.1) Faint sun paradox (~4.5 By)

III.2) Snowball Earth (~2.5 By & .6 By)

III.3) Equable climate (~65 My)

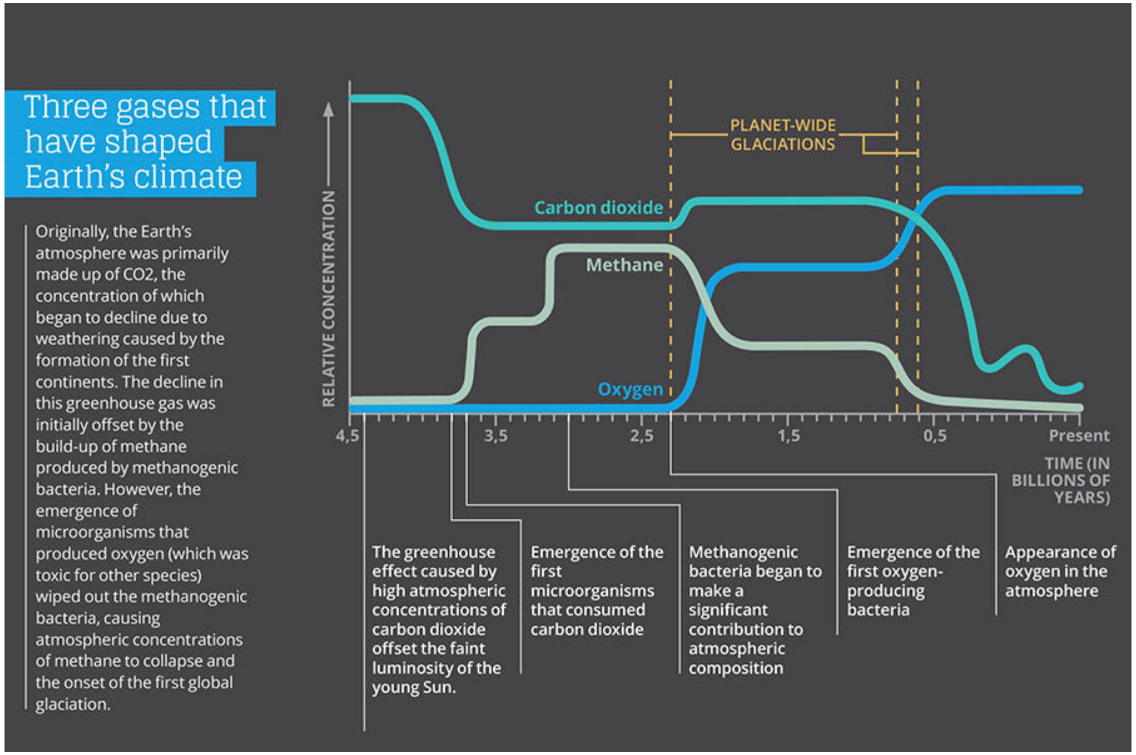
III.4) Ice ages (~1 My)

IV) RECENT CLIMATE CHANGE



Earth first formed (4.5 By), Sun radiated 30% less energy than today.
Since, its power has increased by 7% every billion years.

⇒ paradox: Earth received **less radiation**, but was **much warmer**



Earth first formed (4.5 By), Sun radiated 30% less energy than today.
Since, its power has increased by 7% every billion years.

⇒ paradox: Earth received **less radiation**, but was **much warmer**
⇒ Energy balance TOA = Energy from Sun = **energy returned to space**
⇒ How that related to surface temperature depends on **greenhouse** gases, released by **Volcanic outgassing**
⇒ Earth's atmosphere ~ heating blanket. **Carbon dioxide + methane** are powerful greenhouse gases
⇒ Regulate surface temperatures.
⇒ Also frequent impacts from planetesimals kept Earth molten and extremely hot in early times

Outline of the climate discussion:

I) INTRO: HISTORY OF CLIMATE

Chronology from 4.5 billion years ago

II) KEY PROCESSES THAT SHAPE CLIMATE: OVERVIEW

II.1) Top-Of-Atmosphere (TOA) energy balance

II.2) Surface temperatures: Greenhouse effect

III) HOW THESE PROCESSES SHAPED PAST CLIMATES

III.1) Faint sun paradox (~4.5 By)

III.2) Snowball Earth (~2.5 By & .6 By)

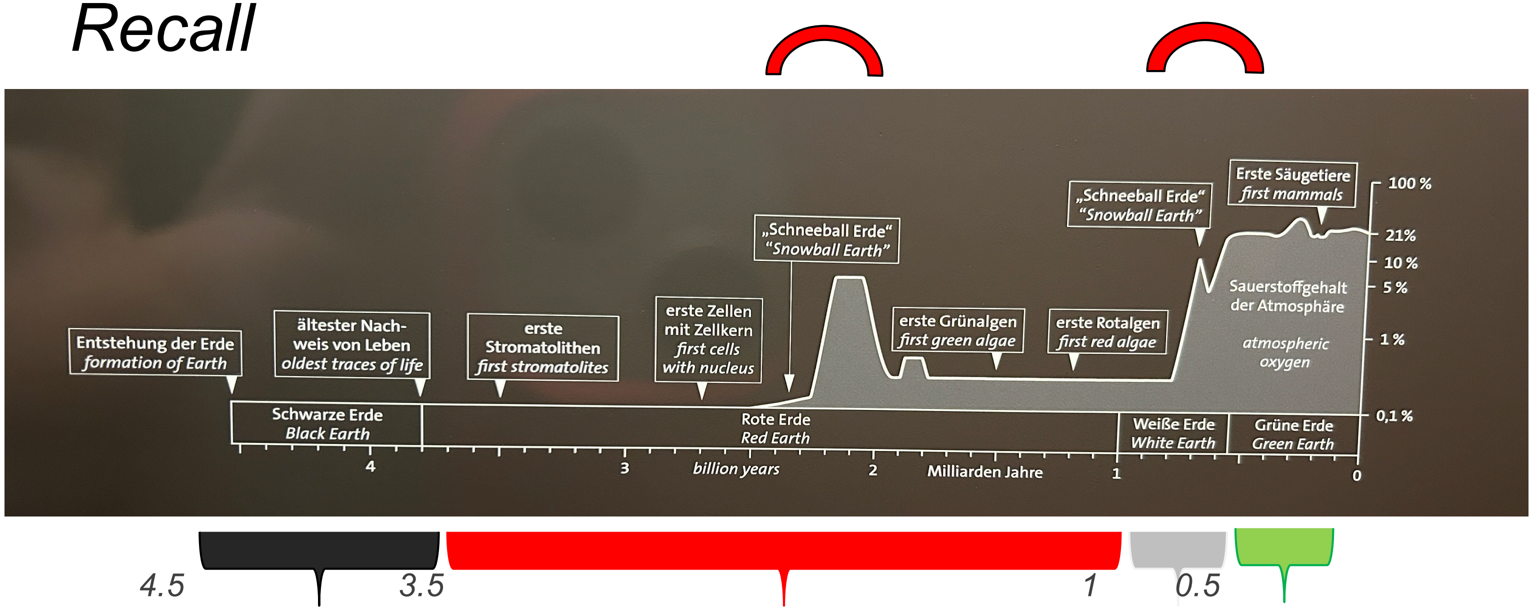
III.3) Equable climate (~65 My)

III.4) Ice ages (~1 My)

IV) RECENT CLIMATE CHANGE

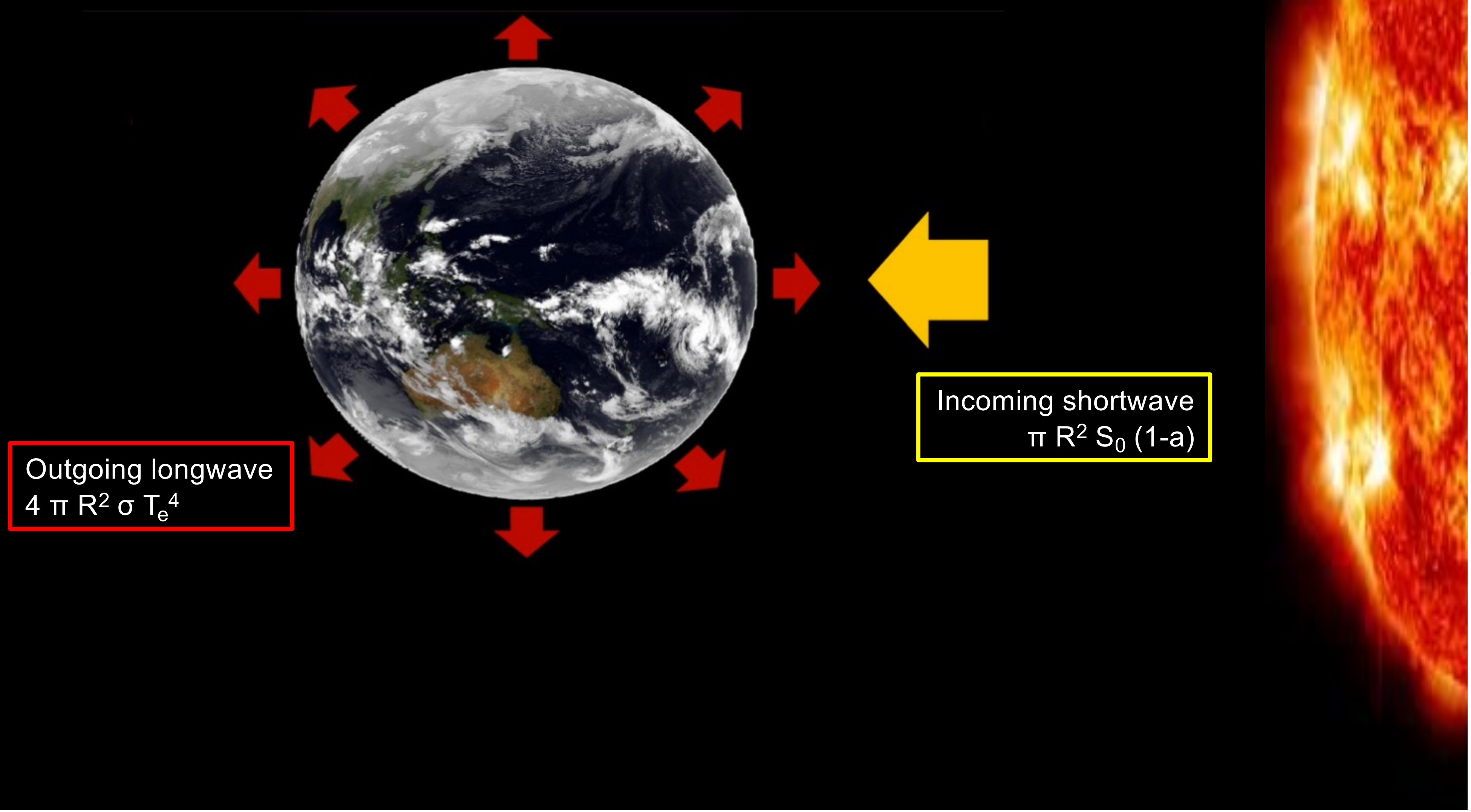
Snowball earth: The ice-albedo feedback

Recall



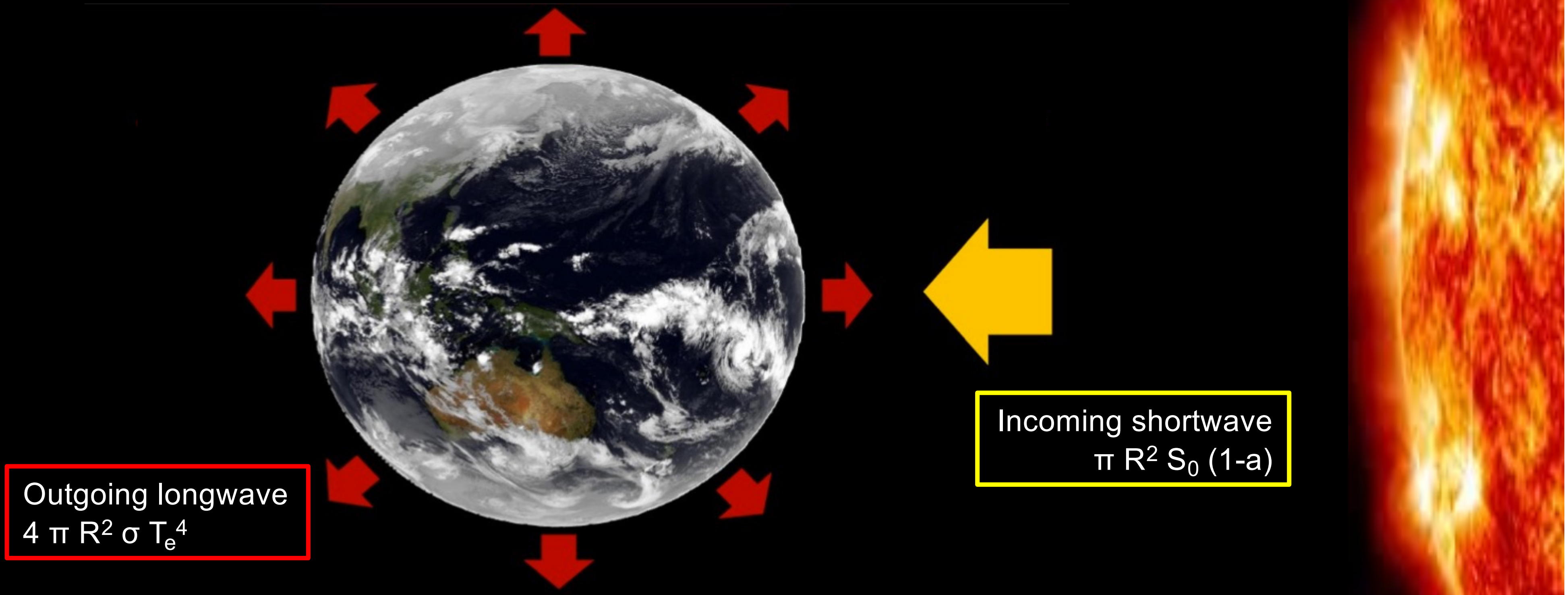
Recall:

Energy balance at the top of the atmosphere:



Recall:

Energy balance at the top of the atmosphere:



ENERGY BALANCE MODEL

$\Rightarrow S_0/4\ (1-a) = A + B\ T$ (linearized outgoing longwave radiation)

Question: Which state do we obtain with a simple
ENERGY BALANCE MODEL

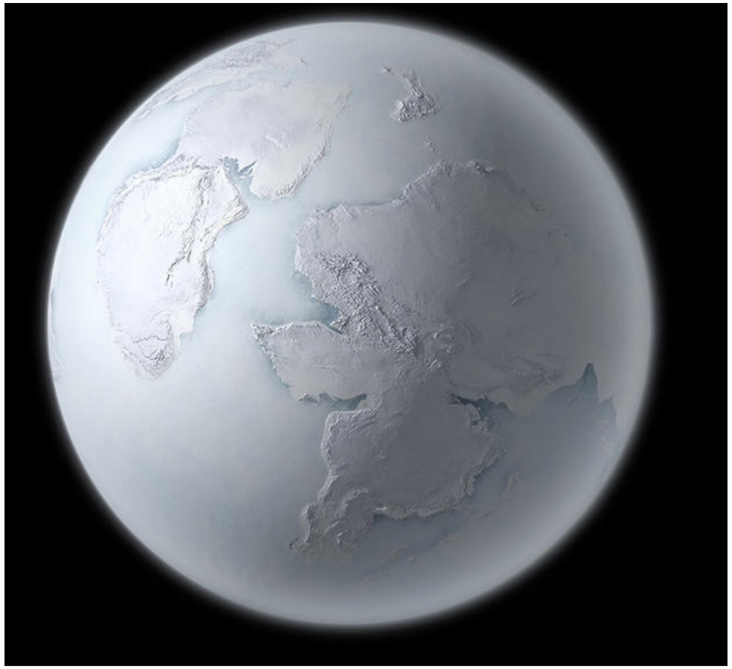
$\Rightarrow$ $S_0/4\ (1-a) = A + B\ T$ (linearized outgoing longwave radiation)

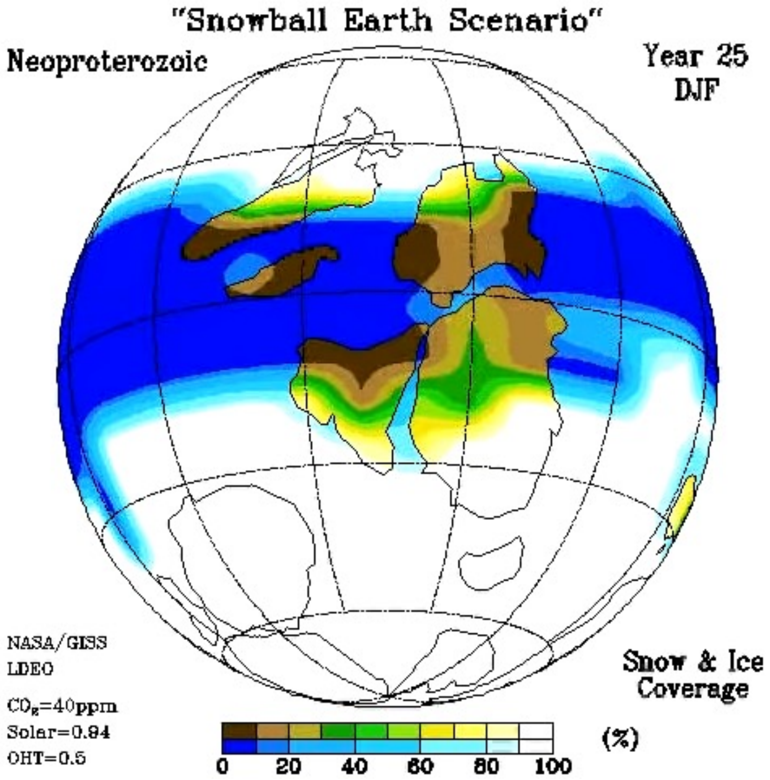
a depends on ice line (lowest latitude reached by ice) thus on T

T depends on a

Question: Which state do we obtain with a simple
ENERGY BALANCE MODEL

⇒ $S_0/4\ (1-a) = A + B\ T$ (linearized outgoing longwave radiation)
a depends on ice line (lowest latitude reached by ice) thus on T
T depends on a

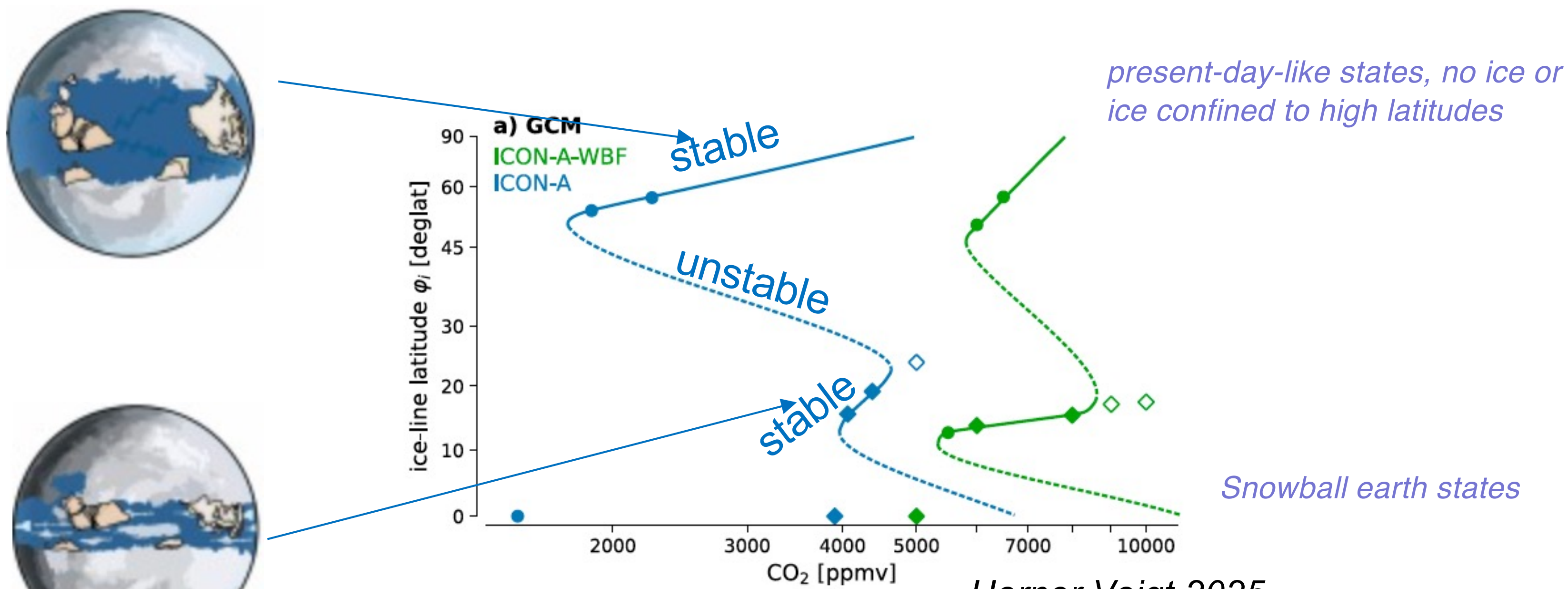




Full snowball ?
⇒ hard to get out of
⇒ any life surviving in the oceans should have suffocated

More likely scenario ?
⇒ Waterbelt state

https://commons.wikimedia.org/wiki/File:SIM_neoproto.ogv



Horner Voigt 2025

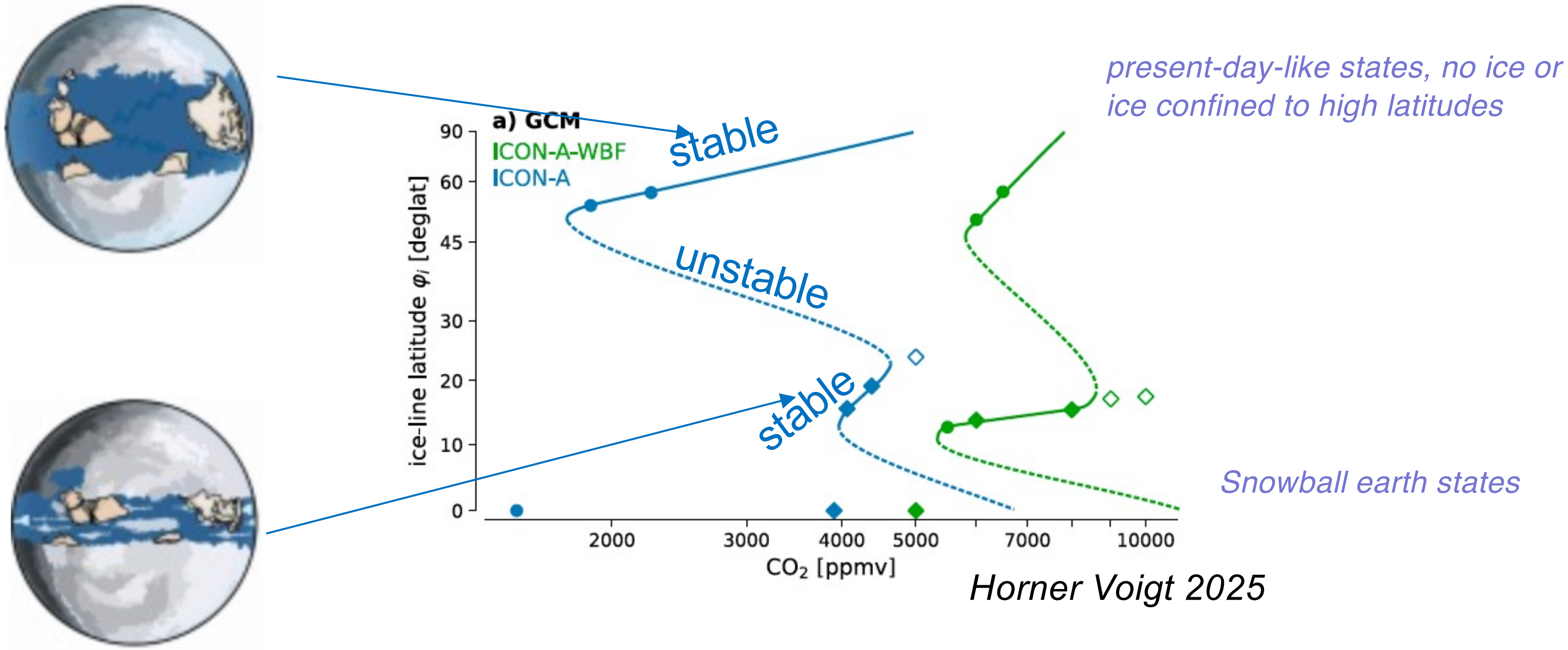
Wang et al 2025

Bifurcation diagram for 2 models (ICON-A and ICON-A-WBF).

Filled symbols ⬄ stable equilibrium states, open symbols ⬄ transient states.

circles = started from present-day state
diamonds = started from waterbelt

$$S_0/4\ (1-a) = A + B\ T$$



Horner Voigt 2025

Wang et al 2025

Bifurcation diagram for 2 models (ICON-A and ICON-A-WBF).
Filled symbols ⬄ stable equilibrium states, open symbols ⬄ transient states.

circles = started from present-day state
diamonds = started from waterbelt

$S_0/4\ (1-a)\ = A + B\ T$

>0 feedback : a ↗ => solar received ↘ => T ↘ => a ↗

Hysteresis as CO2 is varied, multiple equilibria

Outline of the climate discussion:

I) INTRO: HISTORY OF CLIMATE

Chronology from 4.5 billion years ago

II) KEY PROCESSES THAT SHAPE CLIMATE: OVERVIEW

II.1) Top-Of-Atmosphere (TOA) energy balance

II.2) Surface temperatures: Greenhouse effect

III) HOW THESE PROCESSES SHAPED PAST CLIMATES

III.1) Faint sun paradox (~4.5 By)

III.2) Snowball Earth (~2.5 By & .6 By)

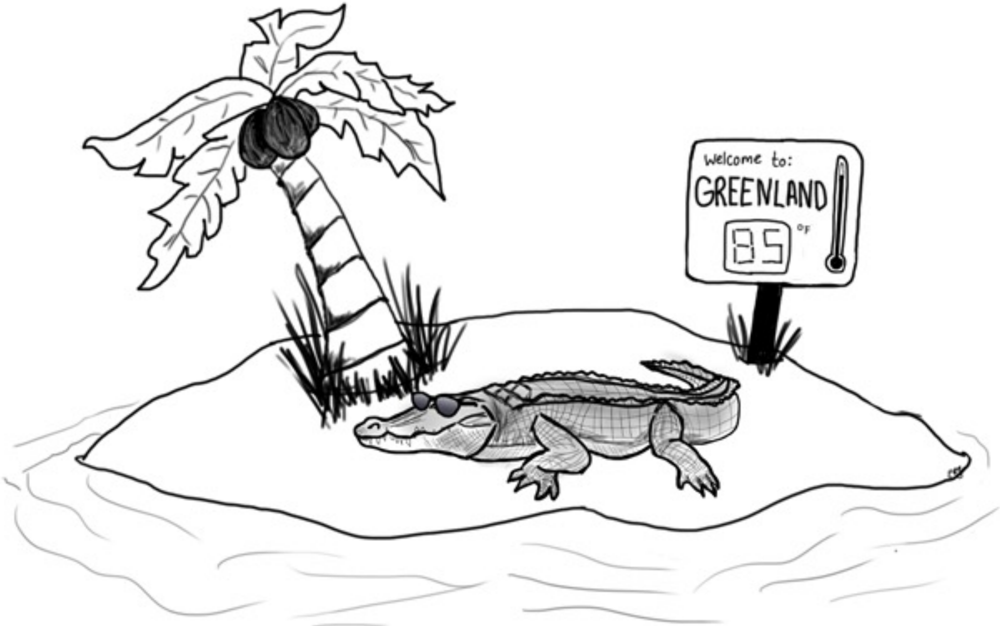
III.3) Equable climate (~65 My)

III.4) Ice ages (~1 My)

IV) RECENT CLIMATE CHANGE

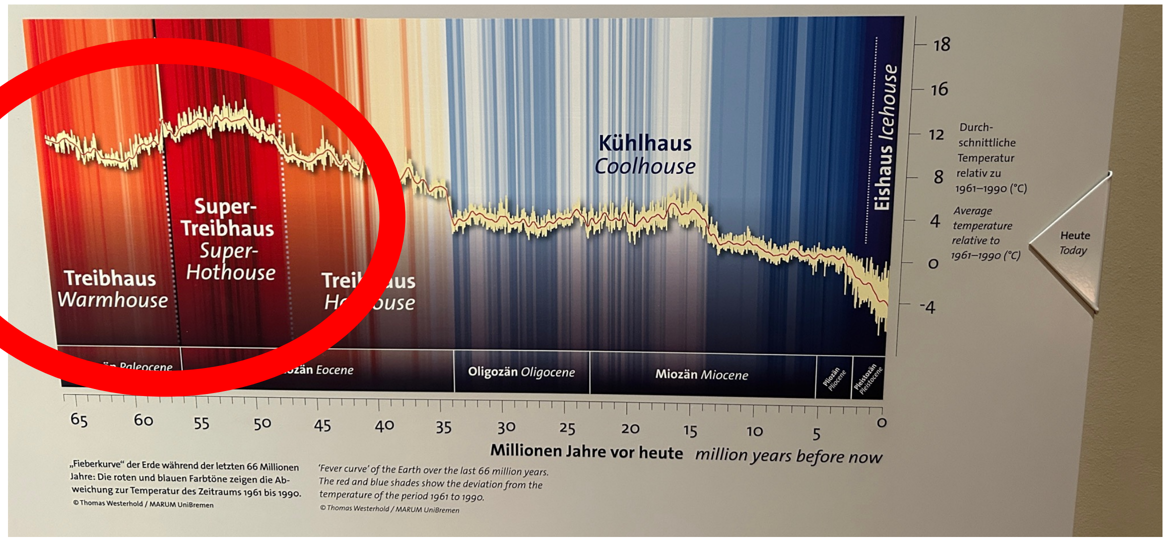
Early Eocene: Equable Climate

Equable climates are periods of roughly equal temperatures throughout the world (at all latitudes)



Cartoon by Emily Greenhalgh, NOAA Climate.gov.

56 million years ago



Early Eocene: Equable Climate

Equable climates are periods of roughly equal temperatures throughout the world (at all latitudes)

During the late Cretaceous period (~100 to 65.5 million years ago)
and the early Eocene period (65.5 to 34 million years ago)

early Eocene was the warmest time interval of the past 65 million years.

Poles much warmer and closer to equatorial temperatures
Also low seasonality in high latitudes

Tropical temperatures stable, but high latitudes much warmer
(North Pole oceans : ~20C @65-55My; ~25C 55-35My)

https://groups.seas.harvard.edu/climate/eli/research/equable/index.html

Evidence:
1/3 American Alligator
typically inhabits regions with temperatures between 25C and 35C
crocodilian fossils in North America up to latitudes of about 50N

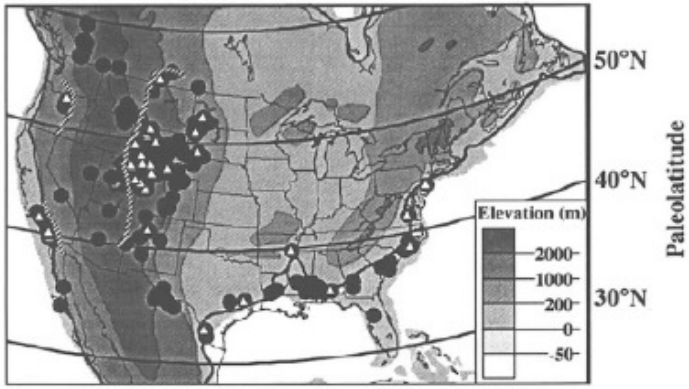


Figure 1. Distribution of Eocene vertebrates and crocodilians. Ellesmere Island localities are not shown because they do not have direct bearing on interior paleoclimates in western United States. Base map (used for all four figures) is for present day plotted on Lambert conformable conic projection. Paleogeography is for middle Eocene (Lutetian Stage). West coast and position of 2000 m contour are speculative at present. Diagonally ruled line represents conservative estimate of limit of crocodilians during Eocene. Circles—vertebrate localities; triangles—localities with fossil crocodilians.

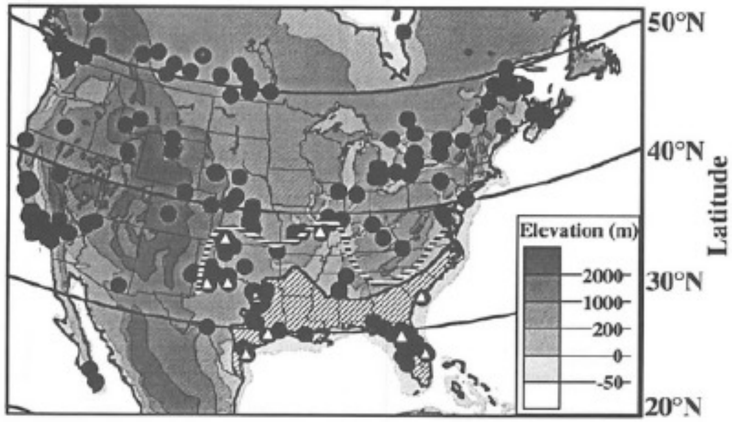


Figure 4. Distribution of vertebrates and crocodilians in Pleistocene and early Holocene time. Topography is for present day. Shaded area in southeastern United States represents present distribution of crocodilians in North America (Neill, 1971). Key to symbols is in Figure 1 caption.

Crocodilian Fossils

Foraminifera Shell Isotopes

2/3 Oxygen isotopes:
Foraminifera are very small sea organisms that create calcium carbonate ($CaCO_3$) shells to protect themselves.
Shells incorporate oxygen from the ocean, contains both ^{16}O and ^{18}O
Can use foraminifera shells to obtain delta-O-18 values and to determine the ocean temperature at the time of the shell's creation.
(Since it is lighter than ^{18}O, ^{16}O evaporates first, so in warm, tropical areas, the ocean is high in ^{18}O.)

3/3 :

Palms, cycads, and gingers have been found from roughly 30N to almost 60N in sediments dating back to about 50 Ma.

Currently, exist mainly between 0 and 30deg.

⇒ at around 50 Ma, typical temperatures were between 8C and 10C in areas between 45N and 50N,

⇒ and mean annual temperatures were between 12C and 18C.

Therefore, these plants are extremely useful for rebuilding the Eocene's climate.

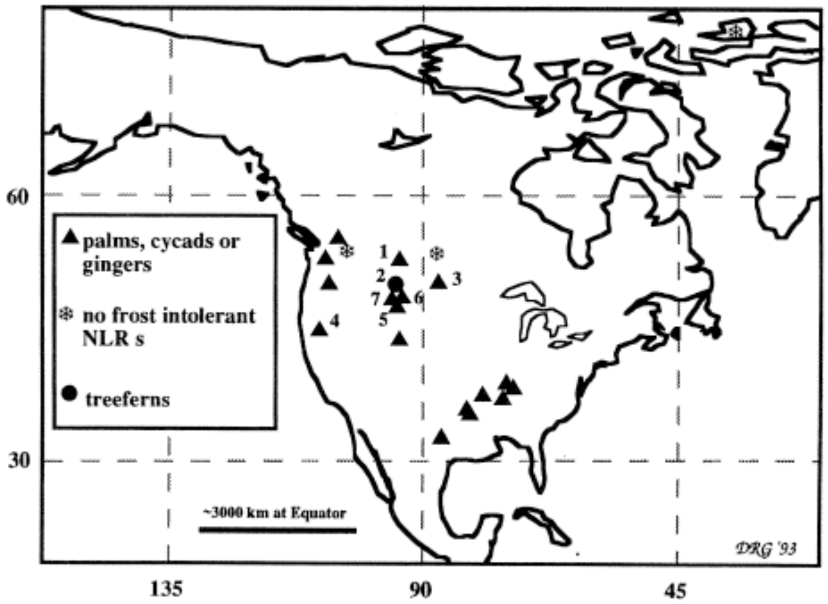


Figure 2. Map of North America at about 50 Ma, palaeogeography from PGIS-MAC. Data symbols indicate floras with palms (triangles), with cycads or zingiberaleans (circles), and lacking all three (snowflakes). Sites: 1, Bear Paw; 2, Sepulcher; 3, Camels Butte; 4, Chalk Bluffs; 5, Green River; 6, Kisinger Lake; 7, Wind River.

Palm fossil from the Eocene

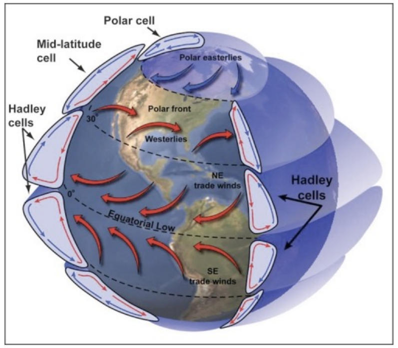
Cause of equable climates?

Still unsolved

Some theories:

- Warming from increased atmospheric carbon dioxide (CO_2) concentration
  CO_2 was very likely at least double the present level during the early Eocene
  But would increase T everywhere, not just at the poles, so not whole story
  => Need mechanism changing either the way heat was transported from the Tropics to the poles or the atmosphere's ability to absorb heat.

-More mixing of oceans by tropical cyclones => more ocean heat transport poleward?



-Hadley cell extending all the way to the pole => more atmospheric heat transport?

-polar stratospheric clouds trapping heat at high latitudes?

-More convective clouds at high latitudes?

Outline of the climate discussion:

I) INTRO: HISTORY OF CLIMATE

Chronology from 4.5 billion years ago

II) KEY PROCESSES THAT SHAPE CLIMATE: OVERVIEW

II.1) Top-Of-Atmosphere (TOA) energy balance

II.2) Surface temperatures: Greenhouse effect

III) HOW THESE PROCESSES SHAPED PAST CLIMATES

III.1) Faint sun paradox (~4.5 By)

III.2) Snowball Earth (~2.5 By & .6 By)

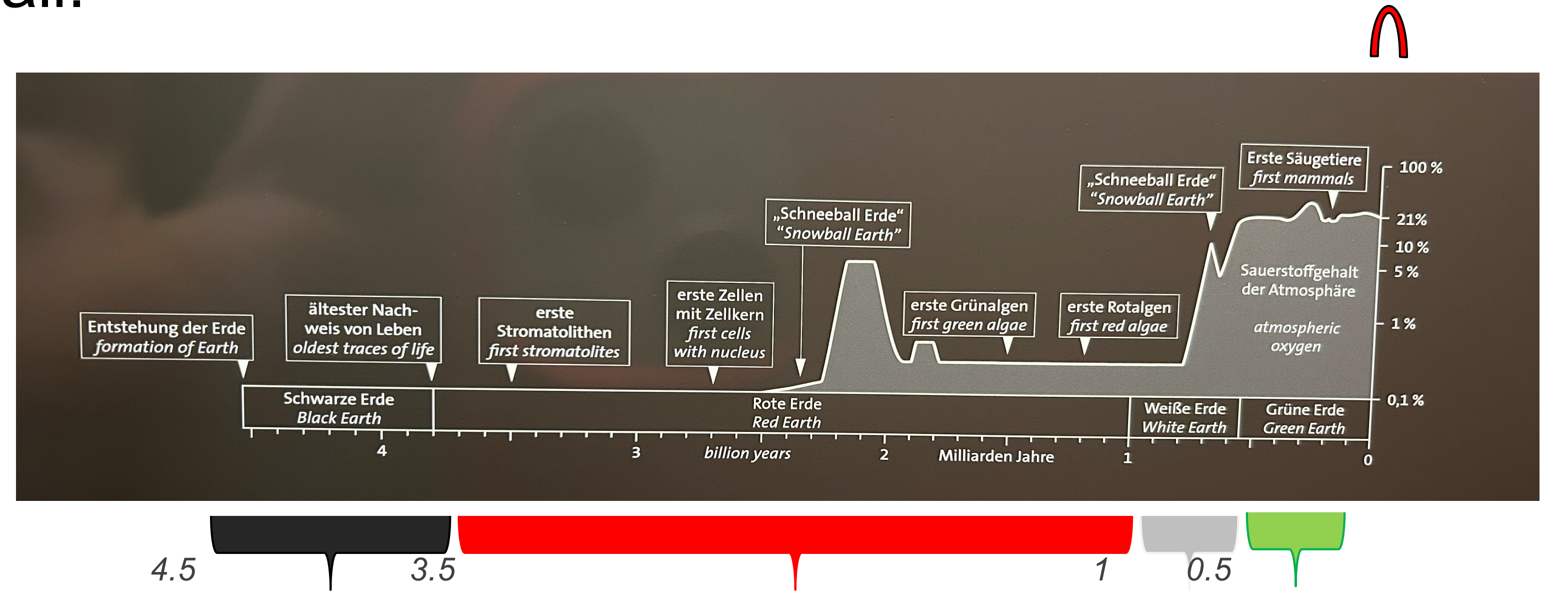
III.3) Equable climate (~65 My)

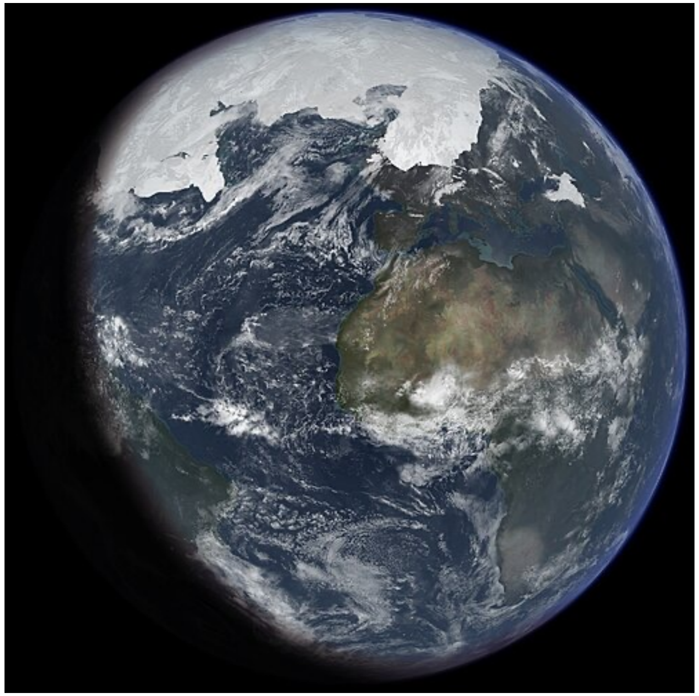
III.4) Ice ages (~1 My)

IV) RECENT CLIMATE CHANGE

Processes leading to ice ages: ORBITAL VARIATIONS

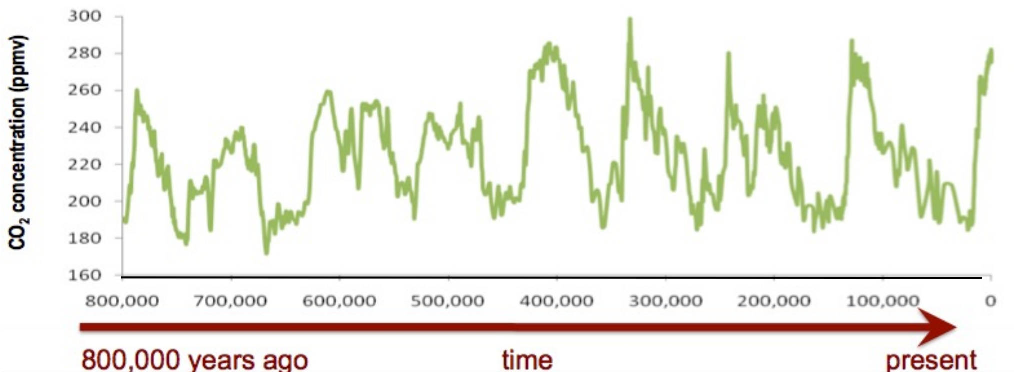
Recall:

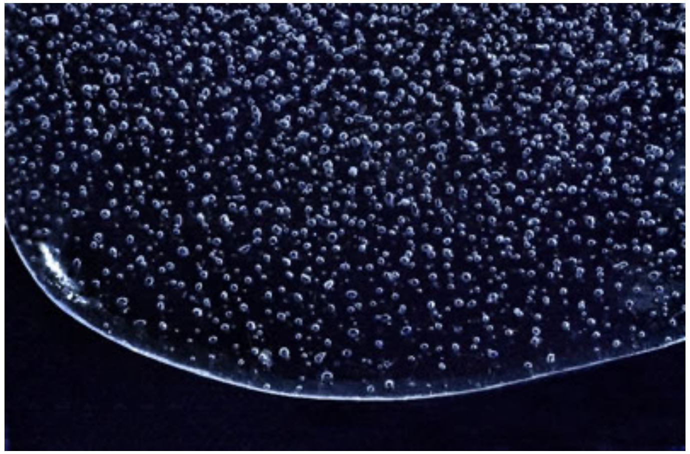




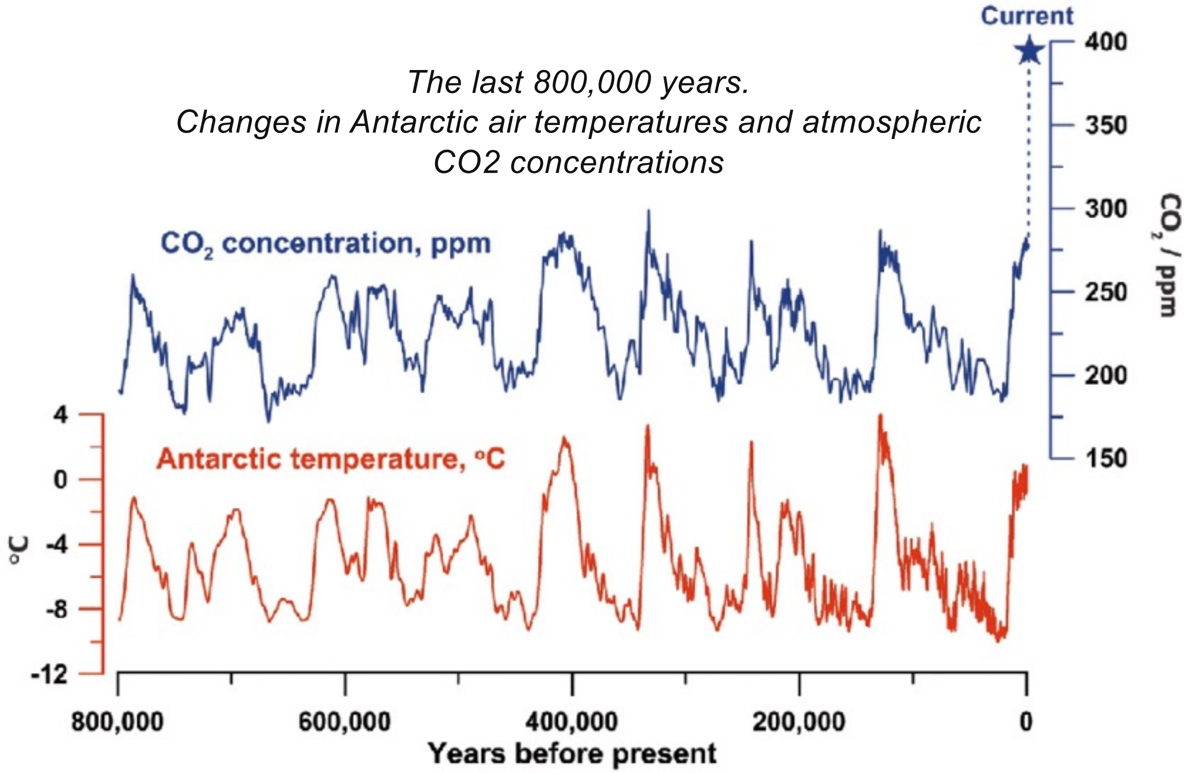
Ice age: cooling Tsfc, expansion of continental and polar ice caps

CO_2 last 800 000 years

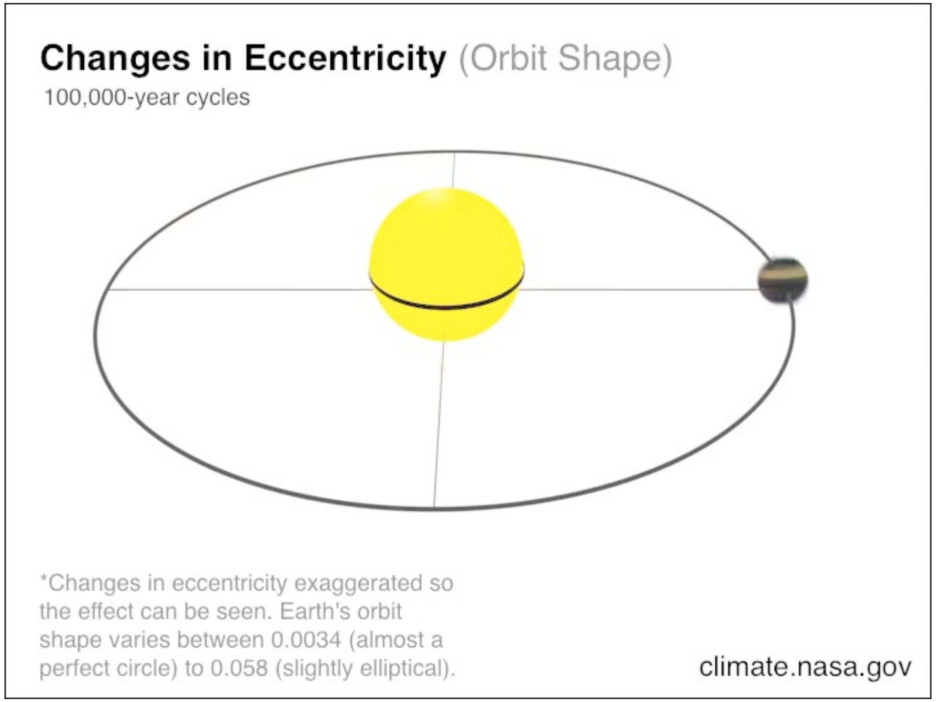


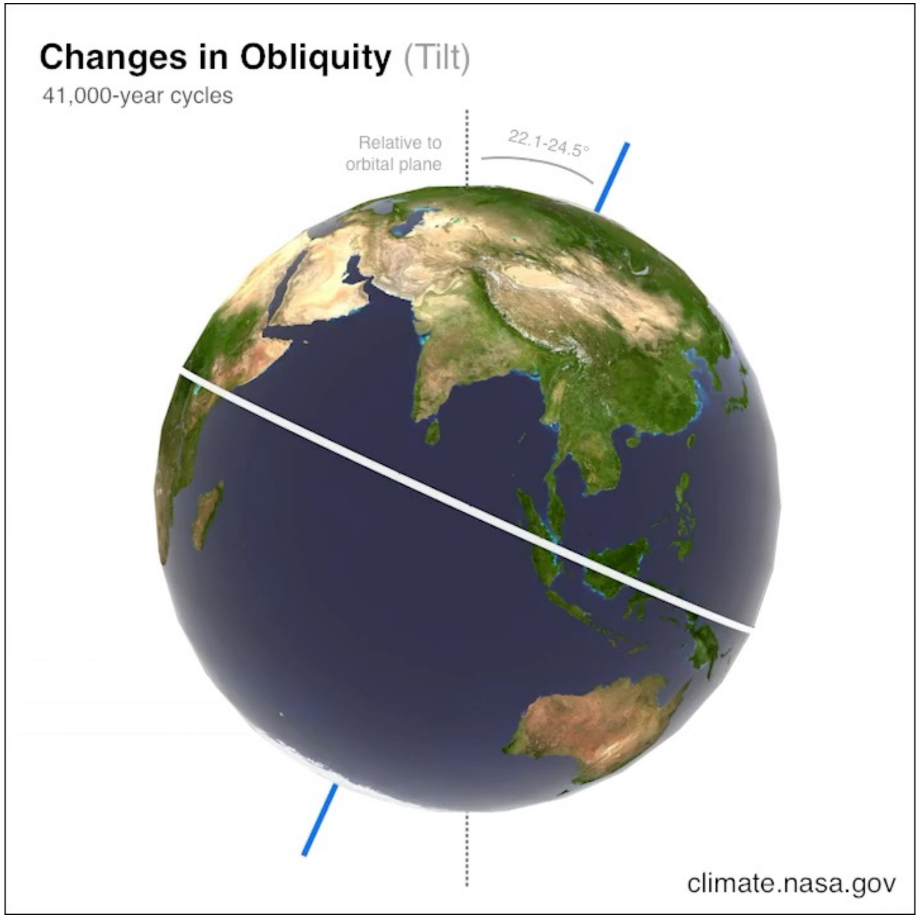


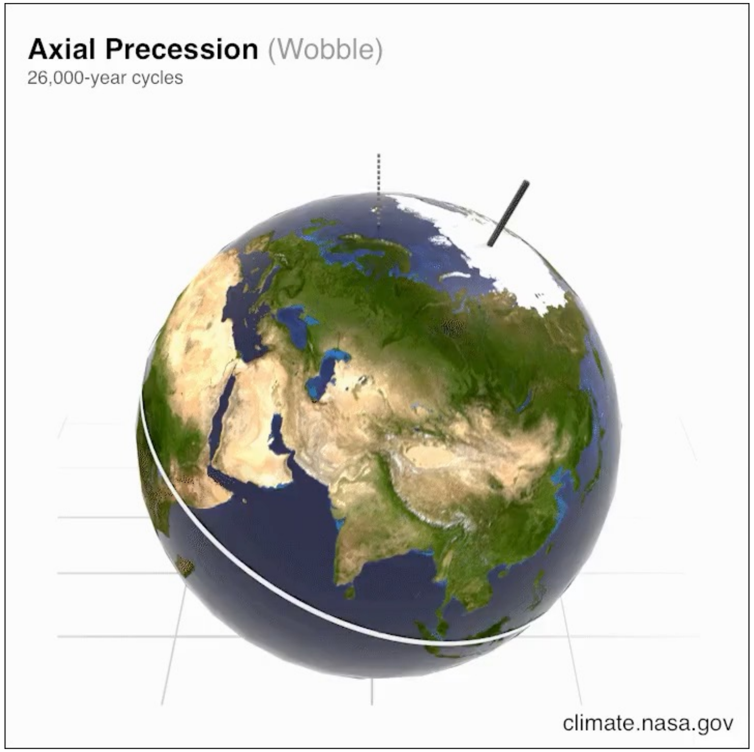
The last 800,000 years.
Changes in Antarctic air temperatures and atmospheric CO2 concentrations



Book: Climate change - a risk assessment (Chapter: 20)

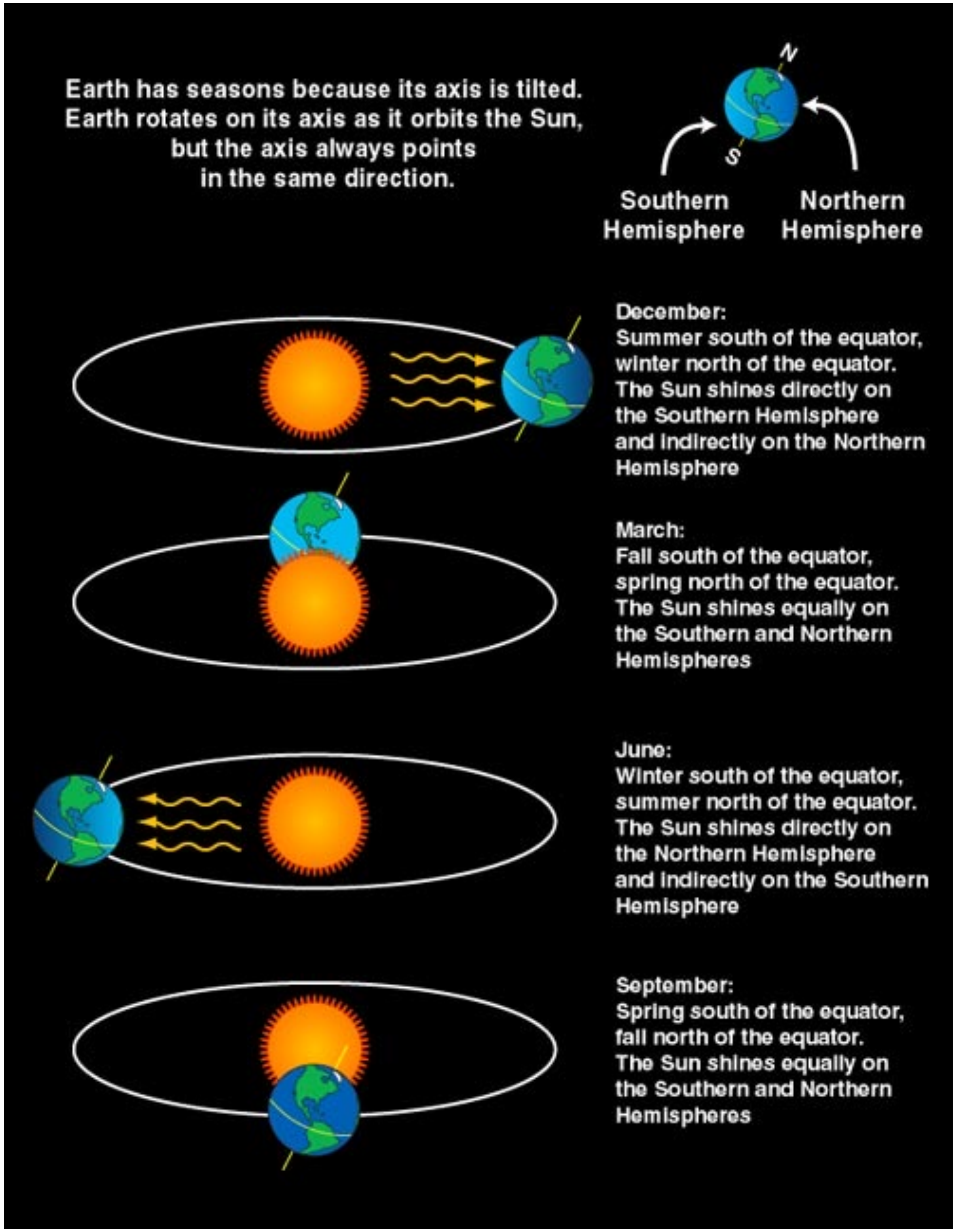

Changes in Eccentricity (Orbit Shape)
100,000-year cycles
*Changes in eccentricity exaggerated so the effect can be seen. Earth's orbit shape varies between 0.0034 (almost a perfect circle) to 0.058 (slightly elliptical).
climate.nasa.gov


Changes in Obliquity (Tilt)
41,000-year cycles
Relative to orbital plane
22.1-24.5°
climate.nasa.gov


Axial Precession (Wobble)
26,000-year cycles
climate.nasa.gov

We know e.g. obliquity matters because…

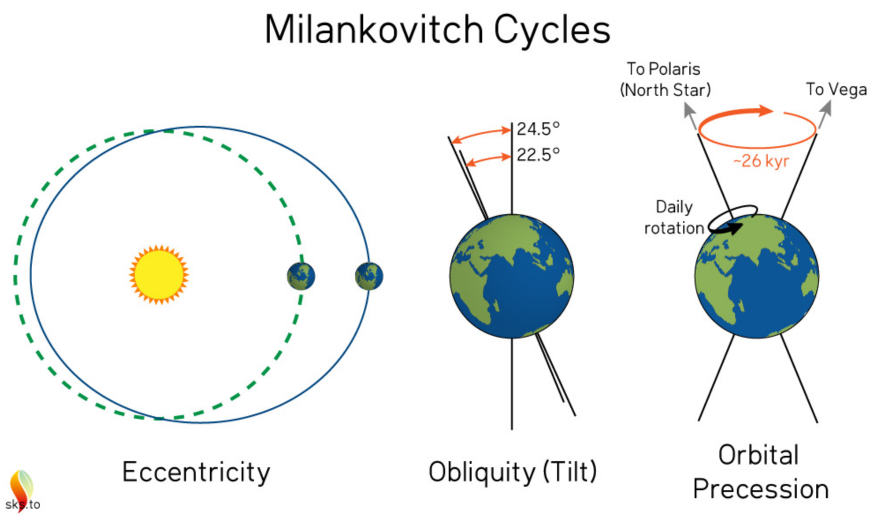
We know e.g. obliquity matters because… we have seasons!



Obliquity gives asymmetry N/S

More sunlight on Southern hemisphere

More sunlight on Northern hemisphere



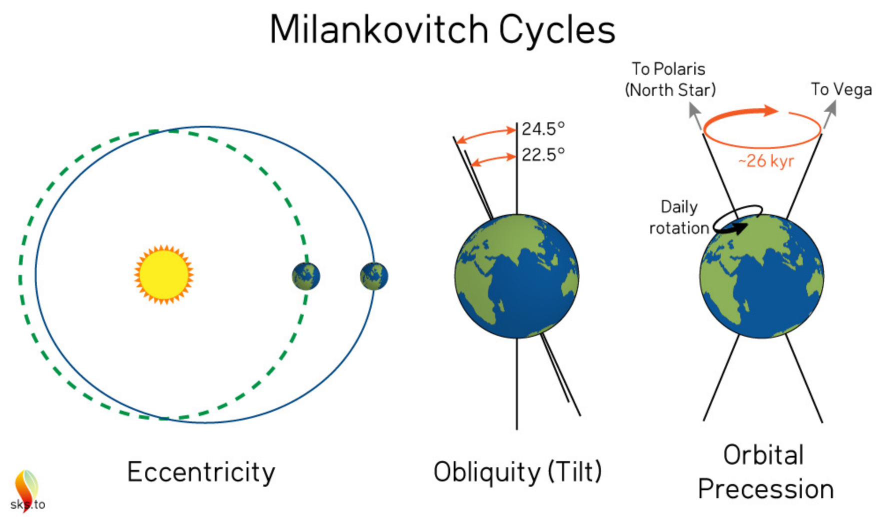
Milankovitch cycles describe the collective effects of changes in the Earth's movements on its climate over thousands of years. The term was coined and named after the Serbian geophysicist and astronomer Milutin Milanković.

Result in cyclical variations in the intra-annual and latitudinal distribution of solar radiation at the Earth's surface, and that this orbital forcing strongly influenced the Earth's climatic patterns

obliquity (tilt ε) - cycle of about 41,000 years

Eccentricity (e) - ~ 100,000-year cycle

Precession index - period of about 25,700 years



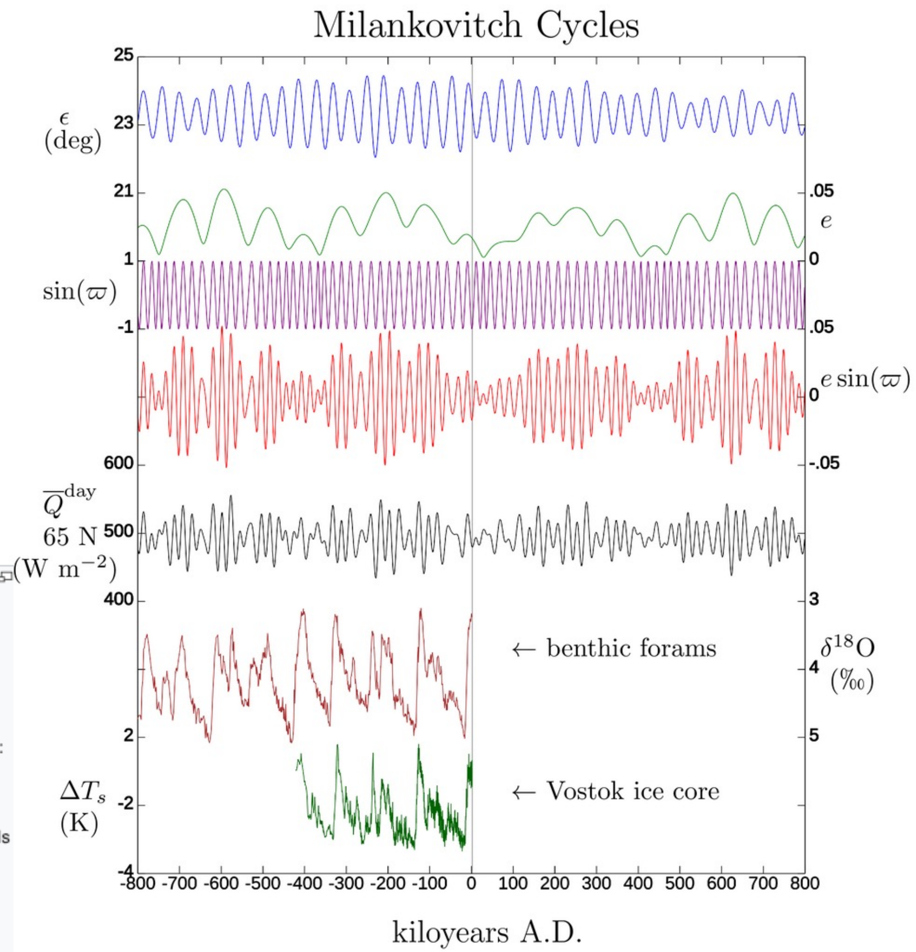
Milankovitch cycles describe the collective effects of changes in the Earth's movements on its climate over thousands of years. The term was coined and named after the Serbian geophysicist and astronomer Milutin Milanković.

Result in cyclical variations in the intra-annual and latitudinal distribution of solar radiation at the Earth's surface, and that this orbital forcing strongly influenced the Earth's climatic patterns

obliquity (tilt ε) - cycle of about 41,000 years

Eccentricity (e) - ~ 100,000-year cycle

Precession index - period of about 25,700 years



Past and future Milankovitch cycles via VSOP model

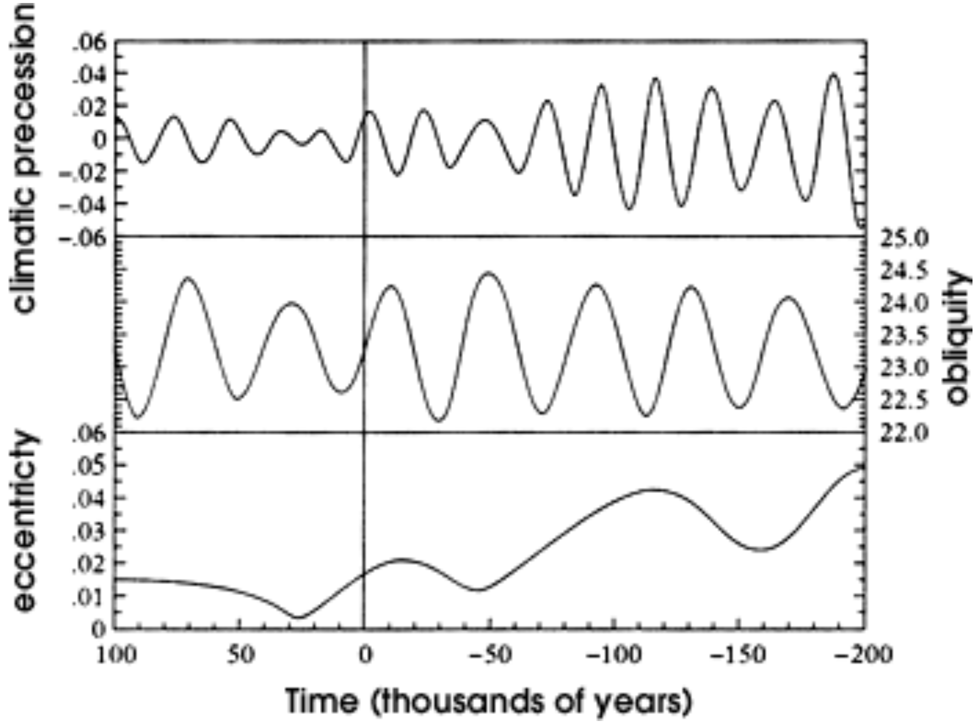
- Graphic shows variations in five orbital elements:
  - Axial tilt or obliquity (ε).
  - Eccentricity (e).
  - Longitude of perihelion ($\sin(\varpi)$).
  - Precession index ($e \sin(\varpi)$)
- Precession index and obliquity control insolation at each latitude:
  - Daily-average insolation at top of atmosphere on summer solstice ($\overline{Q}^{\text{day}}$) at 65° N
- Ocean sediment and Antarctic ice strata record ancient sea levels and temperatures:
  - Benthic forams (57 widespread locations)
  - Vostok ice core (Antarctica)
- Vertical gray line shows present (2000 CE)

Using these three orbital variations, Milankovitch was able to formulate a comprehensive mathematical model that calculated latitudinal differences in insolation and the corresponding surface temperature for 600,000 years prior to the year 1800.

attempted to correlate these changes with the growth and retreat of the Ice Ages

For about 50 years, Milankovitch's theory was largely ignored.

Then, in 1976 (almost 20 years after his death), a study published in the journal *Science* examined deep-sea sediment cores and found that Milankovitch's theory did in fact correspond to periods of climate change (Hays et al. 1976).



Berger and Loutre, 1991

Specifically, the authors were able to extract the record of temperature change going back 450,000 years and found that major variations in climate were closely associated with changes in the geometry (eccentricity, obliquity, and precession) of Earth's orbit.

Indeed, ice ages had occurred when the Earth was going through different stages of orbital variation.

Outline of the climate discussion:

I) INTRO: HISTORY OF CLIMATE

Chronology from 4.5 billion years ago

II) KEY PROCESSES THAT SHAPE CLIMATE: OVERVIEW

II.1) Top-Of-Atmosphere (TOA) energy balance

II.2) Surface temperatures: Greenhouse effect

III) HOW THESE PROCESSES SHAPED PAST CLIMATES

III.1) Faint sun paradox (~4.5 By)

III.2) Snowball Earth (~2.5 By & .6 By)

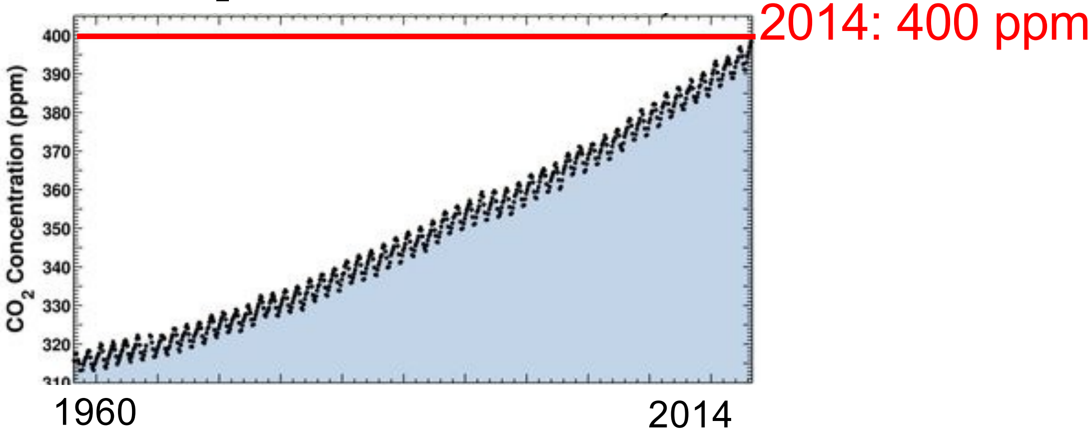
III.3) Equable climate (~65 My)

III.4) Ice ages (~1 My)

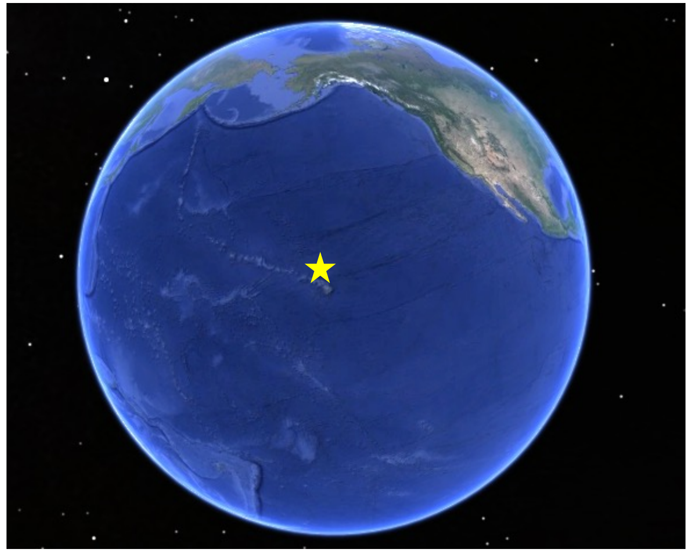
IV) RECENT CLIMATE CHANGE

Climate change

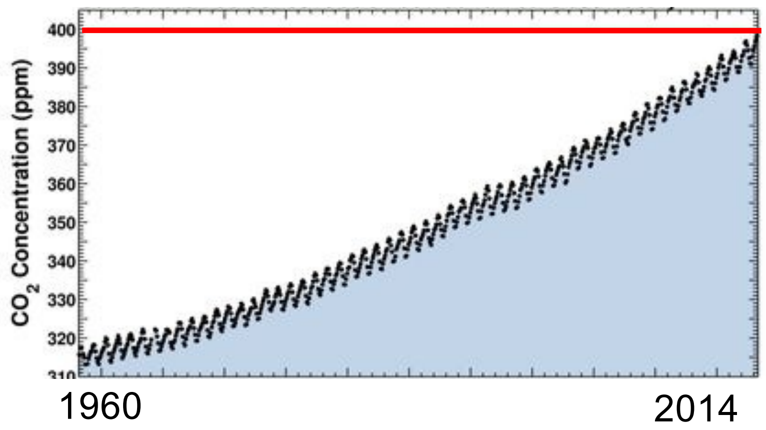
CO_2 measured at Mauna Loa



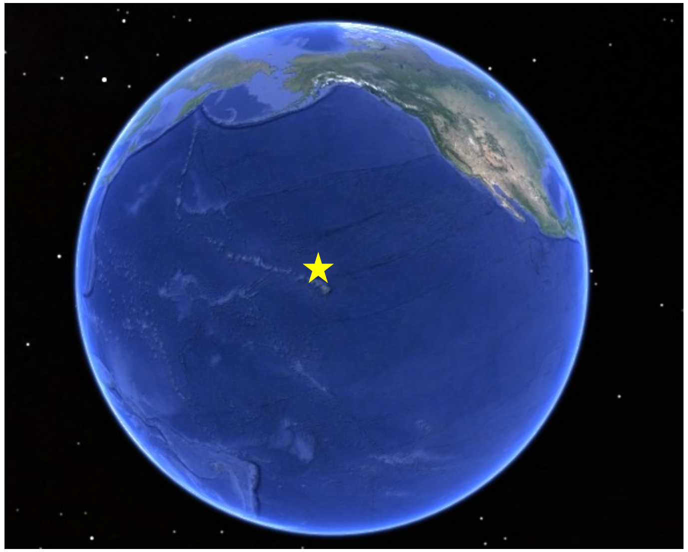
Mauna Loa observatory



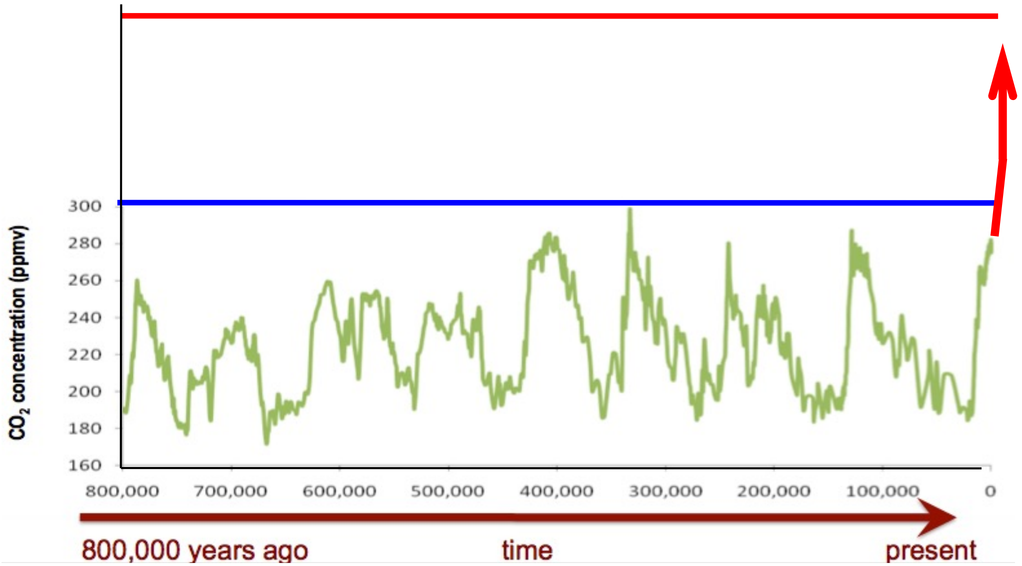
CO$_2$ measured at Mauna Loa



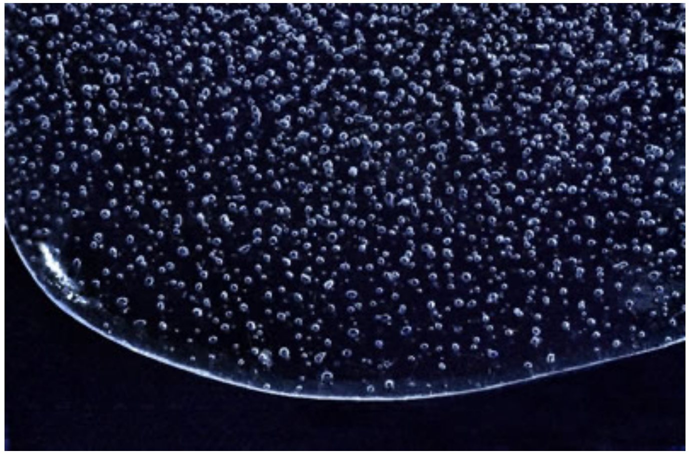
Mauna Loa observatory

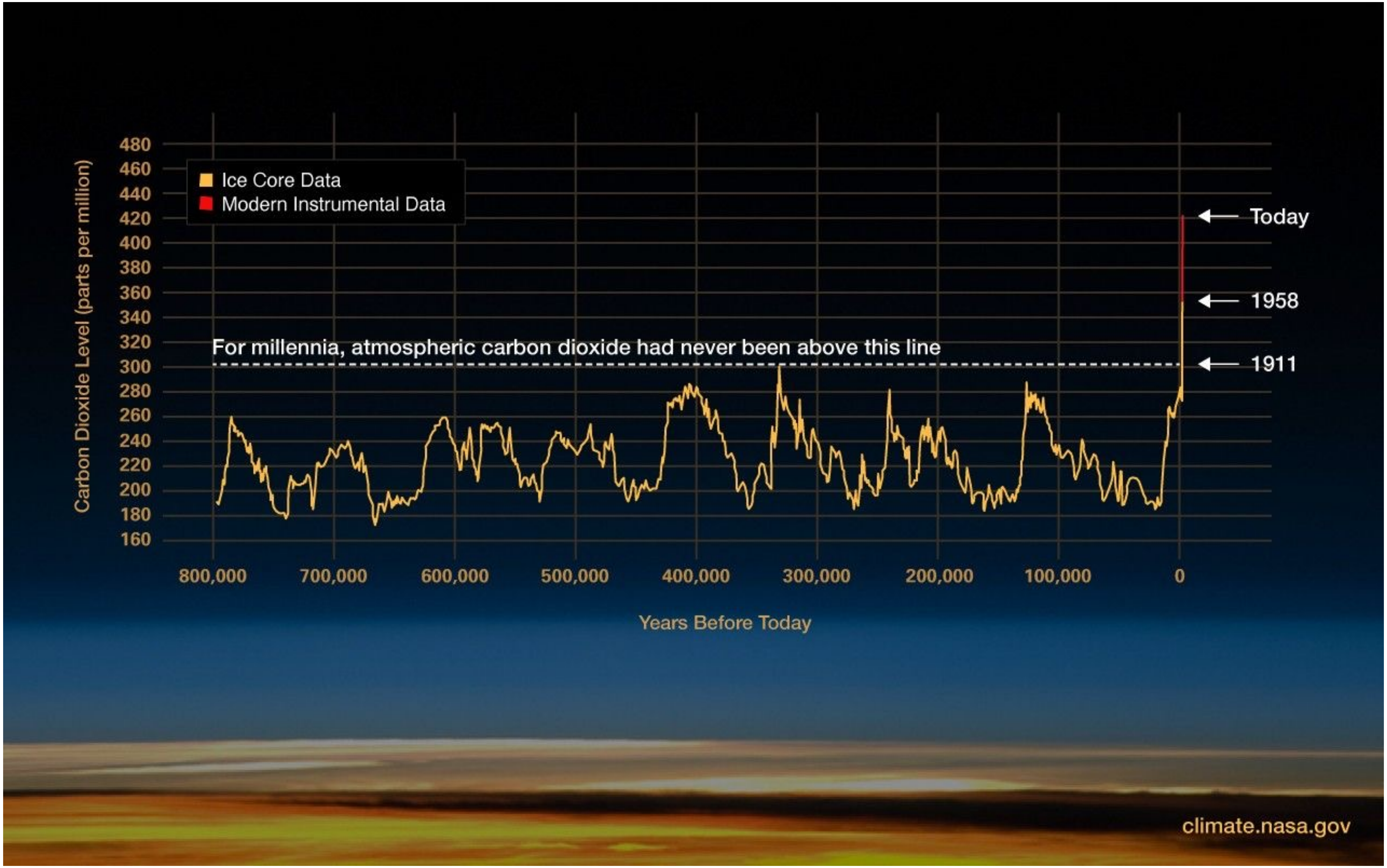


CO$_2$ last 800 000 years

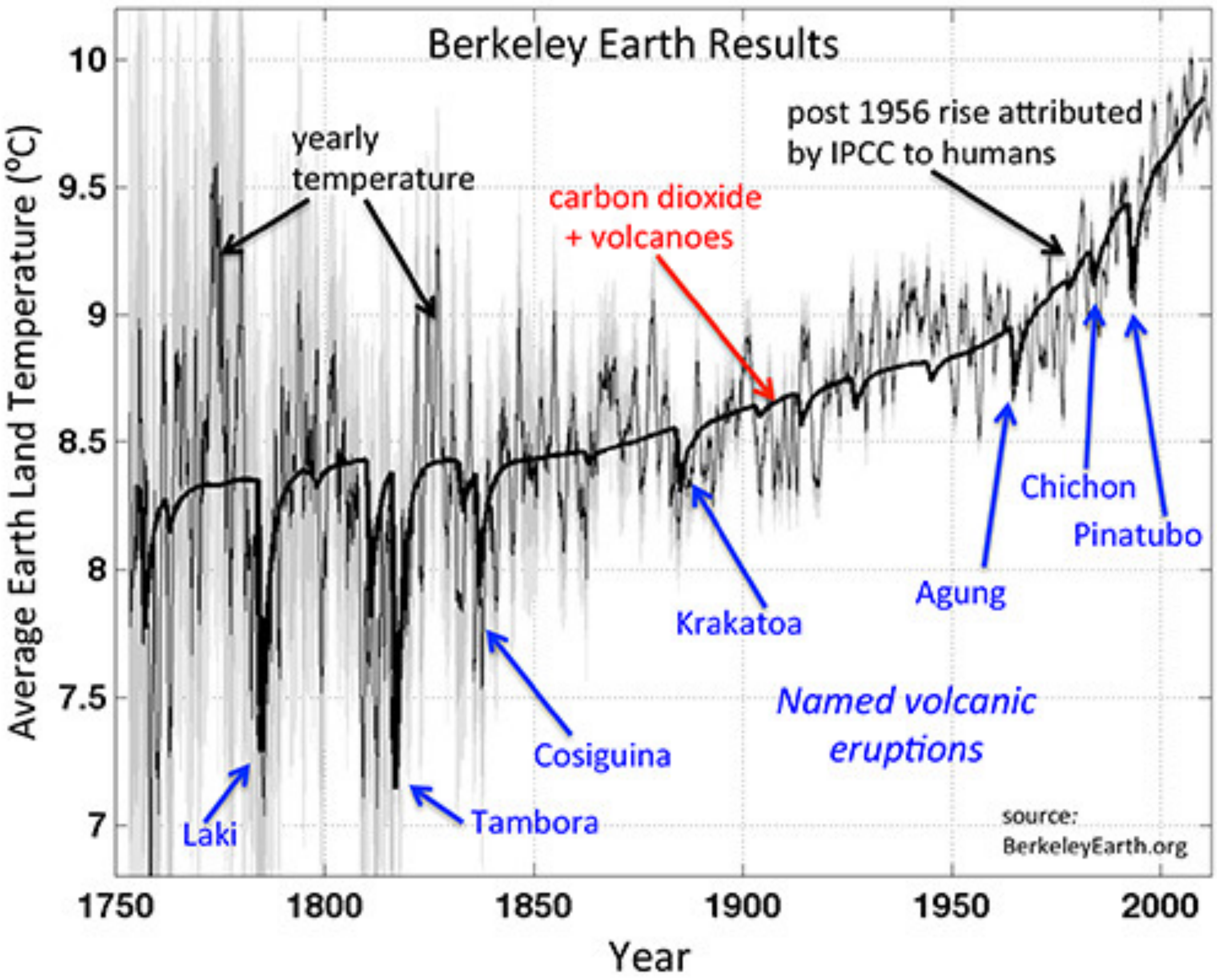


CO$_2$ levels not reached in over half a million years



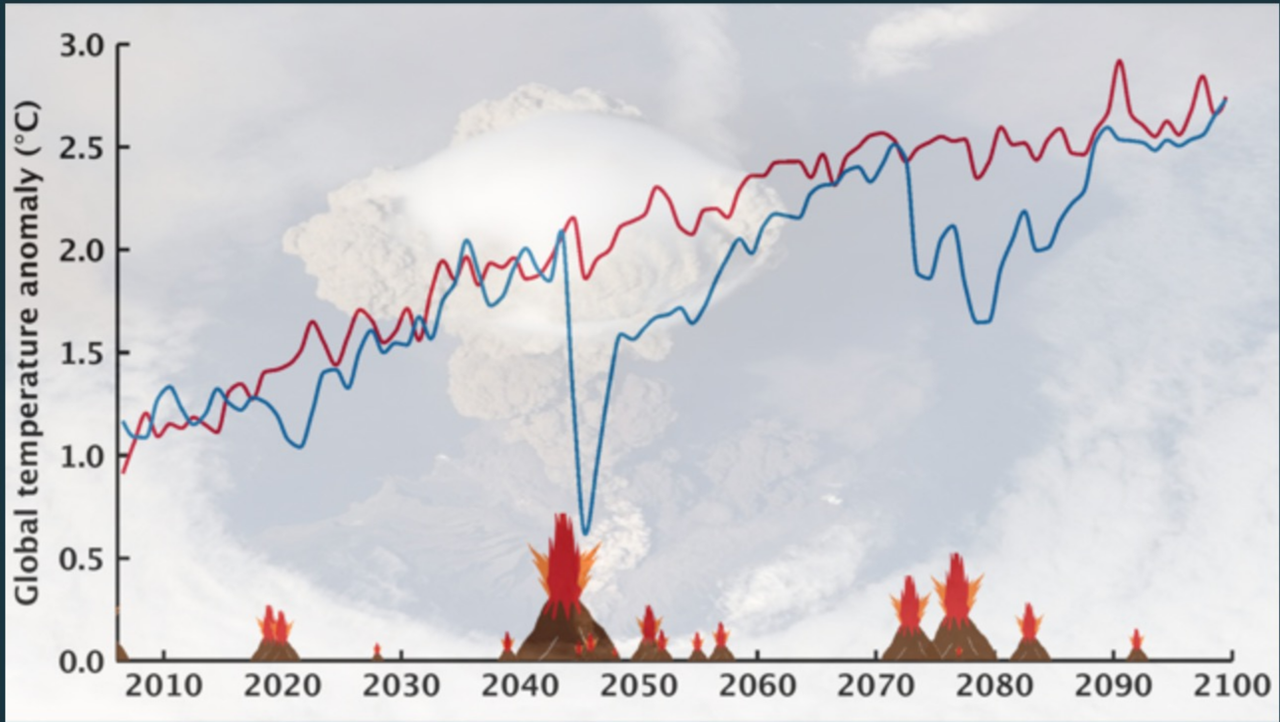

Ice Core Data
Modern Instrumental Data
Carbon Dioxide Level (parts per million)
480
460
440
420
400
380
360
340
320
300
280
260
240
220
200
180
160
For millennia, atmospheric carbon dioxide had never been above this line
Today
1958
1911
800,000
700,000
600,000
500,000
400,000
300,000
200,000
100,000
0
Years Before Today
climate.nasa.gov

Recent warming: Natural variability + climate change



=> Minimum of T at each major volcanic eruption

Natural variability: Volcanoes: (short-term) cooling from stratospheric aerosols



Global-mean temperature evolution with and without volcanic eruptions. The red curve shows how the temperature evolves from year to year in a simulation without volcanic activity. The blue curve shows the result for the simulation of the study with largest volcanic activity. Strong volcanic eruptions lead to periods of cooling that are generally followed by periods of accelerated warming. While making the climate more variable, volcanic eruptions have little influence on the long-term temperature trend. Background: NASA picture of the Sarychev eruption in 2009 on Matua Island.

Natural variability: Volcanoes

Natural variability : an important example ENSO

El Nino: weakening of trade winds
Warmer sea-surface temperatures

Adds variation to T on top of climate change