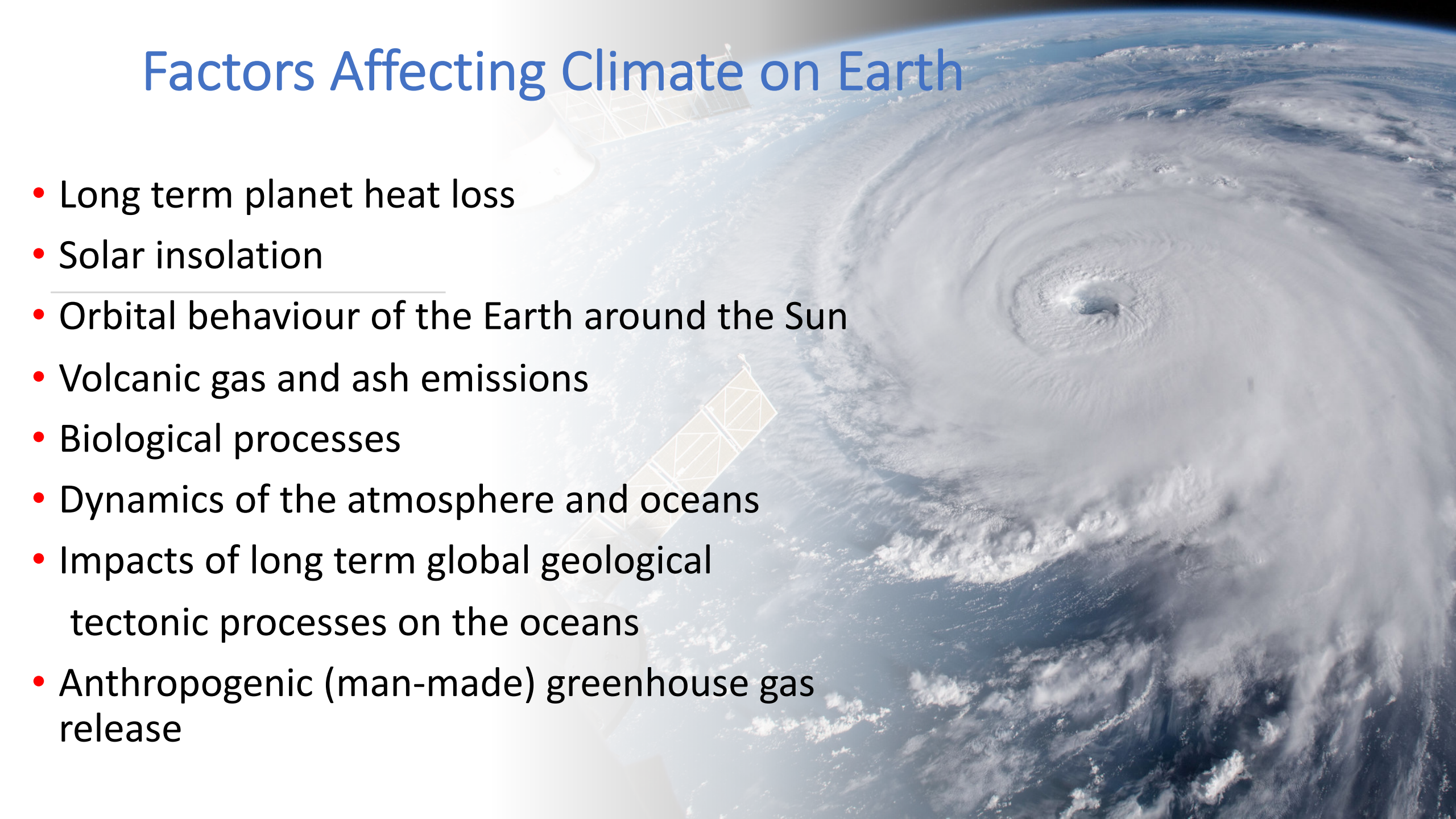
Assessing the factors that cause climate change:

- Are “industrial” greenhouse gases the main cause of recent global warming?
- Has climate change occurred throughout Earth history?
- If so, what factors contribute(d)?

Emeritus Professor Ray Cas,
Monash University

Factors Affecting Climate on Earth

- Long term planet heat loss
- Solar insolation
- Orbital behaviour of the Earth around the Sun
- Volcanic gas and ash emissions
- Biological processes
- Dynamics of the atmosphere and oceans
- Impacts of long term global geological tectonic processes on the oceans
- Anthropogenic (man-made) greenhouse gas release

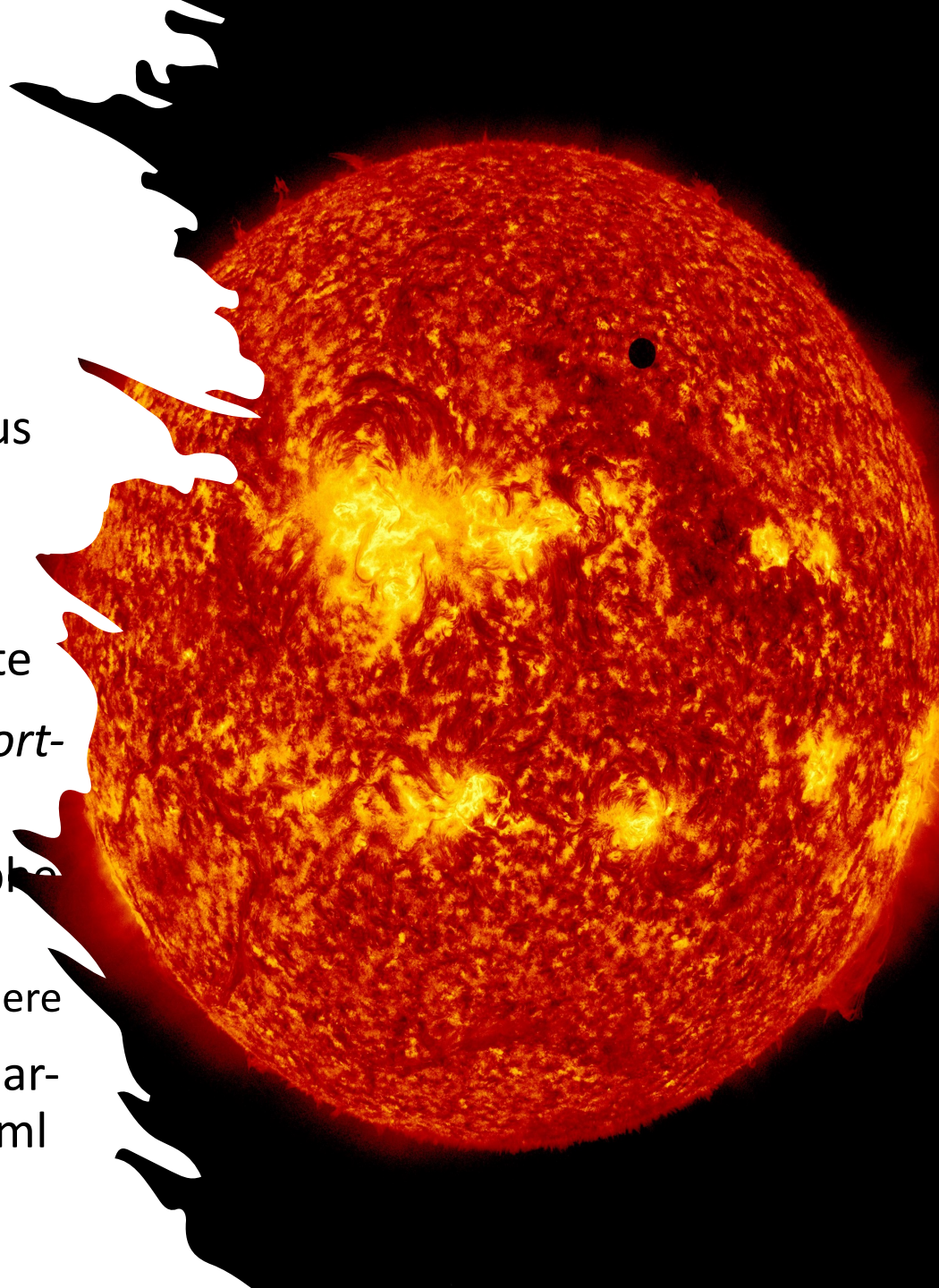


Long Term Planet Heat Loss

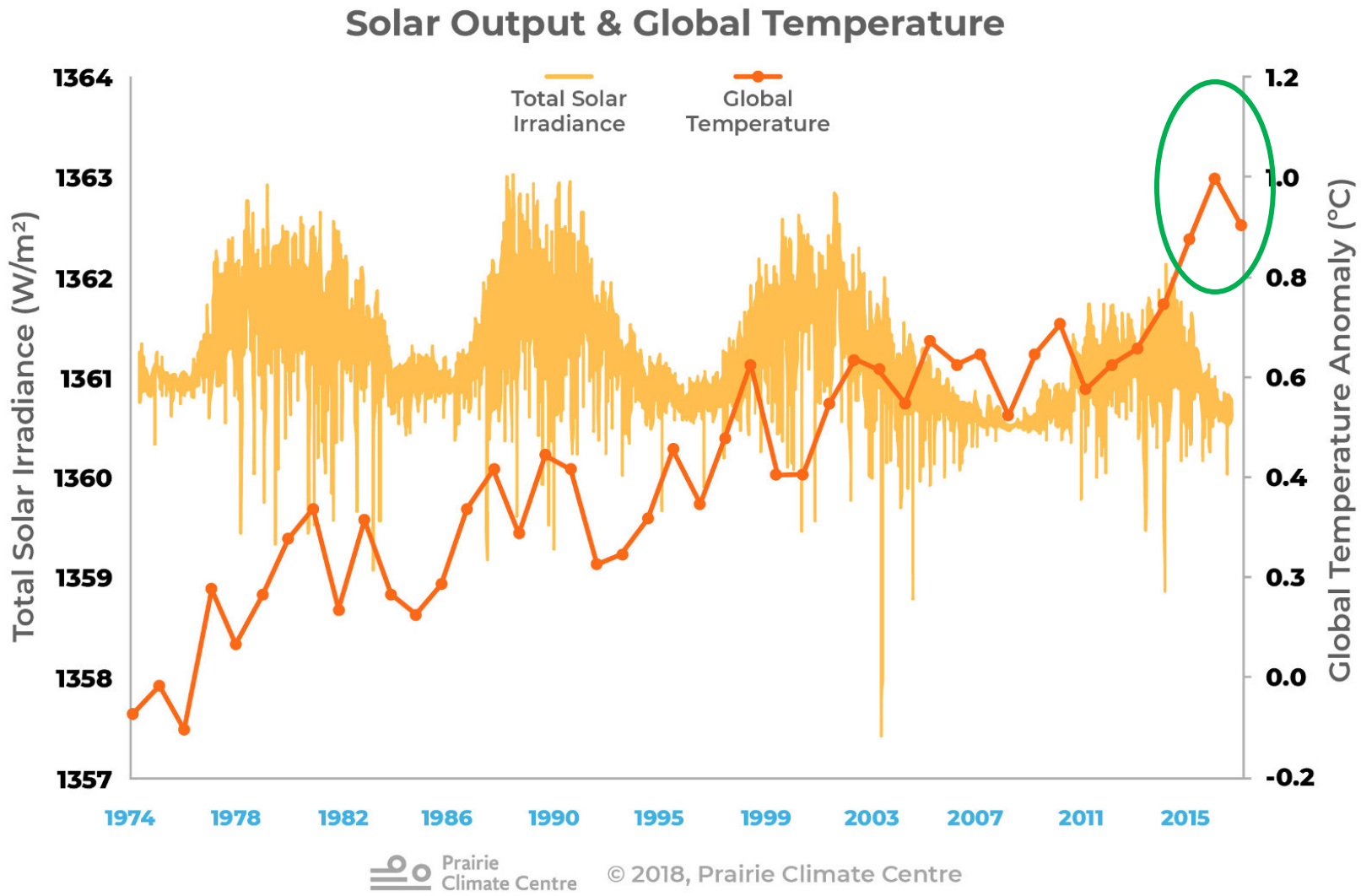
- Earth was a molten mass of magma when it formed ~4.5 Ga ago, surface T > 1200^{o}C
- It cooled to form a solid surface crust over ~ 50-100 Myr
- Since then, heat has been lost largely through volcanic eruptions and radiation
- Sources of heat
  - Residual from initial frictional accretion
  - Heat released from radioactive decay of elements in minerals
- Heat energy released to atmosphere is very small
  - ~ 0.09 watts / m^2
  - **Cf. solar radiation** adds ~ 340.2 watts / m^2
    - Source: Kren et al. J. Space Weather Space Clim., **7**, A10 (2017)

Solar Insolation

- It takes ~ 8 minutes for solar radiation to reach Earth
  - Travelling ~ 300,000 km/second over 150,000,000 km
  - Heating effect on atmosphere and earth is instantaneous
  - Much is reflected back to space
- Solar radiation output varies on an ~ 11 year cycle
- Cycles and atmospheric temperature changes don't correlate
- Global temperature changes due to insolation cycles are *short-term* and ~ 0.1 - 0.4^{o}C according to NASA
- BUT the upper atmosphere is cooling and the lower atmosphere is warming (NASA)
  - -> indicate that heating is coming from the Earth-lower atmosphere
- Source: https://www.nasa.gov/mission_pages/sunearth/solar-events-news/Does-the-Solar-Cycle-Affect-Earths-Climate.html



Solar Insolation: variations vs Earth temperature

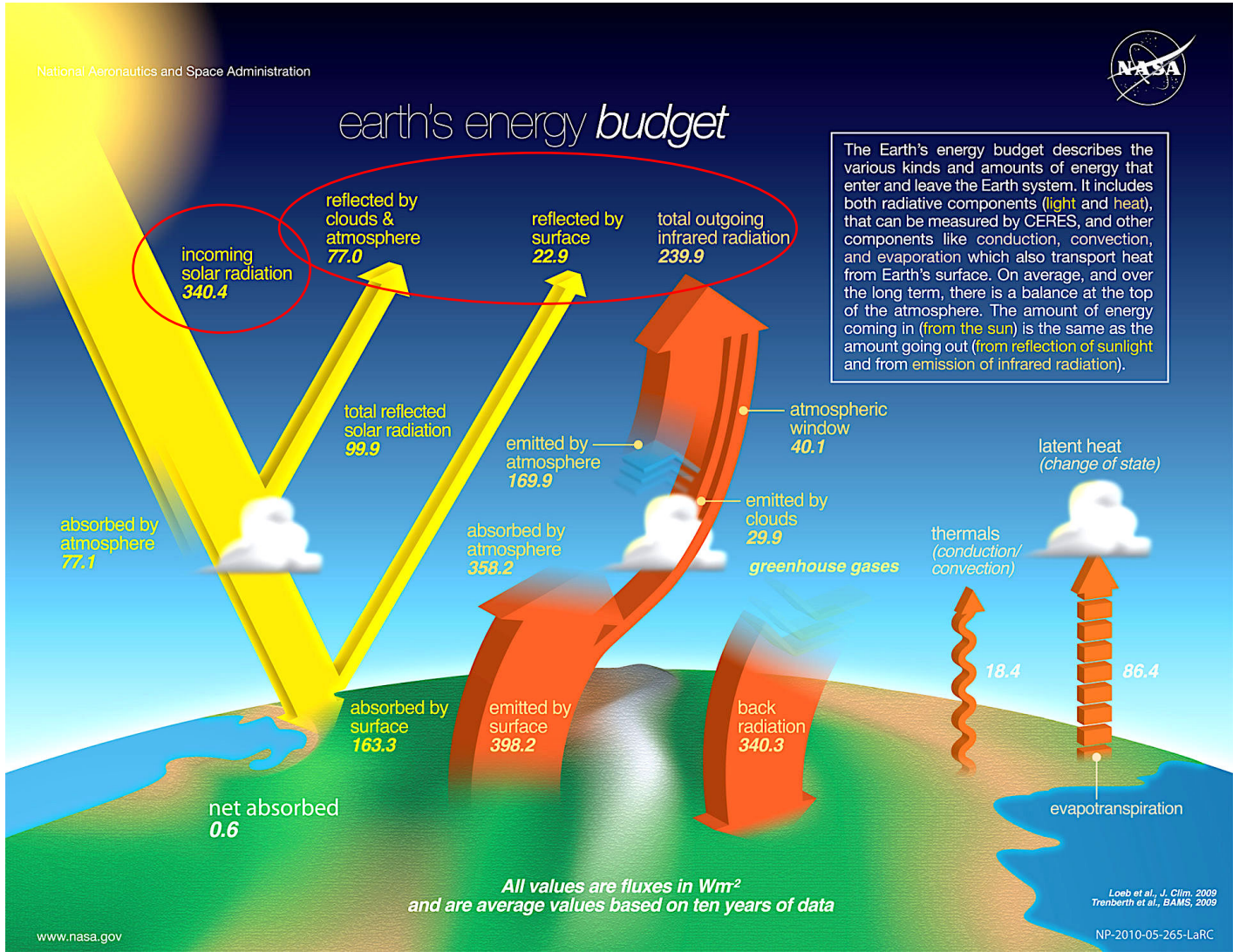


Source: University of Winnipeg, Canada

- **CONCLUSION**: ***Changes in solar irradiance (yellow) do not appear to cause global temperature (red) and climate change***

Balance of Incoming Solar vs. Outgoing Earth Radiation

- According to NASA it's about the same
- Solar insolation does not appear to have caused climate change
- Loeb et al. (2021)* show that the amount of radiation leaving the Earth relative to incoming solar radiation has decreased in the last 20 years
  - i.e. more heat is being retained by the atmosphere

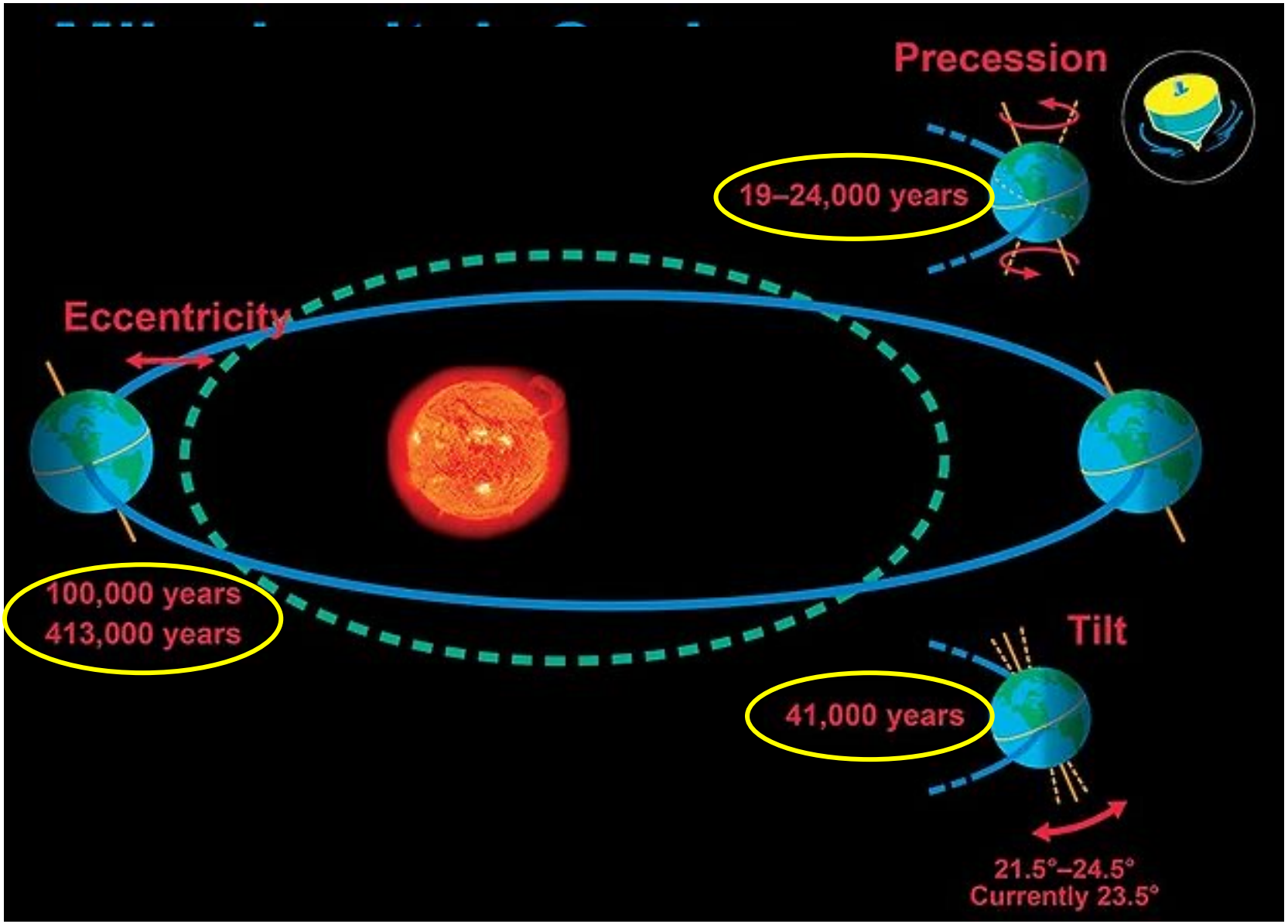


- * Loeb et al. Geophys Res Letts (2021) https://doi.org/10.1029/2021GL093047

Orbital behaviour of the Earth around the Sun

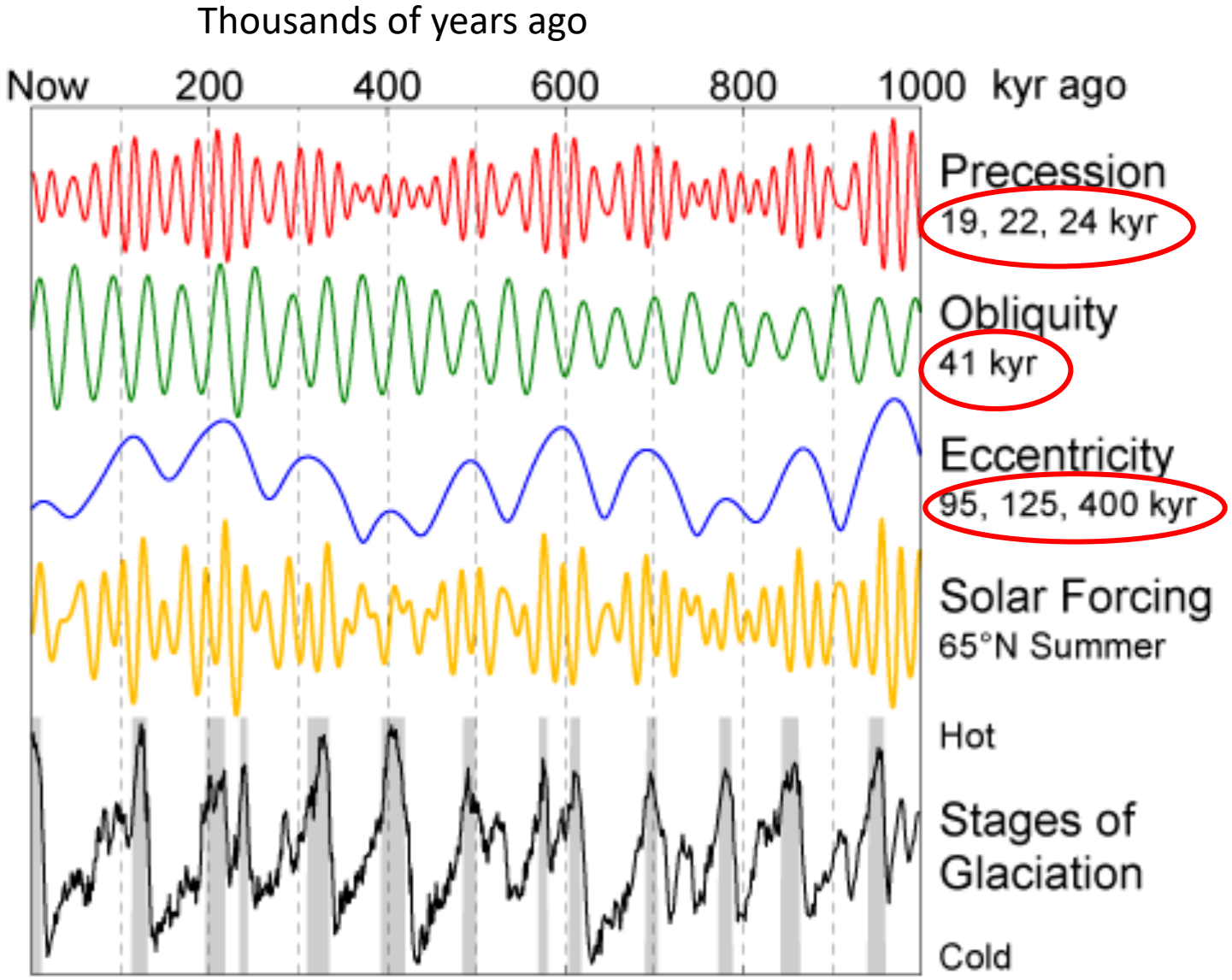
- Three main changes in orbital behaviour of the Earth around the Sun:
  - Changes in the *eccentricity* or shape of the orbit
  - Changes in the *obliquity / tilt* of its axis of rotation relative to the plane of orbit
  - Changes in the *precession* or rotation *of the earth's axis of rotation (i.e. time it takes for the axis to gyrate a full circle as it wobbles; cf. spinning top)*
- Affect global climate
  - Cycles of climate change called Milankovitch Cycles or orbital forcing
    - About 100,000-year cycles of cooling and warming

Orbital behaviour of the Earth around the Sun



Milankovitch* Cycles of climate change?

From NOAA



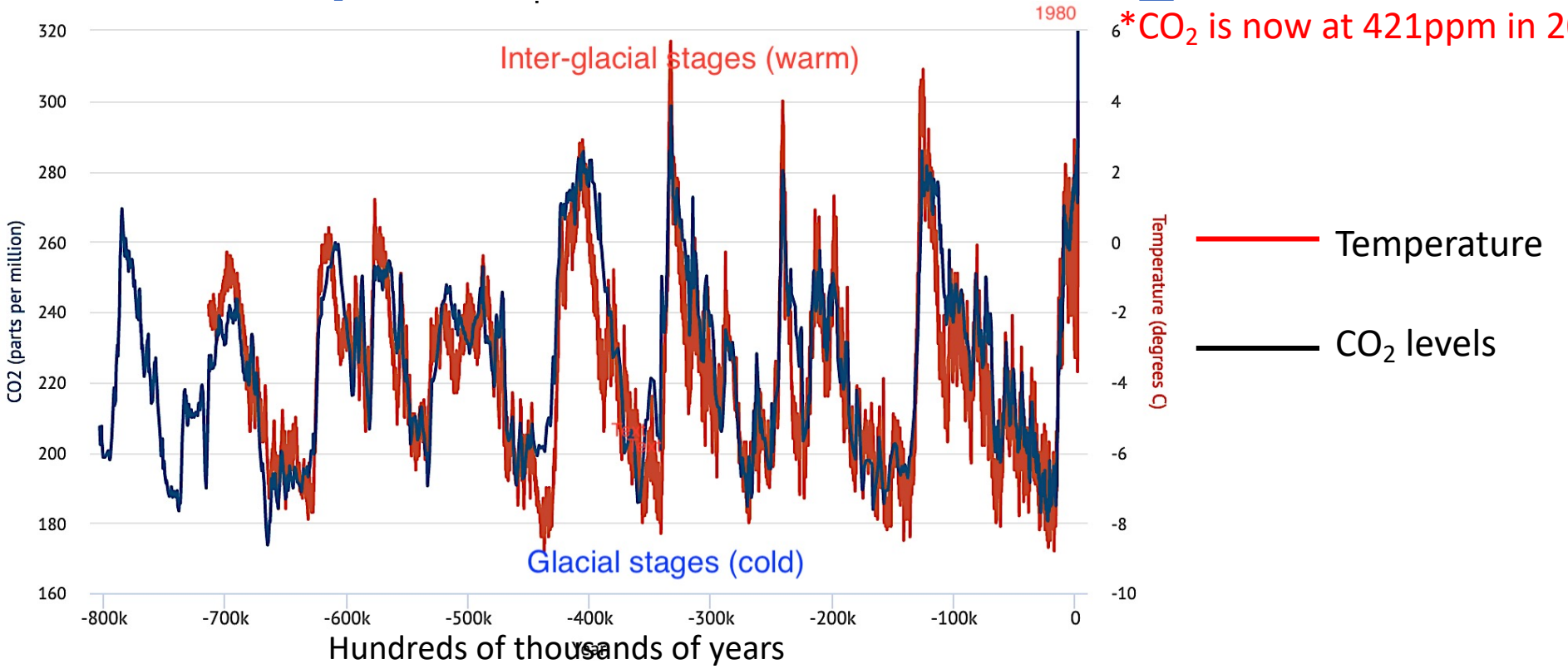
*Serbian astronomer and Geophysicist, 1920's

- ***Temperature changes due to orbital cycles take thousands to tens of 000's of years***

Milankovitch* Cycles of climate change?

*CO_2 is now at 421ppm in 2022

From Carbon Brief



https://www.carbonbrief.org/explainer-how-the-rise-and-fall-of-CO_2-levels-influenced-the-ice-ages/

Antarctic reconstructed air temperature (red line) at Dome Fuji site Antarctica using isotope modelling from Uemura et al (2018) and Antarctic composite ice core atmospheric CO2 data (blue line) from Bereiter et al (2014). Data spans the period from 800,000 BCE to 1980 CE. Chart by Carbon Brief using Highcharts.

- ~ 100,000 year Milankovitch warming and cooling cycles (but also CO_2 levels)
- ***Temperature changes due to orbital cycles take thousands to tens of 000's of years***

  ~ 0.1°C per 100 years

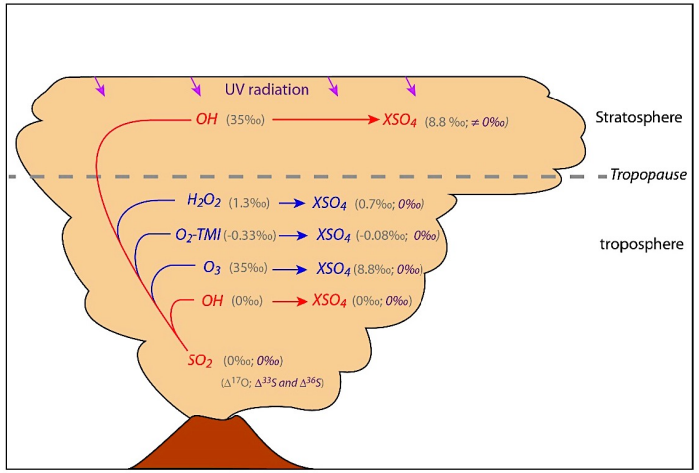
Volcanic Origins of the Atmosphere and the Oceans

- Volcanic gases produced the atmosphere
  - since the Earth formed ~4.54 Ga
  - degassing from the initial Magma Ocean
  - Gases released during ongoing volcanic eruptions
- Volcanic gas compositions:
  - H_2O (77%), CO_2 (11.7%), N_2 (3.0%), SO_2 (6.5%)
- Atmosphere gas compositions:
  - O_2 (21%), CO_2 (0.03%), N_2 (78%)
  - Why so different to volcanic gas?
- Rainfall from the atmosphere produced the oceans

Calbuco Volcano eruption, Chile, 2015

Volcanic Gas and Ash Emissions: Heating and Cooling Effects on Climate

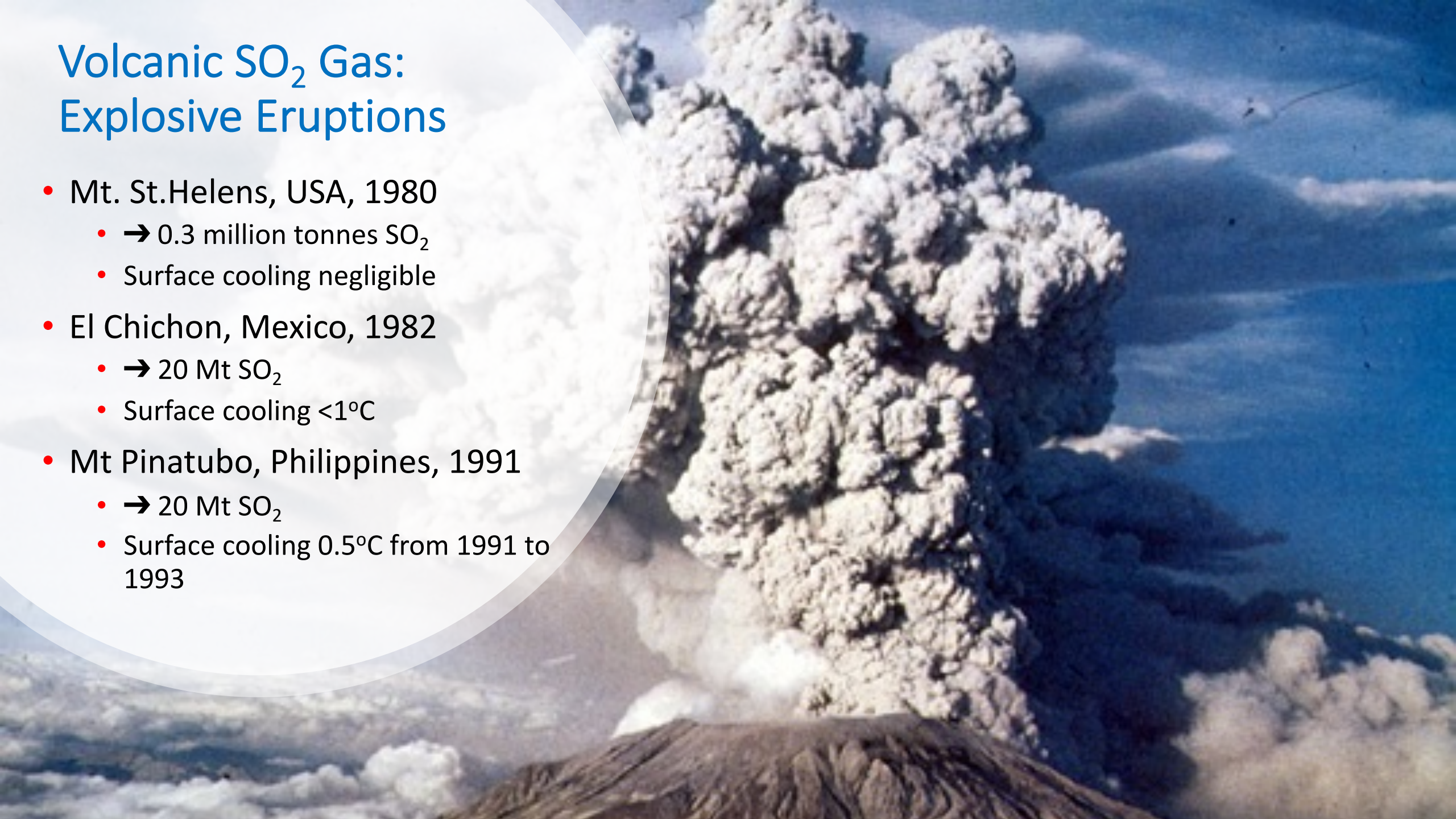
- Long-term release of CO_2
  - *Traps heat in the atmosphere* rather than being released to space
  - ➔ Enhancement of global greenhouse effect
  - Volcanoes annually release ~ 0.4 billion tonnes CO2 / year compared with 35 billion tonnes from man-made CO2 (Gerlach, Eos, v. 92, 2011)
- SO_2
  - *Causes global cooling*
  - Oxidises through multiple reactions to H_2SO_4 (sulphuric acid) droplets
    - Called volcanic aerosol
    - Reflects solar radiation back to space
    - + Produces acid rain
- Fine volcanic ash dispersed into tropo- and stratosphere
  - *Causes global cooling*
  - Reflects solar radiation back to space
  - ➔ Increased atmospheric albedo
  - Large eruptions ->2-5 year effects, but potentially climate changing



From Martin 2018, Geosciences, 8, 198-2017, fig. 1

Volcanic SO_2 Gas: Explosive Eruptions

- Mt. St.Helens, USA, 1980
  - ➔ 0.3 million tonnes SO_2
  - Surface cooling negligible
- El Chichon, Mexico, 1982
  - ➔ 20 Mt SO_2
  - Surface cooling <1°C
- Mt Pinatubo, Philippines, 1991
  - ➔ 20 Mt SO_2
  - Surface cooling 0.5°C from 1991 to 1993

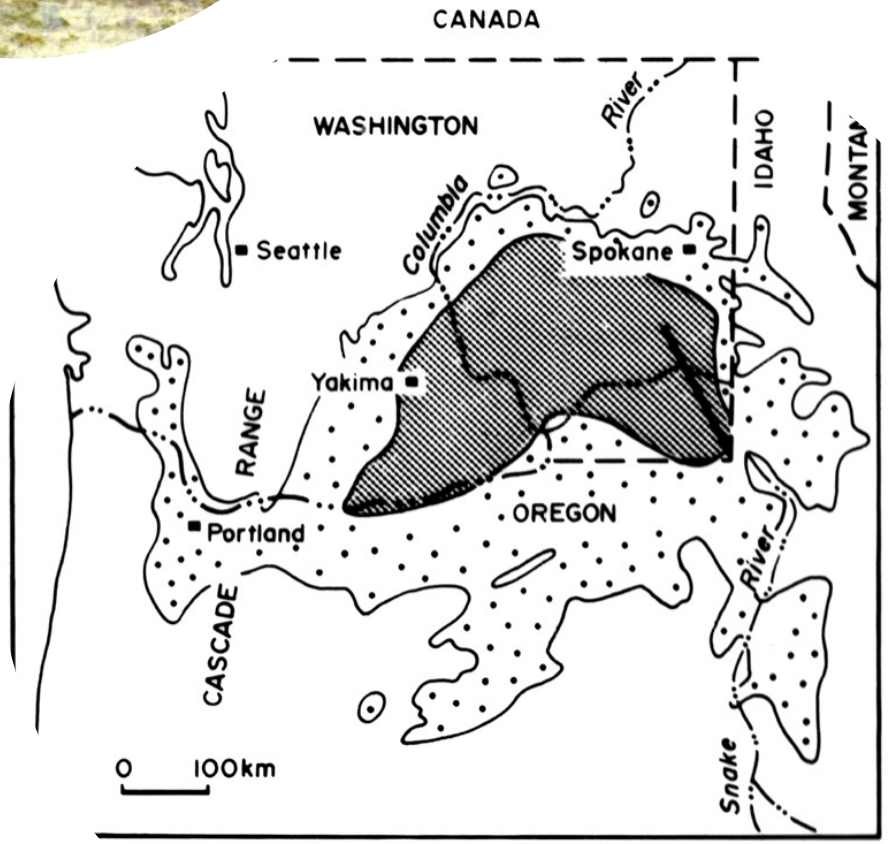


Volcanic SO_2 Gas: Ginormous Explosive Super-Eruptions

- Toba, Sumatra Indonesia, 74 ka, major explosive eruption
  - > 2,800 km^3 of ash
  - + 1000-5000 Mt of SO_2
  - ➔ Combined surface cooling of 3-5^o C+ for 3-4+ years
  - ? acceleration of glacial stage
  - ? threatened survival of homo sapiens

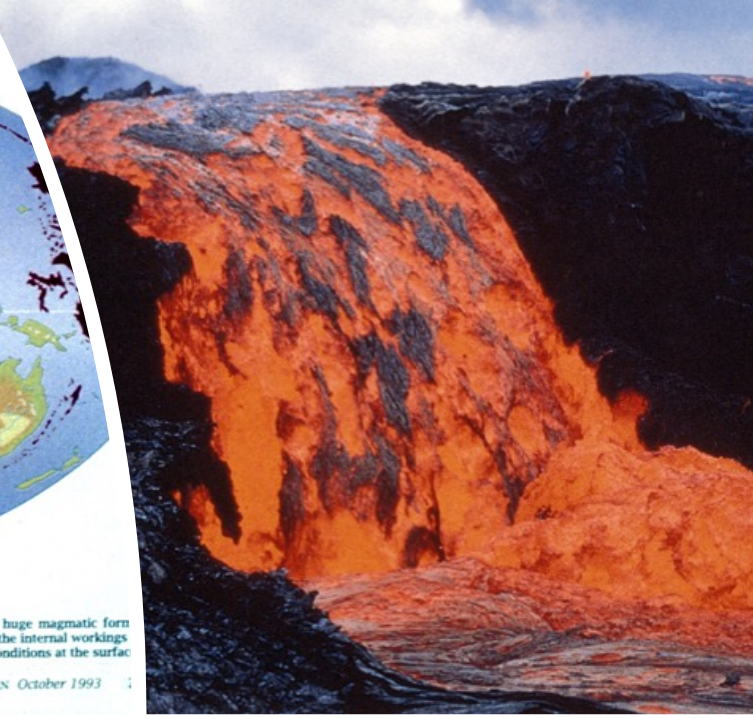
Volcanic SO_2 Gas: Giant "Flood Basalt" lava eruptions

- Roza *flood basalt lava eruption*, U.S.A., 14.7 Myr ago
  - 1300km^3 of lava erupted spread over > 40,000 km^2 (~0.2 area of Victoria)
  - ?10$^+$ year long eruption
  - Produced 12,500 Mt H_2SO_4
  - ?5-15^{o}C surface cooling
  - ➔ Volcanic winters (i.e. summers that are like winters)
  - Also 400 Mt HCl, 1450 Mt HF
    - -> O_3 depletion



Volcanic SO_2 Gas: Flood Basalt lava eruptions

- Major flood basalt events
  - ~Each 30 Ma
  - ? coincide with mass extinctions
    - Volcanic aerosol gases destroy food chains



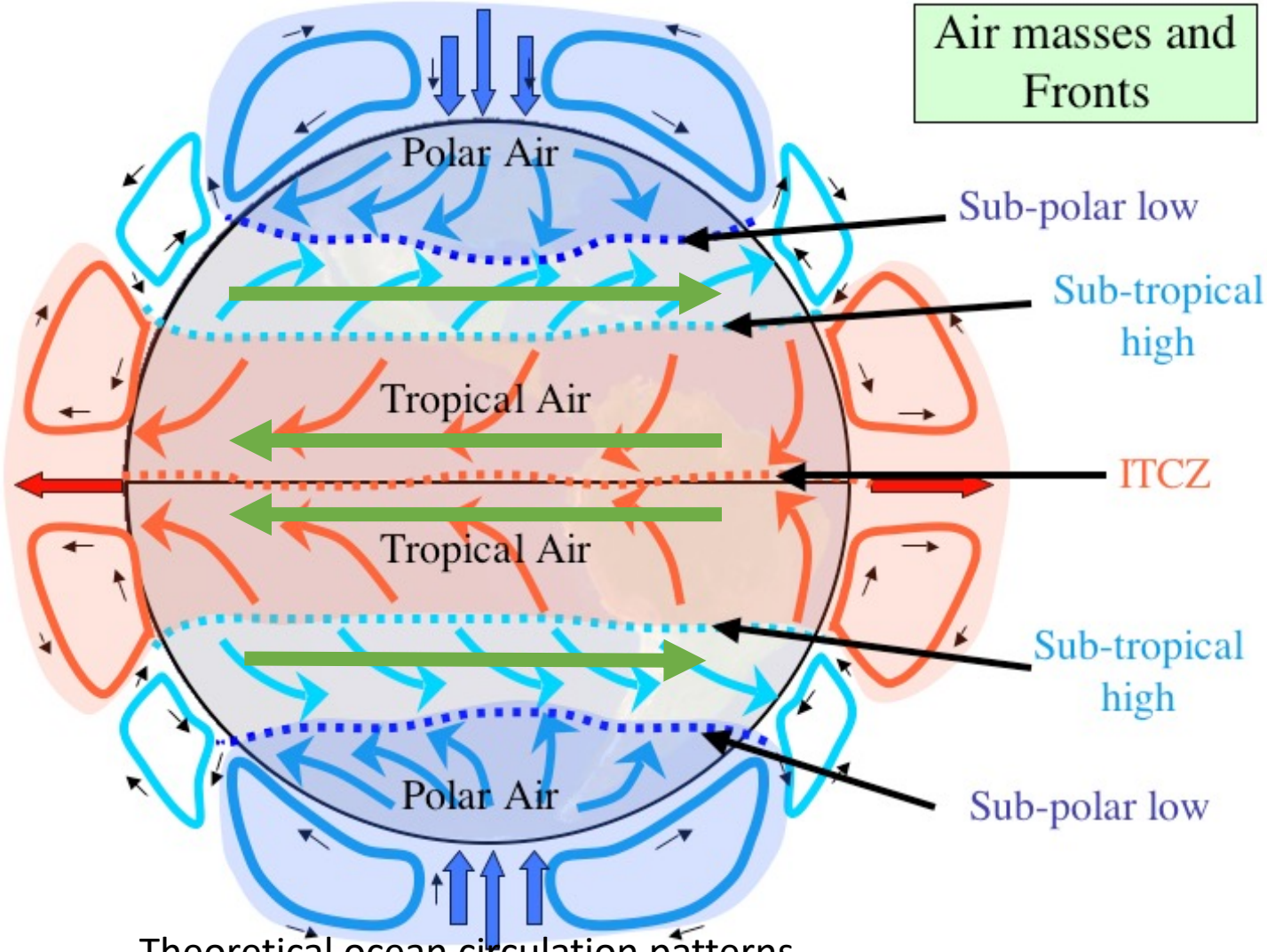
Biological processes

- *Photosynthesis*: Plants absorb CO_2 and release O_2
  - Reducing global plant cover therefore enhances atmospheric CO_2 content
- *Skeletal (endo- and exo-) organisms* use CO_2 to secrete $CaCO_3$ from food and the environment to build skeletons
- *Respiratory aerobic organisms* inhale O_2 and exhale CO_2 and some "release" CH_4 (e.g. cows)
- Decay of organic matter releases CO_2 and CH_4
- Before skeletal organisms evolved (~600 Million yrs ago) CO_2 levels were very high
- Before photosynthetic eucaryotic algal organisms evolved (~ 2 to 1 billion yrs ago) O_2 levels were relatively low and CO_2 levels very high (from volcanism)
- Before invertebrate marine respiratory organisms evolved (~ 550 M Yrs ago) CO_2 levels were relatively lower
- Changes are long term

Factors Affecting Ocean Current Patterns and Directions

- Atmospheric wind currents
  - 3 latitudinal circulation cells (blue and red arrows)
  - deflected by the Earth's anti-clockwise spin (Coriolis Force)
- Oceanic currents (green) are driven by wind shear and
  - also affected by Coriolis Force
  - -> latitudinal circulation cells
    - ***WITHOUT CONTINENTS***
- BUT both are affected by continents

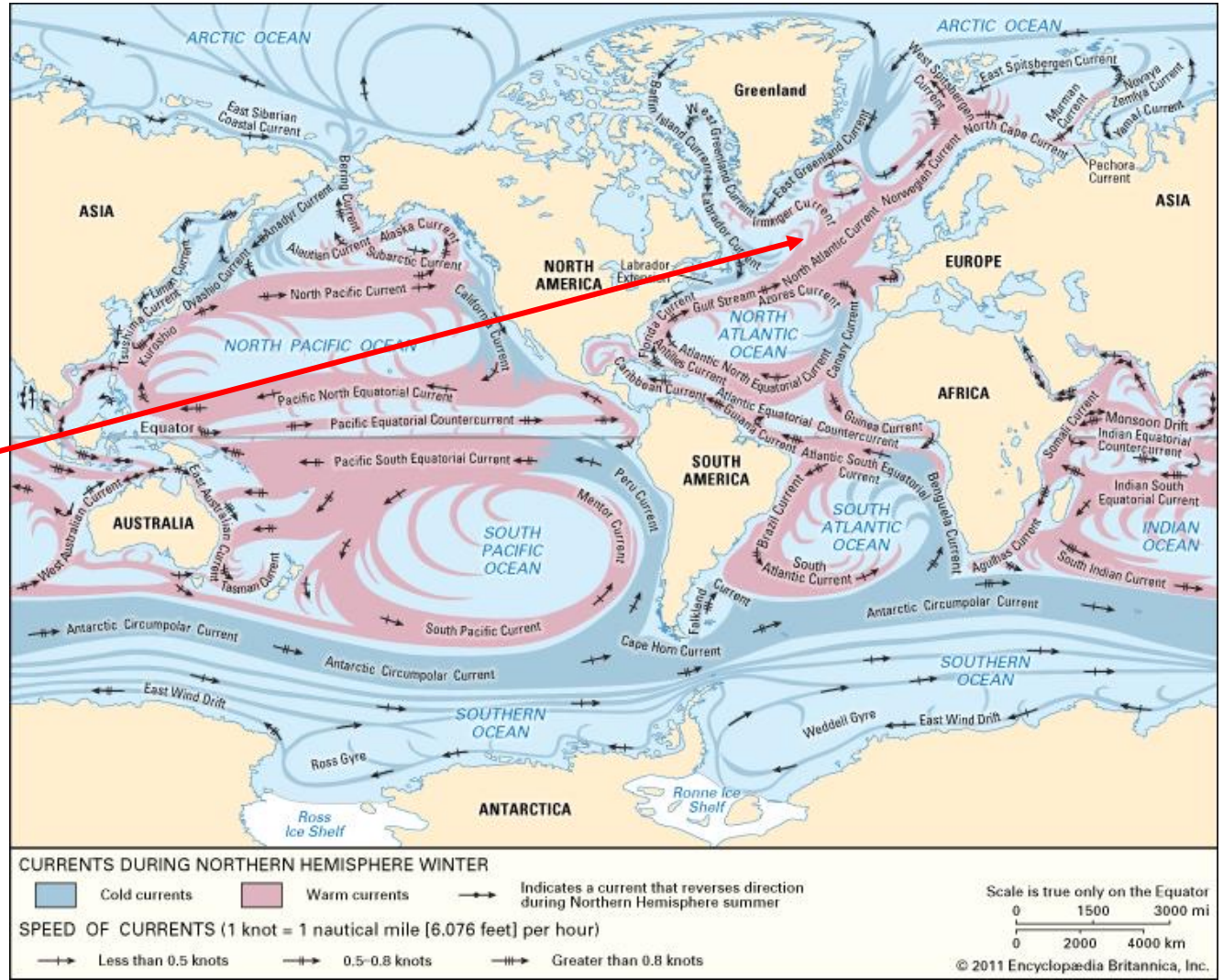
Atmospheric wind and circulation patterns (red and blue) From Wikipedia



Theoretical ocean circulation patterns, ***without continents (green)***

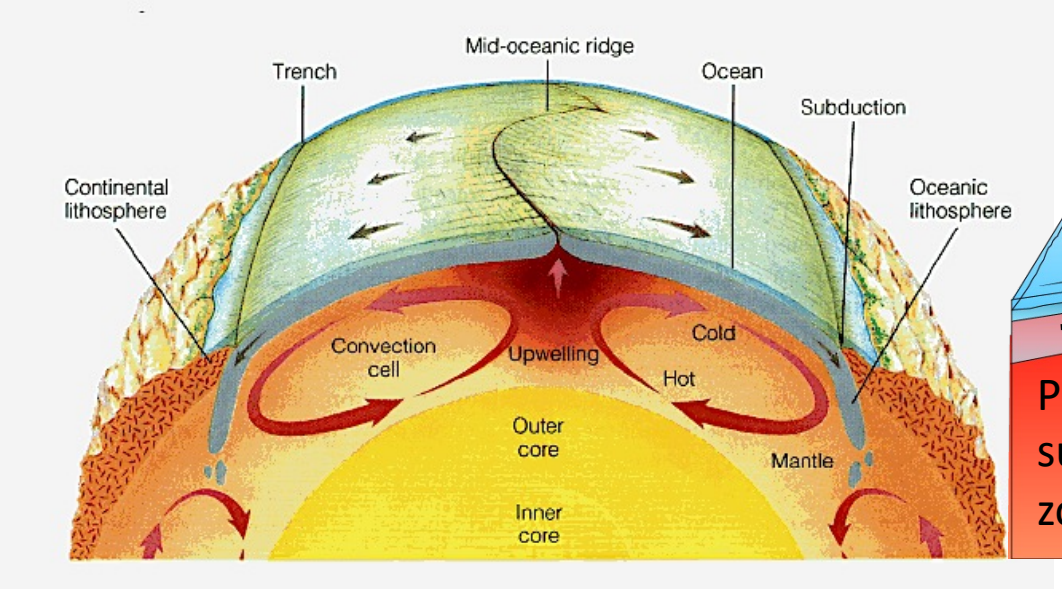
Continents Shape the Oceans and Deflect Ocean Currents North and South

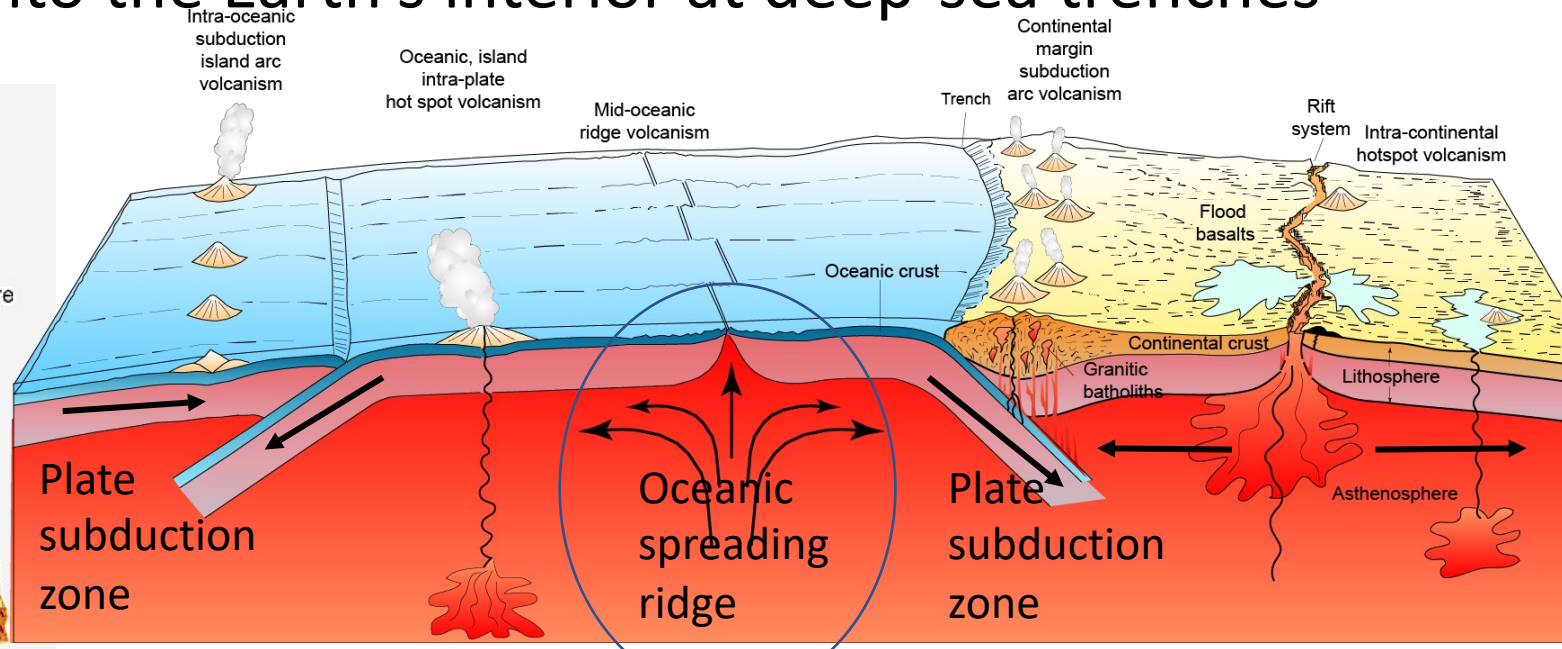
- Oceans are the heat sinks for global climate
- Location of continents
  - determines shapes of oceans
  - and the major gyre circulation cells
- Continents deflect latitudinal currents north and south
- Warm tropical waters deflected towards the poles
  - E.g. Atlantic Gulf Stream
  - ➔ increased evaporation, precipitation, snow fall and ice build up around the poles
- ***BUT have the continents always been where they are?***



Effects of Global Plate Tectonic Processes: Moving the Continents and Reshaping the Oceans

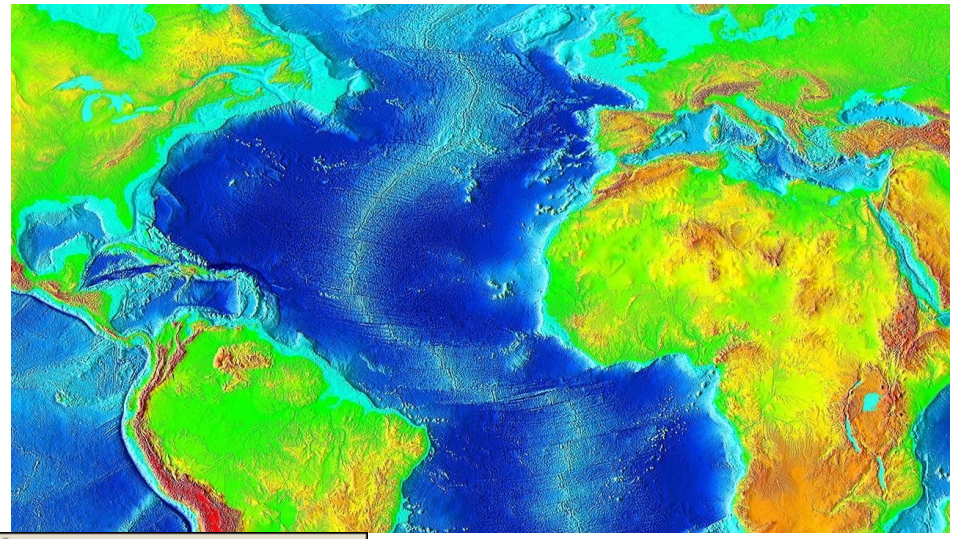
- The shapes of the oceans and the location of continents are constantly changing
  - through ”continents drifting” as passengers on global tectonic plate movement
  - *driven by mantle convection currents*
- Basalt is erupted at Oceanic Spreading Ridges forming new oceanic crust
- Old seafloor is recycled back into the Earth’s interior at deep-sea trenches

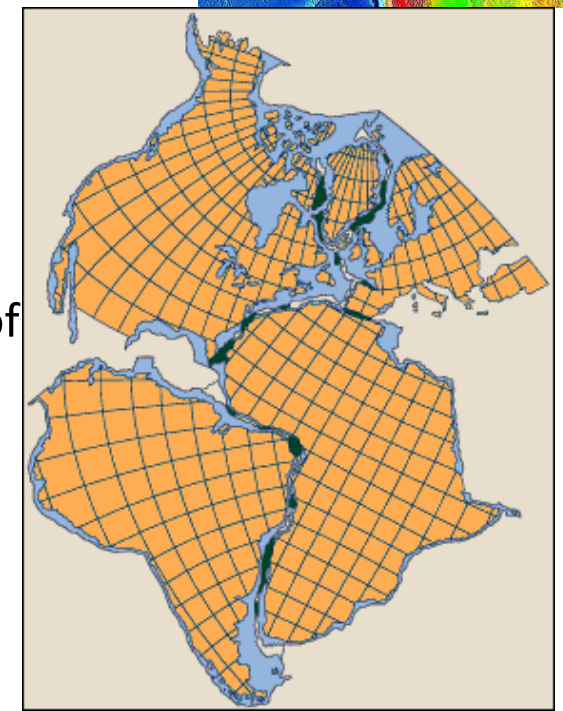


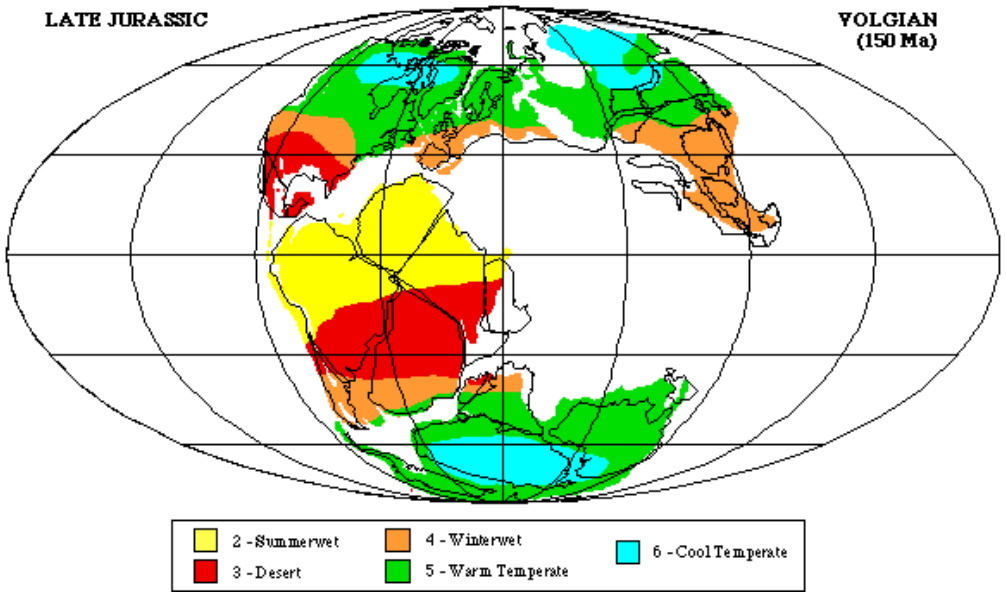


The Discovery of “Continental Drift”

- Alfred Wegener, German meteorologist (1880-1930)
- In 1912 proposed that the continents were drifting
- Based on geometric fit of the Atlantic Ocean continents
- And match of ancient climate belts in reconstructed supercontinent, Pangea
  - Glacial till(ite) that is diagnostic of widespread continental ice sheets
  - Desert dune complexes indicative of arid hot climate
  - Coal deposits indicative of widespread tropical to temperate swamps

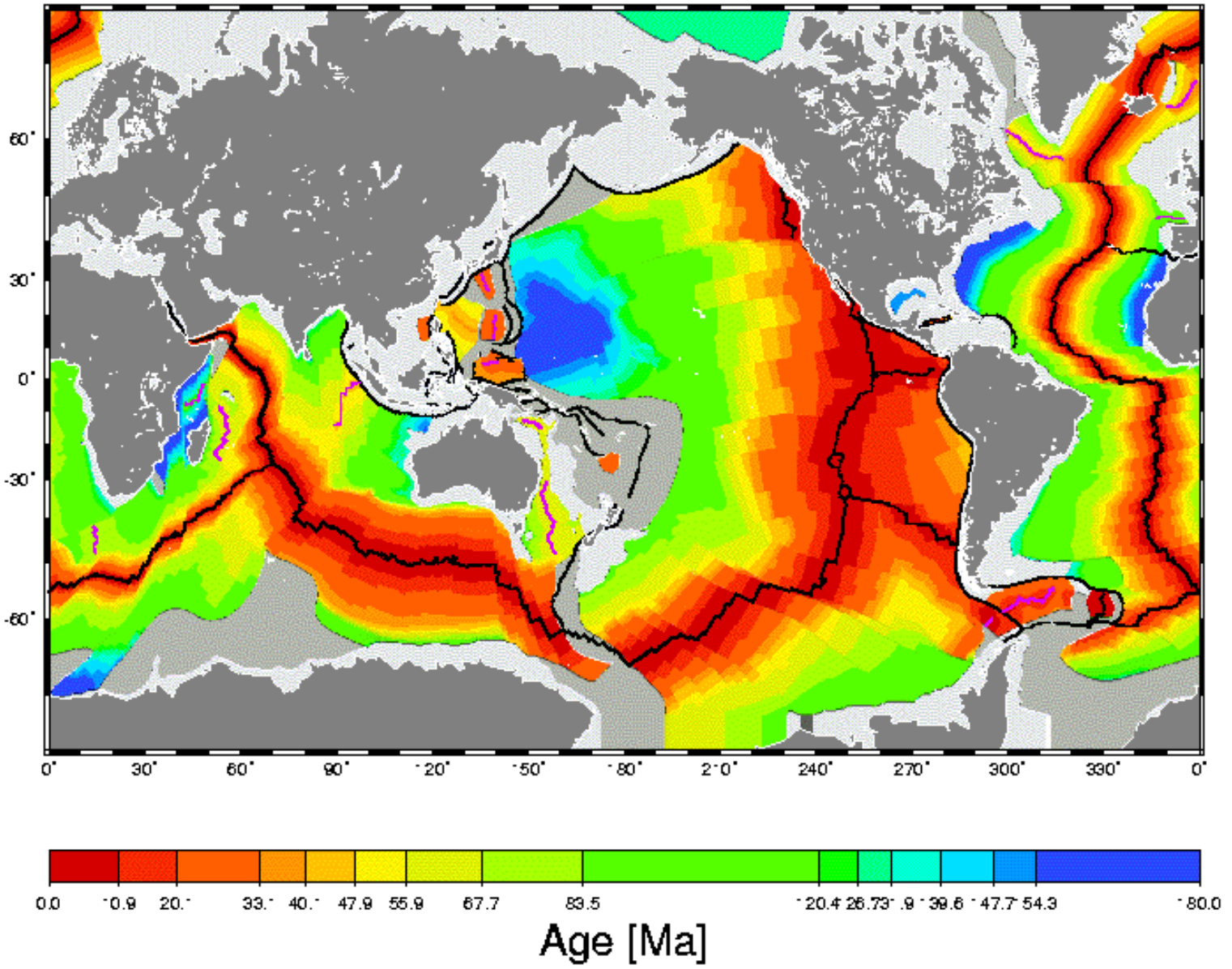






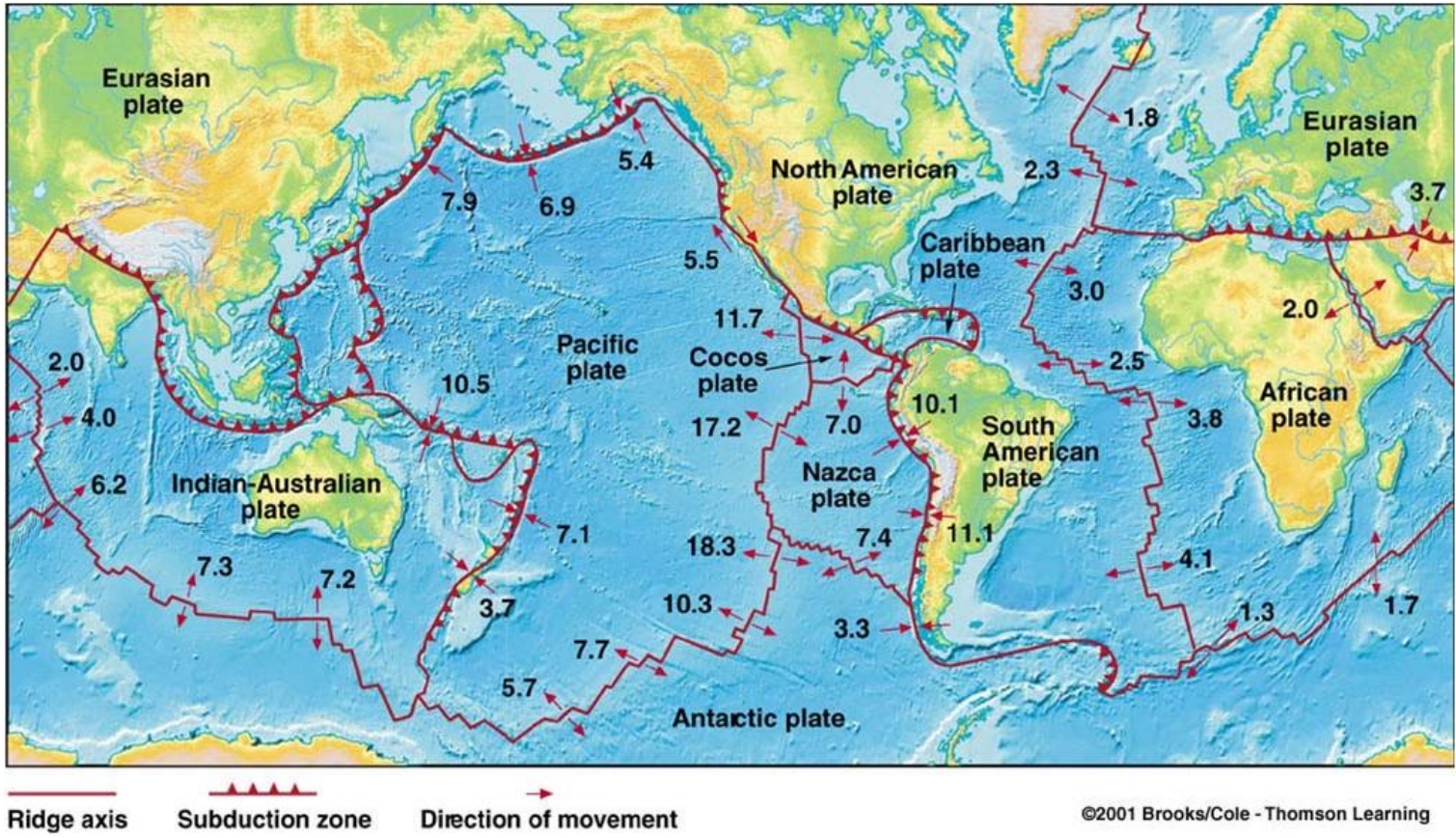
Proven through Discovery of the Age of the Sea Floor

- Discovery of symmetrical ageing of the seafloor either side of mid-oceanic ridges (Vine and Matthews 1962, *Nature*)



Effects of Global Plate Tectonic Processes: Reshaping the Oceans

- Rates of plate and continent movement vary globally (cm/yr)
- Where is Australia heading?
  - We will become even more multi-cultural than expected !
  - Our climate will become warmer
  - BUT our rate of northward migration is very slow
    - ~ 7 cms / year
    - = 7 m / 100 years
    - = 0.000026°C warming / 100 yrs*
    - ***- cf. ~0.8°C warming 1900-2000***



Seafloor Spreading or Movement rates are in cms per year

* Based on mean summer T Melb ~ 20°C, Bris ~25°C, distance between them 1375 km; = 0.0000036°C/m

Moving Continents and Changing Oceans: When Did the Oceans Assume Their Current Shape?

Plate Tectonics, Paleogeography, & Ice Ages
(540 million years ago - Present-day)

by

Christopher R. Scotese

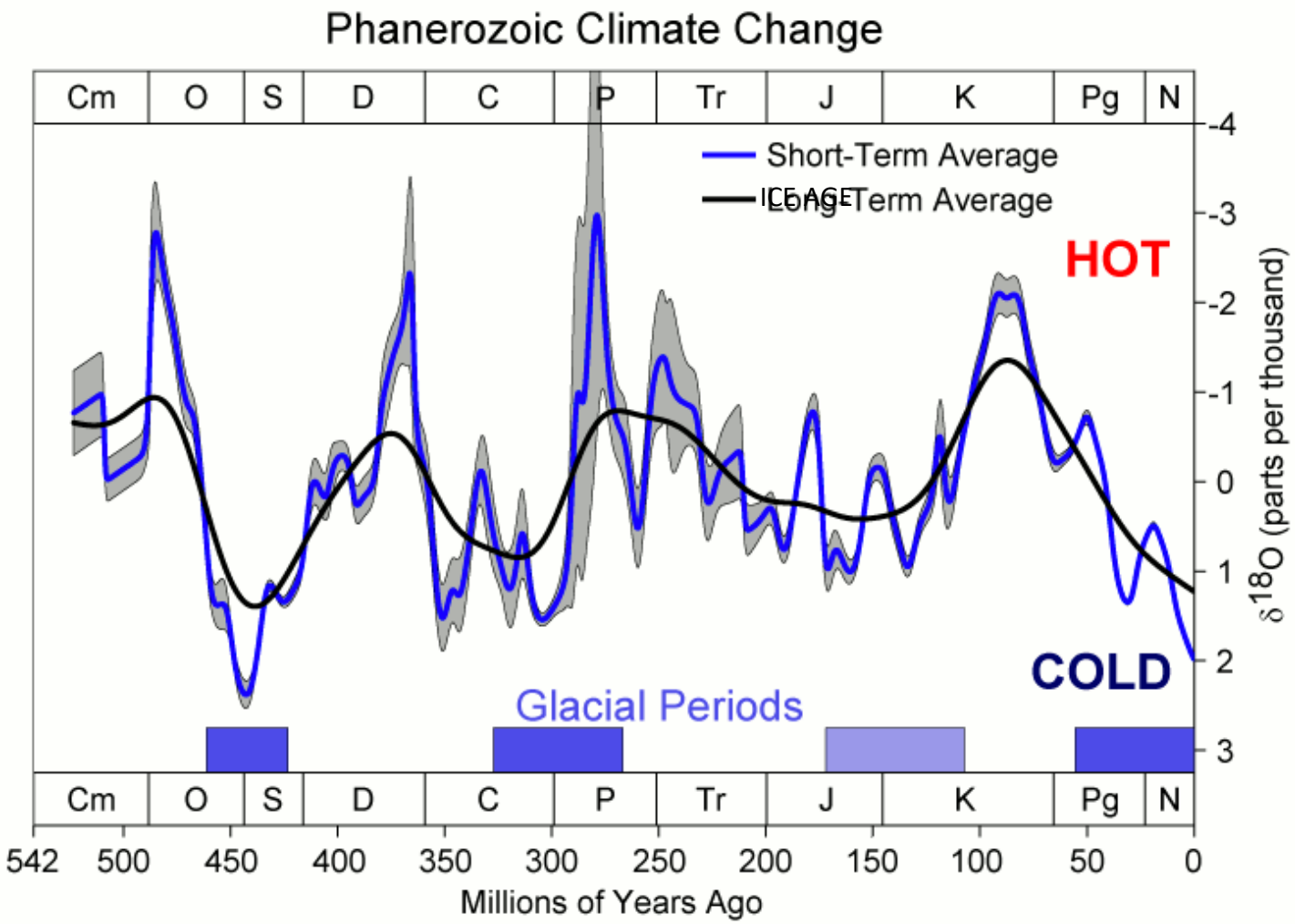
June 1, 2019

Did the Earth Experience Climate Change Before the Recent/Current Change?

- Yes!
- How do we know?
  - 1. Oxygen isotope ratio $_8O^{18}/_8O^{16}$ of fossil marine Ca CO_3 skeletons record ocean temperatures at the time the organisms were alive
    - During cold climatic periods, $_8O^{18}/_8O^{16}$ ratio is low; during warm climates it is high
  - 2. Certain ancient sedimentary rocks are diagnostic of specific climate conditions
    - Glacial till(ite), desert dune complexes, coal deposits
    - Occur at different paleolatitudes at different times in the past
- CHANGES WOULD HAVE BEEN *SLOW*

Long Term Temperature Trends and Climate Events

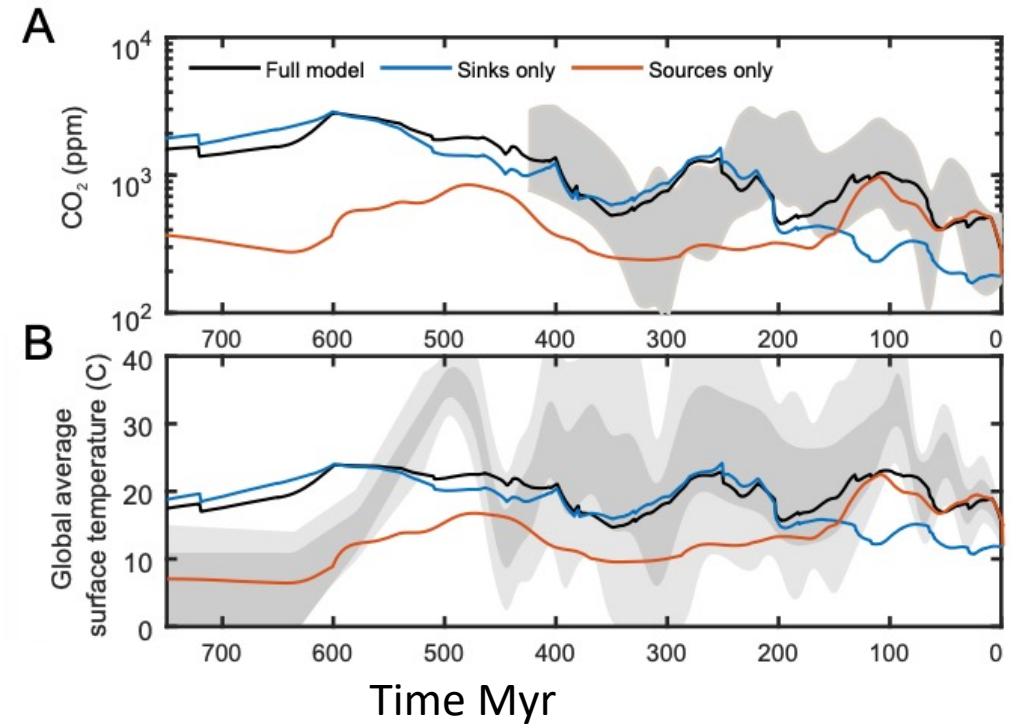
After Veizer et al. 1999, updated 2004
Chemical Geology 161, 59-88



Carbon Dioxide and Temperature Variations Through Time due to Biological and Volcanic Effects

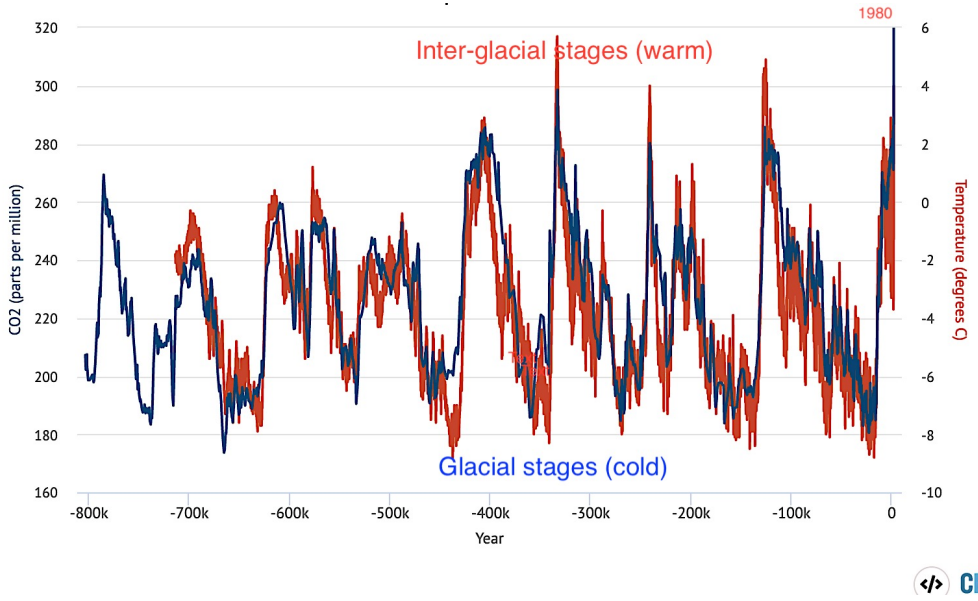
- Difficult to determine in the distant geological past other than through proxies and modelling
  - CO_2 data based on C and Sr isotope analyses of ancient marine sediments
  - T data based on O and Sr isotope analyses of ancient fossil shells

From Mills et al. 2019
Gondwana Research



The Current Pleistocene Ice Age

- The last/current Ice Age began ~ 2.8 M years ago because:
  - Continents converged on North Pole,
  - Isthmus of Panama was built by volcanism and blocked Atlantic west flowing tropical ocean currents by 4 Myrs ago, deflecting them to the Arctic via Gulf Stream
  - Favourable Milankovitch orbital forcing cycle of cooling
- Ice Ages experience cyclical cold glacial and warm inter-glacial stages
  - Multiple glacial and interglacial stages over the last 2.8 M years
- The current warm interglacial stage began about 15,000 years ago
- Will we experience another glacial stage and if so, when?
  - Theoretically, in the next ~20,000 years
- BUT will current global warming stop this? Freeze or Boil?



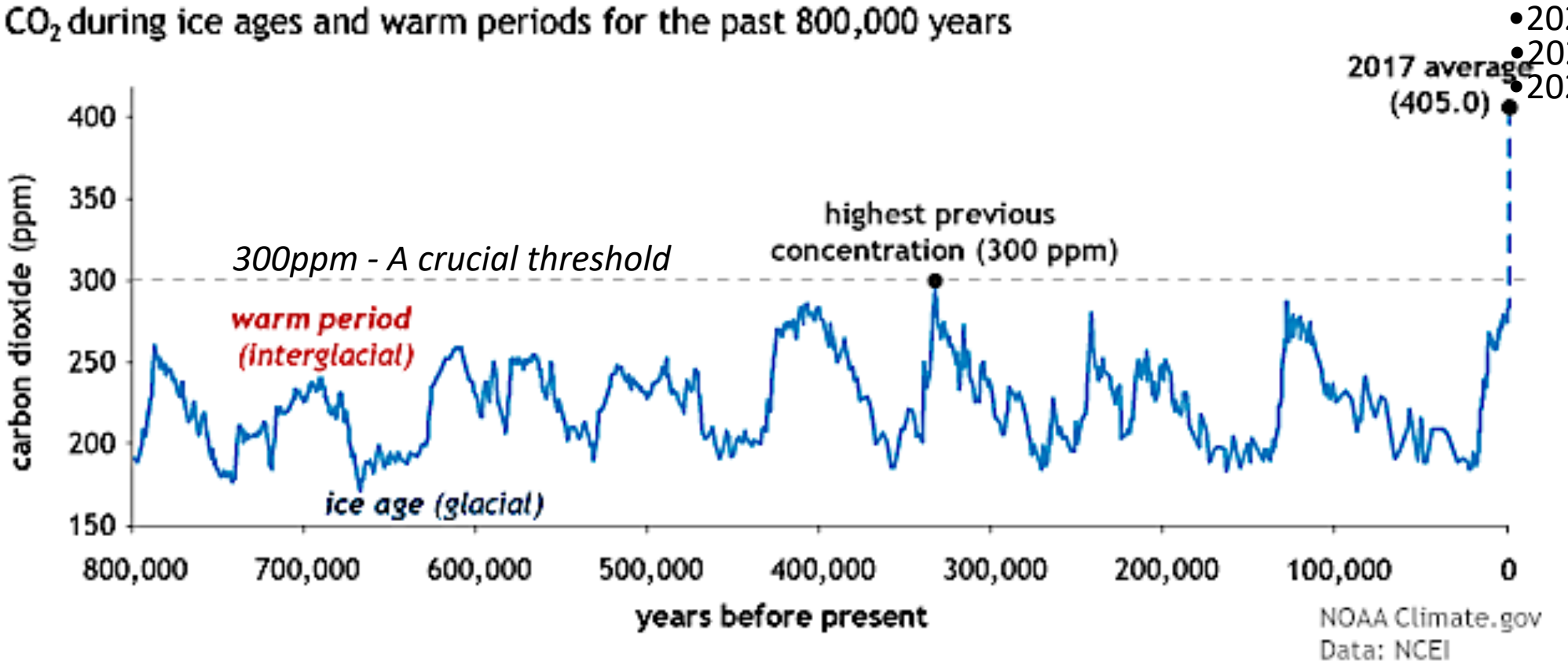
Antarctic reconstructed air temperature (red line) at Dome Fuji site Antarctica using isotope modelling from Uemura et al (2018) and Antarctic composite ice core atmospheric CO2 data (blue line) from Bereiter et al (2014). Data spans the period from 800,000 BCE to 1980 CE. Chart by Carbon Brief using Highcharts.

And finally …… The Current Global Warming Crisis: Man-made (Anthropogenic) Greenhouse Gases - CO_2, CH_4, N_2O and Their Effects

- Absorb and trap heat in the atmosphere -> Greenhouse effect
- CO_2 originates from
  - volcanic emissions, weathering of rocks, respiration, decay and burning of vegetation and fossil fuels, cement and coal extraction, farm ploughing
- Methane (CH_4) is the major component of natural (oil and) gas, and originates from
  - Decay of organic matter, burning oil, gas, coal, animal excretions, landfill
  - it also escapes during coal mining, oil, gas extraction, farm ploughing, permafrost melting
- Nitrous oxide (N_2O) originates as
  - natural emissions from bacteria and fungi in soils, and anthropogenically from *fertilisers*, burning of vegetation and fossil fuels
- CH_4 has ~28x the heat trapping capacity of CO_2
  - Naturally low levels but increasing rapidly post-IRevolution
- N_2O has 265x heat trapping capacity of CO_2
  - Natural levels are low but increasing significantly post-IRevolution

Carbon Dioxide Abundance in the Recent Past

- CO_2, CH_4, N_2O, O_2 levels can be measured in the atmosphere
  - And in the past from ice cores, in tree growth rings, in skeletons of fossil organisms
  - CO2 level changes mirror cycles of glacial (cold) and inter-glacial (warm) stages



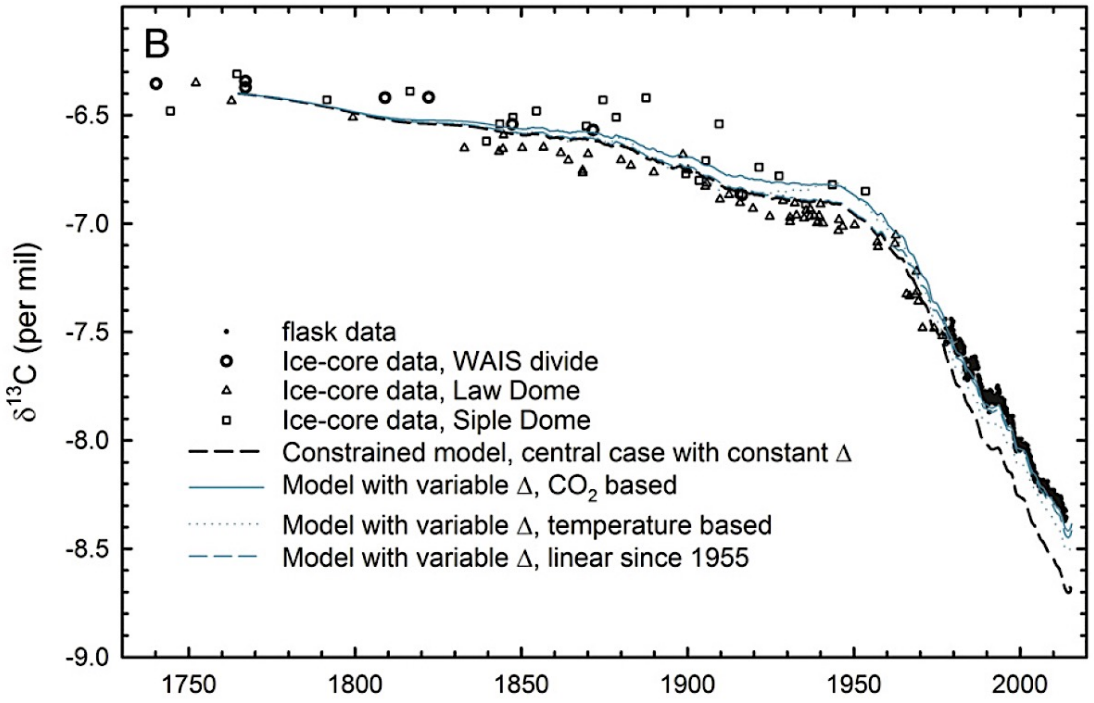
- 2022 421 ppm
- 2021 419 ppm
- 2020 413ppm

(*NOAA: Mauna Loa Observatory, Hawaii, May average; https://gml.noaa.gov/ccgg/trends/)

Based on data from the International Panel for Climate Change (IPCC) reports

The Key Question: Can we Distinguish or Fingerprint Anthropogenic Carbon Dioxide from Normal CO_2? Yes!

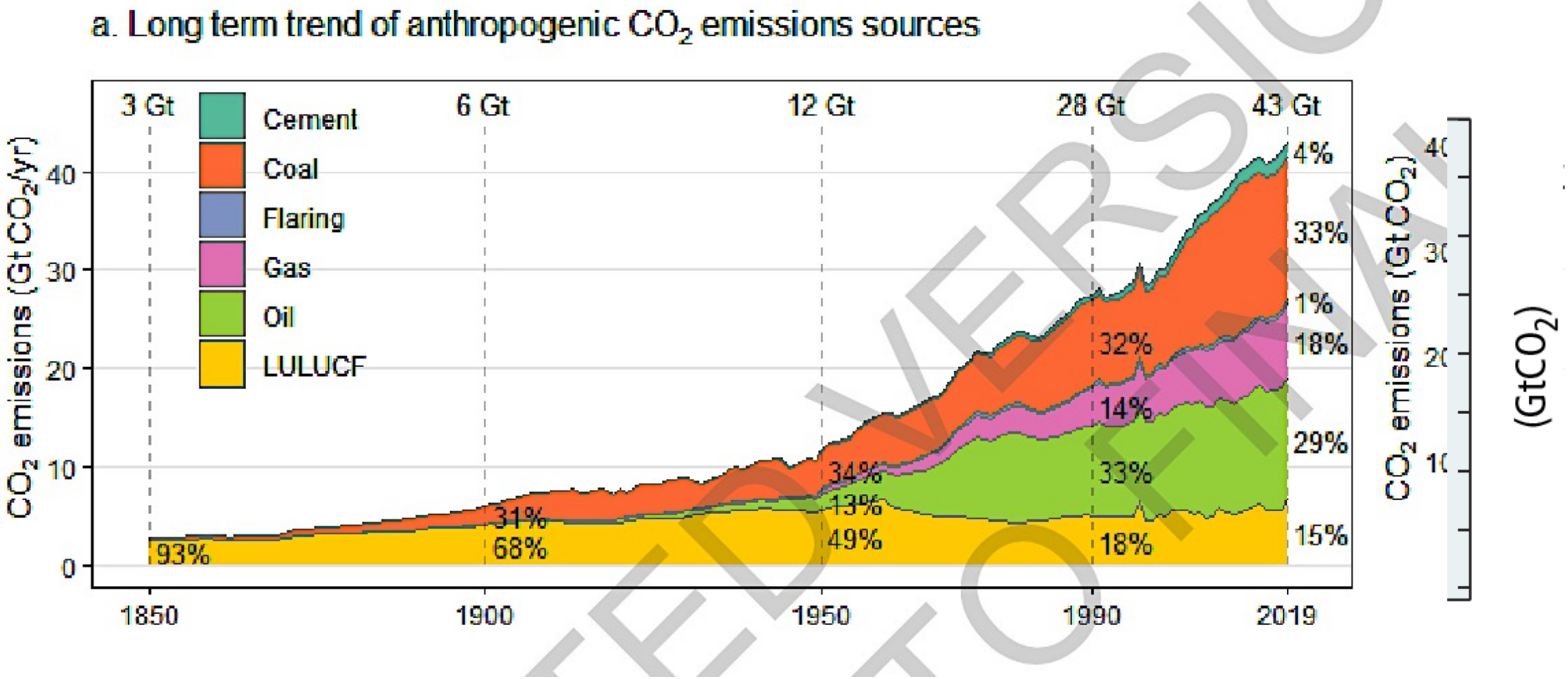
- From: the *RealClimate* website, produced by Climate Scientists:
- Carbon has 3 isotopes:
  - 12C, the lightest and most common (>98%)
  - 13C, heavy, minor (1%)
  - 14C, radioactive, rare
- The combustion of fossil fuels produces CO_2 with lower $^{13}CO_2/^{12}CO_2$ ratio than normal atmospheric CO_2
- The $^{13}CO_2/^{12}CO_2$ ratio of atmospheric CO_2 has decreased since 1750 and rapidly over last 50 yrs
- Therefore, anthropogenic CO_2 has increased
- ***-> the major cause of the increasing atmospheric CO_2.***



From Keeling et al. 2017, PNAS

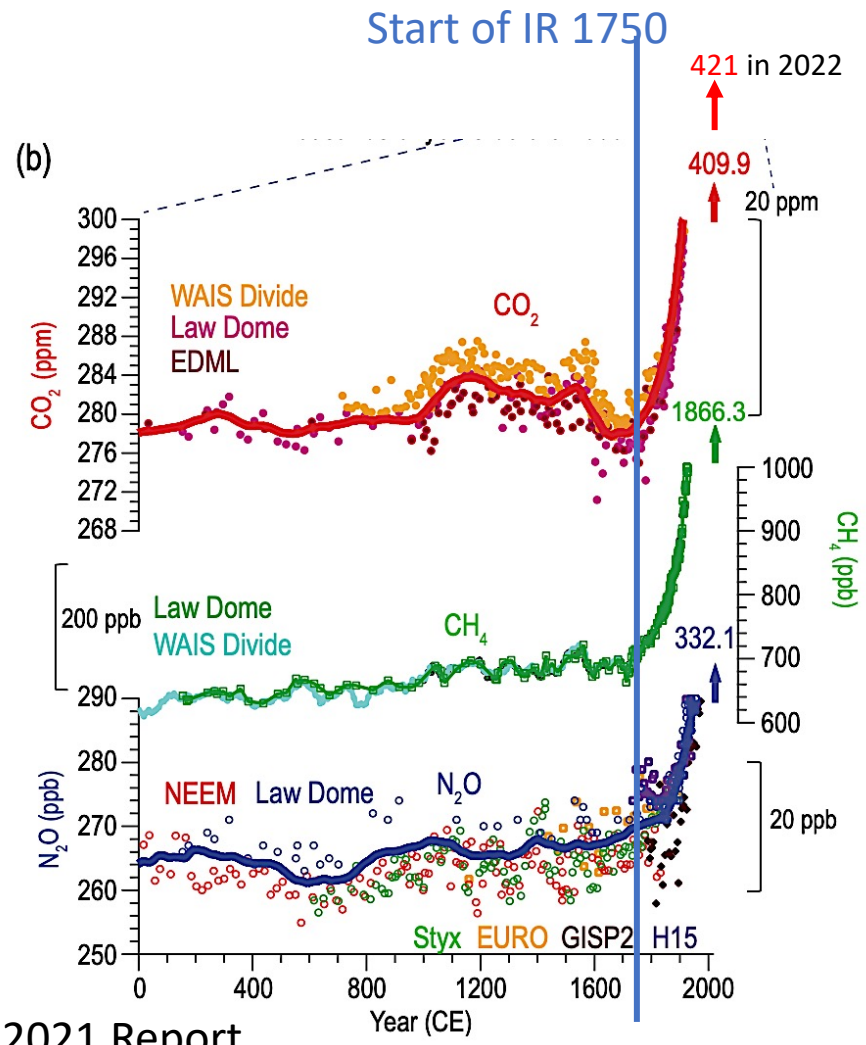
Anthropogenic CO_2 Source Rise Rates post-IRevolution

- Contributions of CO_2 from fossil fuel mining and burning to the atmosphere are accelerating alarmingly

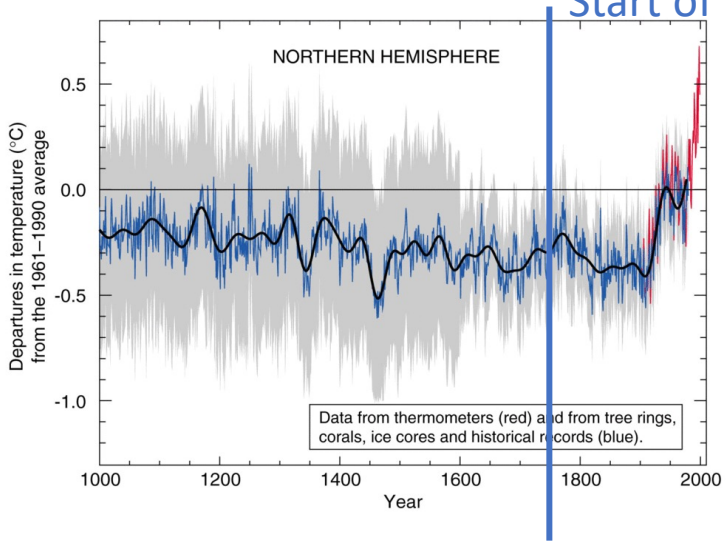


Source: IPCC Report 2021

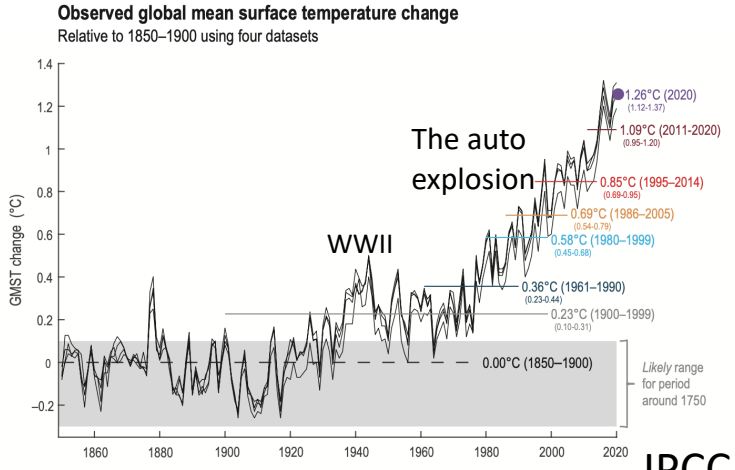
Relationship Between CO_2, Methane CH_4 and Nitrous oxide N_2O Levels and Temperature Change



IPCC 2021 Report



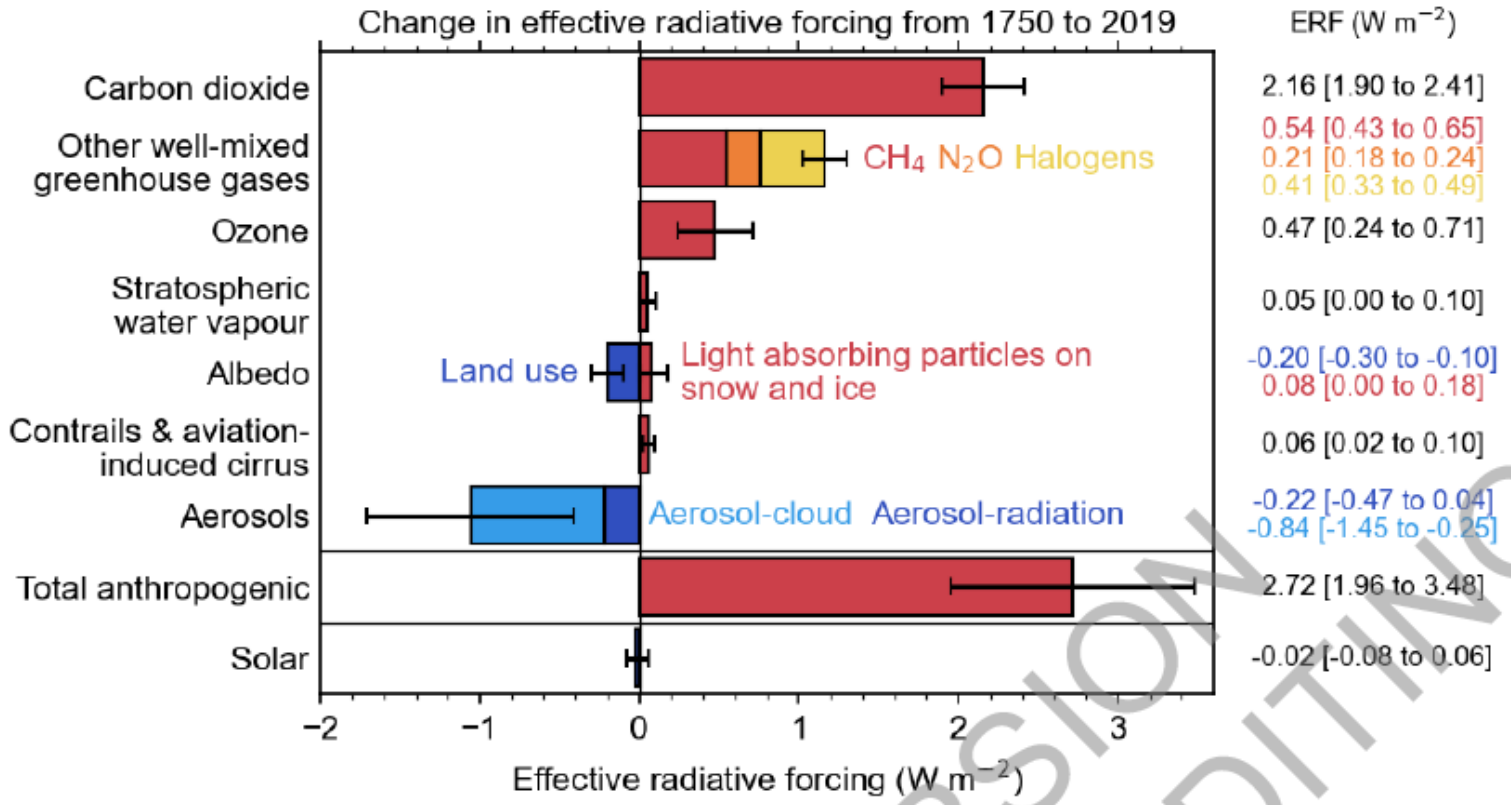
Temperature difference relative to 1961-1990 average



Temperature difference relative to 1850-1900 average

IPCC 2021 Report

Relative Warming Effects since 1750: Anthropogenic CO2, CH4, N2O, Halogens



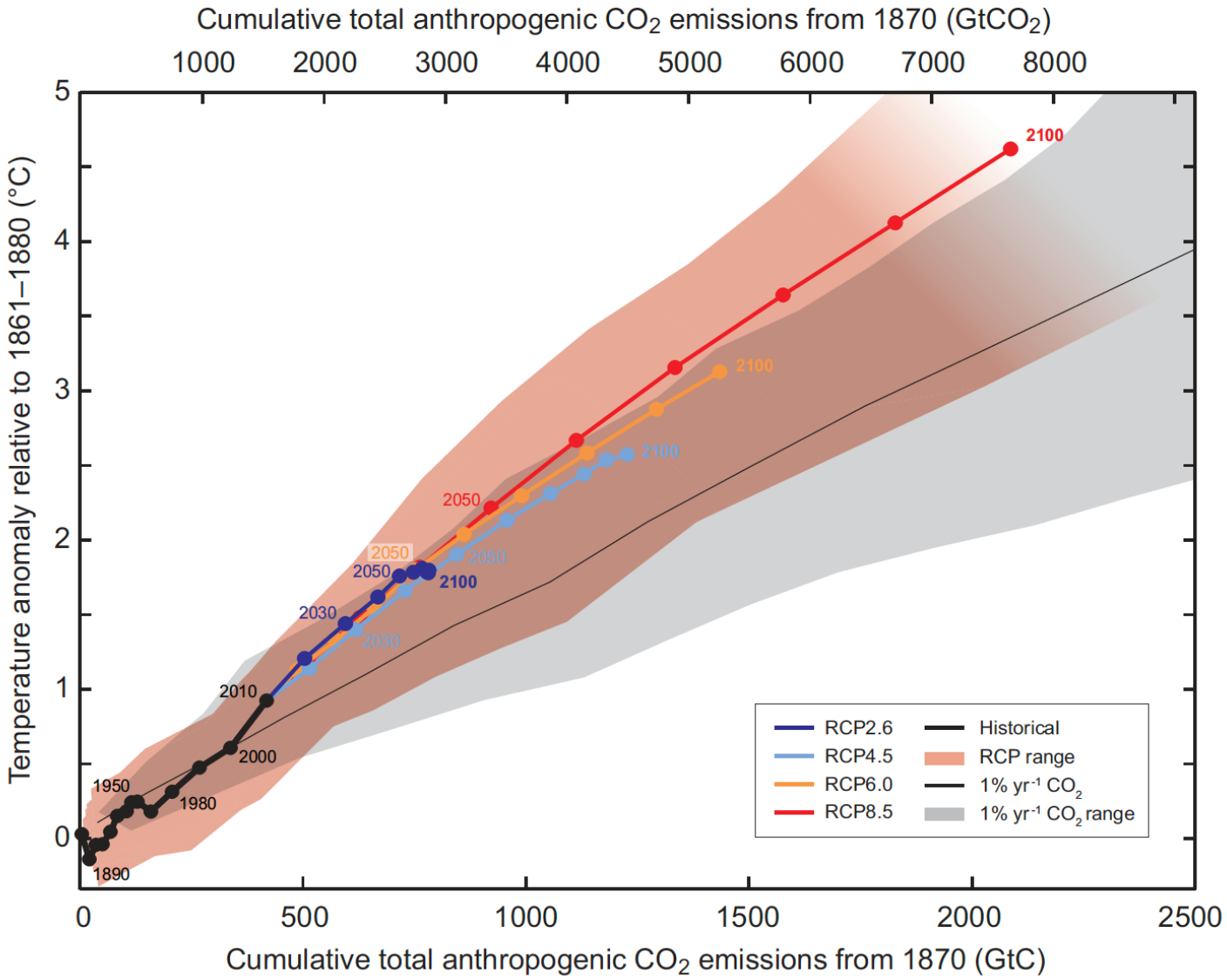
~ 50% CO2

~ 50% CH4, N2O, Halogens

Source : IPCC Report 2021

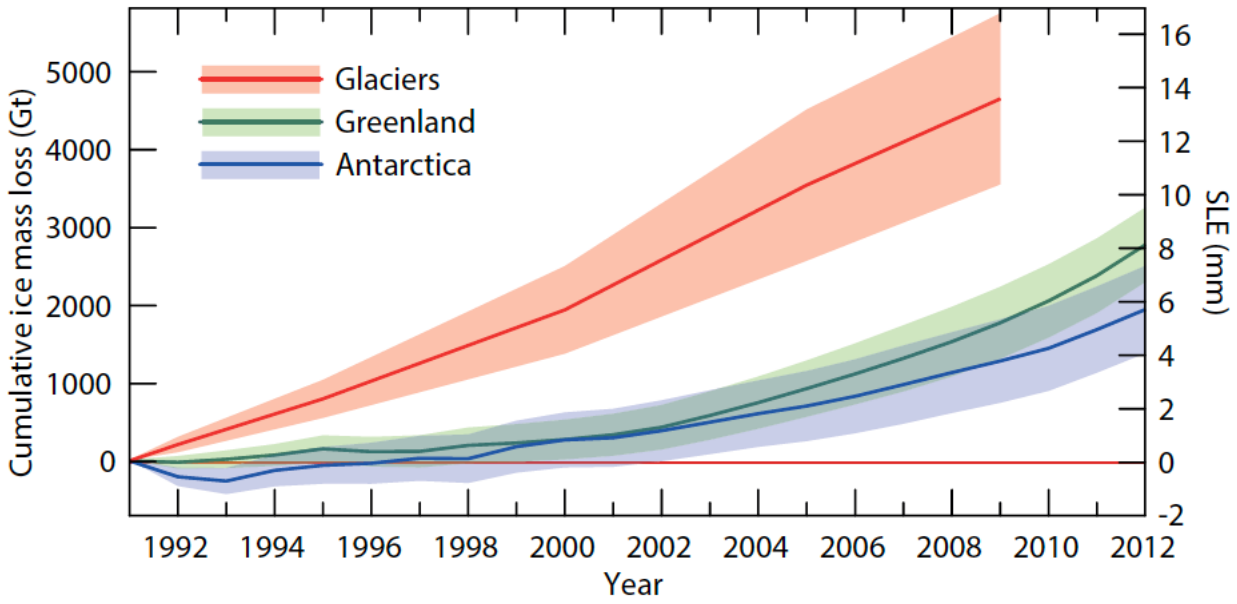
Figure 7.6: **Change in effective radiative forcing from 1750 to 2019 by contributing forcing agents (carbon dioxide, other well-mixed greenhouse gases (WMGHGs), ozone, stratospheric water vapour,**

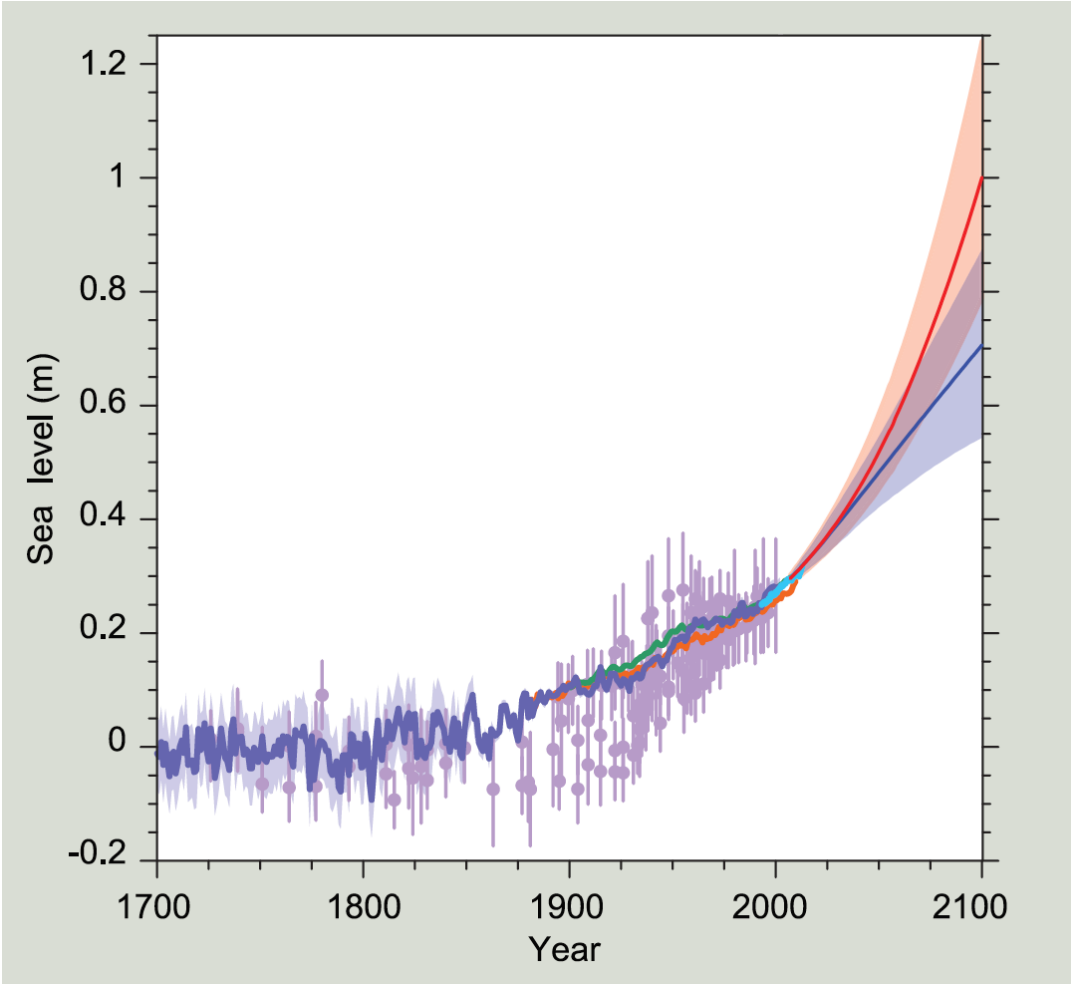
Projected Future Temperature Changes



From IPCC Report 2013

Loss of Glacial and Ice Sheet Ice and Sea-Level Rise





IPCC Technical Rept Summary 2014

Consequences of rising anthropogenic CO_2, CH_4, N_2O levels

- Increased atmospheric and ocean temperatures
- Higher sea level due to melting of glaciers and polar ice caps
  - **->** mass displacement of populations
- More extreme global temperature gradients and extreme weather
  - storms, droughts, fires
- Threats to native fauna and flora
- Threats to food production and water supplies
  - **->** famine
  - **->** mass migrations by “climate refugees”
- Acidification of the oceans
  - Absorption of CO_2
  - Death of marine exoskeleton marine organisms
  - Decay will release more CO_2 and CH_4 into oceans and atmosphere
  - -> further exacerbation of the climate crisis

Conclusions

- Climate change has occurred since the Earth formed involving
- A combination of insolation, biological, astronomical and geological-tectonic causes
  - The effects on climate have been profound
  - BUT the ***rate of change of climate through these processes is slow***
- Anthropogenic CO_2 CH_4, N_2O levels, global temperature and sea-level have increased significantly since the start of the industrial revolution
  - i.e. ***fast***
- Rapidly decreasing atmospheric $^{13}C/^{12}C$ ratio indicates rapidly increasing anthropogenic CO_2 levels
  - since the the start of the industrial revolution
- ***That is, extraction and burning of fossil fuels, extraction and use of cement are the cause of post-IRev climate change***.
- The only other "fast" factor, volcanic gas emissions, cannot explain the rising CO_2 levels.
  - No known major CO_2 emitting volcanic eruption has occurred in the last 250 years


Any questions?