Broadcasting Authority of Ireland Seminar

Climate Change: The Science

22nd September 2022

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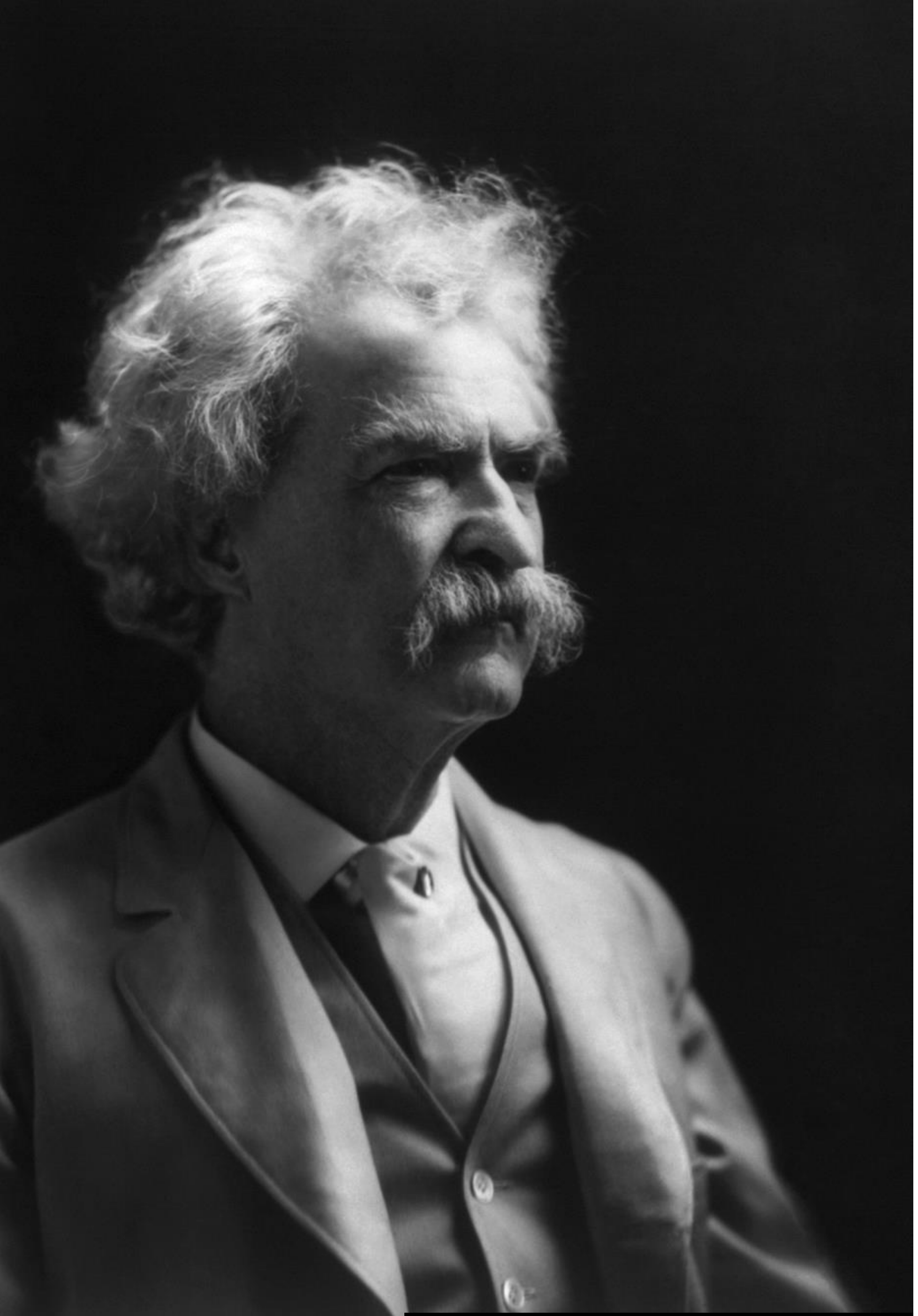
Learning outcomes

By the end of this seminar, you should be able to:

1. Understand how climate is changing
2. Explain radiation and energy balance
3. Discuss the role of climate modelling in climate science
4. Describe the carbon cycle
5. Understand the impacts of climate forcings, feedbacks and climate sensitivity on climate change
6. Causes of climate change
7. Examine future climate change predictions, including for Ireland

1. Understand how climate is changing



Climate and weather

- **Climate:** average weather in a given area over a longer period of time. The classical period used for describing a climate is a **30 years** (World Meteorological Organization).
- **Weather:** weather is short-term (minutes to days) variations in the atmosphere.
- **Mark Twain:** *"Climate is what you expect; weather is what you get"*

Global annual average temperature anomaly

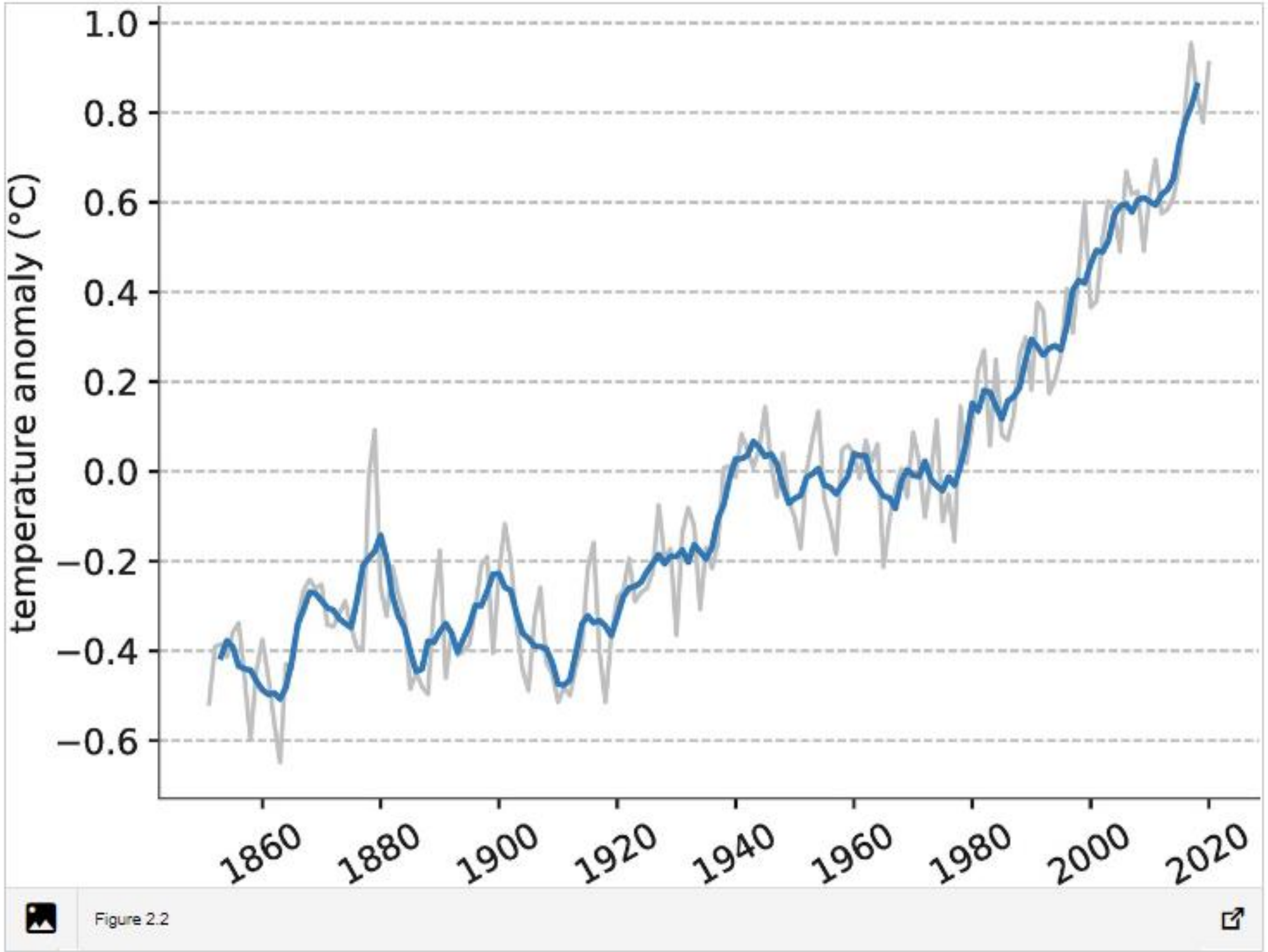


Figure 2.2 Global annual average temperature anomaly (°C); the gray line is the annual average, and the blue line is a smoothed time series. Anomalies are calculated relative to the 1951–1980 average.

Data are from Berkeley Earth (http://berkeleyearth.org/data/, retrieved September 27, 2020).

Source: Dessler (2021)

Distribution of modern warming

Figure 2.3 The distribution of modern warming (in °C).

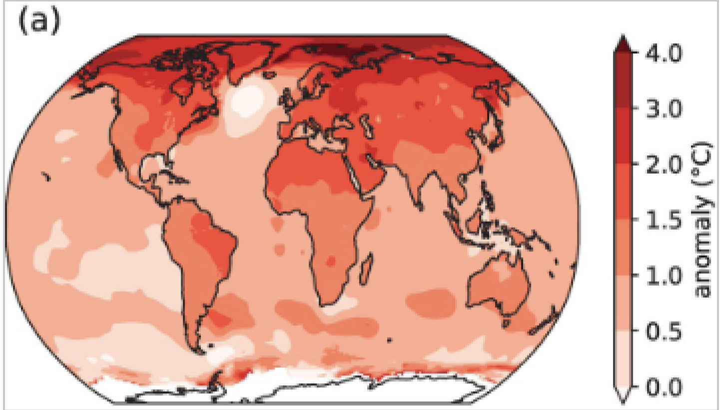


Figure 2.3 (a)

(a) Spatial distribution of the warming;

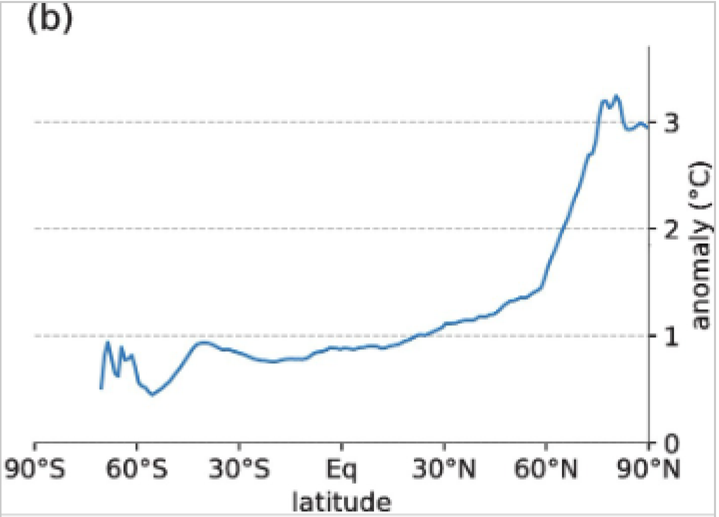


Figure 2.3 (b)

(b) the warming as a function of latitude. Warming is calculated as the difference between the 1850–1900 average and 2009–2018 average.

Source: Dessler (2021)

Data are from Berkeley Earth (http://berkeleyearth.org/data/, retrieved October 14, 2020).

Satellite observations

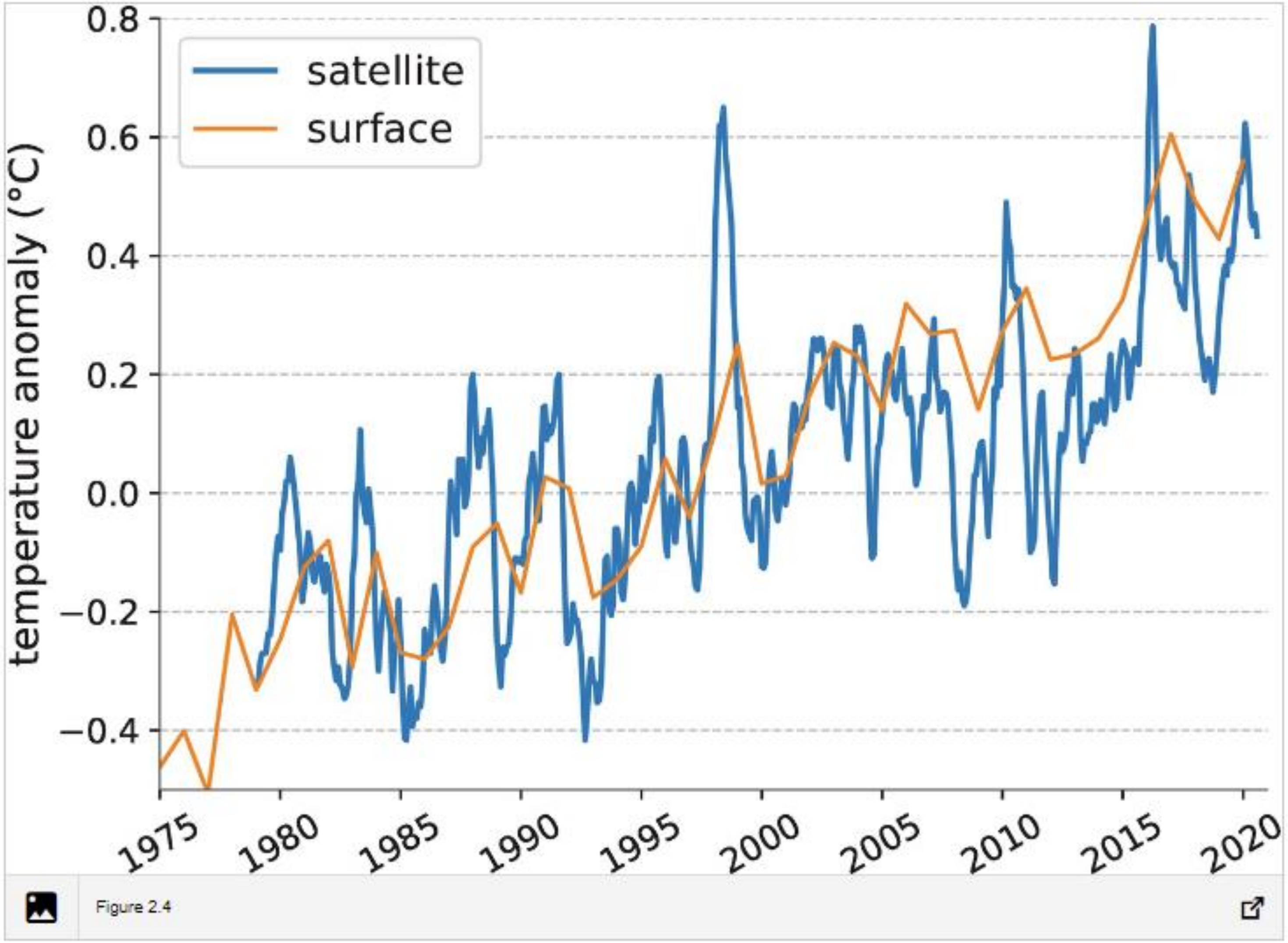


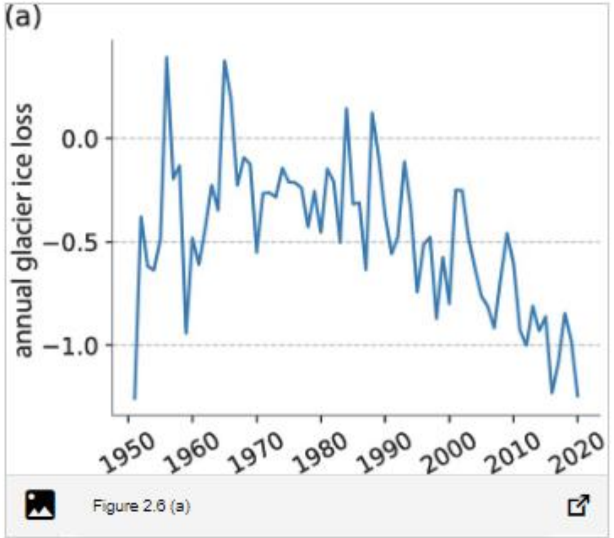
Figure 2.4 Satellite measurements of the global monthly average temperature anomaly (°C) (blue line). The orange line is annual average temperature (°C) from the surface thermometer record plotted in Figures 2.2 and 2.3. Anomalies in this plot are relative to the 1981–2010 period.

Satellite data were obtained from the University of Alabama, Huntsville (http://vortex.nsstc.uah.edu/data/msu/v6.0/tlt/uahncdc_lt_6.0.txt, retrieved September 27, 2020).

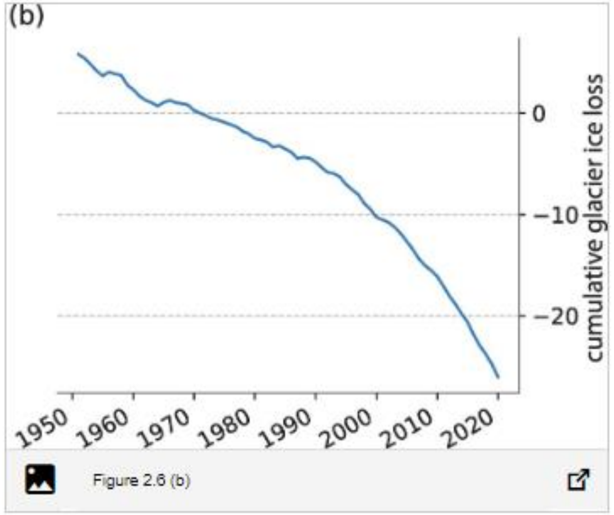
Source: Dessler (2021)

Ice observations - Glaciers

Figure 2.6



(a) Global average annual change in mass of the world's glaciers, in tonnes/m^2/year.



(b) Global average cumulative mass change, in tonnes/m^2. Given that ice has a density of about 0.9 tonnes/m^3, a loss of 1 tonne of ice/m^2 is equal to the loss of about 1.1 m of glacier ice thickness.

Data from WGMS (2020) (obtained from https://wgms.ch/global-glacier-state/, retrieved November 26, 2020).

Source: Dessler (2021)

Ice observations – Sea ice

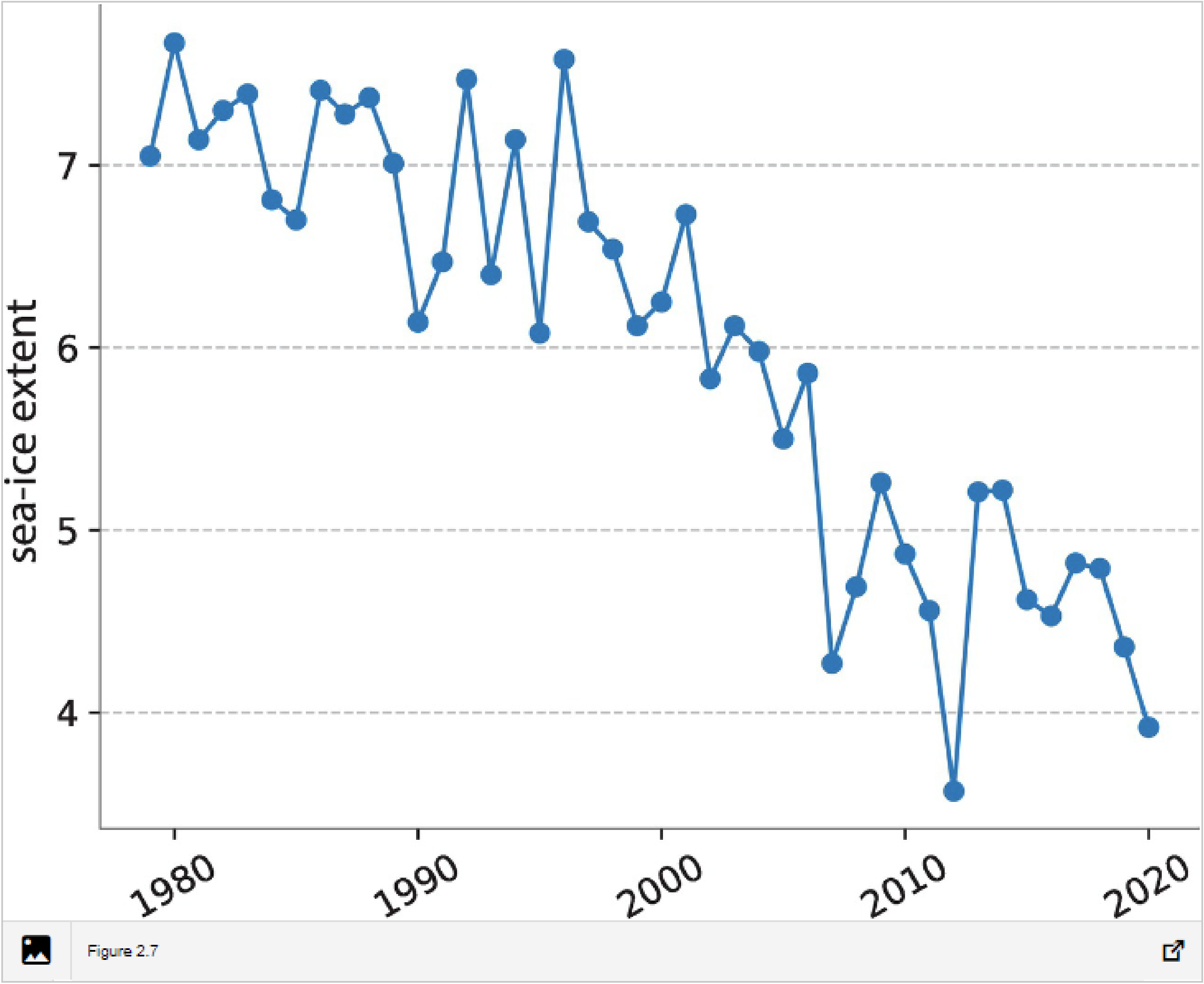
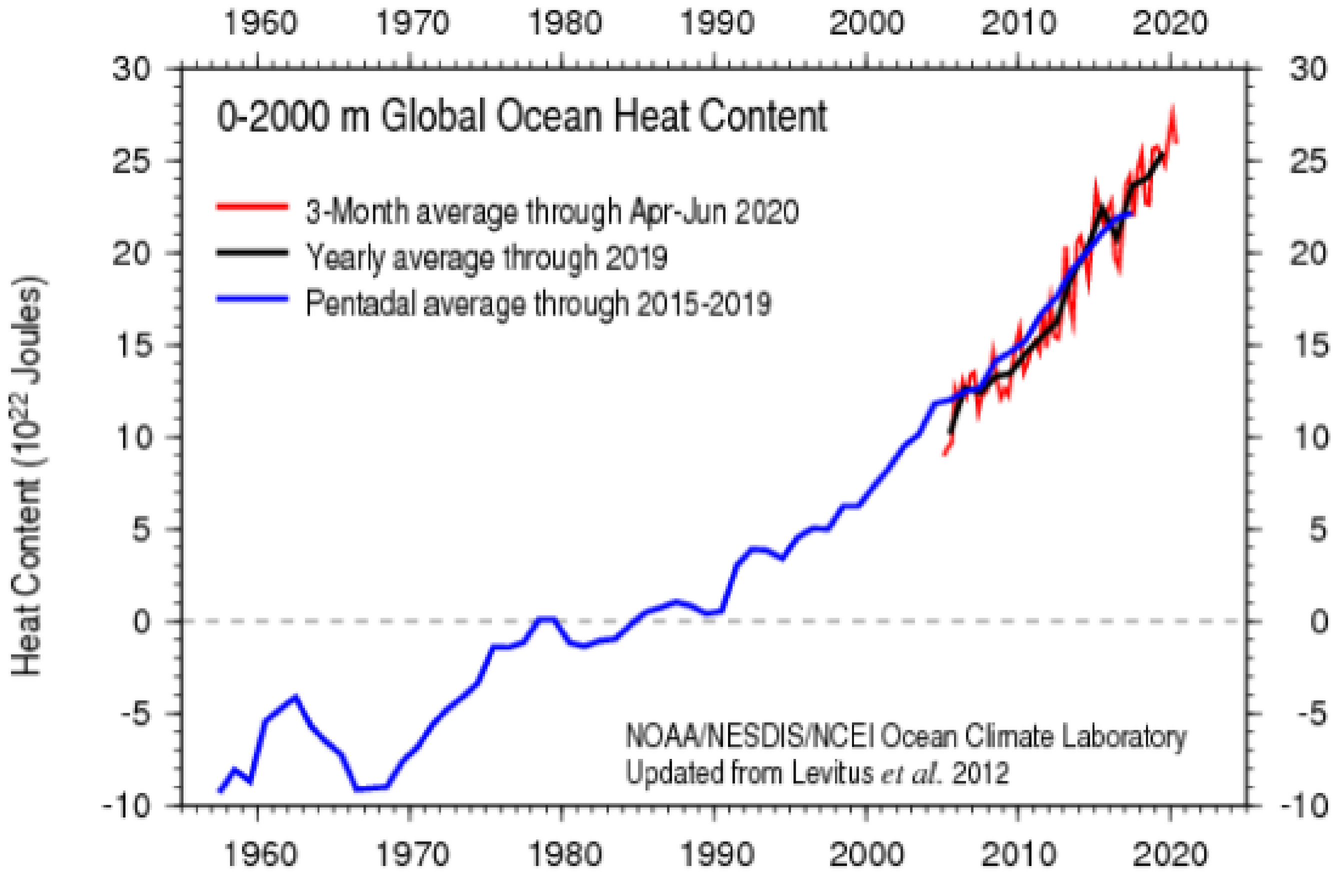


Figure 2.7 Arctic sea-ice area (in millions of square kilometers) in September of each year.

Data from Fetterer et al. (2017). Sea Ice Index, Version 3.0 [Data sets ID NSIDC-0081 and ID NSIDC-0051]. Boulder, Colorado USA: National Snow and Ice Data Center. doi: https://doi.org/10.7265/N5K072F8 (accessed on November 26, 2020).

Source: Dessler (2021)

Ocean temperatures



Source: NOAA (2020)

Sea level

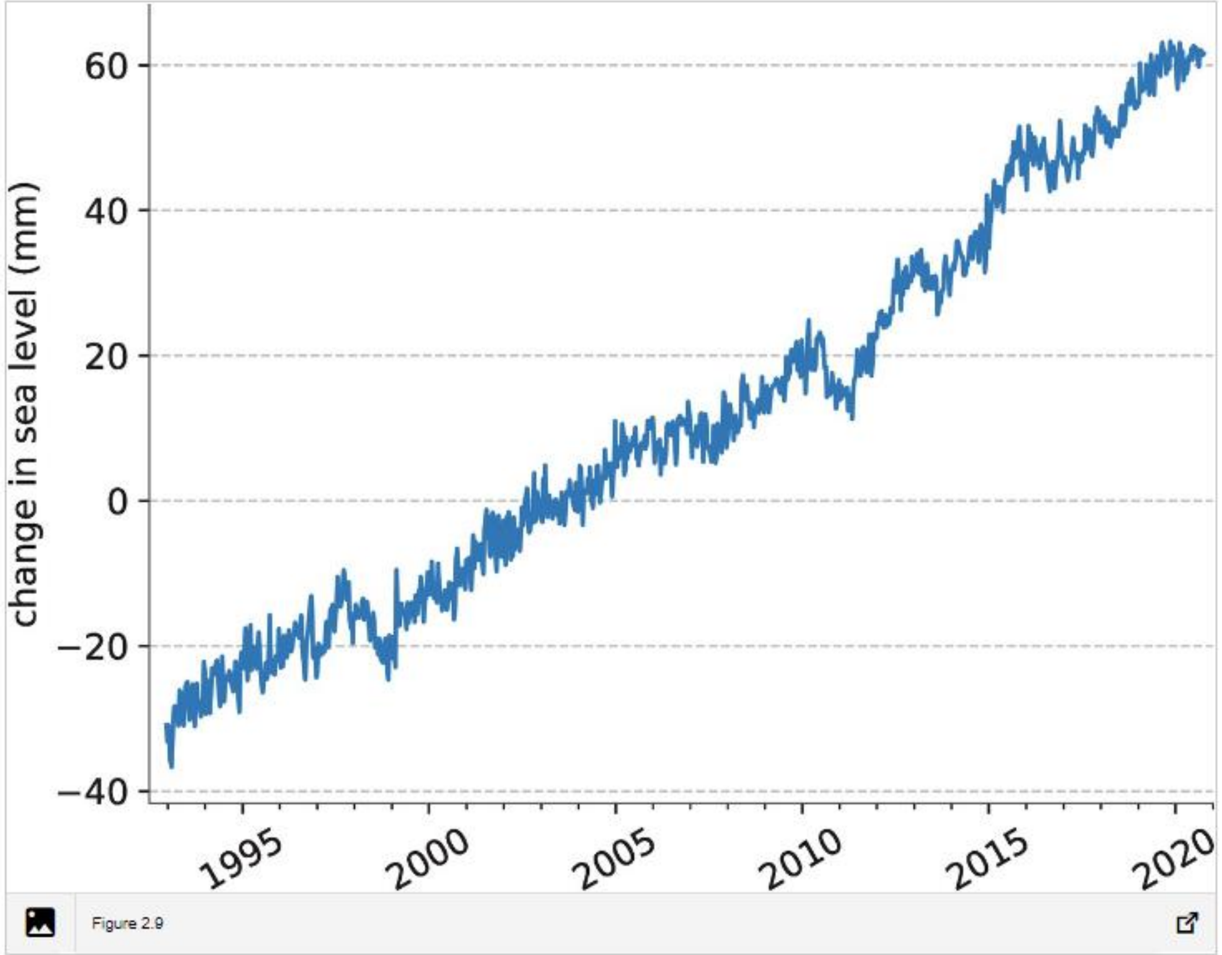


Figure 2.9 Change over time in global-average sea level, in millimeters. The seasonal cycle has been removed.

Data are described by Nerem et al. (2010) (obtained from http://sealevel.colorado.edu/, retrieved on November 26, 2020).

Source: Dessler (2021)

Climate change hiatus?

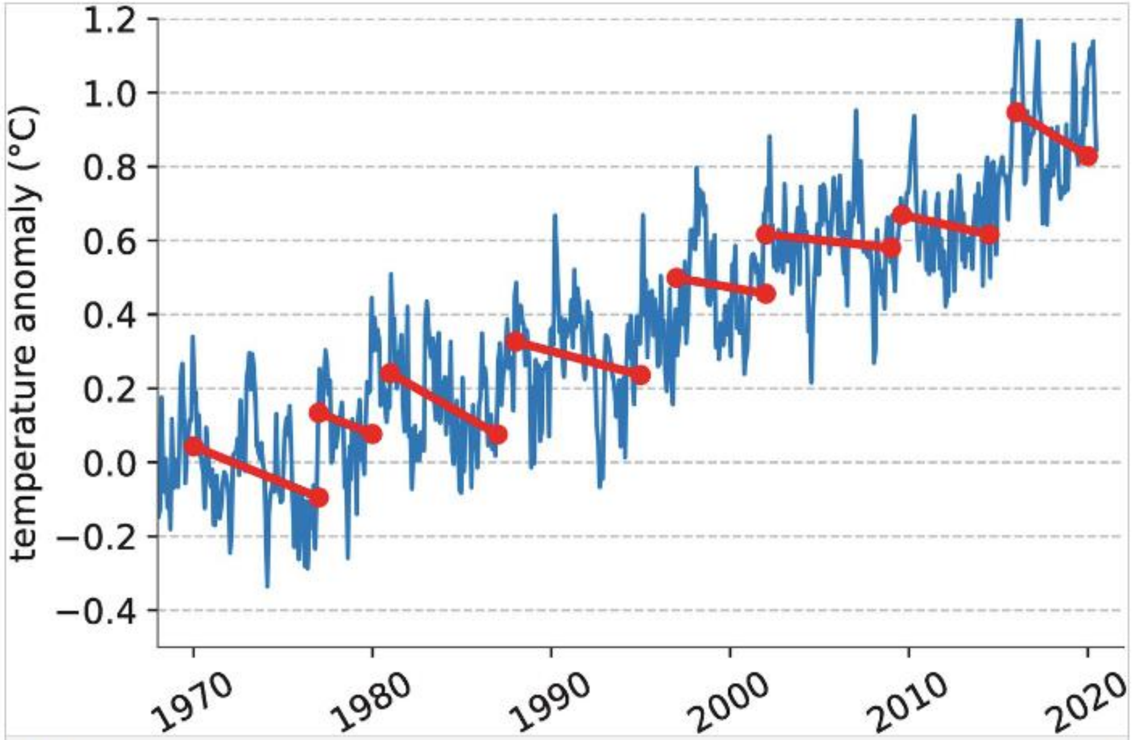


Figure 2.5

Figure 2.5 A plot of monthly and global average surface temperature (°C) from the surface thermometer record (blue line) along with short-term trend lines (red lines). This figure is an adaptation of SkepticalScience's escalator plot (www.skepticalscience.com/graphics.php?g=47).

Data are from Berkeley Earth (http://berkeleyearth.org/data/, retrieved September 28, 2020).

Source: Dessler (2021)

Earth's long-term climate record

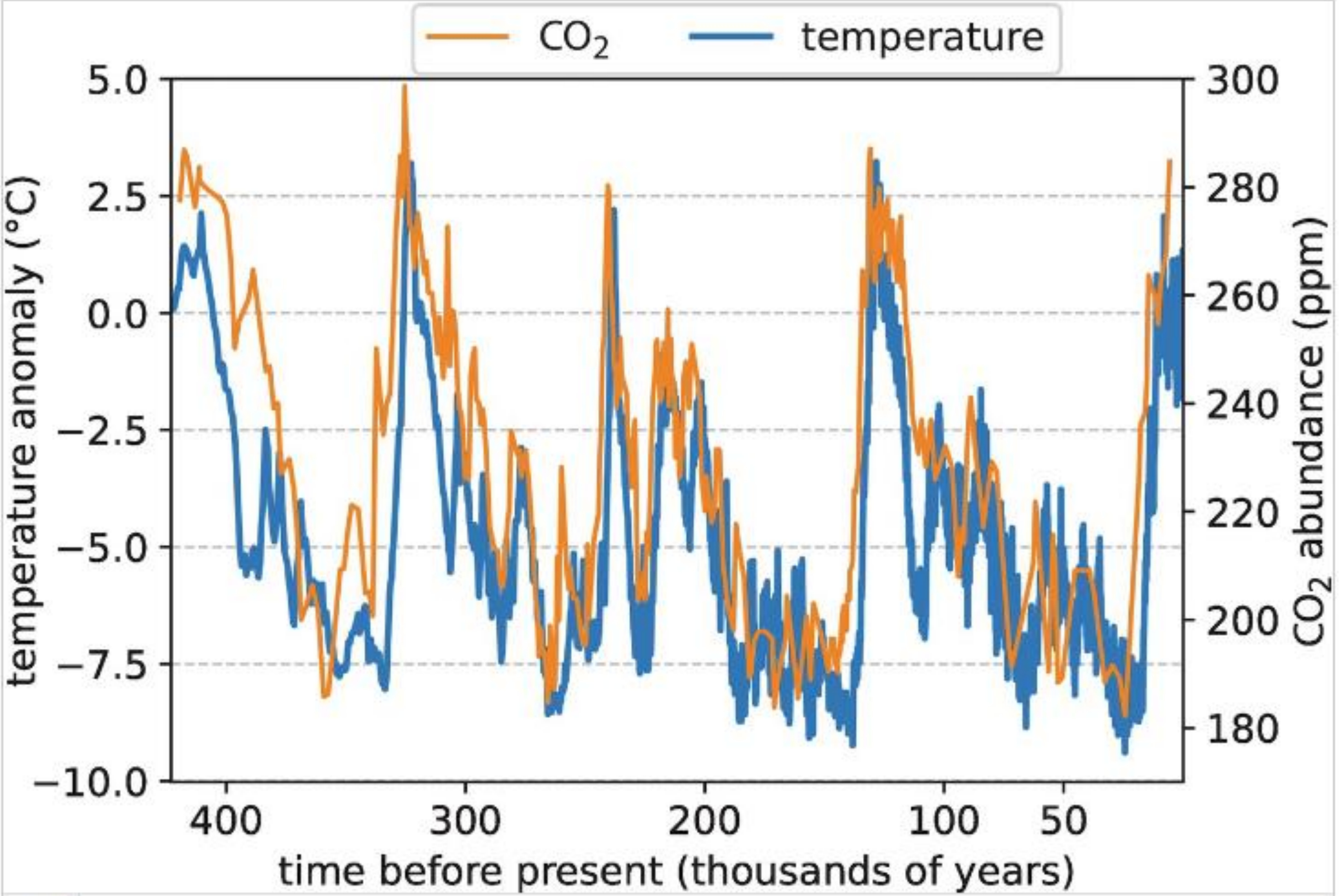
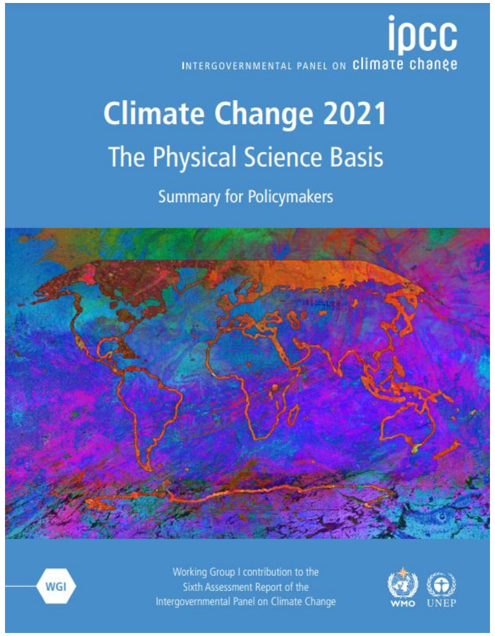


Figure 2.13

Figure 2.13 Temperature anomaly of the southern polar region (blue line) over the past 410,000 years, relative to today's temperature, constructed from an Antarctic ice core. Carbon dioxide (orange line) is from air bubbles trapped in the ice (data from Petit et al. (2000); downloaded from https://cdiac.ess-dive.lbl.gov/climate/paleo/paleo_table.html, accessed September 29, 2020).

Source: Dessler (2021)

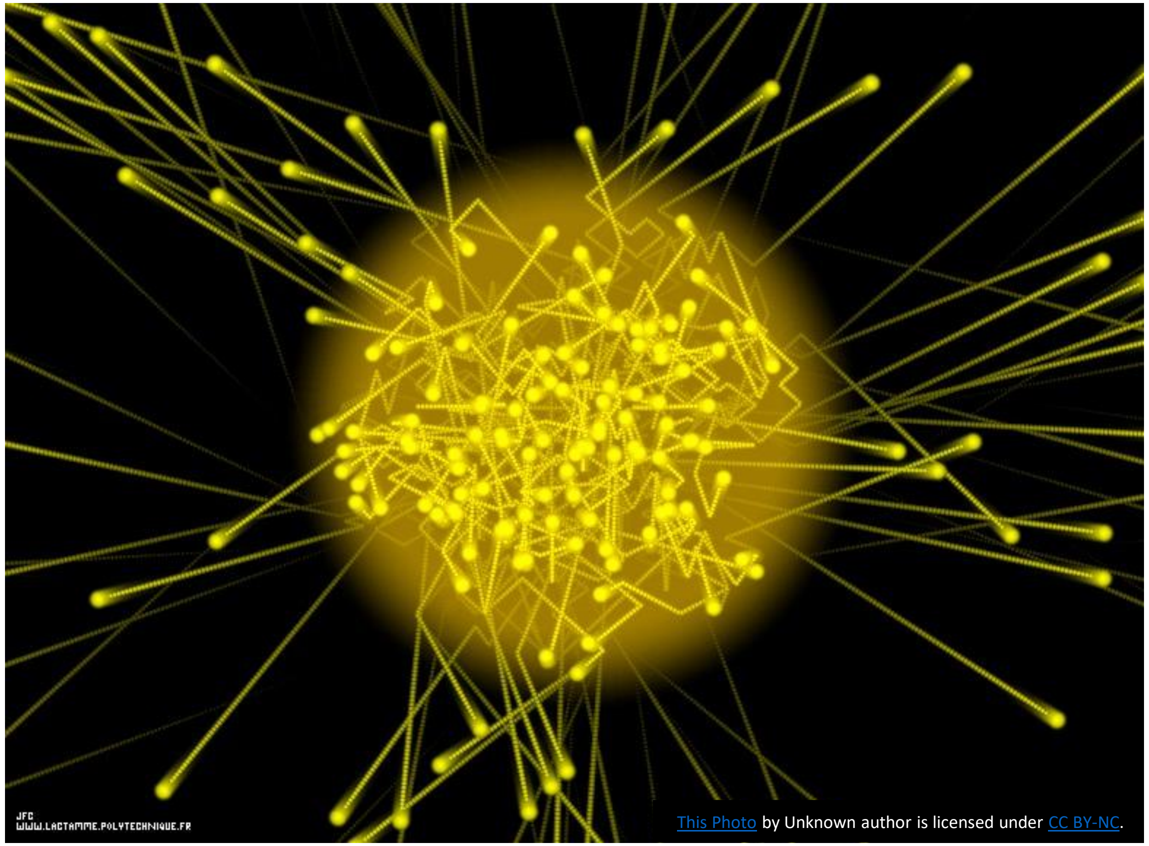
Putting it all together



IPCC assessment	Attribution of cause
First (1990)	The size of this warming is broadly consistent with prediction of climate models, but it is also of the same magnitude as natural climate variability. Thus the **observed increase could be largely due to this natural variability**
Second (1995)	The balance of evidence suggests a **discernible human influence** on the climate
Third (2001)	Most of the observed warming over the past 50 years is **likely to have been due to the increase in greenhouse gas concentrations**
Fourth (2007)	Most of the observed increase in globally averaged temperatures since the mid-twentieth century is **very likely** due to the observed increase in **anthropogenic greenhouse gas concentrations**
Fifth (2013)	It is **extremely likely** that **more than half** of the observed increase in global average surface temperature from 1951 to 2010 was **caused by** the **anthropogenic increase** in greenhouse gas concentrations and other anthropogenic forcings together
Sixth (2021)	**Unequivocal that human influence has warmed the atmosphere, ocean and land**. Widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred. Human-induced climate change is already affecting many weather and climate extremes in every region across the globe. Evidence of observed changes in extremes such as heatwaves, heavy precipitation, droughts, and tropical cyclones, and, in particular, their attribution to human influence, has strengthened since 5th assessment

2. Radiation and energy balance

Photons



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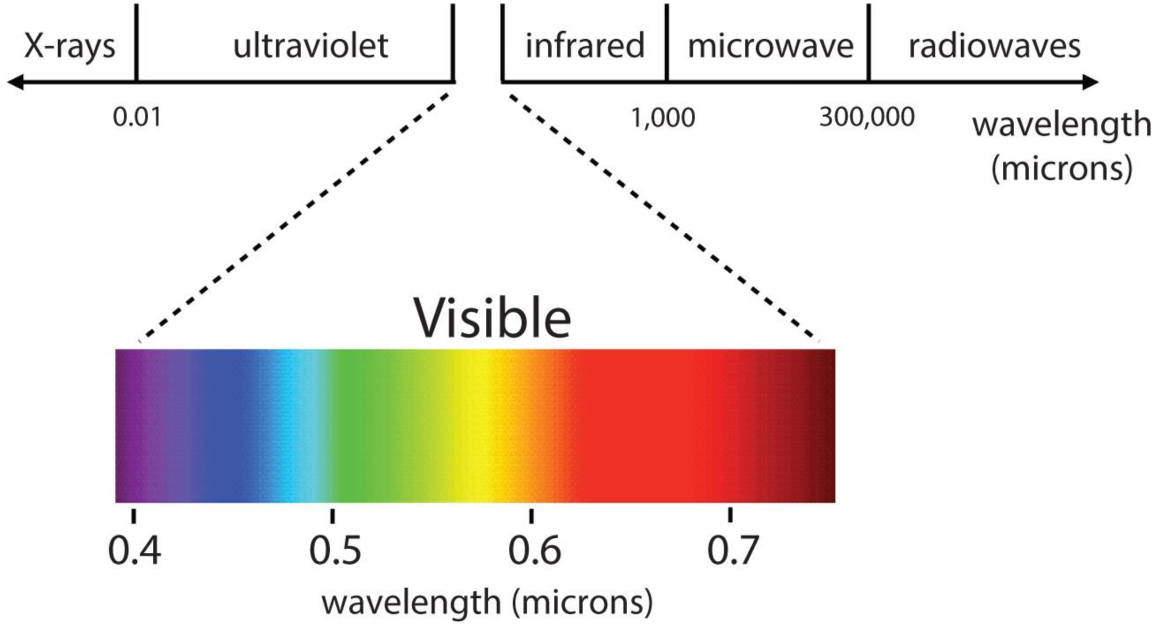
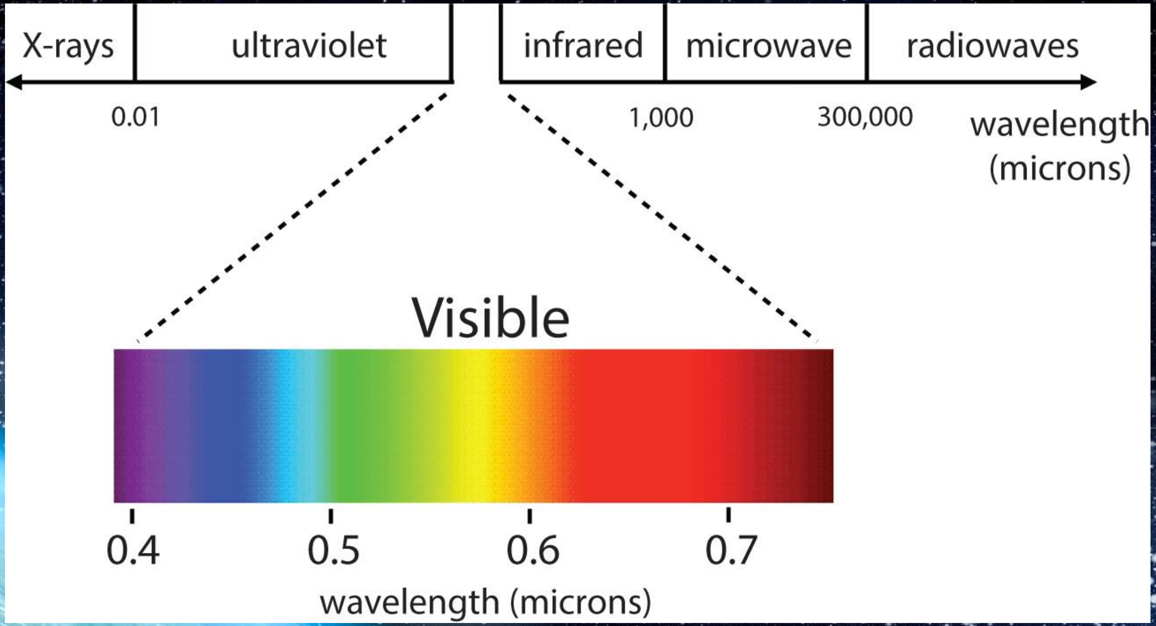


Source: Dessler (2021)



Electromagnetic radiation and the atmosphere

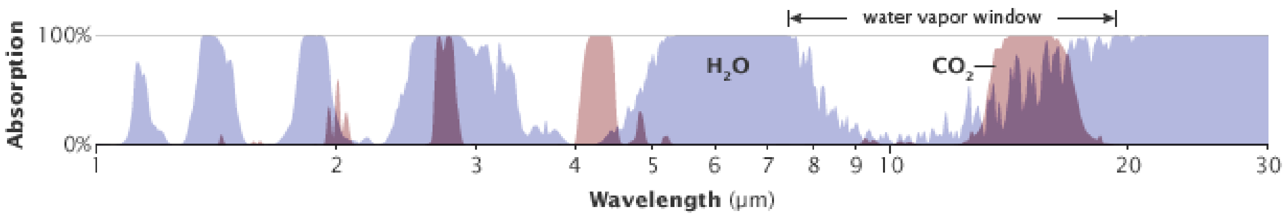
Energy Balance – First Law of Thermodynamics

Table 3.1 **Energy balance summary**

Condition	Effect on internal energy	Effect on temperature
If $E_{in} > E_{out}$ for an object	Internal energy of that object increases	Temperature of that object increases
If $E_{out} > E_{in}$ for an object	Internal energy of that object decreases	Temperature of that object decreases
E_{in} equals E_{out} for an object	Internal energy of that object is not changing	Temperature of that object is not changing

- A cornerstone of physics is the first law of thermodynamics, which says **energy is neither created nor destroyed, only altered in form**.
- If an object loses energy, then some other object must gain that same amount of energy. Furthermore, because photons are just little packets of energy, the first law states that when an object emits a photon, its internal energy decreases.
- And because temperature is a measure of internal energy, the emission of a photon therefore causes the object to cool.
- Equally, if a photon hits an object and is absorbed, then the energy of the photon is transferred to the object's internal energy and the object warms.
- **Radiative forcing:** Imbalance between energy coming in from Sun and energy going out to space

Relationship between radiation and energy balance



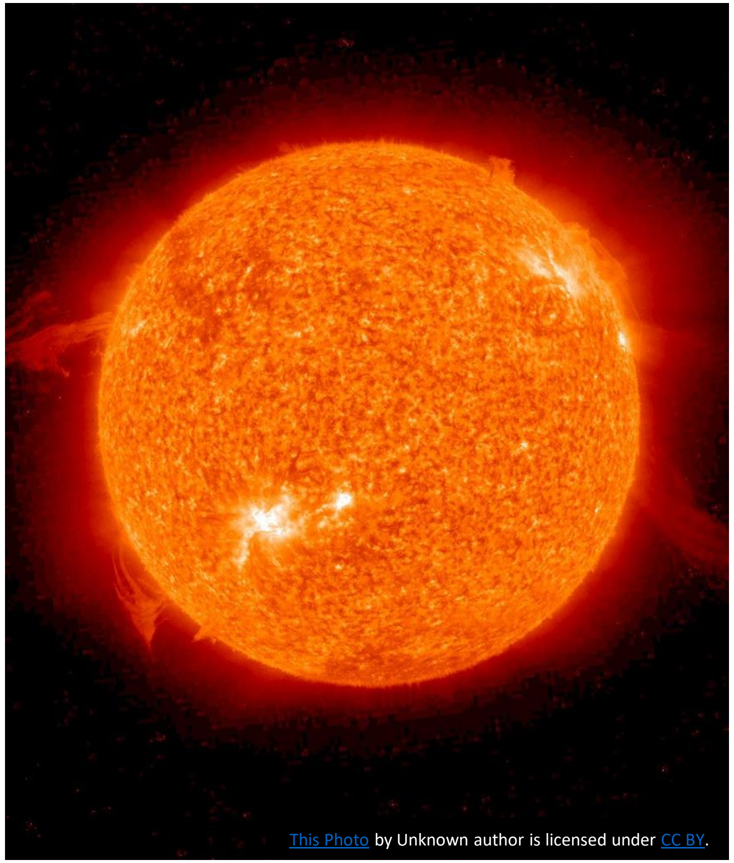
All atmospheric gases have a unique pattern of energy absorption: they absorb some wavelengths of energy but are transparent to others. The absorption patterns of water vapor (blue peaks) and carbon dioxide (pink peaks) overlap in some wavelengths. Carbon dioxide is not as strong a greenhouse gas as water vapor, but it absorbs energy in wavelengths (12-15 micrometers) that water vapor does not, partially closing the "window" through which heat radiated by the surface would normally escape to space. (Illustration adapted from Robert Rohde.)

Source: NASA (n.d.)

- Greenhouse gases (CO_2, CH_4 , N_20) absorb infrared energy with wavelengths in a part of the energy spectrum that other gases, such as H_2O, do not.
- CO_2 is very strong absorber of infrared energy with wavelengths longer than 12-13 micrometers. Wavelengths of outgoing thermal infrared energy that the atmosphere's most abundant GHG —water vapour—would let escape to space are absorbed by CO_2.
- Absorption of outgoing thermal infrared by CO_2 means imbalance of E_{in} and E_{out}

3. Role of climate modelling in climate science

Surface temperature parameters



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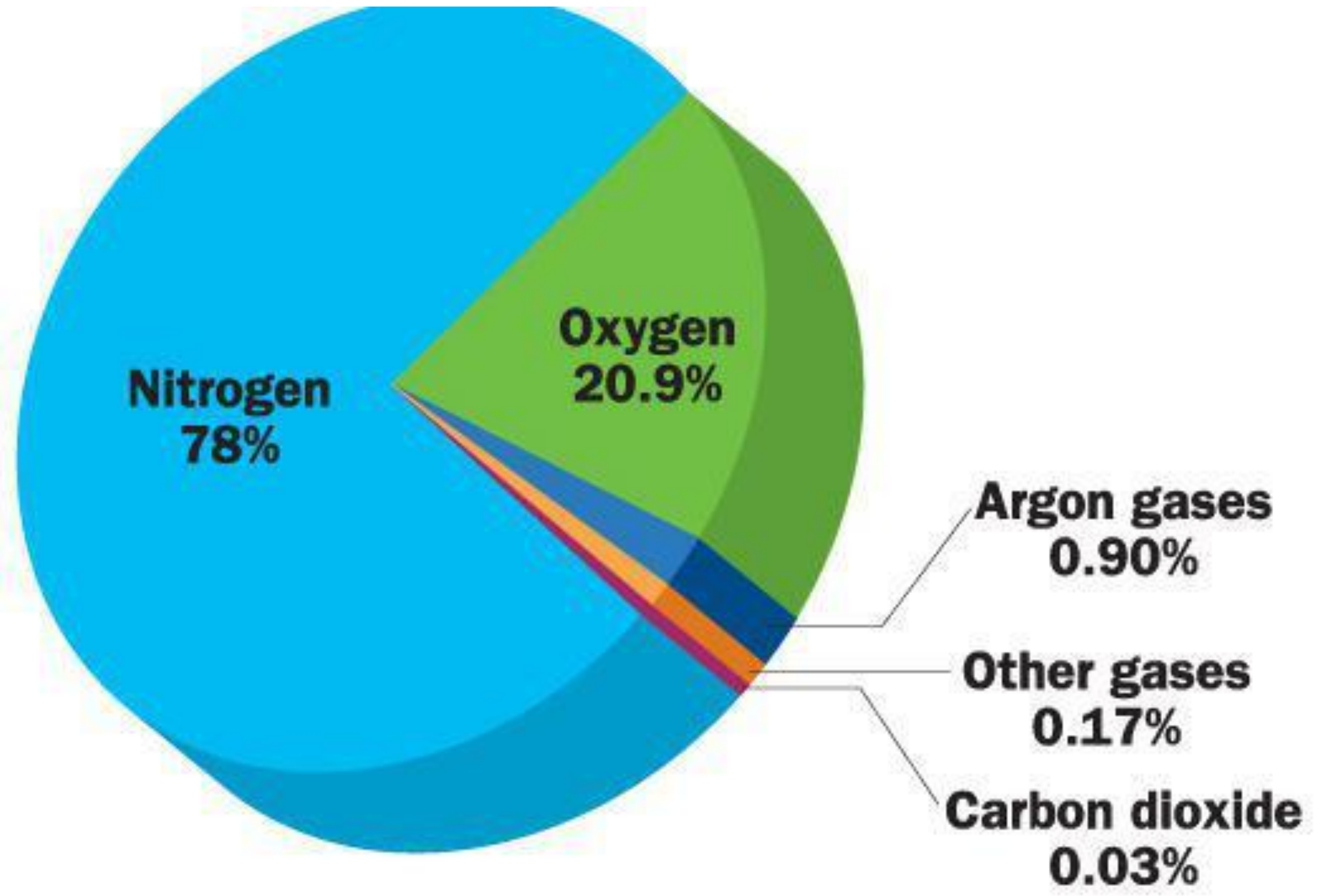
- Surface temperature of the planet is basically determined by three parameters:
  the quantity of greenhouse gases in the atmosphere, the solar energy, and Earth's albedo (reflectivity)
- We can estimate Earth's temperature if we have details for these three variables
- Solar energy is largely constant (1,360 W/m^2), Earth's albedo is ~0.3 (but decreasing), and greenhouse gases are quantifiable

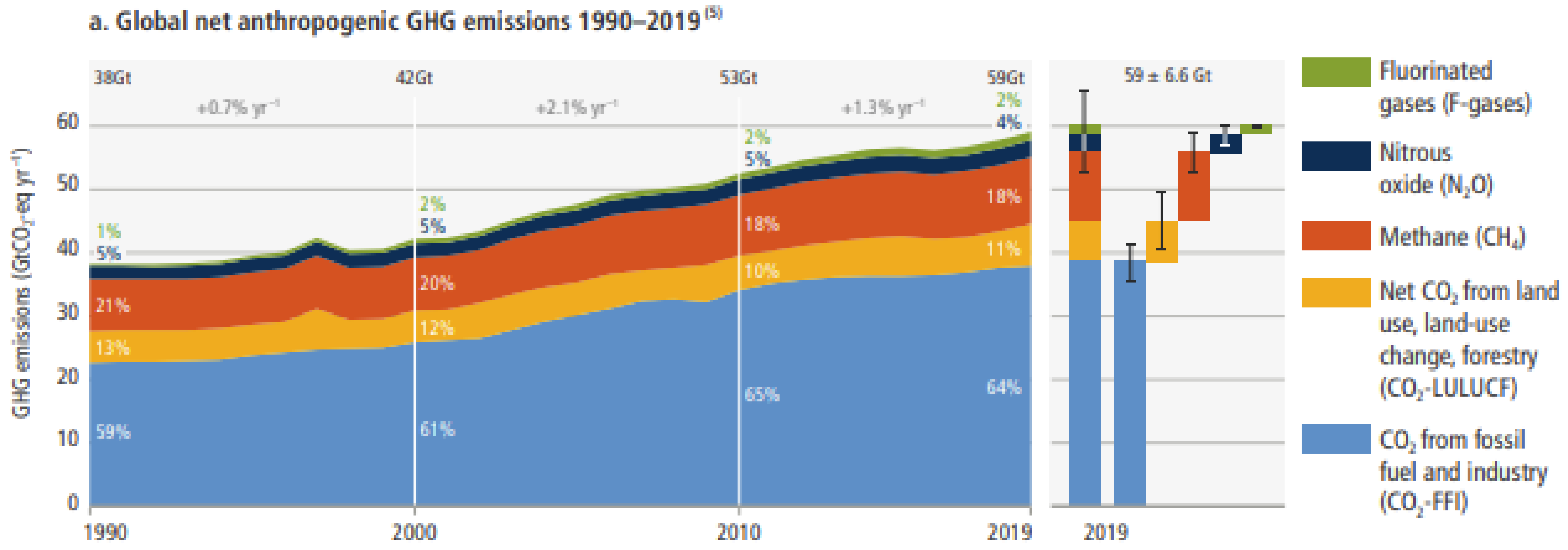
4. Carbon cycle

Composition of atmosphere



What are greenhouse gases?

Global net anthropogenic emissions have continued to rise across all major groups of greenhouse gases.



Source: IPCC (2022)

Greenhouse gases and Global Warming Potential (GWP)

Global Warming Potential (GWP) concept:

- The heat absorbed by any greenhouse gas in the atmosphere, as a multiple of the heat that would be absorbed by the same mass of CO_2.

- GWP depends on gases:
    - Concentration in atmosphere
    - Strength of their absorption of infrared radiation
    - Longevity in atmosphere

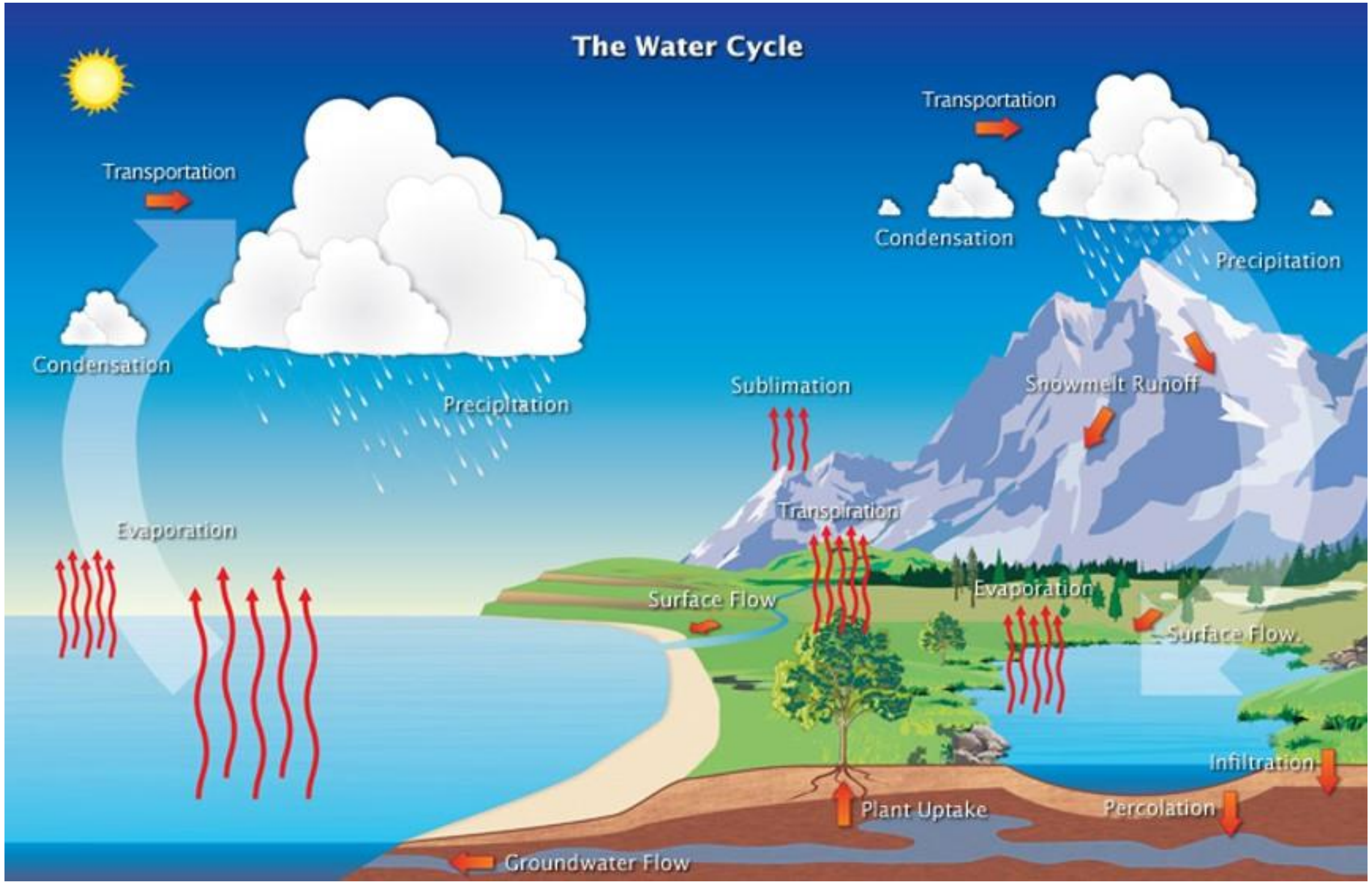
Long-term fate and Global Warming Potential of different GHGs

Table 5.1 Greenhouse-gas metrics

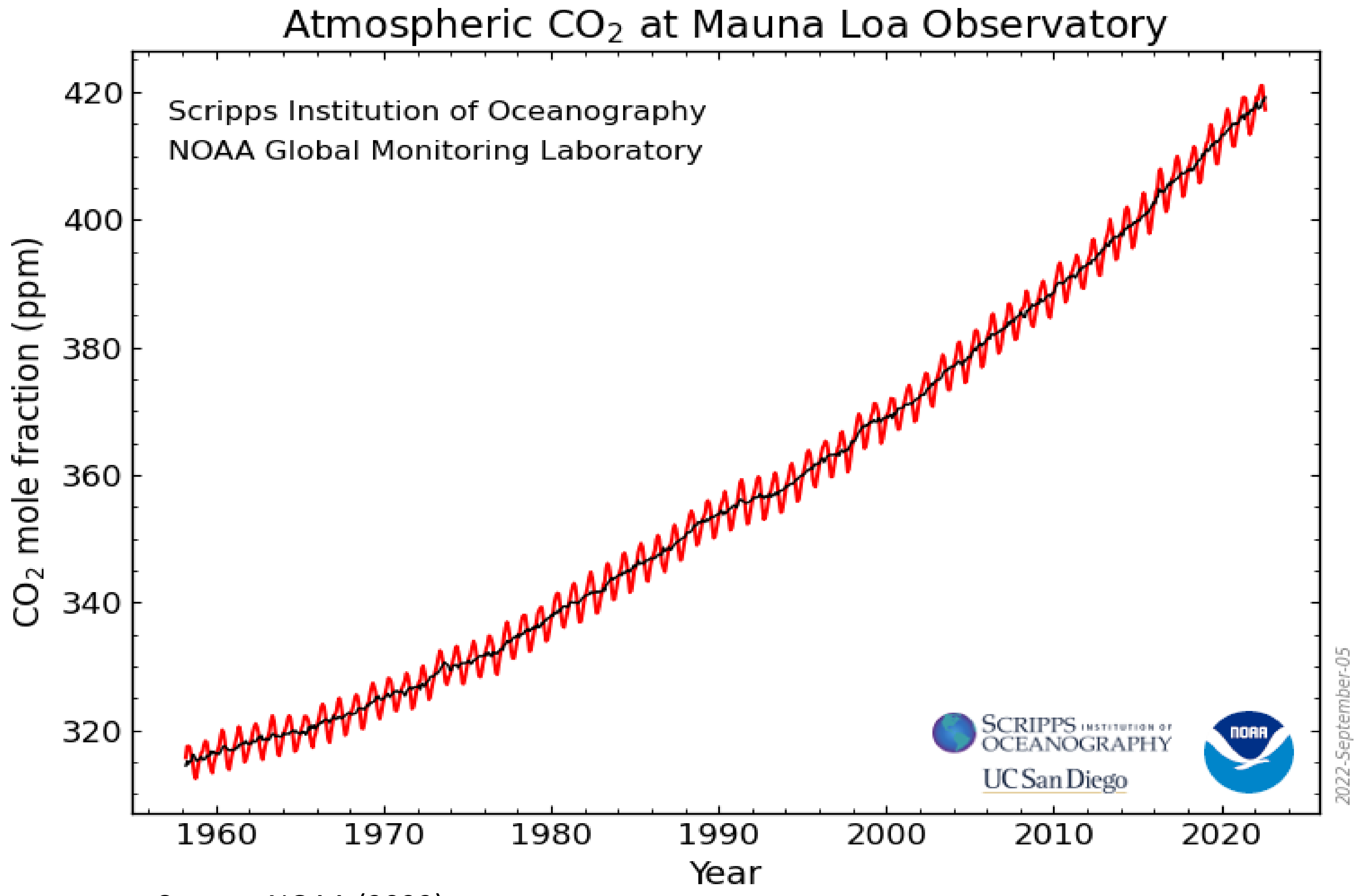
Species	Lifetime	Global warming potential	Increase in abundance since pre-industrial times
Carbon dioxide	500 years	1	130 ppm
Methane	12.4 years	32	1.1 ppm
Nitrous oxide	109 years	260	75 ppb
Halocarbons	Years to millennia	100s to 1,000s	

Source: Dessler (2021)

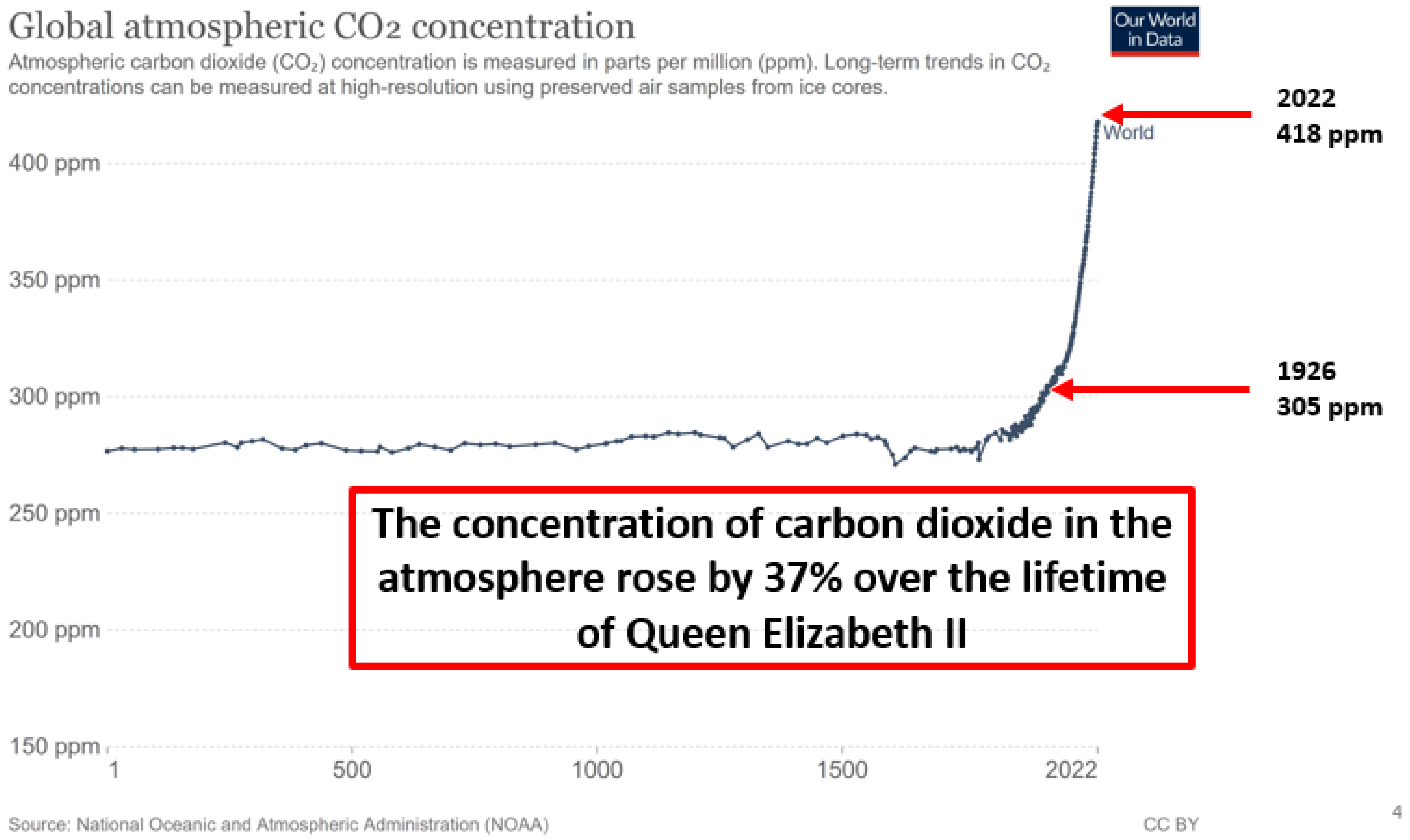
Water vapour (H_2O)



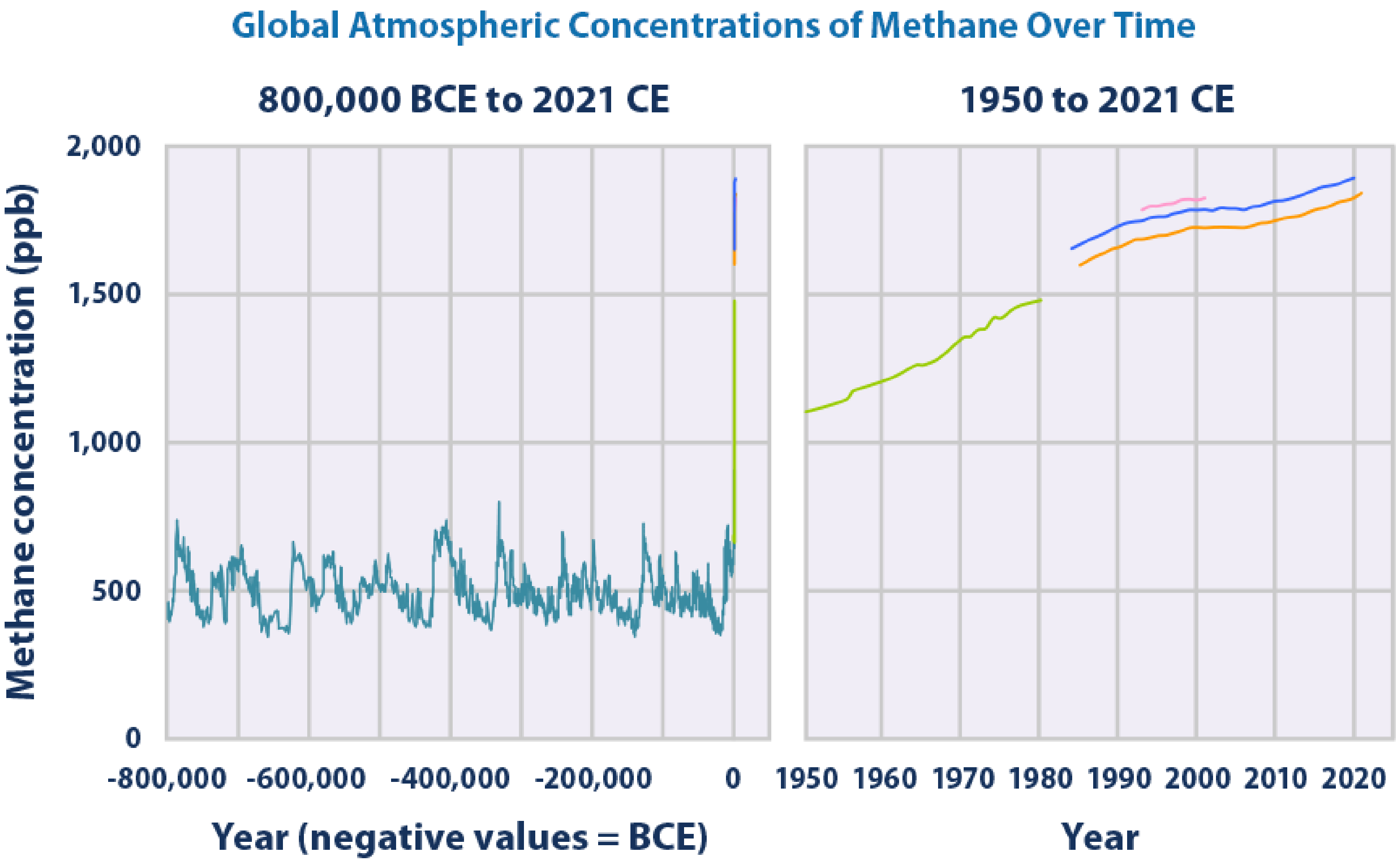
- Air can hold ~7% more water vapour per 1°C warmer atmosphere



Source: NOAA (2022)



Sources: Our World in Data (2022)
Daly (2022)

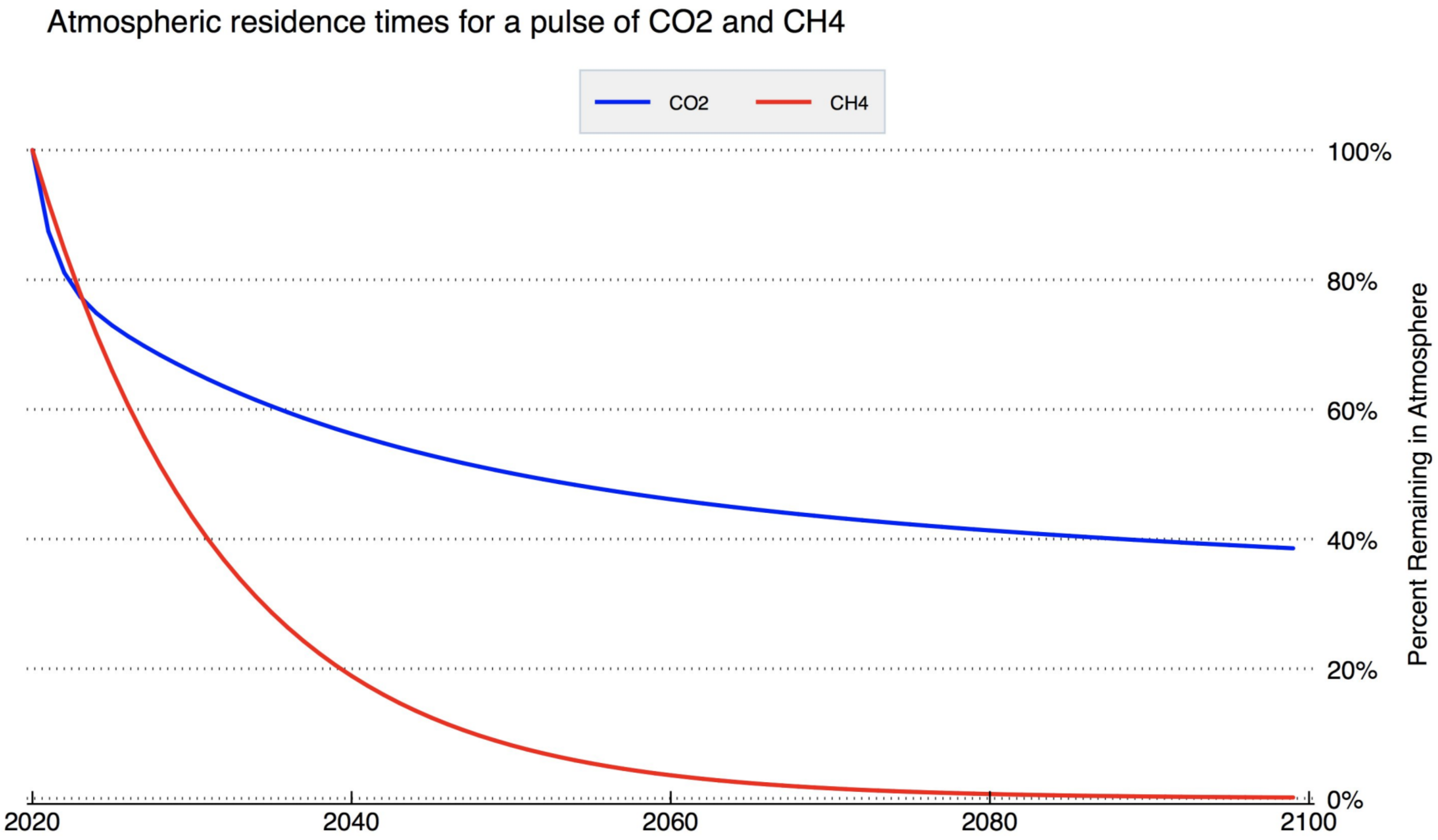


Data source: Compilation of five underlying datasets. See www.epa.gov/climate-indicators for specific information.

For more information, visit U.S. EPA's "Climate Change Indicators in the United States" at www.epa.gov/climate-indicators.

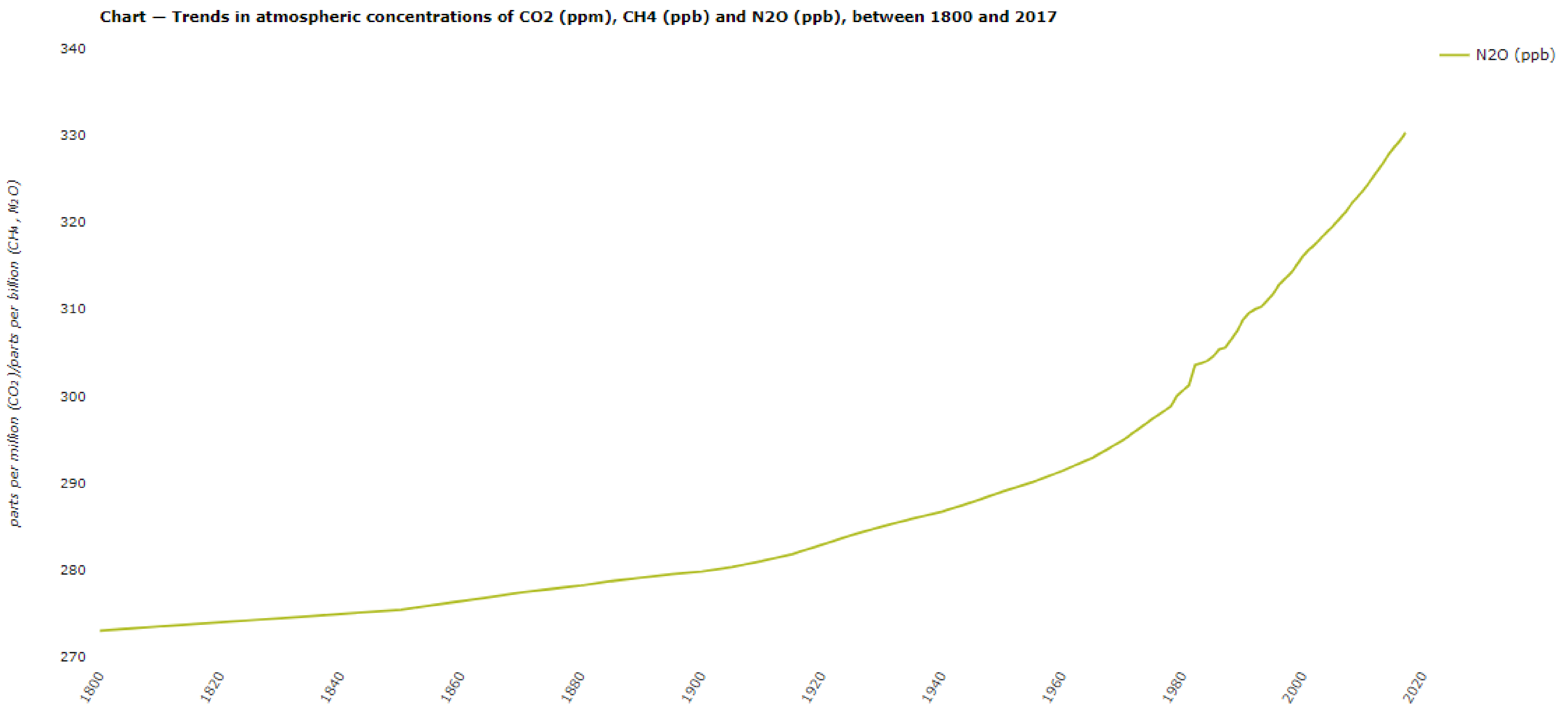
Source: US EPA (2022)

Agriculture and biogenic methane

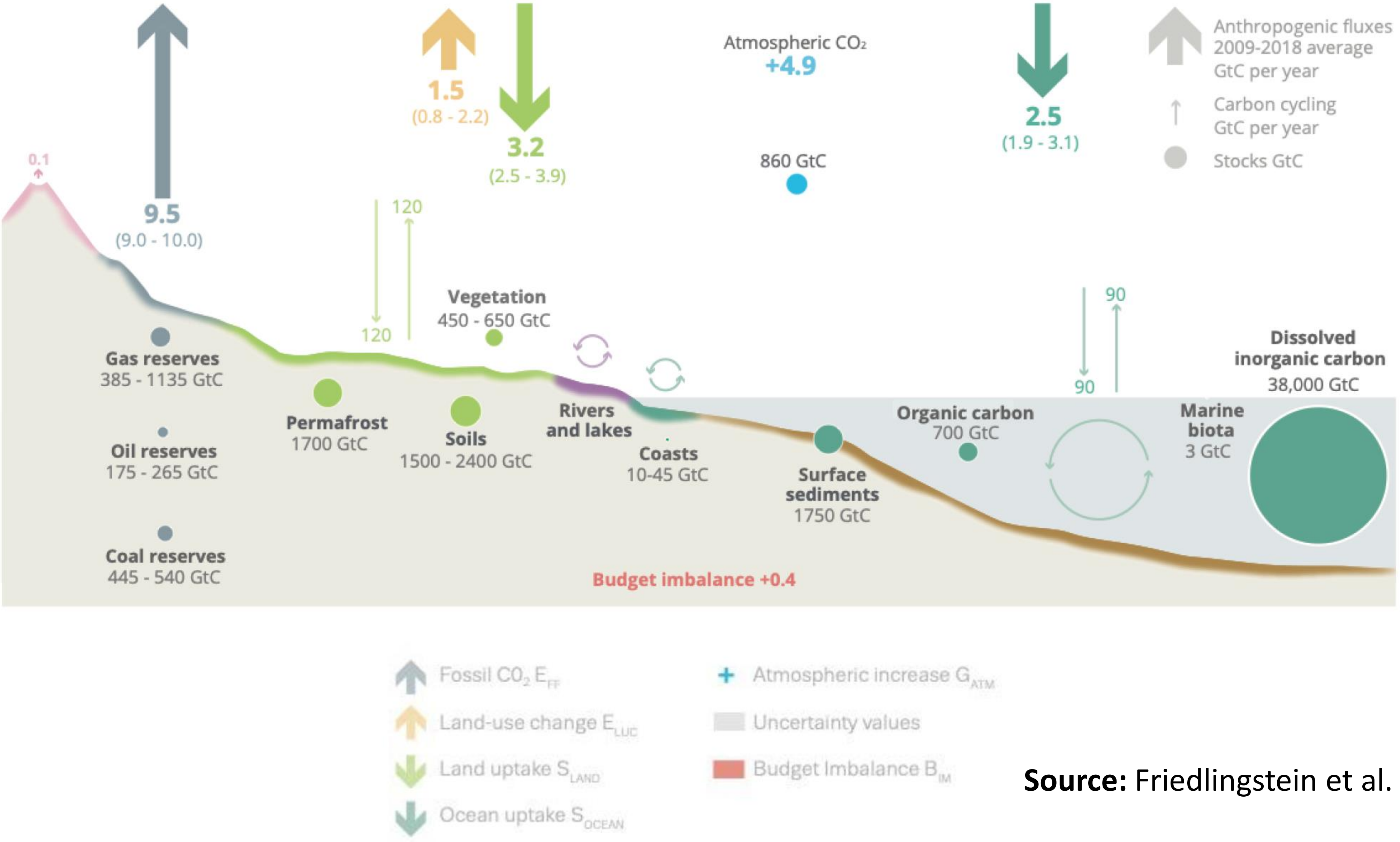


Source: Hausfather (2020)

Nitrous Oxide (N_2O)



The global carbon cycle



Source: Friedlingstein et al. (2019)

Atmosphere-Rock Exchange

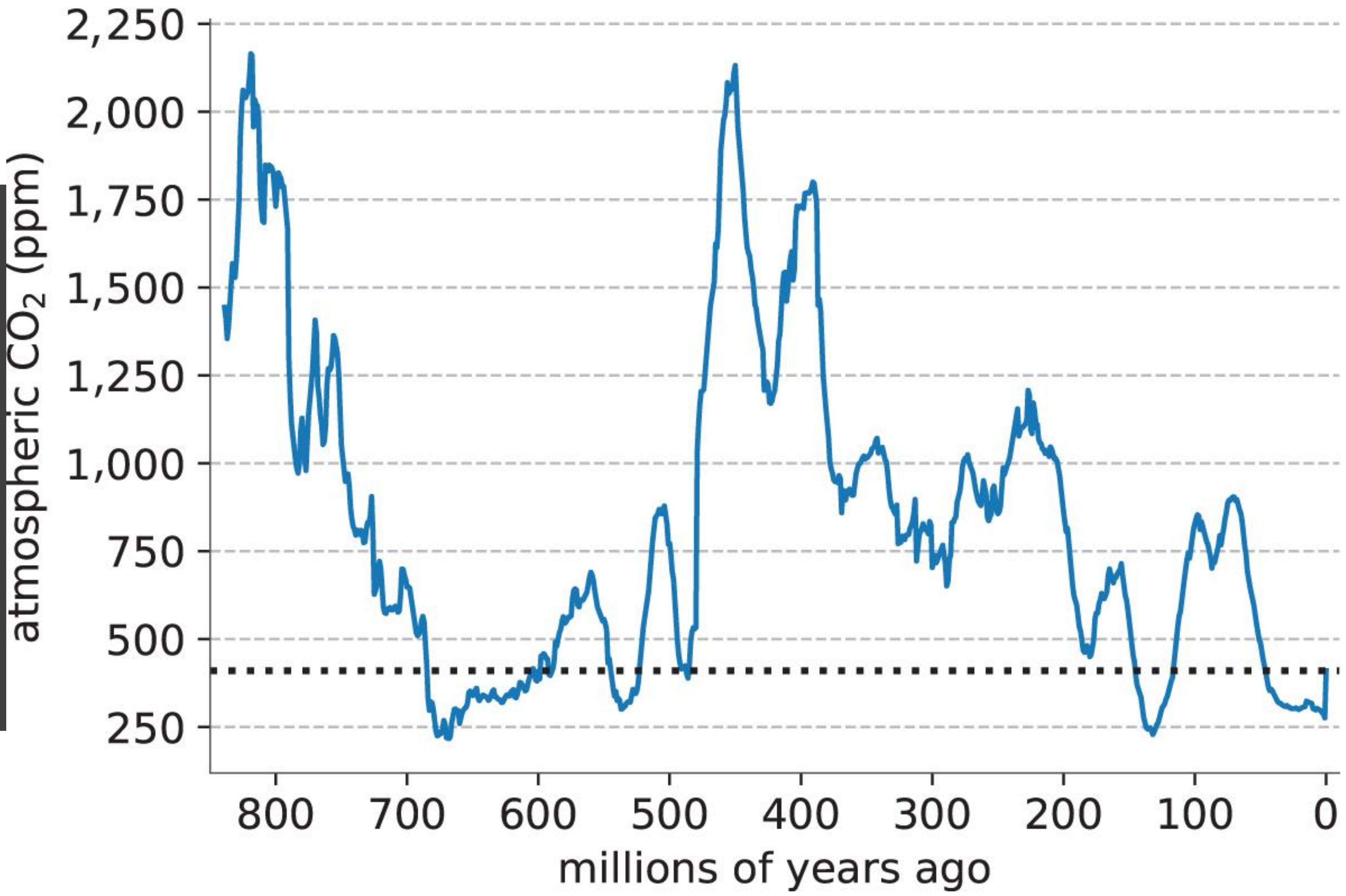


Figure 5.4 Atmospheric carbon dioxide over the past 850 million years, in ppm. The dotted line is the atmospheric abundance in 2020, 410 ppm.

Source: Dessler (2021)

How are humans changing carbon cycle?

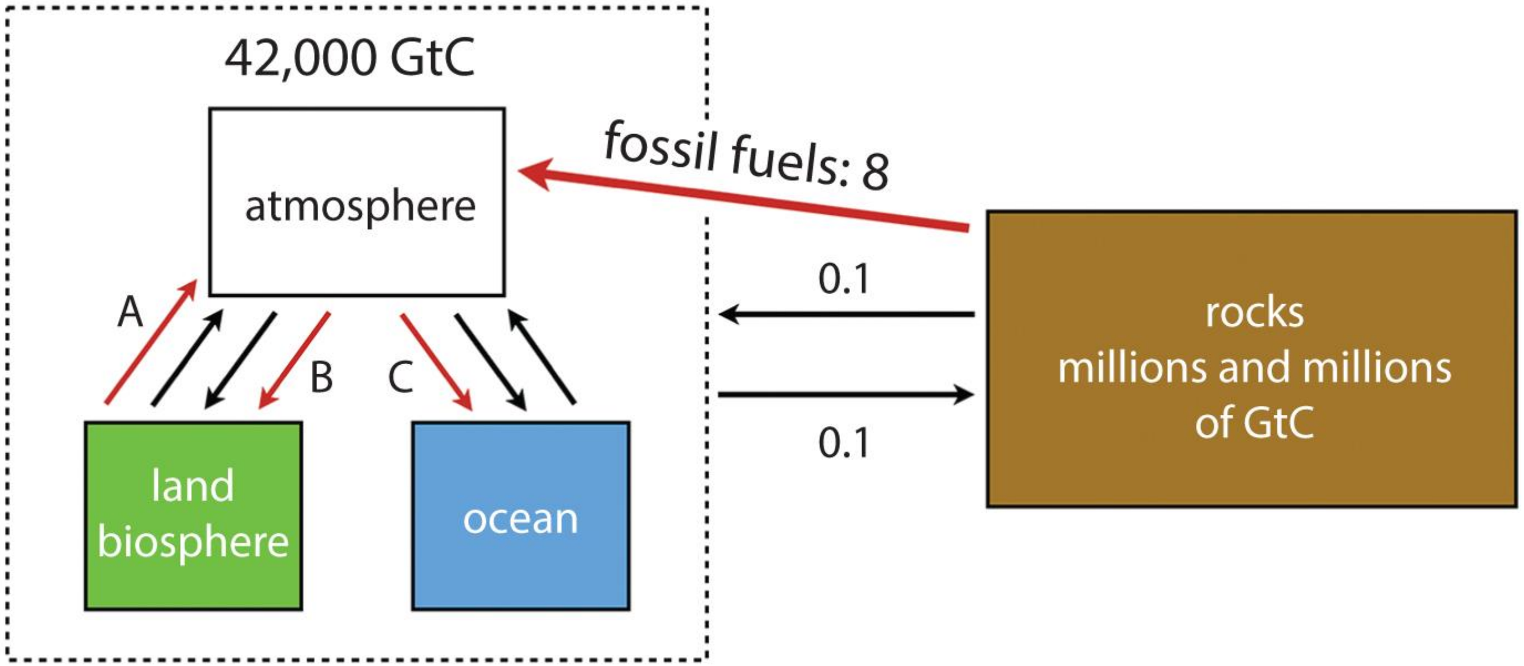


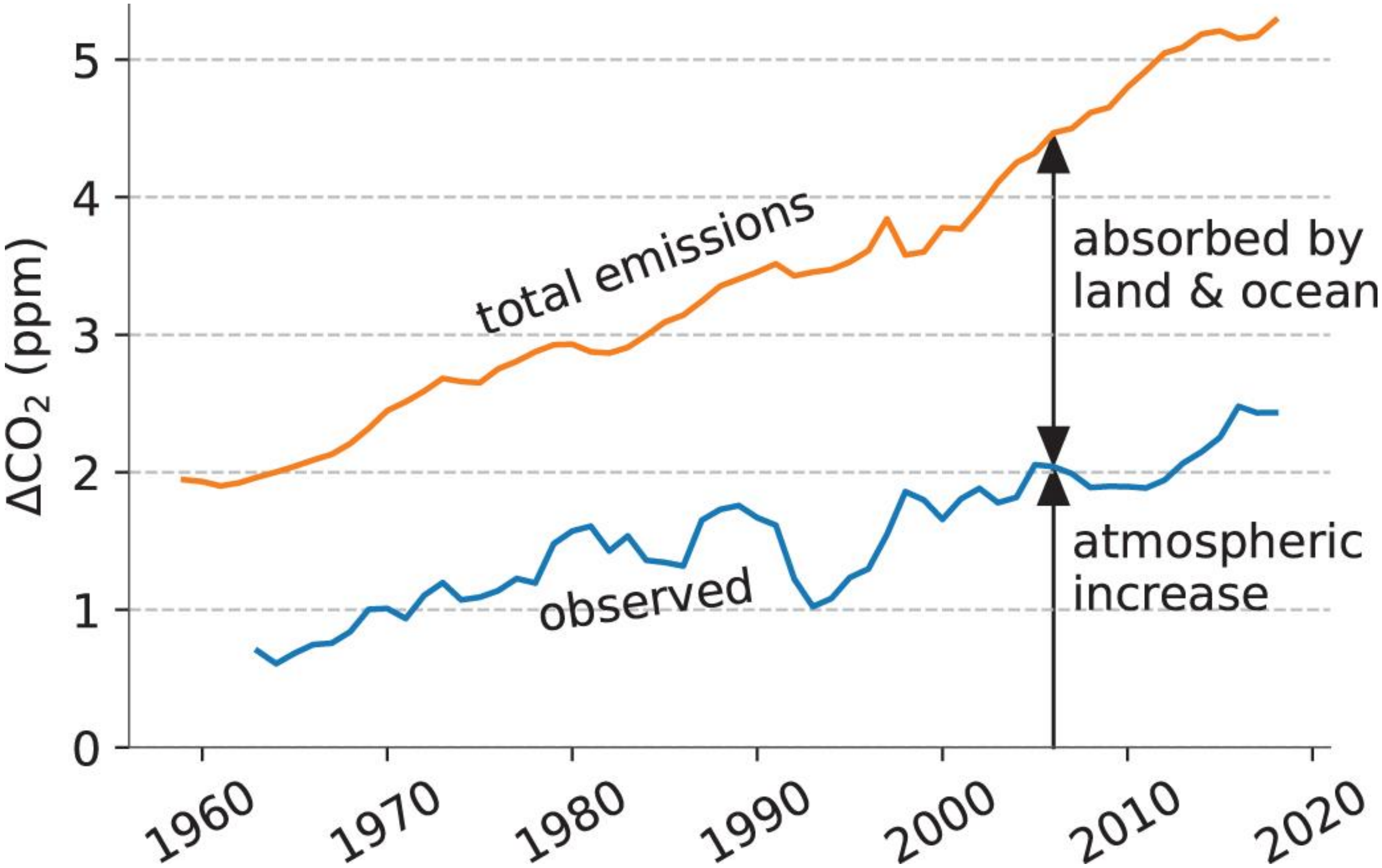
Figure 5.5 Diagram of the carbon cycle as perturbed by humans. Red arrows show net flows of carbon caused by human activities. Red arrows A, B, and C represent deforestation, enhanced absorption of carbon by the land biosphere, and enhanced absorption of carbon by the ocean, respectively.

Source: Dessler (2021)

Atmospheric CO_2 1960 - Present

Figure 5.7 The amount of carbon dioxide released into the atmosphere by human activities (orange line) and the observed annual increase in atmospheric carbon dioxide (blue line). Emissions data are described by Friedlingstein et al. (2019) and were downloaded from www.icos-cp.eu/global-carbon-budget-2019, retrieved June 9, 2020. Observations of atmospheric carbon dioxide were obtained from the NOAA Earth System Research Laboratory/Global Monitoring Division and were downloaded from www.esrl.noaa.gov/gmd/ccgg/trends/data.html, retrieved October 11, 2020.

Source: Dessler (2021)



5. Forcings, feedbacks and climate sensitivity

Radiative forcing – Greenhouse gases

- Increase in atmospheric CO_2 from 280 to 418 ppm between 1750 and September 2022. Corresponds to radiative forcing of +2.5 W/m^2
- Because of long lifetime of CO_2 a fraction of radiative forcing the Earth is experiencing now is due to CO_2 emitted in the early 1800s.
- Increases in methane (CH_4), nitrous oxide (N_2O), halocarbons and surface ozone (O_3) (bad ozone), between 1750 and 2018 produced radiative forcings of +0.54, +0.19, +0.38 and 0.35 W/m^2 respectively.

Radiative forcing

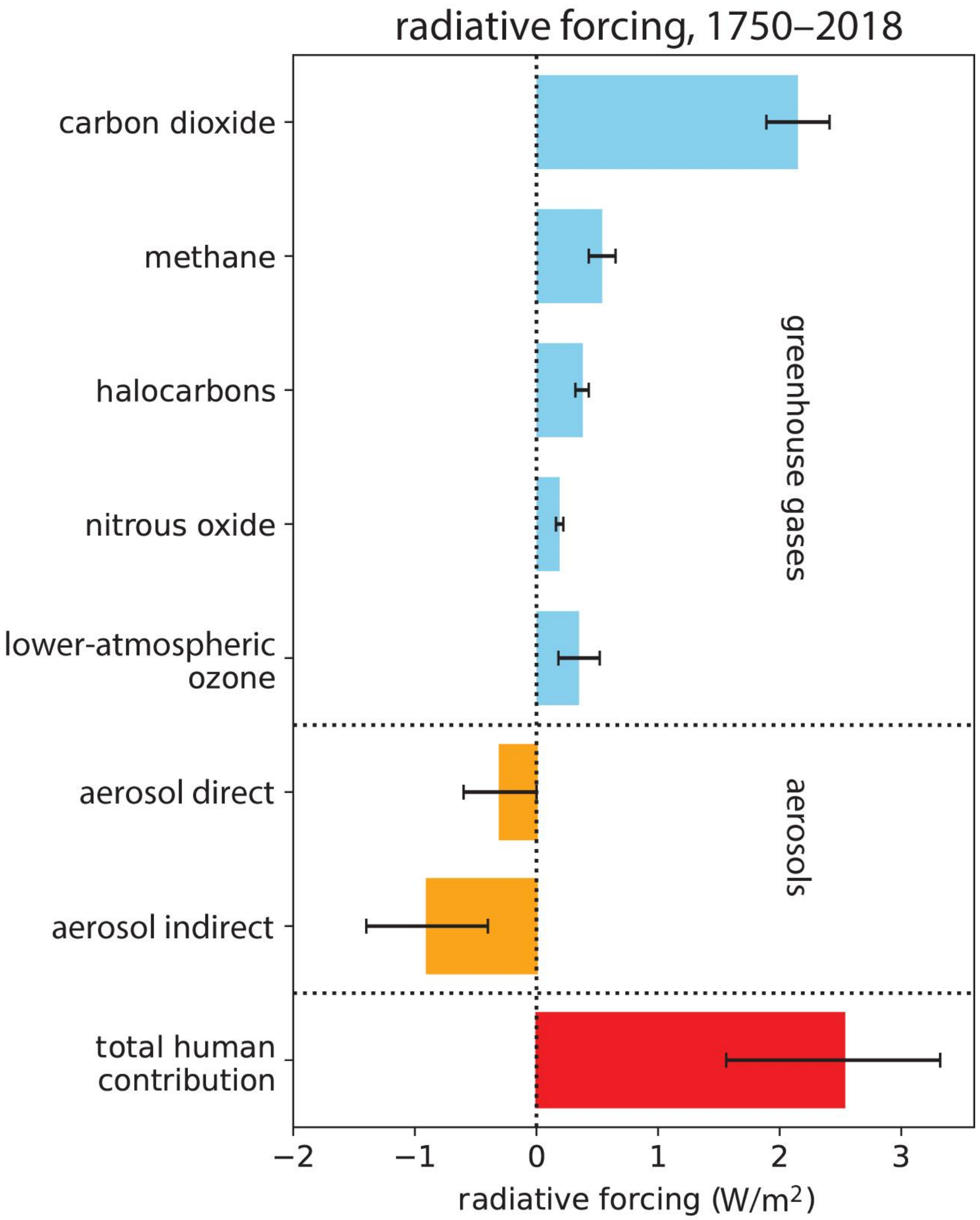


Figure 6.3 Radiative forcing caused by human activities between 1750 and 2018. The error bars indicate the uncertainty of the estimate.

Source: Dessler (2021)

Total net forcing

- Virtually all radiative forcings are linked to humans
- Radiative forcing: $E_{in} > E_{out}$ leads to warming planet
- Current estimates that $E_{in} > E_{out}$ by 0.8 W/m^2. This means that planet has warmed enough in last 250 years to erase +1.7 W/m^2 of radiative forcing

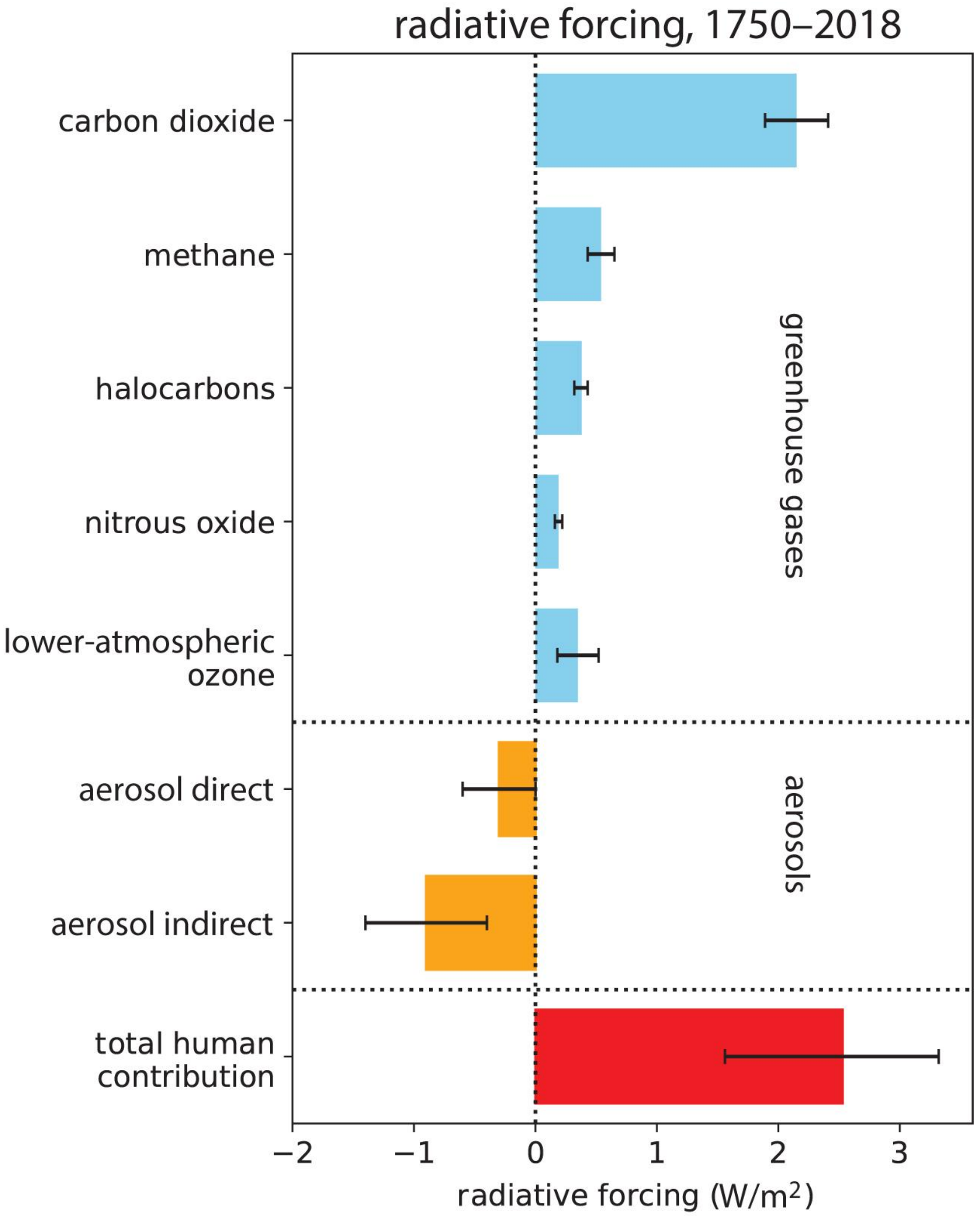


Figure 6.3 Radiative forcing caused by human activities between 1750 and 2018. The error bars indicate the uncertainty of the estimate.

Source: Dessler (2021)

Climate feedbacks

- Feedbacks do not initiate warming but *increase* **(positive feedback)** or *reduce* **(negative feedback)** initial warming
- Fast feedbacks occur rapidly from a change in surface temperature and are important for climate change over coming century
- **Positive feedbacks:** ice albedo and water vapour feedbacks

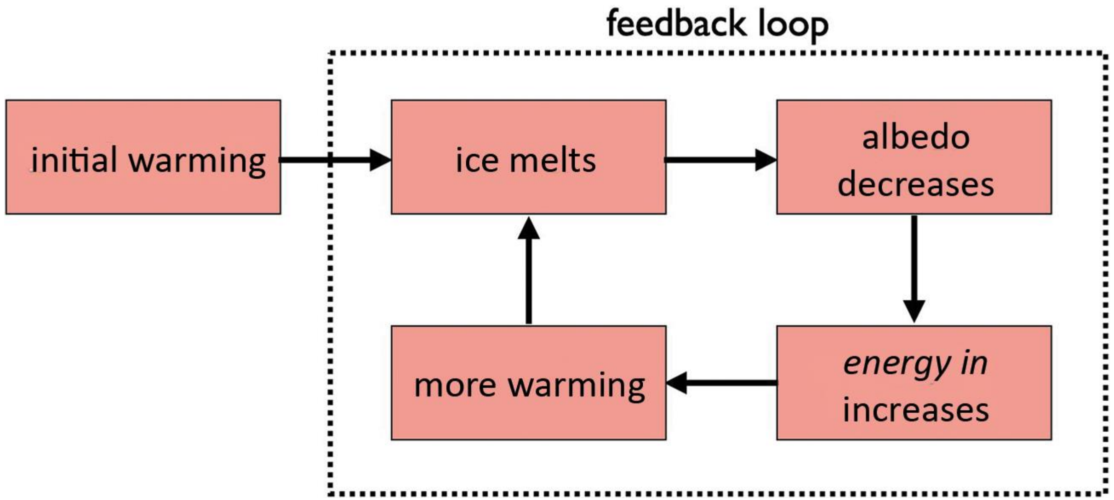


Figure 6.8 The ice-albedo feedback loop.

Source: Dessler (2021)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Impact of fast feedbacks

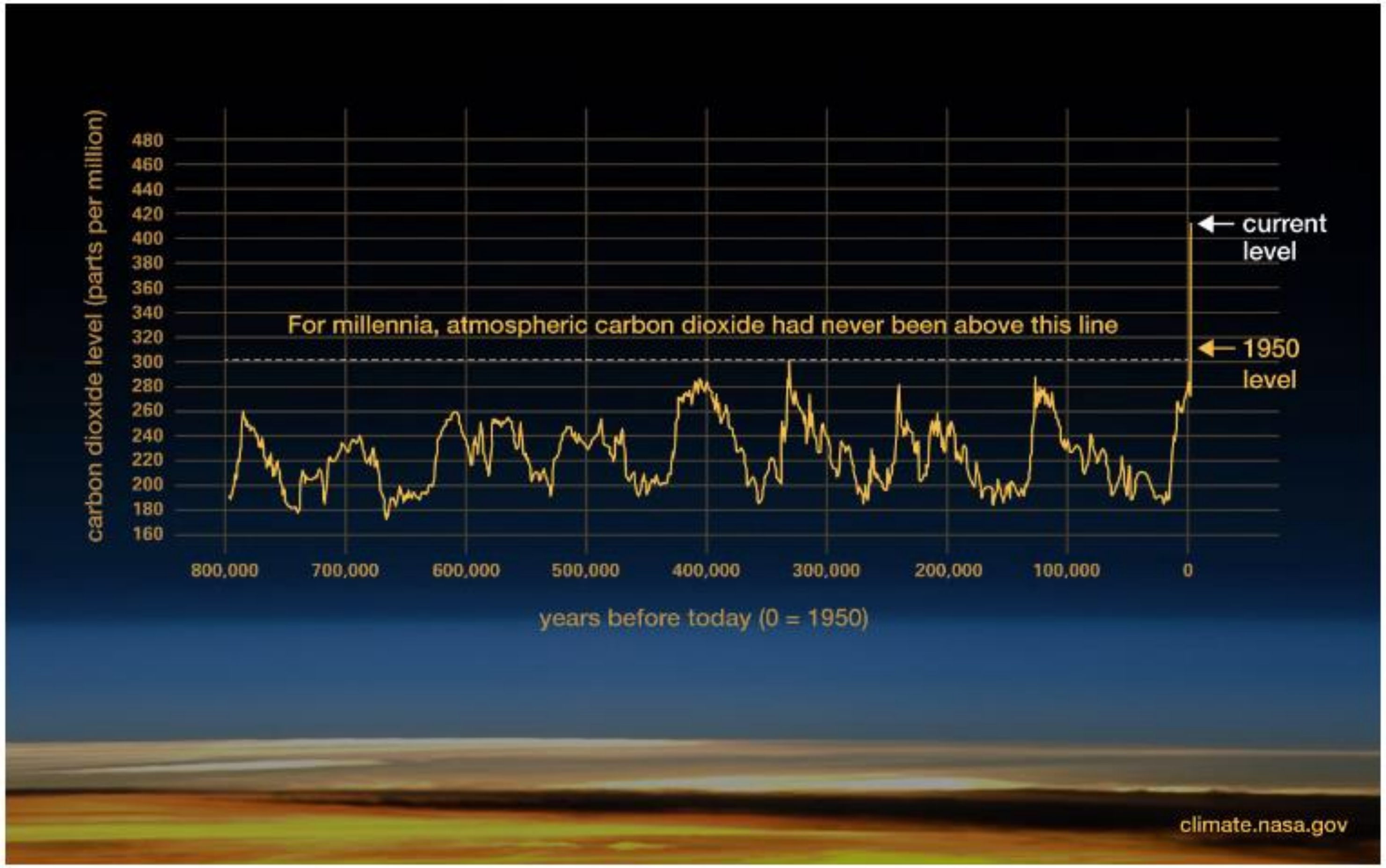
- Climate modelling estimates predict a warming of ~1.2 °C in response to doubled CO_2 **BEFORE** any feedbacks
- The warming **AFTER** feedbacks have been amplified: are 2.4 - 4.8 °C
- Doubled CO_2 (climate sensitivity) corresponds to radiative forcing of +4 W/m^2
- Climate sensitivity best estimates are 0.75 °C (W/m^2) i.e. 4 W/m^2 x 0.75 °C (W/m^2) = 3 °C

6. Causes of climate change

Greenhouse Gases: Evidence of Warming

- **Robust theory:** physical scientific basis for why increased GHGs warm planet

- **Geological and climatological records support theory:** geological evidence of connection between GHGs and climate (e.g. Paleocene-Eocene 55-60 million years BP)

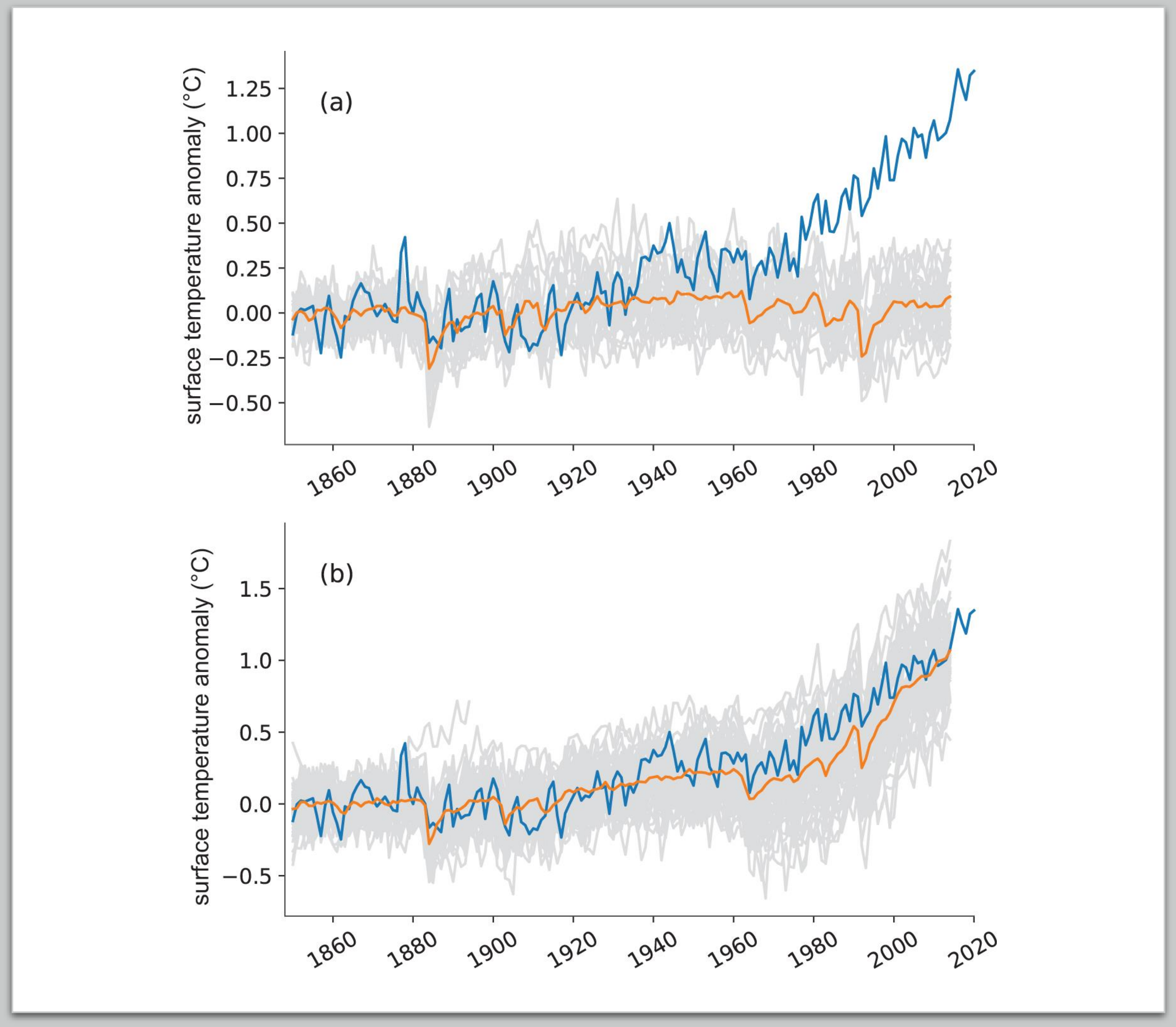


Source: NASA (n.d.)

Greenhouse Gases: Evidence of Warming

- **Computer simulations of climate provide support:** Climate model simulations that exclude the observed increase in GHGs don't show an increase in temperature over the second half of the 20th century

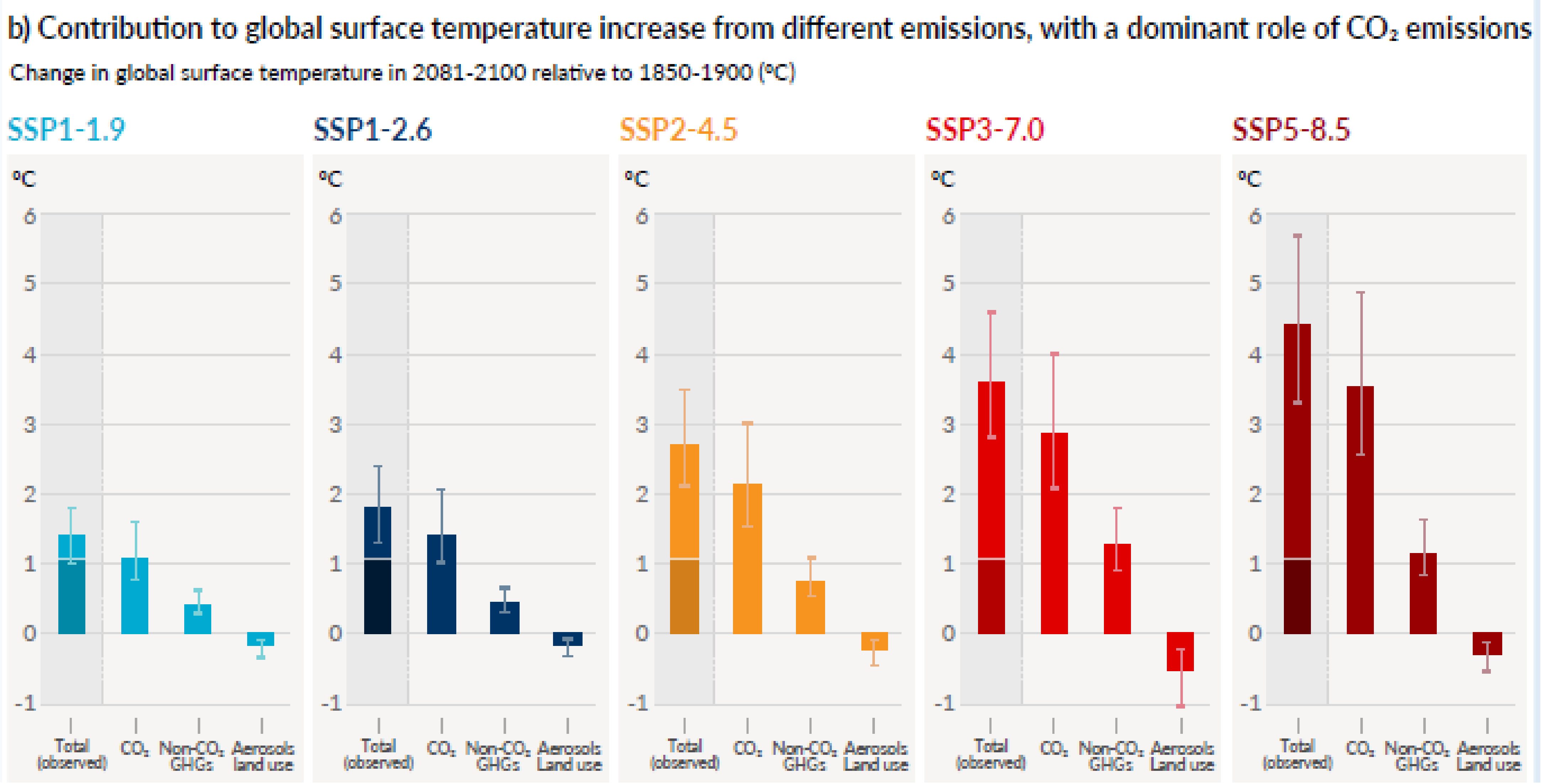
- **Fingerprints of warming:** Different warming mechanisms have unique signatures in pattern of warming



Source: Dessler (2021)

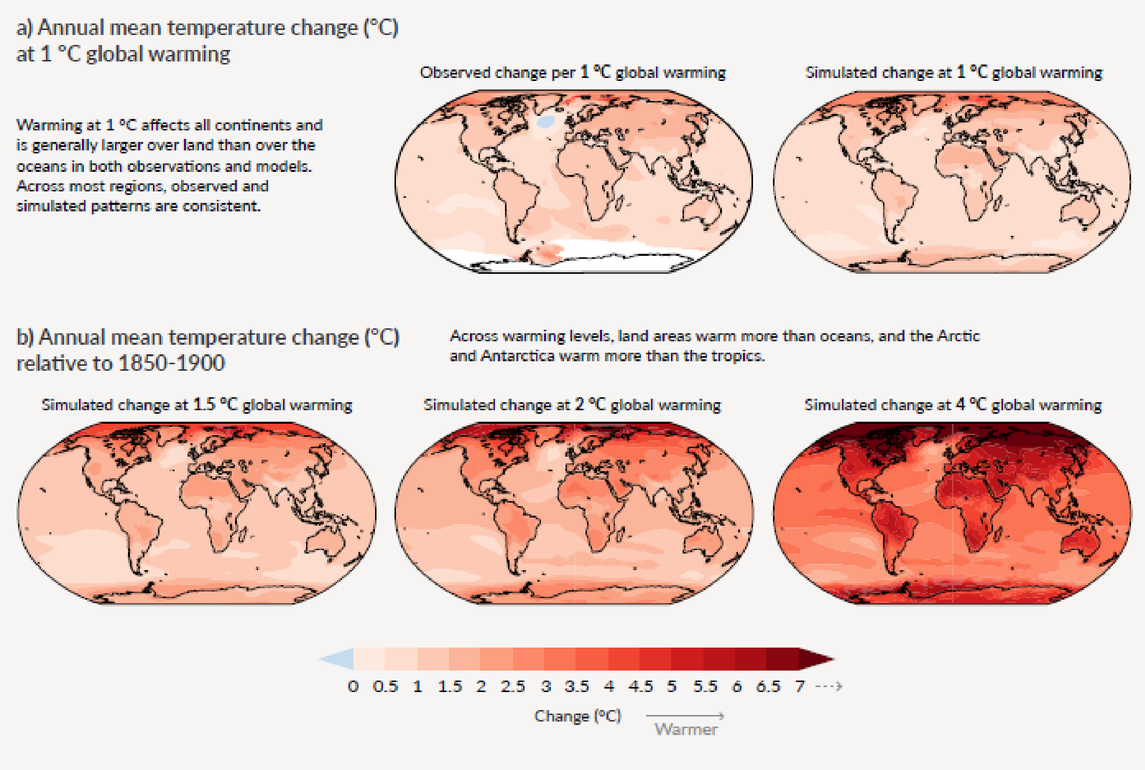
7. Future climate change predictions, including for Ireland

SSPs and future climate change

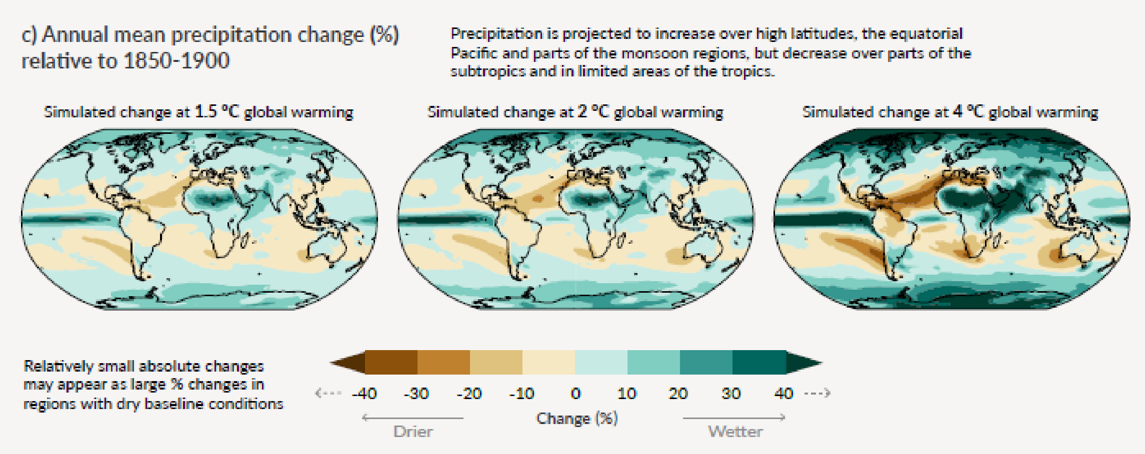


Source: IPCC (2021)

Each increment of global warming causes larger changes in regional mean temperature, precipitation and soil moisture

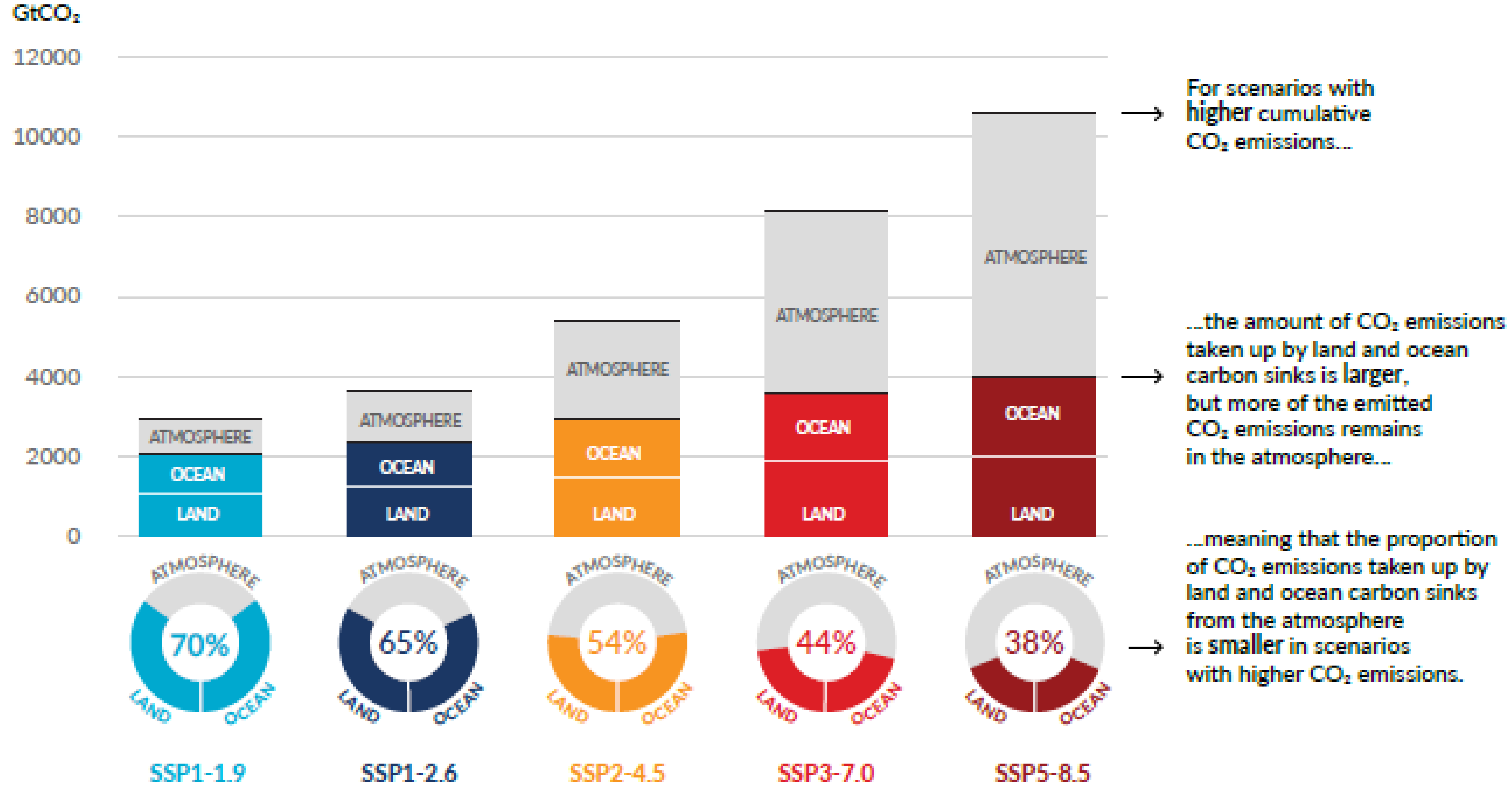


Source: IPCC (2021)



Source: IPCC (2021)

Total cumulative CO_2 emissions taken up by land and oceans (colours) and remaining in the atmosphere (grey) under the five illustrative scenarios from 1850 to 2100



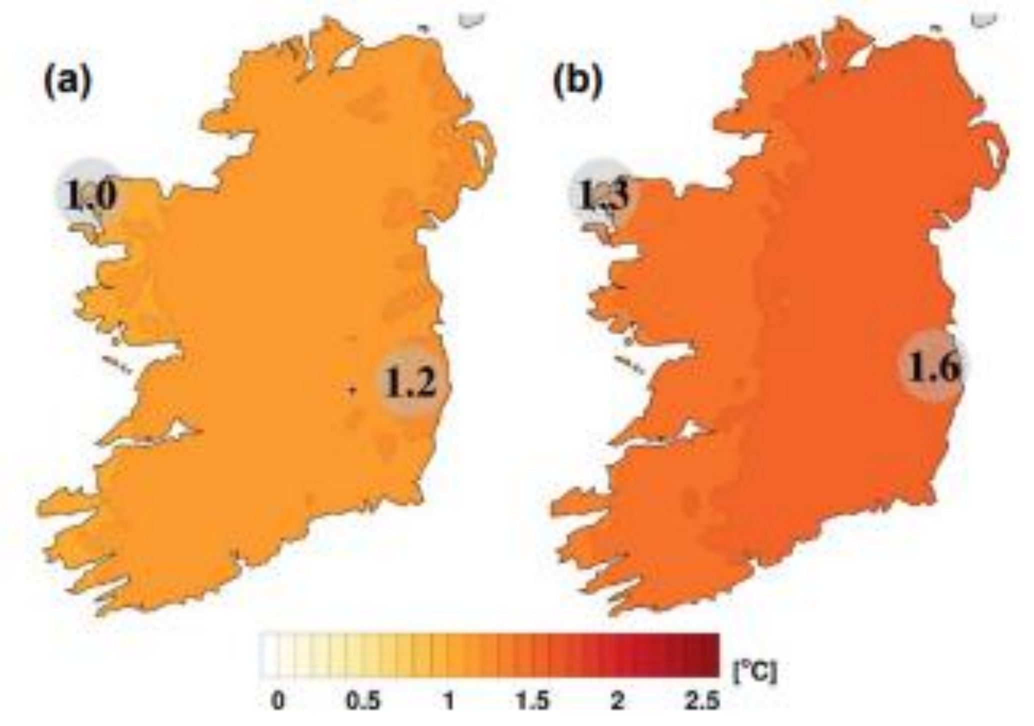
Source: IPCC (2021)

Temperature Projections 2041-2060

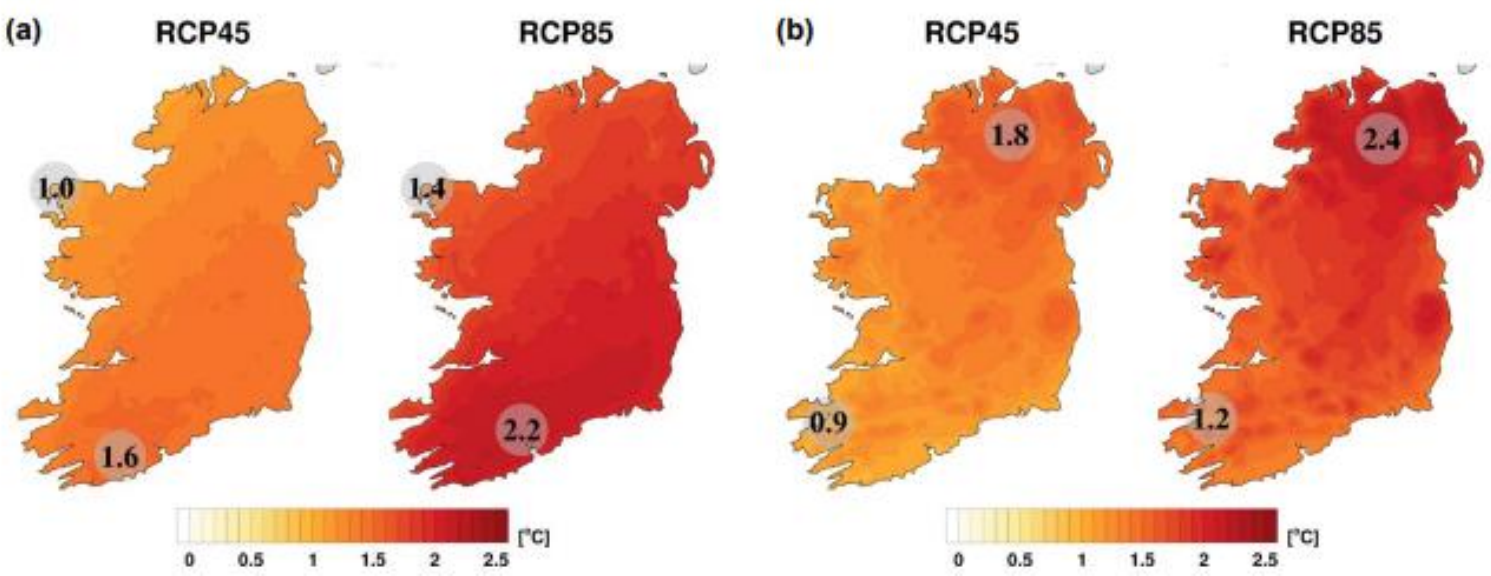
- Projected temperature change for
  a) Low-medium emission scenario (RCP4.5) and
  b) High emission scenario (RCP8.5).

- Future period defined as 2041–2060, and is compared with the past period, 1981–2000.

- Numbers included on each plot are the minimum and maximum projected changes, displayed at their locations (Nolan and Flanagan, 2020).



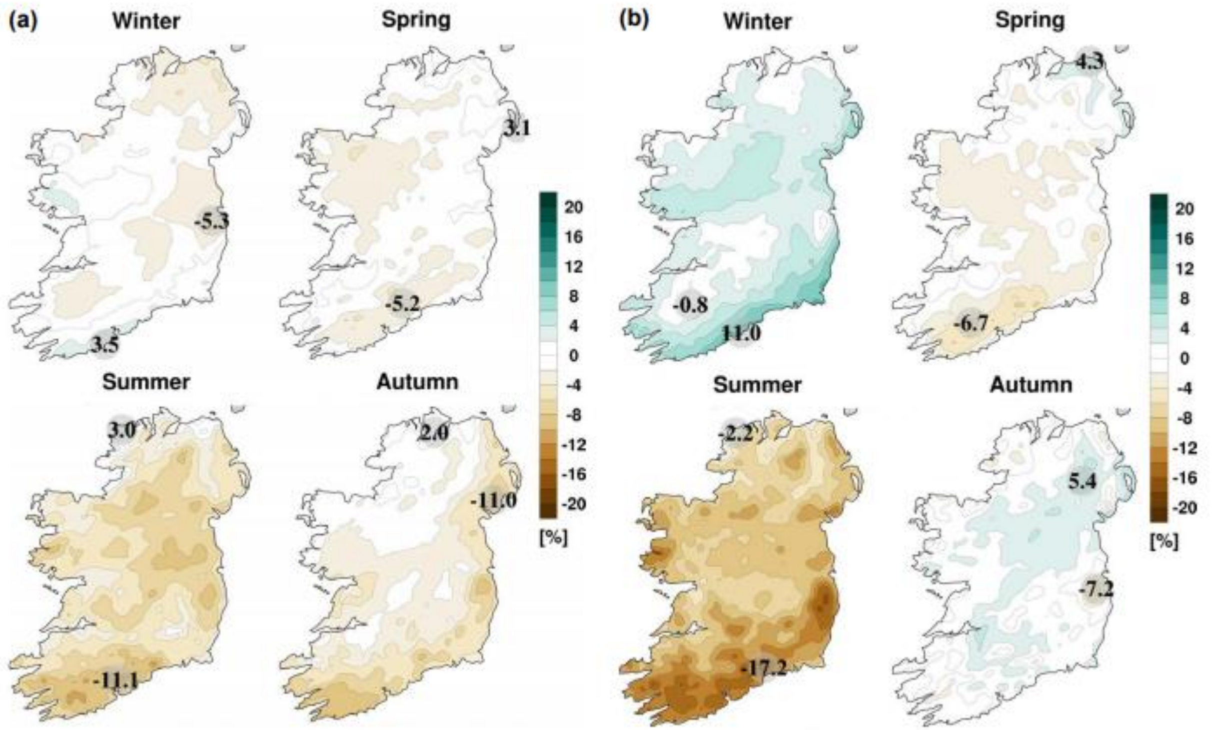
Extreme Temperature Projections 2041-2060

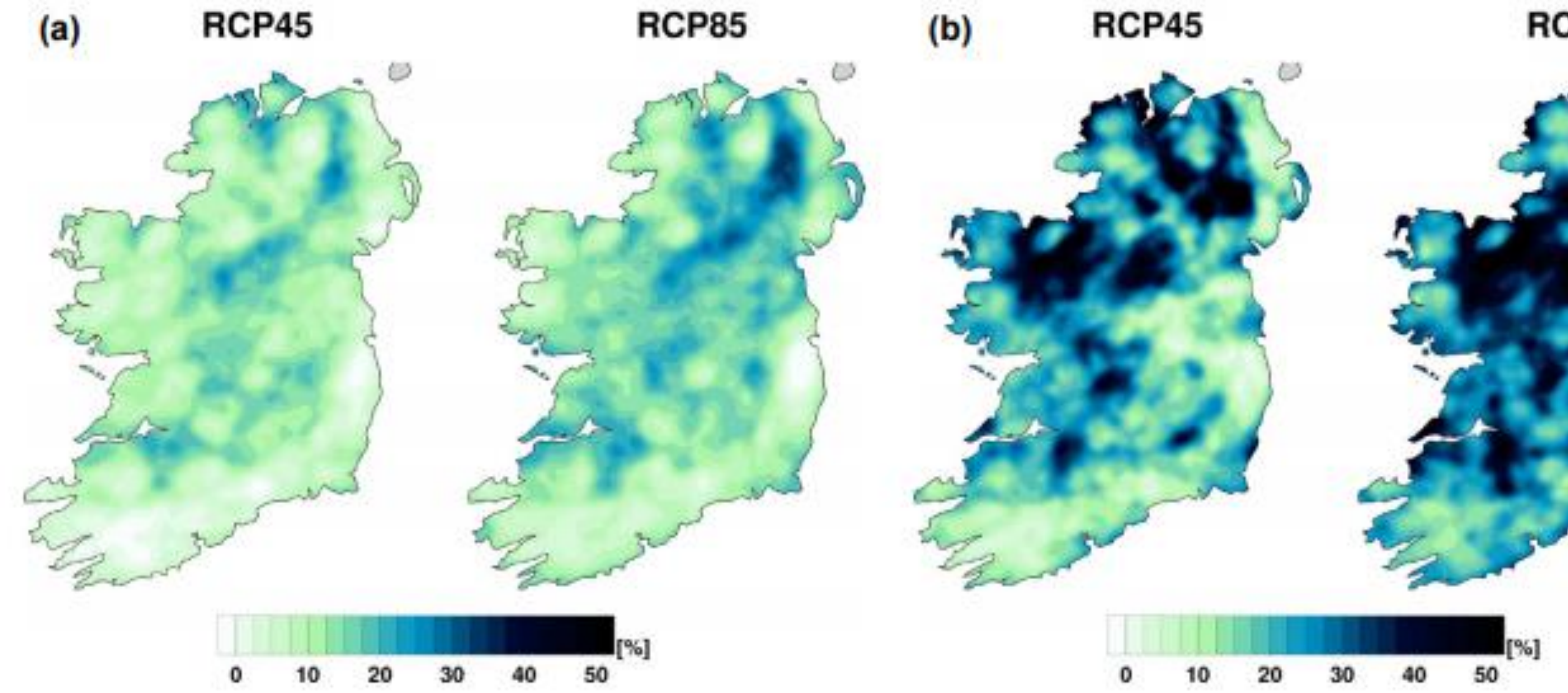


- Projected changes in mid-century extreme temperature:
  a) top 5% of daily maximum temperatures (warm summer days) and
  b) bottom 5% of daily minimum temperatures (cold winter nights).
- In each case, the future period, 2041–2060, is compared with the past period, 1981–2000.
- Numbers included on each plot are the minimum and maximum projected changes, displayed at their locations.

Seasonal Precipitation Projections 2041-2060

- Mid-century seasonal projections of average precipitation (%) for
  a) RCP4.5 and
  b) RCP8.5 scenarios.
- In each case, the future period, 2041–2060, is compared with the past period, 1981–2000.
- The numbers included on each plot are the minimum and maximum projected changes, displayed at their locations





Wet and Very Wet Days Projections 2041-2060

- Projected changes (%) in mid-century number of annual
  a) Wet days (precipitation >20mm day) and
  b) very wet days (precipitation >30mm day).
- In each case, the future period, 2041– 2060, is compared with the past period, 1981–2000.

Seminar summary

1. Understand how climate is changing
2. Explain radiation and energy balance
3. Discuss the role of climate modelling in climate science
4. Describe the carbon cycle
5. Understand the impacts of climate forcings, feedbacks and climate sensitivity on climate change
6. Causes of climate change
7. Examine future climate change predictions, including for Ireland

Thank you – Questions welcome

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