Climate and Ocean Change: Physical Foundations and Impacts Lab

Module 2: Contemporary changes

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Ministero dell'Università e della Ricerca

Italiadomani

Contents of the course (modules 1-2)

1. Physical foundations

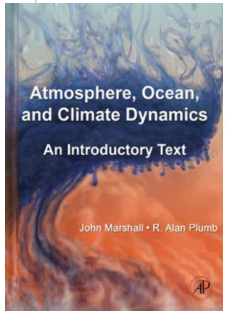
- Greenhouse effect
- Climate feedbacks
- Aerosols
- Convection
- Meridional structure of the atmosphere
- General circulation: atmosphere, ocean
- Natural variability and teleconnections

2. Contemporary changes

- Observations of change
- Overshoot
- Attribution
- Climate projections

Bibliography

- [MP08] (textbook): J. Marshall, R. Alan Plumb "Atmosphere, Ocean and Climate Dynamics: An Introductory Text", Academic Press (2008)
- [IPCC6] "Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change"
- [IPCC5] "Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change"
- [H16] (selected figures) D. L. Hartman "Global Physical Climatology, 2nd edition", Elsevier (2016)
- Selected journal papers and websites (as indicated in the slides)



Observations of change

Main climate factors

Forcings

Solar irradiance

Orbital parameters

Greenhouse gases *

Aerosols *

Volcanos

Land Use *

Internal variability

ENSO, IOD

AMOC

NAO

Feedbacks

Water vapour

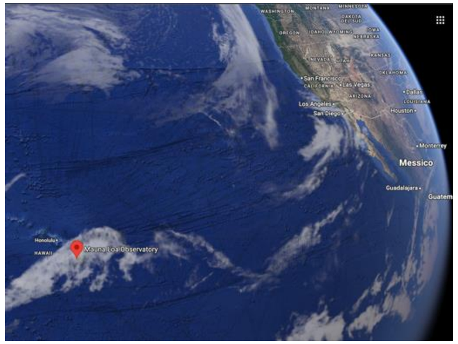
Ice-albedo

Clouds

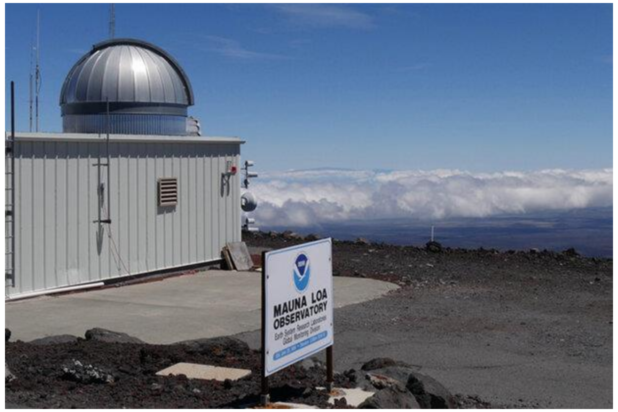
*) These can directly be affected by human activities

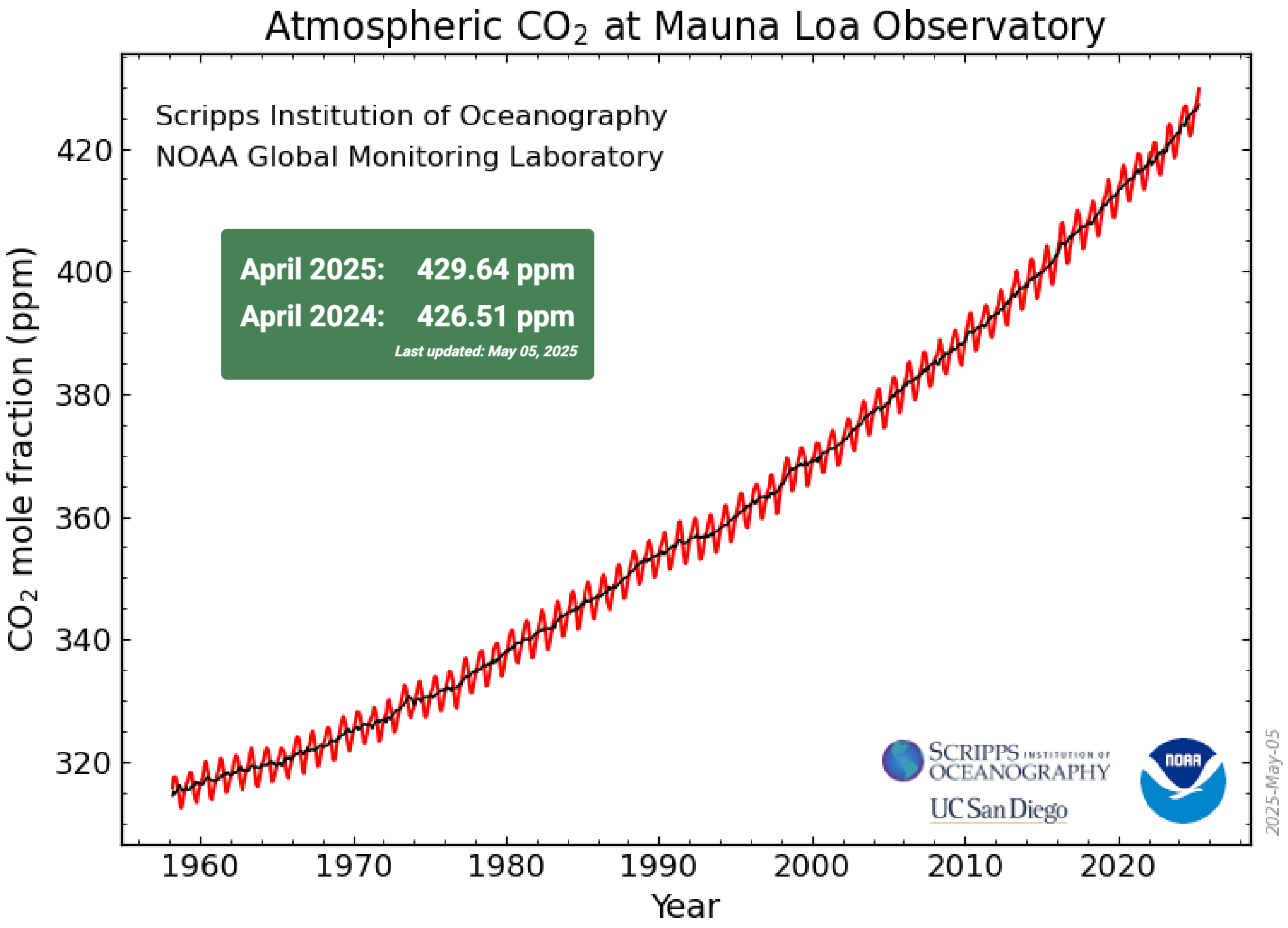
Observations of change

CO_2 mixing ratio from air measurements



Mauna Loa → a remote site at 3400 m, ideal for background measurements (away from sources or sinks)



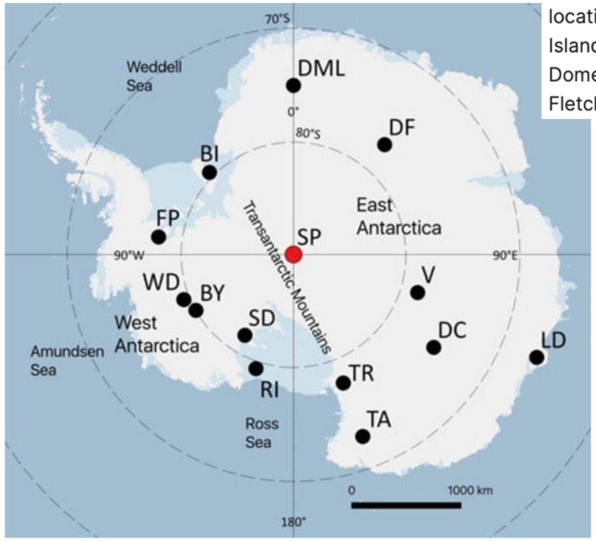


https://gml.noaa.gov/ccgg/trends/

Observations of change

CO_2 mixing ratio from ice cores

Kimberly A. Casey



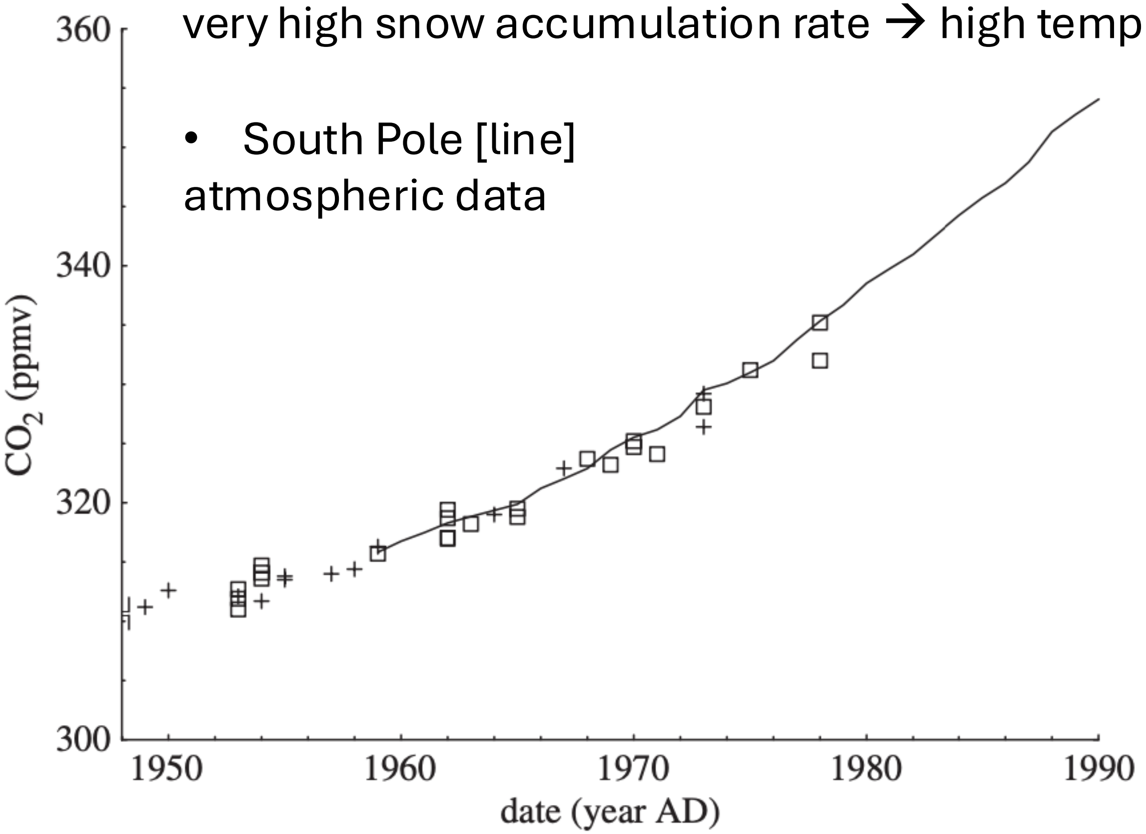
locations labeled: South Pole (SP), Berkner Island (BI), Byrd (BY), EPICA Dome C (DC), Dome Fuji (DF), Dronning Maud Land (DML), Fletcher Promontory (FP), Law Dome (LD),

- Law Dome [markers]

very high snow accumulation rate → high temporal resolution

- South Pole [line]

atmospheric data



Wolff (2011), Phil. Trans. R. Soc. A

Raynaus (1982) Annals of Glaciology

Observations of change

CO_2 mixing ratio: last

➔ agreement among sites with different characteristics (coastal/inland, warm/cold, low/high impurities)

site	resolution (years)	impurities
Law Dome	~10	high
EPICA DML	~15	
South Pole	~50	
Dome C	400	very low

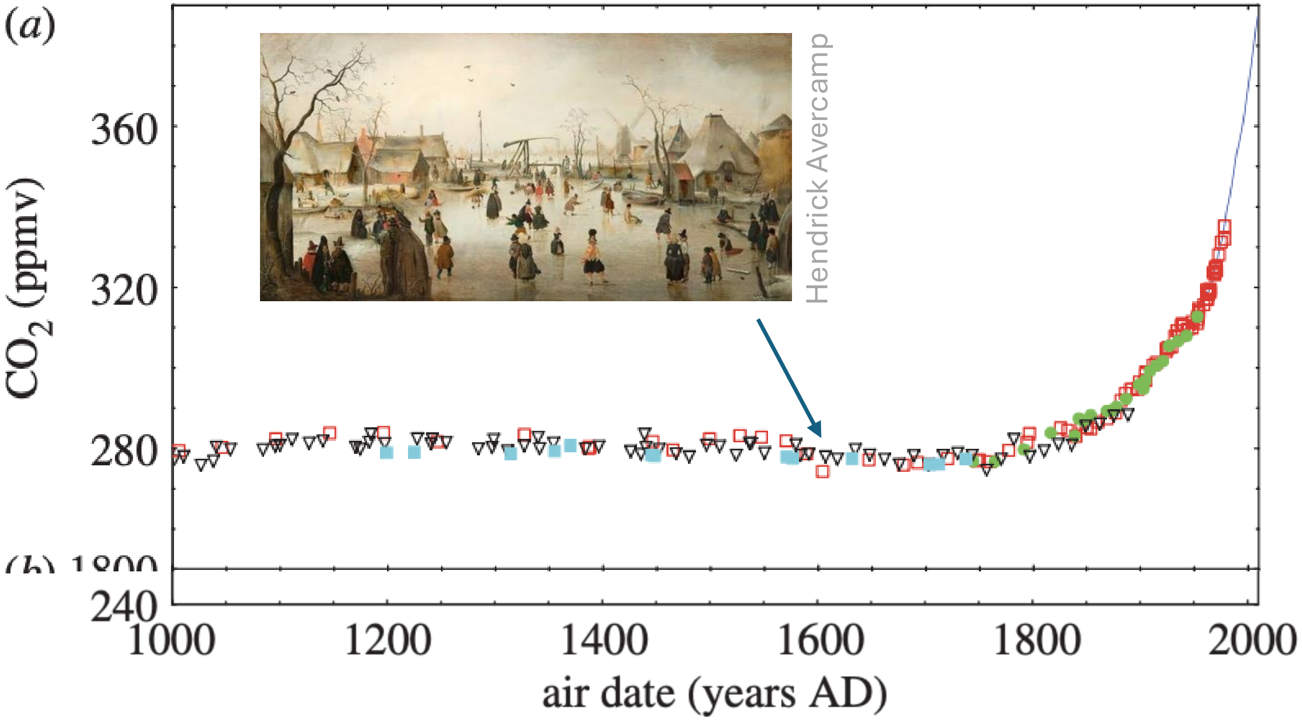


Figure 2. Trace gas mixing ratios over the last 1000 years from ice cores and atmospheric measurements. (*a*) CO_2; the solid line is Mauna Loa annual average atmospheric data; red squares are from Law Dome [16]; green circles from Siple [18]; black triangles from the EPICA DML site; turquoise squares from South Pole [19]. (*b*) CH_4 on the CSIRO calibration scale; line is annual

Wolff (2011), Phil. Trans. R. Soc. A

Observations of change

Signature of fossil CO_2

Suess effect:
- ^{12}C and ^{13}C stable isotopes
- plants mainly absorb ^{12}C during photosynthesis

→ ancient organic matter too is poor in ^{13}C
→ fossil fuels combustion (releasing CO_2) leads to emission of ^{12}C
→ dilution of ^{13}C in the atmosphere

Alternative processes for CO_2 increase (ruled out by $\delta^{13}C$ data):
- volcanic origin
- ocean outgasing

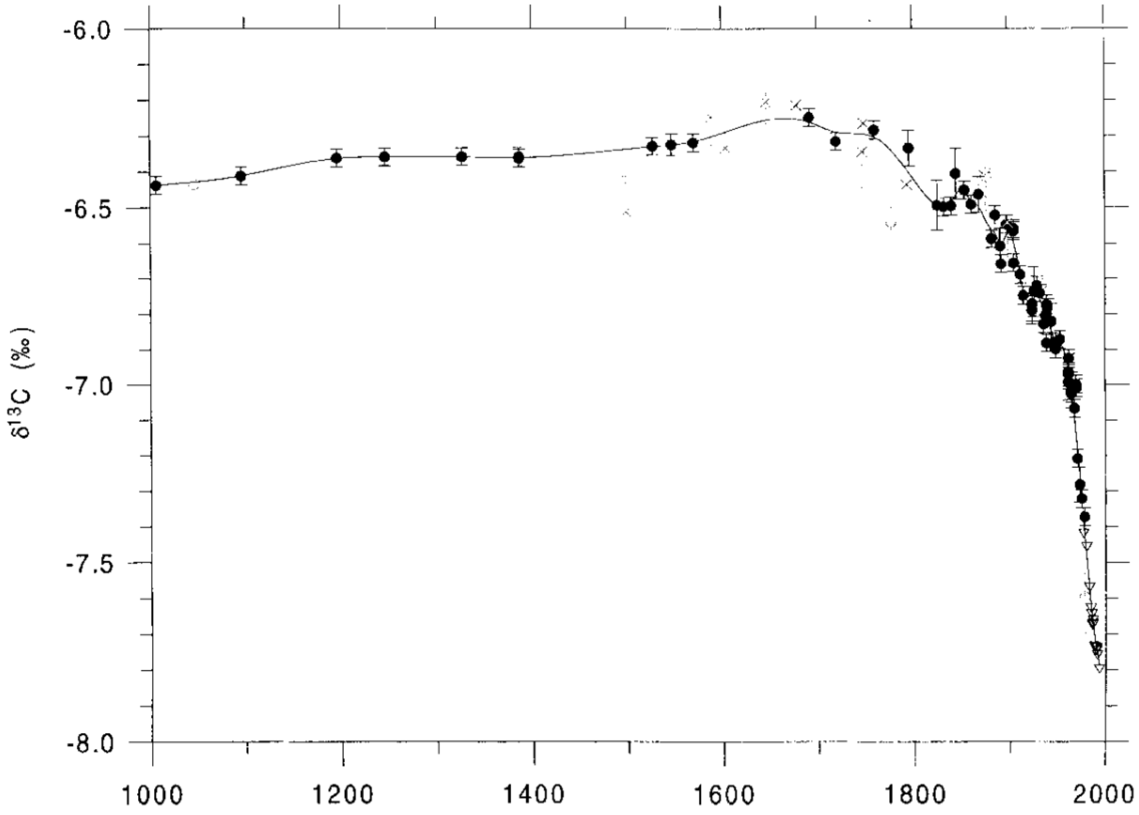


Fig. 9. The complete record of CO_2 and $\delta^{13}C$ from the Law Dome ice cores and firn. The smoothing spline is weighted by the statistical error in, and density of, data; effective smoothing is 25 years after 1800 AD and ~130 years before 1800 AD. (Light grey symbols are rejected points from the section "Summary of data selections and corrections" and are included here only to provide a perspective on the selection processes. Crosses indicate ethanol contaminated samples, open circles are other rejections).

Francey et al. (2009), Tellus

Observations of change

CO_2 mixing ratio during the Holocene

debate about whether the slow increase after 6000 BP is the result of early anthropogenic activities

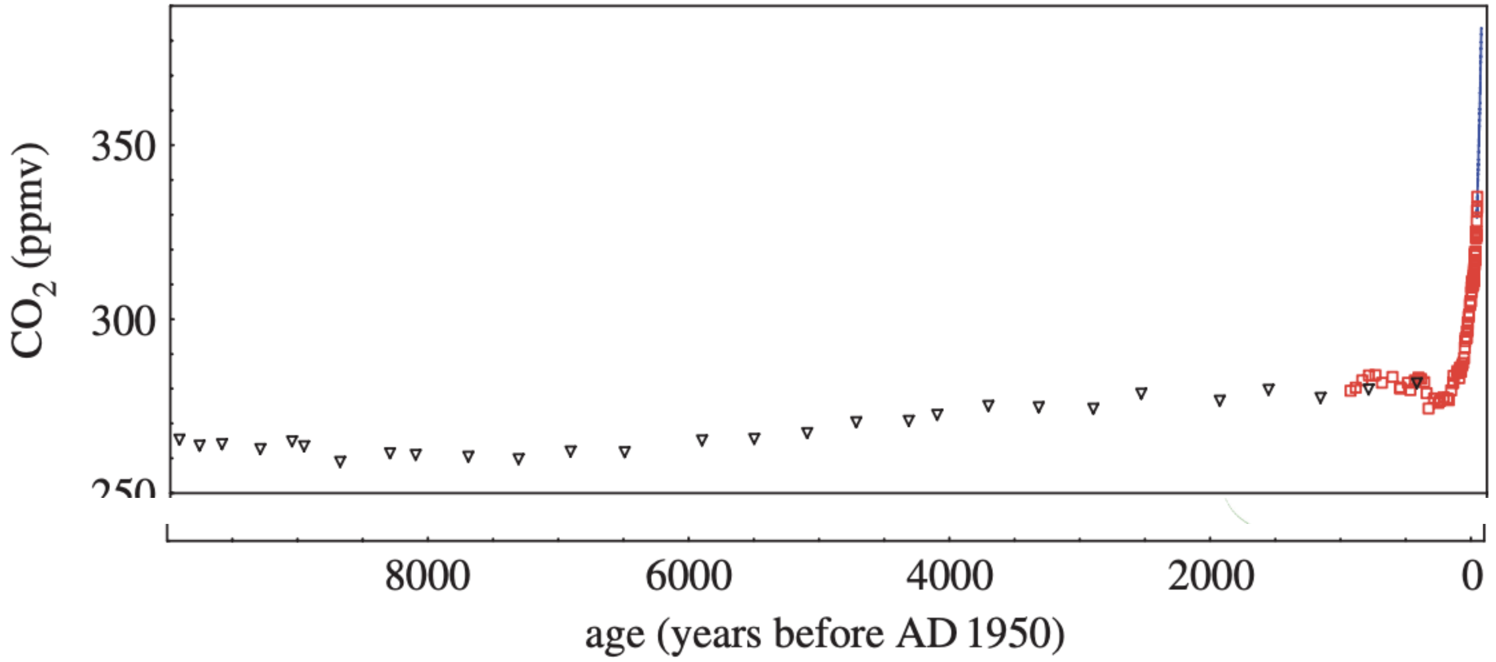


Figure 3. CO_2 and CH_4 mixing ratios over the last 10 kyr. The blue lines represent atmospheric measurements from flasks collected at South Pole; the red squares are from Law Dome ice cores [10,16]; the black triangles are from Dome C ice cores [25]. Note that Dome C has a much wider age distribution for each sample (see text) and therefore shows a smoothed signal compared with Law Dome.

Wolff (2011), Phil. Trans. R. Soc. A

Observations of change

CO_2 mixing ratio in the late Quaternary

Holocene optimum

LIG (Last Inter-Glacial)

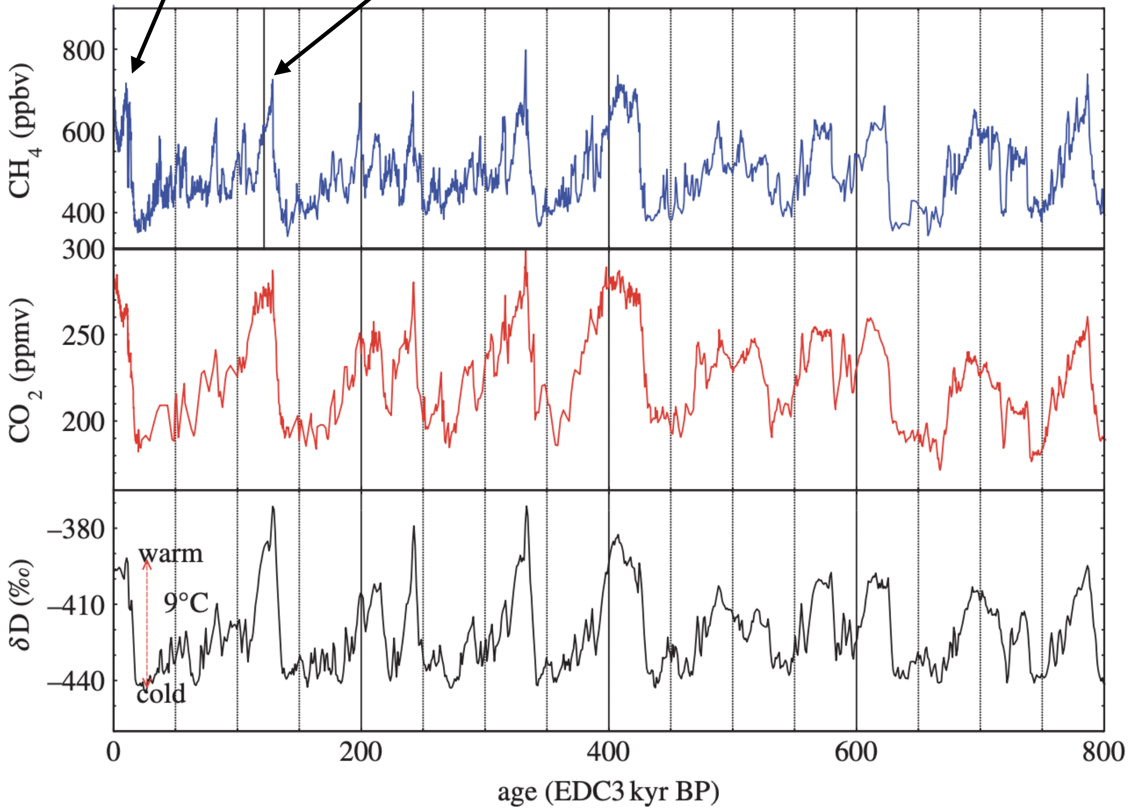
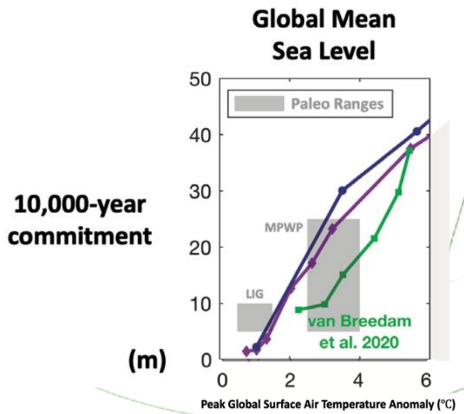


Figure 4. CO_2 and CH_4 mixing ratios over the last 800 kyr. Also shown for comparison is the Dome C deuterium profile [3], which acts as an Antarctic temperature proxy. CO_2 is from Dome C and Vostok ([9] and references therein); CH_4 is from Dome C ([8] and references therein). Note that the plots are shown with time running from right to left and that the increased values of the last 200 years are not included. The black vertical line on the CH_4 plot is the period of known warmth above present in the last interglacial in Greenland (referred to in §5*a*).

Deuterium is a proxy of Antarctic temperature

Wolff (2011), Phil. Trans. R. Soc. A

MPWP (Mid-Pleicene Warm Period, -3.3 Myr)



IPCC AR6 WG1 Fig.9.30

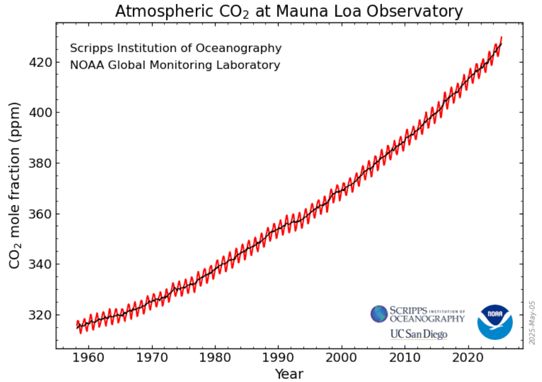
➔ The observed sea level rise is only a partial response to the already realized warming.

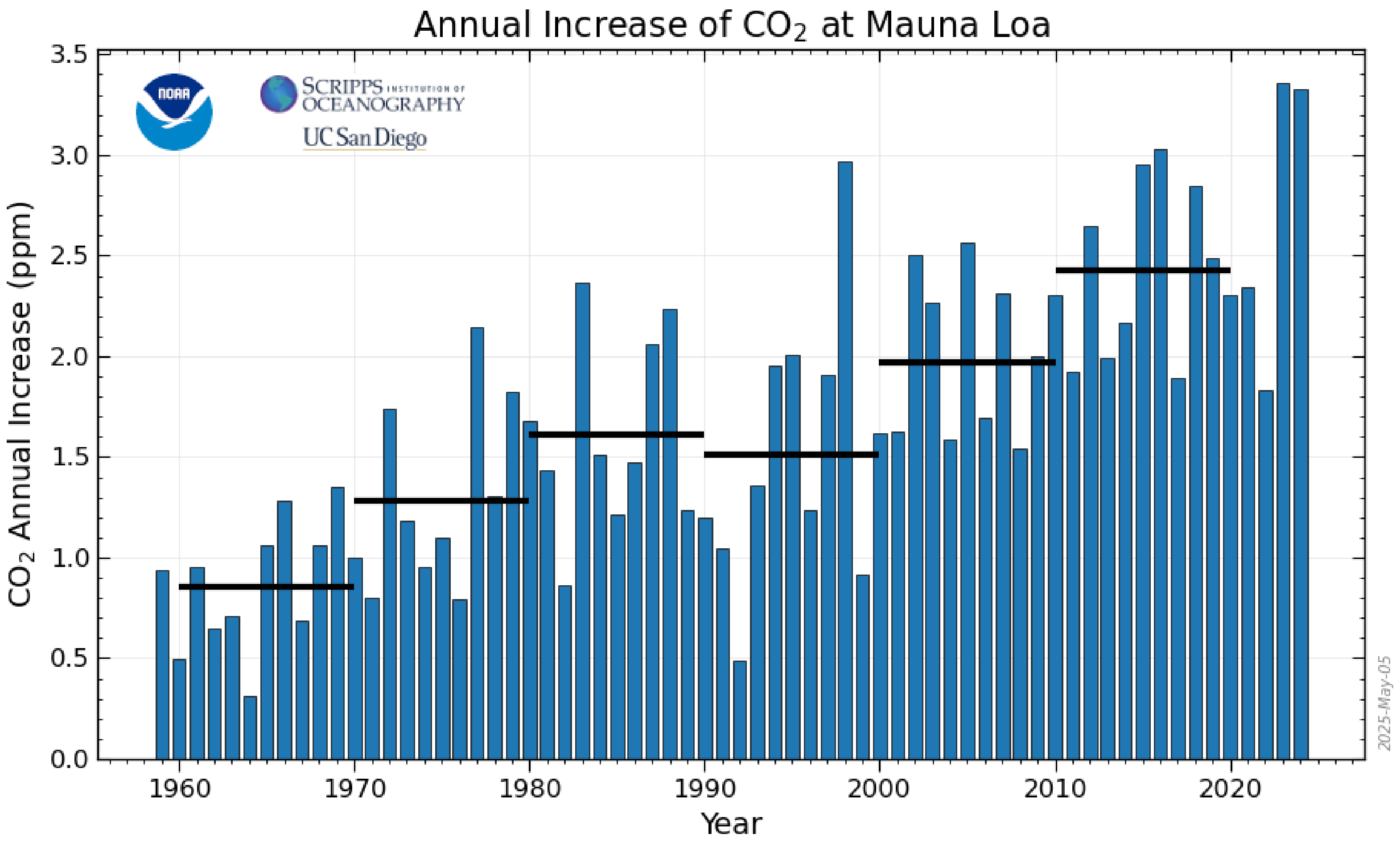
Ice sheets and glaciers are committed to losing considerable mass in the future, even without further change in air temperature

Observations of change

today's growth rate is 3x the value of the 1960s➔

one ‘business-as-usual’ year now equals three from 70 years ago





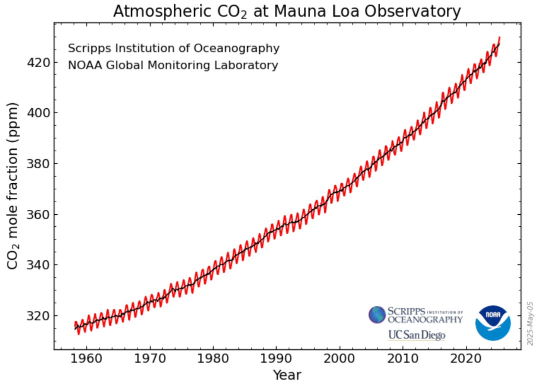
https://gml.noaa.gov/ccgg/trends/

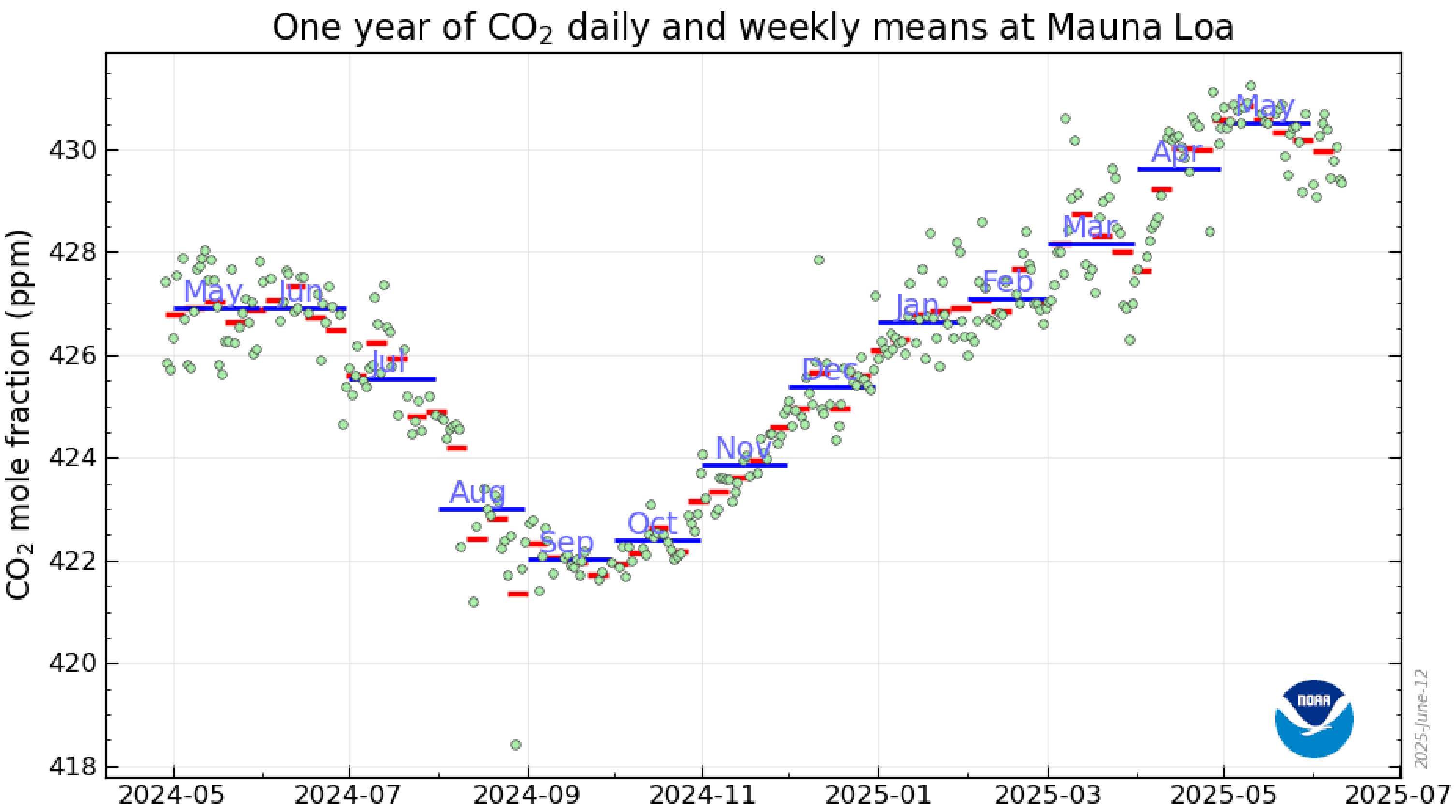
Observations of change

Seasonal cycle amplitude now at about 8 ppm

➔ An all-time record mixing ratio of ~430 ppm was reached in May 2025

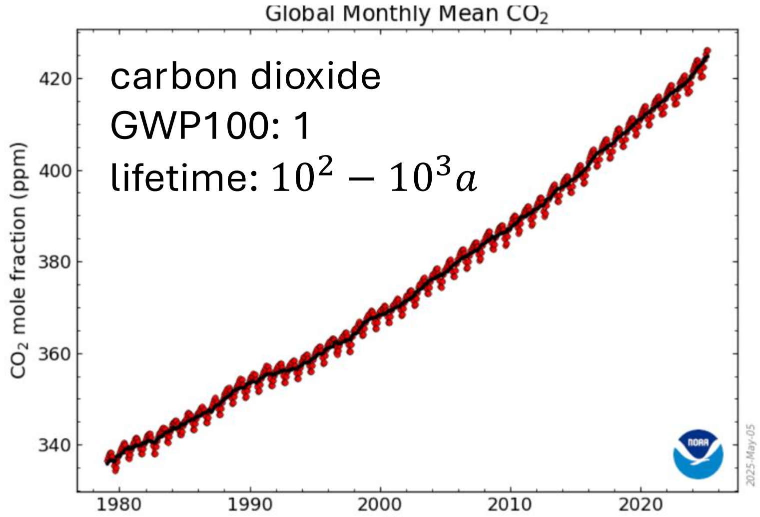
By May 2026, monthly-mean atmospheric CO_2 levels are likely to exceed 432 ppm

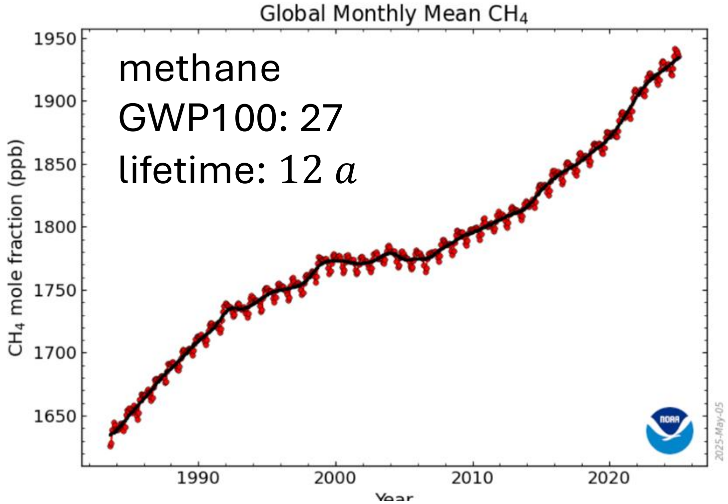


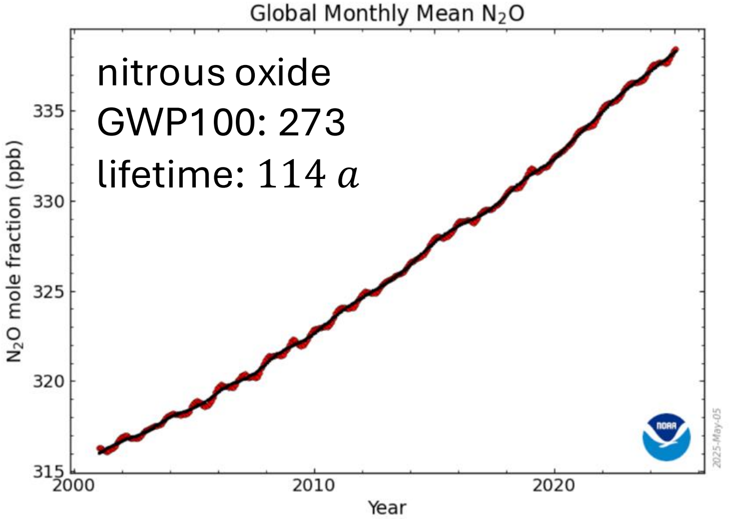


https://gml.noaa.gov/ccgg/trends/

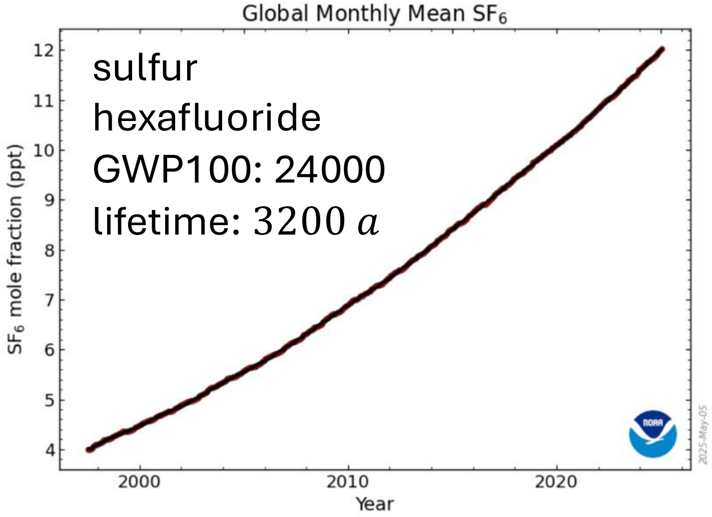
Observations of change





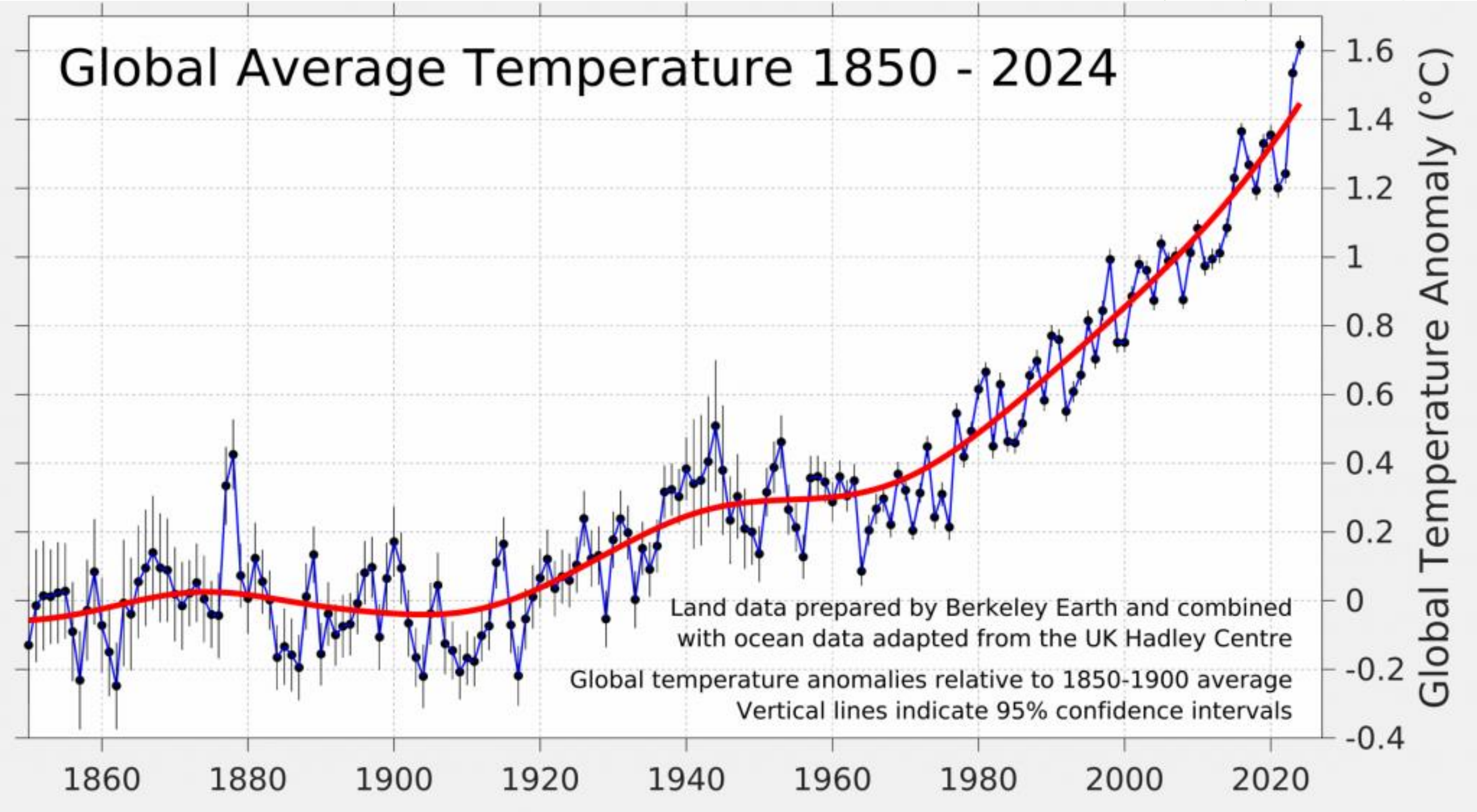


Global-mean, not Mauna Loa's



https://gml.noaa.gov/ccgg/trends/

Observations of change



https://berkeleyearth.org/global-temperature-report-for-2024/

The warming in 2023/2024 has been extraordinary.

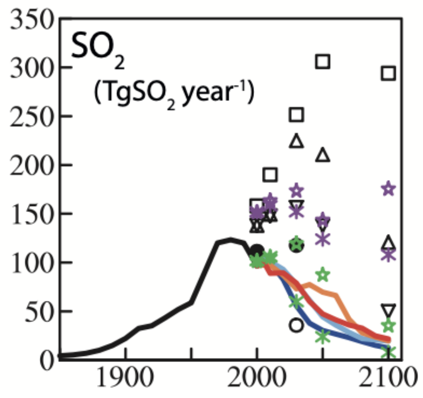
Naturale causes:
- ElNino
- HungaTonga?

Human causes:
- GHG emissions
- reduction in man-made sulfur aerosols from shipping

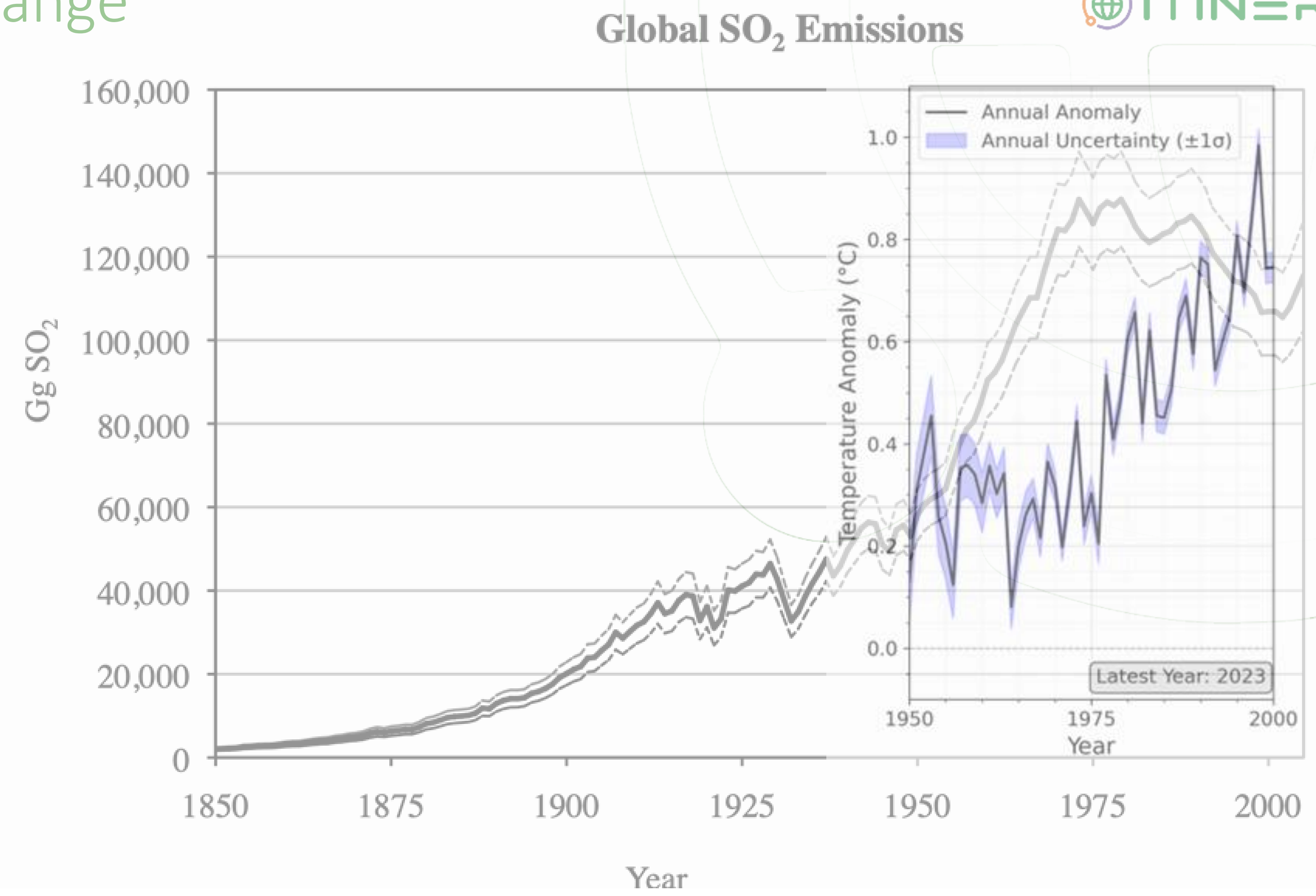
BERKELEY EARTH

Observations of change

1950-1980’s growth rate of temperatures much lower than CO_2 ‘s one due to cooling effect of sulfate aerosols emissions



IPCC AR5 WG1 Fig.8.2

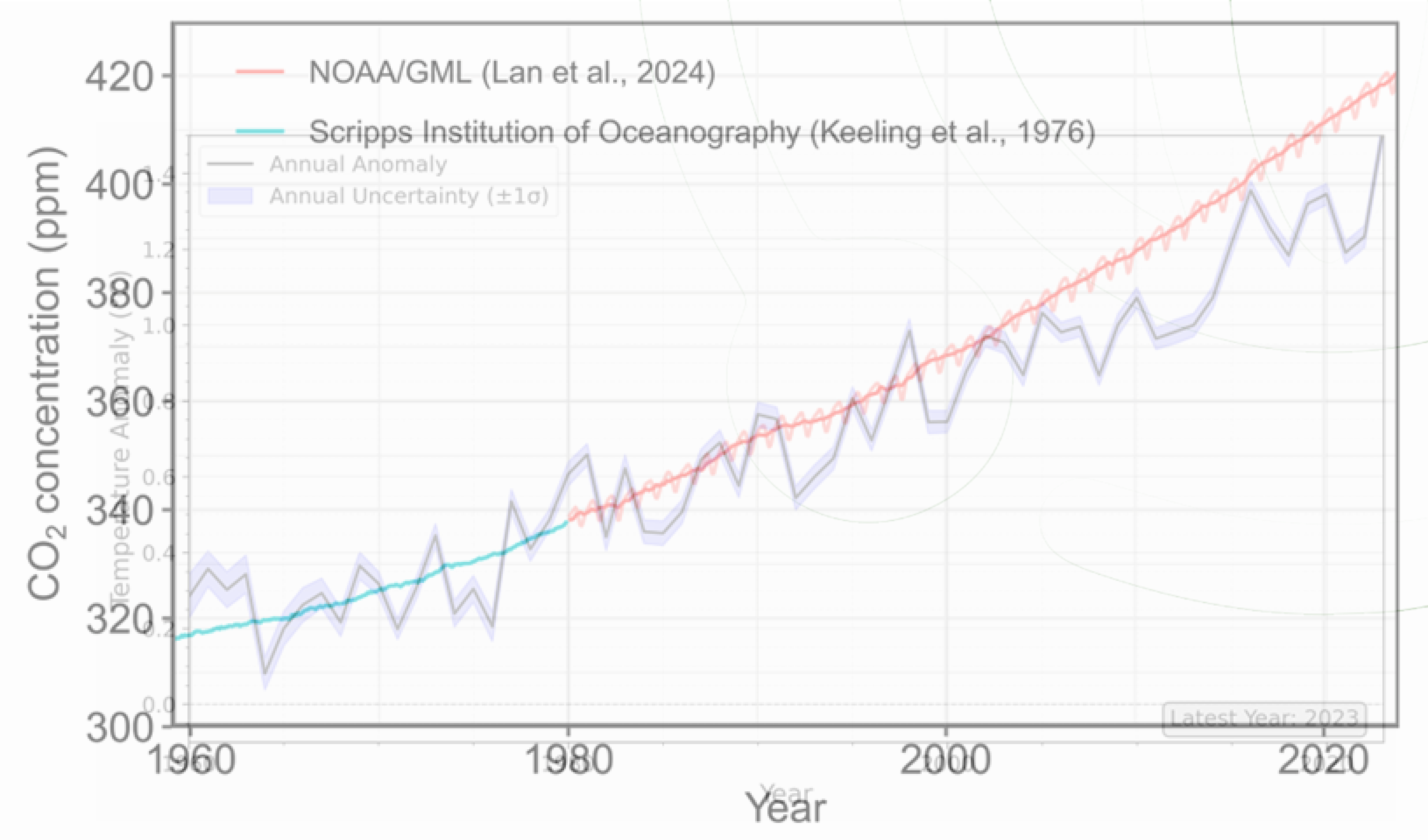


Smith_2011 (Fig.3a) DOI: 10.5194/acp-11-1101-2011

Observations of change

last half century's growth rate of temperatures and CO_2 are well correlated

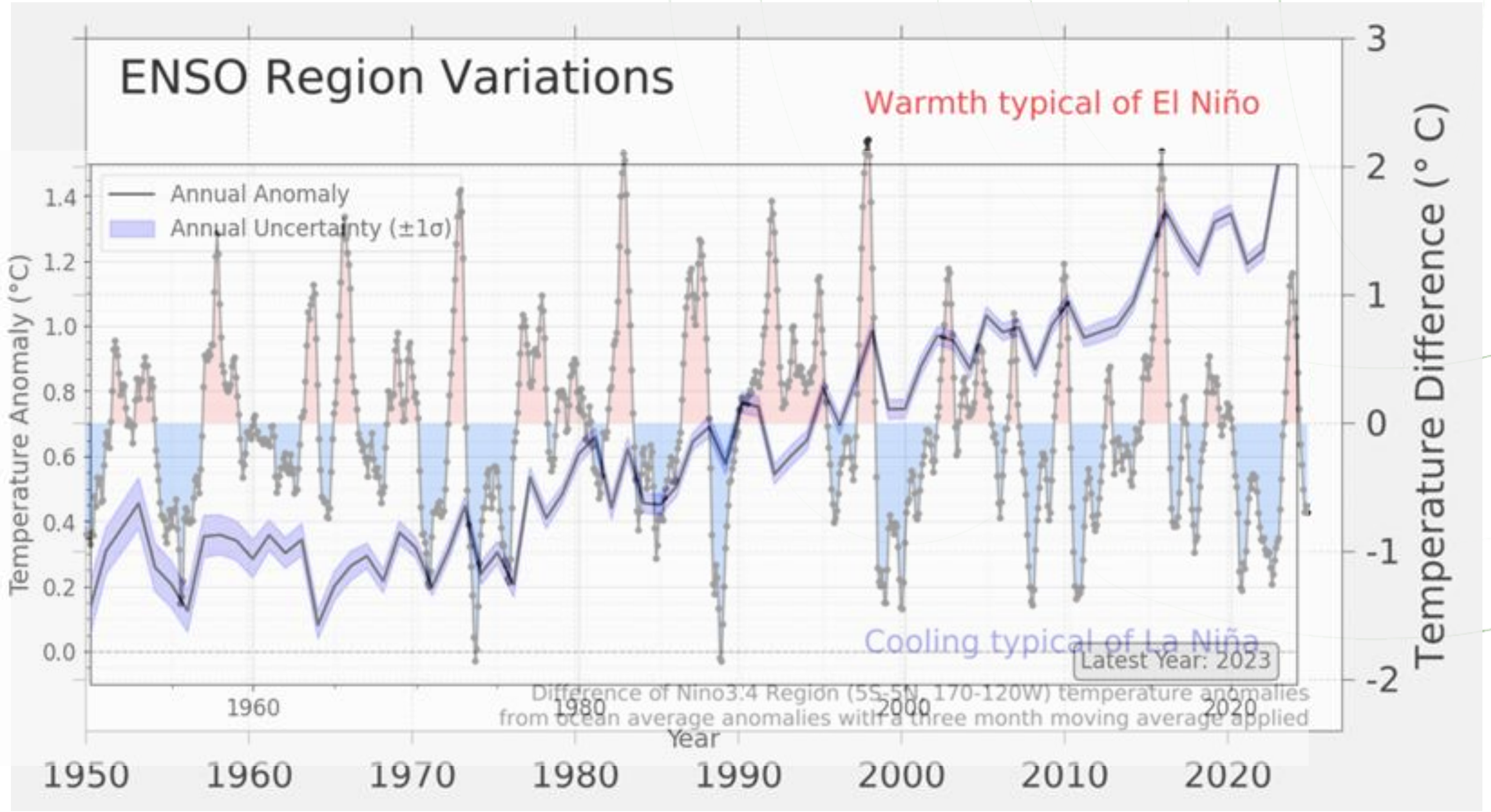
Also other factors (such as volcanic eruptions and oceanic cycles) influence T variability



Friedlingstein et al. (2025) Earth Syst. Sci. Data

Observations of change

Interannual variability of global temperatures and ENSO peaks are well correlated



Observations of change

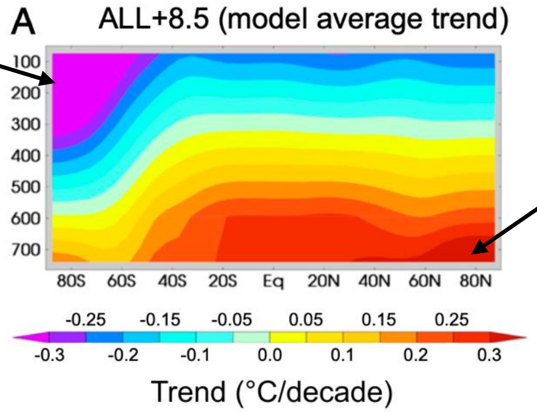
Thermal structure of the atmosphere

A human-caused fingerprint can be identied against the natural variability

complete simulation with all forcings

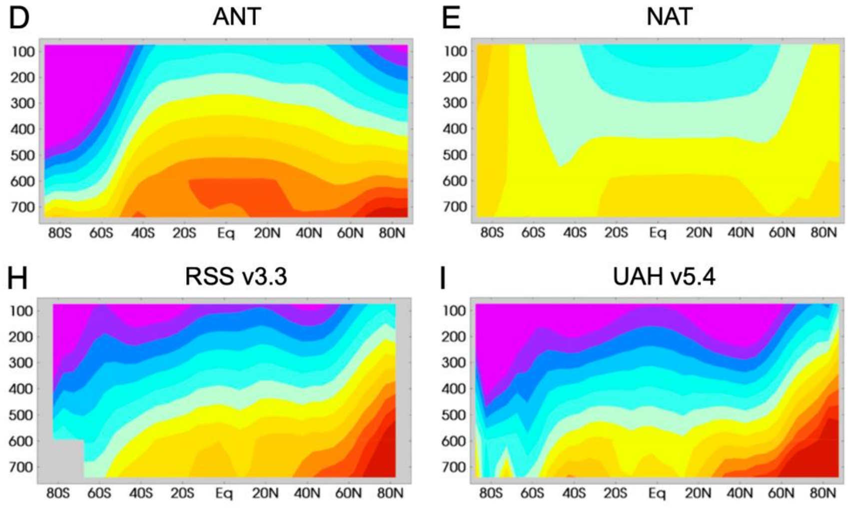
ozone hole

Arctic amplification



Modeled Anthropogenic and Natural Forcings

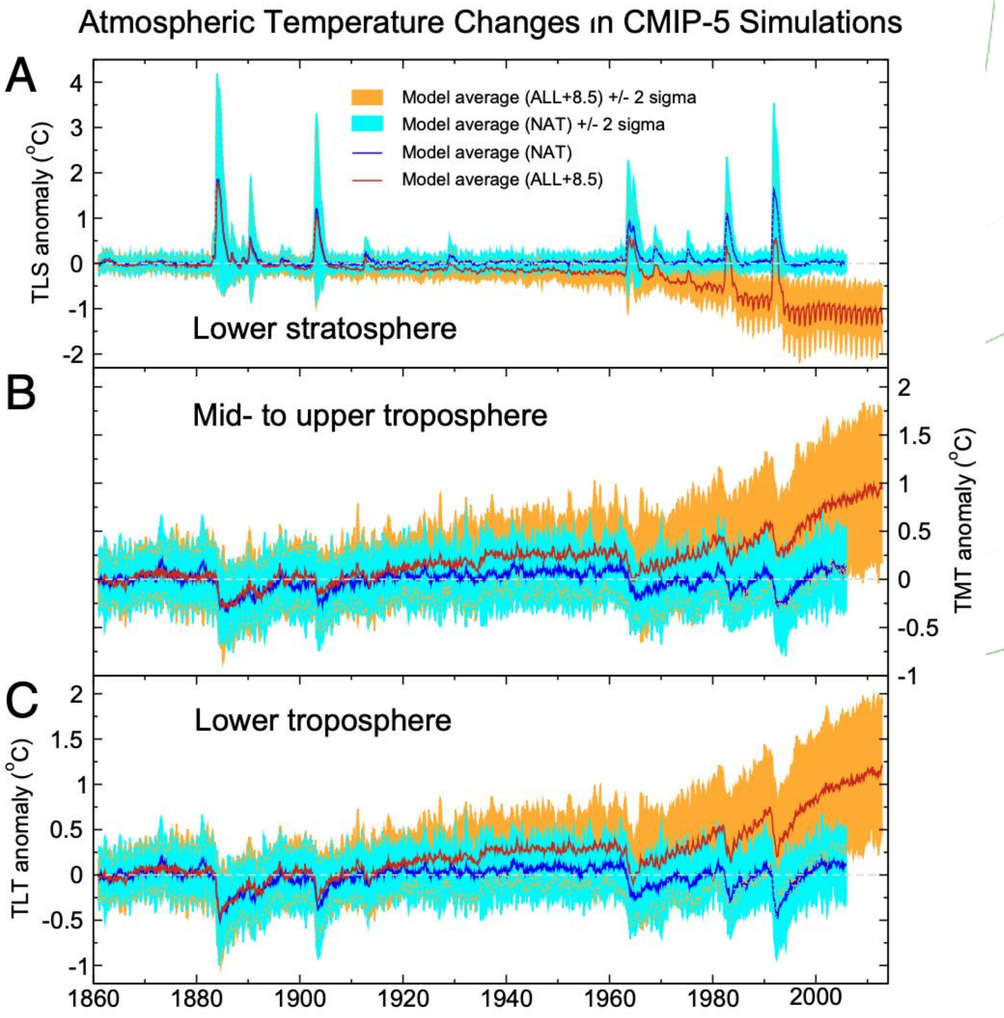
Observations (Microwave Sounding Units)



stratosphere warms (IR absorption) and the troposphere cools (visible light reflection) after major volcanic eruption

longer recovery in the troposphere due to large thermal inertia of the oceanic mixed layer

Krakatoa
Novarupta
Mount Agung
El Chichón
Pinatubo

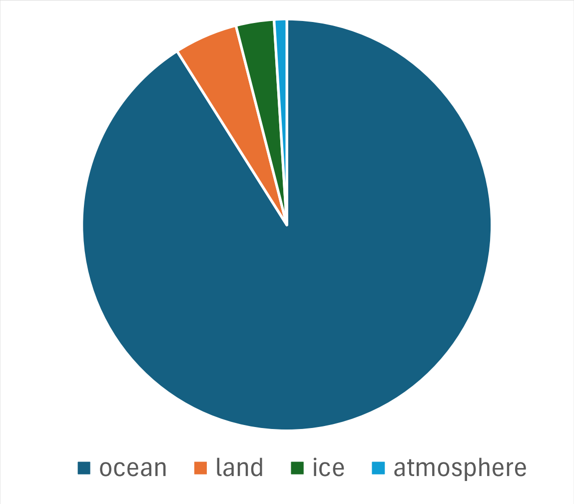


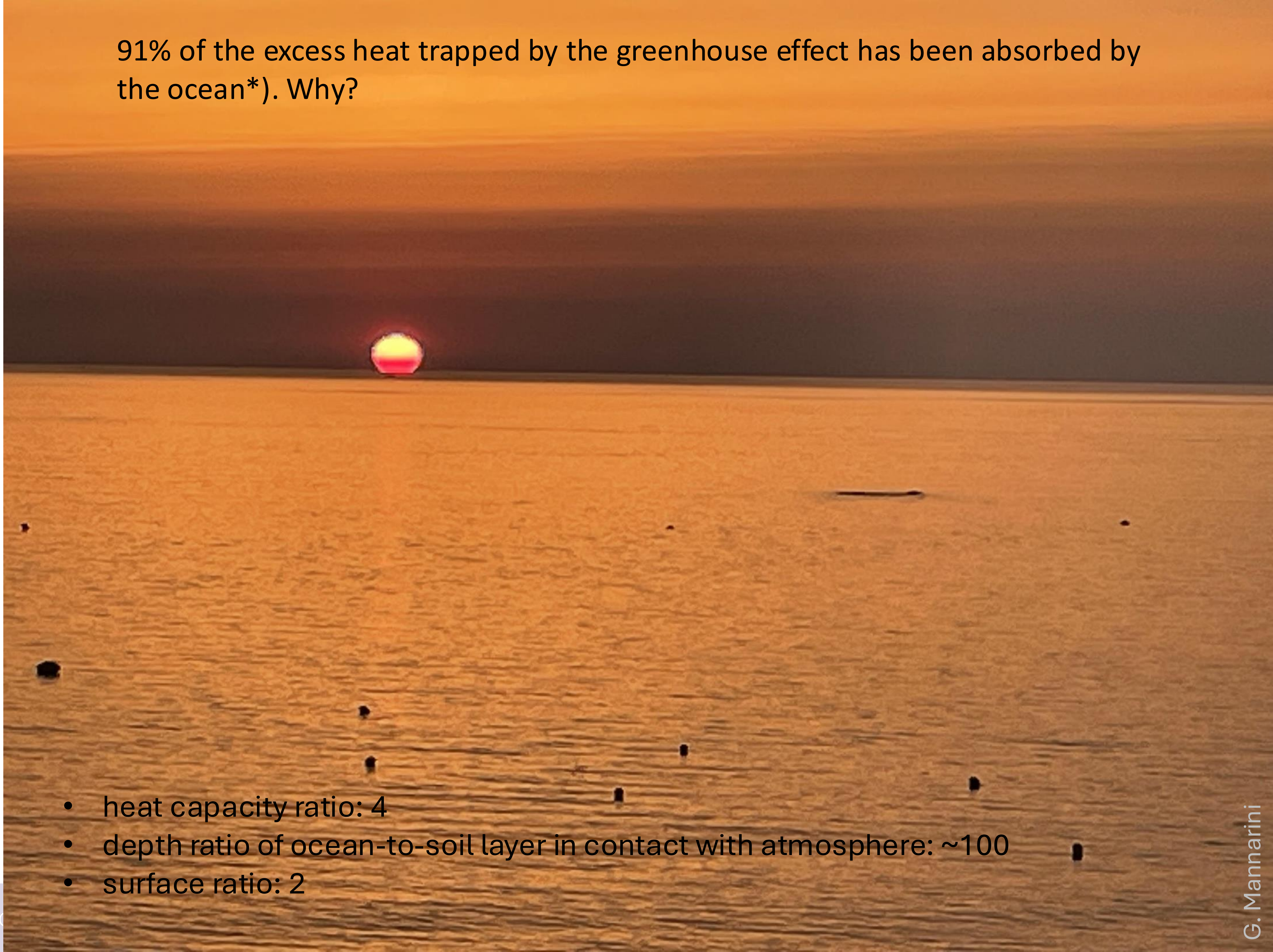
Santer et al. (2013) PNAS

Observations of

Ocean warming

91% of the excess heat trapped by the greenhouse effect has been absorbed by the ocean*). Why?



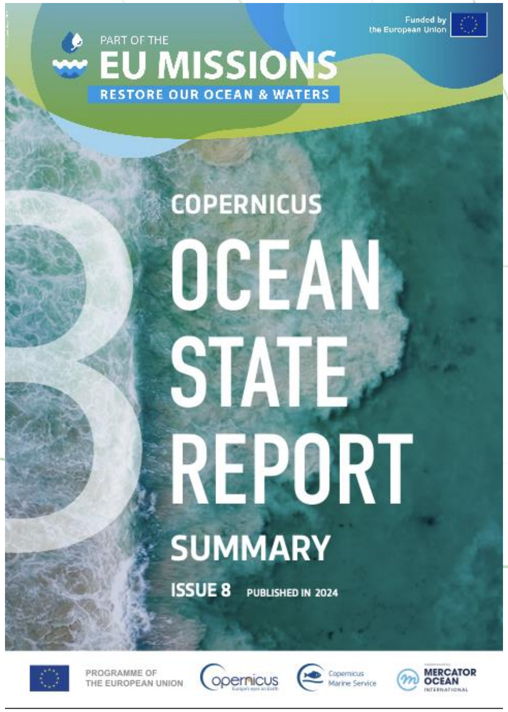


- heat capacity ratio: 4
- depth ratio of ocean-to-soil layer in contact with atmosphere: ~100
- surface ratio: 2

*) IPCC AR6 SYR (2022)

Observations of change

Copernicus Ocean State Report (data till 2023)



- state-of-the-art scientific knowledge for the European regional seas and the global ocean
- Using model data as well as satellite and in-situ measurements
- 120 scientific experts and a peer-review process
- contributes to the EU Mission: Restore Our Ocean and Water

https://marine.copernicus.eu/access-data/ocean-state-report

Observations of change

Copernicus Ocean State Report (data till 2023)

SEA SURFACE TEMPERATURE

UNITS: °C/decade **TIME:** 1982-2023

Ocean and Water

Global Ocean	↑ 0.13	±0.01 °C/decade
Northeast Atlantic and Adjacent Seas	↑ 0.25	±0.03 °C/decade
North West Shelf	↑ 0.22	±0.02 °C/decade
Iberian-Biscay-Ireland	↑ 0.24	±0.02 °C/decade
Baltic Sea	↑ 0.38	±0.04 °C/decade
Black Sea	↑ 0.65	±0.02 °C/decade
Mediterranean Sea	↑ 0.41	±0.01 °C/decade

KEY FIGURES

Global sea surface is warming differently. **75%** of the ocean surface in the northern hemisphere is warming **faster** than the global average, and **35%** in the southern hemisphere.

Observations of change

Copernicus Ocean State Report (data till 2023)

OCEAN HEAT CONTENT

UNITS: watts/m² **TIME:** 1960-2023

Ocean and Water

	0–300 m	0–700 m	0–2000 m
Global Ocean	↑ 0.27 ±0.03 watts/m²	↑ 0.41 ±0.09 watts/m²	↑ 0.59 ±0.11 watts/m²
Northeast Atlantic and Adjacent Seas	↑ 0.39 ±0.02 watts/m²	↑ 0.55 ±0.07 watts/m²	↑ 0.72 ±0.08 watts/m²

KEY FIGURES

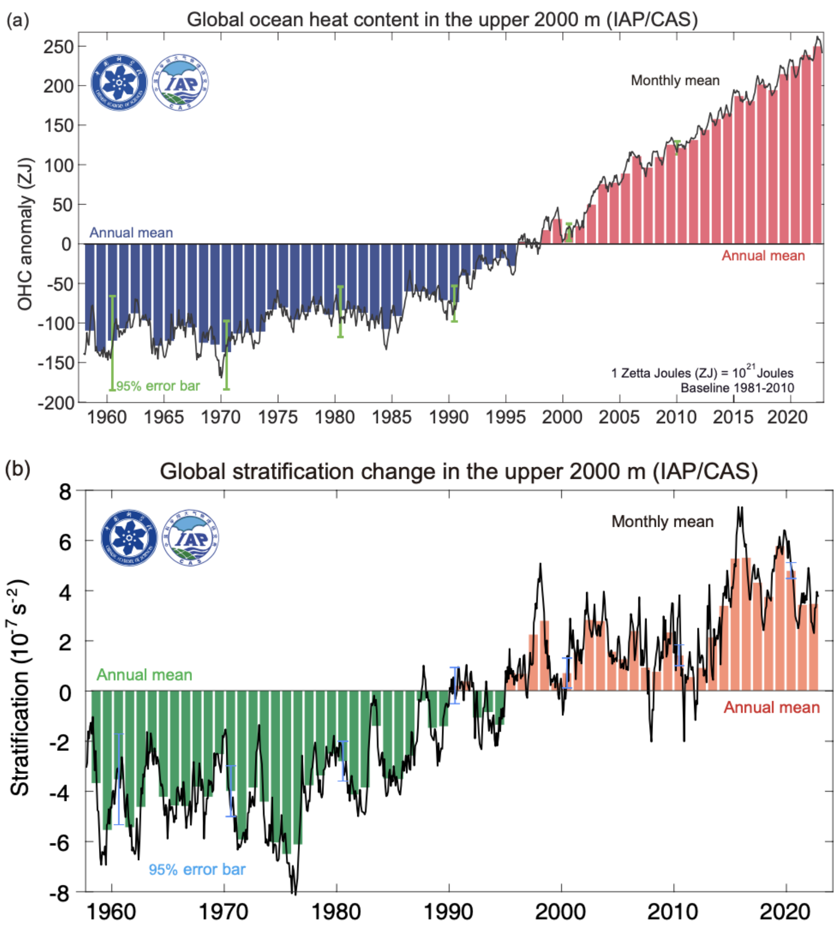
Since 1960, the global ocean (down to 2000 metres) has absorbed on average **1.5 million TWh** of heat each year, nearly **9x the world's energy consumption** in 2023.

Observations of change

Ocean Heat Content and Stratification

- ❑ +10 ZJ per year
- ❑ equivalent to the explosion of ~9 Hiroshima bombs per second

- ❑ stratification of the ocean's upper 2000 m has increased by 5.3% since 1960 (Li et al (2020) Nature Climate Change



Cheng et al (2023) Advances in Atmospheric Sciences

Observations of change

Copernicus Ocean State Report (data till 2023)

SEA LEVEL

UNITS: mm/year **TIME:** 1999-2023

Ocean and Water

Global Ocean ↑ 3.4 ±0.3 mm/year

Northeast Atlantic and Adjacent Seas ↑ 3.2 ±0.8 mm/year

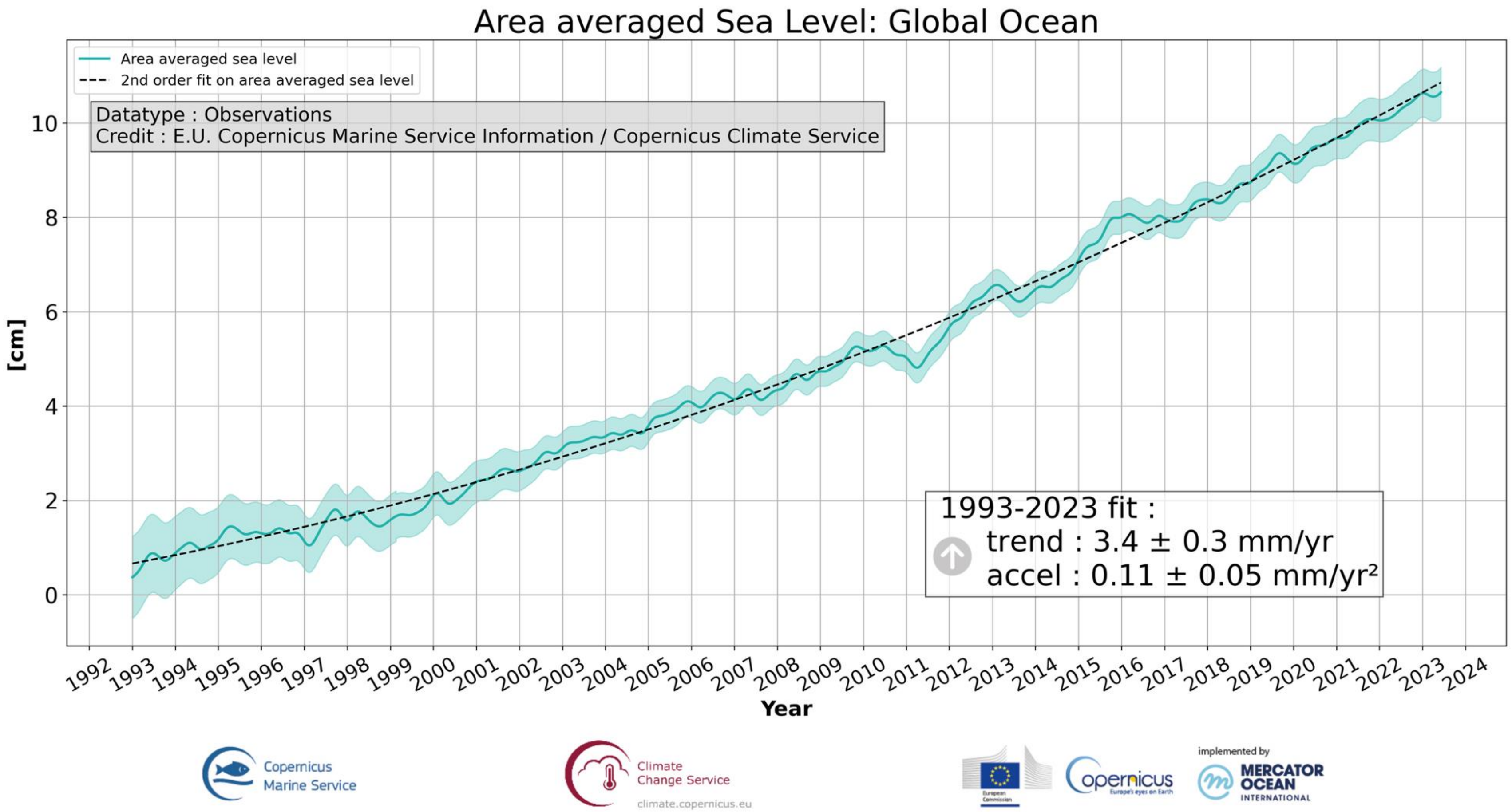
North West Shelf	Iberian-Biscay-Ireland	Baltic Sea	Black Sea	Mediterranean Sea
↑ 3.2	↑ 4.0	↑ 4.1	↑ 1.0	↑ 2.5
±0.8 mm/year	±0.8 mm/year	±0.8 mm/year	±0.8 mm/year	±0.8 mm/year

KEY FIGURES OSR 8

The North Atlantic Ocean has expanded its size almost continuously since 2002, due to the loss of mass from land ice melt, thermal expansion, and land water storage.

Observations of change

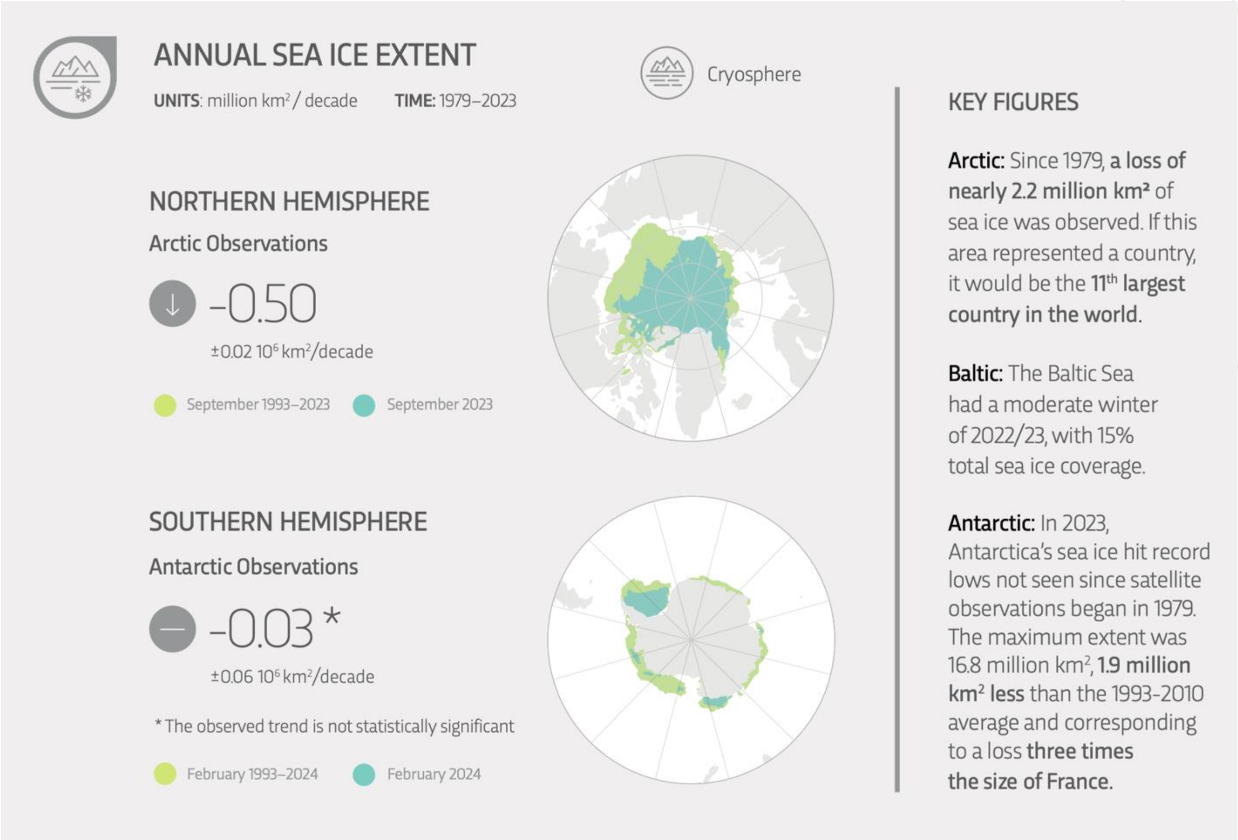
Mean sea level rise

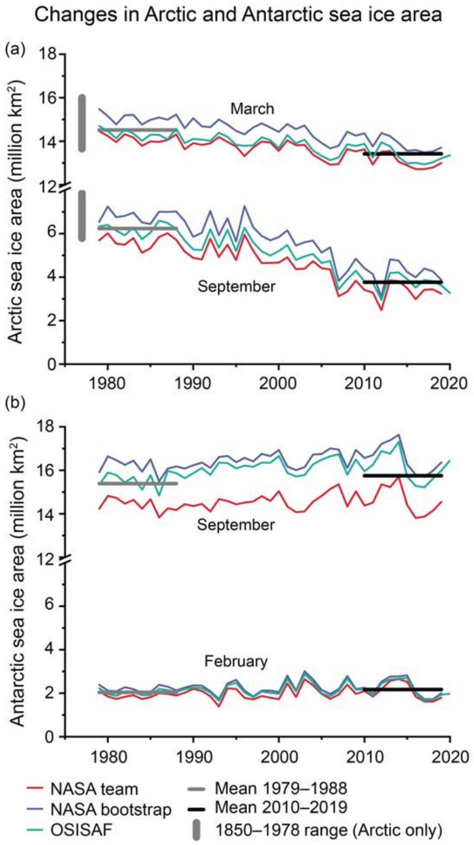


Observations of change

Copernicus Ocean State Report (data till 2023)

Italy's surface is
$0.30 \cdot 10^6 km^2$





IPCC AR6 WG1 Fig.2.20

Overshoot

Paris Agreement

UNITED NATIONS
2015

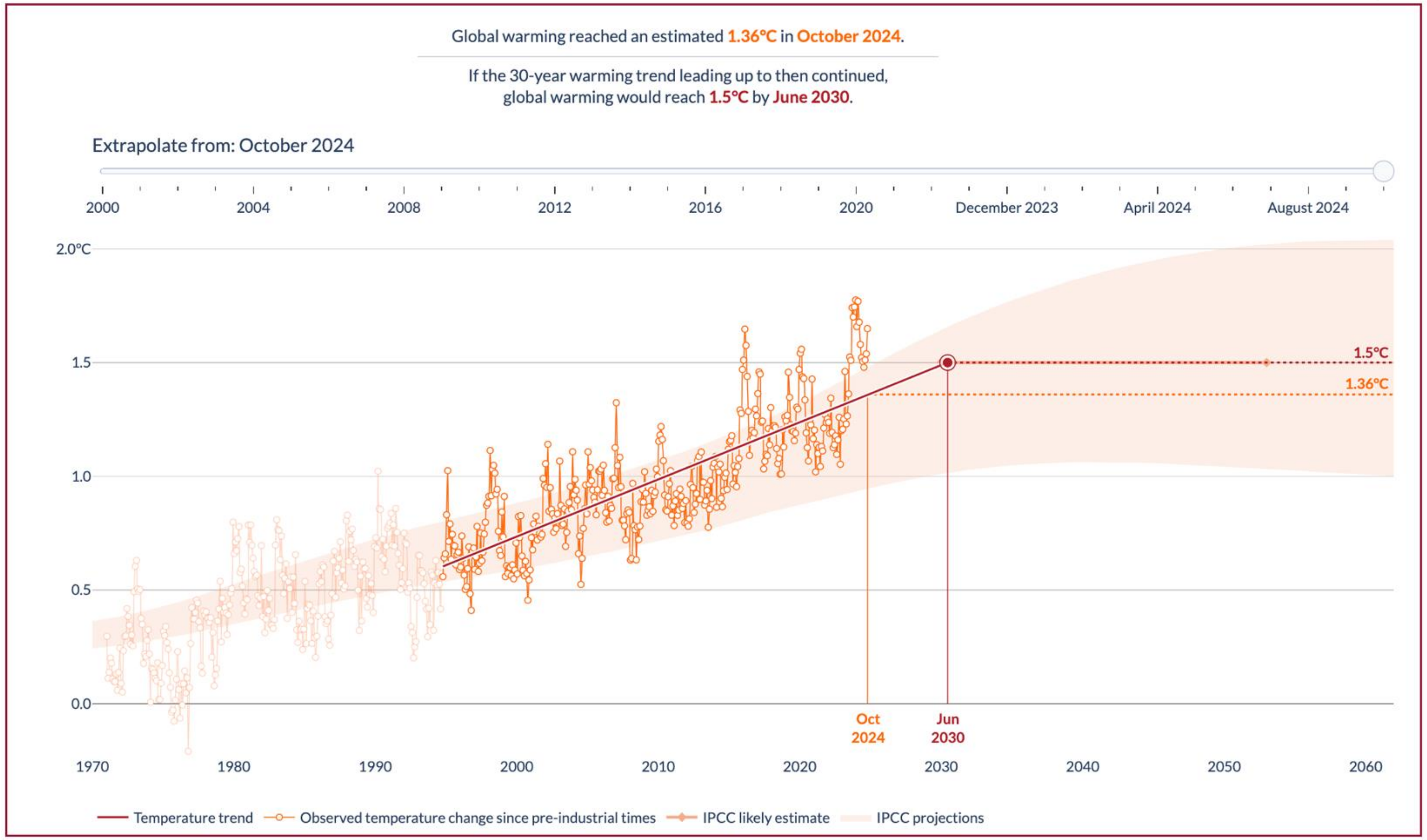
Article 2

1. This Agreement, in enhancing the implementation of the Convention, including its objective, aims to strengthen the global response to the threat of climate change, in the context of sustainable development and efforts to eradicate poverty, including by:

(a) Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change;

Overshoot

Paris Agreement: first threshold (+1.5 °C) is quickly approaching



- The 1.5 °C global warming threshold is going to be reached before end of 2030, assuming rate of growth of last 15 years

https://atlas.climate.copernicus.eu/atlas

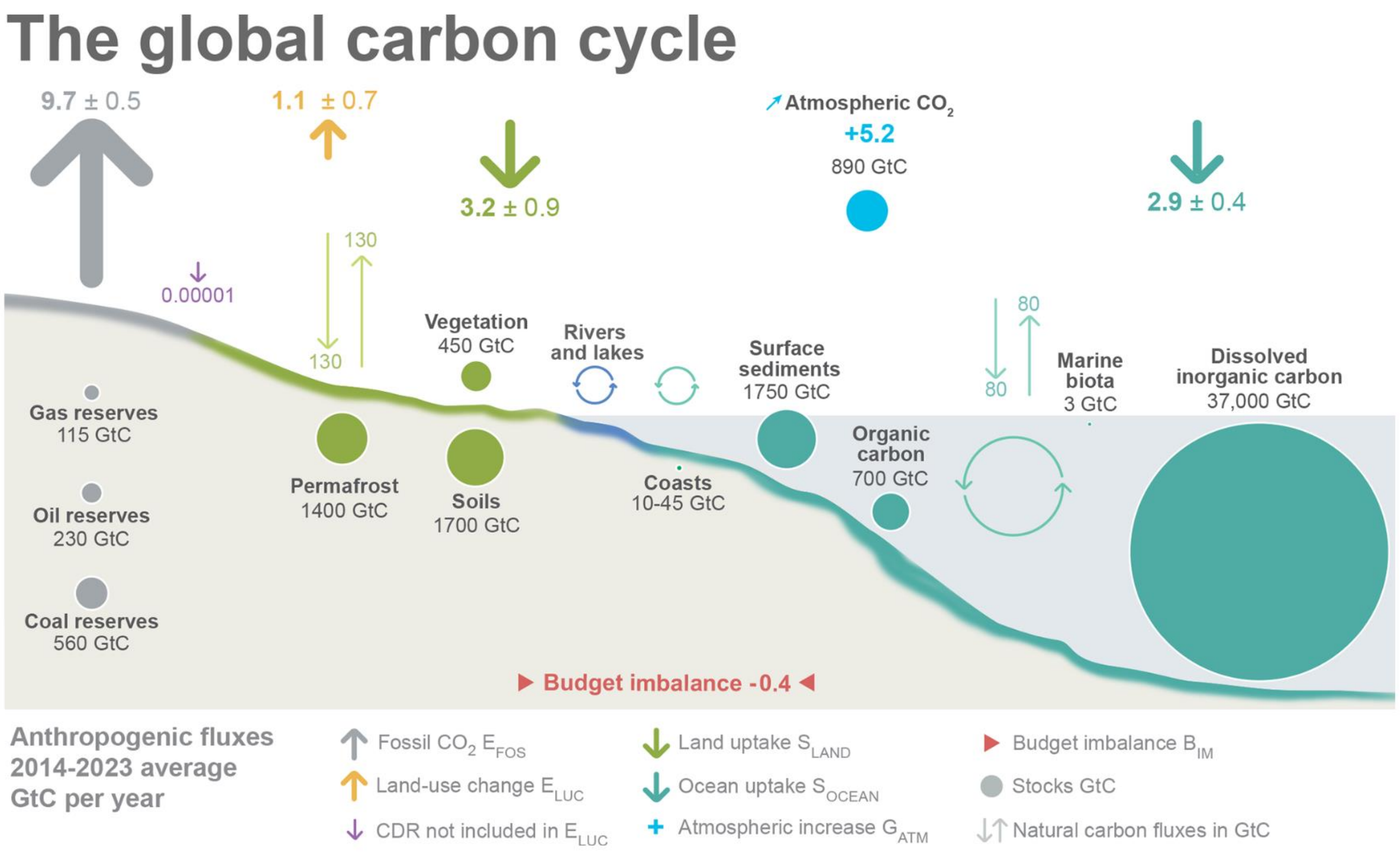
Overshoot

Carbon budget – a tool for policy

	Radiative budget	Carbon budget
Strengths	Includes all climate drivers	Linear, simple, cumulative, actionable
Weaknesses	Complex, non-linear, uncertain, short-lived effects (aerosols, methane) hard to model	Ignores non-CO_2 short-lived effects (*)

*) considered in Earth system models and climate scenarios

Overshoot

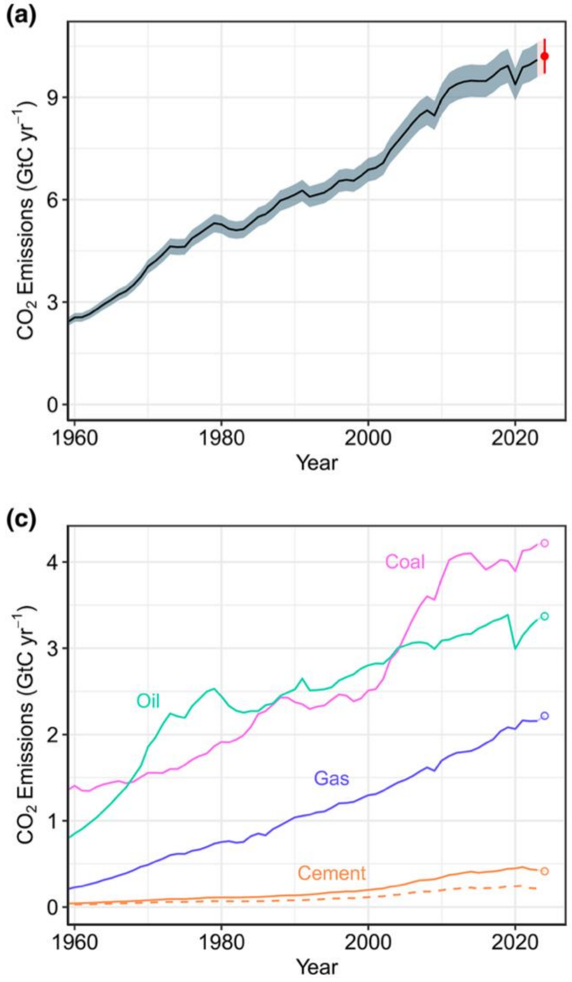


The anthropogenic perturbation occurs on top of an active carbon cycle

Friedlingstein (2025), Earth Syst. Sci. Data

Overshoot

Carbon budget

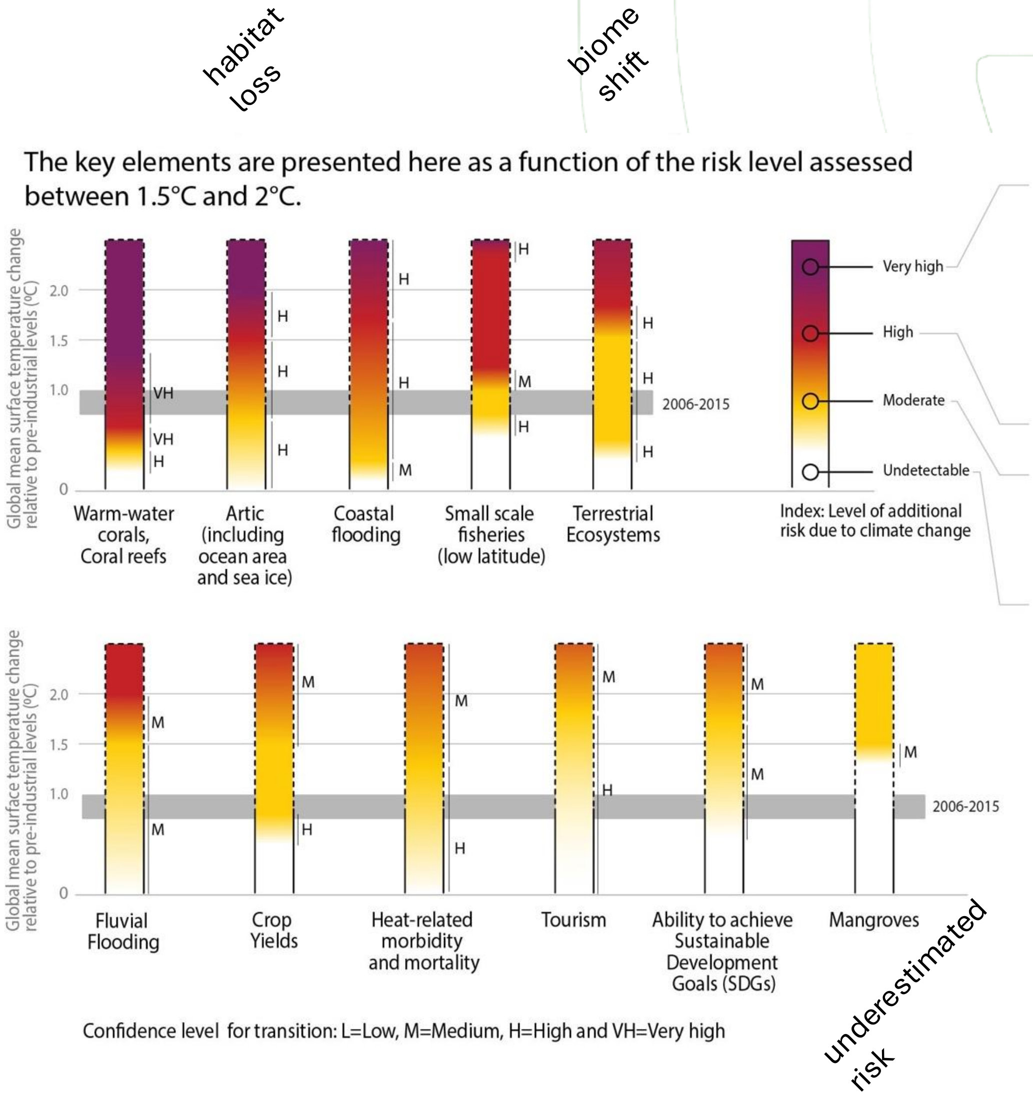


- Total anthropogenic emissions have been stable over the last decade ($\sim 11\ GtC\ a^{-1}$)
- 1.7 $GtC\ a^{-1}$: strong potential of halting deforestation for emissions reductions
- The remaining carbon budget for a 50 % likelihood to limit global warming to 1.5 °C is 65 GtC from the beginning of 2025, equivalent to around 6 years, assuming 2024 emissions levels

Friedlingstein (2025), Earth Syst. Sci. Data

Overshoot

Impacts of a 1.5 °C and warmer world



IPCC SR1.5 Fig.3.20

Attribution

Case Study: May 2025’s Iberian heat wave

EL PAÍS — España — SUSCRÍBETE — INICIAR SESIÓN

EL TIEMPO >

Las claves del episodio de calor extraordinario: estará en el podio de los tres peores registrados en mayo

Este miércoles comienza la fase más dura del fenómeno, que se prolongará hasta el domingo y en el que se esperan más de 10 grados por encima de lo normal

VICTORIA TORRES BENAYAS

Madrid - 28 MAY 2025 - 05:30 CEST

https://elpais.com/espana/2025-05-28/las-claves-del-episodio-de-calor-extraordinario-estara-en-el-podio-de-los-tres-peores-registrados-en-mayo.html

Attribution

Case Study: May 2025's Iberian heat wave

Dataset:

Anomaly of:

Storyline Simulations

Climate Conditions:

- ( ) Pre-industrial conditions
- (•) Present-day conditions
- ( ) Conditions under 4°C global warming

Time Period:

- (•) Single Day
- ( ) Multiple Days

2025-05-30

Variable:

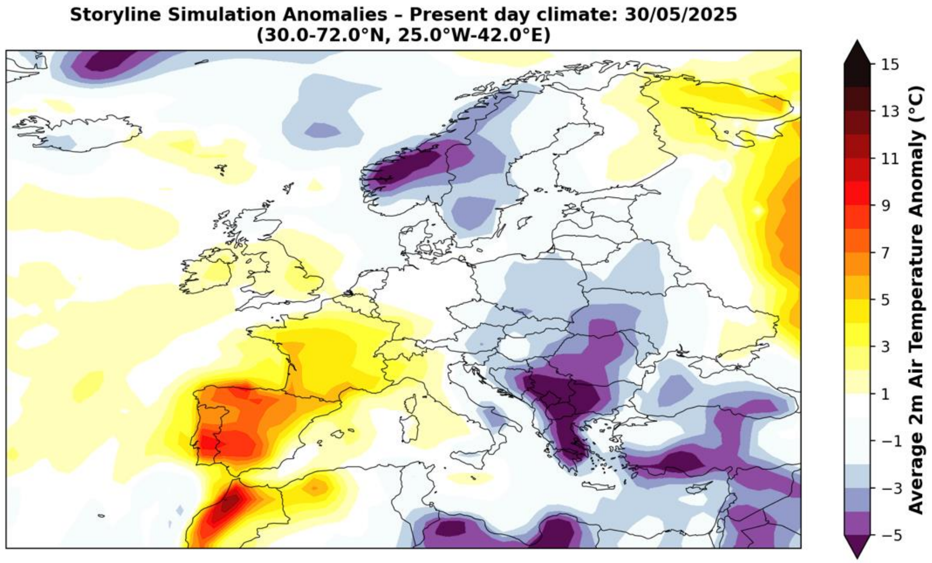
Average 2m Air Temperature

Region:

- (•) Predefined selection
- ( ) Manual selection

Europe (30-72°N, 25°W-42°E)

Create Plot



Show statistics ⓘ

( ) Land and sea (•) Land only ( ) Sea only

Spatial mean (°C)	Spatial standard deviation (°C)	Minimum (°C)	Maximum (°C)
-0.73	3.00	-7.63	12.07

Please choose parameters and click on 'Create Plot' to create a new plot!

Anomaly

difference between simulation* and climatology (usually, last 30-year average) for a specific date

*) using a CMIP6 coupled climate model

https://climate-storylines.awi.de/

➔ the heatwave over Iberian peninsula reached +10 °C with respect to present climatology

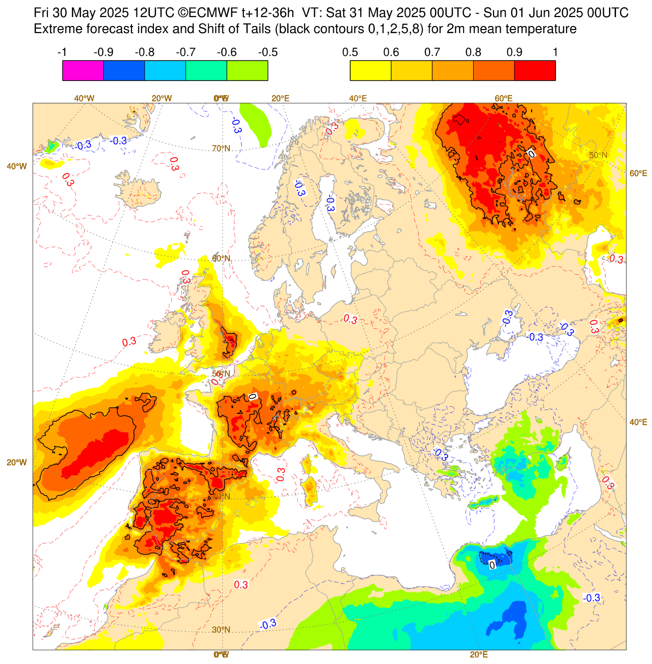
Attribution

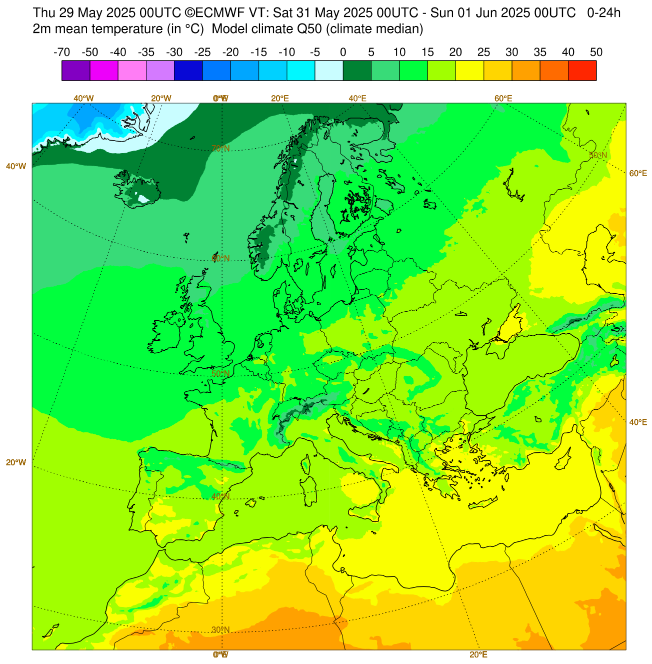
Case Study: May 2025’s Iberian heat wave

EFI 2 m temperature

Extreme Forecast Index - EFI

difference between cumulative distribution function of the Model-climate and the distribution of the current forecast’s ensemble





Model-climate

average from a set of medium range re-forecasts, created using the same calendar start dates over several (usually 30) years

➔ the statistical exceptionality of the event is also confirmed by the ECMWF model

Attribution

Case Study: May 2025's Iberian heat wave: storyline scenario

Dataset:

Differences between:

Storyline Simulations

- PD - PI
- +4°C - PD
- +4°C - PI

Time Period:

- Single Day
- Multiple Days

2025-05-30

Variable:

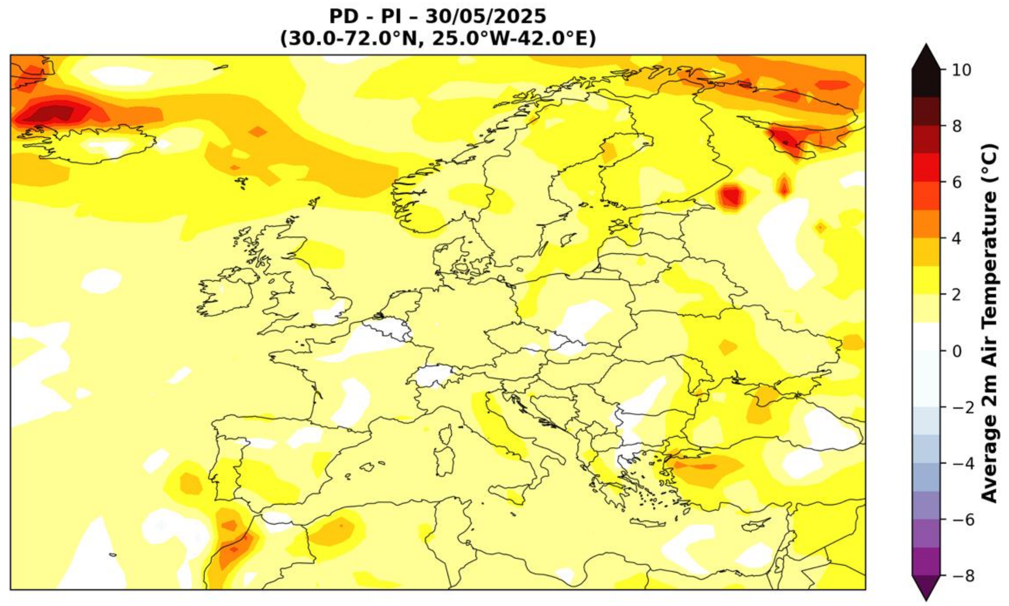
Average 2m Air Temperature

Region:

- Predefined selection
- Manual selection

Europe (30-72°N, 25°W-42°E)

Create Plot



Show statistics

Land and sea · Land only · Sea only

Spatial mean (°C)	Spatial standard deviation (°C)	Minimum (°C)	Maximum (°C)
1.80	0.67	0.07	5.95

Present Day – PreIndustrial difference or "warming signal of the day"

difference between simulation for a specific date and simulation with pre-industrial forcing, nudged* to the synoptic conditions of the same date

*) i.e., the temporal evolution of the large-scale midtroposphere dynamics has been prescribed

Benítez et al (2022) J. of Climate

➔ the heatwave over Iberian peninsula would have reached just +7 °C with respect to present climatology

Attribution

Case Study: May 2025's Iberian heat wave: storyline scenario

Dataset:

Differences between:

Storyline Simulations

- PD - PI
- +4°C - PD
- +4°C - PI

Time Period:

- Single Day
- Multiple Days

2025-05-30

Variable:

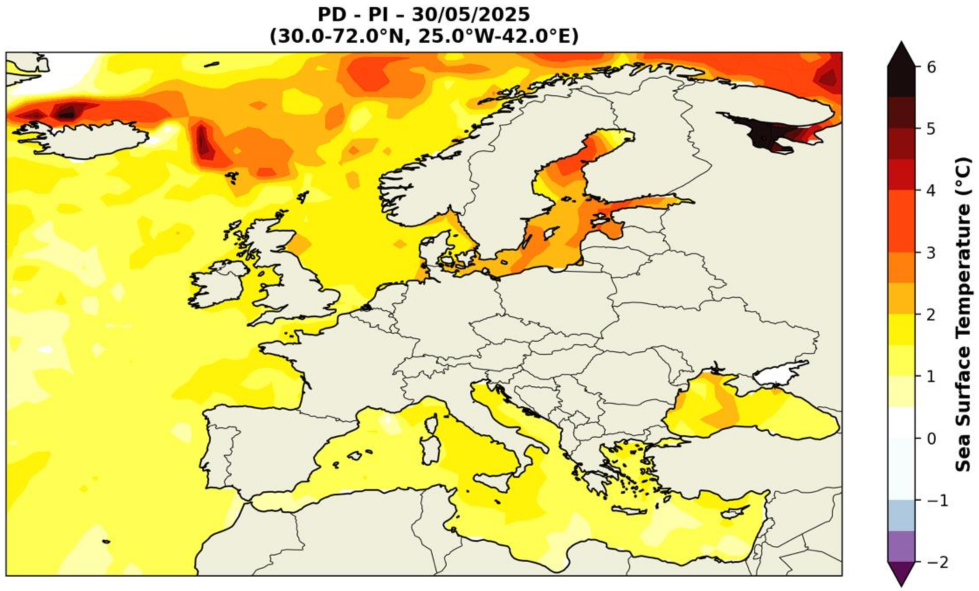
Sea Surface Temperature

Region:

- Predefined selection
- Manual selection

Europe (30-72°N, 25°W-42°E)

Create Plot



Show statistics

Spatial mean (°C)	Spatial standard deviation (°C)	Minimum (°C)	Maximum (°C)
1.74	0.75	-0.24	6.80

Present Day – PreIndustrial difference or "warming signal of the day"

difference between simulation for a specific date and simulation with pre-industrial forcing, nudged to the synoptic conditions of the same date

➔ much warmer Barents, Baltic, and North Seas surface

Attribution

Case Study: May 2025’s Iberian heat wave: storyline scenario

Dataset:

Differences between:

Storyline Simulations

- PD - PI
- +4°C - PD (selected)
- +4°C - PI

Time Period:

- Single Day (selected)
- Multiple Days

2025-05-30

Variable:

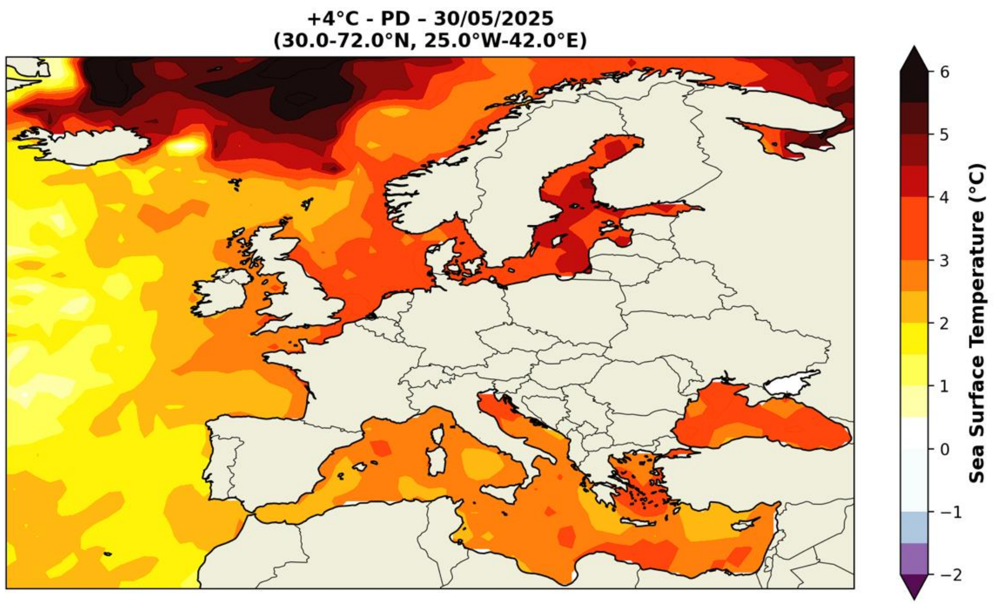
Sea Surface Temperature

Region:

- Predefined selection (selected)
- Manual selection

Europe (30-72°N, 25°W-42°E)

Create Plot



Show statistics

Spatial mean (°C)	Spatial standard deviation (°C)	Minimum (°C)	Maximum (°C)
3.11	0.79	0.00	7.26

4K warmer world– PresentDay difference

difference between a simulation for a 4 °K warmer world, nudged to the synoptic conditions of the specific, present-day date, and the simulation for the same day

➔ clear footprint of Arctic amplification in the Greenland Sea

Case Study: May 2025's Iberian heat wave: storyline scenario

Dataset:

Differences between:

Storyline Simulations

- PD - PI
- +4°C - PD (selected)
- +4°C - PI

Time Period:

- Single Day (selected)
- Multiple Days

2025-05-30

Date format: yyyy-mm-dd

Variable:

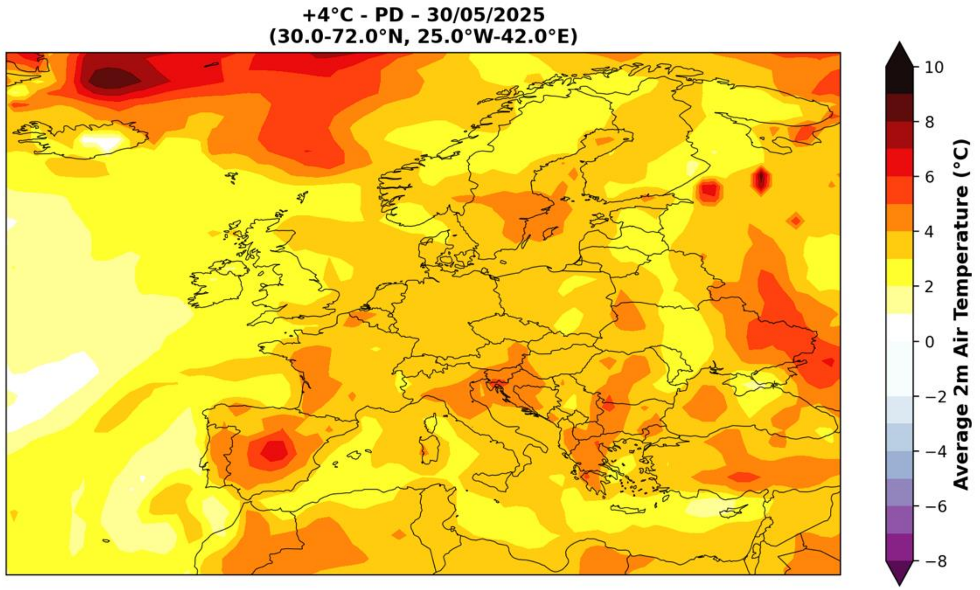
Average 2m Air Temperature

Region:

- Predefined selection (selected)
- Manual selection

Europe (30-72°N, 25°W-42°E)

Create Plot



Show statistics

Land and sea · Land only (selected) · Sea only

Spatial mean (°C)	Spatial standard deviation (°C)	Minimum (°C)	Maximum (°C)
3.61	0.69	0.23	6.78

4K warmer world– PresentDay difference

difference between a simulation for a 4 °K warmer world, nudged to the synoptic conditions of the specific, present-day date, and the simulation for the same day

➔ anthropogenic warming will be strongest over land, the same heatwave would reach +15 °C

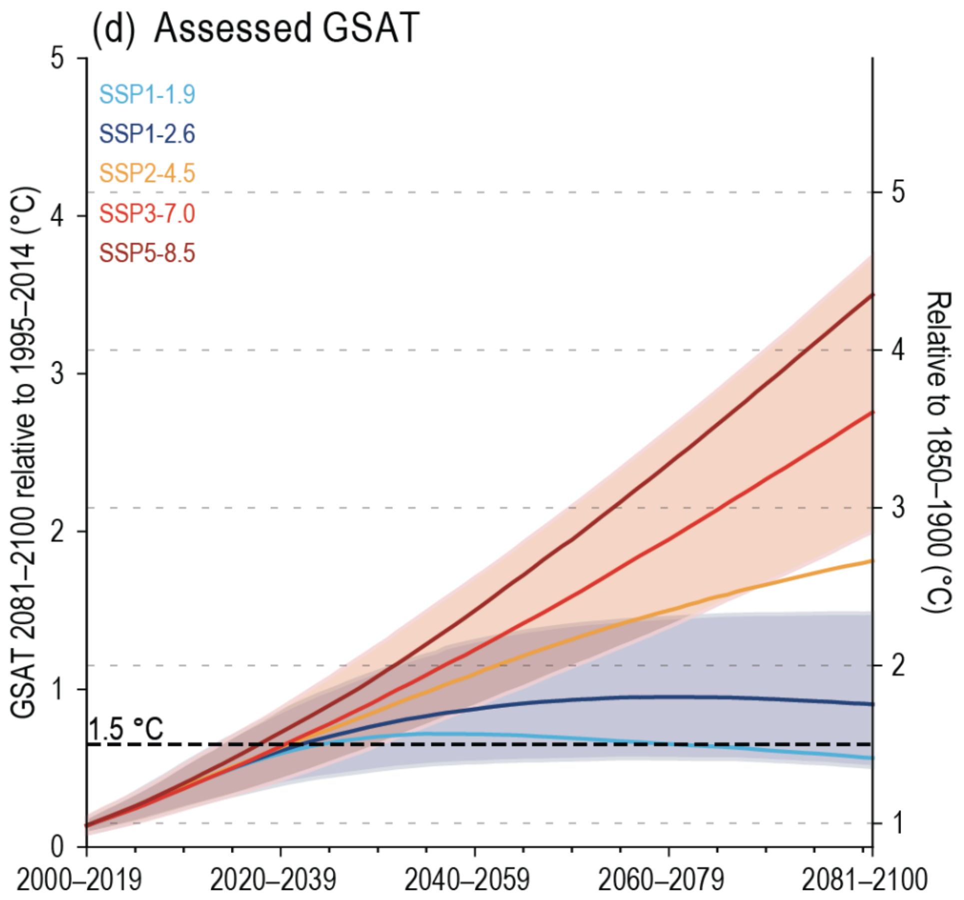
Scenarios and Projections

IPCC AR6 – global mean surface temperature

AR6 scenarios were based on SSPs:

socio-economic and technological *storylines* and drivers underlying the emissions and land use pathway:

- SSP1: Sustainability
- SSP2: "Middle of the Road"
- SSP3: Regional Rivalry
- SSP4: Inequality
- SSP5: Fossil-fueled Development

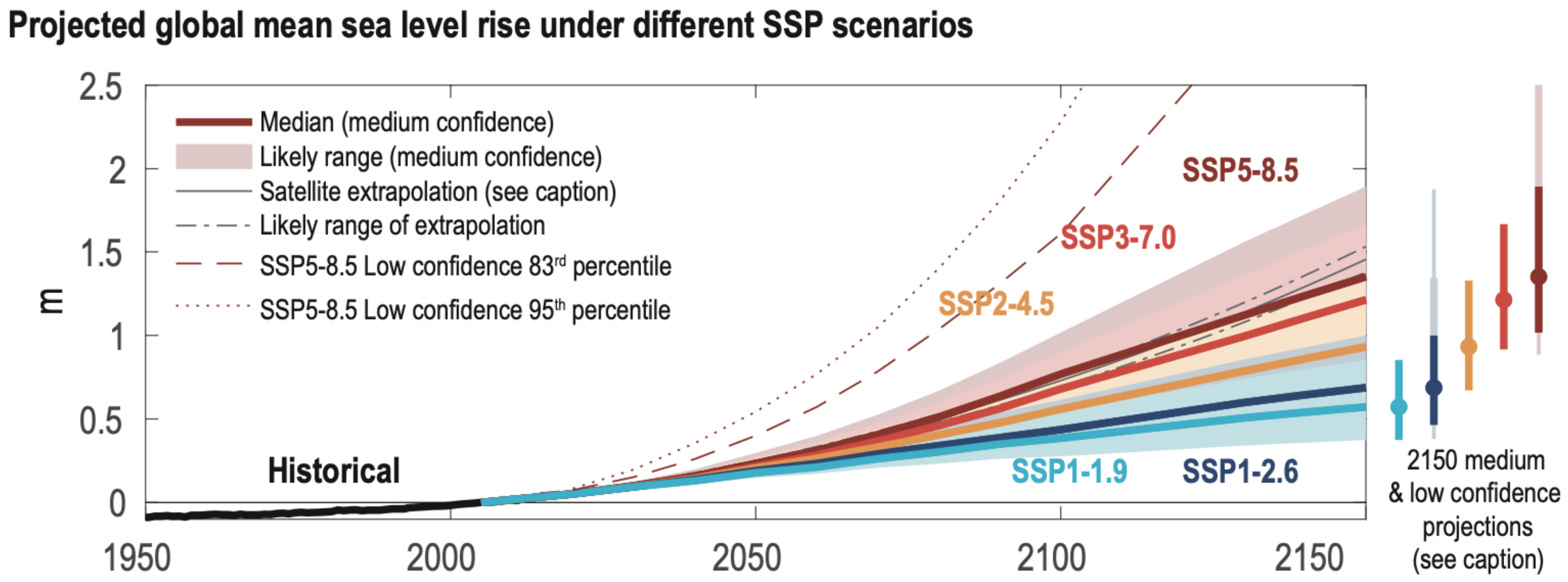


IPCC AR6 (2021) WG1 Fig.4.11

➔ Future warming levels remain uncertain, varying by scenario from climate stabilization (SSP1) to sustained warming (SSP2-5)

Scenarios and Projections

IPCC AR6 – sea level rise



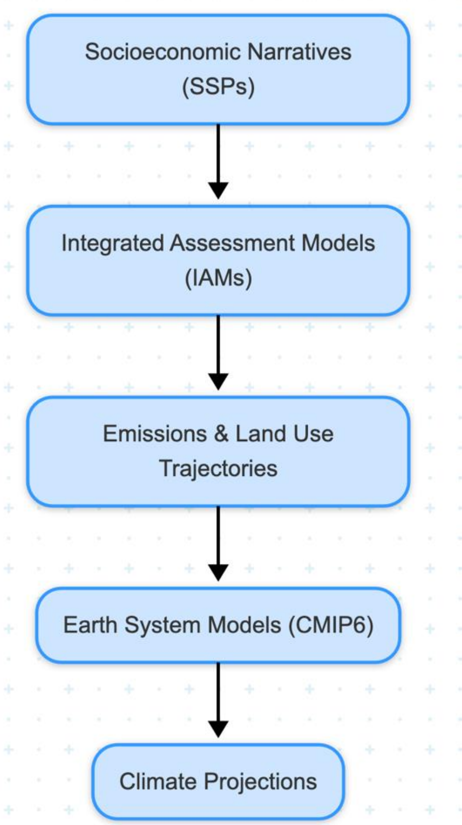
IPCC AR6 (2021) Figure 9.25

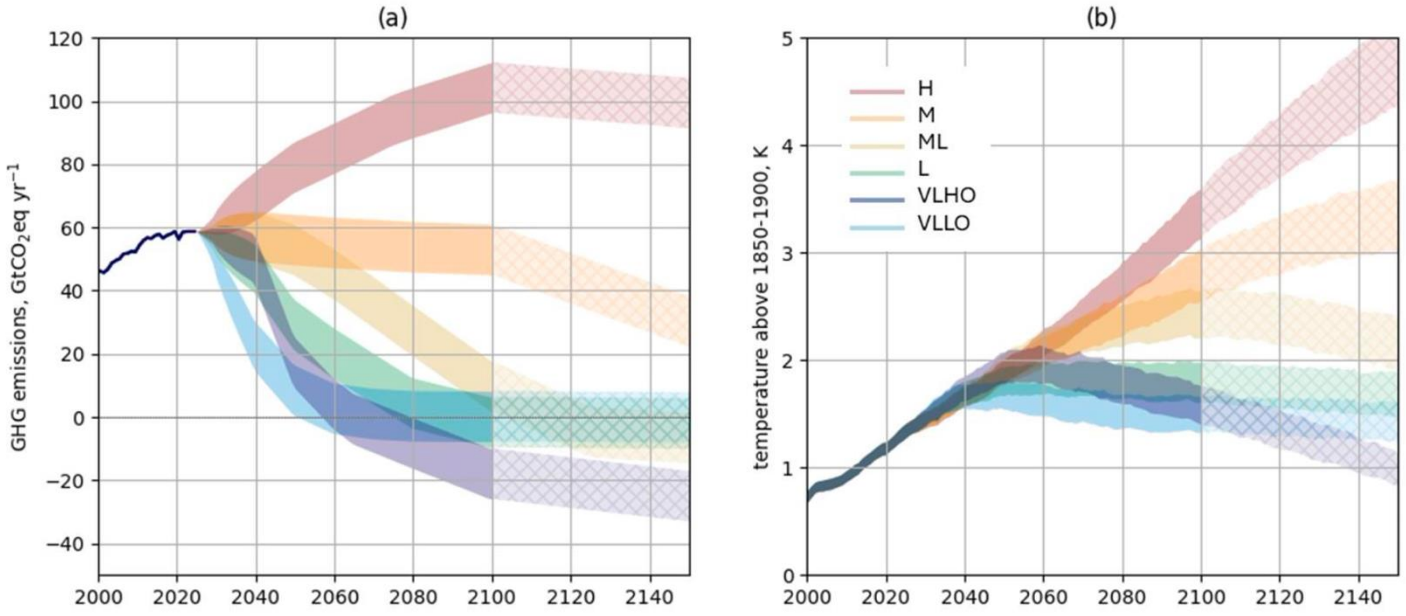
➔ Sea levels will continue to rise even in the scenarios (SSP1-*) where global temperatures stabilize

Scenarios and Projections

IPCC AR7: proposed scenarios

AR7 scenarios will be emission-driven and plausible (i.e., having a non-negligible likelihood of occurring)





emissions pathways for the proposed scenarios

expected temperature outcomes using a probabilistic model

Van Vuuren et al. (2025), https://egusphere.copernicus.org/preprints/2025/egusphere-2024-3765/

THANKS!

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