Overview of Global Warming

AOSC 680

Ross Salawitch

Class Web Sites:
http://www2.atmos.umd.edu/~rjs/class/fall2024
https://umd.instructure.com/courses/1367293

https://www.videoblocks.com/video/earth-sunset-spacewalk-view-from-space-station-r7dydlcsgjd23vml0

Lecture 2

3 September 2024

Overview of Global Warming

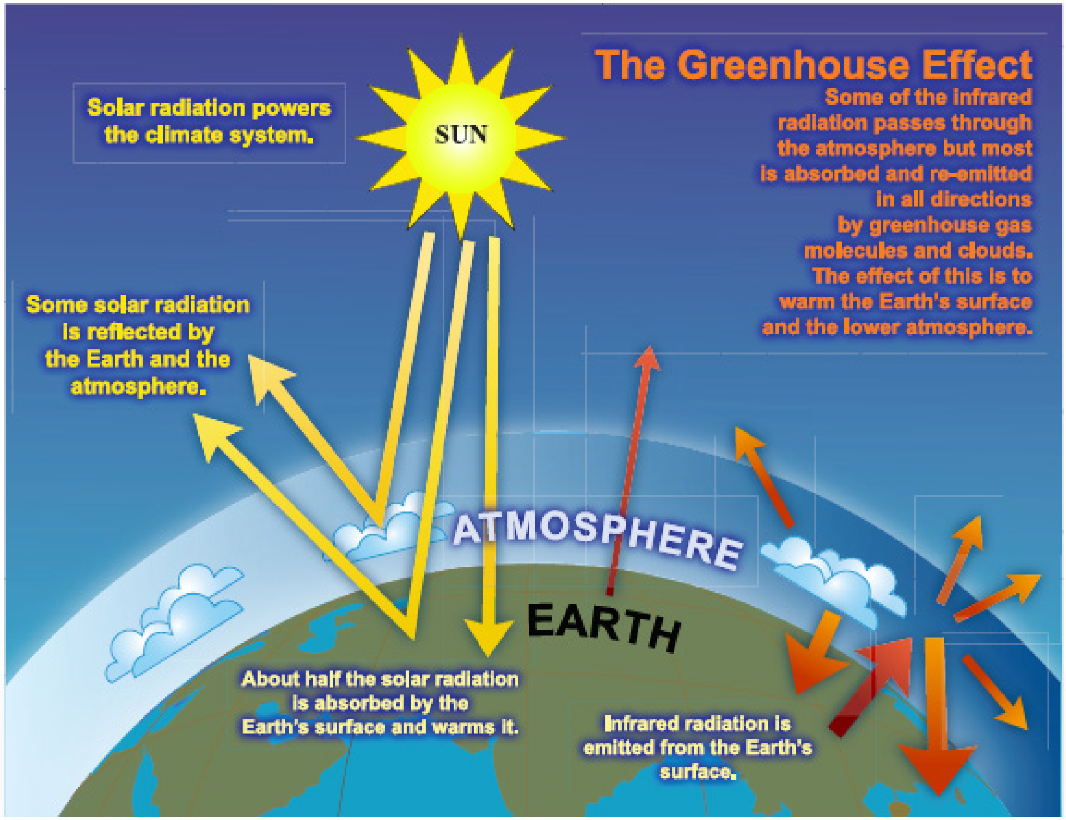
Today's goals:

1) Overview of global warming and atmospheric / oceanic science

2) Will provide lots of "detail" today … **do not expect all of these details to "stick"**. However, when you review this lecture for the exam, details should be understandable

3) Speaking of the exam; please note my **exams consist of a series of conceptual questions**, rather than calculations. Exam will be closed book, no calculator. Lectures are the "glue" of the first third of class, and exams will focus on essay-like conceptual questions drawn from lectures, accentuated in the readings, ATs, and learning outcome quizzes.

Greenhouse Effect



FAQ 1.3, Figure 1. *An idealised model of the natural greenhouse effect. See text for explanation.*

Question 1.3, IPCC, 2007

Radiative Forcing of Climate, 1750 to 2019

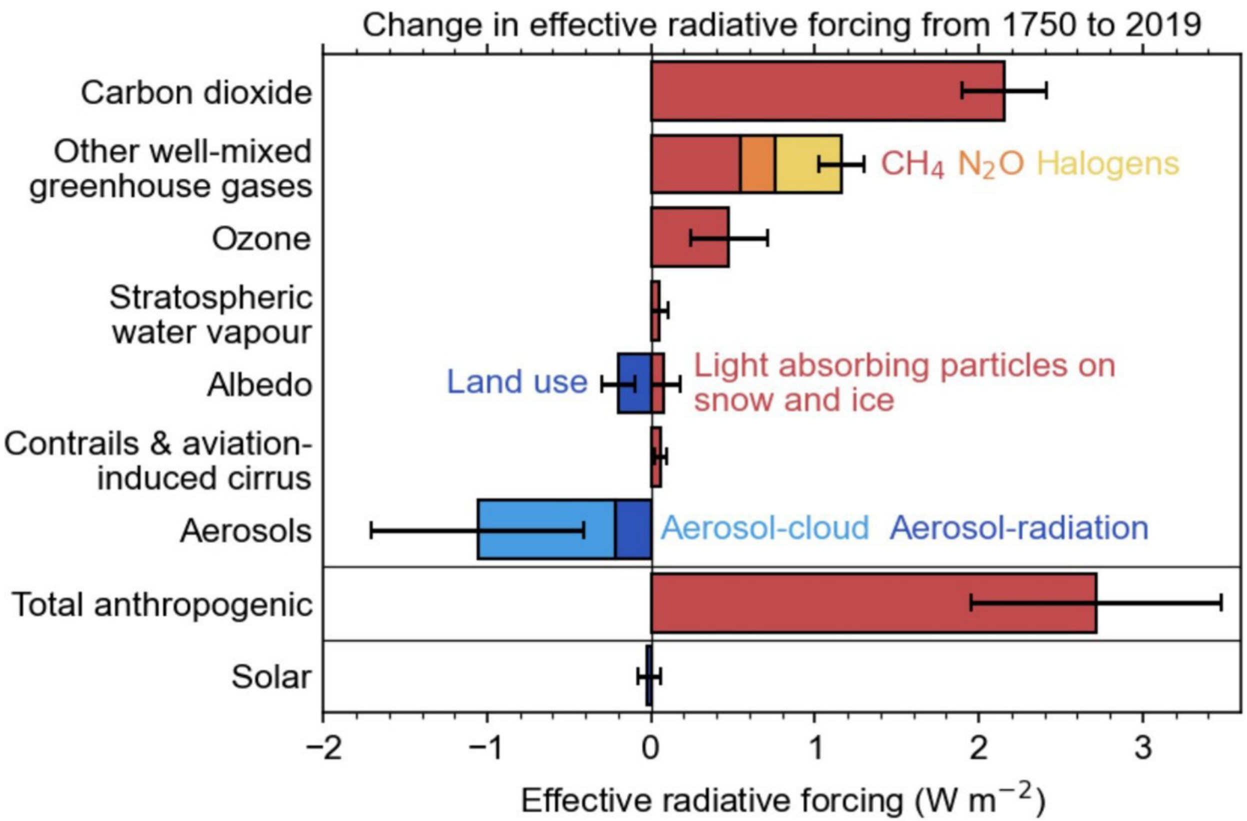
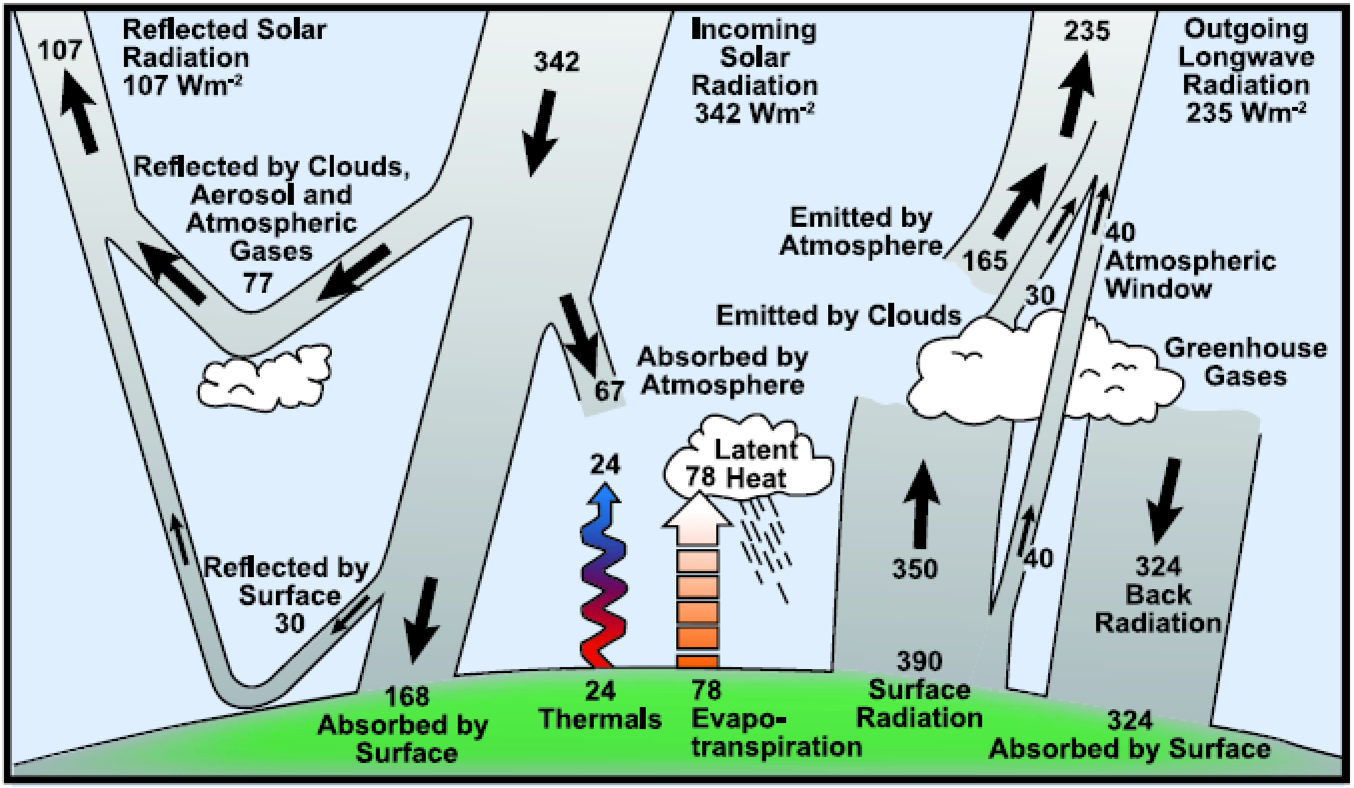


Figure 7.6, IPCC (2021)
https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_TS.pdf

Radiative Forcing



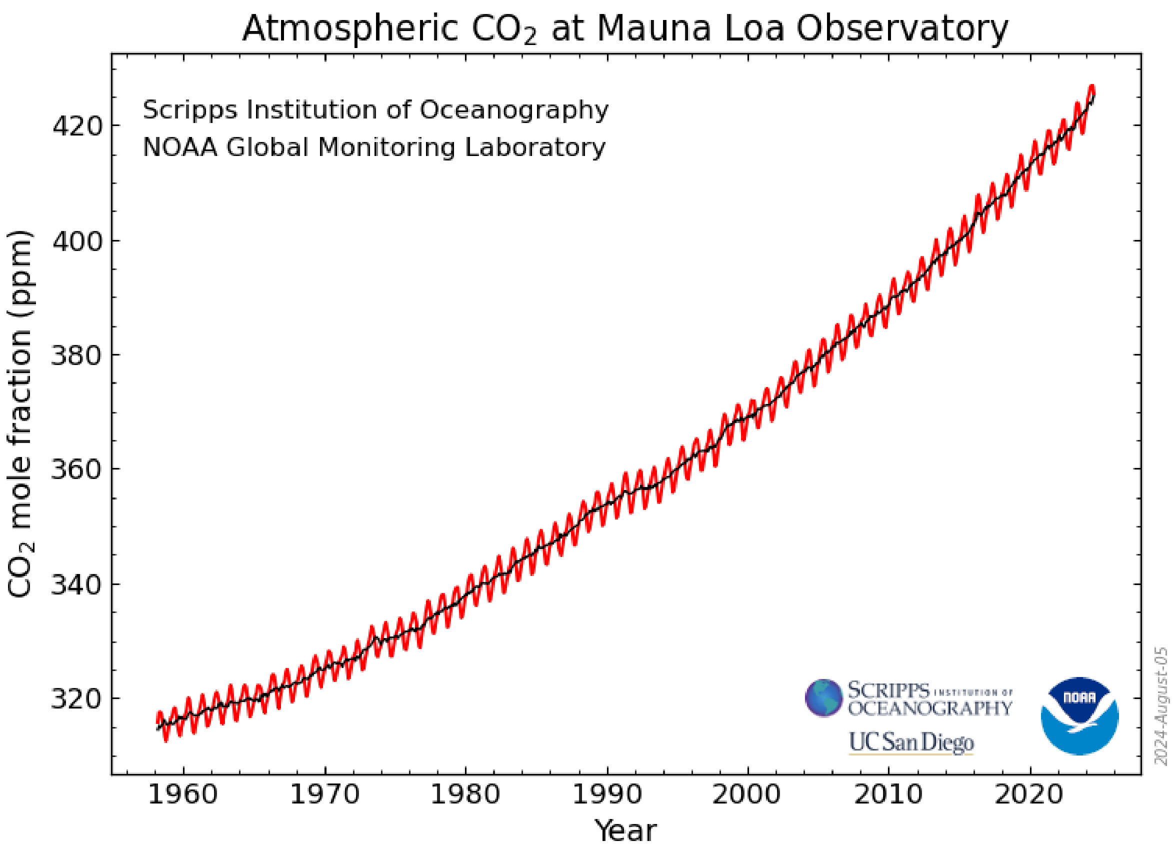
FAQ 1.1, Figure 1. *Estimate of the Earth's annual and global mean energy balance. Over the long term, the amount of incoming solar radiation absorbed by the Earth and atmosphere is balanced by the Earth and atmosphere releasing the same amount of outgoing longwave radiation. About half of the incoming solar radiation is absorbed by the Earth's surface. This energy is transferred to the atmosphere by warming the air in contact with the surface (thermals), by evapotranspiration and by longwave radiation that is absorbed by clouds and greenhouse gases. The atmosphere in turn radiates longwave energy back to Earth as well as out to space. Source: Kiehl and Trenberth (1997).*

Question 1.1, IPCC, 2007

Radiative Forcing of Climate **is** ***Change in Energy***
reaching the lower atmosphere (surface to tropopause) as GHGs rise.
"Back Radiation" is most important term.

Modern CO_2 Record

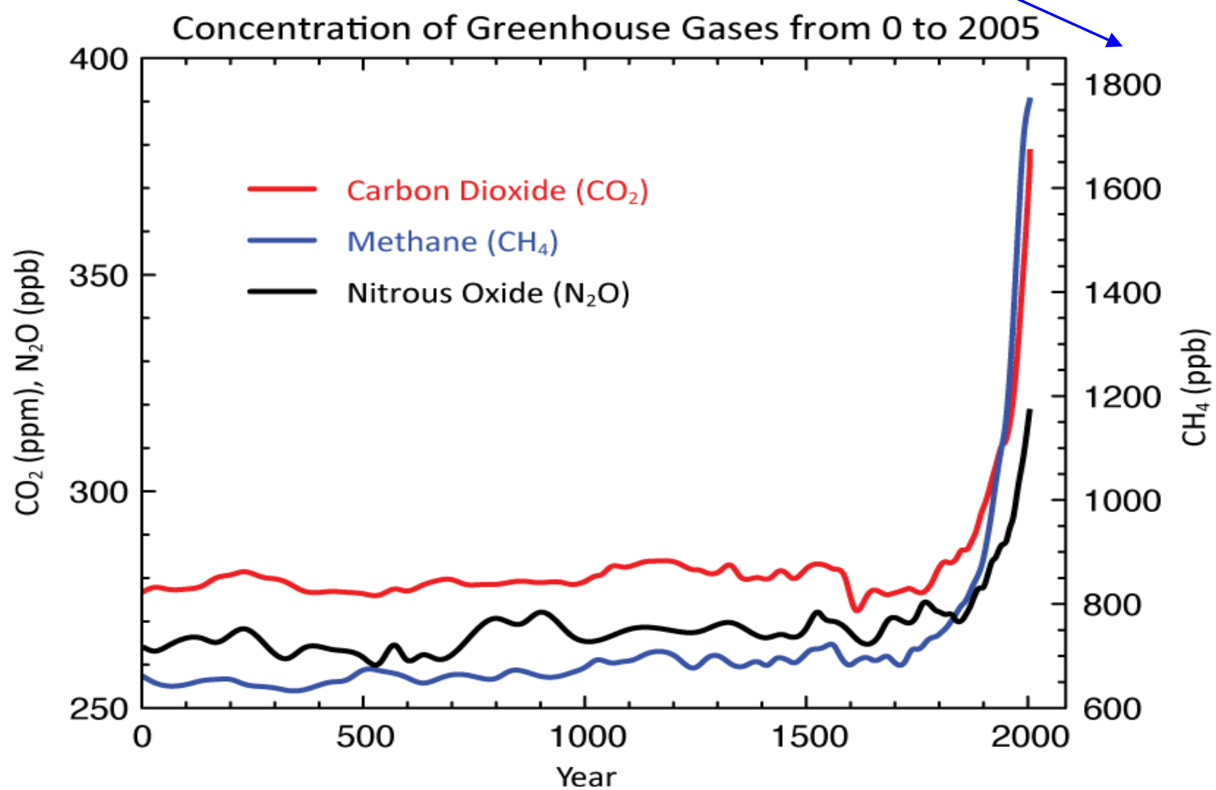
Global Mean, May 2024: 423.43 parts per million (ppm)
May 2023: 420.52 parts per million (ppm)
Annual Rise about 2.91 ppm (~0.7%)



Legacy of Charles Keeling, Scripps Institution of Oceanography, La Jolla, CA
https://www.esrl.noaa.gov/gmd/webdata/ccgg/trends/co2_data_mlo.png
See also https://www.co2.earth/daily-co2 and https://gml.noaa.gov/ccgg/trends/global.html

GHG Record Over Last Several Millennia

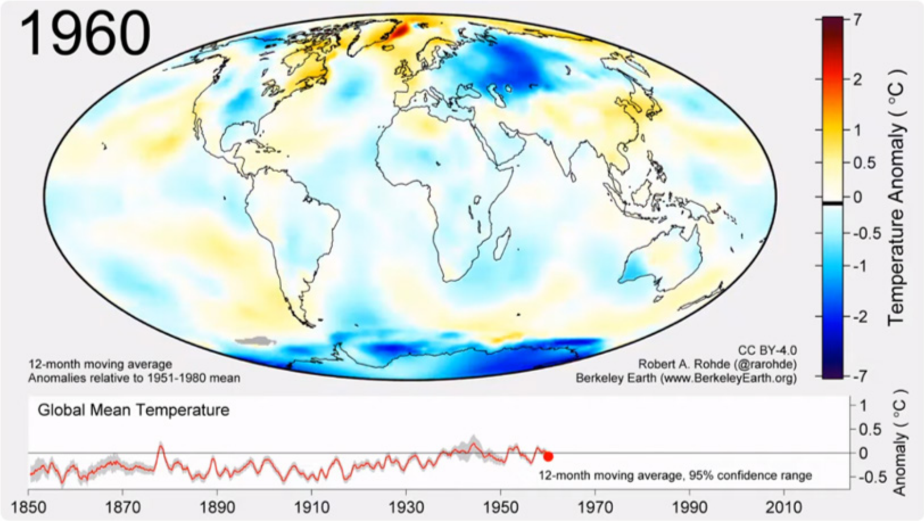
Figure in the reading had a slight error in the axis used for CH_4

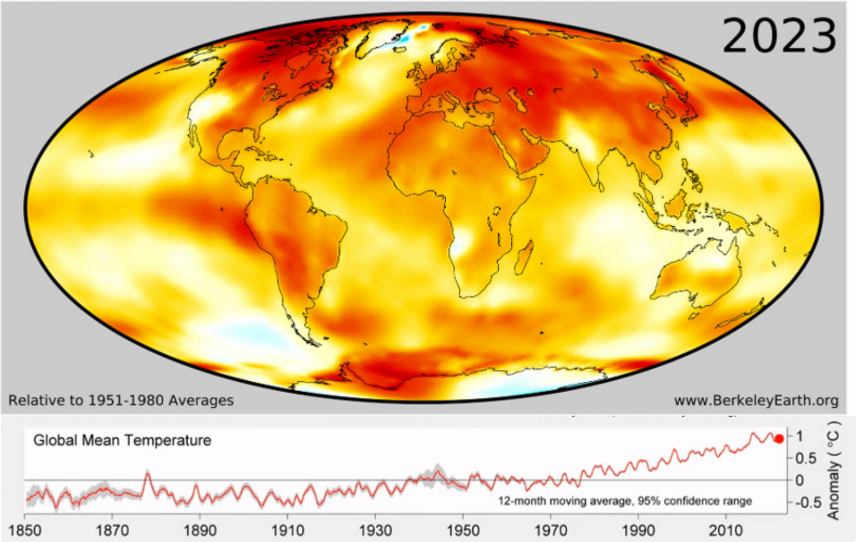


FAQ 2.1, Figure 1 (Errata). *Revised figure showing atmospheric concentrations of important long-lived greenhouse gases over the last 2,000 years. Using the combined and simplified data from Chapters 6 and 2, the original figure displayed the CH_4 curve incorrectly. The revised figure shows the same data correctly plotted. For further details please refer to the original figure caption.*

https://www.ipcc.ch/site/assets/uploads/2018/05/ar4-wg1-errata.pdf

Berkeley Earth Animation of Global Warming

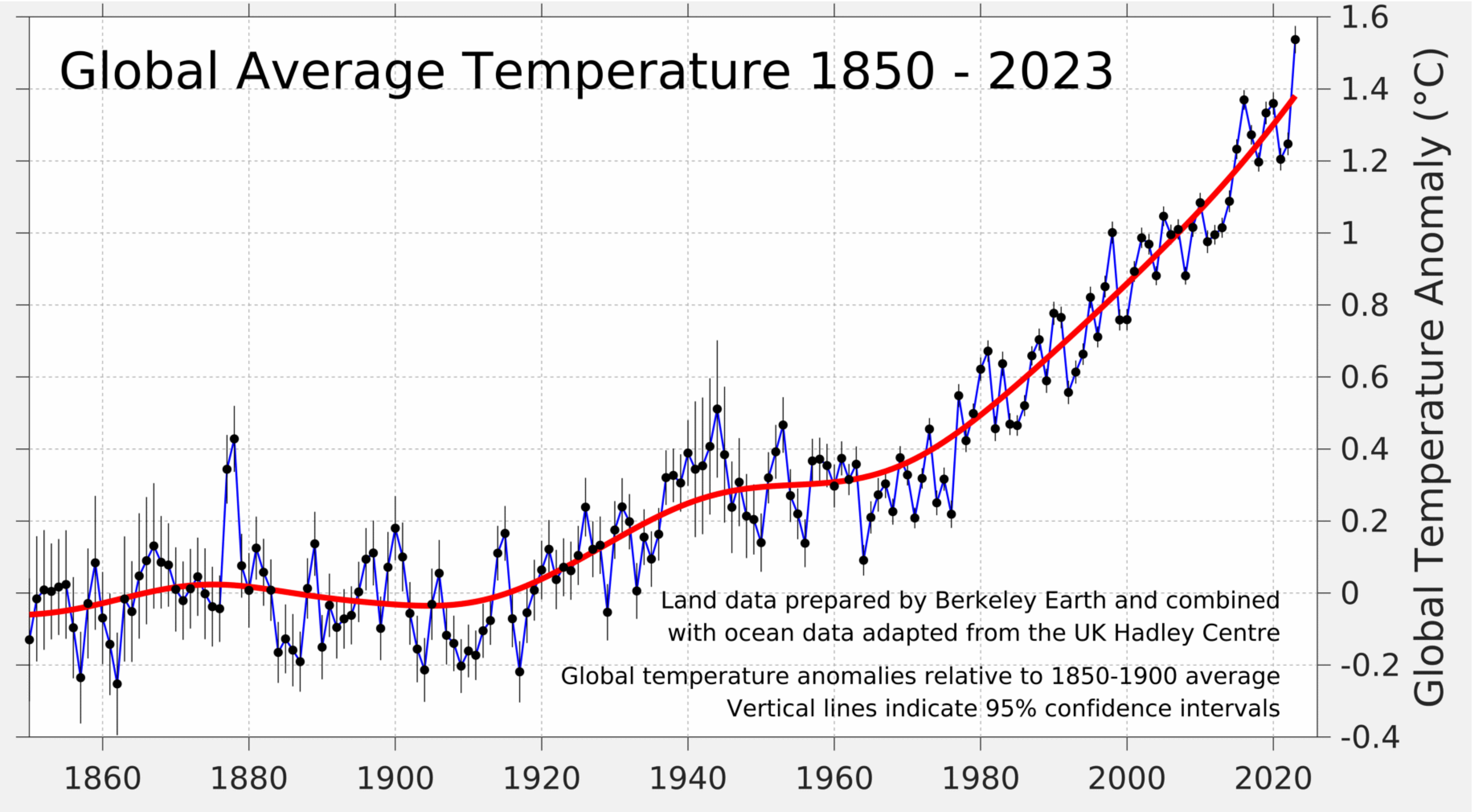




1°C (Celsius) warming is equivalent to 1.8°F (Fahrenheit) warming

Work of Robert Rohde and the Berkeley Earth Team
http://berkeleyearth.org
Animation at https://www.youtube.com/watch?v=DqHKQZGwtw4

Berkeley Earth Animation of Global Warming

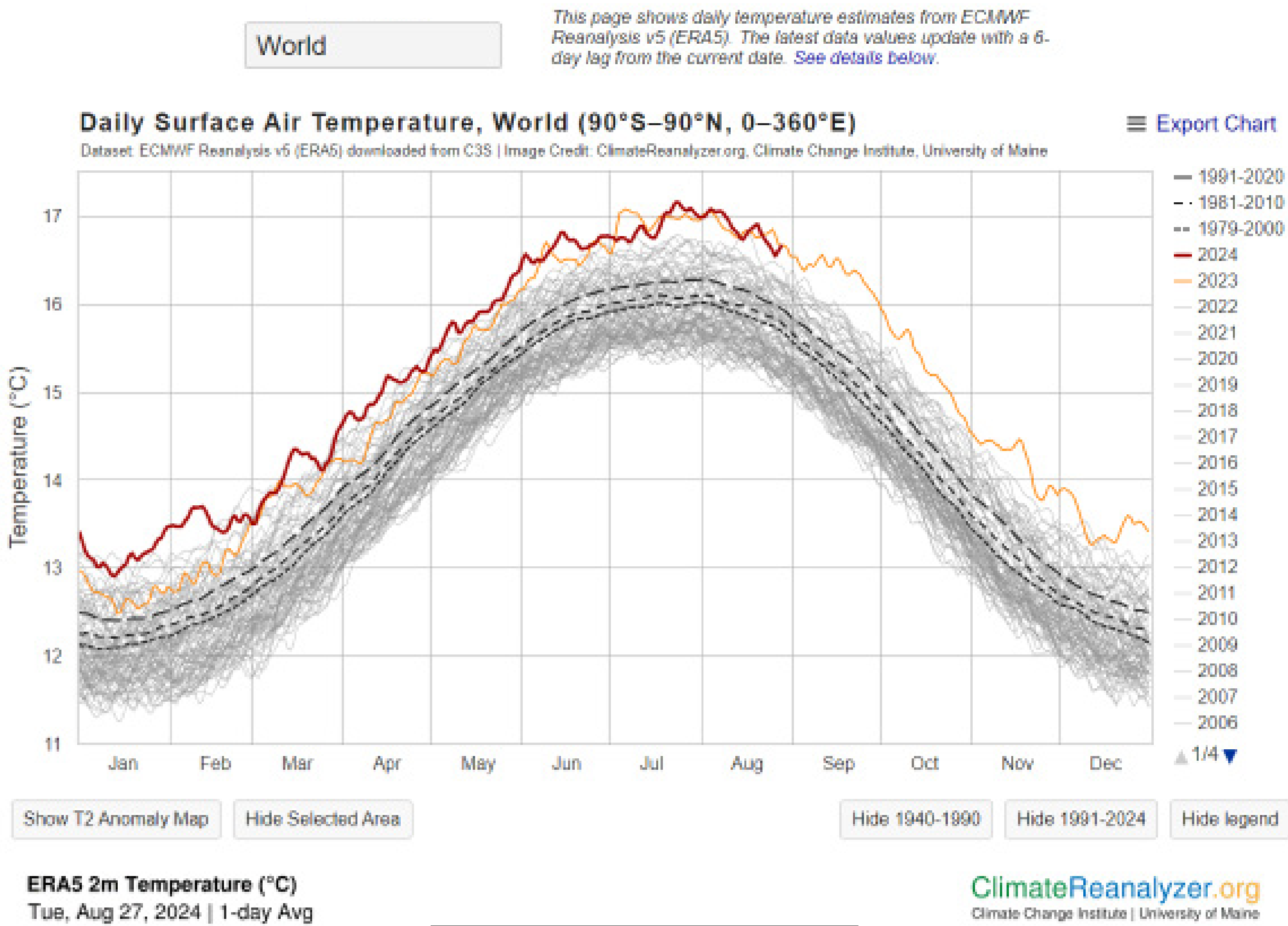


The global mean temperature in 2023 was about 1.54°C (2.78°F) above the average temperature from **1850-1900**, a period often used as a pre-industrial baseline for global temperature targets.

2023 was warmest year to have been directly observed by modern thermometers.

Work of Robert Rohde and the Berkeley Earth Team
http://berkeleyearth.org
https://berkeleyearth.org/global-temperature-report-for-2023

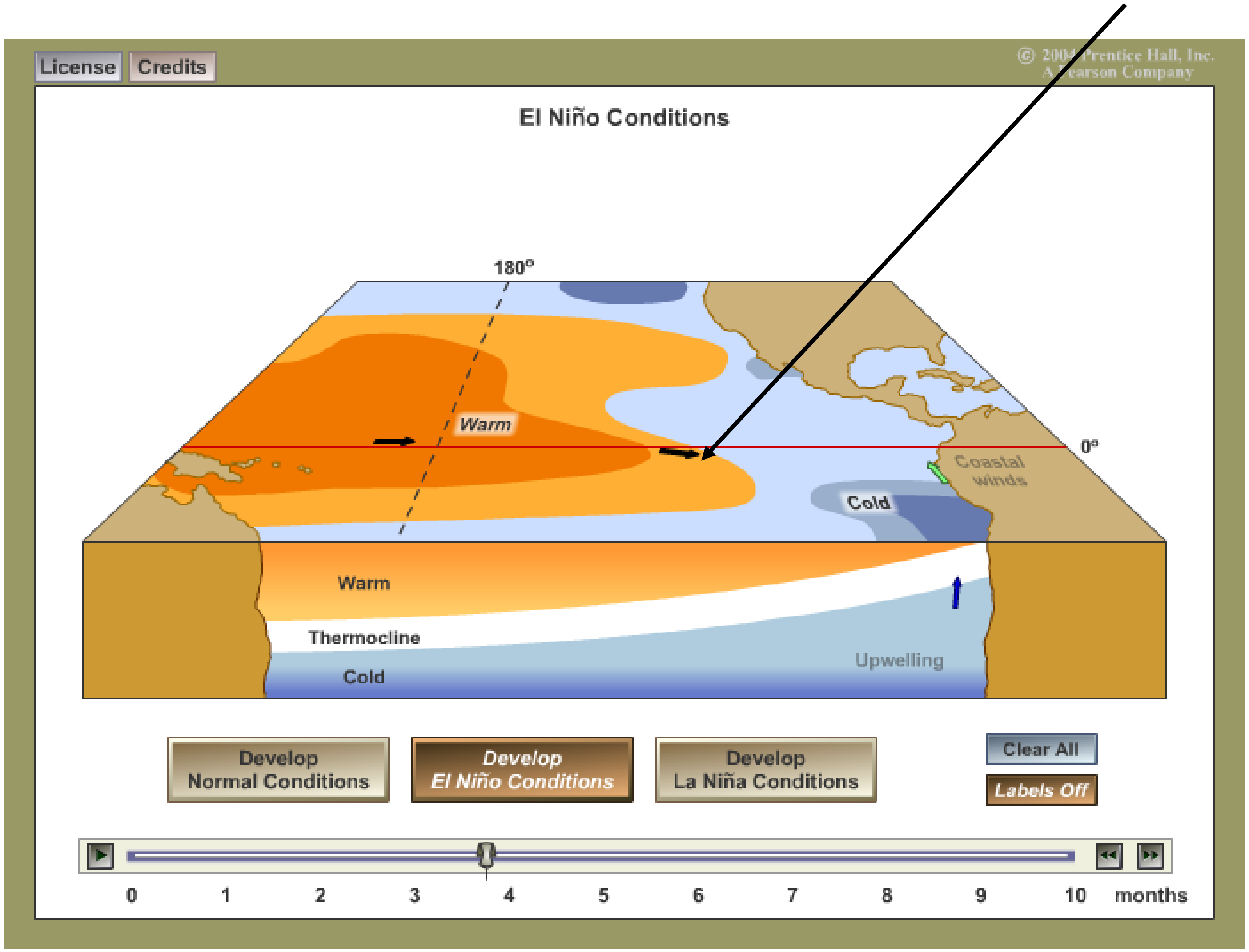
2024 May or May Not Replace 2023 As The Warmest Year On Record



https://climatereanalyzer.org/clim/t2_daily

El Niño – Southern Oscillation (ENSO)

Every 5 to 10 years, this warm pool of water migrates to the East



https://www.youtube.com/watch?v=tyPq86yM_Ic

GWP – Global Warming Potential

$$\mathrm{GWP}\,(\mathrm{CH_4}) = \frac{\int_{\text{time initial}}^{\text{time final}} a_{\mathrm{CH4}} \times [\mathrm{CH_4(t)}]\ \mathrm{dt}}{\int_{\text{time initial}}^{\text{time final}} a_{\mathrm{CO2}} \times [\mathrm{CO_2(t)\ dt}]}$$

where:

a_{CH4} = Radiative Efficiency (W m^{-2} kg $^{-1}$) due to an increase in CH_4

a_{CO2} = Radiative Efficiency (W m^{-2} kg^{-1}) due to an increase in CO_2

CH_4 (t) = time-dependent response to an instantaneous release of a pulse of CH_4

CO_2 (t) = time-dependent response to an instantaneous release of a pulse of CO_2

$$\mathrm{GWP}\,(\mathrm{N_2O}) = \frac{\int_{\text{time initial}}^{\text{time final}} a_{\mathrm{N2O}} \times [\mathrm{N_2O(t)}]\ \mathrm{dt}}{\int_{\text{time initial}}^{\text{time final}} a_{\mathrm{CO2}} \times [\mathrm{CO_2(t)\ dt}]}$$

GWP – Global Warming Potential

Table TS.2. *Lifetimes, radiative efficiencies and direct (except for CH_4) global warming potentials (GWP) relative to CO_2. {Table 2.14}*

Industrial Designation or Common Name (years)	Chemical Formula	Lifetime (years)	Radiative Efficiency ($W\ m^{-2}\ ppb^{-1}$)	Global Warming Potential for Given Time Horizon: SAR‡ (100-yr)	20-yr	100-yr	500-yr
Carbon dioxide	CO_2	See below[a]	[b]1.4×10^{-5}	1	1	1	1
Methane[c]	CH_4	12[c]	3.7×10^{-4}	21	72	25	7.6
Nitrous oxide	N_2O	114	3.03×10^{-3}	310	289	298	153

Notes:

‡ SAR refers to the IPCC Second Assessment Report (1995) used for reporting under the UNFCCC.

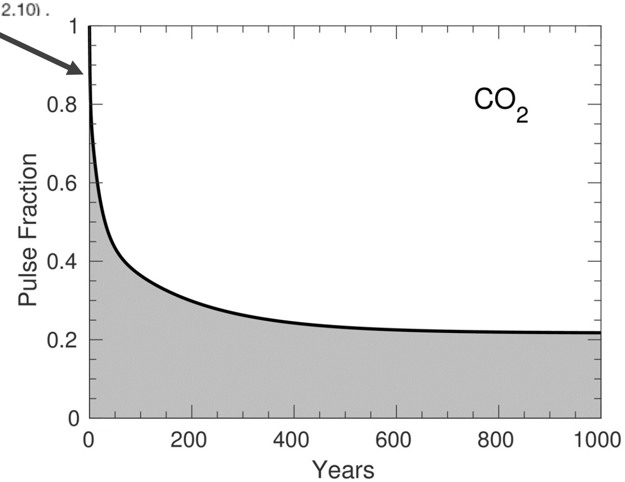
a The CO_2 response function used in this report is based on the revised version of the Bern Carbon cycle model used in Chapter 10 of this report (Bern2.5CC; Joos et al. 2001) using a background CO_2 concentration value of 378 ppm. The decay of a pulse of CO_2 with time t is given by

$a_0 + \sum_{i=1}^{3} a_i \cdot e^{-t/\tau_i}$ where $a_0 = 0.217$, $a_1 = 0.259$, $a_2 = 0.338$, $a_3 = 0.186$, $\tau_1 = 172.9$ years, $\tau_2 = 18.51$ years, and $\tau_3 = 1.186$ years, for $t < 1{,}000$ years.

b The radiative efficiency of CO_2 is calculated using the IPCC (1990) simplified expression as revised in the TAR, with an updated background concentration value of 378 ppm and a perturbation of +1 ppm (see Section 2.10.2).

c The perturbation lifetime for CH_4 is 12 years as in the TAR (see also Section 7.4). The GWP for CH_4 includes indirect effects from enhancements of ozone and stratospheric water vapour (see Section 2.10).

from IPCC 2007 "Physical Science Basis"



$$CO_2(t) = 0.217 + 0.186\times CO_2(t{=}0)\, e^{-t/1.286} + 0.338\times CO_2(t{=}0)\, e^{-t/18.59} + 0.249\times CO_2(t{=}0)\, e^{-t/172.9}$$

where all times are given in units of year

GWPs Now Come In **Two Flavors** (20 yr & 100 yr time horizons) And Are *Slight Moving Targets*

Global Warming Potentials (dimensionless)					
GHG	IPCC (1995) **SAR**	IPCC (2001) **AR3**	IPCC (2007) **AR4**	IPCC (2013) **AR5**	IPCC (2021) **AR6**
100 Year Time Horizon					
CH_4	21	23	25	28	27.2[a] or 29.8[b]
N_2O	310	296	298	265	273
20 Year Time Horizon					
CH_4	56	62	72	84	80.8[a] or 82.5[b]
N_2O	280	275	289	264	273

[a]CH_4 from non-fossil fuel sources such as agriculture
[b]CH_4 from fossil fuel sources

In part because best estimate of atmospheric lifetimes has evolved:

Atmospheric Lifetime (year)					
GHG	IPCC (1995) **SAR**	IPCC (2001) **AR3**	IPCC (2007) **AR4**	IPCC (2013) **AR5**	IPCC (2021) **AR6**
CH_4	12	12	12	12.4	11.8
N_2O	114	114	114	121	109

IPCC : Intergovernmental Panel on Climate Change
SAR : Second Assessment Report; AR3: Third Assessment Report; AR4: Fourth Assessment Report
AR5: Fifth Assessment Report; AR6: Sixth Assessment Report

100 yr time time-horizon GWPs from latest IPCC report supposed to be used for International Book-Keeping

IPCC Sixth Assessment Report Global Warming Potentials

Greenhouse Gas	100 Year Time Period			20 Year Time Period		
	AR4 2007	AR5 2014	AR6 2021	AR4 2007	AR5 2014	AR6 2021
CO_2	1	1	1	1	1	1
CH_4 fossil origin	25	28	29.8	72	84	82.5
CH_4 non fossil origin			27.2			80.8
N_2O	298	265	273	289	264	273

Does the new report mean your company has to update your calculations, and should you be adopting the 100-year or 20-year GWPs? The answer is not as simple as you might think and depends on regulation in your region and the purpose of your report. However, in the absence of any bespoke requirements, the best practice is to adopt the new AR6 100-year GWPs.

The Paris Rulebook states: ' *Each Party shall use the 100-year time-horizon global warming potential (GWP) values from the IPCC Fifth Assessment Report, or 100-year time-horizon GWP values from a subsequent IPCC assessment report as agreed upon by the 'Conference of the Parties serving as the meeting of the Parties to the Paris Agreement' (CMA), to report aggregate emissions and removals of GHGs, expressed in CO2-eq. Each Party may in addition also use other metrics (e.g., global temperature potential) to report supplemental information on aggregate emissions and removals of GHGs, expressed in CO2-eq*".

https://www.ercevolution.energy/ipcc-sixth-assessment-report

GWP – Global Warming Potential

$$\mathrm{GWP\,(CH_4)} = \frac{\int_{\text{time initial}}^{\text{time final}} a_{CH4} \times [CH_4(t)]\, dt}{\int_{\text{time initial}}^{\text{time final}} a_{CO2} \times [CO_2(t)\, dt]}$$

$$\mathrm{GWP\,(N_2O)} = \frac{\int_{\text{time initial}}^{\text{time final}} a_{N2O} \times [N_2O(t)]\, dt}{\int_{\text{time initial}}^{\text{time final}} a_{CO2} \times [CO_2(t)\, dt]}$$

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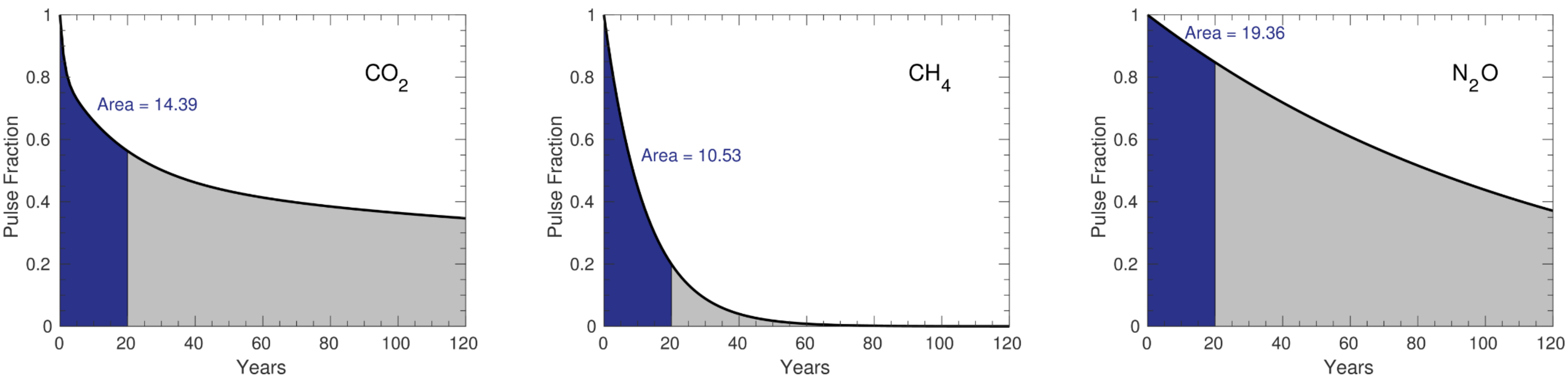
20 Year Time Horizon means time final = 20 years in these integrals



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$$CH_4(t) = CH_4(t{=}0)\, e^{-t/12.4}$$

$$N_2O(t) = N_2O(t{=}0)\, e^{-t/121.0}$$

where all times are given in units of year

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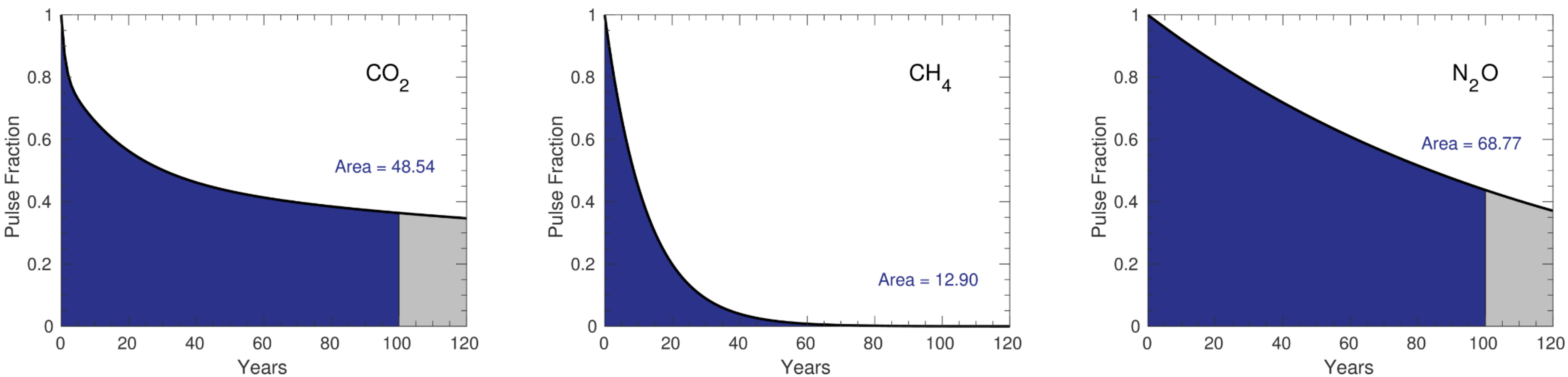
100 Year Time Horizon means time final = 100 years in these integrals



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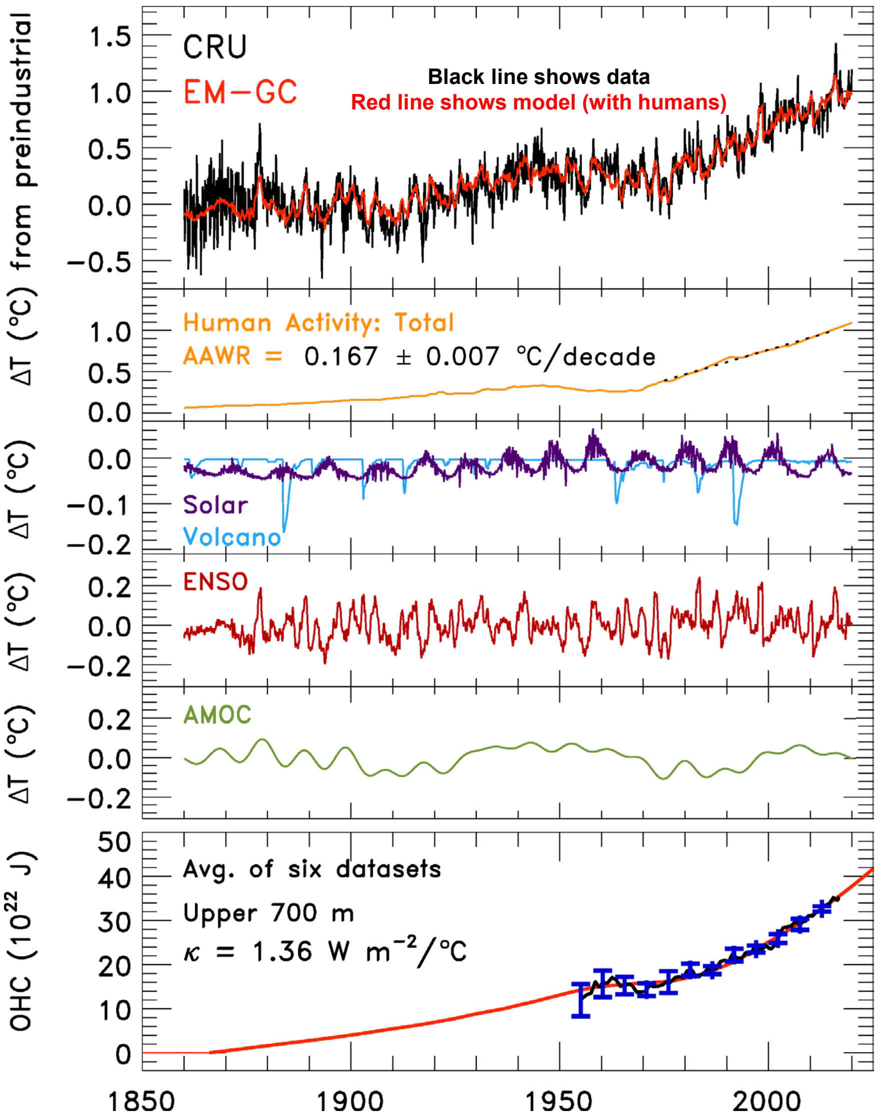
[a]CH_4 from fossil fuel sources
[b]CH_4 from non-fossil fuel sources such as agriculture

CO_2 – equivalent emissions = Emissions of CO_2 +
Emissions of CH_4 × GWP of CH_4 +
Emissions of N_2O × GWP of N_2O +
etc.

Commonly, GWPs on 100 year time horizon are used, although ***many of us*** would prefer the 20 year time horizon

Are humans responsible?



Global warming is caused by CO_2, the greatest waste product of modern society, as well as CH_4, N_2O, and other GHGs.

Temperature will continue to rise until human emission of GHGs is curtailed

CRU: Climate Research Unit of East Anglia, United Kingdom
EM-GC: Empirical Model of Global Climate, Univ of Maryland

Canty *et al.*, 2013 https://www.atmos-chem-phys.net/13/3997/2013/acp-13-3997-2013.html
McBride *et al.*, 2021 https://esd.copernicus.org/articles/12/545/2021
Nicholls *et al.*, 2021 https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2020EF001900
Figure provided by Laura McBride.

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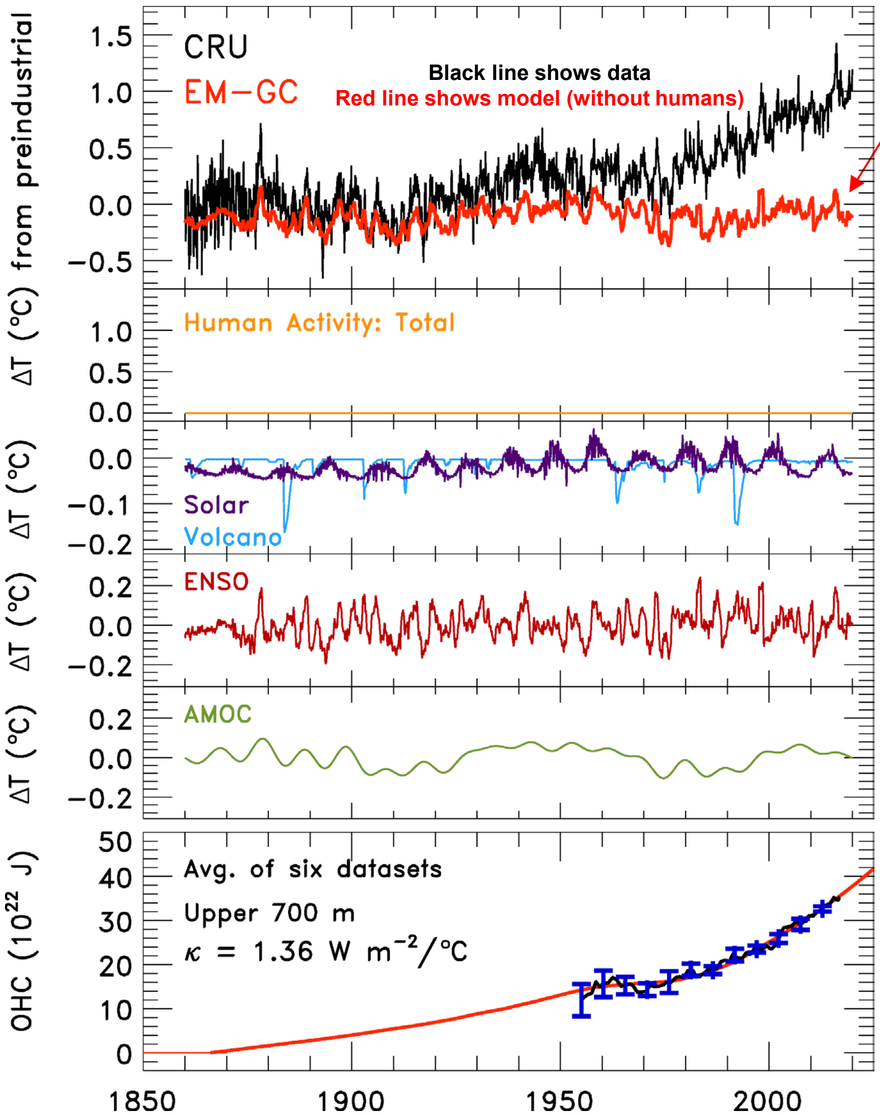

$$\Delta T_{MDL\,i} = (1+\gamma)\left(\frac{GHG\,RF_i + LUC\,RF_i + Aerosol\,RF_i}{\lambda_p}\right) + C_0 + C_1 \times SOD_{i-6} + C_2 \times TSI_{i-1} + C_3 \times ENSO_{i-2} + C_4 \times AMOC_i - \left(\frac{Q_{OCEAN\,i}}{\lambda_p}\right)$$

where:

- i denotes month
- $\lambda_p = 3.2$ W m^{-2} °C^{-1}
- $1+\gamma = \{1 - \lambda_\Sigma/\lambda_p\}^{-1}$
- ~~GHG RF = RF due to all anthropogenic GHGs~~
- ~~LUC RF = RF due to Land Use Change~~
- ~~Aerosol RF = RF due to Tropospheric Aerosols~~
- SOD = Stratospheric Optical Depth
- TSI = Total Solar Irradiance
- ENSO = El Niño Southern Oscillation
- AMOC = Atlantic Meridional Overturning Circulation
- ~~Q_{OCEAN} = Ocean heat export = $\kappa(1+\gamma)\{\Delta T_{MDL\,i} - \Delta T_{OCEAN\,SURFACE\,i}\}$~~

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EM-GC: Empirical Model of Global Climate, Univ of Maryland

Canty *et al.*, 2013 https://www.atmos-chem-phys.net/13/3997/2013/acp-13-3997-2013.html
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Figure provided by Laura McBride.

The future's uncertain and the end is never clear

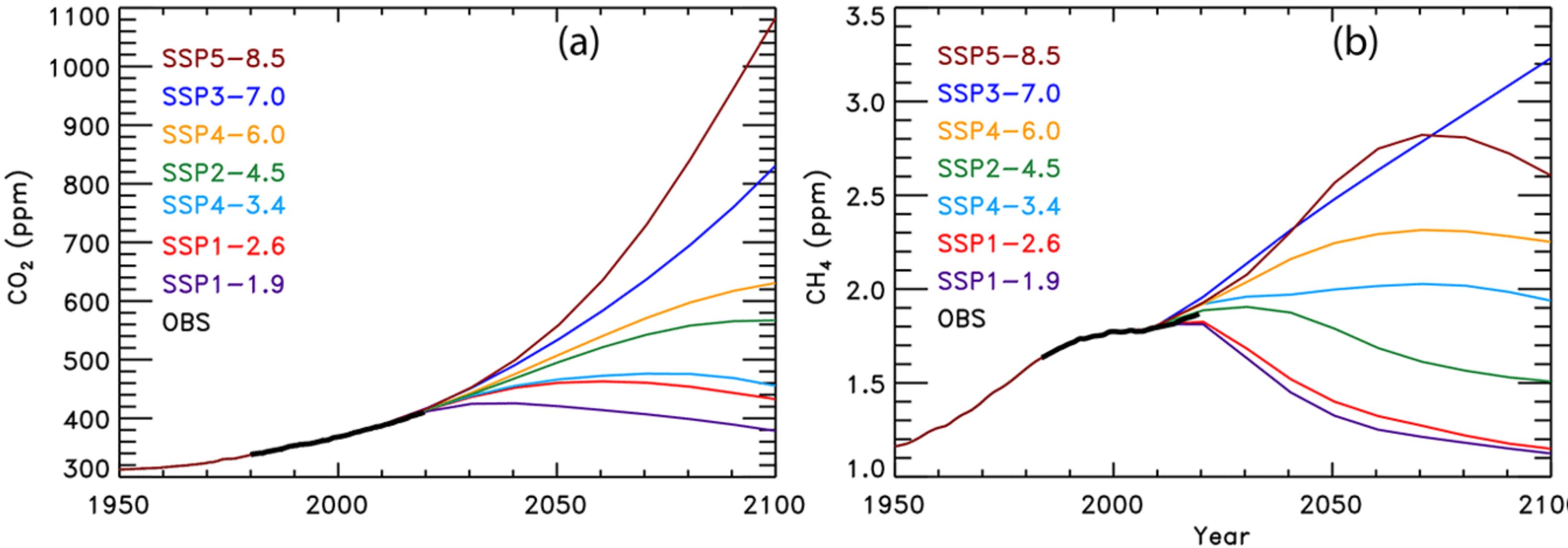


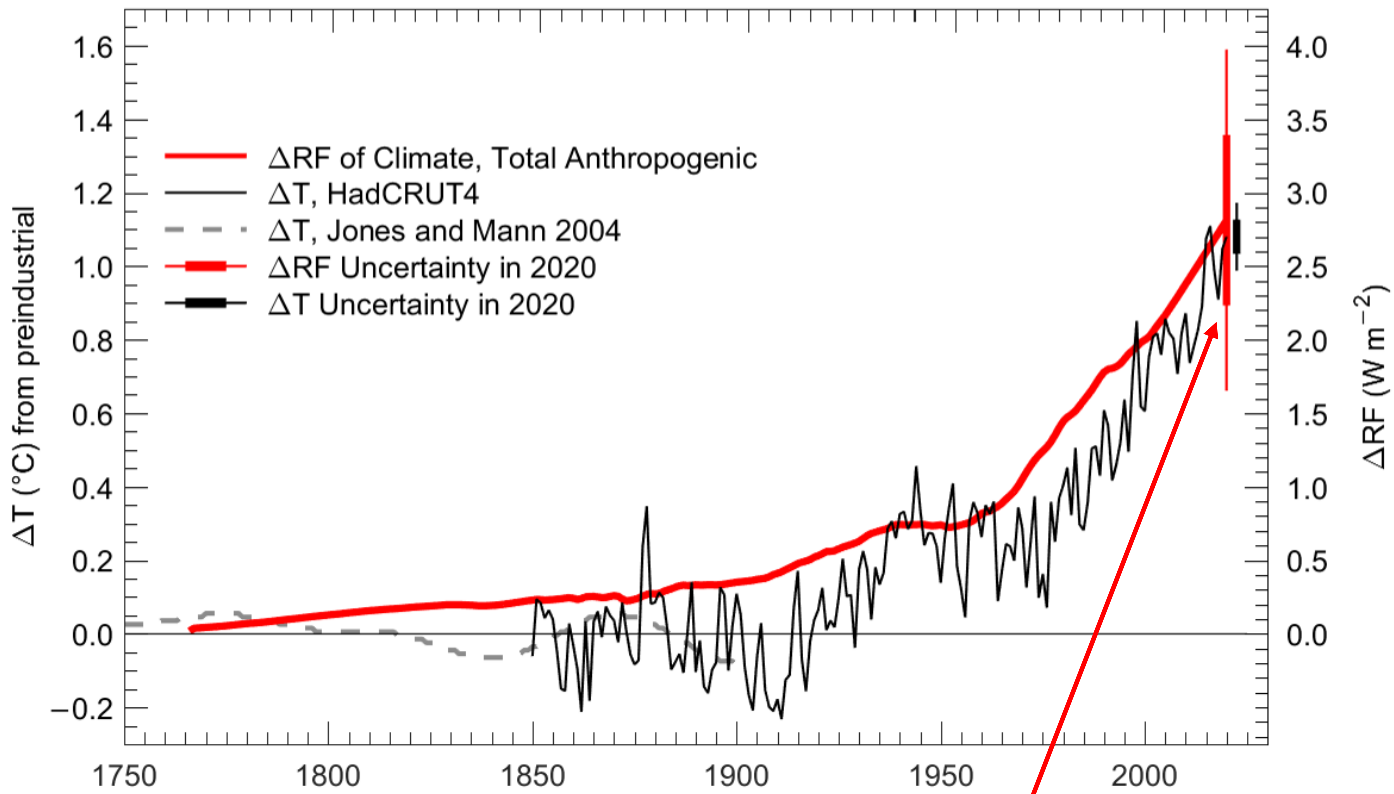
Figure 2, McBride et al., 2021

SSP: **S**hared **S**ocioeconomic **P**athway

Number represents W m^{-2} RF of climate at end of century

https://esd.copernicus.org/articles/12/545/2021

Radiative Forcing of Climate and
Rise of Global Mean Surface Temperature (GMST)



Our knowledge of the "true value" of the rise in temperature is much more precise than the "true value" of the RF of climate

Fig 1.3b, Salawitch *et al.*, *Paris Climate Agreement: Beacon of Hope*, 2017 (updated).

- Past: tropospheric aerosols have offset some fraction of GHG induced warming
- Precise offset not well known
- Future: this “mask” is going away due to air quality concerns

71 plausible scenarios for RF of climate due to Tropospheric aerosols (direct & indirect effect) from Smith and Bond (2012)

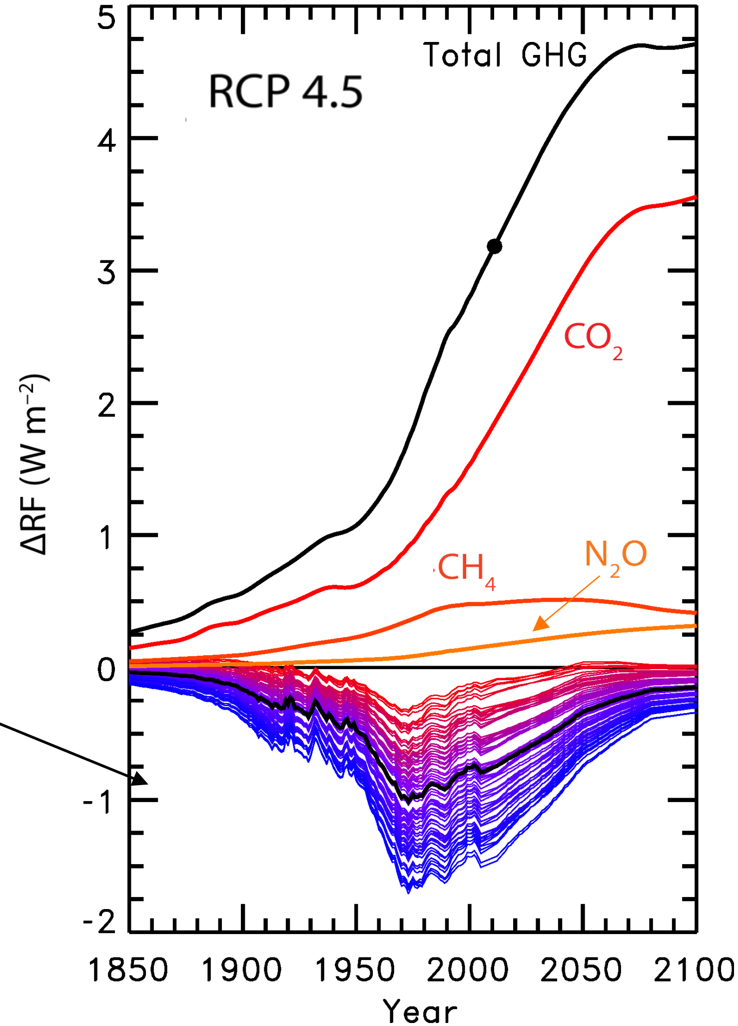


Fig 1.10, Salawitch *et al.*, *Paris Climate Agreement: Beacon of Hope*, 2017.

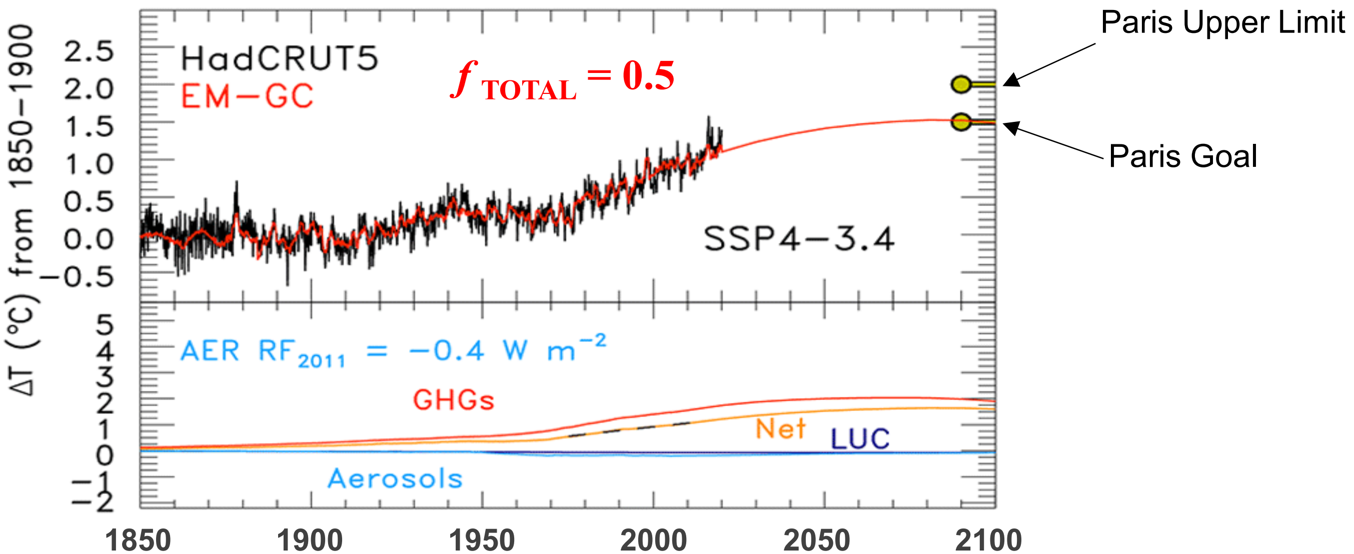
Uncertainty in RF due to aerosols is a huge complication that places a fundamental uncertainty on how well future global warming can be forecast

$$\Delta T = \lambda_{Planck} \times (1 + f_{TOTAL}) \times \Delta RF - OHE$$

where:

f_{TOTAL} = feedbacks due to water vapor, clouds, lapse rate, etc

OHE = ocean heat export



McBride *et al.*, 2021
https://esd.copernicus.org/articles/12/545/2021

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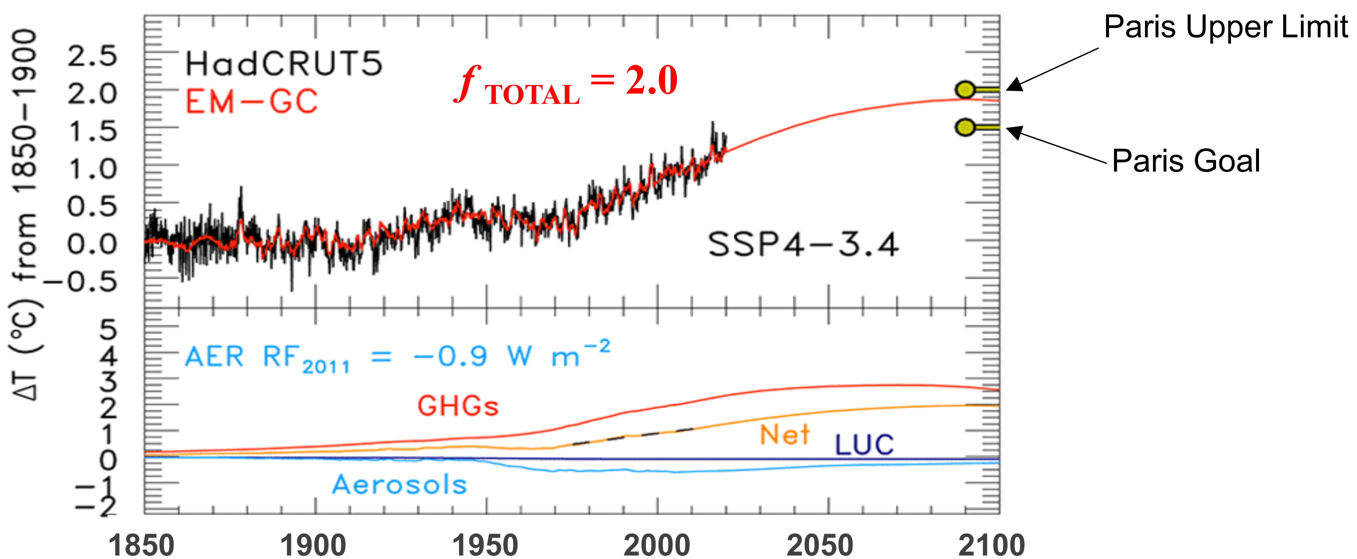

McBride *et al.*, 2021
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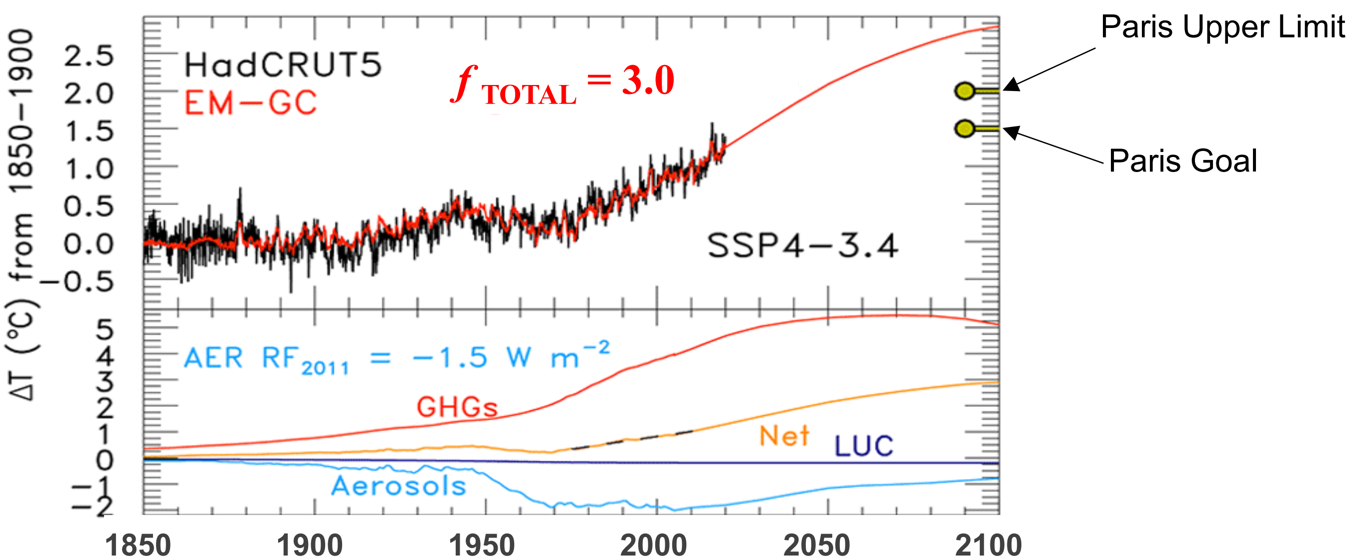


McBride *et al*., 2021
https://esd.copernicus.org/articles/12/545/2021

Are humans responsible?

Orbital variations: drive the ice ages but too small to drive modern warming

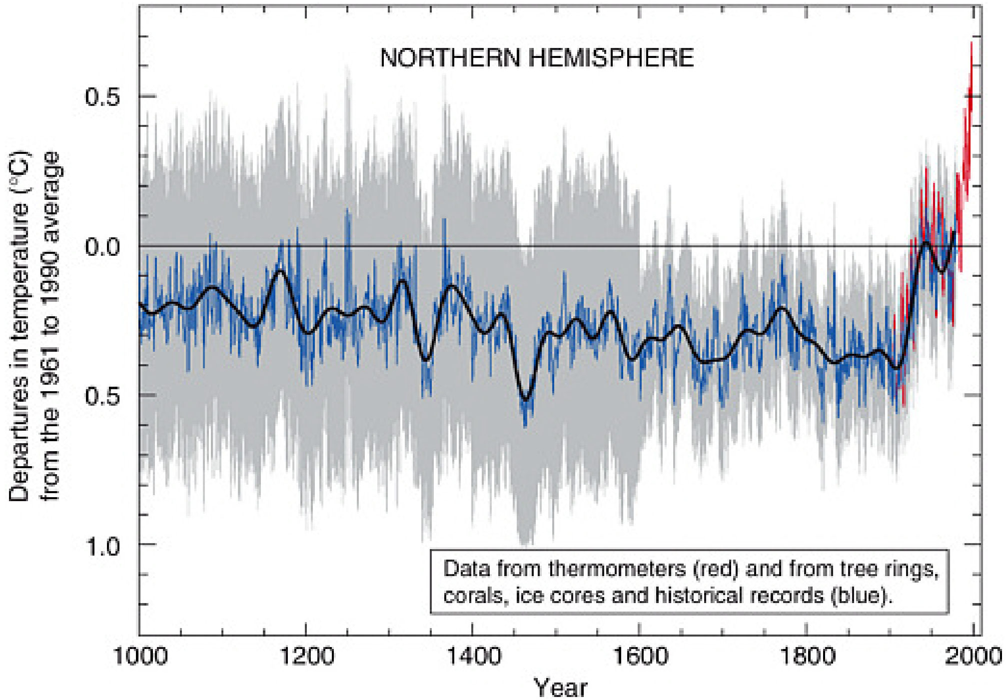
Volcanoes: no sustained forcing

Solar variability:

- **Perhaps dominant forcing of Medieval Warming and Little Ice Age**
- **Small effect since ~1860**

Internal variability (eg, El Niño / La Niña) :

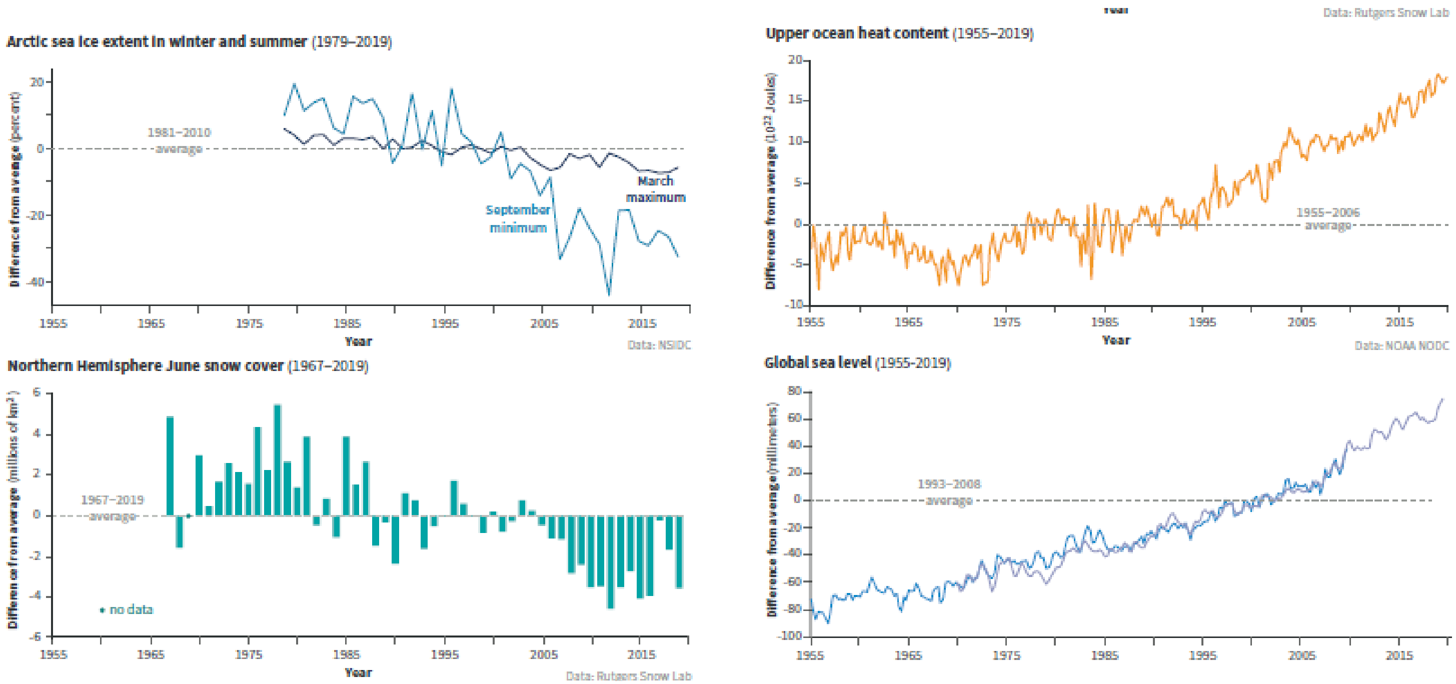
- **Climate record from 1000 to 1850 shows nothing like sustained, present rate of warming**



https://www.nap.edu/read/11676/chapter/3#14

Climate Change Is Much More than GMST

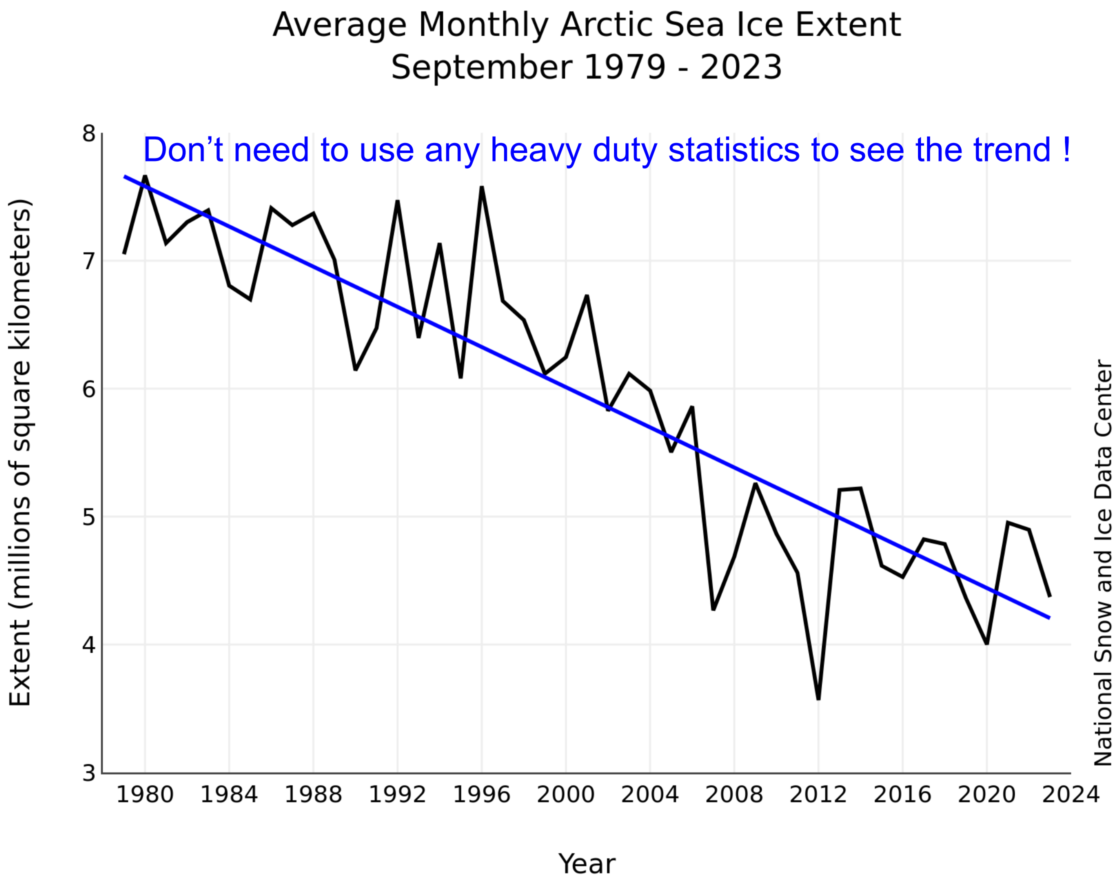
FIGURE 1B. A large amount of observational evidence besides surface temperature records shows that Earth's climate is changing. For example, additional evidence of a warming trend can be found in the dramatic decrease in the extent of Arctic sea ice at its summer minimum (which occurs in September), the decrease in June snow cover in the Northern Hemisphere, the increases in the global average upper ocean (upper 700 m or 2300 feet) heat content (shown relative to the 1955–2006 average), and the rise in global sea level. *Source: NOAA Climate.gov*



RS & NAS, 2020

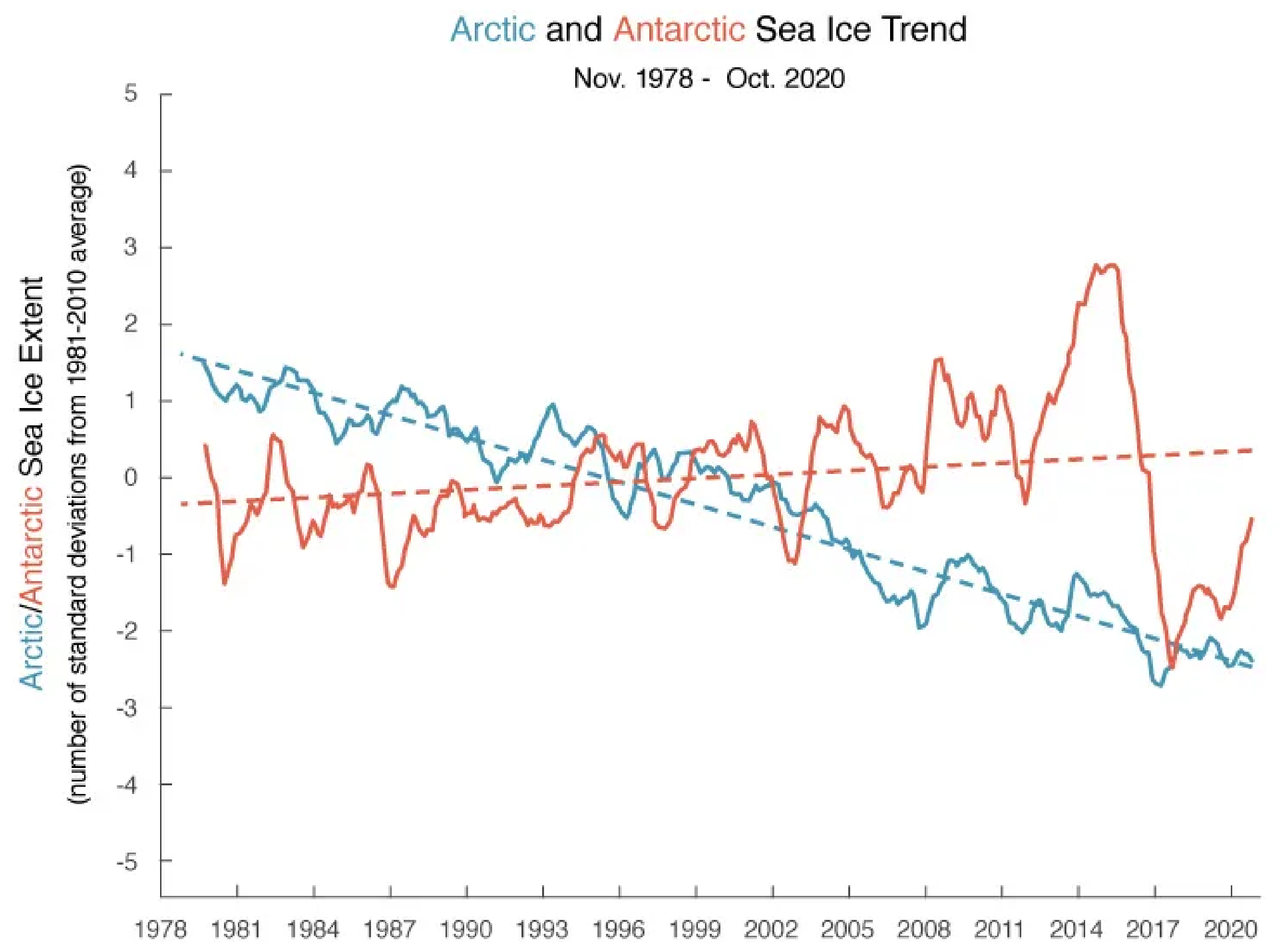
https://royalsociety.org/-/media/Royal_Society_Content/policy/projects/climate-evidence-causes/climate-change-evidence-causes.pdf

Arctic Sea-Ice: Canary of Climate Change



- Sea ice: ice overlying ocean
- Annual minimum occurs each September
- Decline of ~12.2% / decade over satellite era

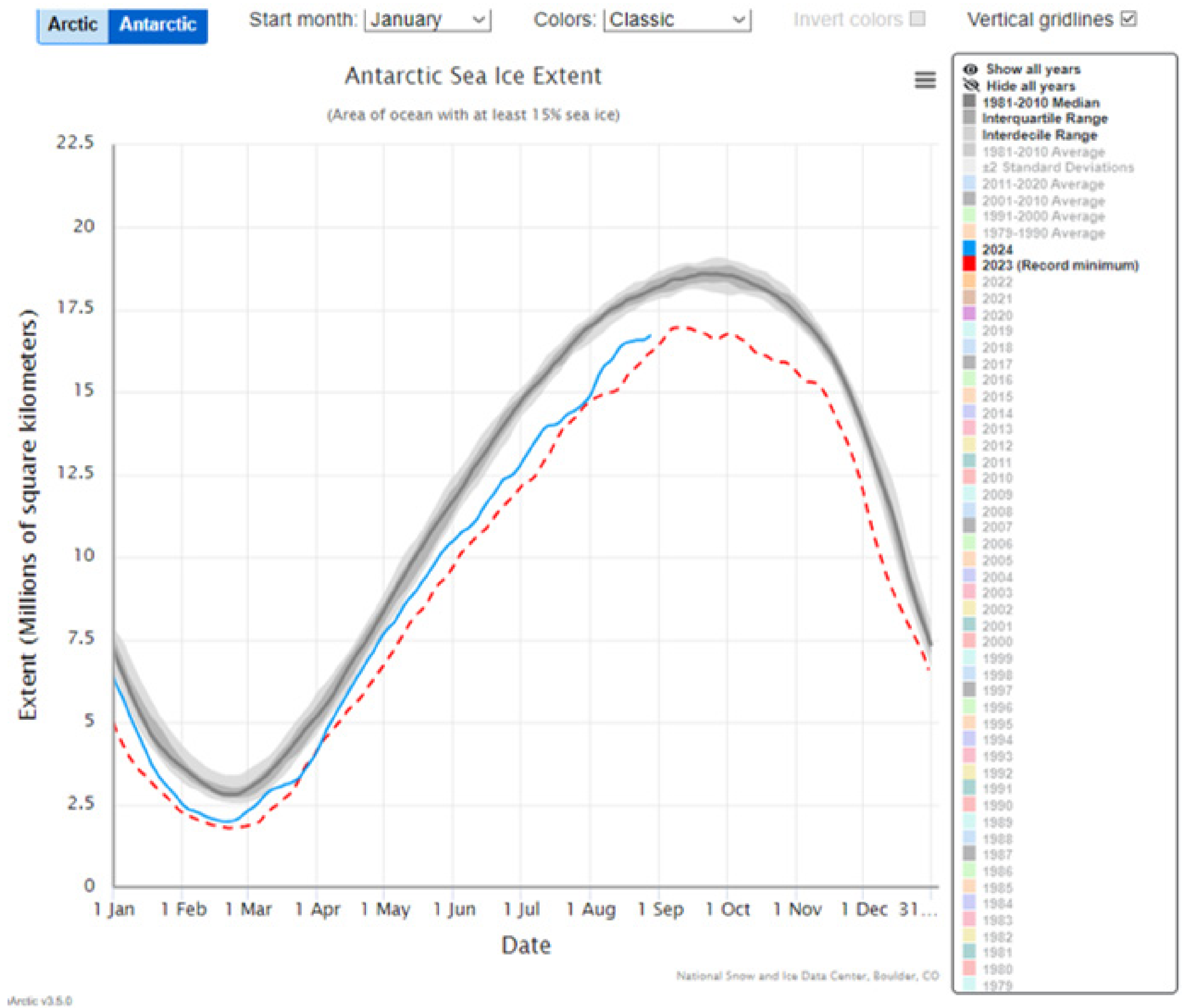
http://nsidc.org/arcticseaicenews/2023/10
as archived at http://web.archive.org/web/20240702095340/https://nsidc.org/arcticseaicenews/2023/10/



Arctic sea ice extent underwent a strong decline from 1979 to 2012 and Antarctic sea ice underwent a slight increase, although some regions of the Antarctic experienced strong declining trends in sea ice extent. The solid lines indicate 12-month running averages, while the dotted lines indicate the overall trend. Units of extent are shown as standard deviations, which refer to the extent of change from the average. (Source: National Snow and Ice Data Center)

https://science.nasa.gov/earth/climate-change/arctic-and-antarctic-sea-ice-how-are-they-different

Antarctic Sea-Ice: 2023 and 2024 Very Anomalous

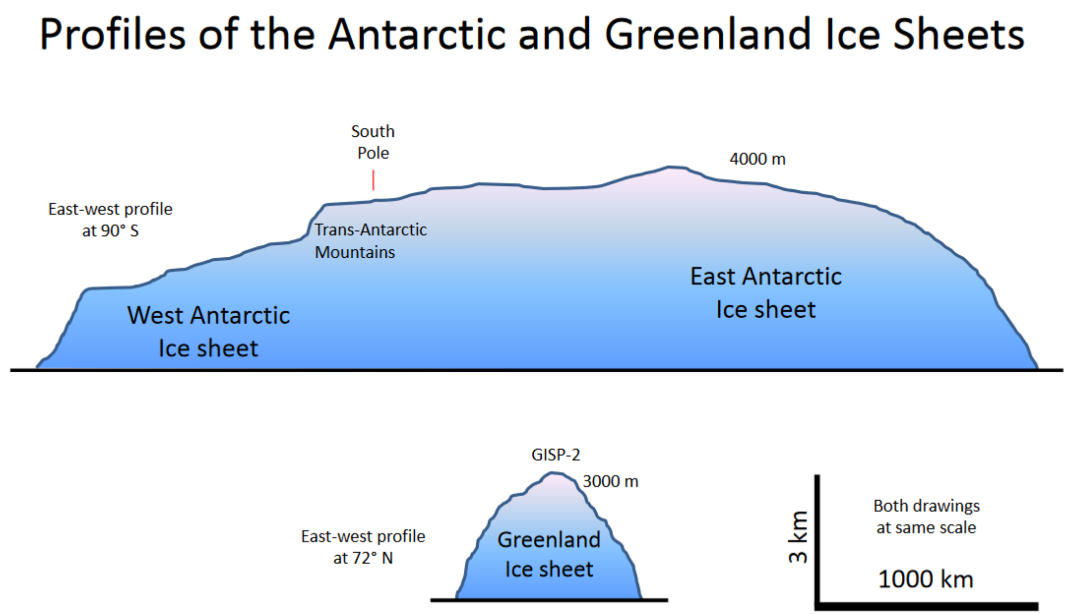


https://nsidc.org/sea-ice-today/sea-ice-tools/charctic-interactive-sea-ice-graph

Volume of Antarctic and **Greenland** Ice Sheets

Volume of Antarctic Ice Sheet ~26.5 × 10^6 km^3 and volume of cubic Greenland Ice Sheet **~2.85 × 10^6 km^3**

https://en.wikipedia.org/wiki/Antarctic_ice_sheet & https://en.wikipedia.org/wiki/Greenland_ice_sheet

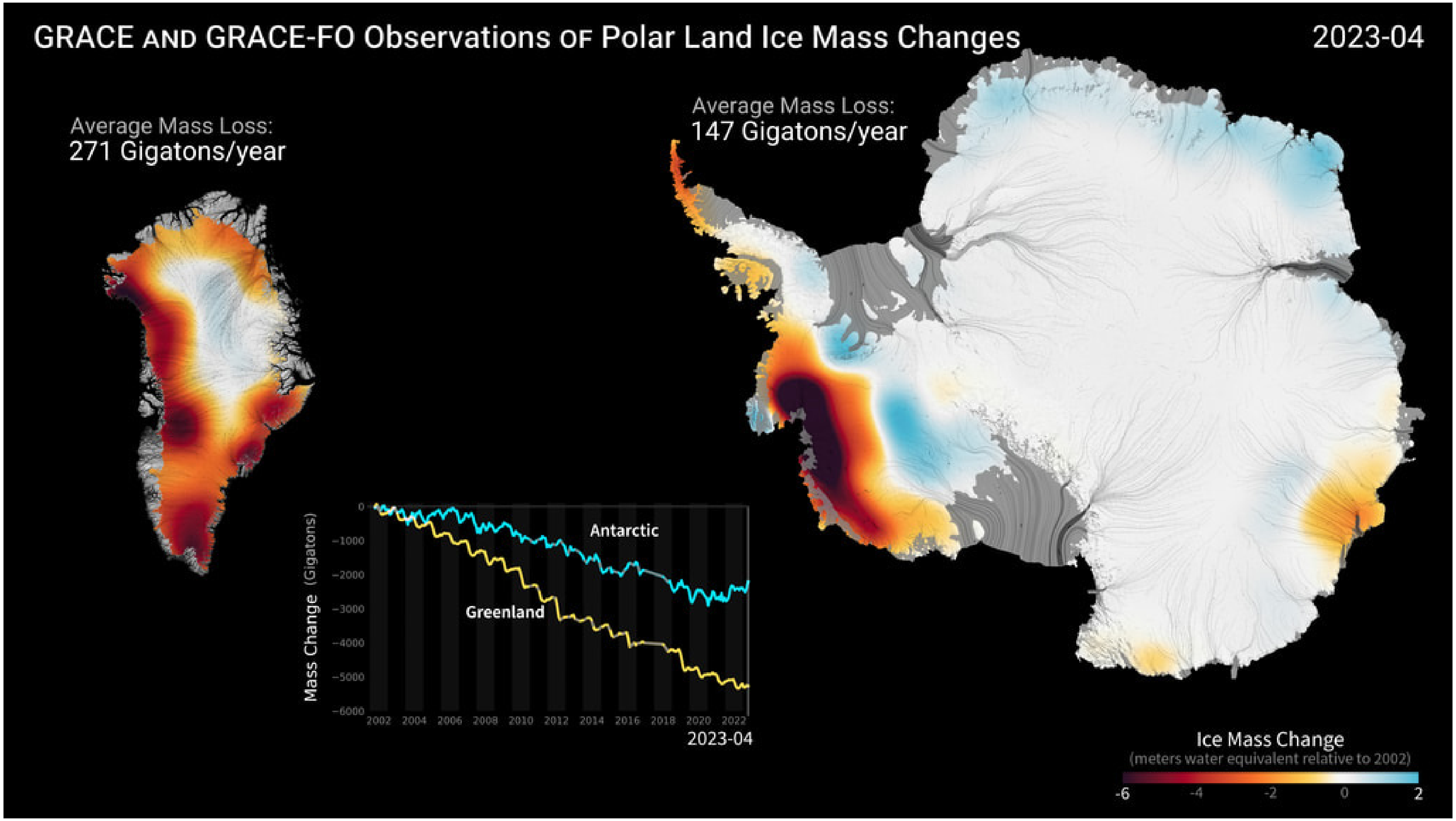


https://web.viu.ca/earle/geol305/The%20Greenland%20Ice%20Sheet.pdf

Radius of Earth = 6371 km; Surface area of Earth = 510 × 10^6 km^2
70% of earth, or 357 × 10^6 km^2 is covered by water.

The complete collapse of Greenland would lead to sea-level rise of
2.85 × 10^6 km^3 / 357 × 10^6 km^2 = 8 meters according to these numbers.
Since more area would be covered by water following the collapse,
the actual rise in sea level is closer to 7 meters … or **23 feet**!

Greenland and Antarctica Ice Mass



https://svs.gsfc.nasa.gov/31166

Next Lecture: Fundamentals of Earth's Atmosphere

Great if you can complete Learning Outcome Quizzes
to review salient "take away" messages

Next Reading:

Chemistry in Context, Secs 1.3, 1.5, 1.14, and 2.1 (~10 pages)
Chapter 2 of the *Houghton* book (11 pages)
7 pages from *Atmospheric Environment* by Michael McElroy

Admission Ticket for Lecture 3 is posted on ELMS-Canvas

Please have a calculator available for class on Thursday