Review for Exam

AOSC 680

Ross Salawitch

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

Exam will be in class on Thursday:

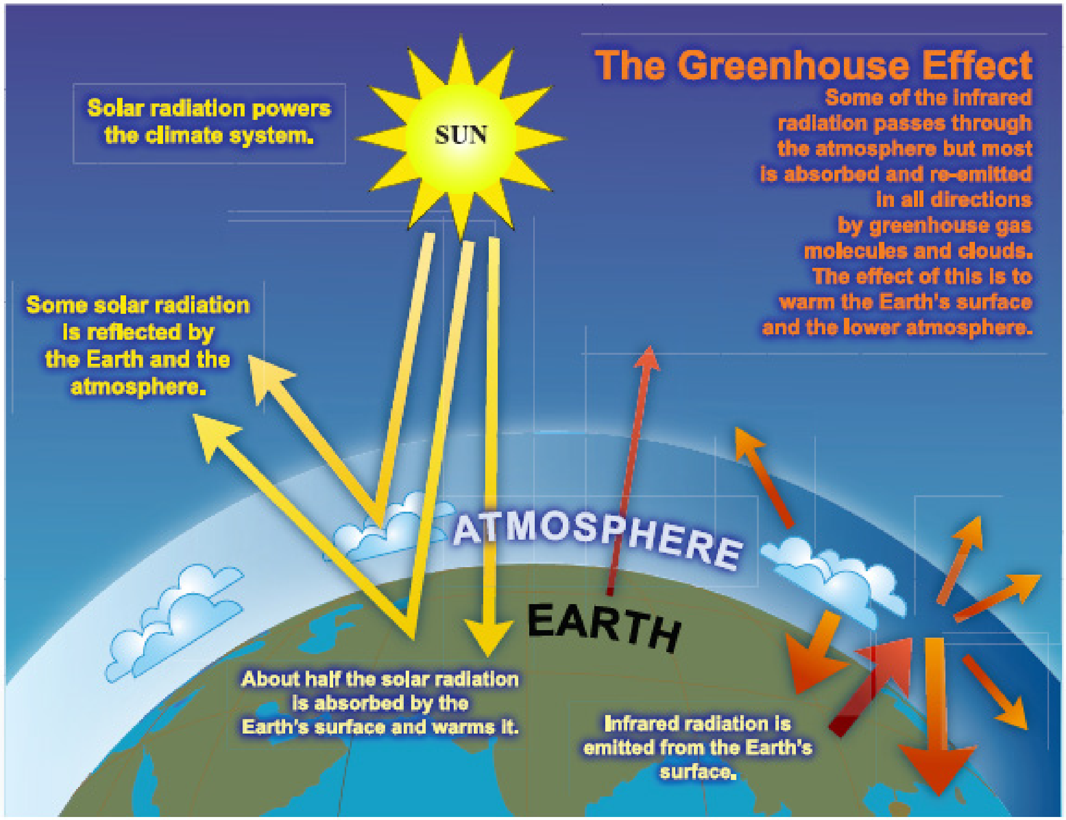
- Closed book
- Focus on concepts, no calculations
- Will cover material & required readings, Lectures 1 to 9

- Today, I will review:
  - Problem Set 2
  - Lectures 1 to 9 (but mainly 1 to 8, since Lecture 9 was so recent)
- Exam given last year

Review of First Part of Class

1 October 2024

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

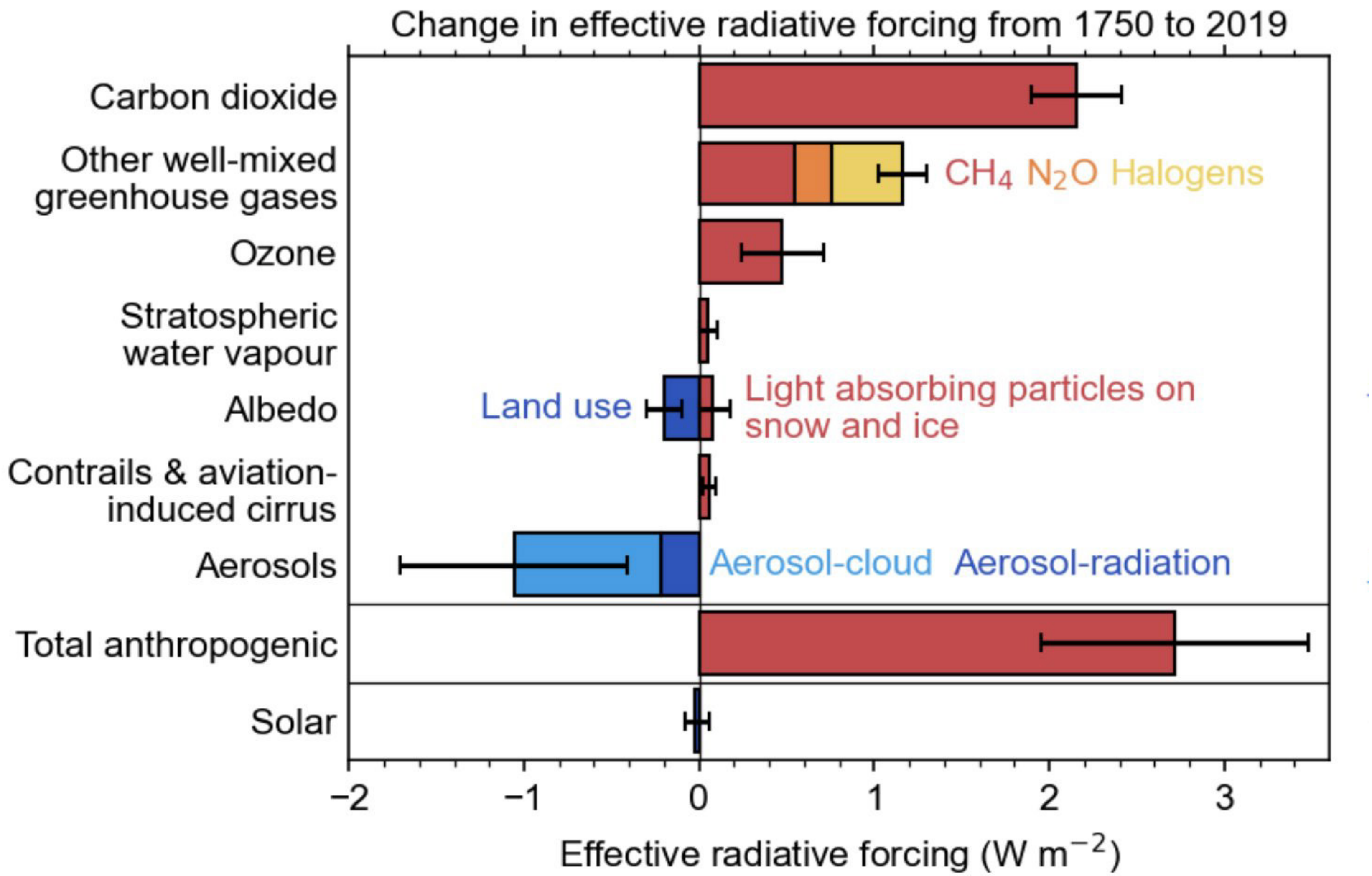
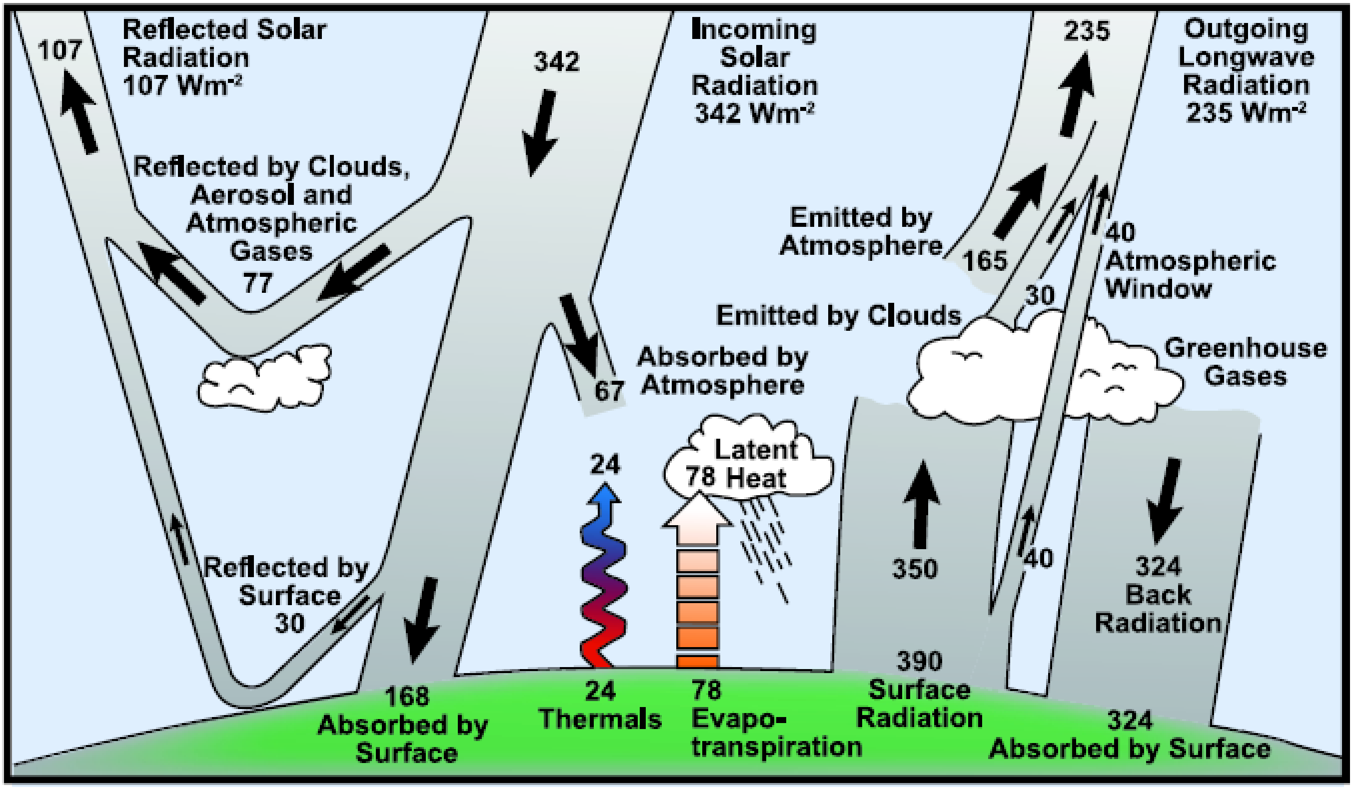


Figure 7.6, IPCC (2021)
https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_TS.pdf

Radiative Forcing

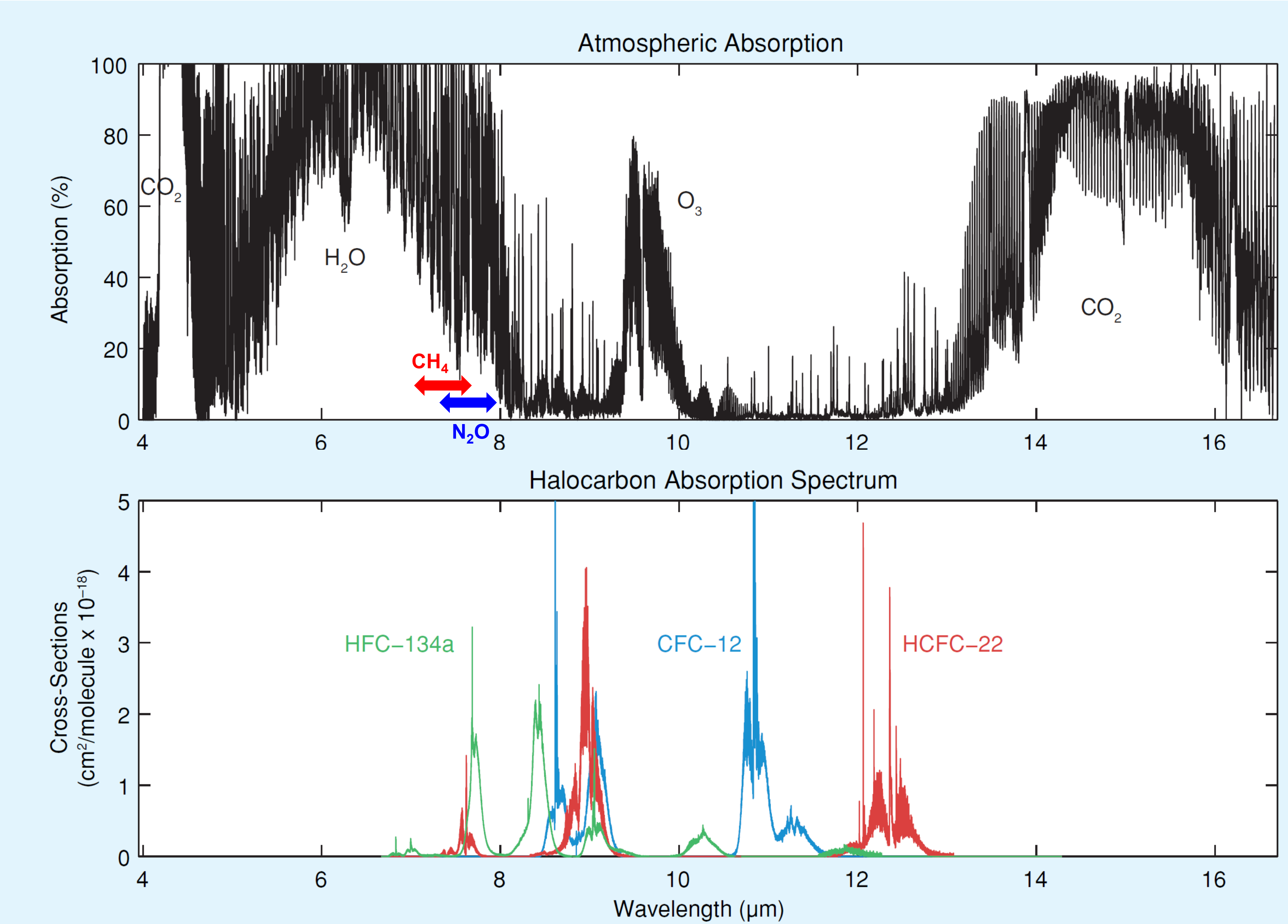


FAQ 1.1, Figure 1. *Estimate of the Earth's annual and global mean energy balance. Over the long term, the amount of incoming solar radiation absorbed by the Earth and atmosphere is balanced by the Earth and atmosphere releasing the same amount of outgoing longwave radiation. About half of the incoming 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.

Absorption vs. Wavelength



GHG Record Over Last Several Millennia

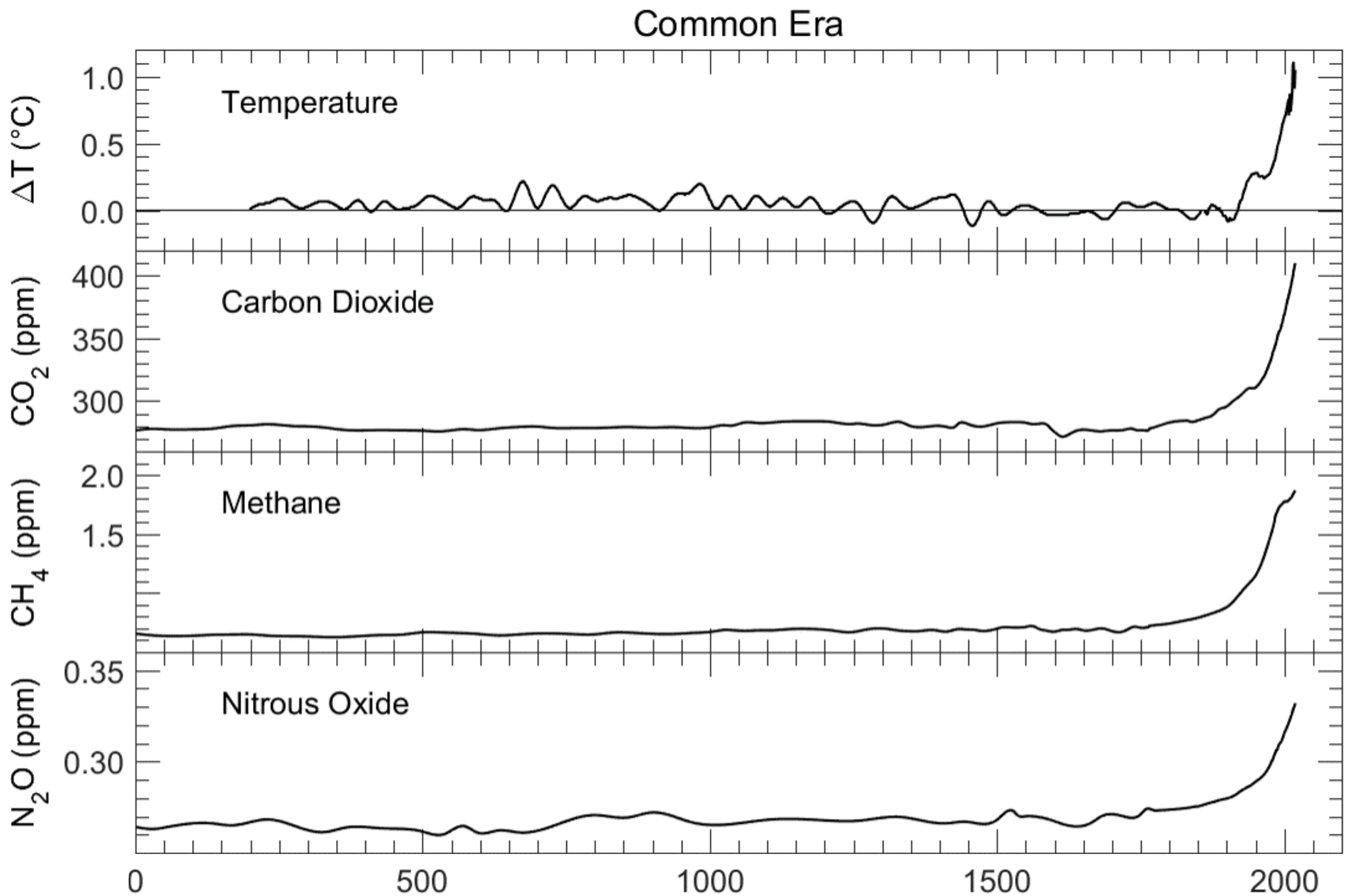


Figure 1.2, Paris Beacon of Hope (updated)

Going Back 600,000 years

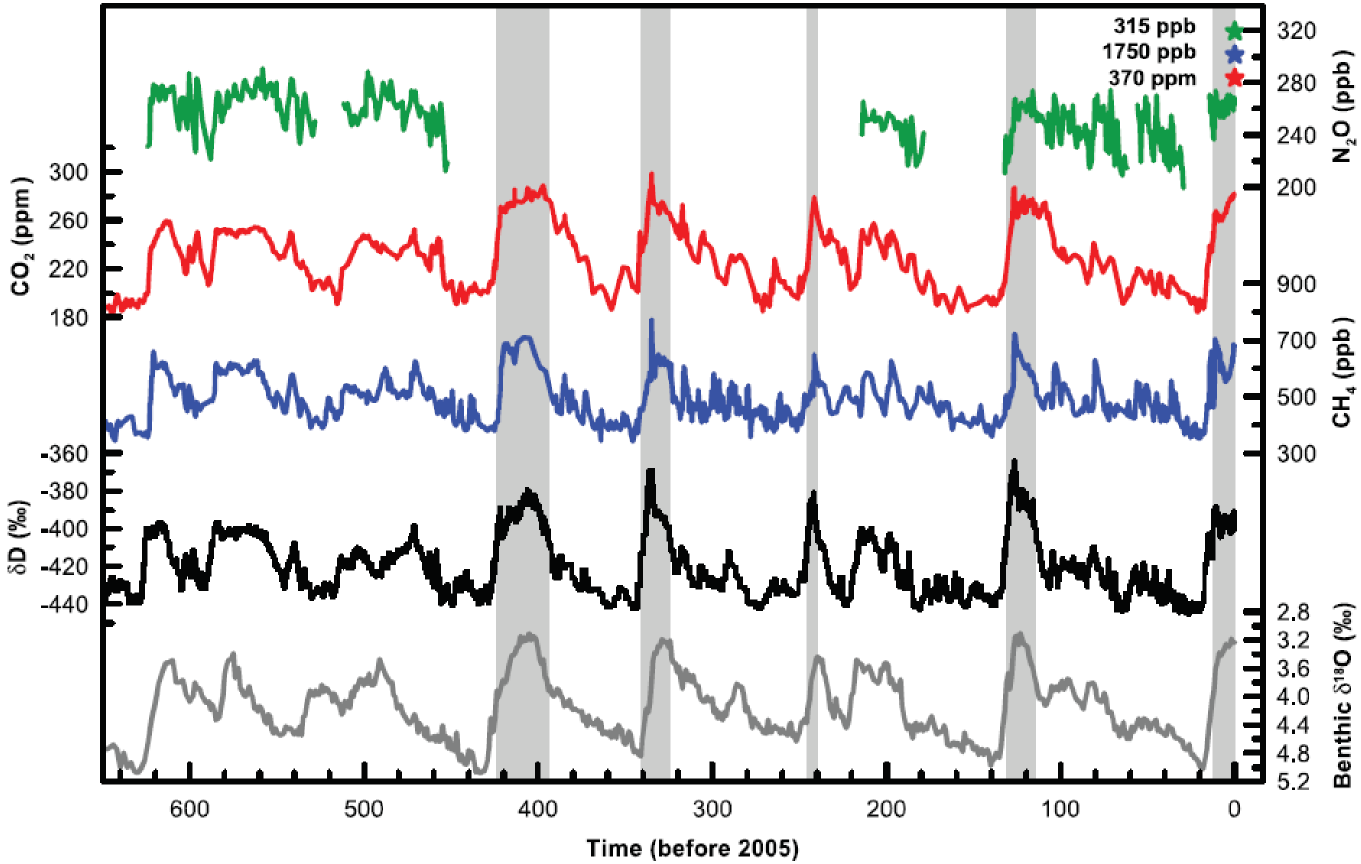


Figure 6.3. *Variations of deuterium (δD; black), a proxy for local temperature, and the atmospheric concentrations of the greenhouse gases CO_2 (red), CH_4 (blue), and nitrous oxide (N_2O; green) derived from air trapped within ice cores from Antarctica and from recent atmospheric measurements (Petit et al., 1999; Indermühle et al., 2000; EPICA community members, 2004; Spahni et al., 2005; Siegenthaler et al., 2005a,b). The shading indicates the last interglacial warm periods. Interglacial periods also existed prior to 450 ka, but these were apparently colder than the typical interglacials of the latest Quaternary. The length of the current interglacial is not unusual in the context of the last 650 kyr. The stack of 57 globally distributed benthic $\delta^{18}O$ marine records (dark grey), a proxy for global ice volume fluctuations (Lisiecki and Raymo, 2005), is displayed for comparison with the ice core data. Downward trends in the benthic $\delta^{18}O$ curve reflect increasing ice volumes on land. Note that the shaded vertical bars are based on the ice core age model (EPICA community members, 2004), and that the marine record is plotted on its original time scale based on tuning to the orbital parameters (Lisiecki and Raymo, 2005). The stars and labels indicate atmospheric concentrations at year 2000.*

Figure 6.3, IPCC 2007

See https://epic.awi.de/id/eprint/18400/1/Oer2008a.pdf for description of EPICA , European Project for Ice Coring in Antarctica

GWP – Global Warming Potential

$$\text{GWP}\,(\text{CH}_4) = \frac{\displaystyle\int_{\text{time initial}}^{\text{time final}} a_{\text{CH4}} \times [\text{CH}_4(\text{t})]\ \text{dt}}{\displaystyle\int_{\text{time initial}}^{\text{time final}} a_{\text{CO2}} \times [\text{CO}_2(\text{t})\ \text{dt}]}$$

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 *certain mass* of CH_4

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

$$\text{GWP}\,(\text{N}_2\text{O}) = \frac{\displaystyle\int_{\text{time initial}}^{\text{time final}} a_{\text{N2O}} \times [\text{N}_2\text{O}(\text{t})]\ \text{dt}}{\displaystyle\int_{\text{time initial}}^{\text{time final}} a_{\text{CO2}} \times [\text{CO}_2(\text{t})\ \text{dt}]}$$

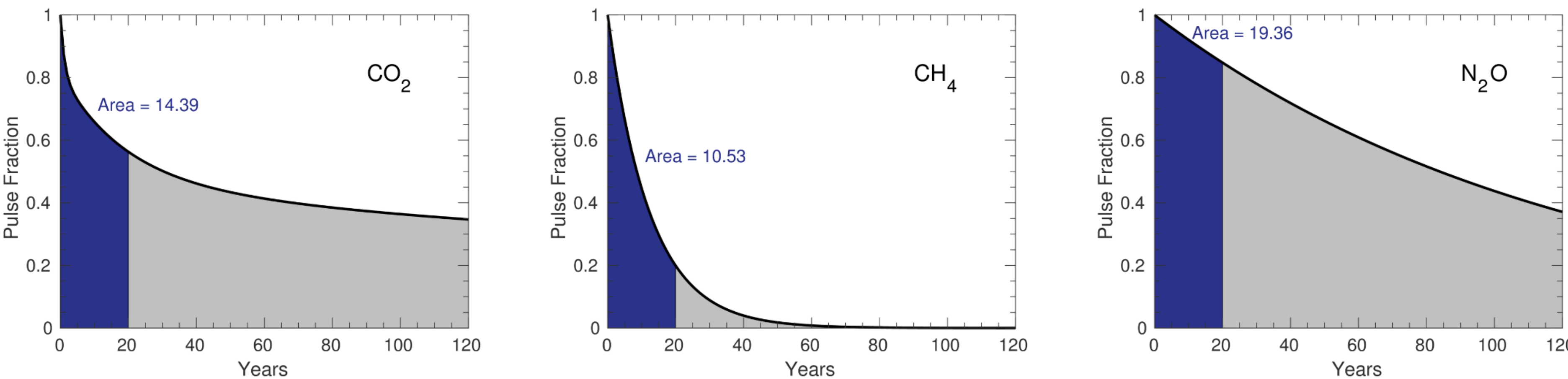
GWP – Global Warming Potential

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

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

Global Warming Potentials				
GHG	IPCC (1995)	IPCC (2001)	IPCC (2007)	IPCC (2013)
100 Year Time Horizon				
CH_4	21	23	25	28
N_2O	310	296	298	265
20 Year Time Horizon				
CH_4	56	62	72	84
N_2O	280	275	289	264

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



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

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

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

where all times are given in units of year

GWP – Global Warming Potential

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

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

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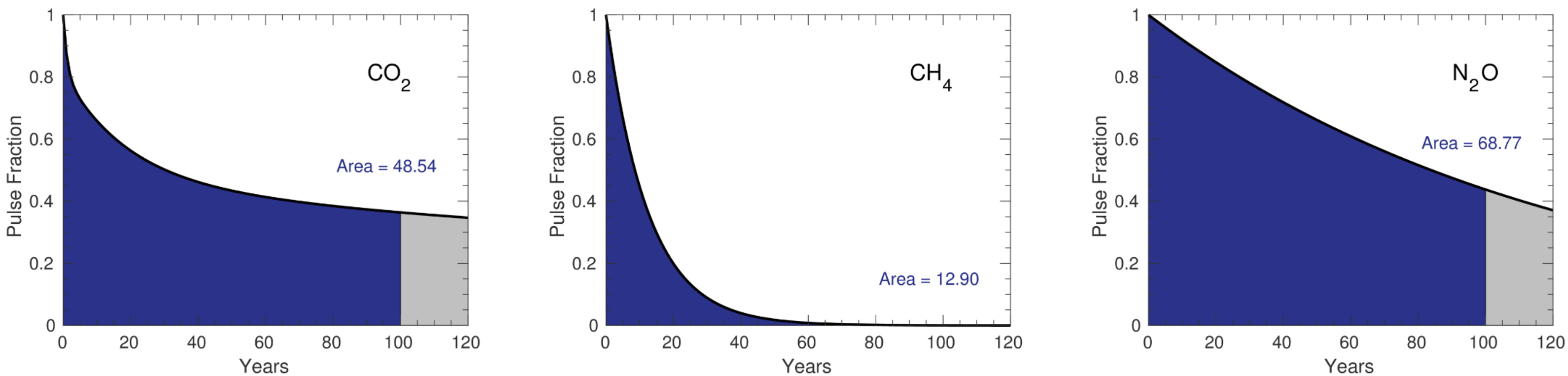
100 Year Time Horizon means time final = 100 years in these integrals



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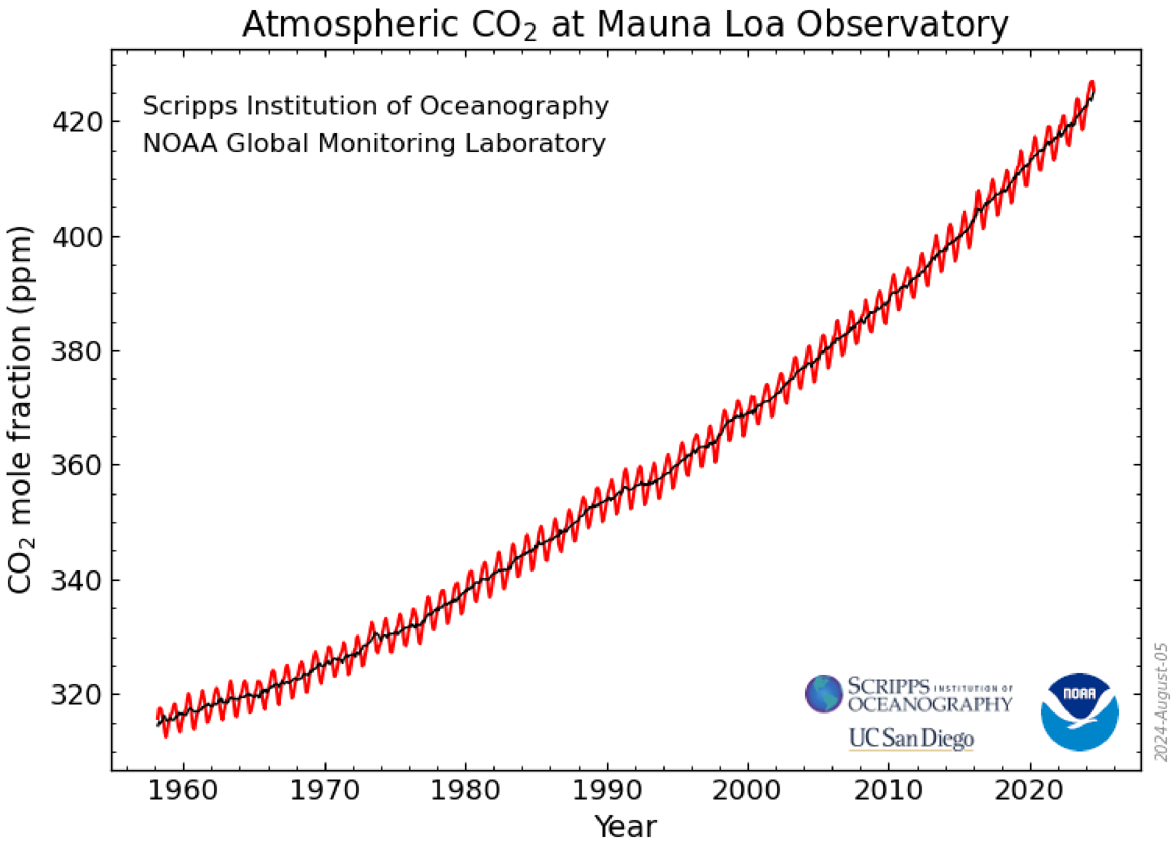
where all times are given in units of year

Modern CO_2 Record

Lecture 02

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

Human "Fingerprints" on Atmospheric CO_2

Lecture 05

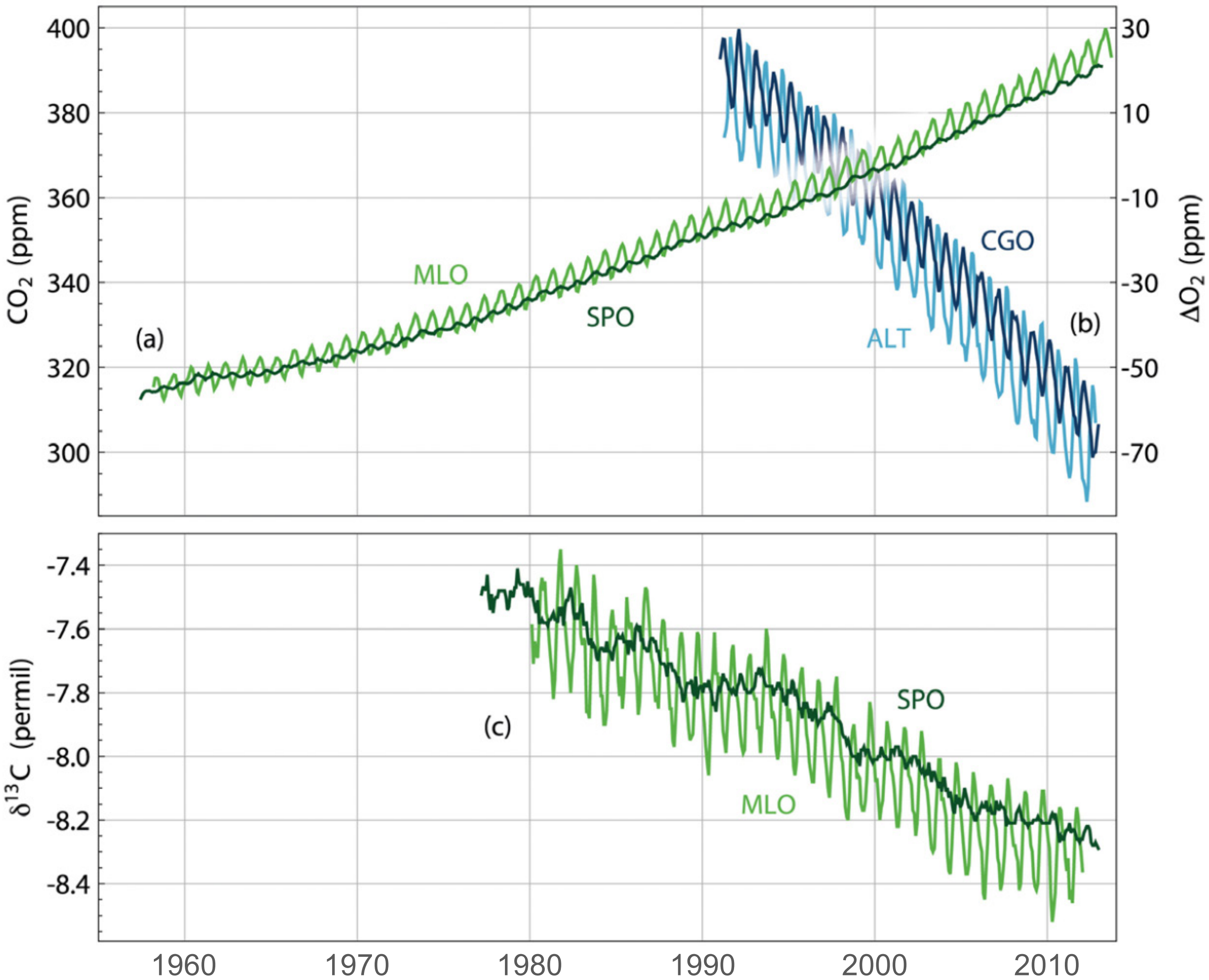


Figure 3.4 Atmospheric concentrations observed at representative stations of (a) carbon dioxide from Mauna Loa (MLO) Northern Hemisphere and South Pole (SPO) Southern Hemisphere; (b) Oxygen from Alert (ALT) Canada, 82°N, and Cape Grim (CGO), Australia, 41°S; (c) $^{13}C/^{12}C$ from Mauna Loa (MLO) and South Pole (SPO) stations.

Fig 3.4, Houghton

Atmospheric CH_4

AT6, Q1:
According to Table 3.2 of Chemistry in Context, what was pre-industrial atmospheric abundance of CH_4 ***and*** is this consistent with Figure 3.7 of the Houghton reading?

700 ppb

Broadly

Table 3.2 Examples of Greenhouse Gases

Name and Chemical Formula	Preindustrial Concentration (1750)	Concentration in 2008	Atmospheric Lifetime (years)	Anthropogenic Sources	Global Warming Potential
carbon dioxide CO_2	270 ppm	388 ppm	50-200*	Fossil fuel combustion, deforestation, cement production	1
methane CH_4	700 ppb	1760 ppb	12	Rice paddies, waste dumps, livestock	21
nitrous oxide N_2O					310
CFC-12 CCl_2F_2					8100

*A single value for … e given is an estimate based on several …

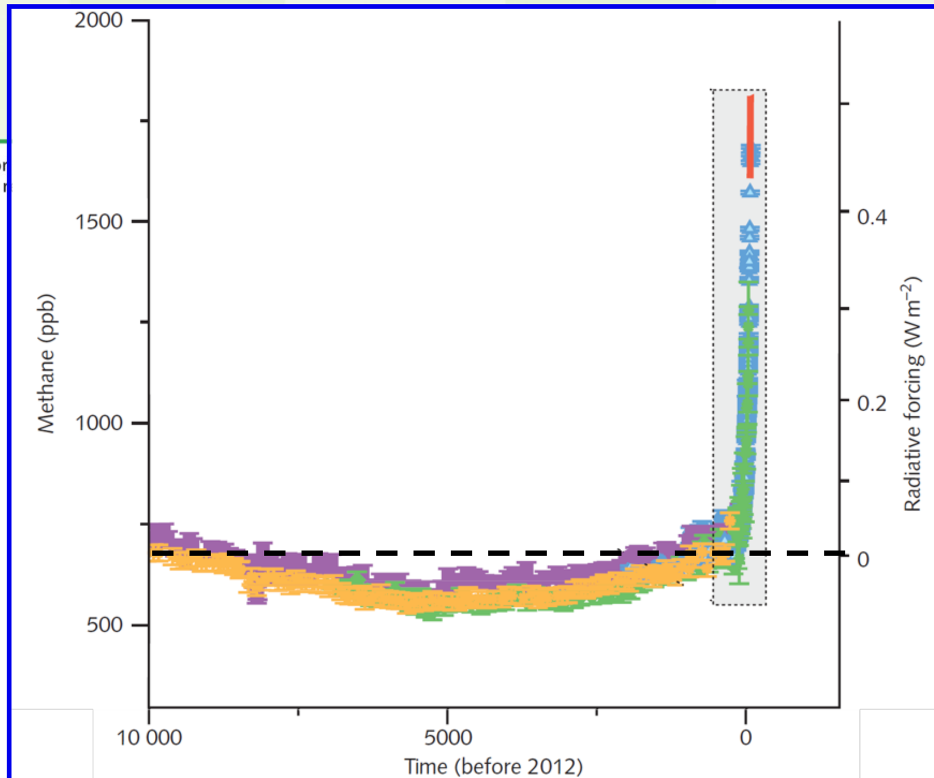


Figure 3.7, *Houghton*

Atmospheric CH_4

AT6, Q2:
What is the approximate current atmospheric abundance of CH_4?

Table 3.2 Examples of Greenhouse Gases

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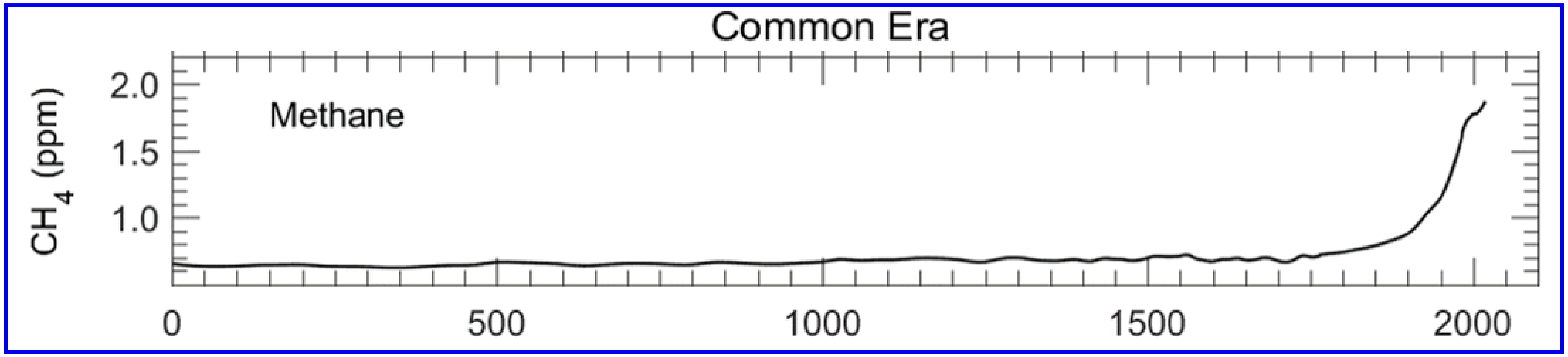
methane CH_4	700 ppb	$\boxed{\text{1760 ppb}}$	12	Rice paddies, waste dumps, livestock	21
nitrous oxide N_2O	275 ppb	322 ppb	120	Fertilizers, industrial production, combustion	310
CFC-12 CCl_2F_2	0	0.56 ppb	102	Liquid coolants, foams	8100

*A single value for the atmospheric lifetime of CO_2 is not possible. Removal mechanisms take place at different rates. The range given is an estimate based on several removal mechanisms.

as well as Fig 1.2 from
Paris Climate Agreement: Beacon of Hope also shown in Lecture 2

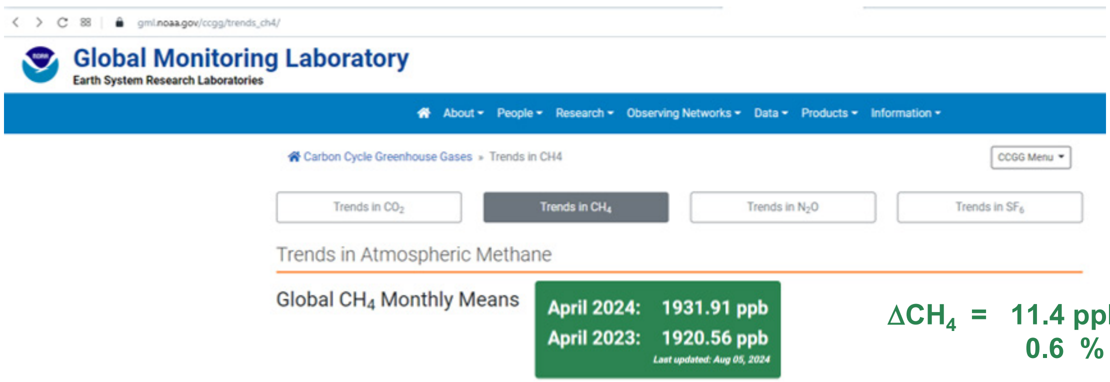


Atmospheric CH_4

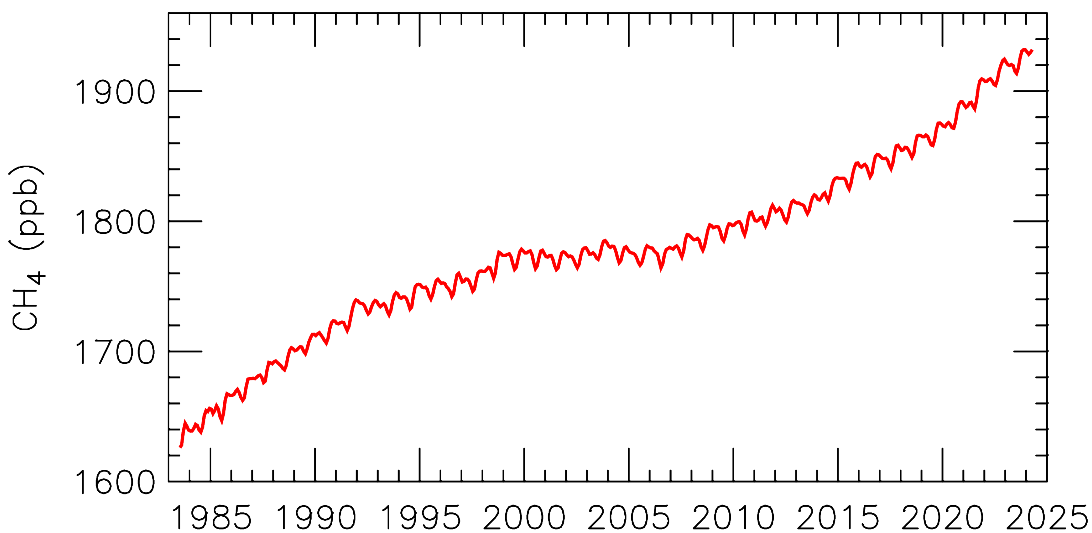
AT6, Q2:
What is the approximate current atmospheric abundance of CH_4?

NOAA Earth System Research Laboratory (Boulder, Co) is “go to” place for information regarding GHGs

Latest data indicate CH_4 is over 1900 ppb and rising and also that CH_4 was about 1760 ppb in late-1990s and about 1.84 ppm in mid-2017.



ΔCH_4 = 11.4 ppb per year
0.6 % per year



https://www.esrl.noaa.gov/gmd/ccgg/trends_ch4

Atmospheric CH_4

Scientific utility of quantifying the human and natural sources of CH_4

CH_4 Sources:
Human: 335 Tg yr^{-1}
Natural: 218 Tg yr^{-1}
Total: 553 Tg yr^{-1}

Human ≈ 60% of total

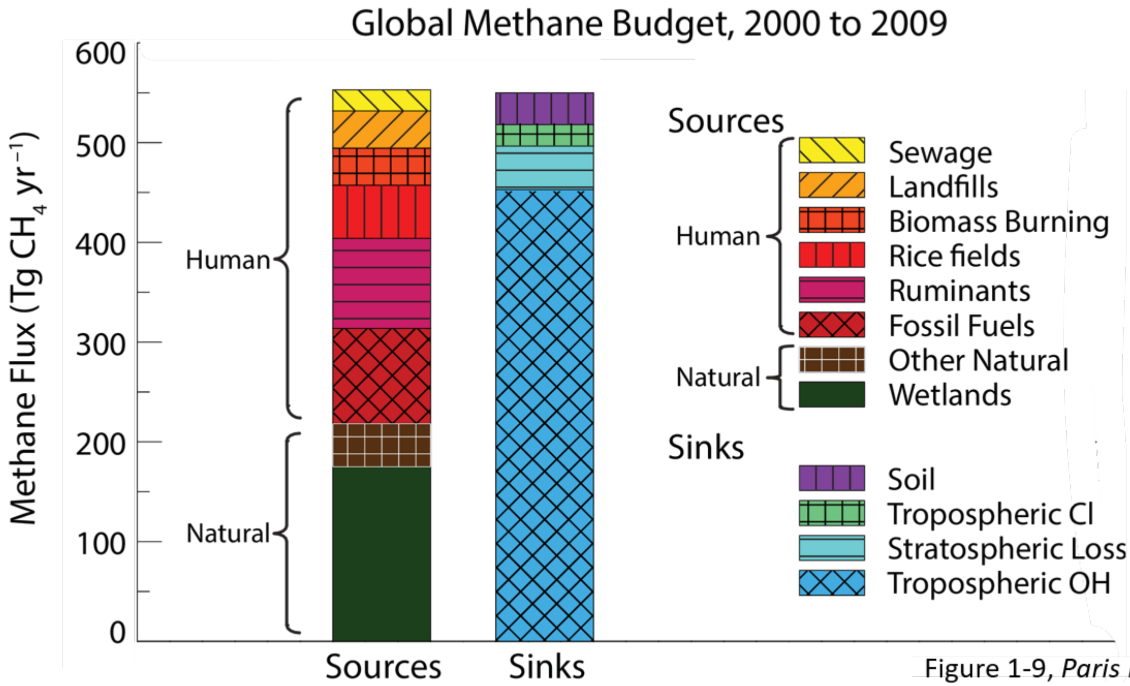


Figure 1-9, *Paris Beacon of Hope*

From prior slide:

$$[CH_4]^{Preindustrial} / [CH_4]^{Present} = Source^{Preindustrial} / Source^{Present}$$

Presumably:

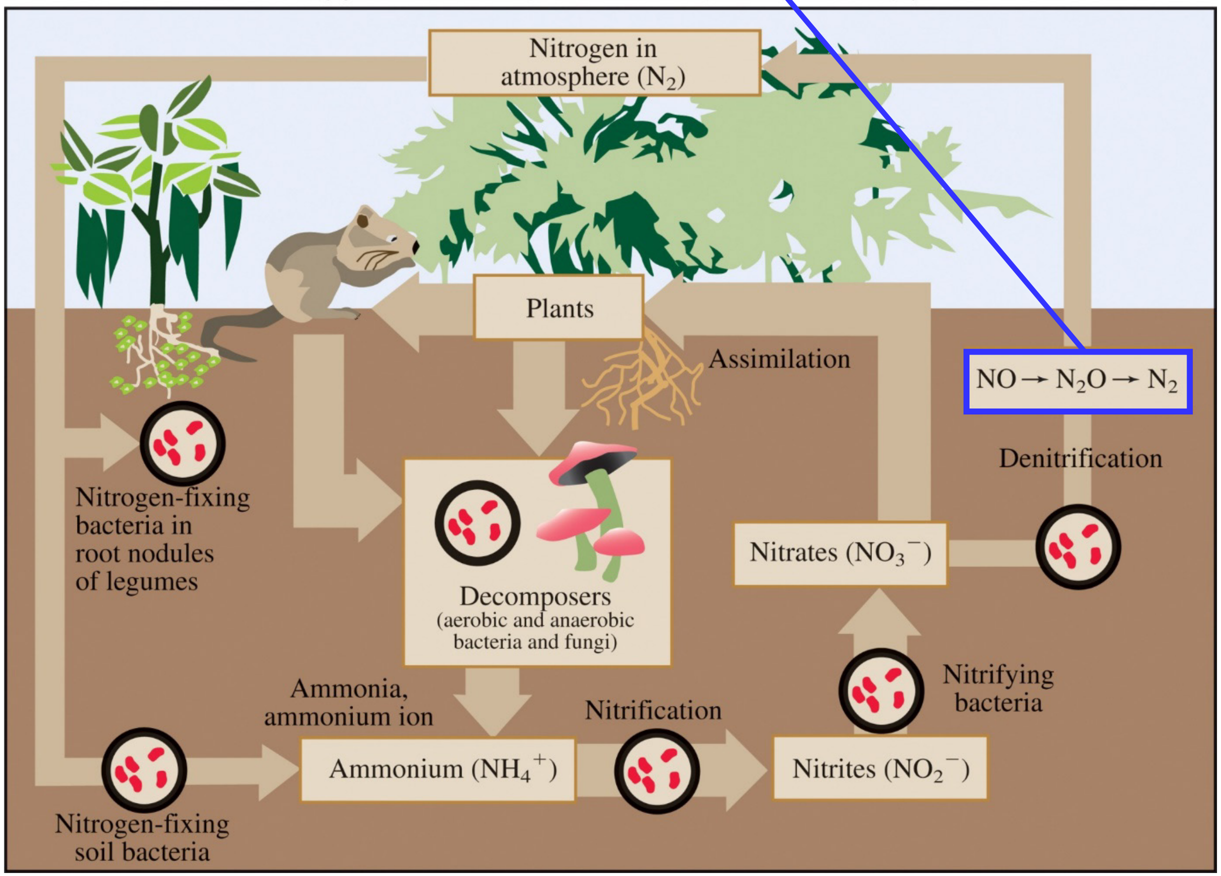
$$Source^{Preindustrial} = Source^{Present} - Source^{Human}$$ **(i.e., presumably "natural state" has not changed)**

If so, then top equation can be written as:

$$[CH_4]^{Preindustrial} / [CH_4]^{Present} = (Source^{Present} - Source^{Human}) / Source^{Present}$$
$$= 1 - Source^{Human} / Source^{Present} = 1 - (335\ Tg\ yr^{-1}) / (553\ Tg\ yr^{-1})$$
$$= 1 - 0.61 = 0.39$$

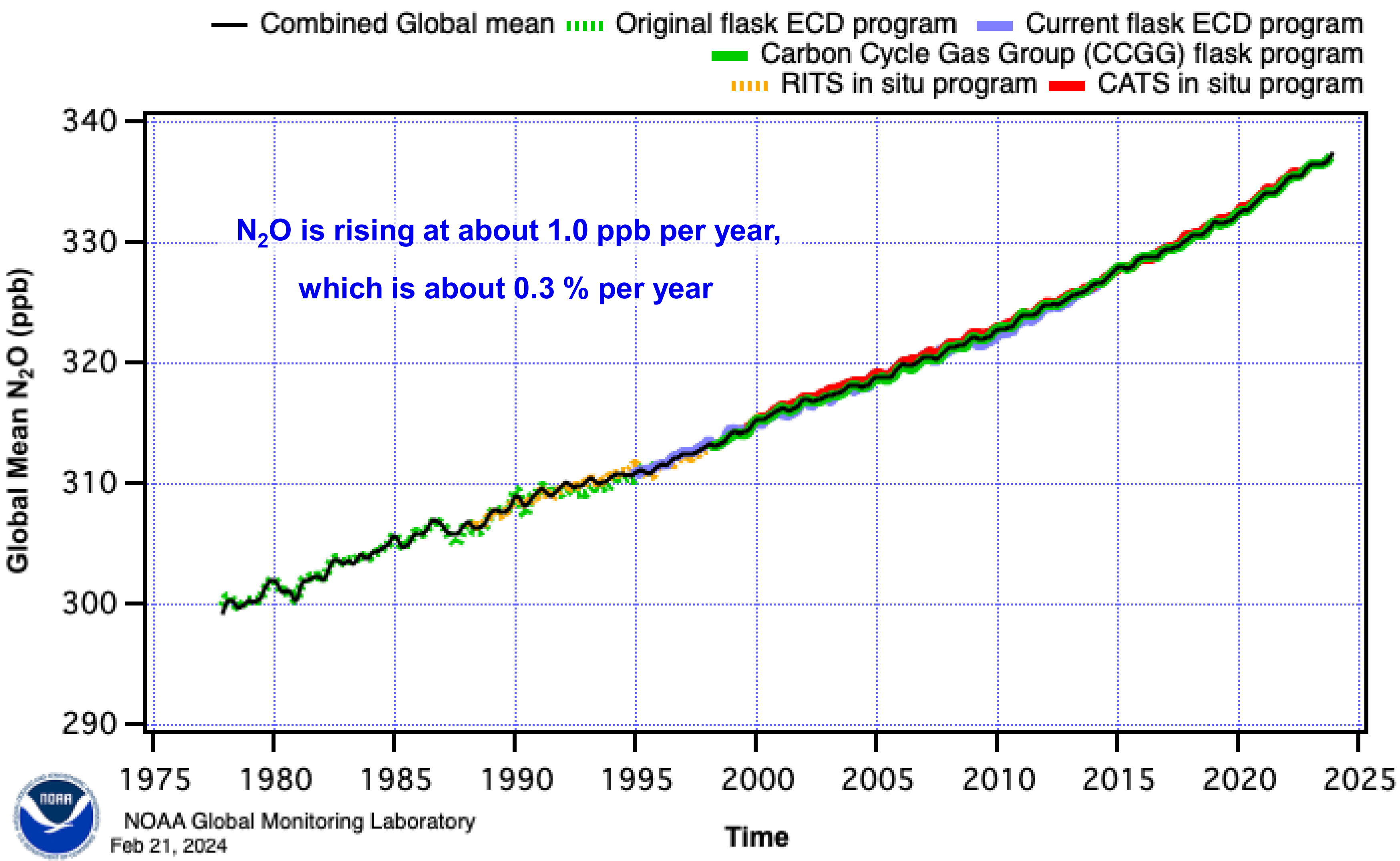
The Nitrogen Cycle

The reactive forms of nitrogen in this cycle continuously change chemical forms. Thus, the ammonia that starts out as fertilizer may end up as NO, in turn increasing the acidity of the atmosphere. Or the NO may end up as N_2O, a GHG that is currently rising.



Chapter 6, *Chemistry in Context*

N_2O Time Series



http://www.esrl.noaa.gov/gmd/hats/combined/N2O.html

Geological Evolution of Earth's Atmosphere: *Atmospheric O_2 on Geological Time Scales*

Lecture 1

- **Rise of atmospheric O_2 linked to evolution of life:**

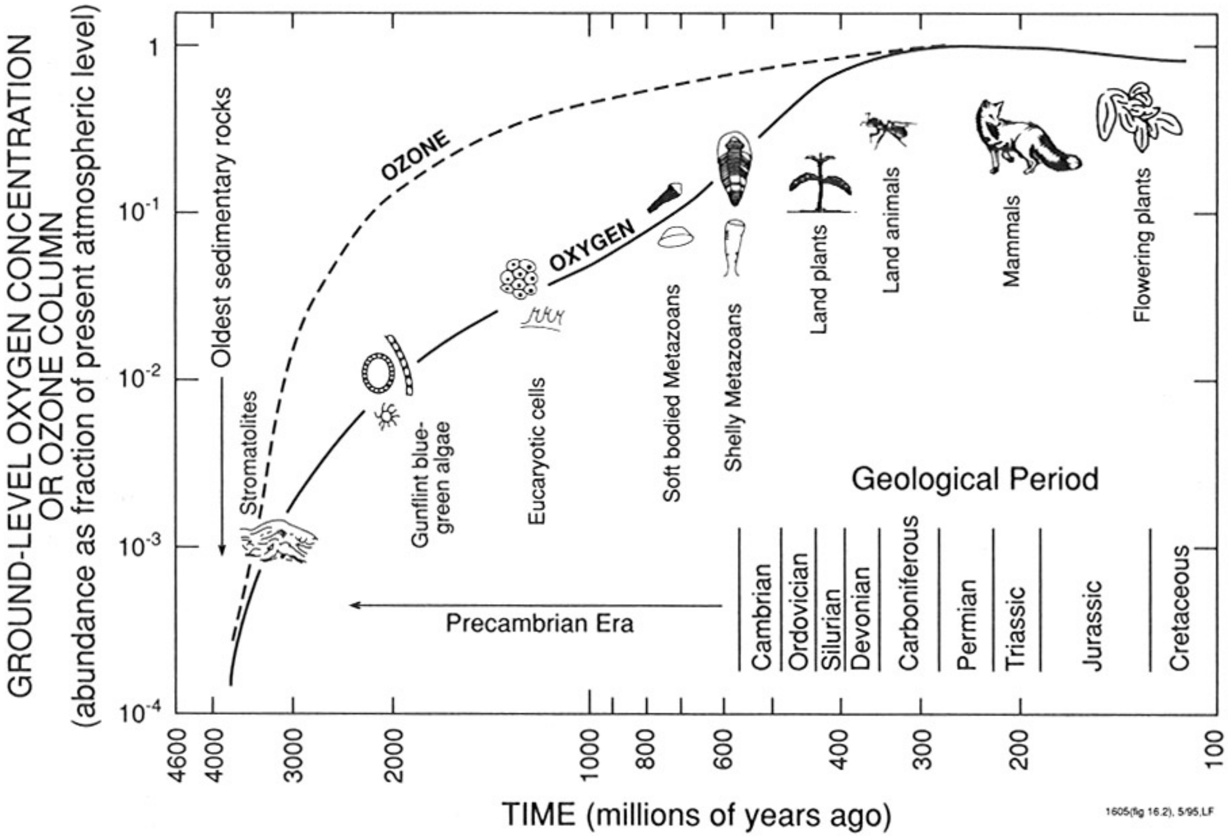


Figure 16.3. *Probable evolution of the oxygen and ozone abundance in the atmosphere (fraction of present levels) during the different geological periods of the Earth's history (Wayne, 1991; reprinted by permission of Oxford University Press).*

Geological Evolution of Earth's Atmosphere: *Atmospheric O_2 on Geological Time Scales*

Lecture 1

My : Million of Years

- **Rise of atmospheric O_2 linked to evolution of life:**
  - **400 My B.P. O_2 high enough to form an ozone layer**
  - **400 to 300 My B.P.: first air breathing lung fish & primitive amphibians**

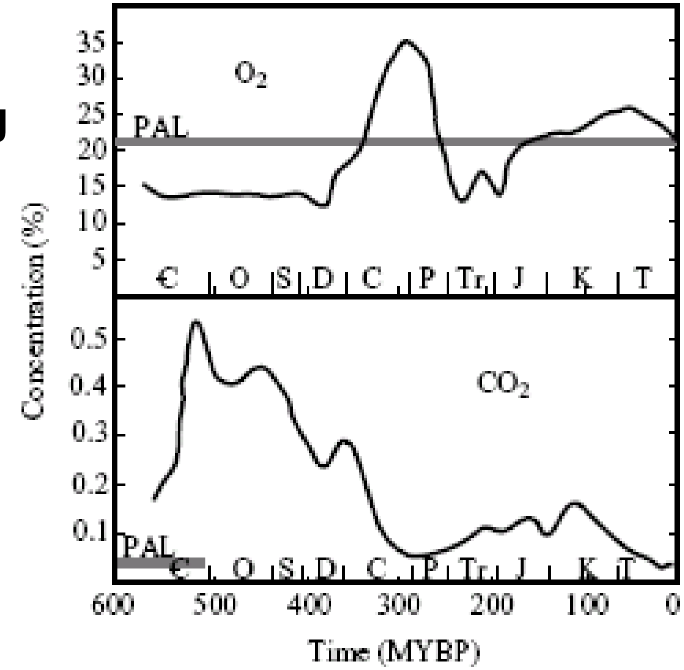
PAL: Present Atmospheric Level

- **On geological timescales, level of O_2 represents balance between burial of organic C & weathering of sedimentary material:**

  (see Chapter 12, "Evolution of the Atmosphere" in *Chemistry of the Natural Atmosphere* by P. Warneck (2nd ed) for an excellent discussion)

- **Present atmosphere is oxidizing:**

  $CH_4 \Rightarrow CO_2$ with time scale of ~9 years



From R. Dudley, Atmospheric O_2, Giant Paleozoic Insects, and the Evolution of Aerial Locomotor Performance, *J. Exper. Biol.,* 201, 1043, 1998.

Going Back 600,000 years

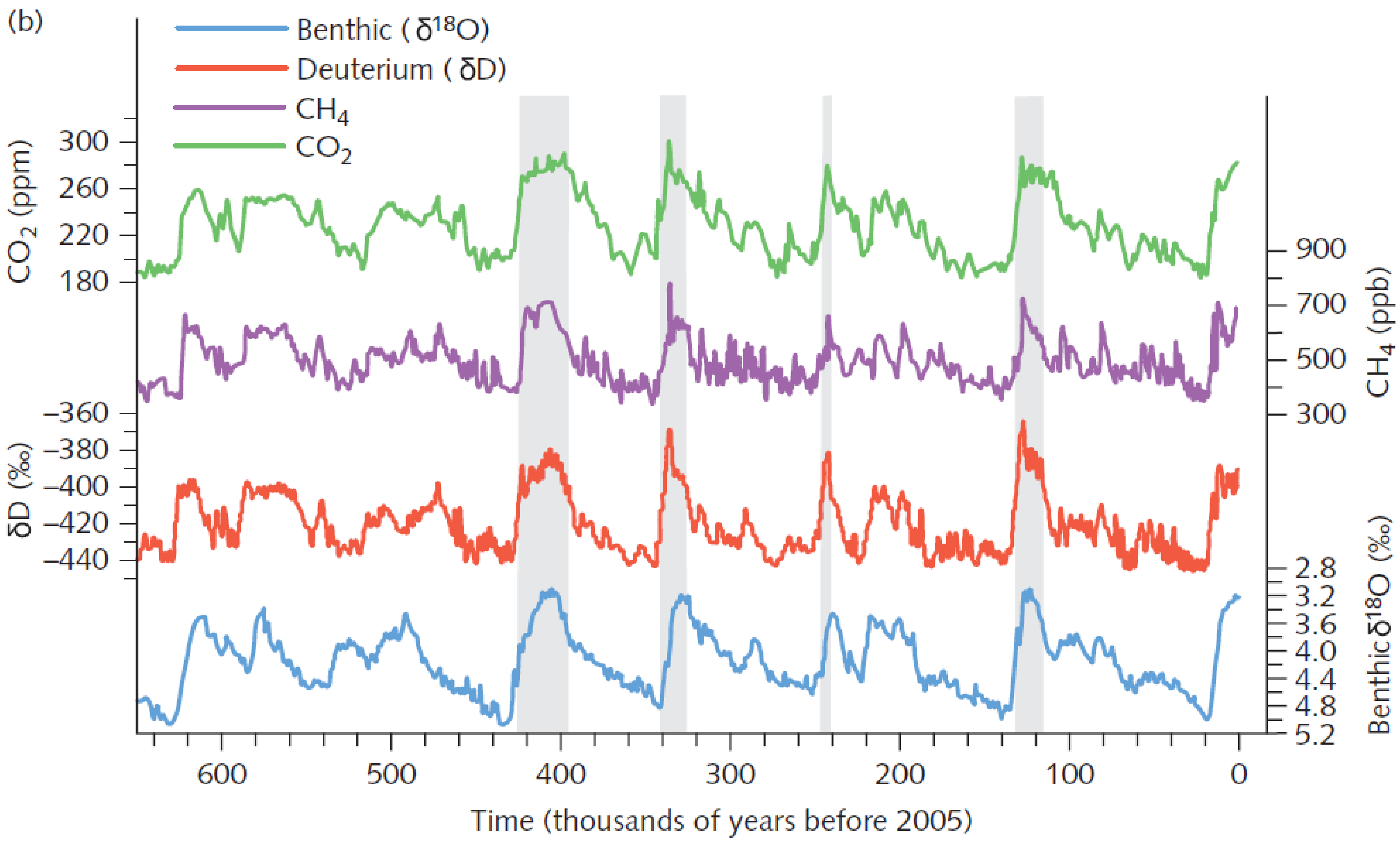


Figure 4.9 (b) Variations of deuterium (δD), a proxy for local temperature; $\delta^{18}O$, a proxy for global ice volume fluctuations; and the atmospheric concentrations of CO_2 and CH_4 derived from air trapped within ice cores from Antarctica. Shading indicates interglacial periods.

Houghton, 2015

See https://epic.awi.de/id/eprint/18400/1/Oer2008a.pdf for description of EPICA , European Project for Ice Coring in Antarctica

Fourier analysis reveals Earth's climate is changing in a periodic fashion

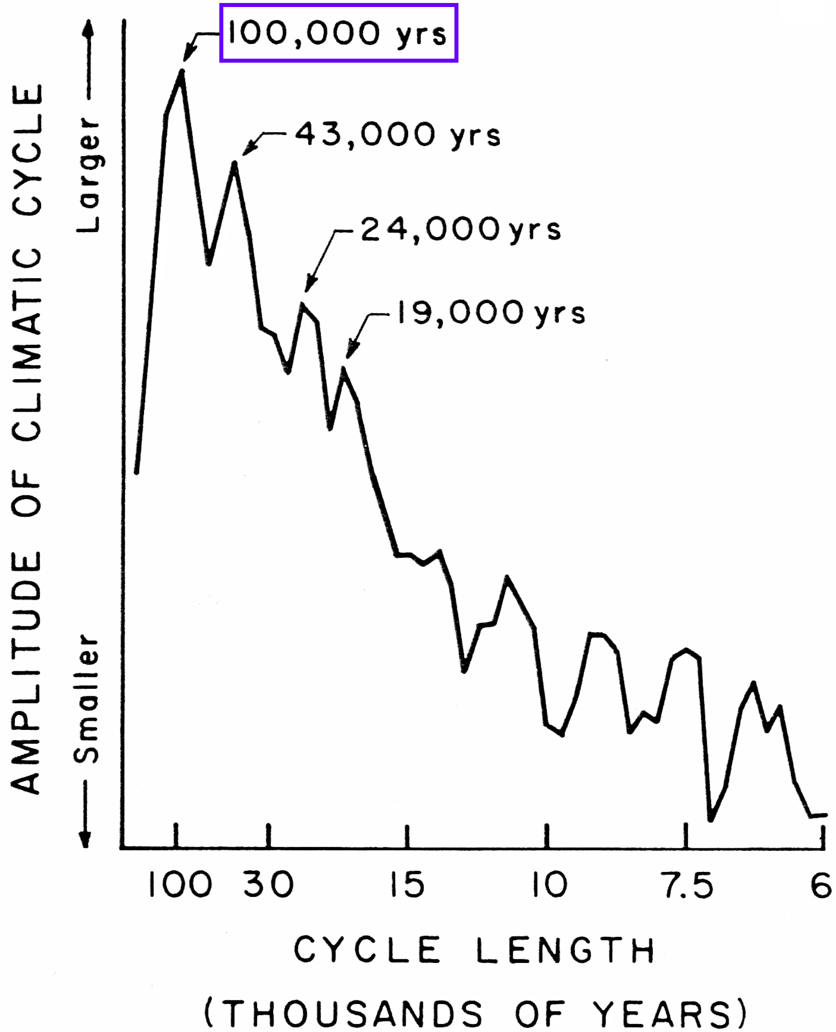
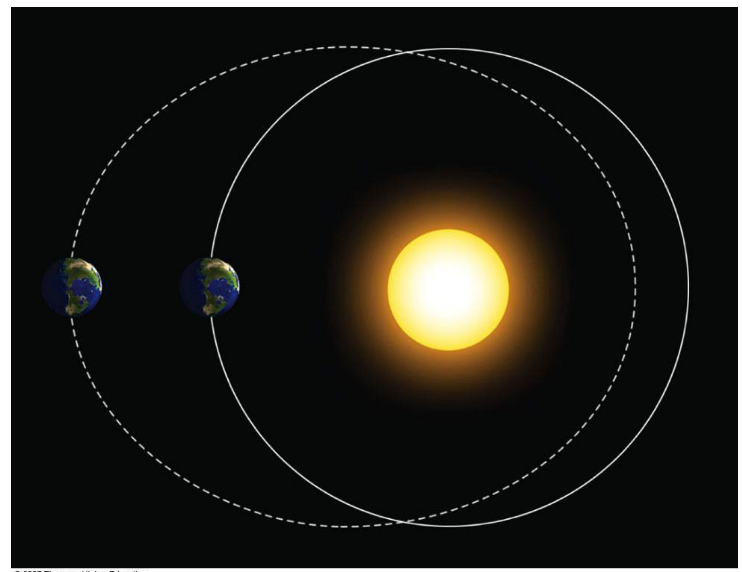


Figure 42. Spectrum of climatic variation over the past half-million years. This graph—showing the relative importance of different climatic cycles in the isotopic record of two Indian Ocean cores—confirmed many predictions of the Milankovitch theory. (Data from J.D. Hays et al., 1976.)

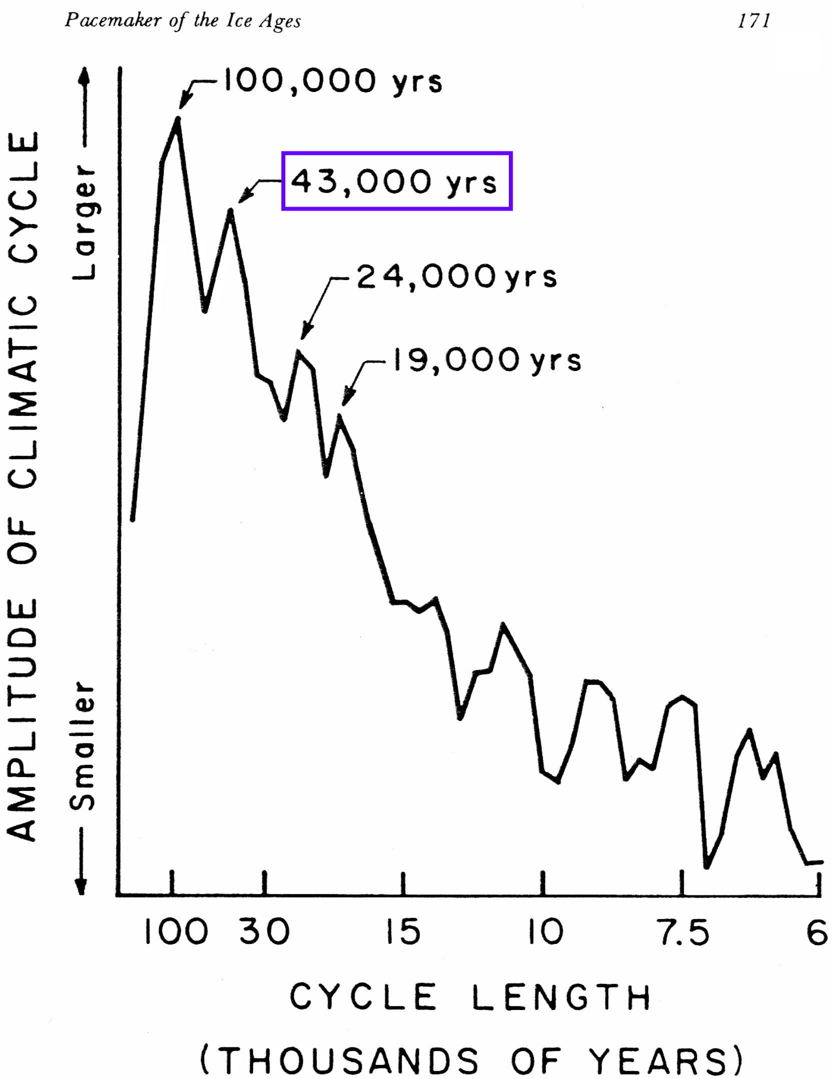
Ice Ages, Imbrie and Imbrie, Harvard Univ Pres, 1979

100,000 year cycle due to changes in the eccentricity of Earth's orbit, mainly due to gravitational pull of Jupiter and Saturn.



Lecture 4

Fourier analysis reveals Earth's climate is changing in a periodic fashion



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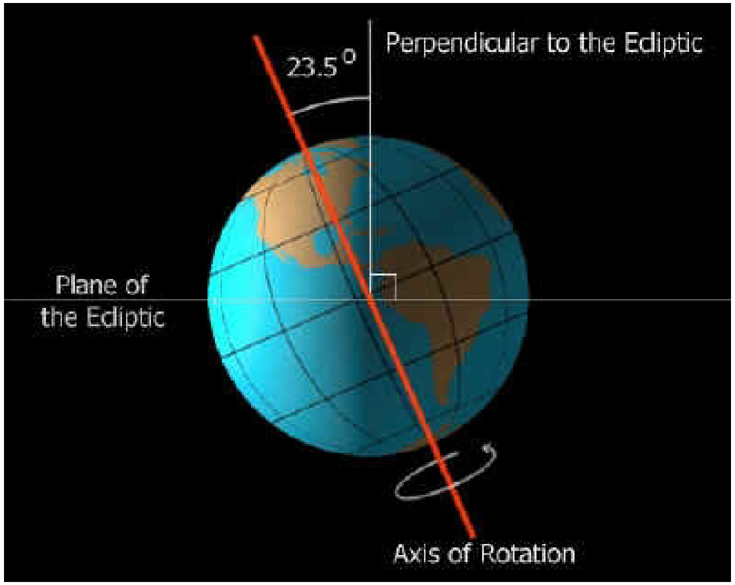
Ice Ages, Imbrie and Imbrie, Harvard Univ Pres, 1979

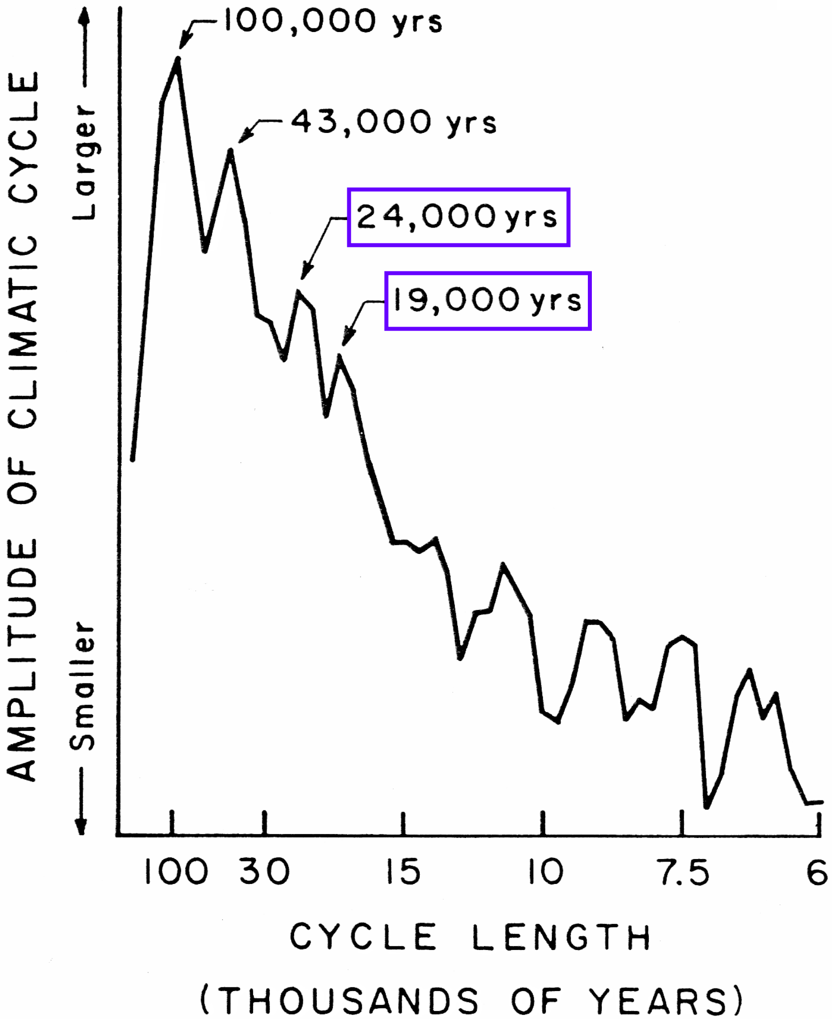
43,000 year cycle due to changes in tilt of Earth's axis (obliquity).



Lecture 4

Fourier analysis reveals Earth's climate is changing in a periodic fashion

Pacemaker of the Ice Ages 171



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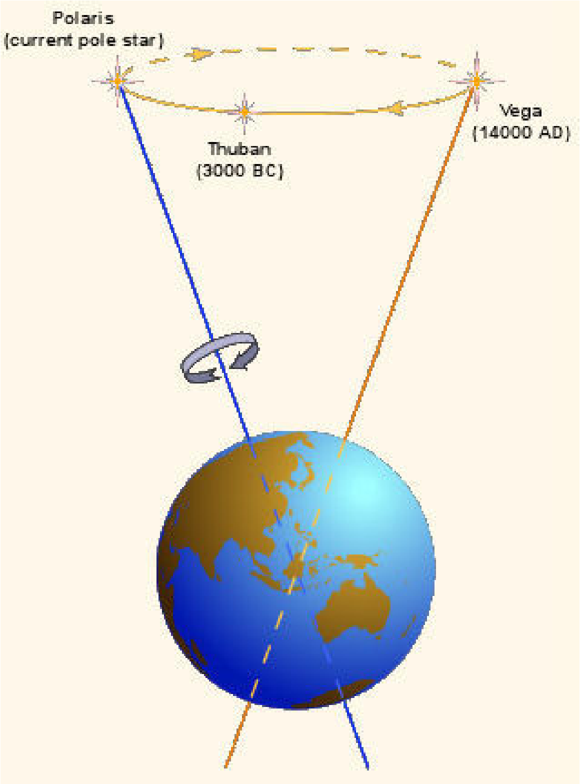
Ice Ages, Imbrie and Imbrie, Harvard Univ Pres, 1979

24,000 and **19,000 year cycles** due to Earth "wobbling" on its axis.



Lecture 4

Glacial Periods MUCH Dustier than Interglacials

Lecture 4

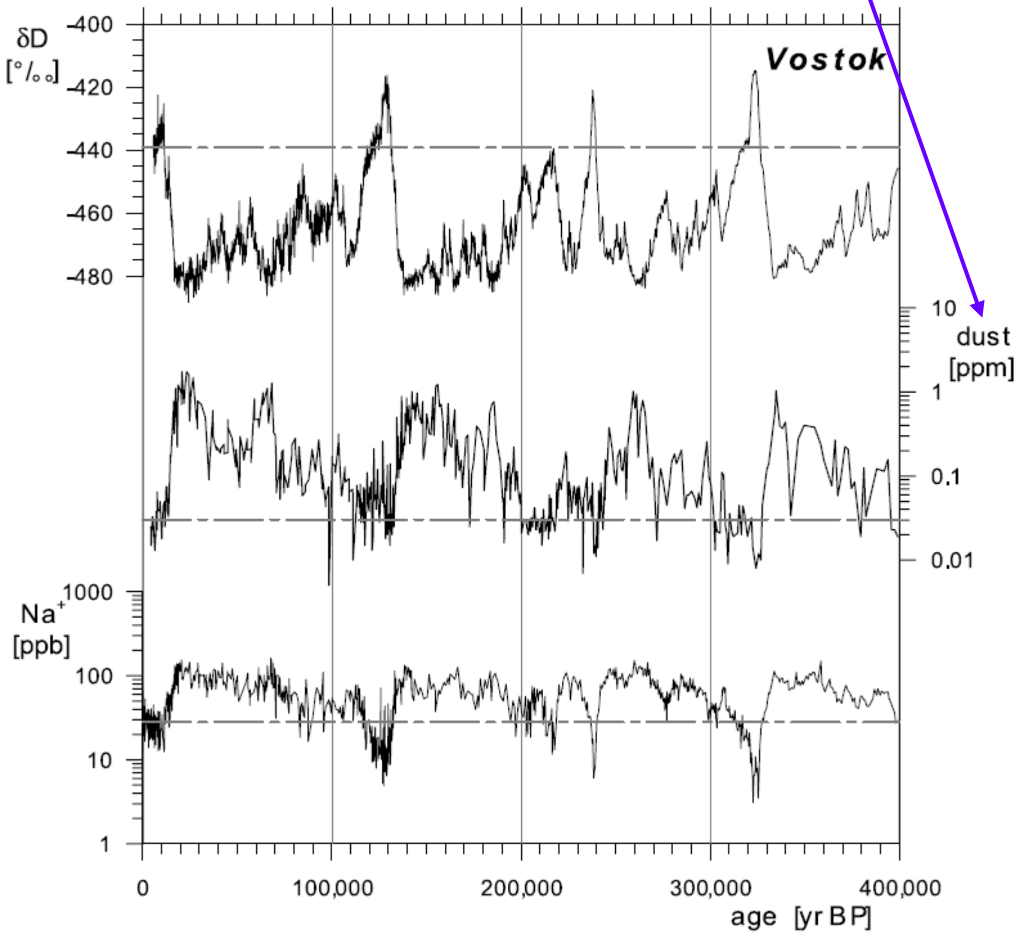
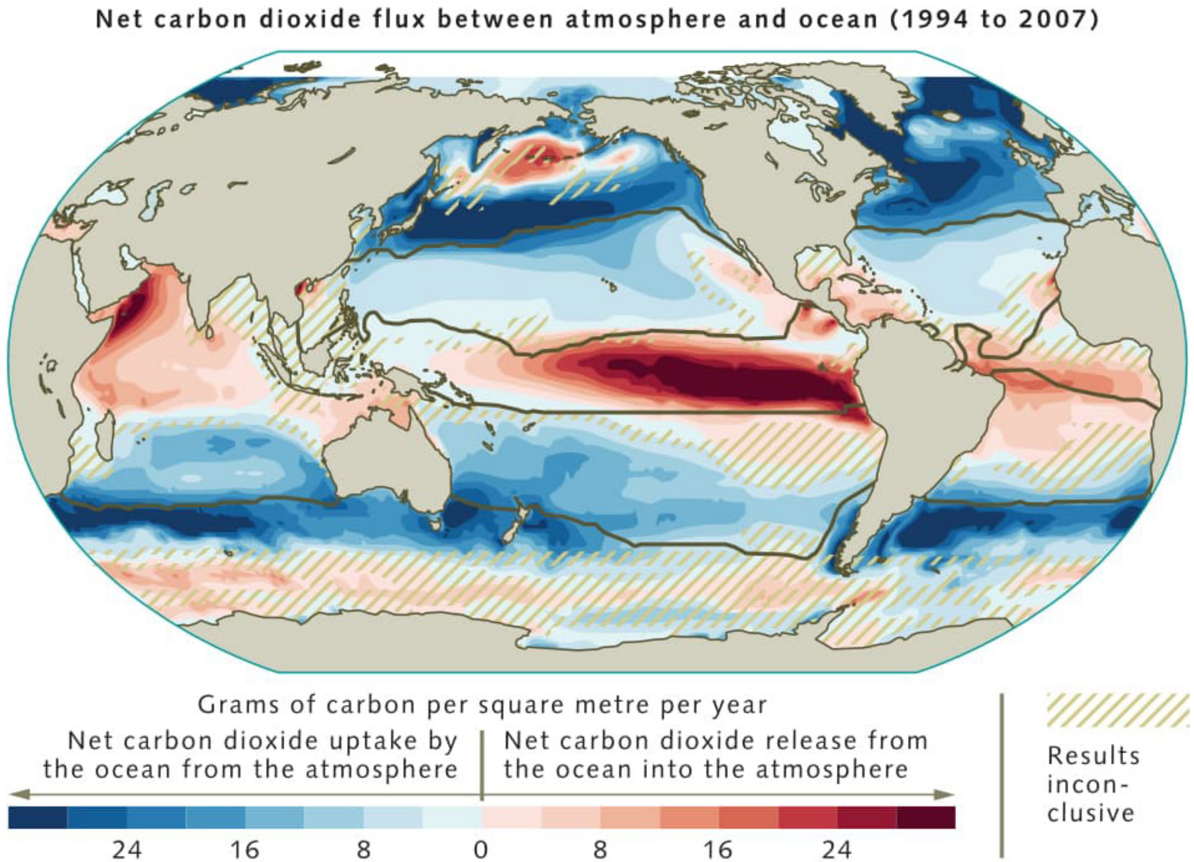


Figure 3. Temporal evolution of δD representing changes in the average local condensation temperature during snow formation, the particulate dust, and the sea-salt component Na^+ over the last four glacial cycles as recorded in the East Antarctic Vostok ice core [*Petit et al.*, 1999]. Dashed-dotted lines indicate the mean Holocene level from 0 to 10,000 years B.P.

Fischer *et al.*, Reviews of Geophysics, 2007

To Understand The Drawdown of Atmospheric CO_2 During Glacial Times, let's first have a look at Today's Flux Of CO_2 From Atmosphere to Ocean

Lecture 4



The ocean does not absorb the same amounts of CO_2 from the atmosphere everywhere. As this map illustrates, CO_2 uptake occurs primarily in the cold Southern Ocean and in the North Atlantic and North Pacific Oceans (blue shading). In the warm tropical regions, on the other hand, the ocean releases considerably more CO_2 into the atmosphere than it absorbs (red shading).

https://worldoceanreview.com/en/wor-8/the-role-of-the-ocean-in-the-global-carbon-cyclee/how-the-ocean-absorbs-carbon-dioxide

Drawdown of Atmospheric CO_2 During Glacial Times

Lecture 4

4.1. Initial decrease in atmospheric CO_2 during glacial inception (115–100 ka) **35 ppm drawdown**

We argue based on existing proxy data that the initial drawdown of atmospheric CO_2 was driven primarily by barrier mechanisms, mostly through expanded sea ice cover. We rule out deep ocean ventilation as a mechanism for early CO_2 drawdown because proxies show no evidence for widespread changes in deep ocean circulation until the MIS 5/4 transition ~30 ka after the initial CO_2 drop.

4.2. Second decrease in atmospheric CO_2, 80–65 ka **40 ppm drawdown**

Between MIS 5a and 4, atmospheric CO_2 dropped a second time by 40 ppmv, just as polar temperatures cooled to near-Ice Age levels, North Atlantic SSTs plunged to 8 °C below interglacial levels, and benthic $\delta^{13}C$ and εNd proxies show their largest deep ocean changes (Fig. 5, Fig. 6d).

We argue that this second decrease in atmospheric CO_2 was driven largely by a more sluggish overturning circulation, which trapped respired CO_2 in the deep ocean and increased whole ocean alkalinity via the carbonate compensation mechanism (Watson and Naveiro Garabato, 2006, Lund et al., 2011, Adkins, 2013). As described above,

4.3. Final decrease in atmospheric CO_2, 40–18 ka **5 to 20 ppm drawdown**

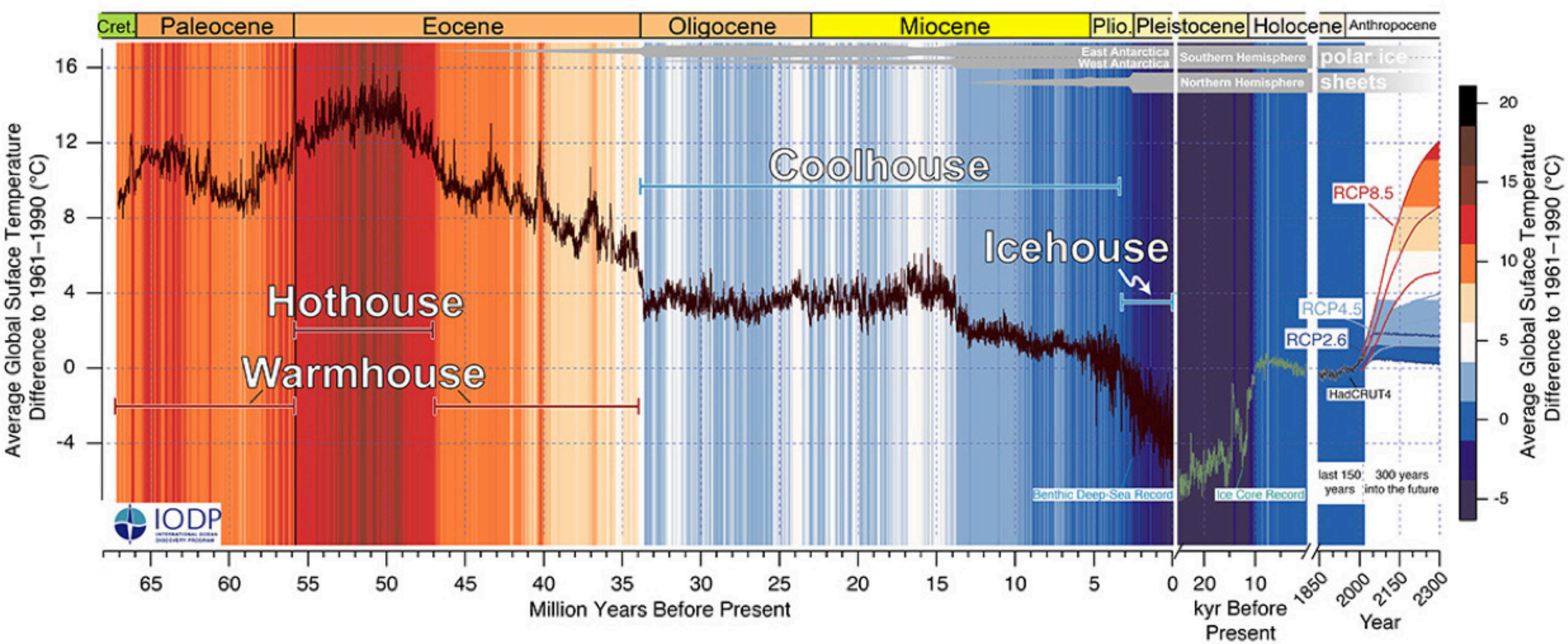
The final 5–10 ppmv decrease in atmospheric CO_2 occurred between 40 to 18 ka. The first, strong candidate for enhanced CO_2 uptake by the ocean during this time is an increase in the strength of the biological pump, as dust deposition increased to the highest levels observed during the glacial cycle (Fig. 5). Therefore, the maximum 15–20 ppmv effect of this CO_2 uptake mechanism is likely to have occurred during this time. A second, complementary possibility is that enhanced deep-ocean stratification allowed for additional trapping of carbon in the deepest layers of the ocean. Continued reductions

Kohfeld and Chase, *Earth and Planetary Science Letters*, 2017
https://www.sciencedirect.com/science/article/pii/S0012821X17302753

See also Marino, McElroy, Salawitch, and Spaulding, *Nature*, 1992
https://www.nature.com/articles/357461a0
for early work on this topic.

Earth's Climate History

Lecture 4



Past and future trends in global mean temperature spanning the last 67 million years. Oxygen isotope values in deep-sea benthic foraminifera from sediment cores are a measure of global temperature and ice volume. Temperature is relative to the 1961–1990 global mean. Data from ice core records of the last 25,000 years illustrate the transition from the last glacial to the current warmer period, the Holocene. Historic data from 1850 to today show the distinct increase after 1950 marking the onset of the Anthropocene. Future projections for global temperature for three Representative Concentration Pathways (RCP) scenarios in relation to the benthic deep-sea record suggest that by 2100 the climate state will be comparable to the Miocene Climate Optimum (~16 million years ago), well beyond the threshold for nucleating continental ice sheets. If emissions are constant after 2100 and are not stabilized before 2250, global climate by 2300 might enter the hothouse world of the early Eocene (~50 million years ago) with its multiple global warming events and no large ice sheets at the poles. (Credit: Westerhold et al., CENOGRID)

https://news.ucsc.edu/2020/09/climate-variability.html
https://news.ucsc.edu/2020/09/images/climate-states-lg-cap.jpg

Simple Climate Model

$$\Delta T = \lambda_{BB}\ (1 + f_{H2O})\,(\Delta F_{CO2} + \Delta F_{CH4+N2O} + \Delta F_{OTHER\ GHGs} + \Delta F_{AEROSOLS}) - OHE$$

where

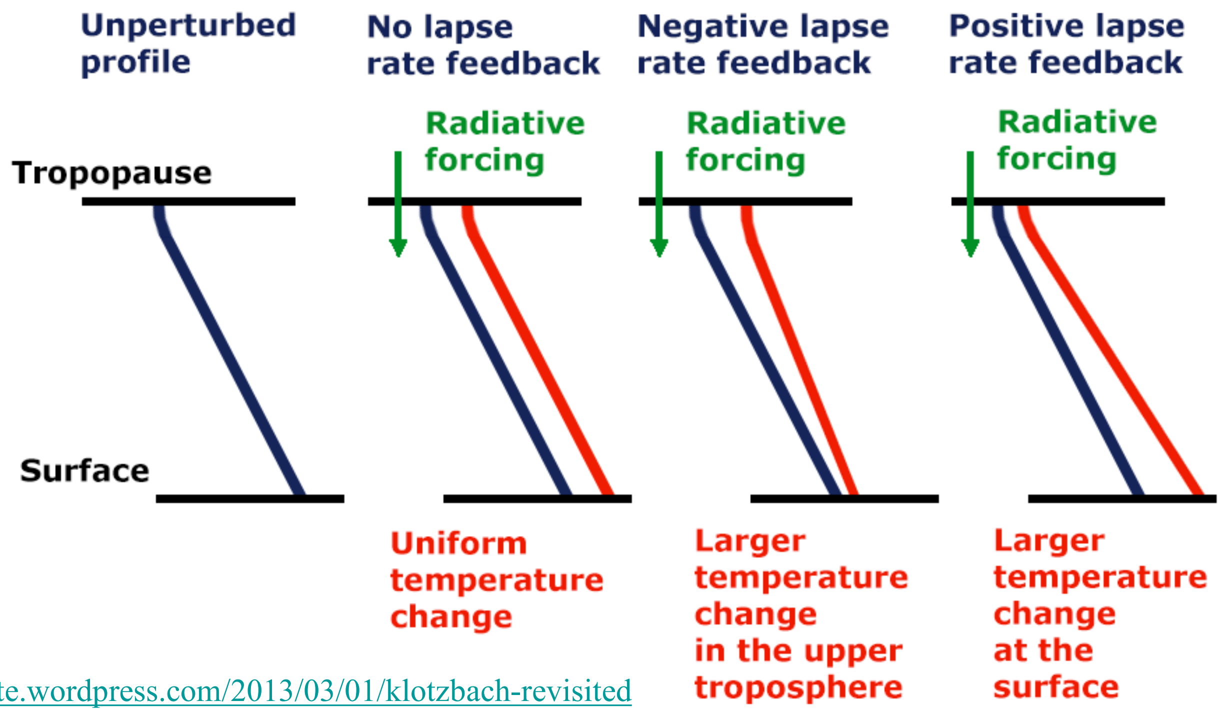
$$\lambda_{BB} = 0.3\ K\ /\ W\ m^{-2}$$

OHE = Ocean Heat Export

Climate models that consider water vapor feedback find:

$\lambda \approx 0.63\ K\ /\ W\ m^{-2}$, from which we deduce ***f_{H2O} = 1.08***

Lapse Rate Feedback

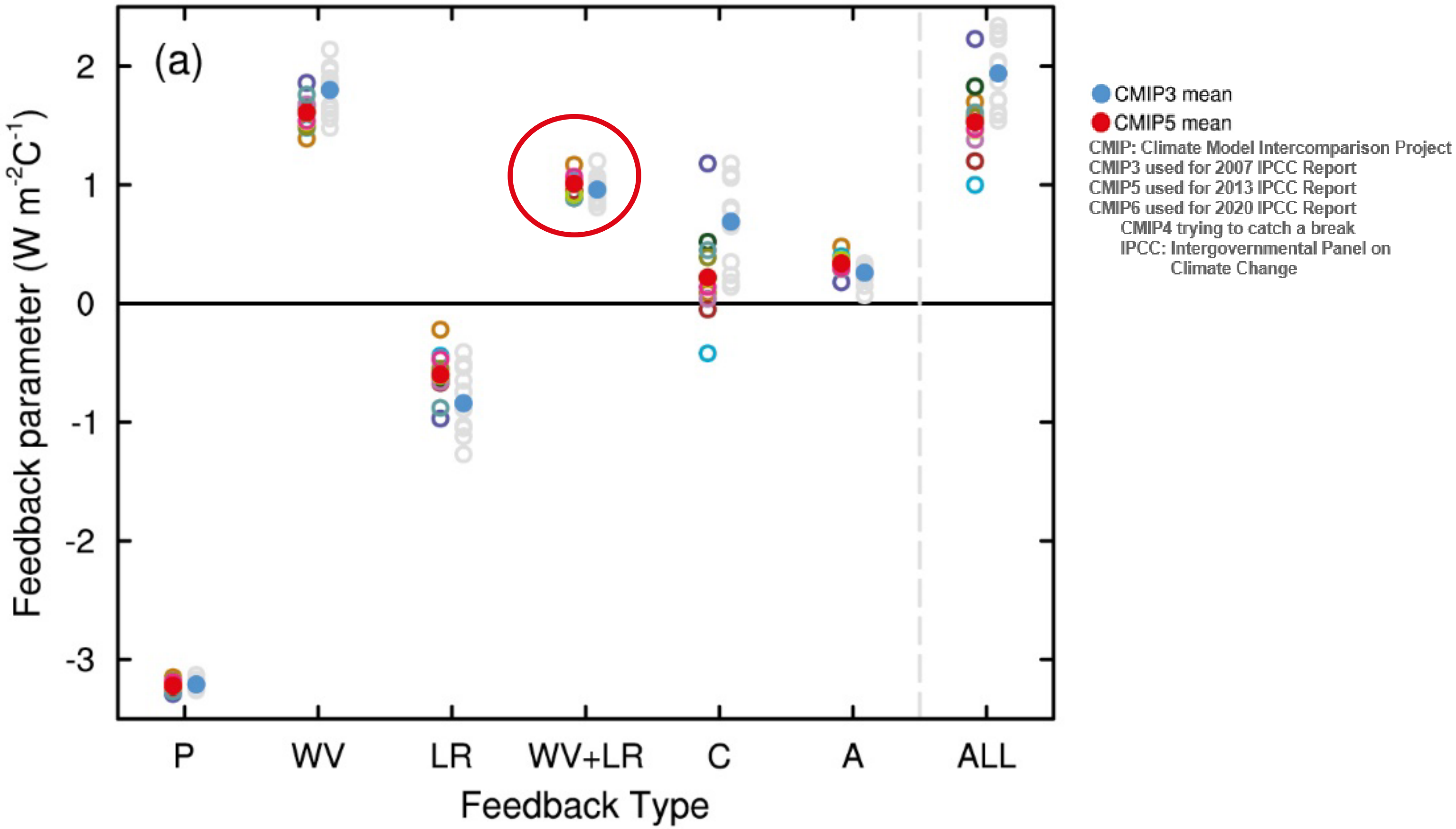


https://ourchangingclimate.wordpress.com/2013/03/01/klotzbach-revisited

- Photons emitted in UT can escape to space more easily than photons emitted near surface
- If UT warms more than surface, bulk atmospheric emissivity increases

UT :upper troposphere   Emissivity: efficiency in which thermal energy is radiated

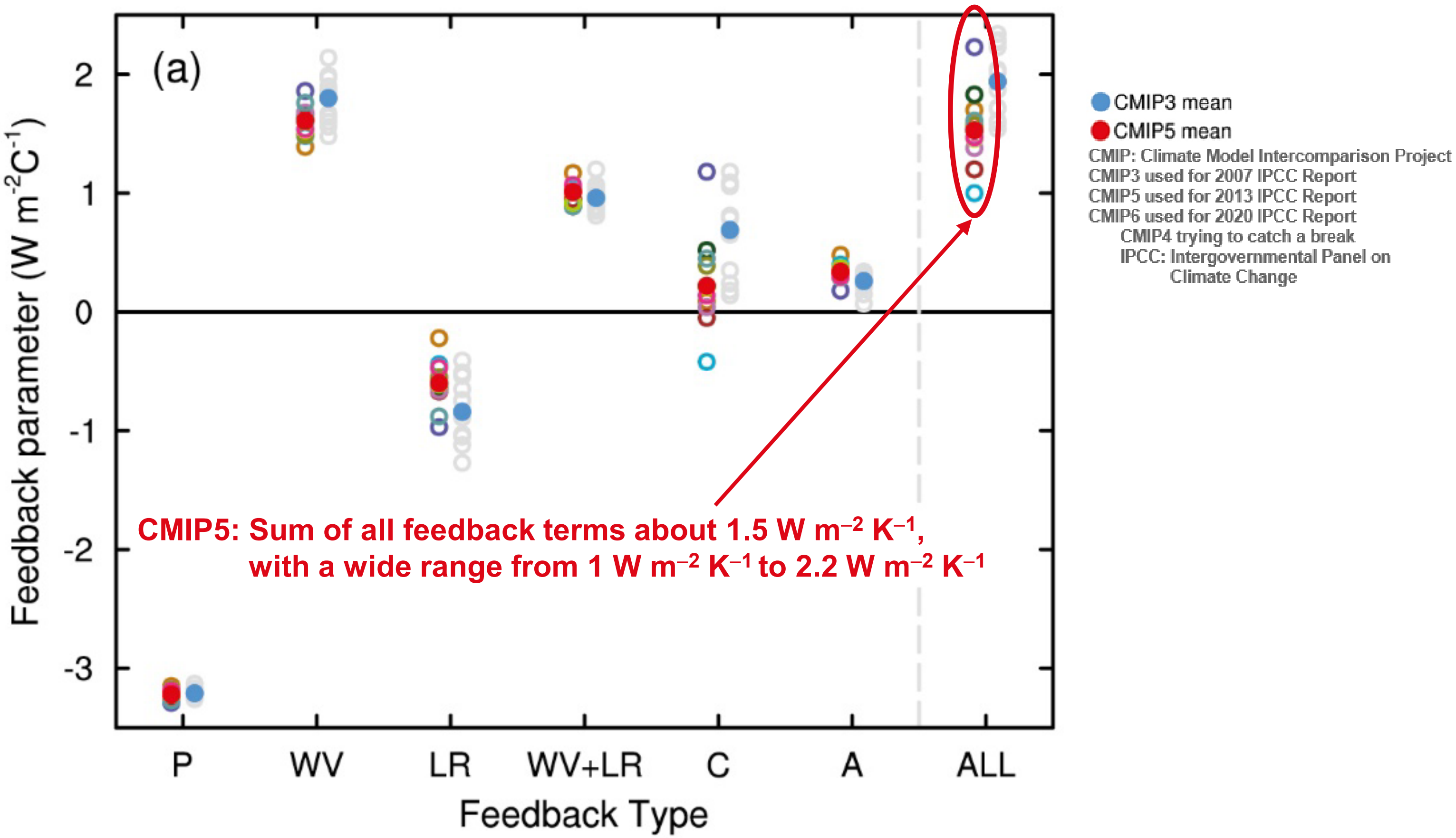
- GCMs indicate water vapor & lapse rate feedbacks are intricately linked, with the former almost certainly being positive (in response to rising GHGs), the latter almost certainly being negative, and the sum probably being positive



If $FB_{WV+LR} = 1.0 \text{ W m}^{-2} \text{ K}^{-1}$ and we assume other feedbacks are zero, then:

$$1 + f_{\text{TOTAL}} = \frac{1}{1 - 1.0 \text{ W m}^{-2} \text{ K}^{-1} \times 0.31 \text{ K W m}^{-2}} = 1.45$$

Therefore, $f_{\text{TOTAL}} = 0.45$; i.e., climate models suggest $f_{\text{WV+LR}} = 0.45$



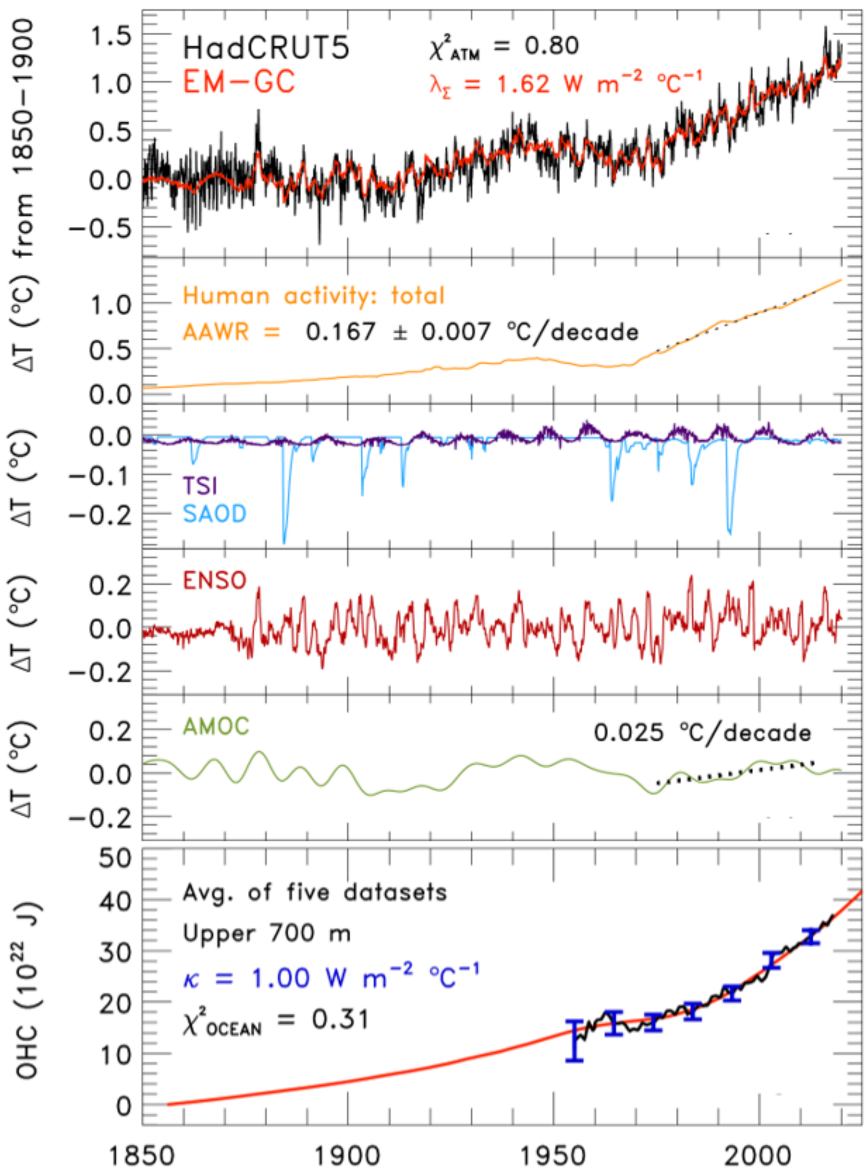
If $FB_{ALL} = 1.5\ \mathrm{W\ m^{-2}\ K^{-1}}$ and we assume other feedbacks are zero, then:

$$1 + f_{TOTAL} = \frac{1}{1 - 1.5\ \mathrm{W\ m^{-2}\ K^{-1}} \times 0.31\ \mathrm{K\ W\ m^{-2}}} = 1.87$$

Therefore, $f_{TOTAL} = 0.87$; i.e., CMIP5 climate models suggest sum of all feedbacks amplify by 0.87

If $FB_{ALL} = 2.25\ \mathrm{W\ m^{-2}\ K^{-1}}$ (upper limit) amplification rises to 2.3

If $FB_{ALL} = 1.0\ \mathrm{W\ m^{-2}\ K^{-1}}$ (upper limit) amplification drops to 0.45



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

Model computes influence on global mean surface temperature (GMST) of:

a) RF due to GHGs & Tropospheric Aerosols

b) Total Solar Irradiance (TSI) & Stratospheric Aerosol Optical Depth (SAOD)

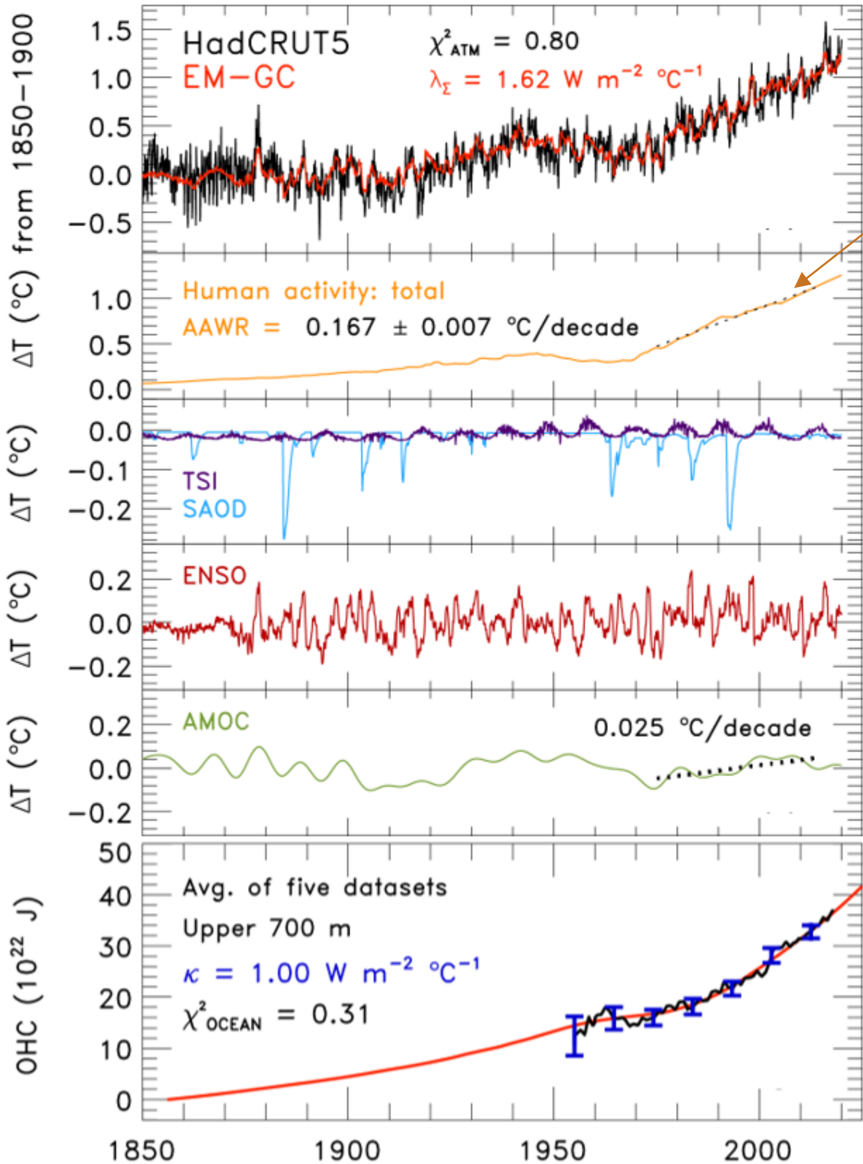
c) El Niño – Southern Oscillation (ENSO)

d) Atlantic Meridional Overturning Circulation (AMOC)

e) Transfer of heat from atmosphere to ocean

Similar to *Lecture 2, Slide 19* (Handout)

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



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

$$\Delta T^{HUMAN} = \lambda_P\,(1 + f_{TOTAL})\,(\Delta F_{CO2} + \Delta F_{CH4+N2O} + \Delta F_{OTHER\ GHGs} + \Delta F_{AEROSOLS}) - \text{OHE}$$

Here, $f_{TOTAL} \approx 1.0$

where f_{TOTAL} is dimensionless climate sensitivty parameter that represents feedbacks, and is related to IPCC definition of feedbacks (Bony et al., *J. Climate*, 2006) via:

$$1 + f_{TOTAL} = \frac{1}{1 - FB_{TOTAL}\ \lambda_P}$$

and $FB_{TOTAL} = FB_{WATER\ VAPOR} + FB_{LAPSE\ RATE} + FB_{CLOUDS} + FB_{SURFACE\ ALBEDO} + \text{etc}$

Each FB term has units of W m^{-2} K^{-1}, the recipricol of the units of λ_P

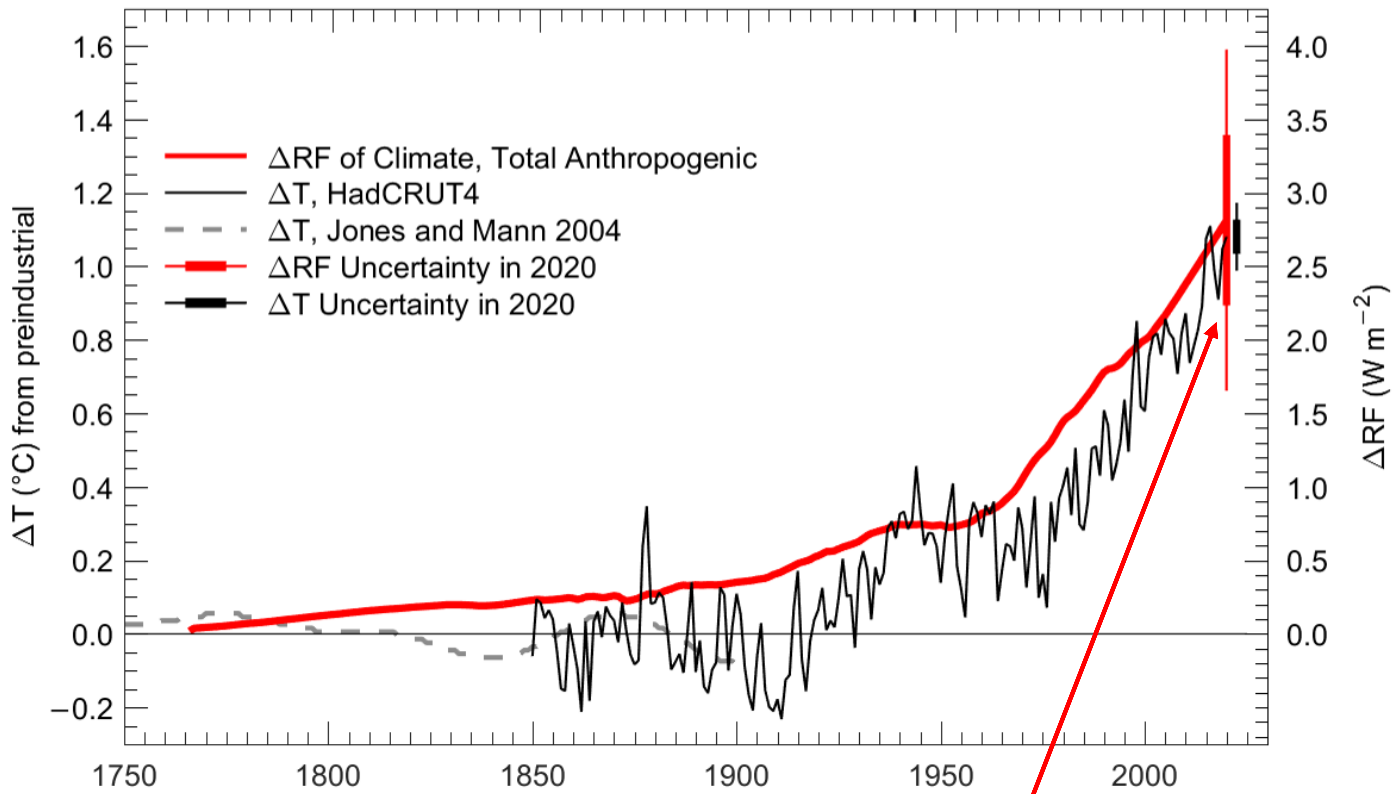
The utility of this approach is that feedbacks can be summed to get FB_{TOTAL}

$$1 + f_{TOTAL} = \frac{1}{1 - 1.62\ \text{W m}^{-2}/\text{K} \times 0.31\ \text{K} / \text{Wm}^{-2}} = \frac{1}{1-0.506} = 2.02 \approx 2$$

Similar to *Lecture 2, Slide 19* (Handout)

McBride *et al.*, 2021: 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).

Combining RF GHGs & Aerosols

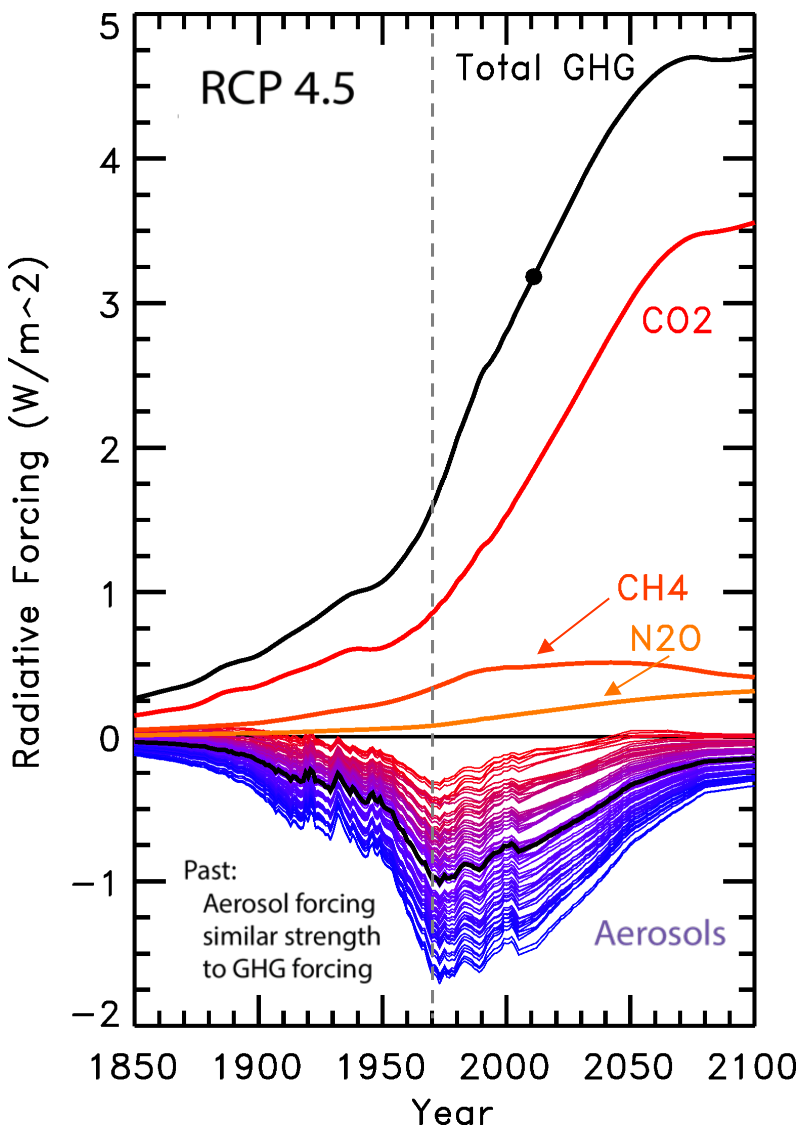
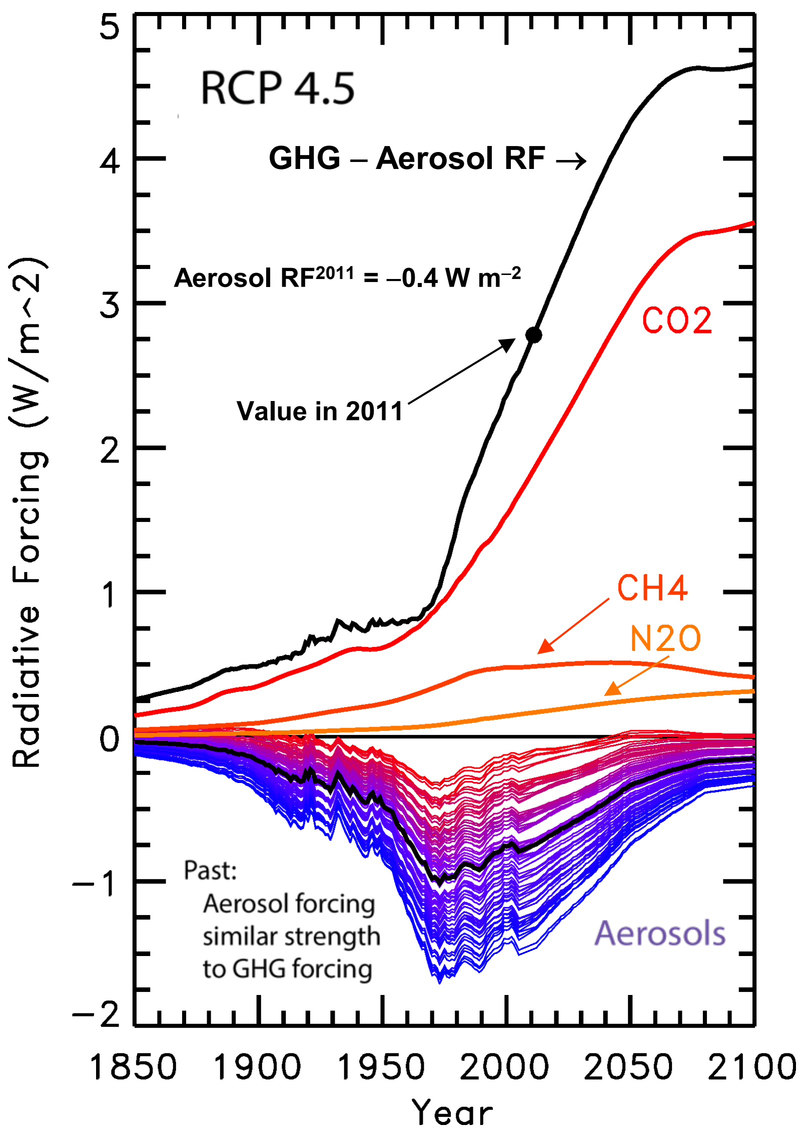


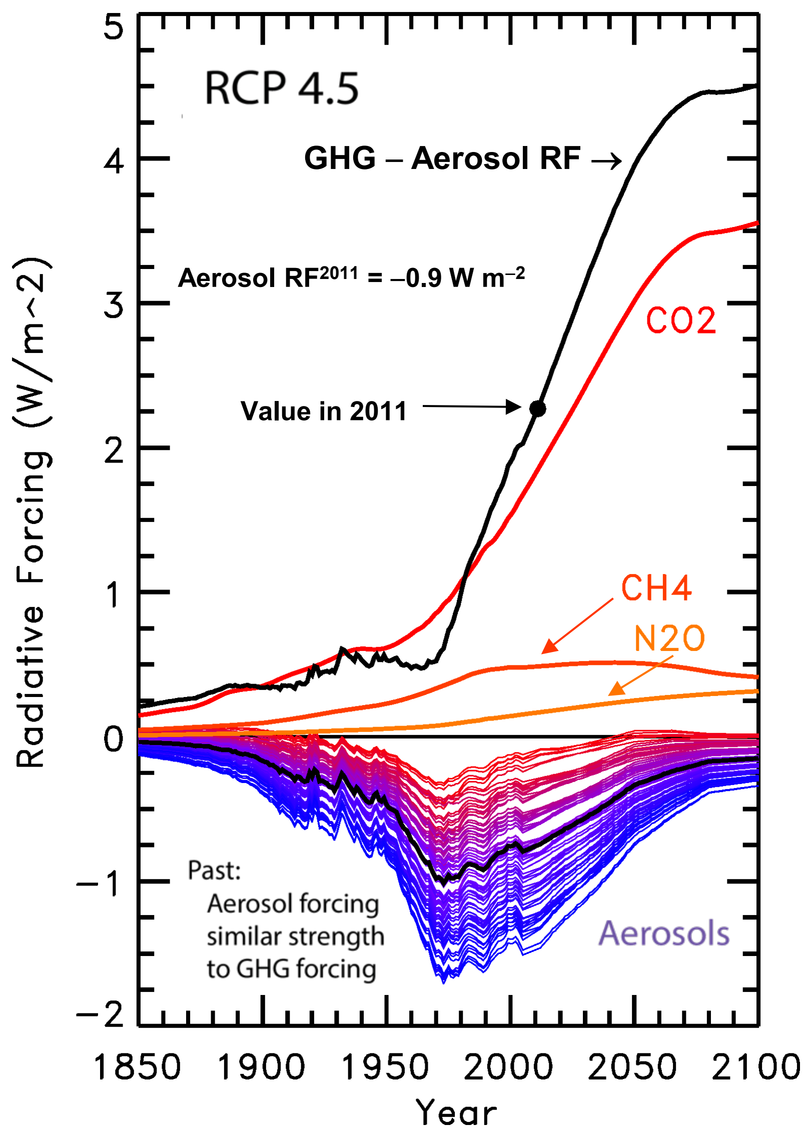
Fig 1.10, *Paris, Beacon of Hope*

Combining RF GHGs & Aerosols



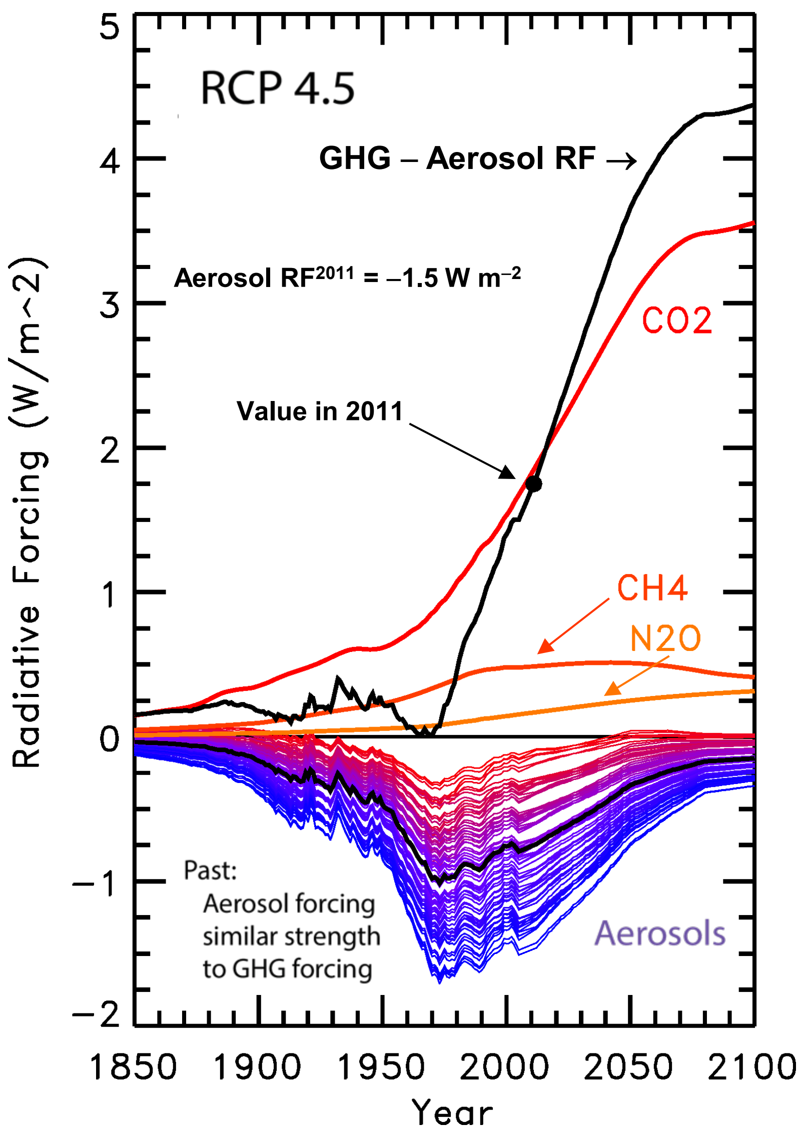
Based upon Fig 1.10, *Paris, Beacon of Hope*

Combining RF GHGs & Aerosols



Based upon Fig 1.10, *Paris, Beacon of Hope*

Combining RF GHGs & Aerosols



Based upon Fig 1.10, *Paris, Beacon of Hope*

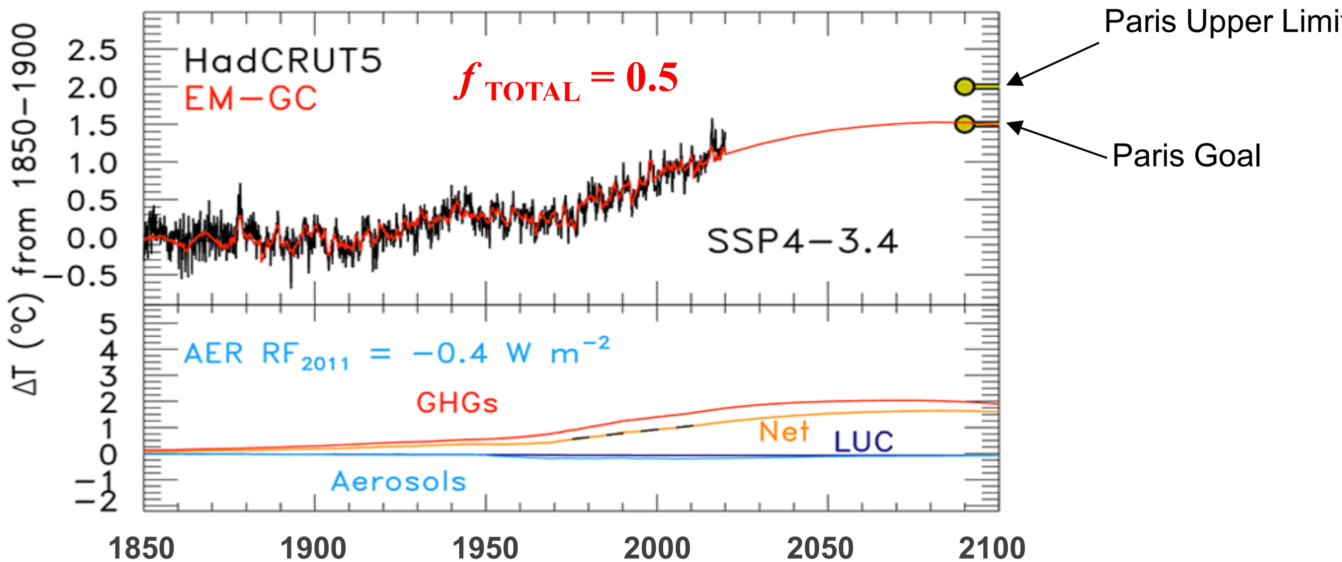
Uncertainty in RF of climate due to tropospheric aerosols is huge complication leading to fundamental uncertainty on forecasts of future global warming

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

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

We assume that whatever value of climate feedback is inferred from the climate record will persist into the future. For Aerosol RF in 2011 of **-0.4 W m^{-2}** & assuming best estimate for H_2O and Lapse Rate feedback is correct, this simulation implies sum of other feedbacks (clouds, surface albedo) must be ***close to zero***.

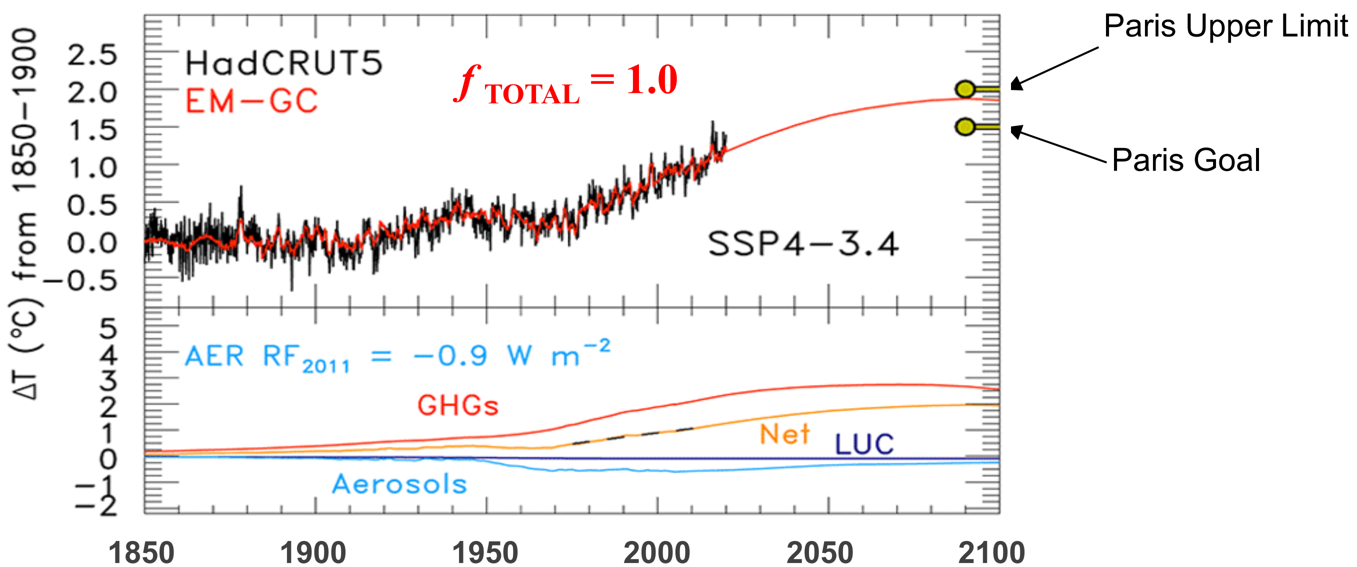
Uncertainty in RF of climate due to tropospheric aerosols is huge complication leading to fundamental uncertainty on forecasts of future global warming

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

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

We assume that whatever value of climate feedback is inferred from the climate record will persist into the future. For Aerosol RF in 2011 of **–0.9 W m^{-2}** & assuming best estimate for H_2O and Lapse Rate feedback is correct, this simulation implies sum of other feedbacks (clouds, surface albedo) must be ***moderately positive***.

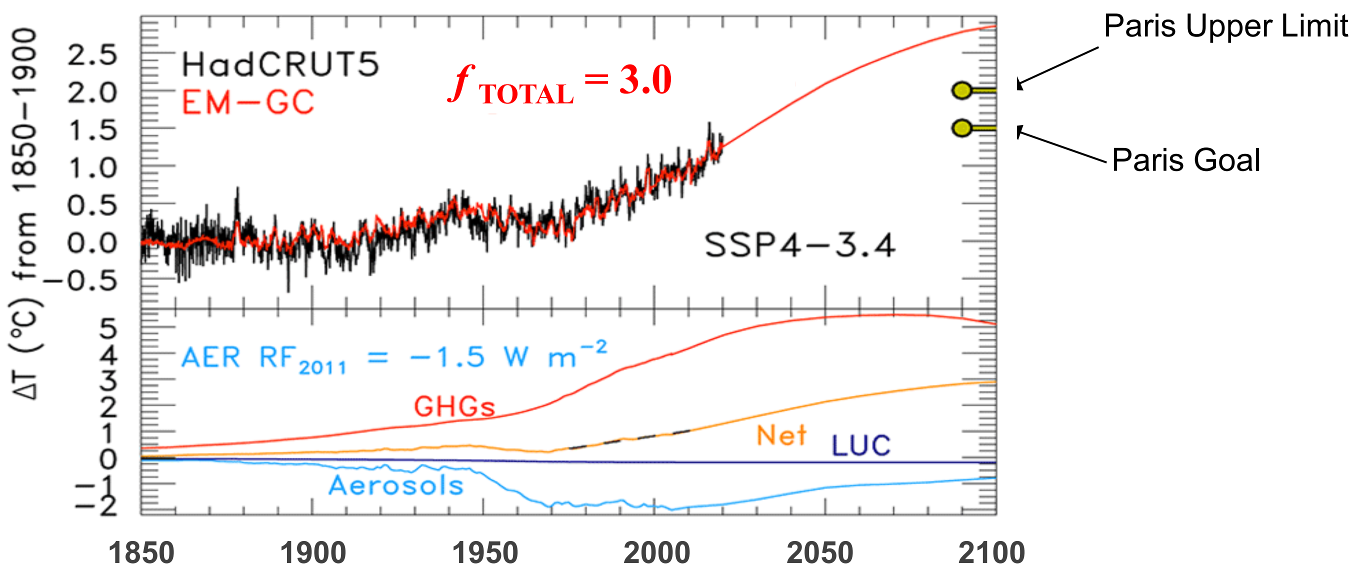
Uncertainty in RF of climate due to tropospheric aerosols is huge complication leading to fundamental uncertainty on forecasts of future global warming

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

where:

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

OHE = ocean heat export



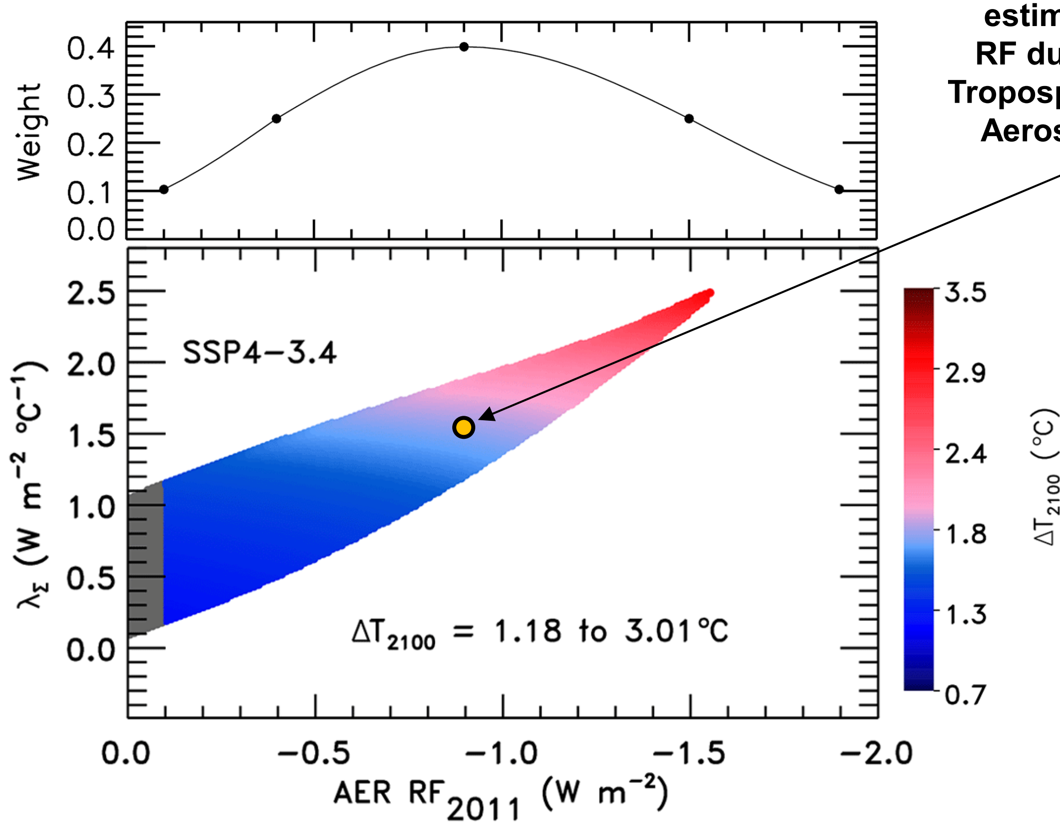
McBride *et al*., 2021
https://esd.copernicus.org/articles/12/545/2021

We assume that whatever value of climate feedback is inferred from the climate record will persist into the future. For Aerosol RF in 2011 of **–1.5 W m^{-2}** & assuming best estimate for H_2O and Lapse Rate feedback is correct, this simulation implies sum of other feedbacks (clouds, surface albedo) must be ***strongly positive***.

End of Century Warming, SSP4-3.4, as a fn of Feedback & Aerosol RF

AR5 best estimate RF due to Tropospheric Aerosols

Same as FB_{TOTAL}



Model space for which at $\chi^2 \leq 2$, where: $$\chi^2 = \frac{1}{(N_{YEARS} - N_{FITTING\ PARAMETERS} - 1)} \times \sum_{j=1}^{N_{YEARS}} \frac{1}{(\sigma_{OBS\,j}{}^2)} \left(\langle \Delta T_{OBS\,j} \rangle - \langle \Delta T_{EM-GC\,j} \rangle \right)^2$$

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

IPCC AR5 “downgraded” warming forecast by CMIP5 models

Chapter 11 of IPCC (2013) suggested *CMIP5 GCMs warm too quickly* compared to observations, resulting in “likely range” (red trapezoid) for rise in GMST relative to pre-industrial baseline (ΔT) being considerably less than actual archived ΔT from the CMIP5 GCM runs

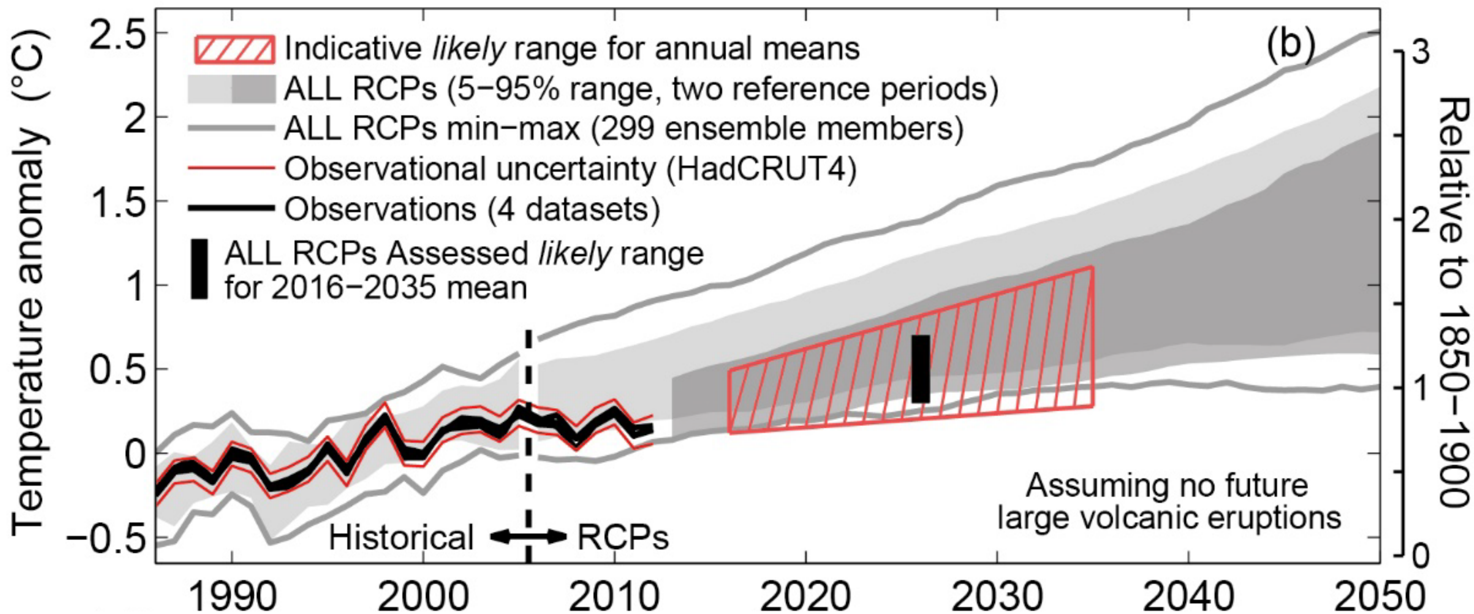
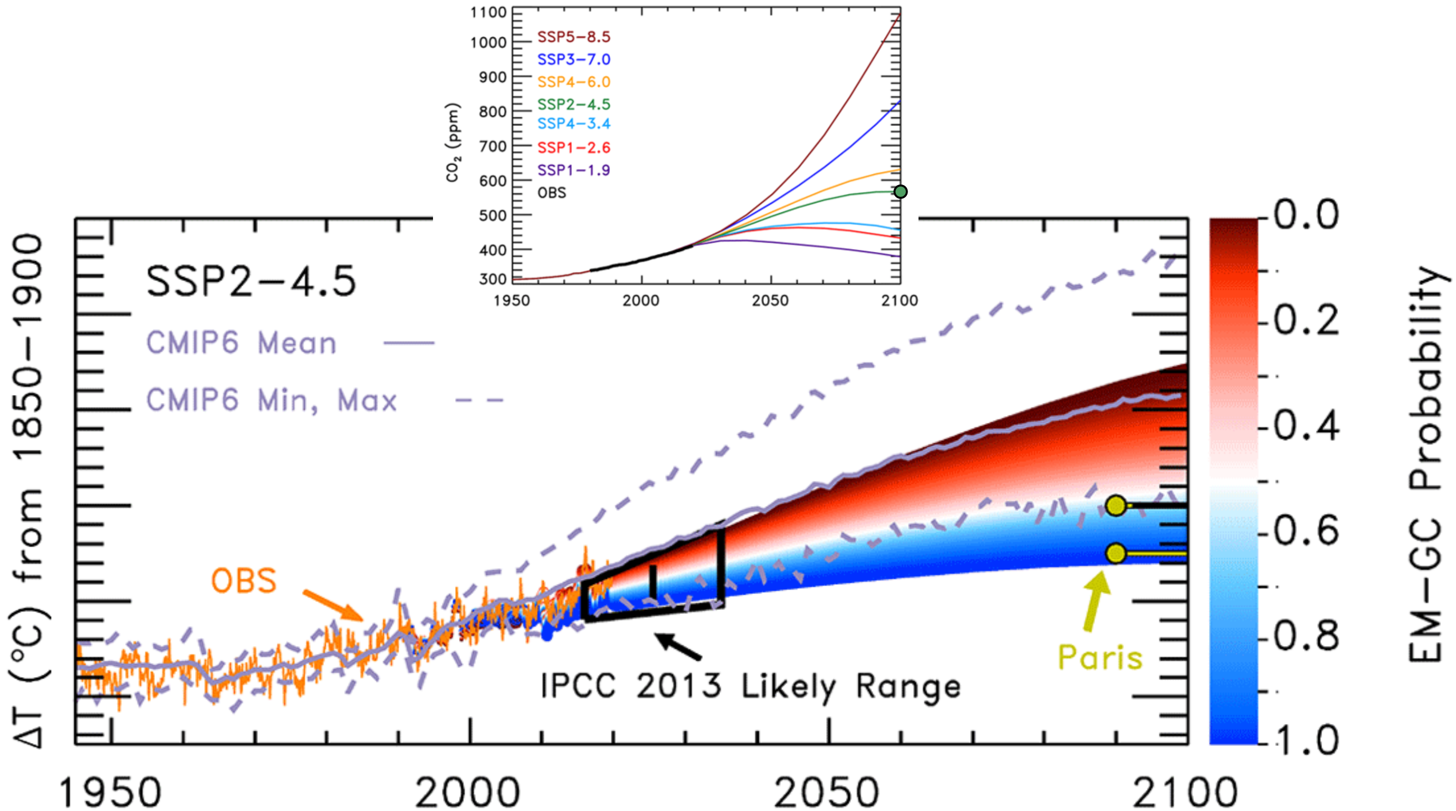


Fig 11.25b, IPCC (2013)

Probabilistic Forecast of ***Human-Induced Rise in GMST*** for model trained on data acquired until end of 2019 and future GHG levels from SSP2-4.5

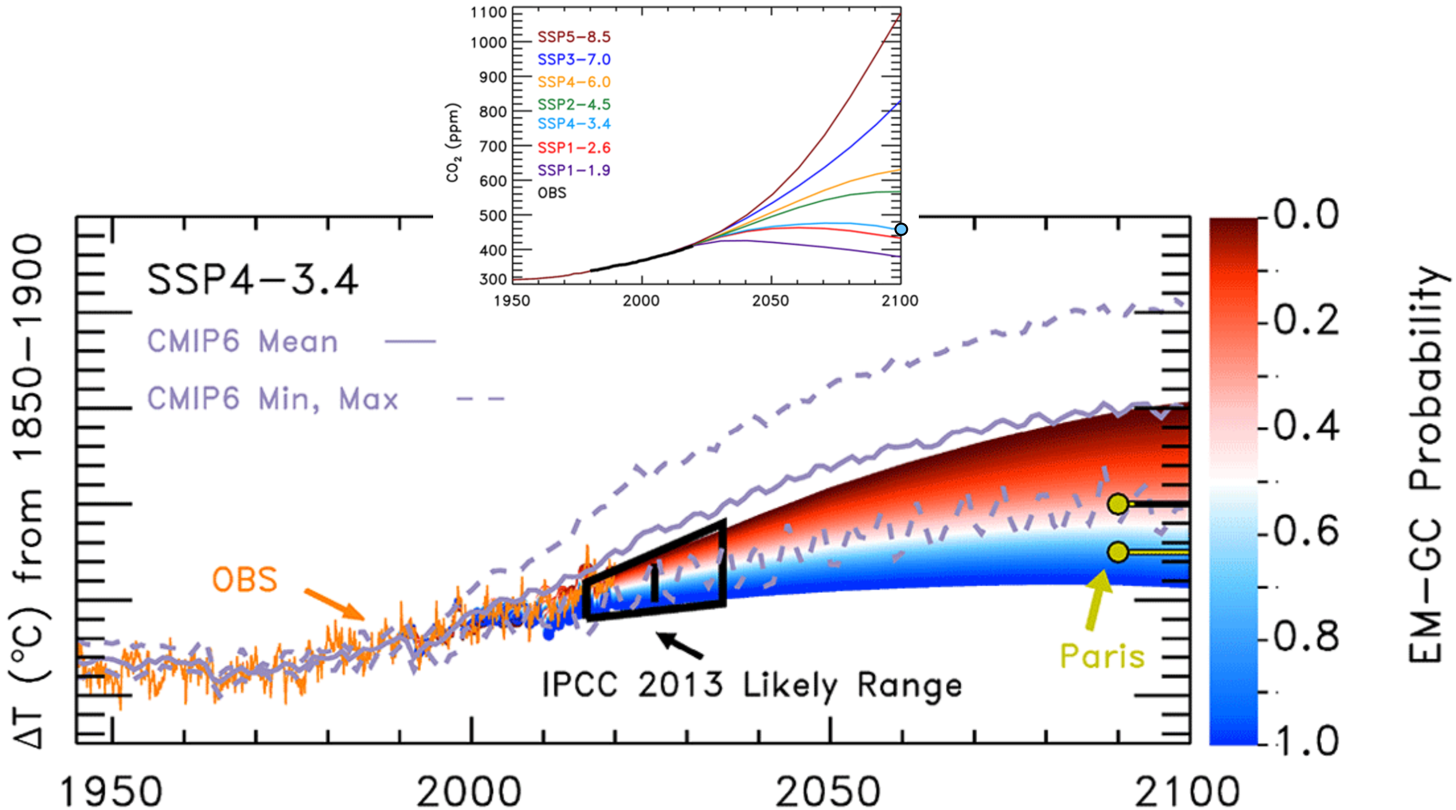


If GHGs follow SSP2-4.5, **2%** chance rise GMST stays below **1.5°C** and **33%** chance stays below **2.0°C**

EM-GC: University of Maryland Empirical Model of Global Climate
ΔT: rise in GMST (Global Mean Surface Temperature) relative to pre-industrial
CRU: Climate Research Unit, Easy Anglia, UK: Premier source of data for ΔT

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

Probabilistic Forecast of ***Human-Induced Rise in GMST*** for model trained on data acquired until end of 2019 and future GHG levels from SSP4-3.4

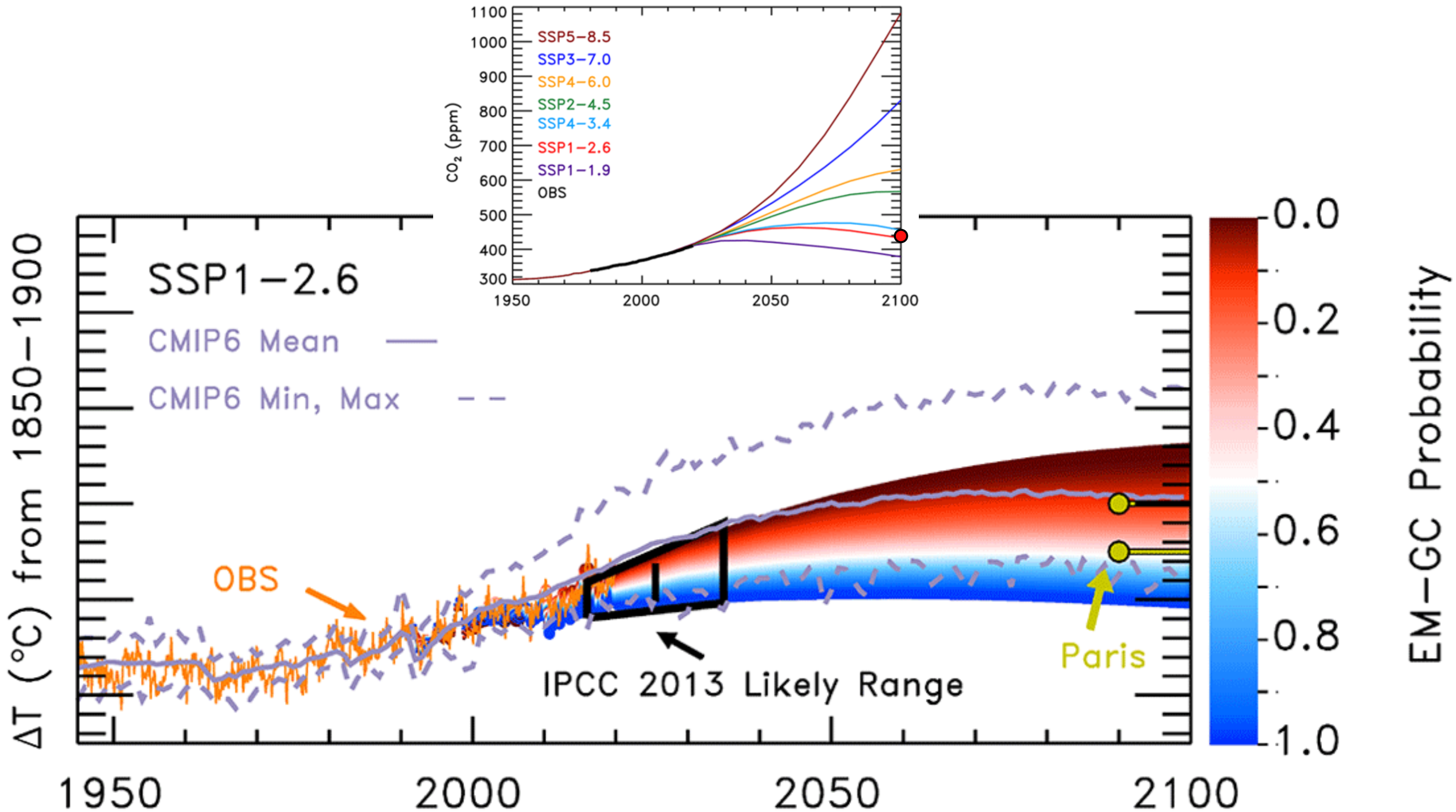


If GHGs follow SSP4-3.4, **19%** chance rise GMST stays below **1.5°C** and **64%** chance stays below **2.0°C**

EM-GC: University of Maryland Empirical Model of Global Climate
ΔT: rise in GMST (Global Mean Surface Temperature) relative to pre-industrial
CRU: Climate Research Unit, Easy Anglia, UK: Premier source of data for ΔT

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

Probabilistic Forecast of ***Human-Induced Rise in GMST*** for model trained on data acquired until end of 2019 and future GHG levels from SSP1-2.6

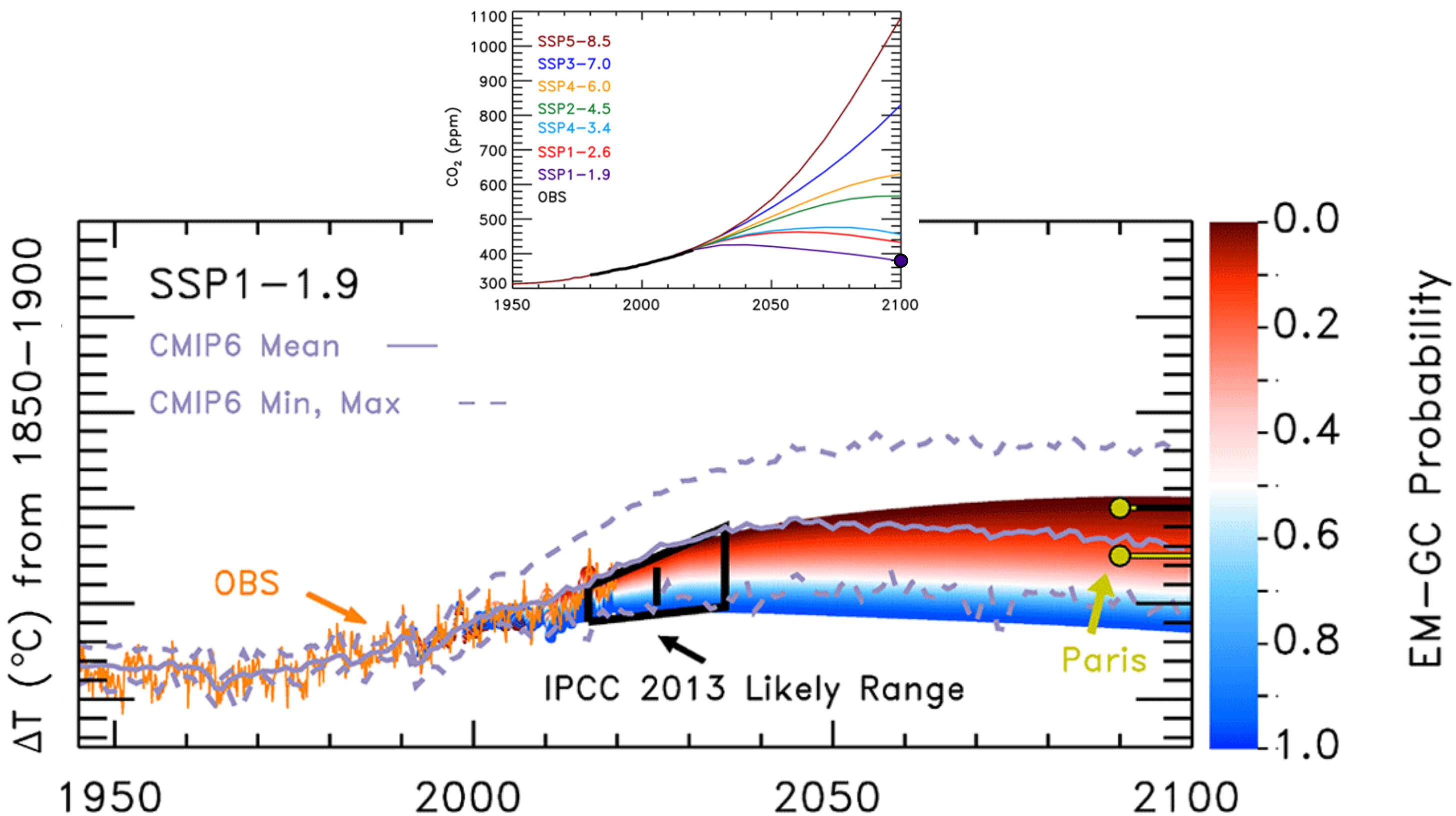


If GHGs follow SSP1-2.6, **53%** chance rise GMST stays below **1.5°C** and **86%** chance stays below **2.0°C**

EM-GC: University of Maryland Empirical Model of Global Climate
ΔT: rise in GMST (Global Mean Surface Temperature) relative to pre-industrial
CRU: Climate Research Unit, Easy Anglia, UK: Premier source of data for ΔT

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

Probabilistic Forecast of ***Human-Induced Rise in GMST*** for model trained on data acquired until end of 2019 and future GHG levels from SSP1-1.9



If GHGs follow SSP1-1.9, **81%** chance rise GMST stays below **1.5°C** and **98%** chance stays below **2.0°C**

EM-GC: University of Maryland Empirical Model of Global Climate
ΔT: rise in GMST (Global Mean Surface Temperature) relative to pre-industrial
CRU: Climate Research Unit, Easy Anglia, UK: Premier source of data for ΔT

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