Review for Exam

AOSC 680

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Class Web Sites:
http://www2.atmos.umd.edu/~rjs/class/fall2022
https://umd.instructure.com/courses/1327017

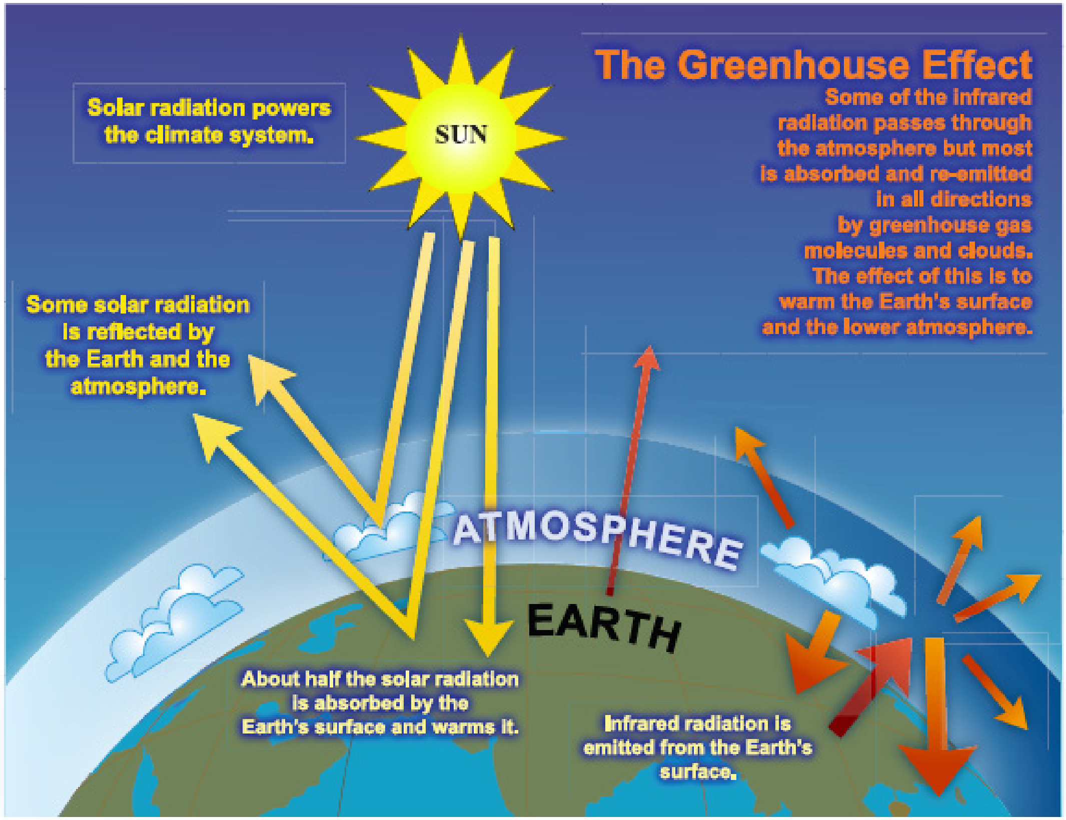
Exam will be in class on Thursday:

- Closed book
- Focus on concepts, no calculations
- Will cover material & required readings, Lectures 1 to 8
- Today, I will review:
  - Problem Set
  - Lectures 1 to 8

Review of First Third of Class

4 October 2022

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

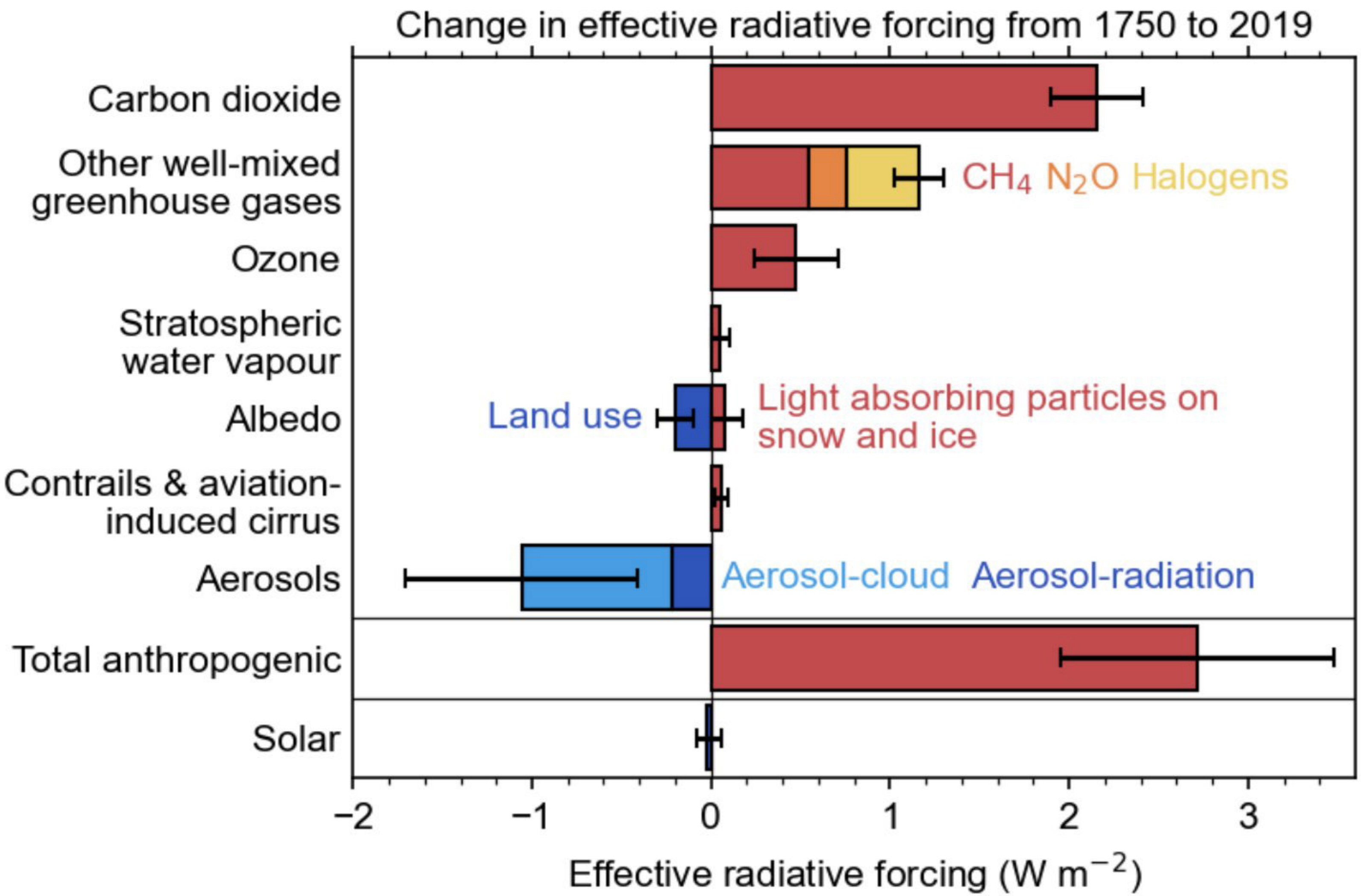
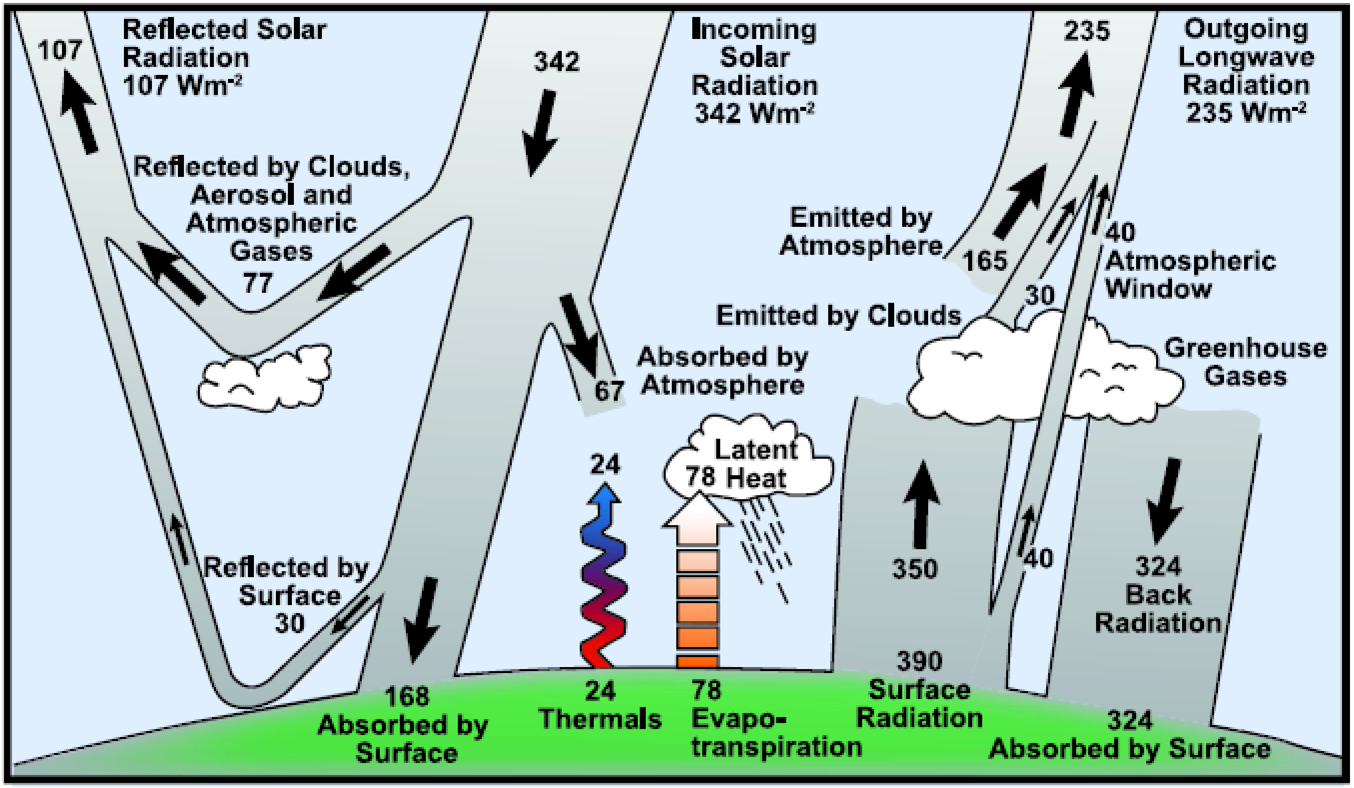


Figure 7.6, IPCC (2021)
https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_TS.pdf

Radiative Forcing

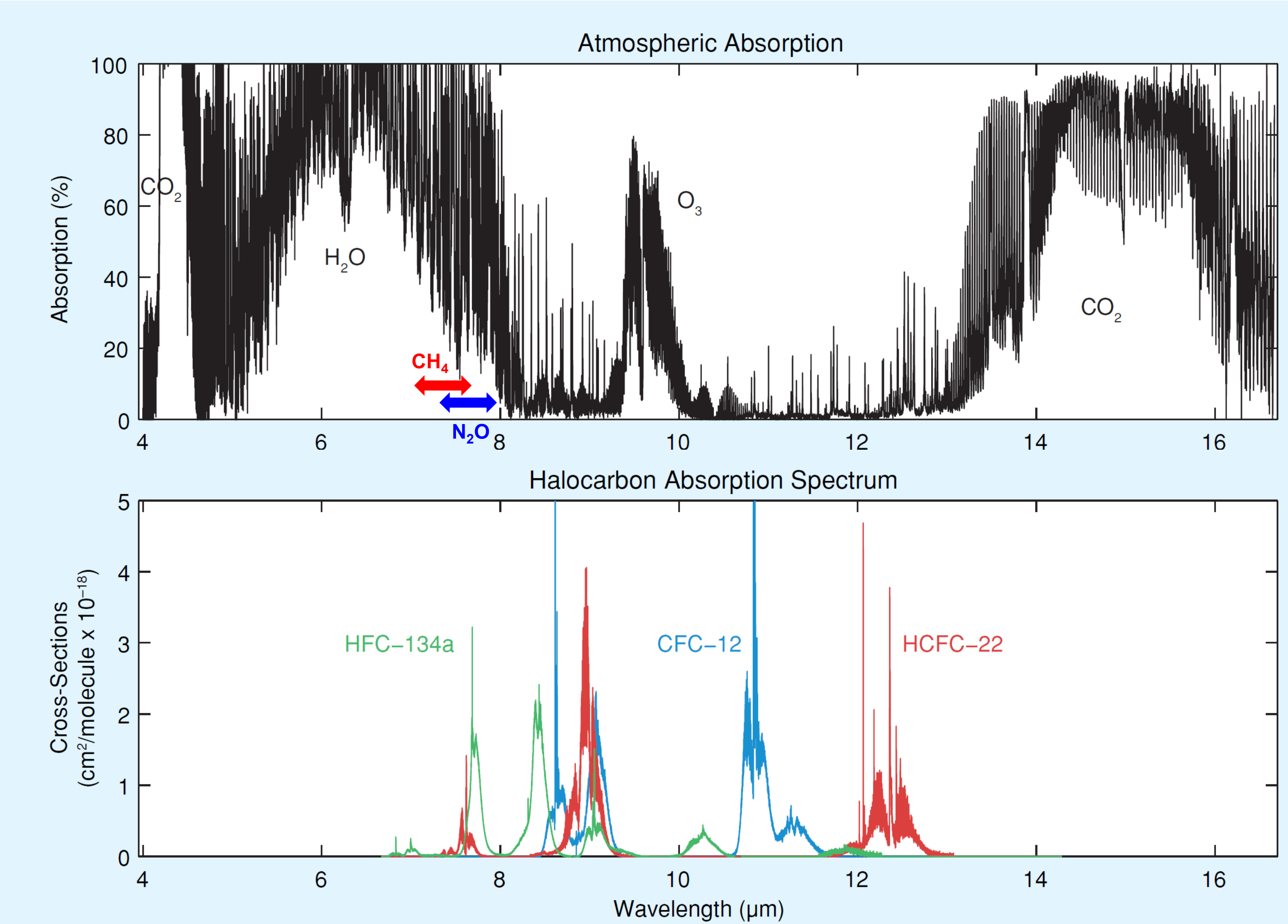


FAQ 1.1, Figure 1. *Estimate of the Earth's annual and global mean energy balance. Over the long term, the amount of incoming solar radiation absorbed by the Earth and atmosphere is balanced by the Earth and atmosphere releasing the same amount of outgoing longwave radiation. About half of the incoming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

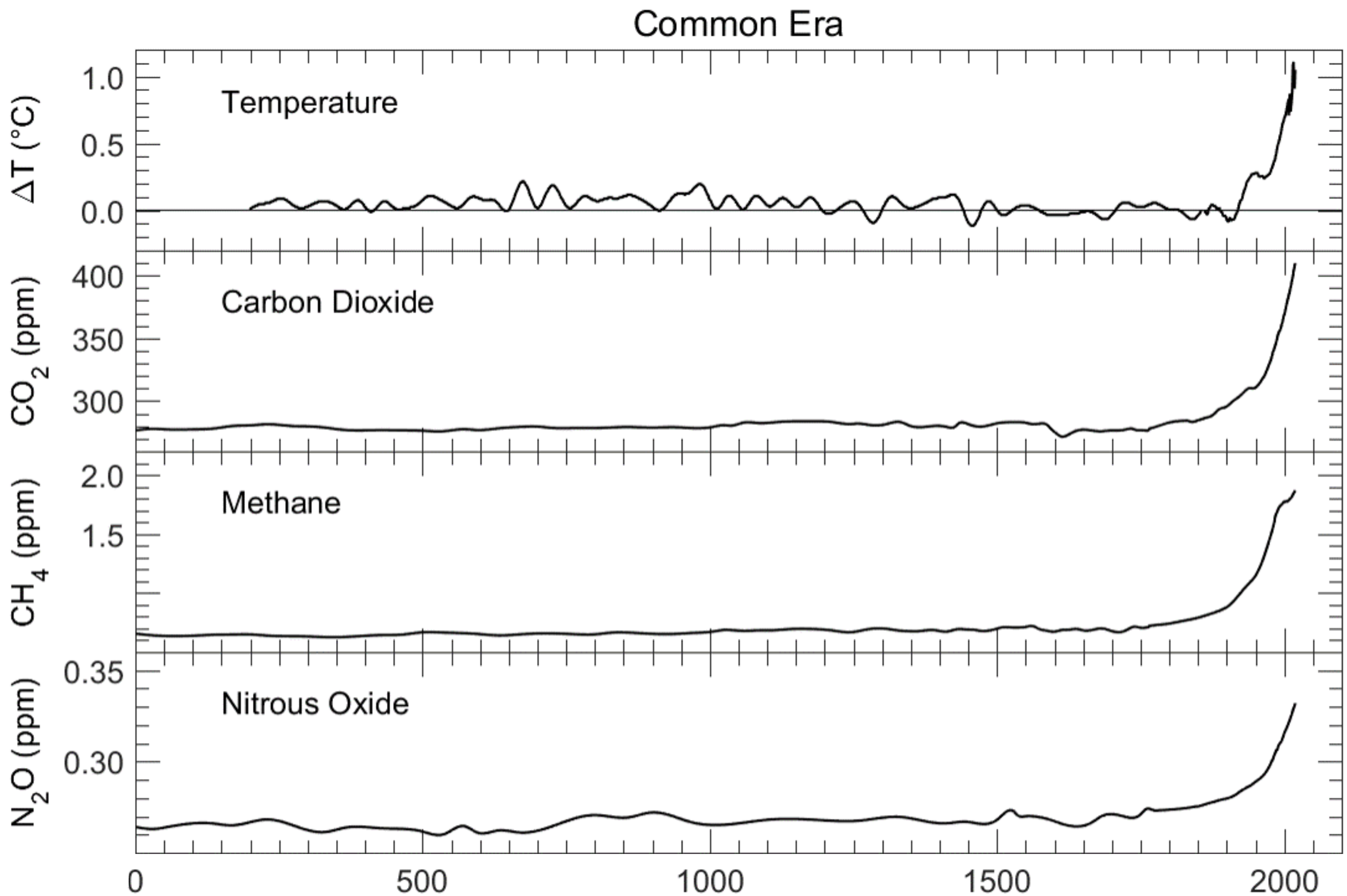


Figure 1.2, Paris Beacon of Hope (updated)

Going Back 600,000 years

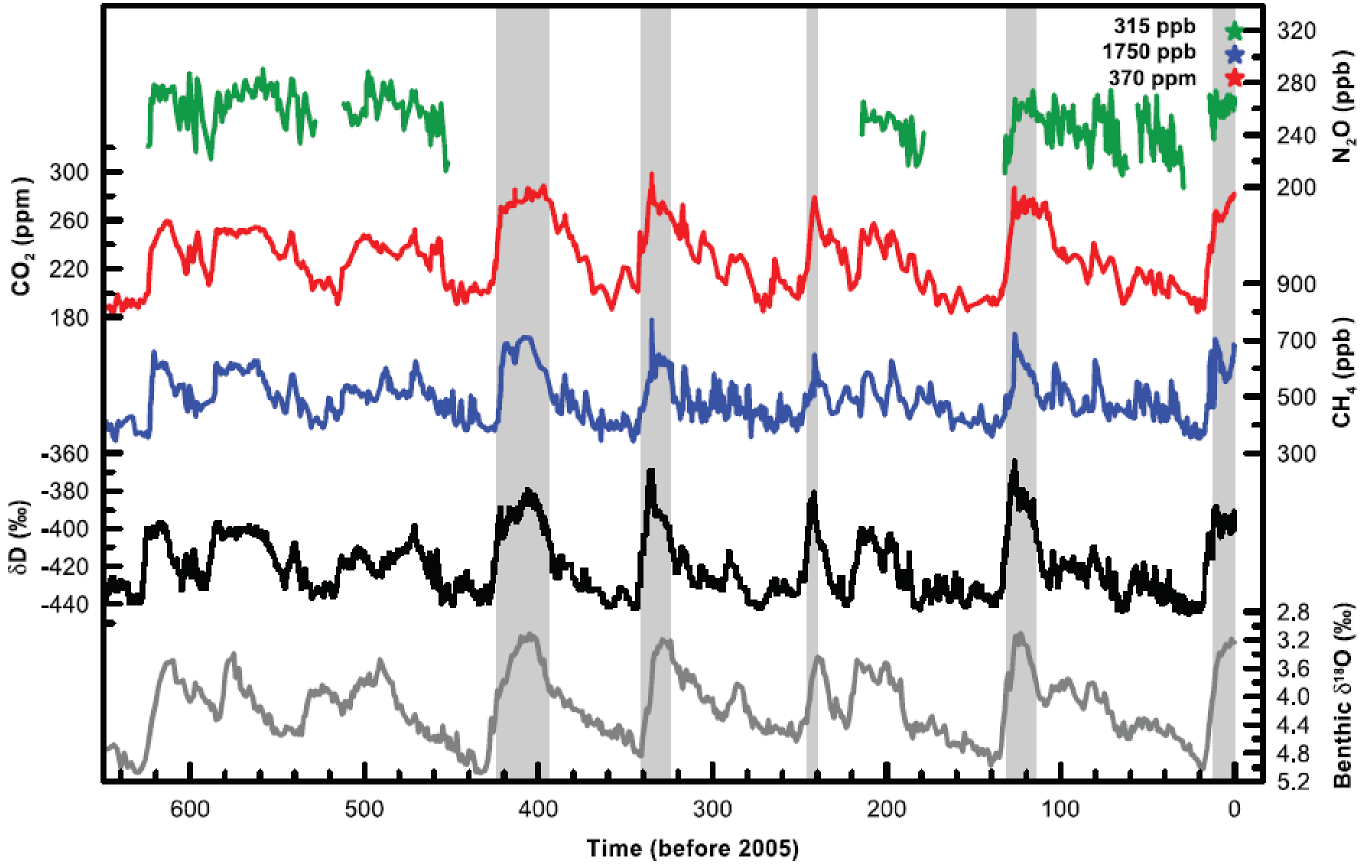


Figure 6.3. *Variations of deuterium (δD; black), a proxy for local temperature, and the atmospheric concentrations of the greenhouse gases CO_2 (red), CH_4 (blue), and nitrous oxide (N_2O; green) derived from air trapped within ice cores from Antarctica and from recent atmospheric measurements (Petit 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

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

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

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

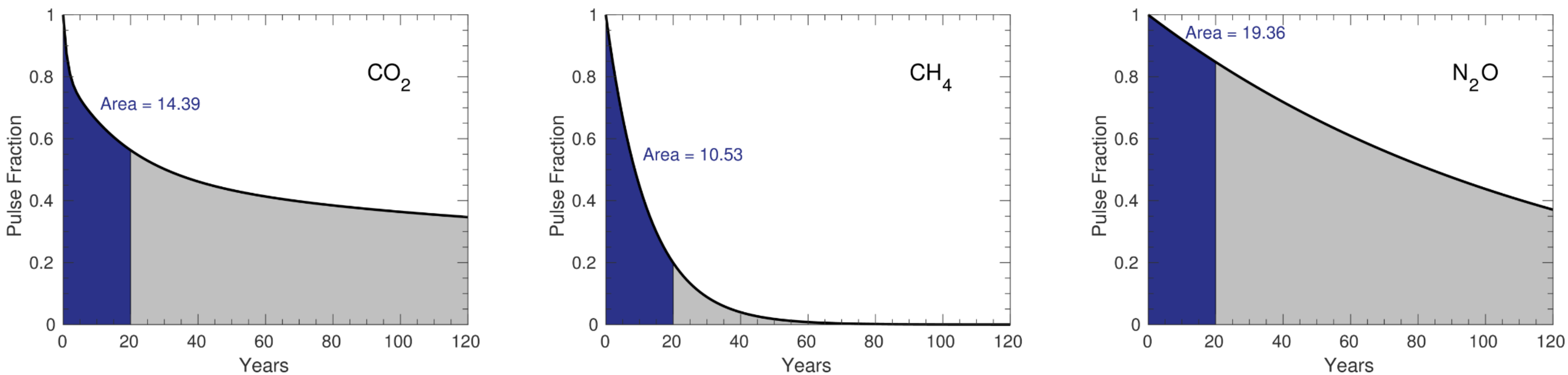
GWP – Global Warming Potential

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

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

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



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

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

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

where all times are given in units of year

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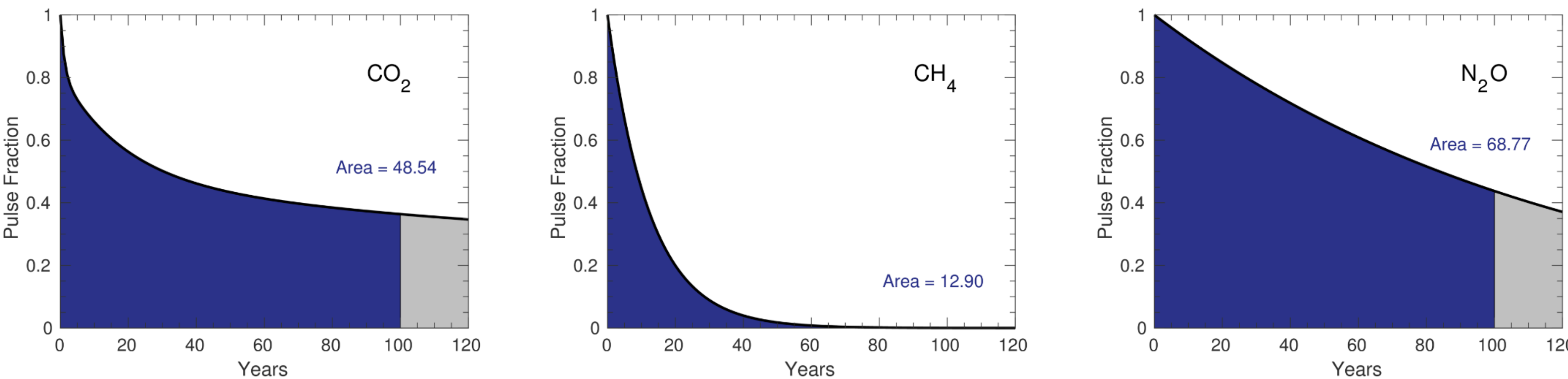
100 Year Time Horizon means time final = 100 years in these integrals



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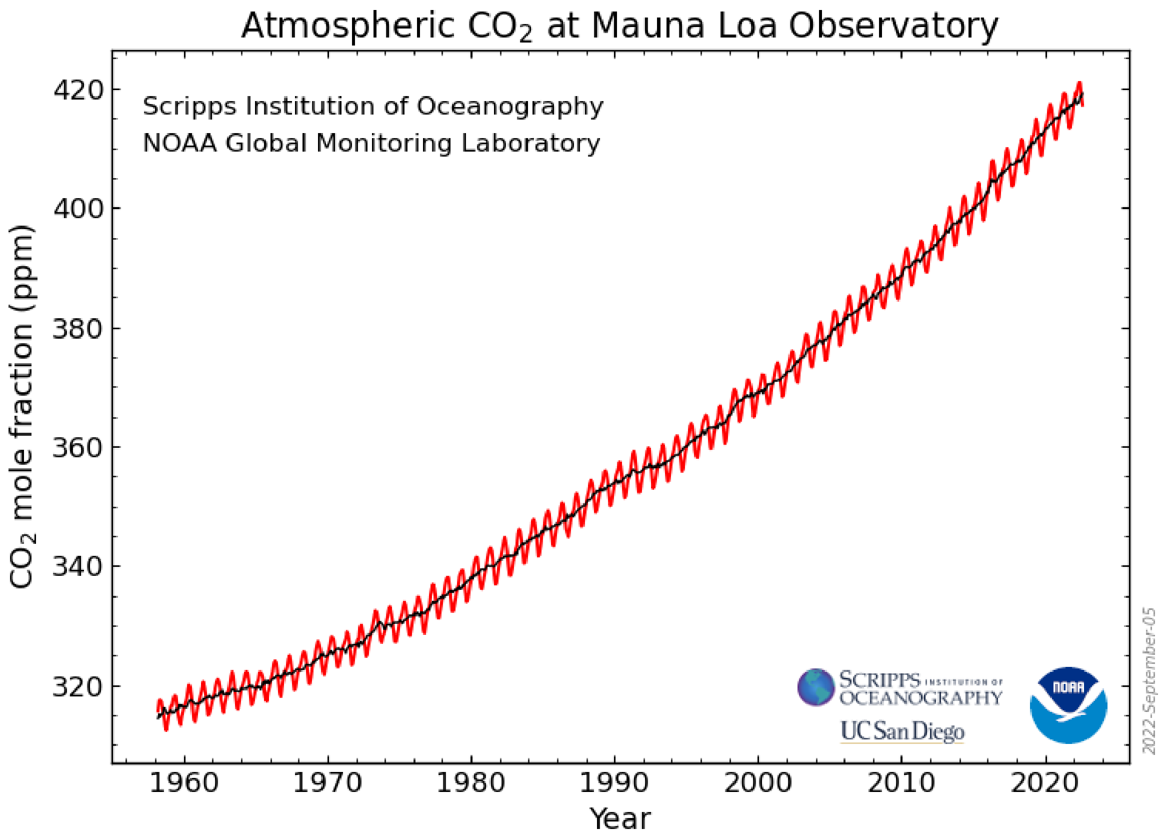
where all times are given in units of year

Modern CO_2 Record

CO_2 at MLO on 4 Sep 2022: 416.68 parts per million (ppm)
CO_2 at MLO on 4 Sep 2021: 413.43 parts per million (ppm)

ΔCO_2 = 3.25 ppm per year
or 0.8 % per year



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

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 ... based on several ... e given is an estimate

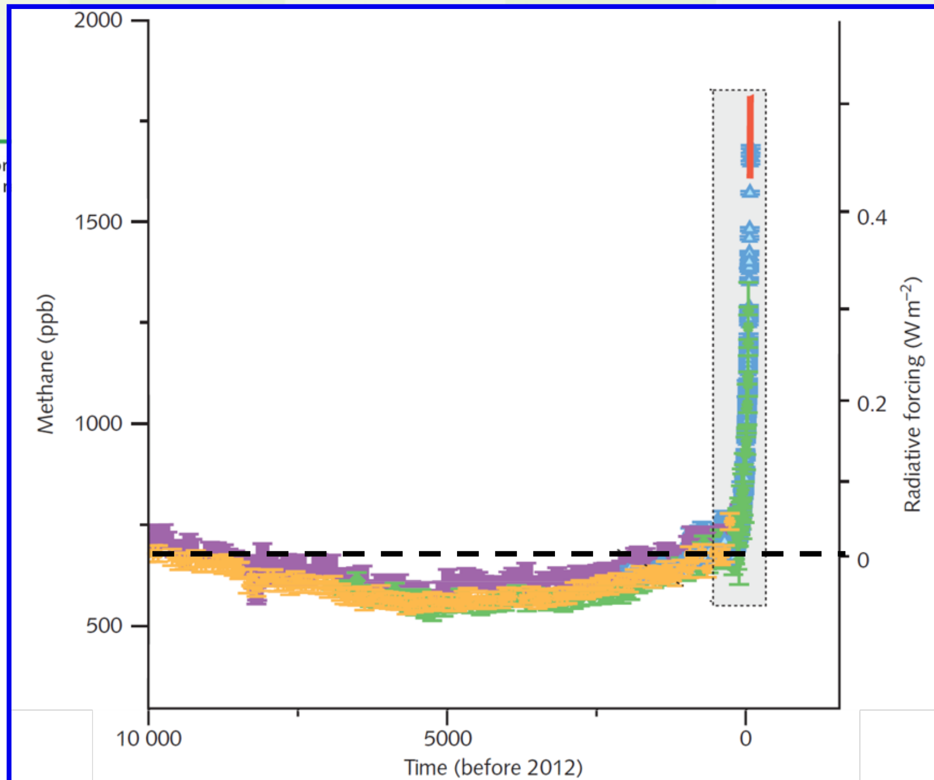


Figure 3.7, *Houghton*

Atmospheric CH_4

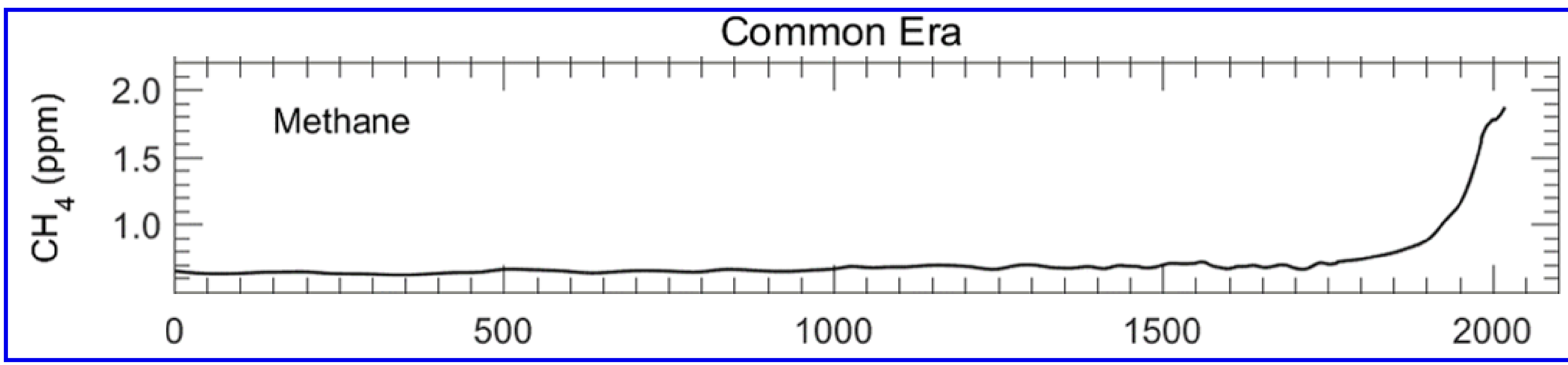
AT6, Q2:
What is the approximate current atmospheric abundance of CH_4?

Table 3.2 Examples of Greenhouse Gases

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	$\boxed{\text{1760 ppb}}$	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

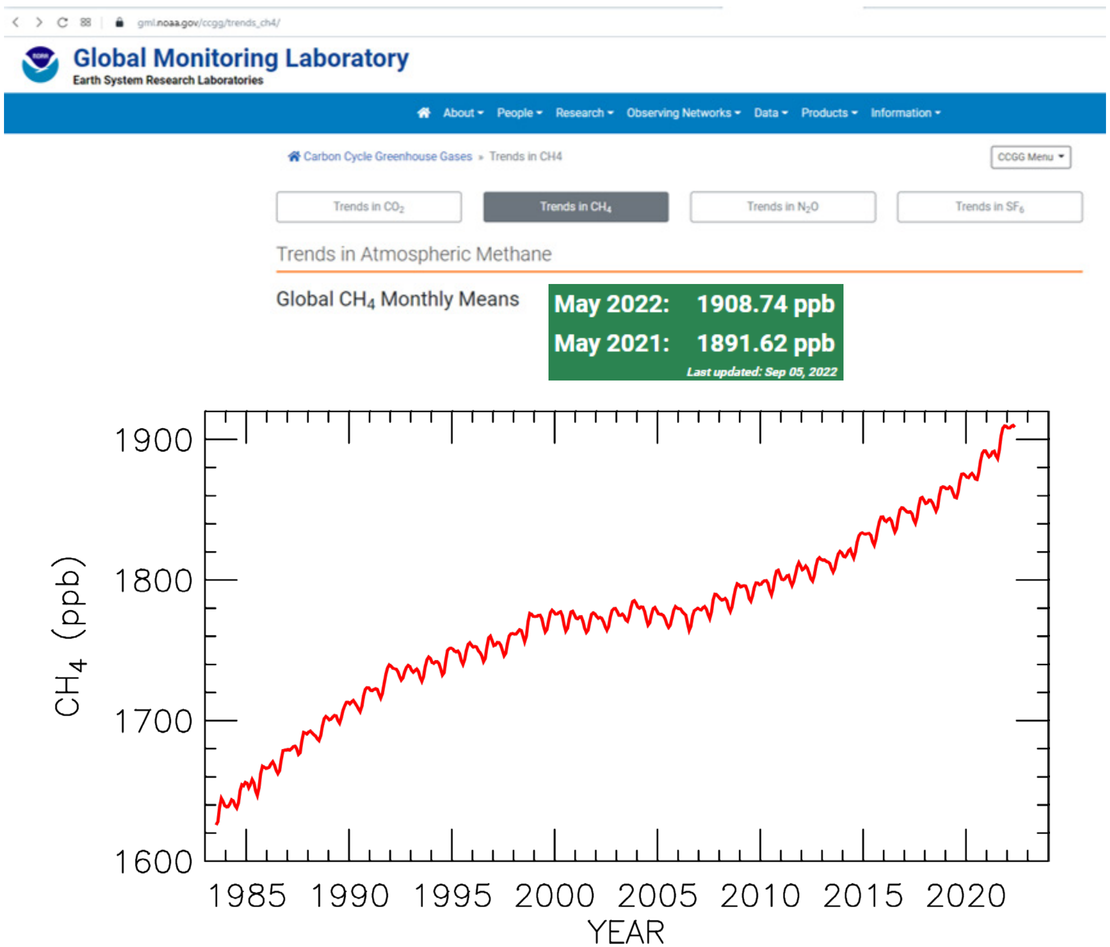


Atmospheric CH_4

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 exceeded 1760 ppb in late-1990s and exceeded 1.84 ppm in mid-2017.



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

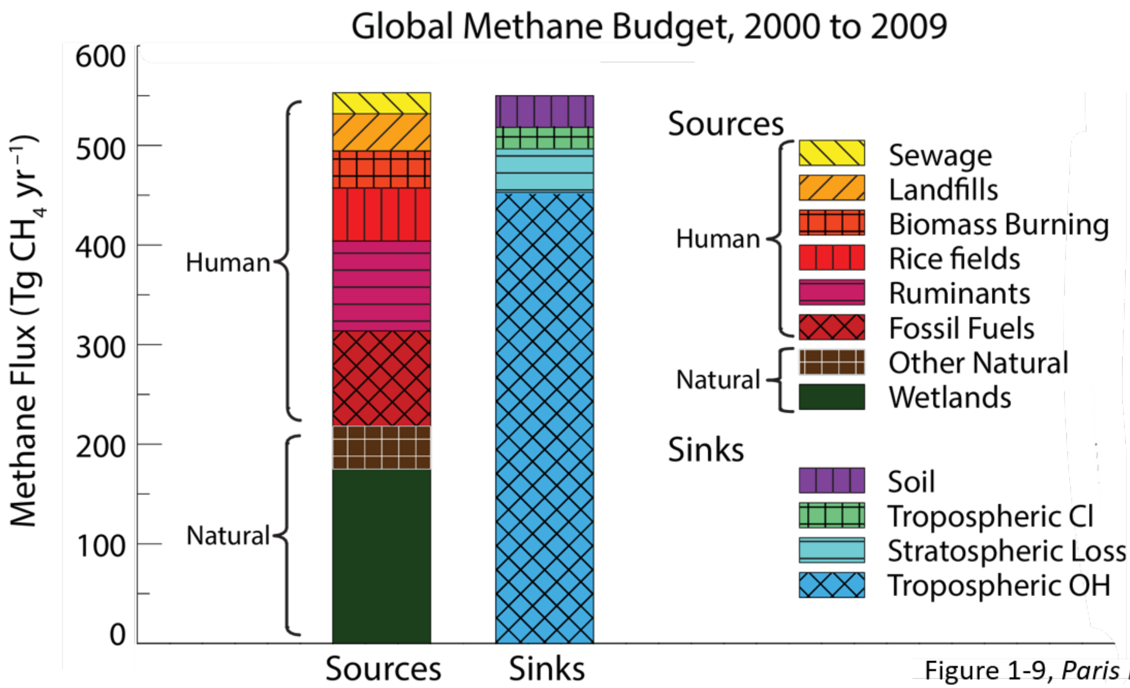


Figure 1-9, *Paris Beacon of Hope*

From prior slide:

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

Presumably:

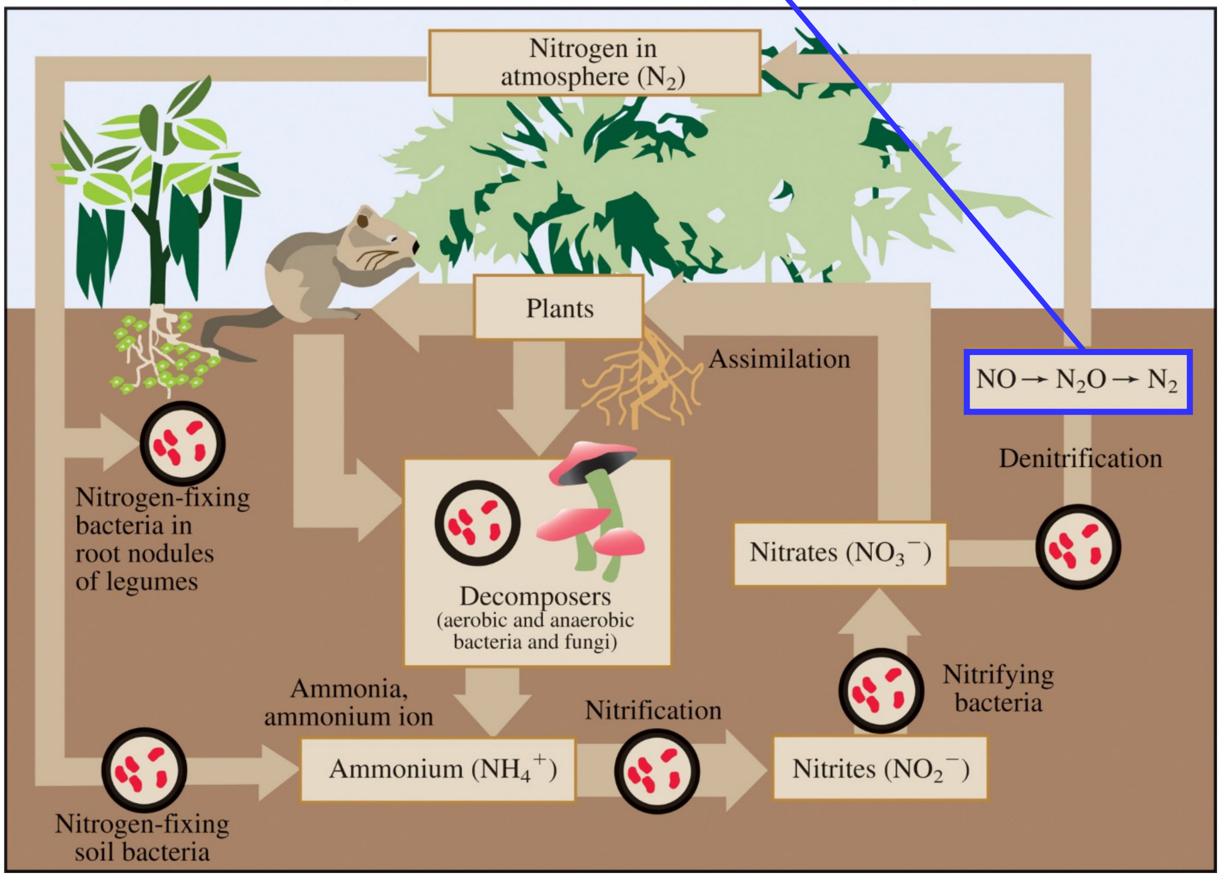
$$Source^{Preindustrial} = Source^{Present} - Source^{Human}$$ **(i.e., presumably "natural state" has not changed)**

If so, then top equation can be written as:

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

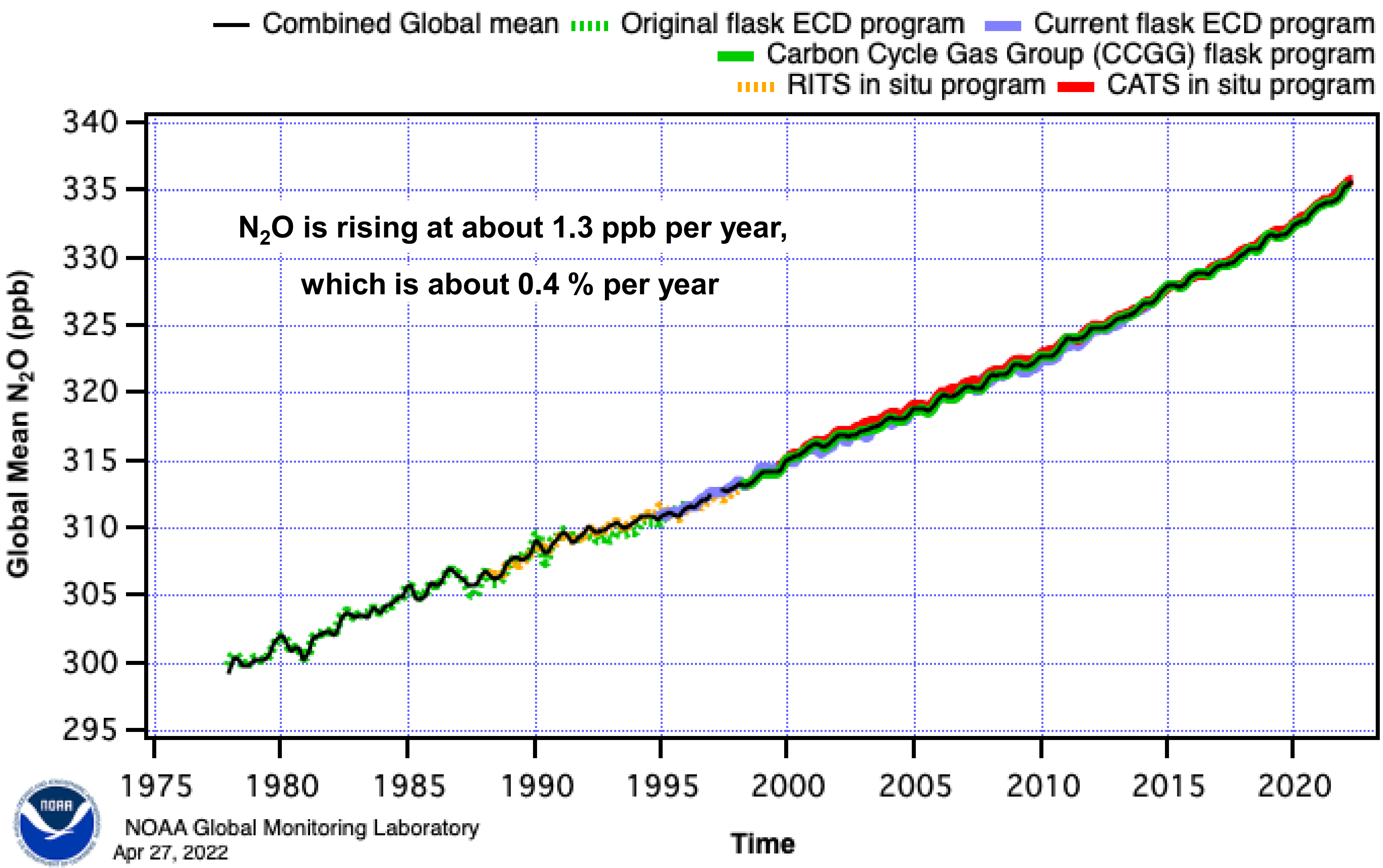
The Nitrogen Cycle

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

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

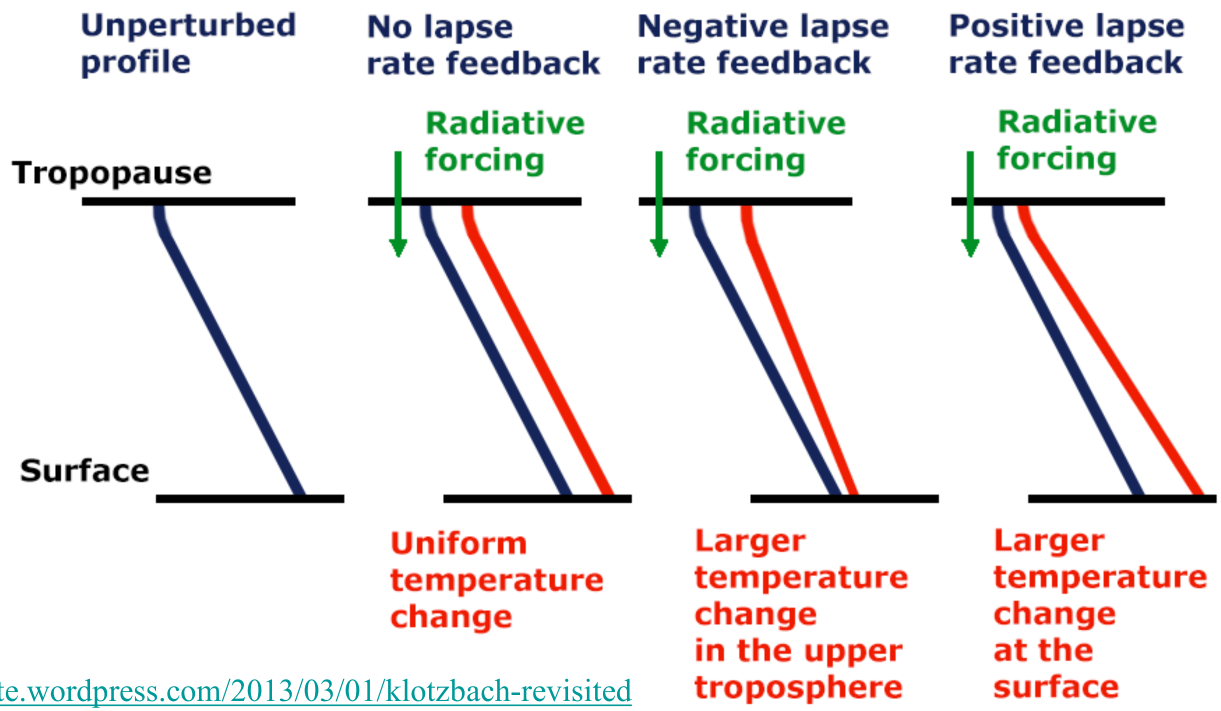
$$\lambda_{BB} = 0.3\ K\ /\ W\ m^{-2}$$

OHE = Ocean Heat Export

Climate models that consider water vapor feedback find:

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

Lapse Rate Feedback

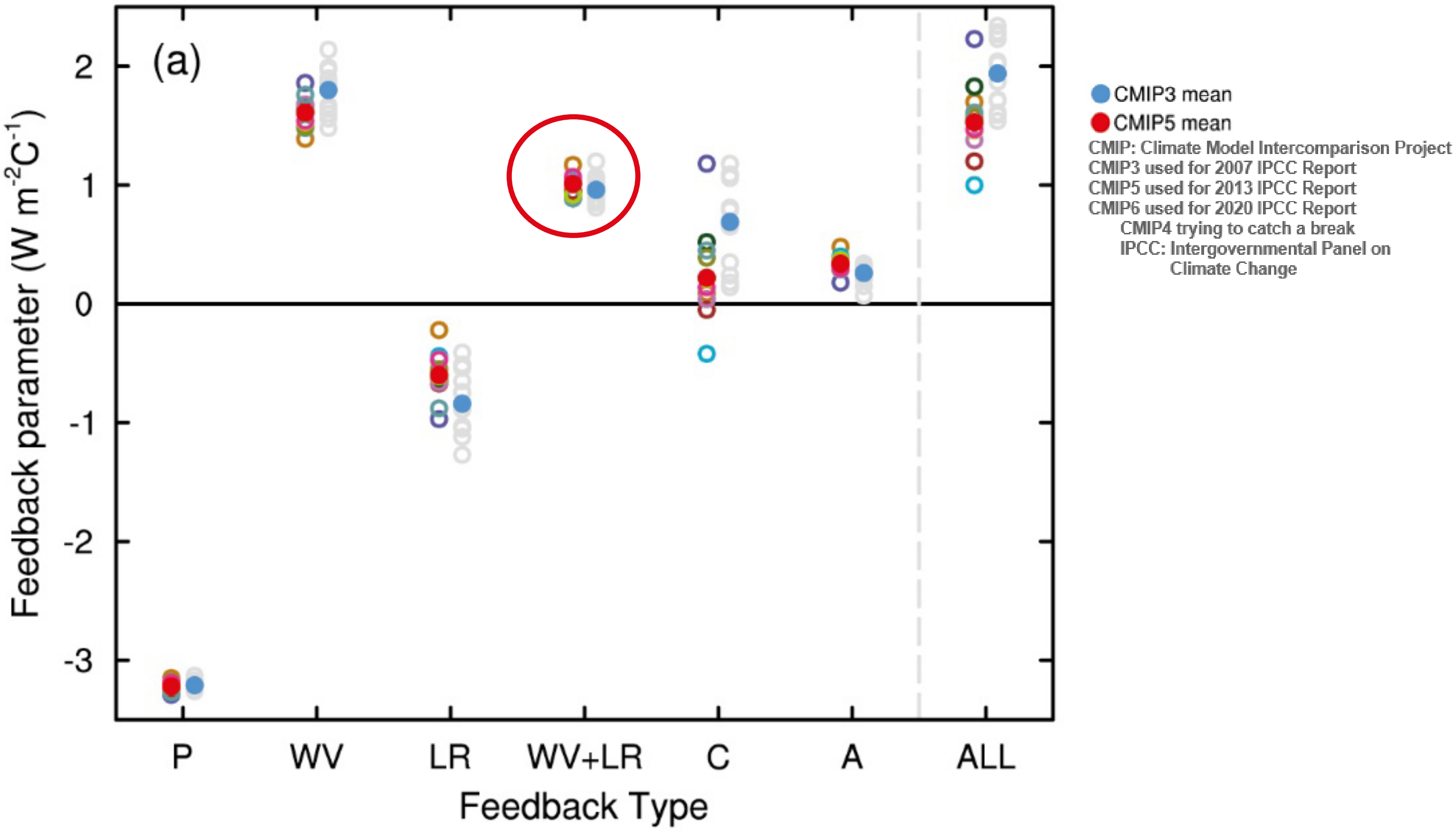


https://ourchangingclimate.wordpress.com/2013/03/01/klotzbach-revisited

- 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

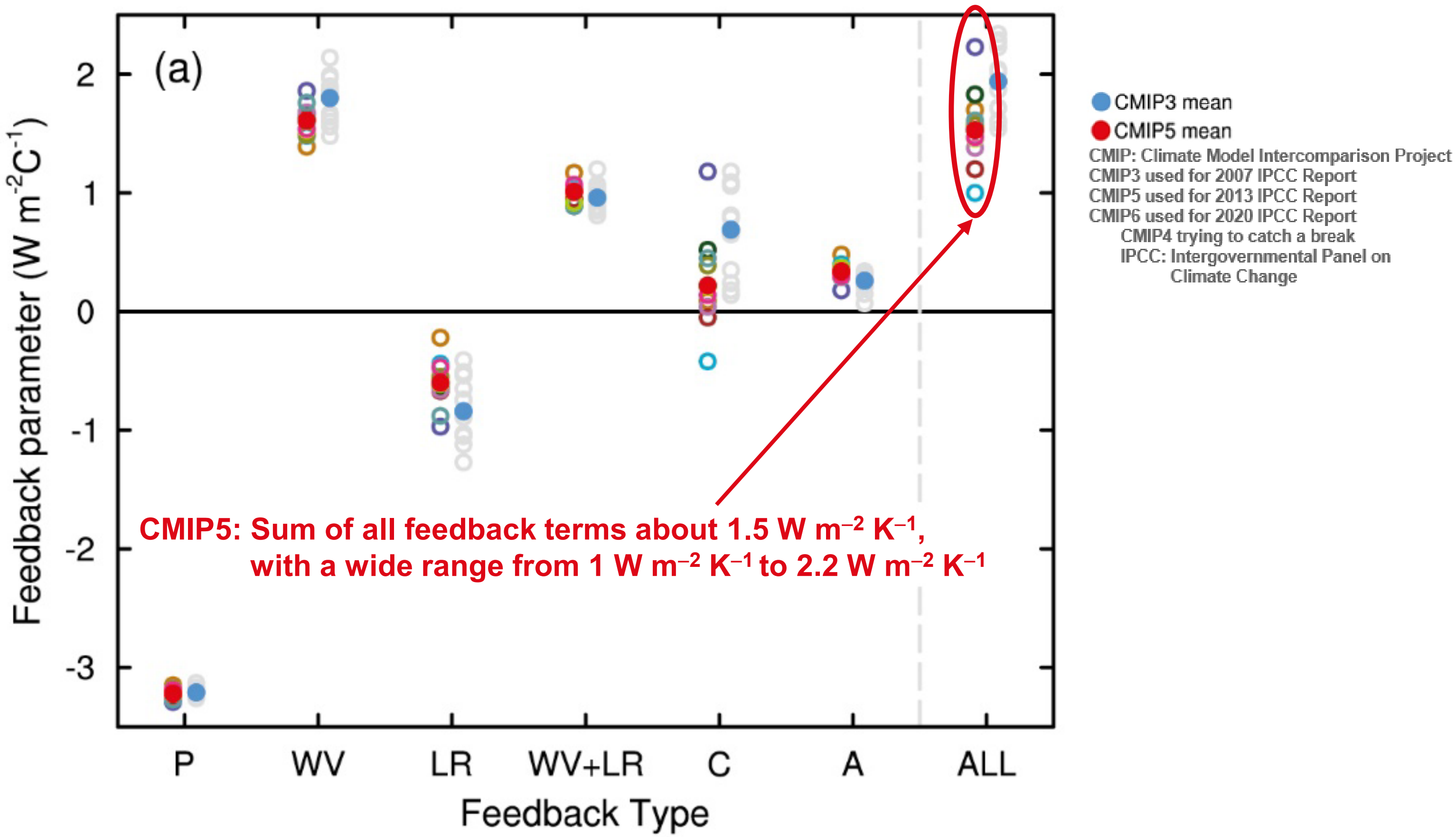
- GCMs indicate water vapor & lapse rate feedbacks are intricately linked, with the former almost certainly being positive (in response to rising GHGs), the latter almost certainly being negative, and the sum probably being positive



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

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

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



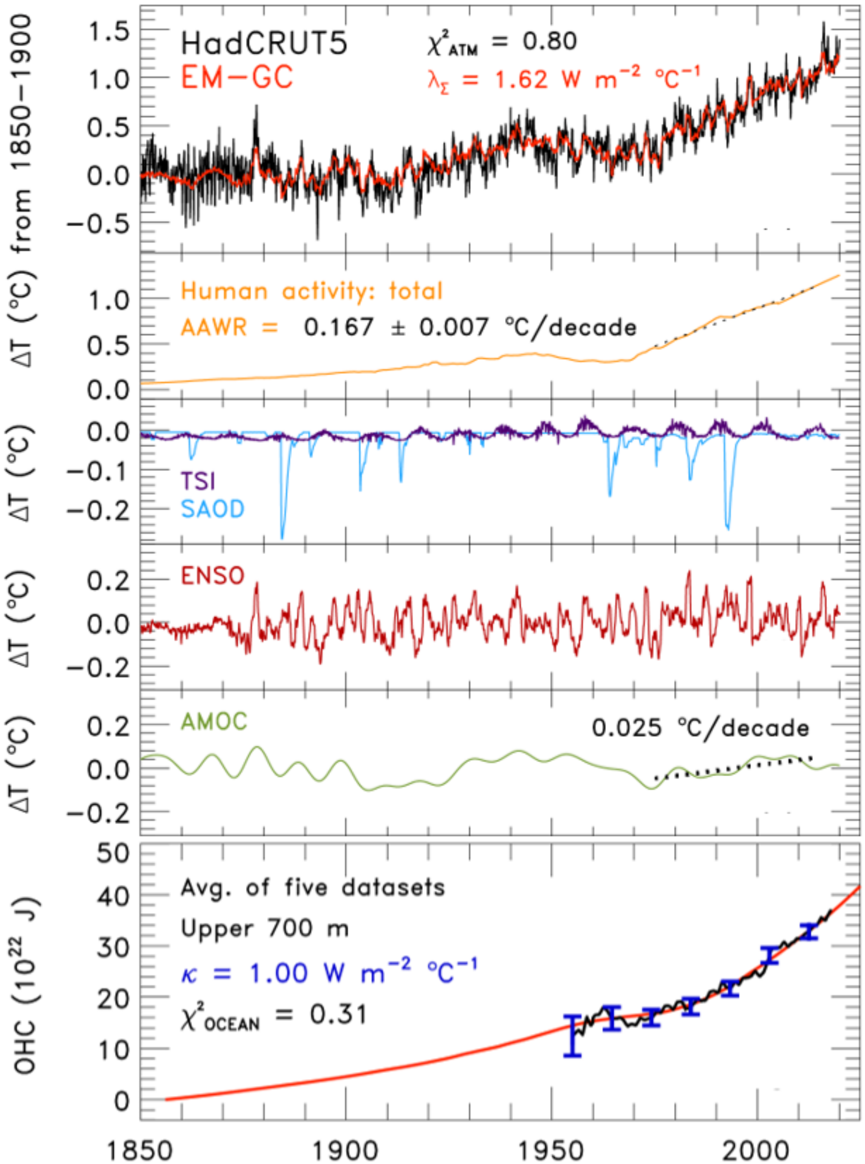
If $FB_{ALL} = 1.5\ \mathrm{W\ m^{-2}\ K^{-1}}$ and we assume other feedbacks are zero, then:

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

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 16* (Handout)

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

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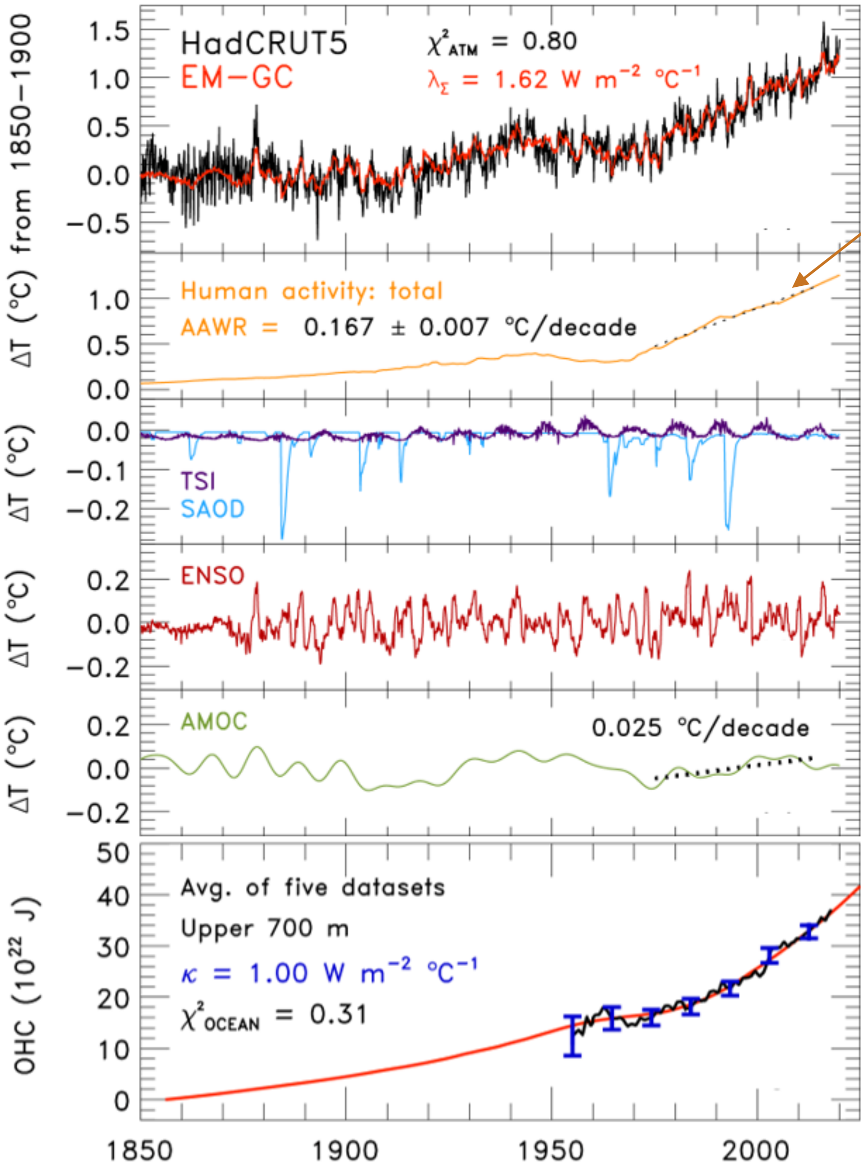


$$\Delta T^{HUMAN} = \lambda_P\,(1 + f_{TOTAL})\,(\Delta F_{CO2} + \Delta F_{CH4+N2O} + \Delta F_{OTHER\ GHGs} + \Delta F_{AEROSOLS}) - \text{OHE}$$

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 reciprical 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 16* (Handout)

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

Combining RF GHGs & Aerosols

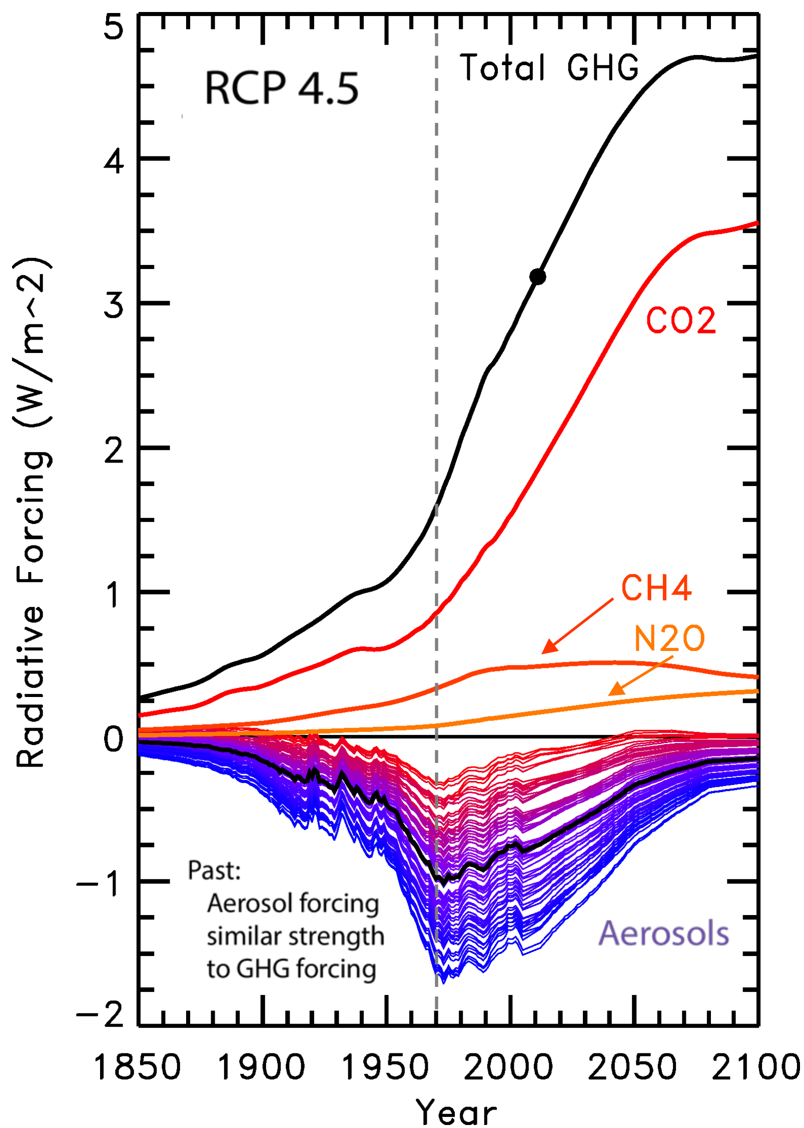
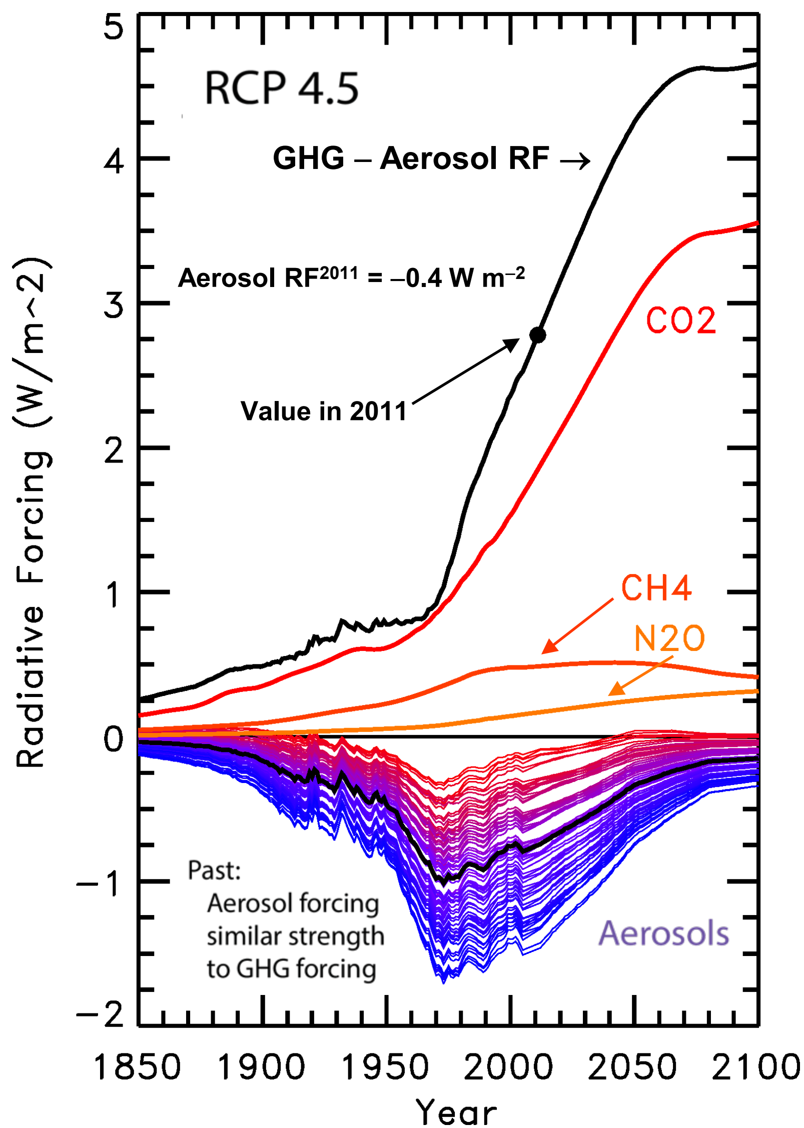


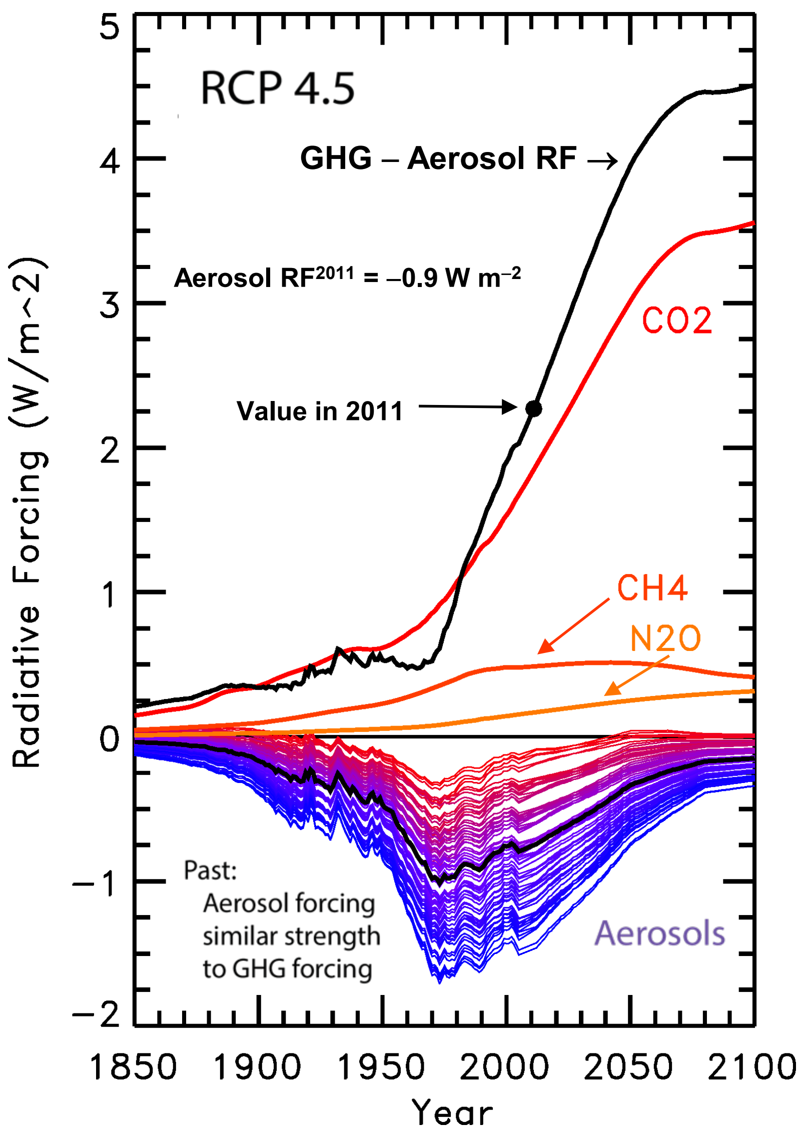
Fig 1.10, *Paris, Beacon of Hope*

Combining RF GHGs & Aerosols



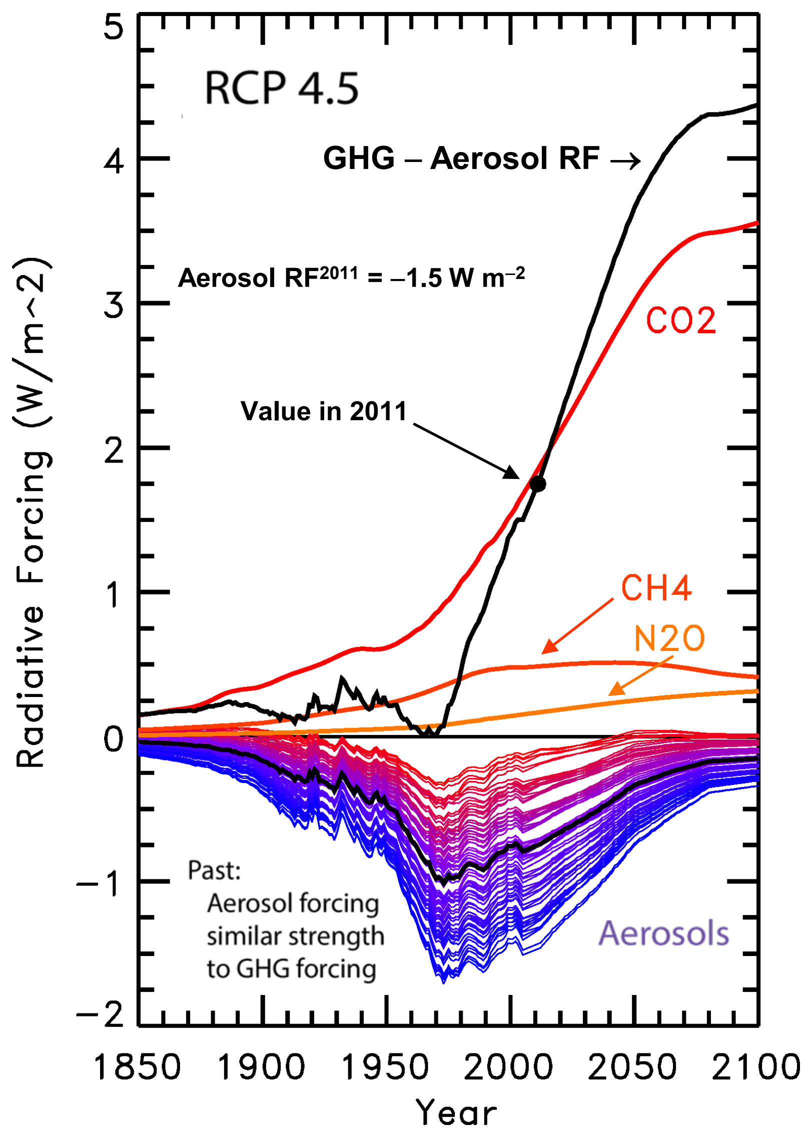
Based upon Fig 1.10, *Paris, Beacon of Hope*

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*

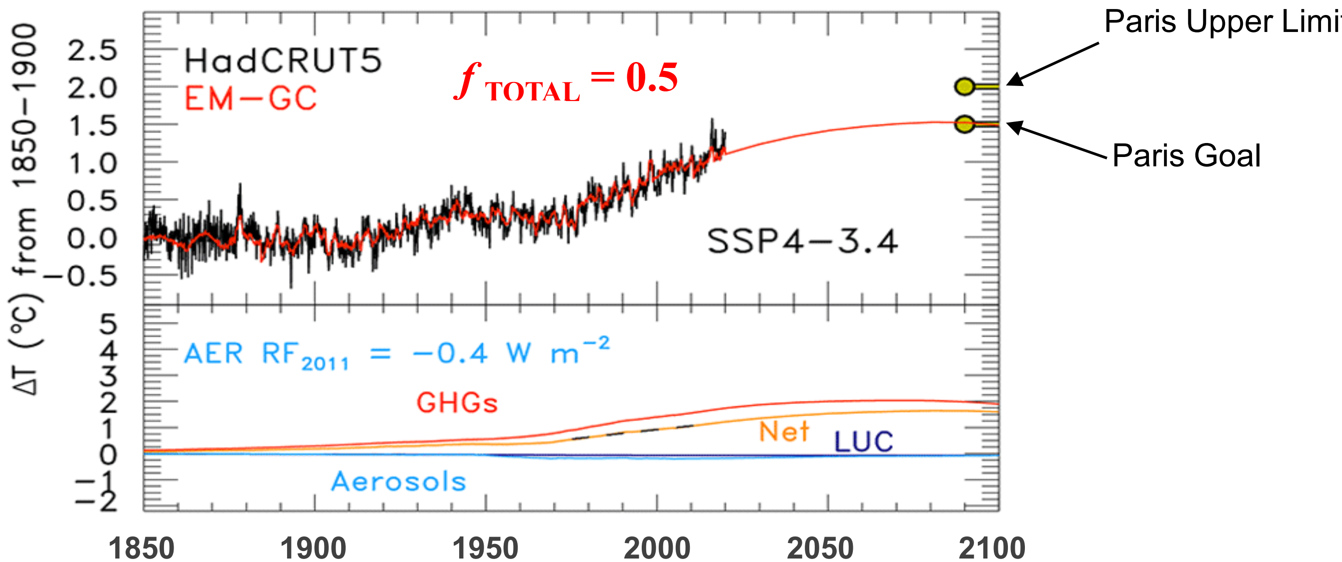
Uncertainty in RF of climate due to tropospheric aerosols is huge complication leading to fundamental uncertainty on forecasts of future global warming

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

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

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

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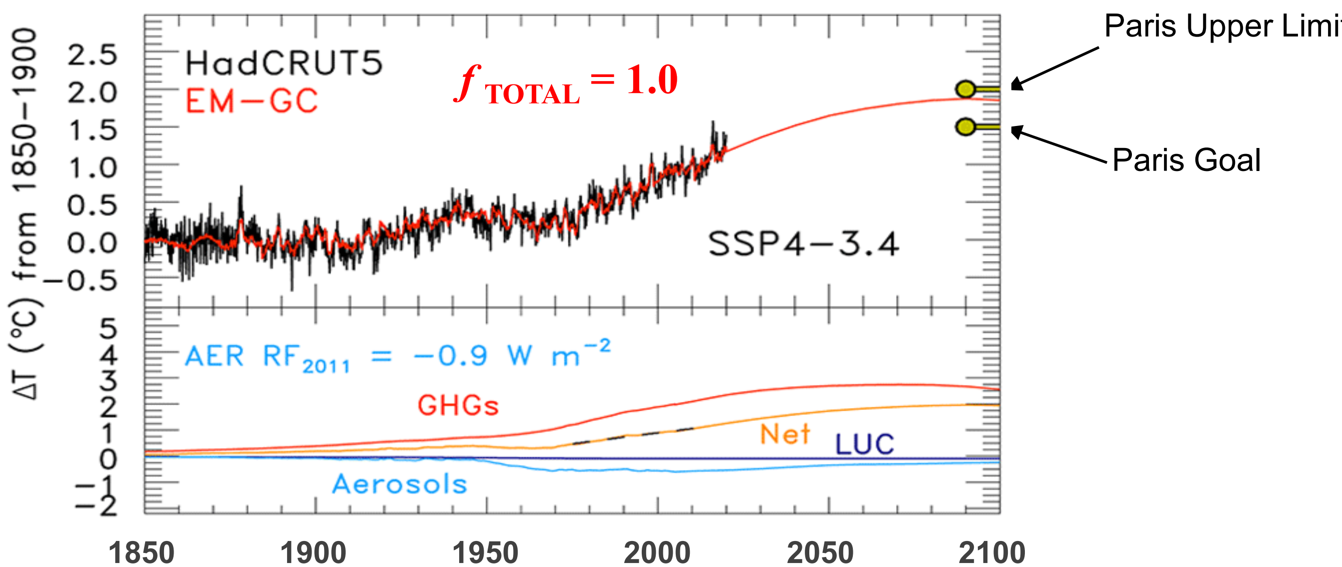


McBride *et al.*, 2021
https://esd.copernicus.org/articles/12/545/2021

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***.

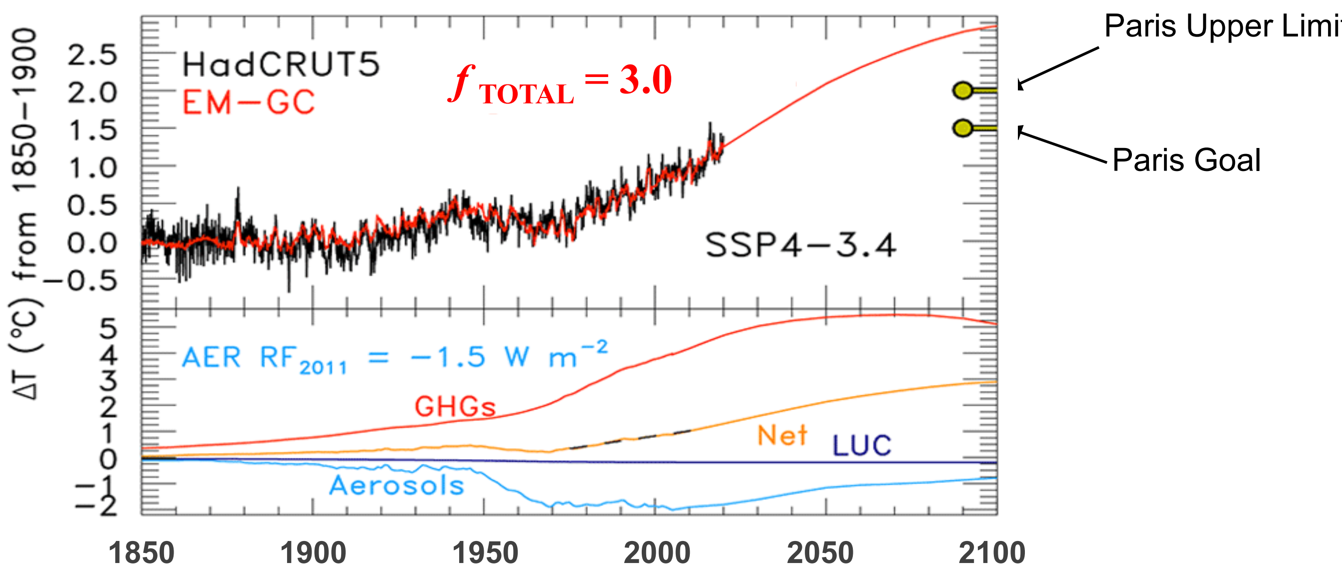
Uncertainty in RF of climate due to tropospheric aerosols is huge complication leading to fundamental uncertainty on forecasts of future global warming

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

where:

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

OHE = ocean heat export



McBride *et al.*, 2021
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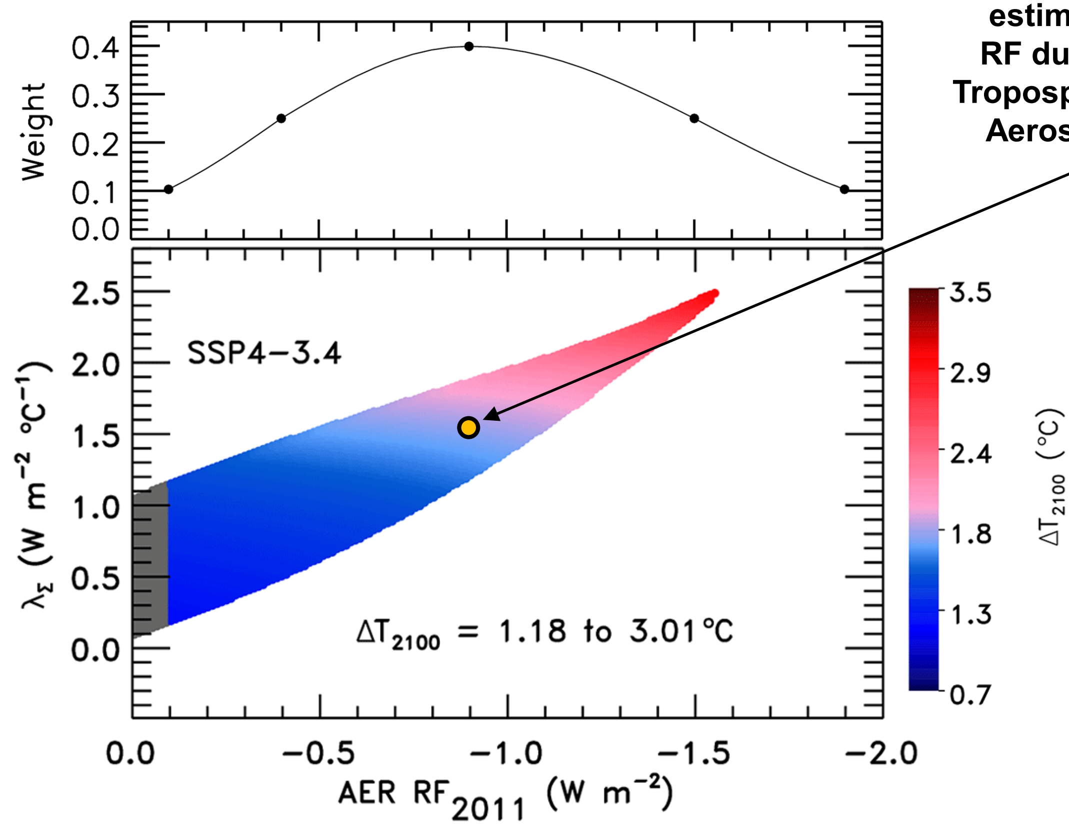
We assume that whatever value of climate feedback is inferred from the climate record will persist into the future. For Aerosol RF in 2011 of **–1.5 W m^{-2}** & assuming best estimate for H_2O and Lapse Rate feedback is correct, this simulation implies sum of other feedbacks (clouds, surface albedo) must be ***strongly positive***.

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

Same as FB_{TOTAL}



AR5 best estimate RF due to Tropospheric Aerosols

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

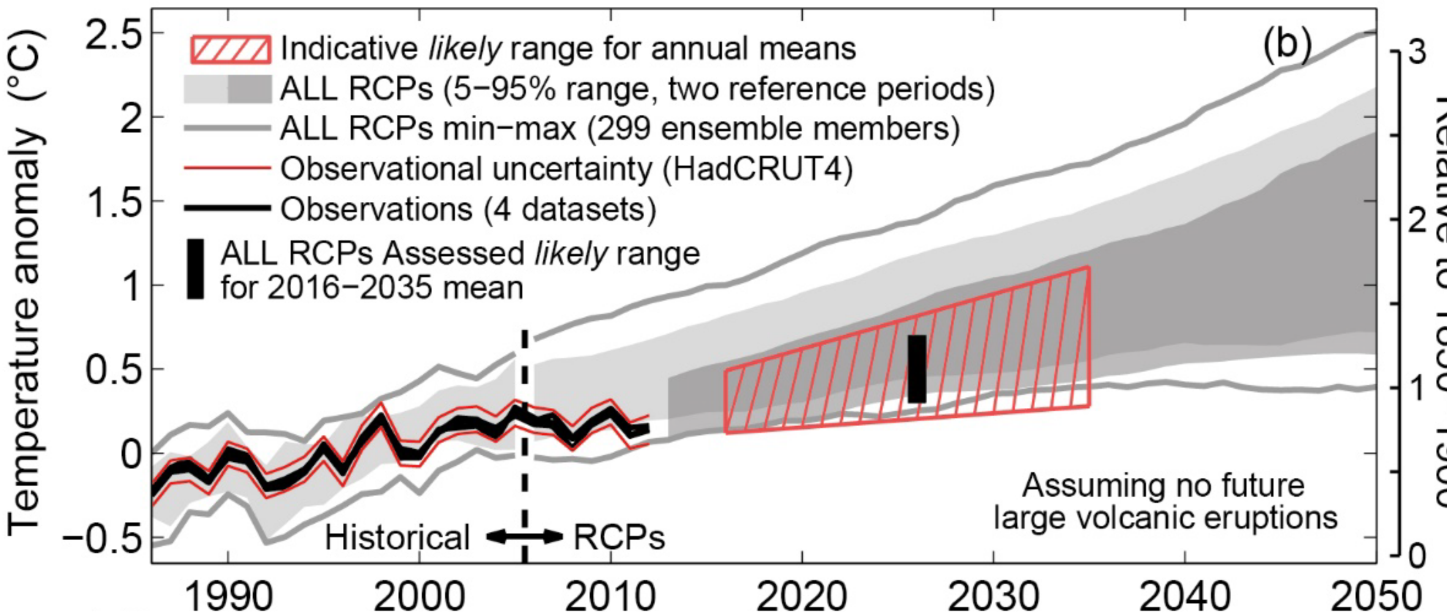
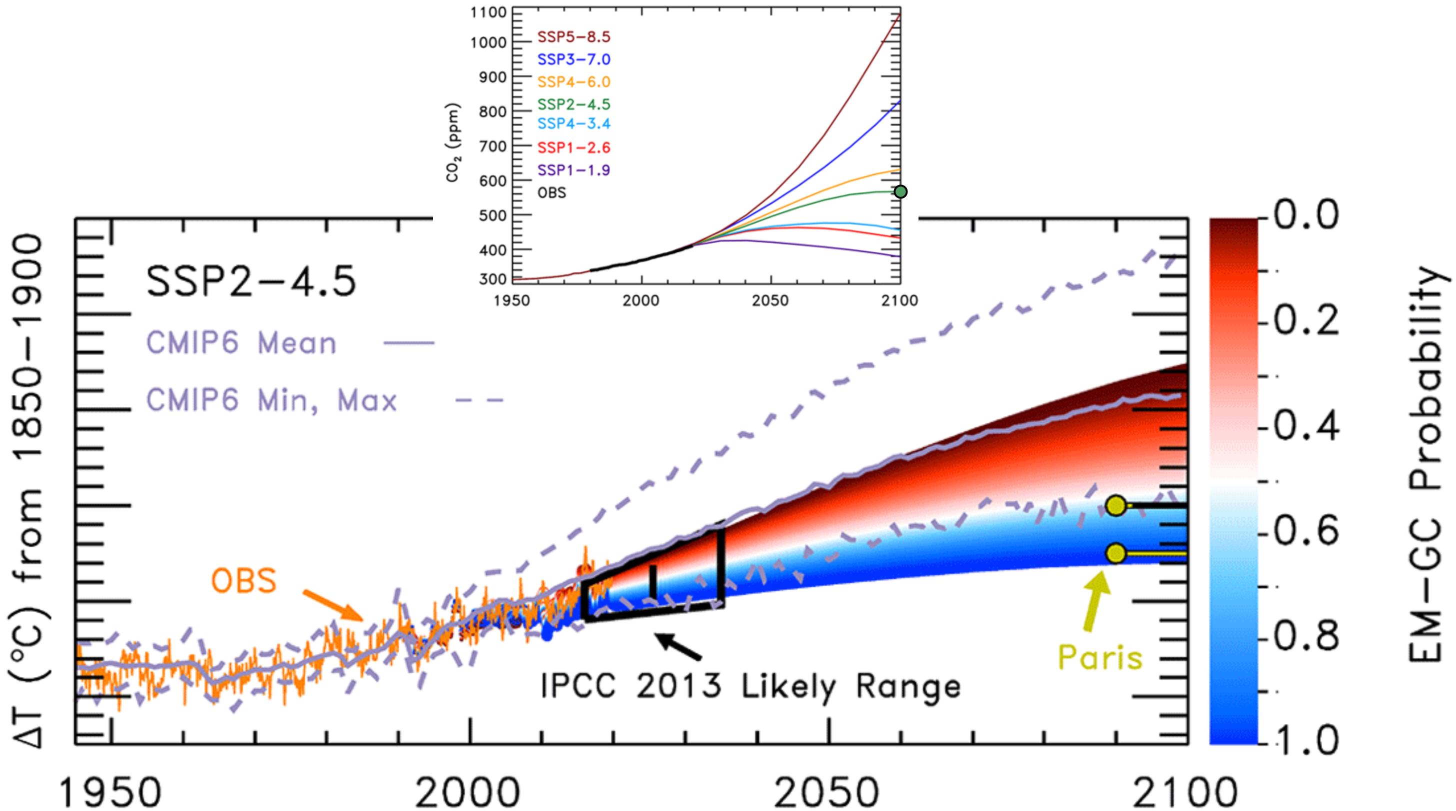


Fig 11.25b, IPCC (2013)

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

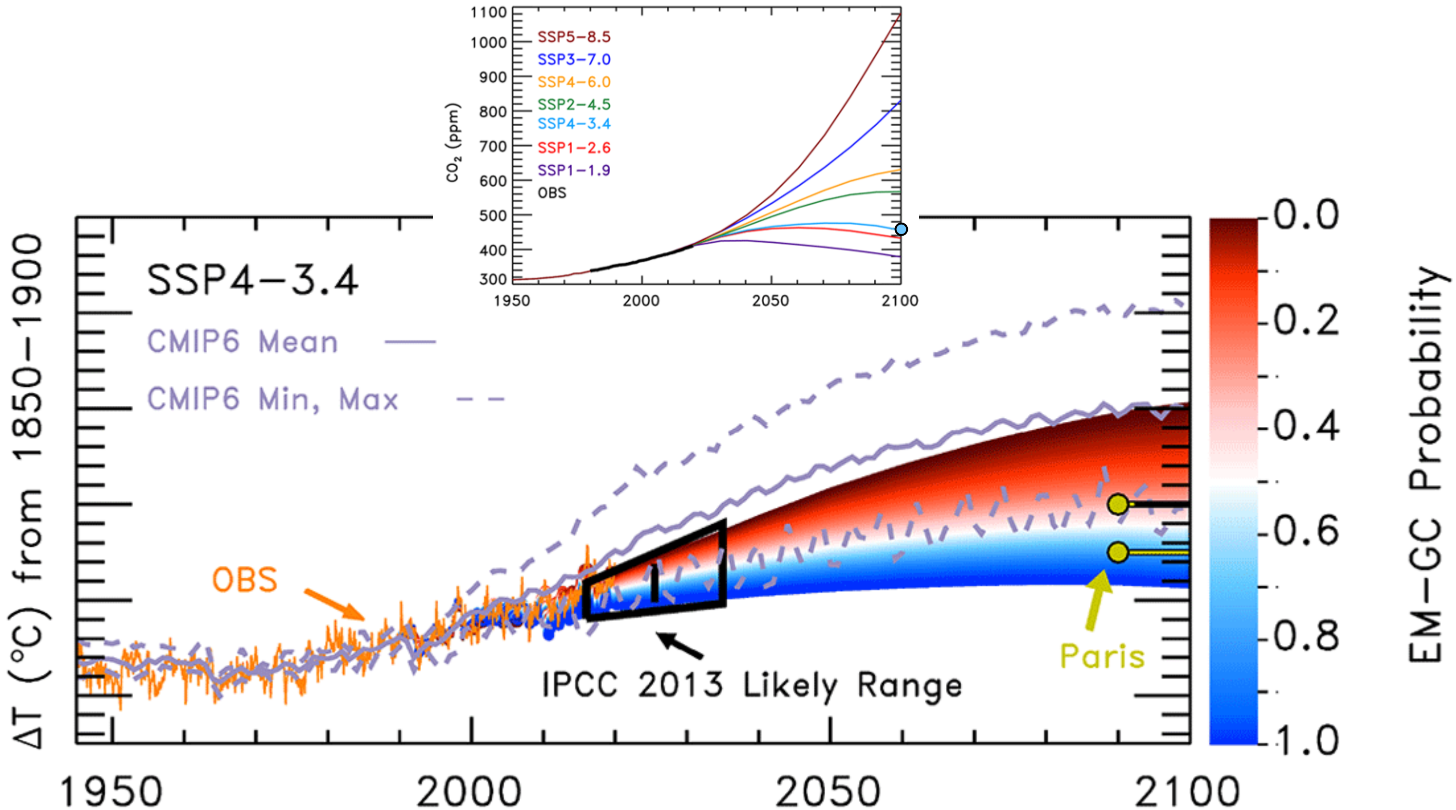


If GHGs follow SSP2-4.5, **2%** chance rise GMST stays below **1.5°C** and **33%** chance stays below **2.0°C**

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

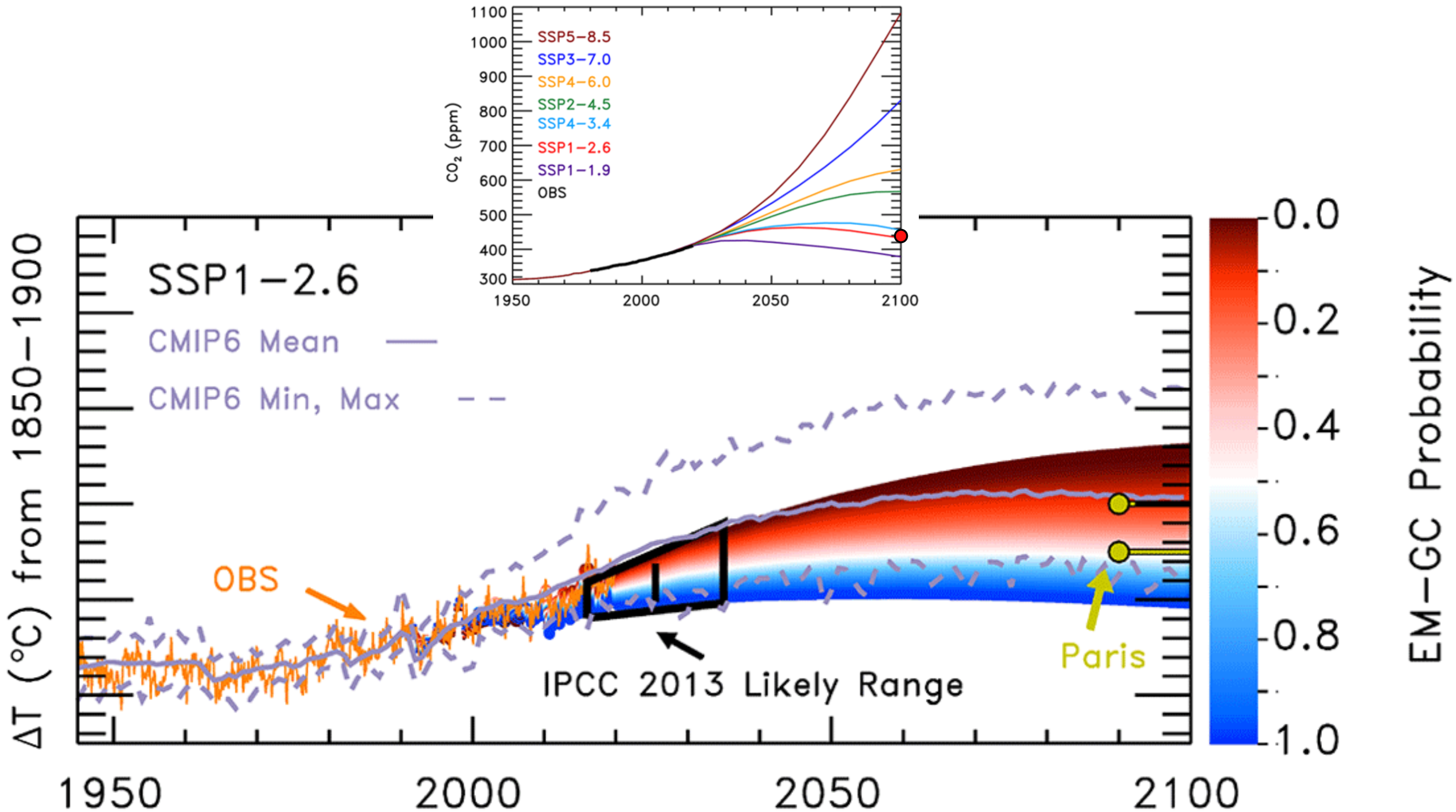


If GHGs follow SSP4-3.4, **19%** chance rise GMST stays below **1.5°C** and **64%** chance stays below **2.0°C**

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

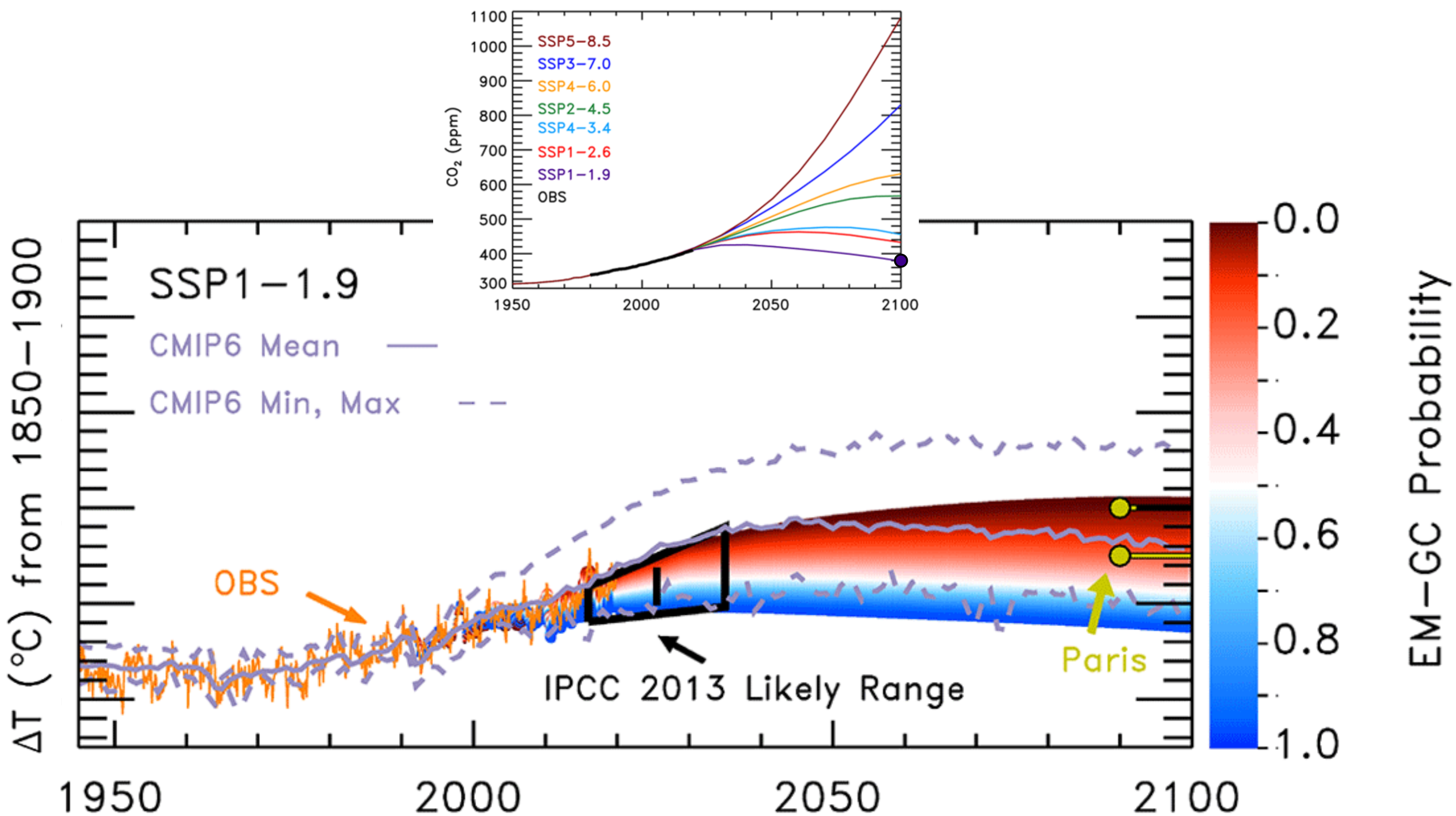


If GHGs follow SSP1-2.6, **53%** chance rise GMST stays below **1.5°C** and **86%** chance stays below **2.0°C**

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