Review for First Exam

AOSC / CHEM 433 & AOSC / CHEM 633

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Class Web Sites:
http://www2.atmos.umd.edu/~rjs/class/spr2022
https://myelms.umd.edu/courses/137772

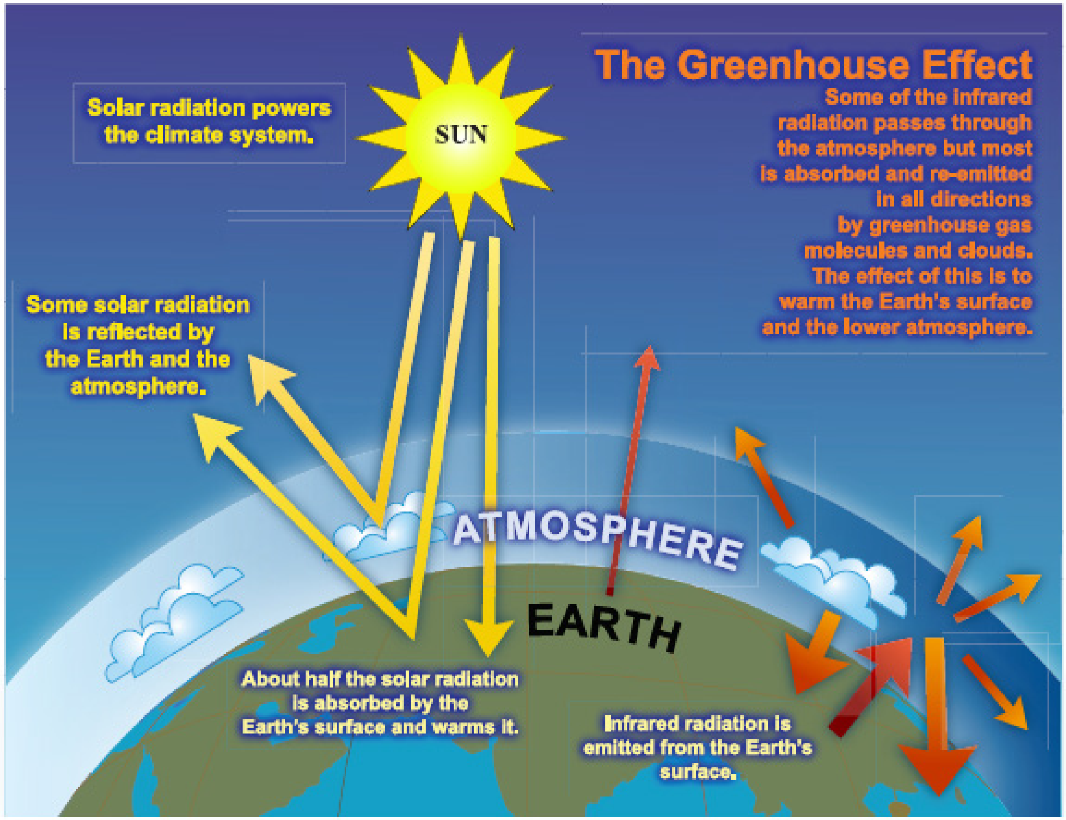
First exam is Thurs, 3 March, in class:

- Closed book
- Focus on concepts, no calculations
- Will cover material & required readings, Lectures 1 to 8
- Today, I will:
  - quickly review Problem Set 2
  - review Lectures 1 to 8
  - review exam given last time we had an in class exam

Review A

1 March 2022

Greenhouse Effect

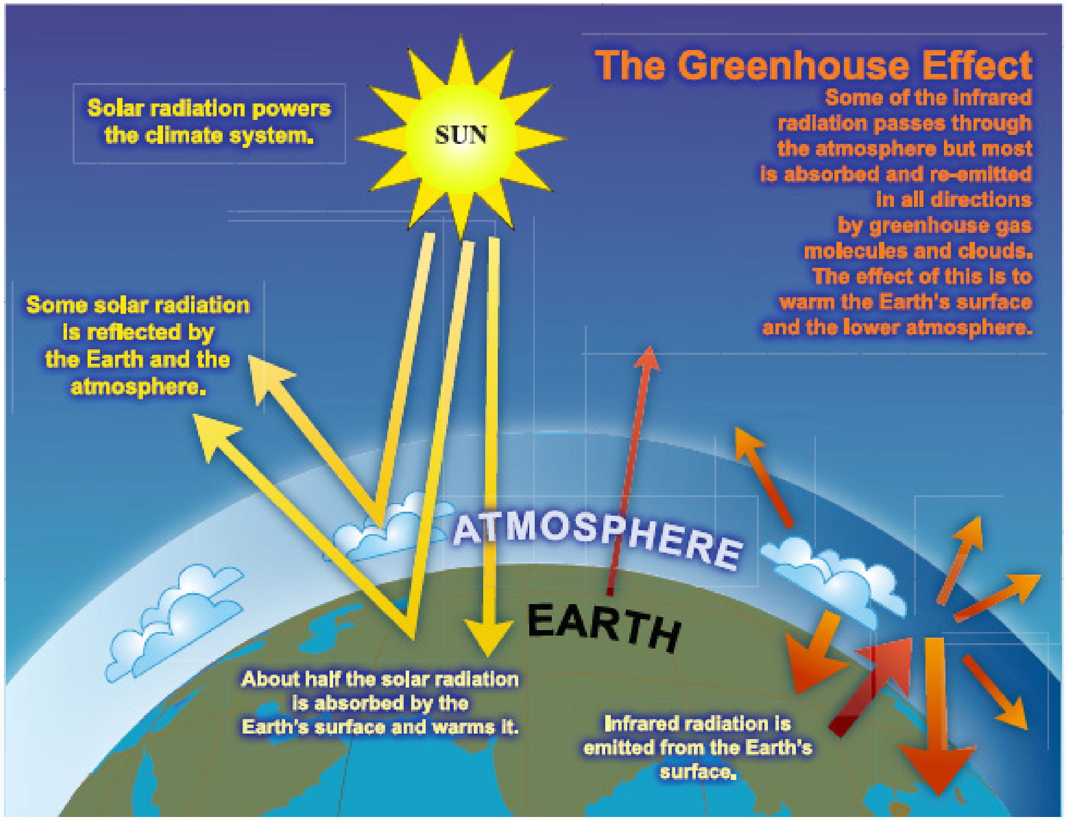


FAQ 1.3, Figure 1. *An idealised model of the natural greenhouse effect. See text for explanation.*

Question 1.3, IPCC, 2007

What is the most important greenhouse gas (GHG) ?

Greenhouse Effect



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

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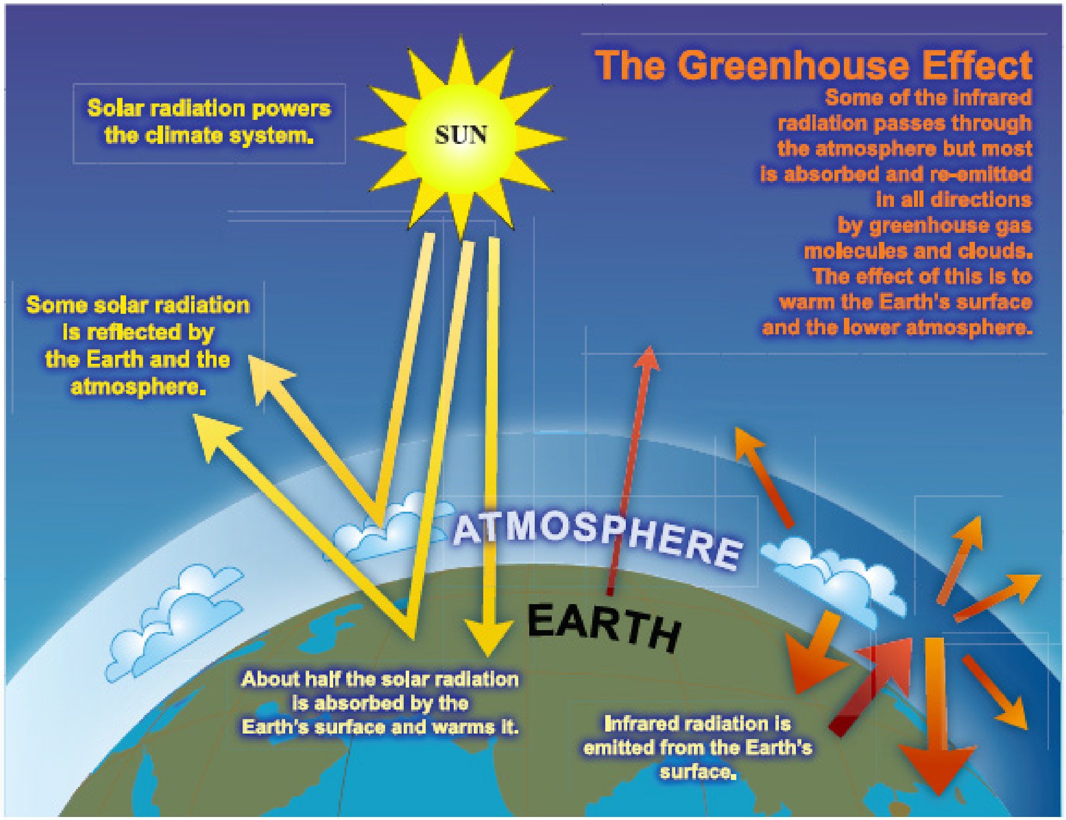
What is the most important *anthropogenic* greenhouse gas (GHG) ?

Greenhouse Effect



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

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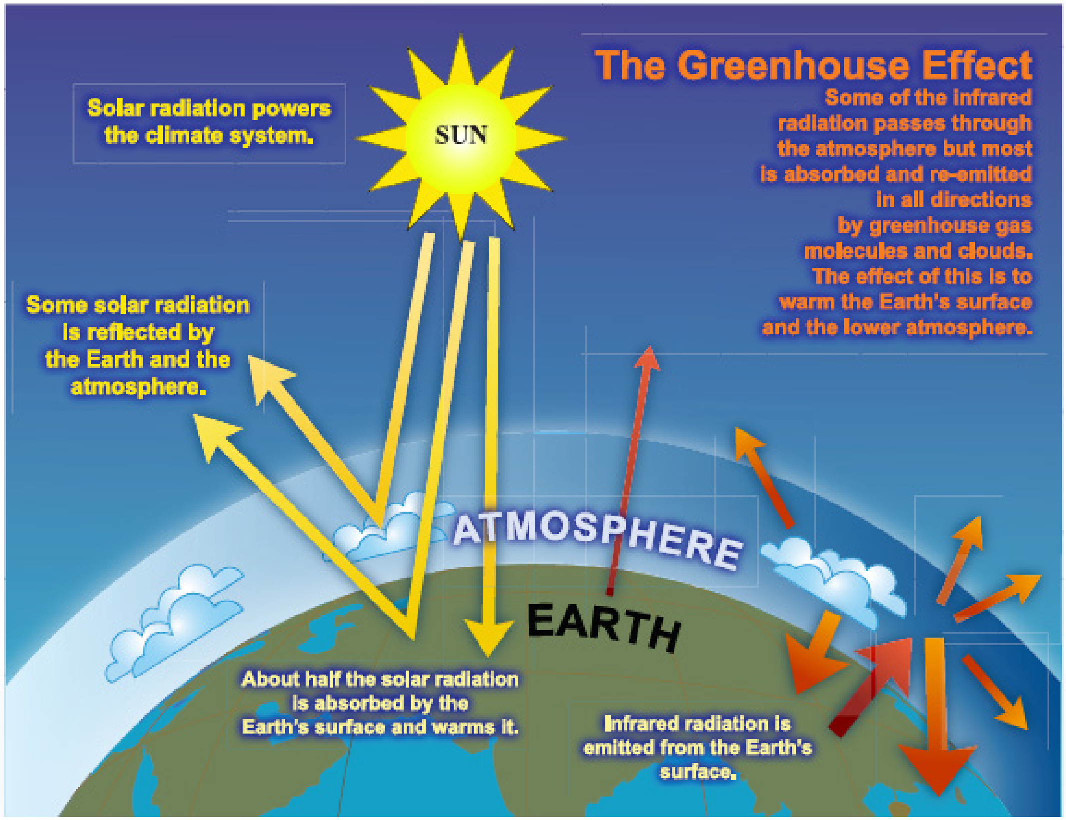
What is the most important *__anthropogenic__* greenhouse gas (GHG) ?

Second most important ?

Greenhouse Effect



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

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What is the most important *anthropogenic* greenhouse gas (GHG) ?

Second most important ?

Third ?

Radiative Forcing of Climate, 1750 to 2019

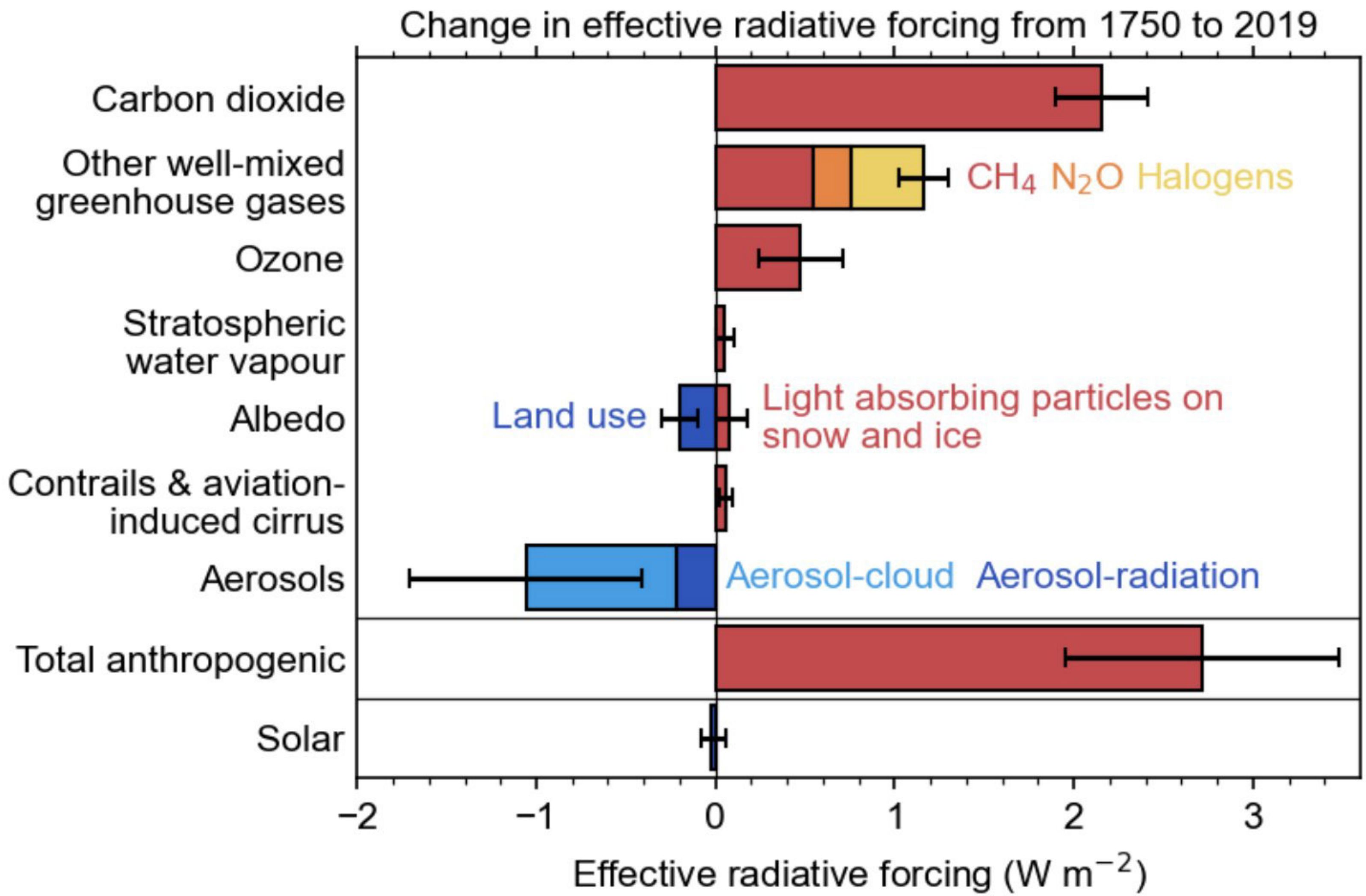
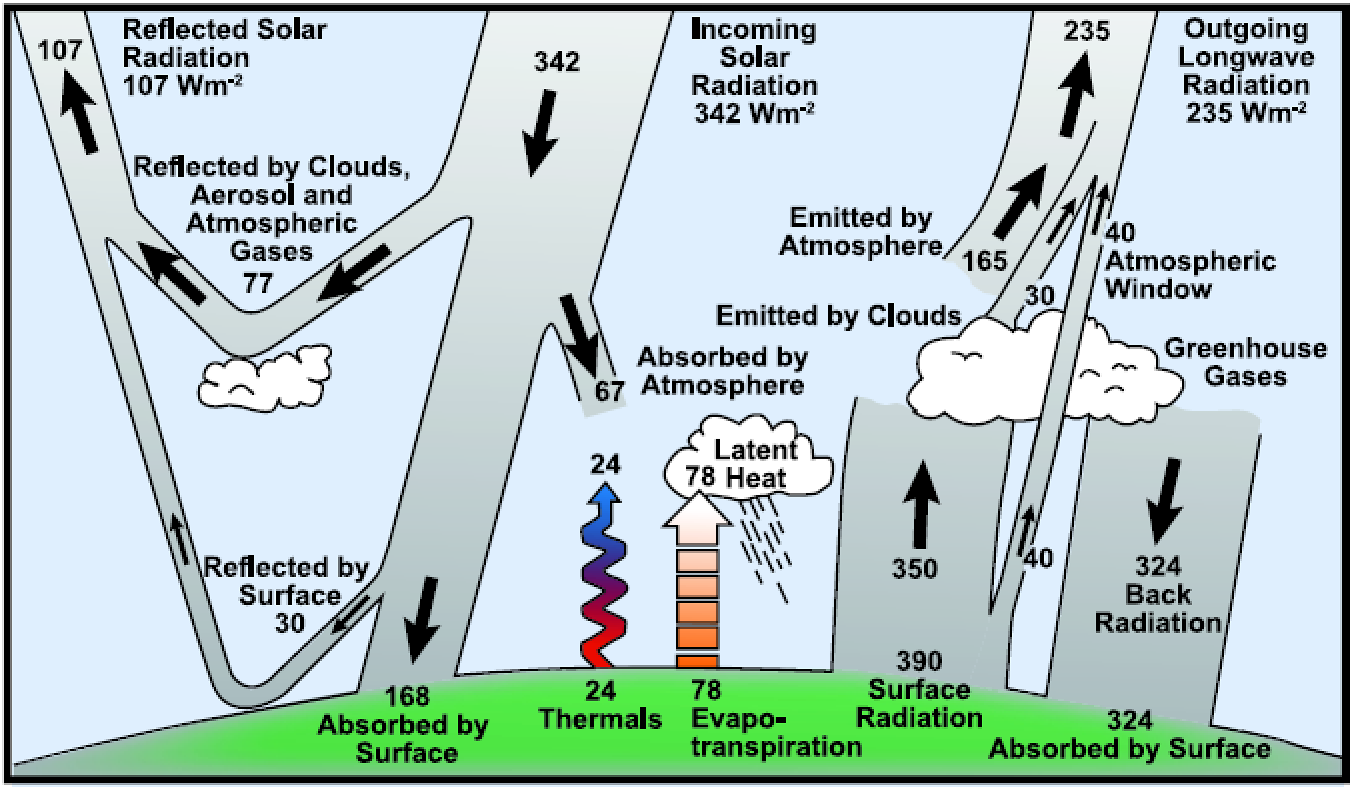


Figure 7.6, IPCC (2021)
https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_TS.pdf

Radiative Forcing

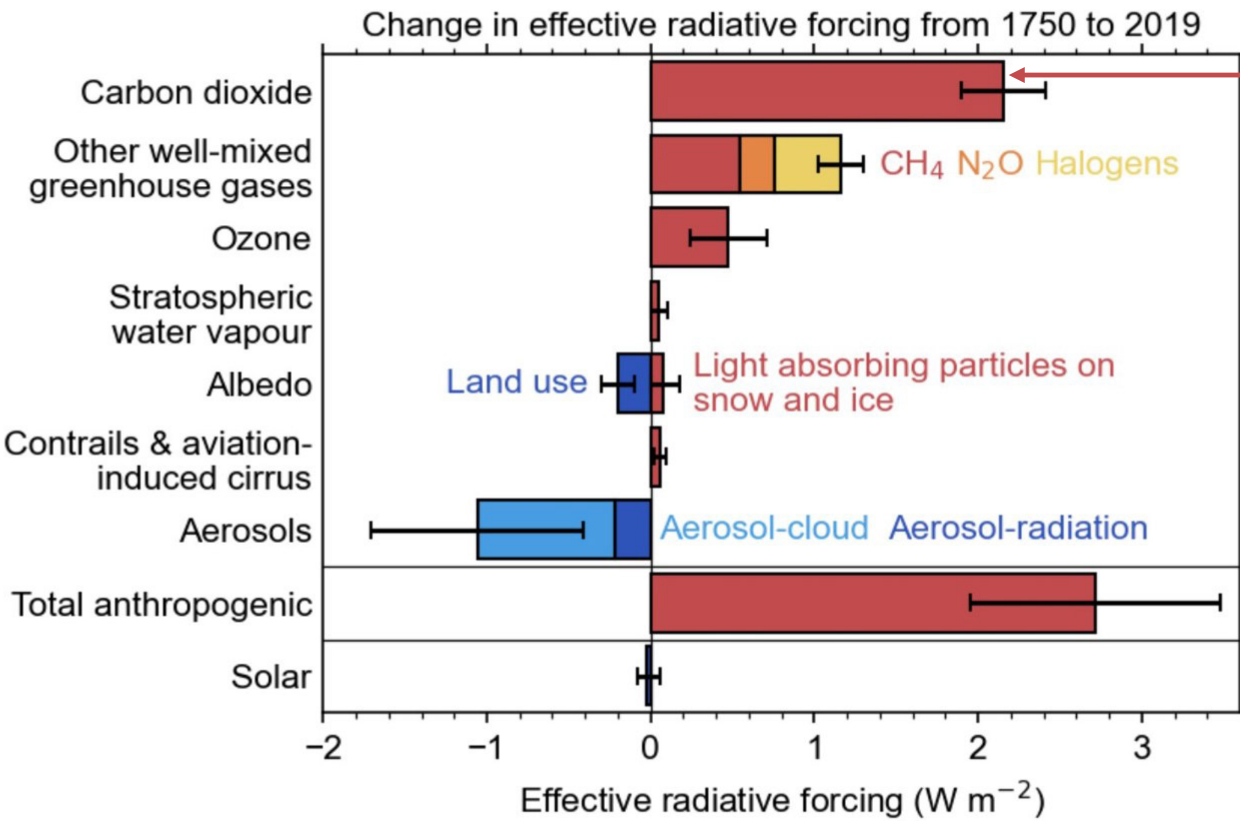


FAQ 1.1, Figure 1. *Estimate of the Earth's annual and global mean energy balance. Over the long term, the amount of incoming solar radiation absorbed by the Earth and atmosphere is balanced by the Earth and atmosphere releasing the same amount of outgoing longwave radiation. About half of the incoming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

Radiative Forcing of Climate, 1750 to 2019

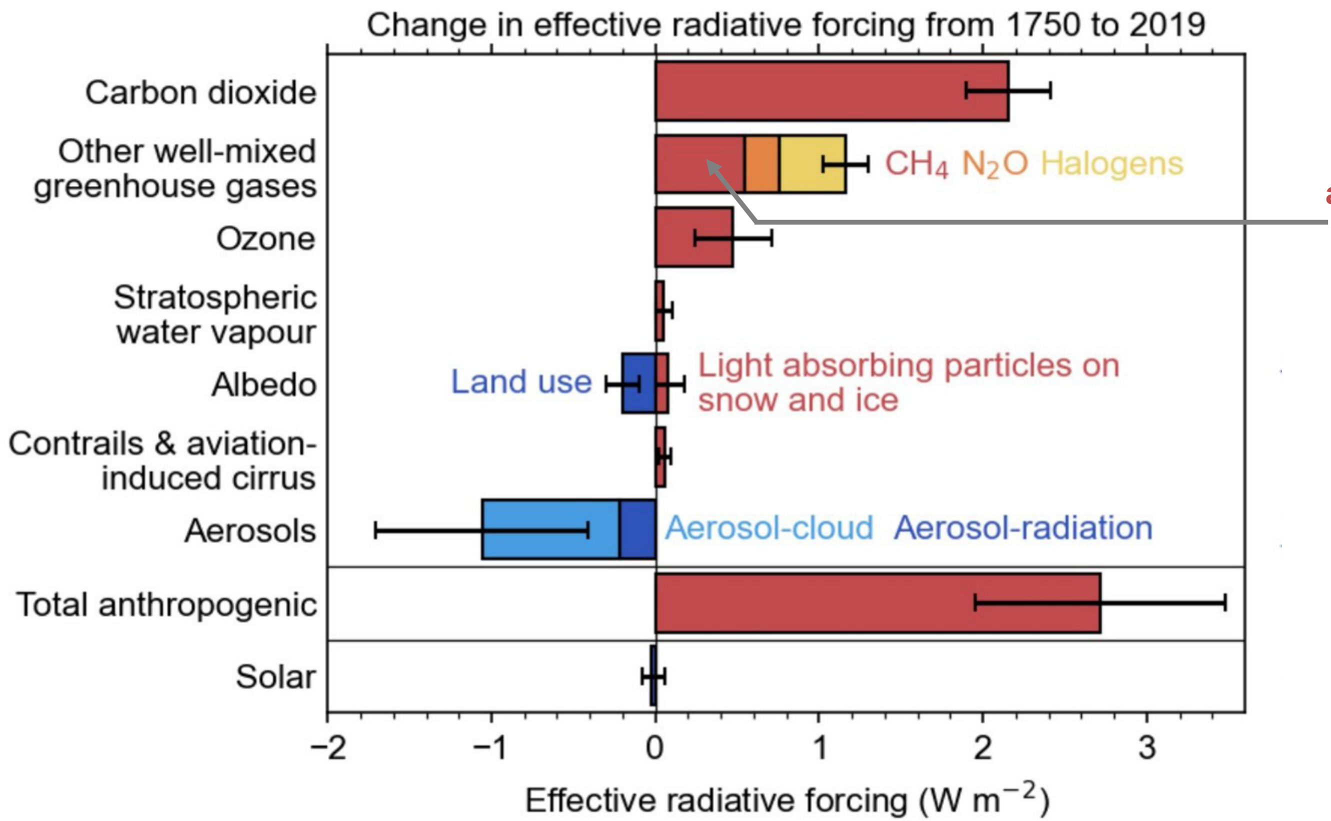


CO_2 is dominant anthropogenic (human) greenhouse gas (GHG). Once released, CO_2 persists in the atmosphere for hundreds of years.

Between 1750 and 2019, the rise in atmospheric CO_2 caused RF of climate to rise by 2.2 W m^{-2}

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

Radiative Forcing of Climate, 1750 to 2019



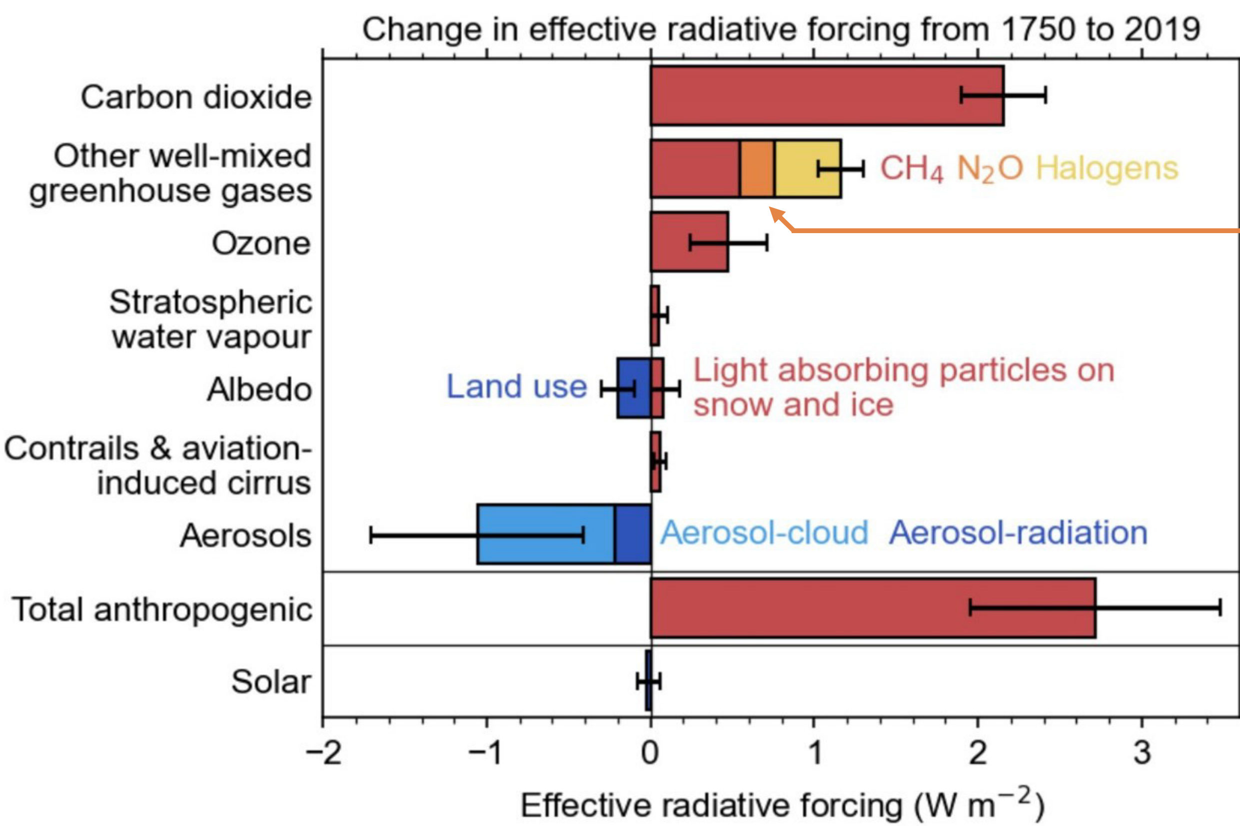
Methane (CH_4) is the 2nd most important human GHG. Once released, CH_4 persists in the atmosphere for about decade.

On a per molecule basis, CH_4 causes 30 times more warming than CO_2 over a 20-yr time horizon.

Between 1750 and 2019 the rise in atmospheric CH_4 caused RF of climate to rise by 0.54 W m^{-2}

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

Radiative Forcing of Climate, 1750 to 2019



Nitrous oxide (N_2O) is commonly identified as the third most important anthropogenic GHG.

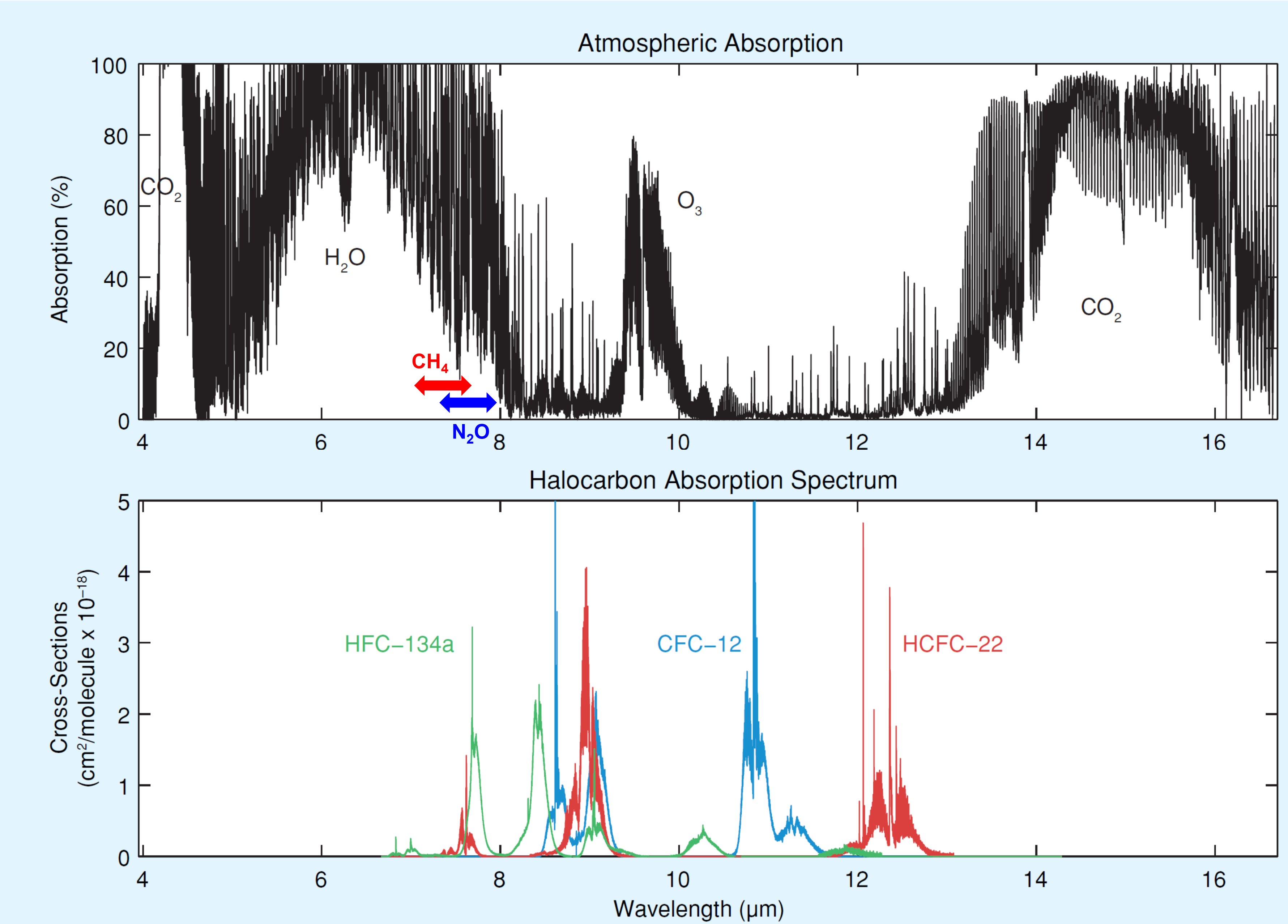
On either a per molecule or a per mass basis, N_2O causes 264 times more warming than CO_2 over a 20-yr time horizon.

Between 1750 and 2011, the rise in atmospheric N_2O caused RF of climate to rise by 0.21 W m^{-2}

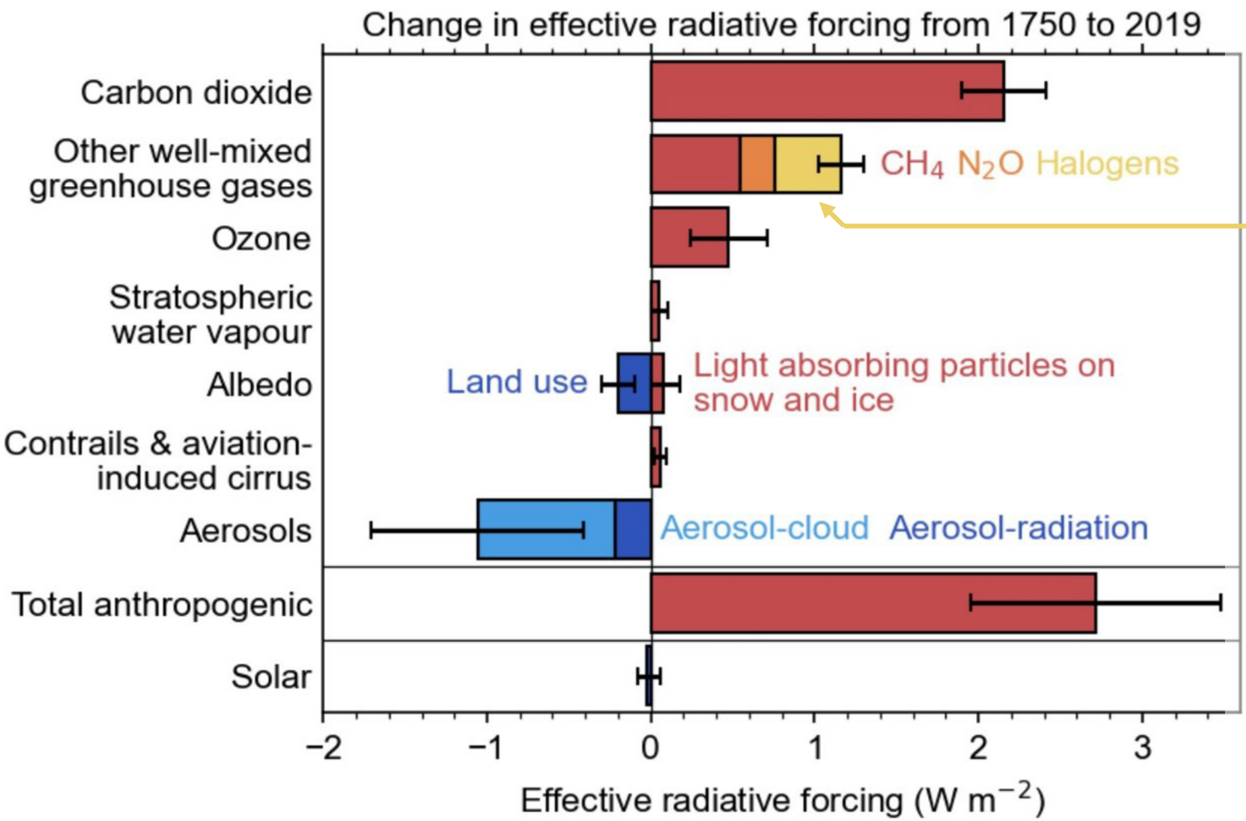
Together, the rise in RF of climate due to CH_4 and N_2O was about one-third the rise in RF of climate due to CO_2

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

Absorption vs. Wavelength



Radiative Forcing of Climate, 1750 to 2019



CFCs and other ozone depleting substances (ODSs), which are all Halogens, also act as GHGs.

Between 1750 and 2019, the rise in ODS caused RF of climate to rise by 0.41 W m^{-2}

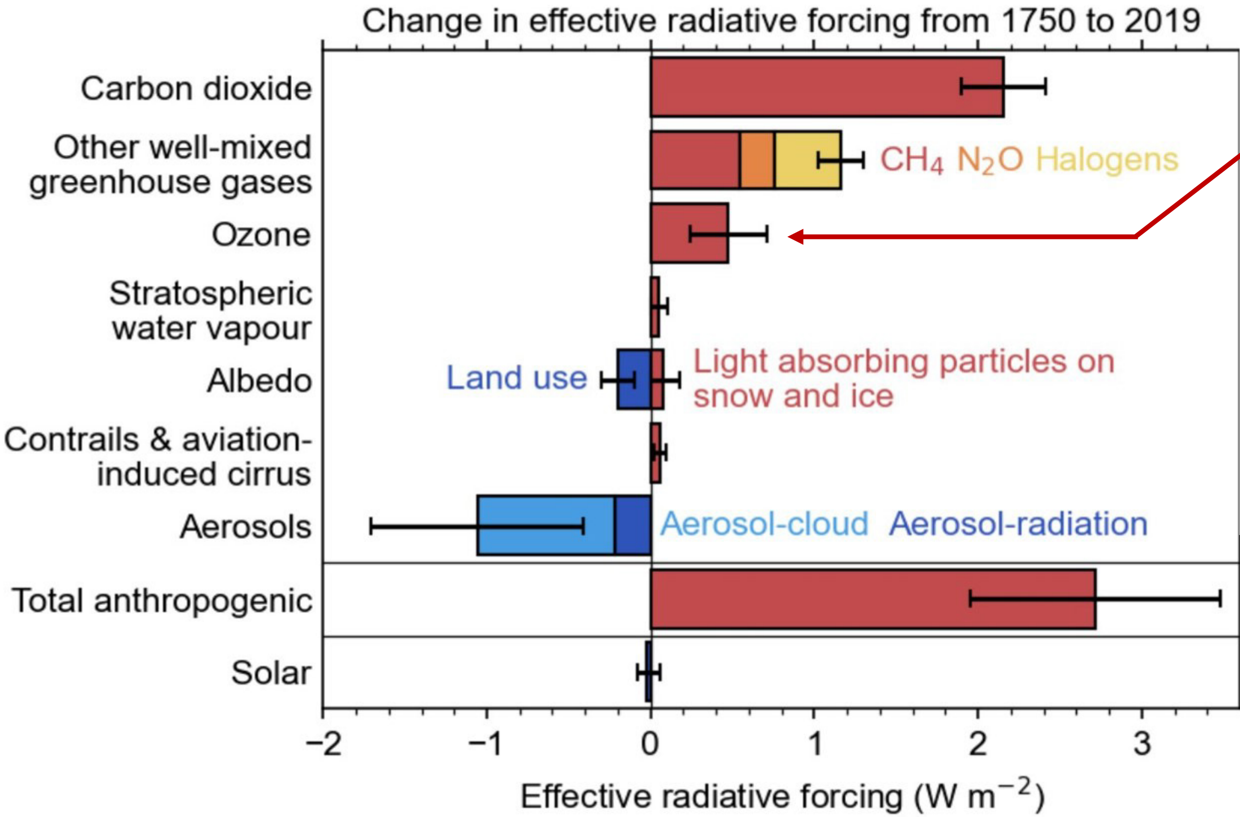
The rise in RF of climate due to CH_4, N_2O, and ODSs was *about half* of the the rise in RF of climate due to CO_2

Industrial production of CFCs and other ODS was banned by the Montreal Protocol.

Atmospheric levels of CFCs have declined, although not quite as fast as had been expected.

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

Radiative Forcing of Climate, 1750 to 2019



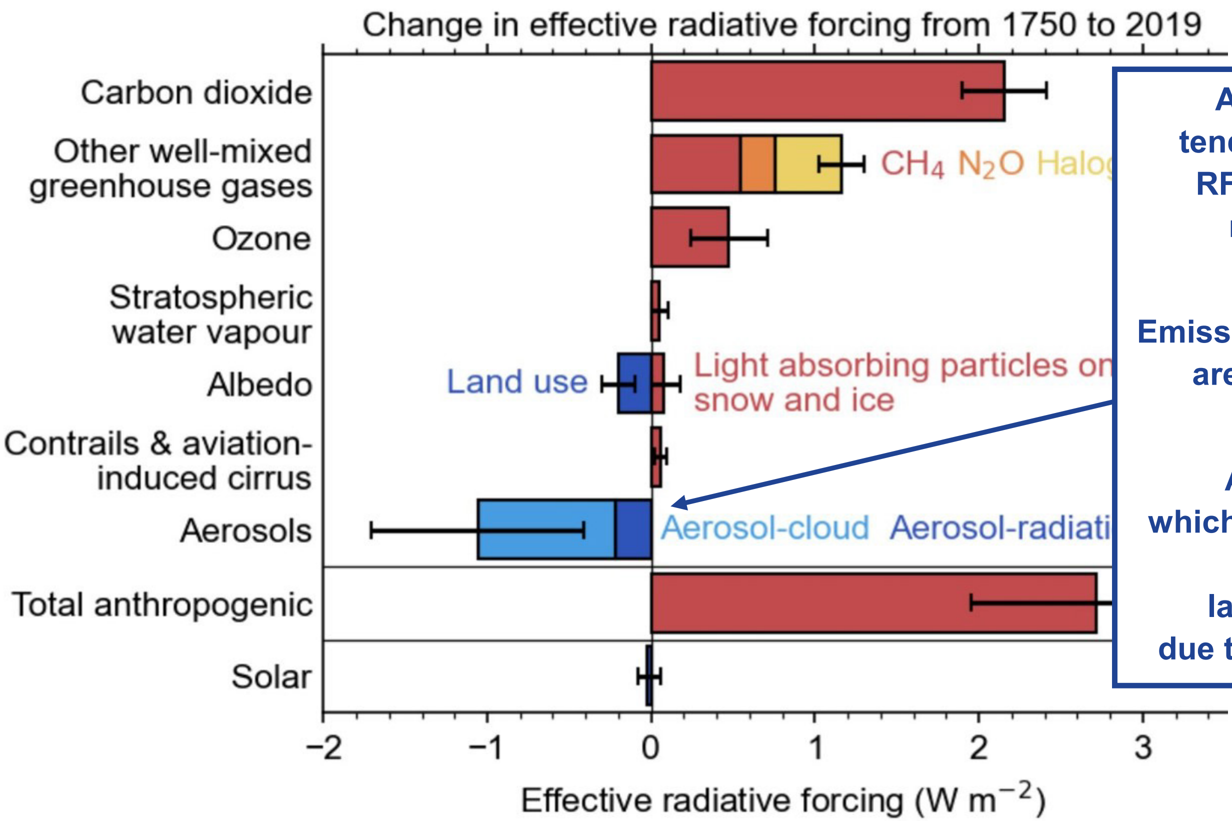
Ozone (O_3) acts as a GHG.

Between 1750 and 2011, the rise in tropospheric O_3 caused RF of climate to rise by 0.47 W m^{-2}

This rise is due to increasing levels of O_3 in Earth's troposphere, leading to poor public health. Efforts to combat the rise in tropospheric O_3 are led by air quality agencies.

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

Radiative Forcing of Climate, 1750 to 2019



Aerosols (small particulate matter) tend to cool climate, counter-acting the RF of climate due to GHGs. However, magnitude of this counter-action is not well known.

Emissions of pollutants that lead to aerosols are regulated worldwide by air quality agencies.

Aerosol levels are on the decline, which will either "unleash" a small amount, moderate amount, or perhaps a large amount of additional warming due to GHGs that are presently "masked".

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

Ozone in the Atmosphere

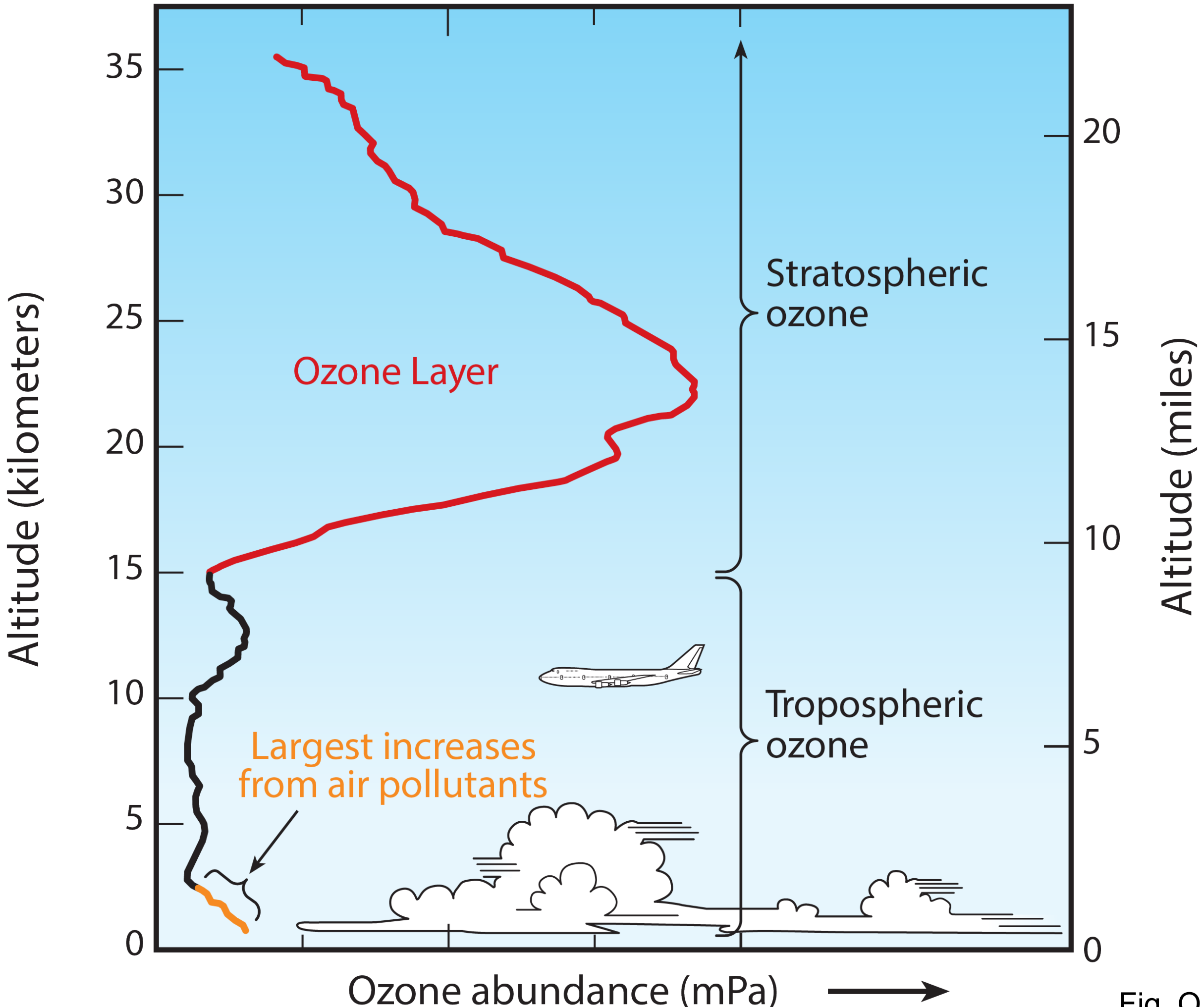
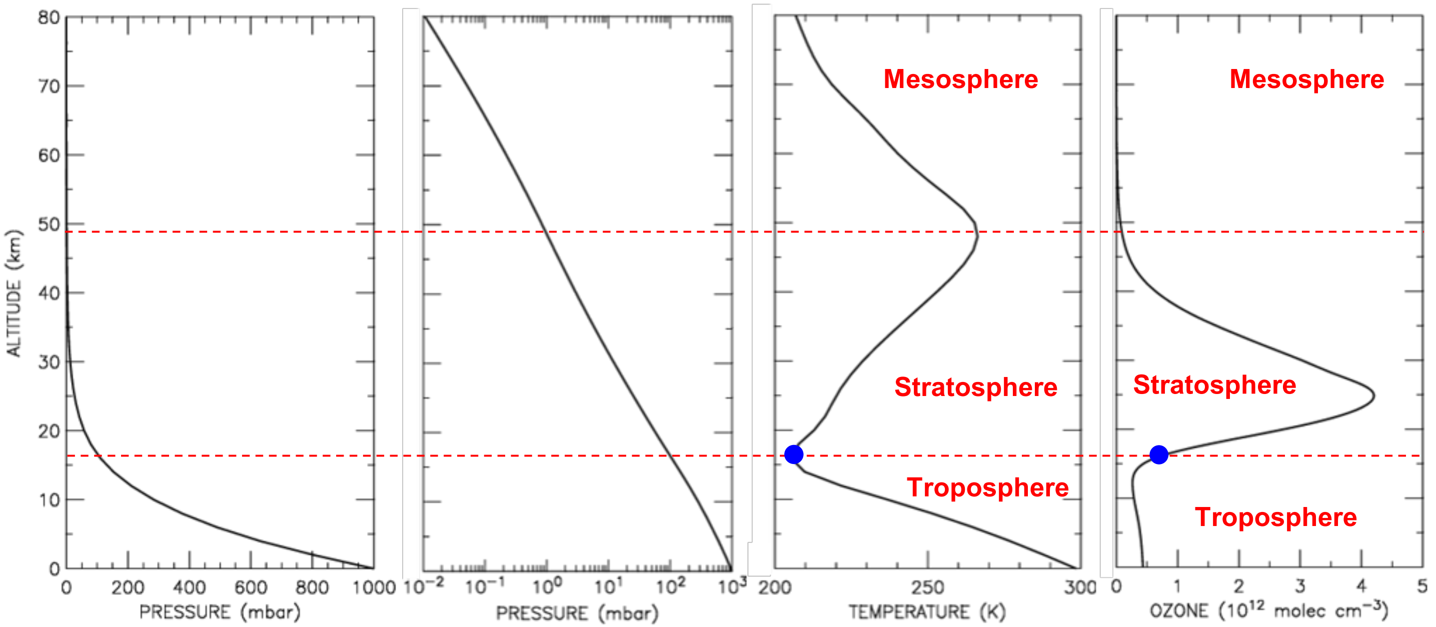


Fig. Q1-2
20 QAs about the Ozone Layer

It is incredible that human activity both destroys stratospheric ozone (so-called good ozone) and produces tropospheric ozone (so-called bad ozone)

Temperature versus Altitude

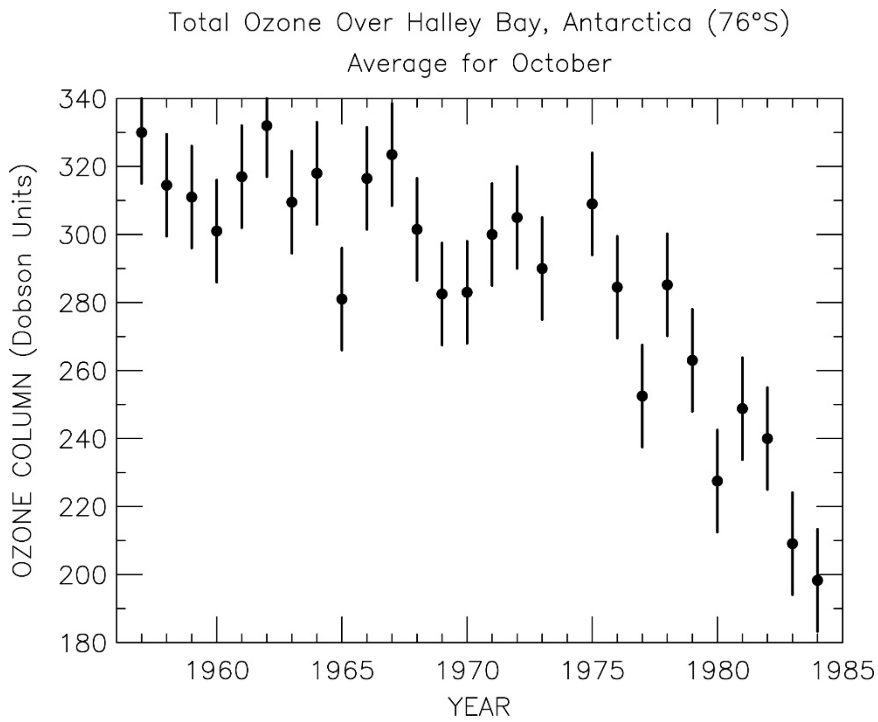


•T falls wrt increasing altit until the tropopause, then rises wrt altit until the stratopause, then falls wrt to rising altitude

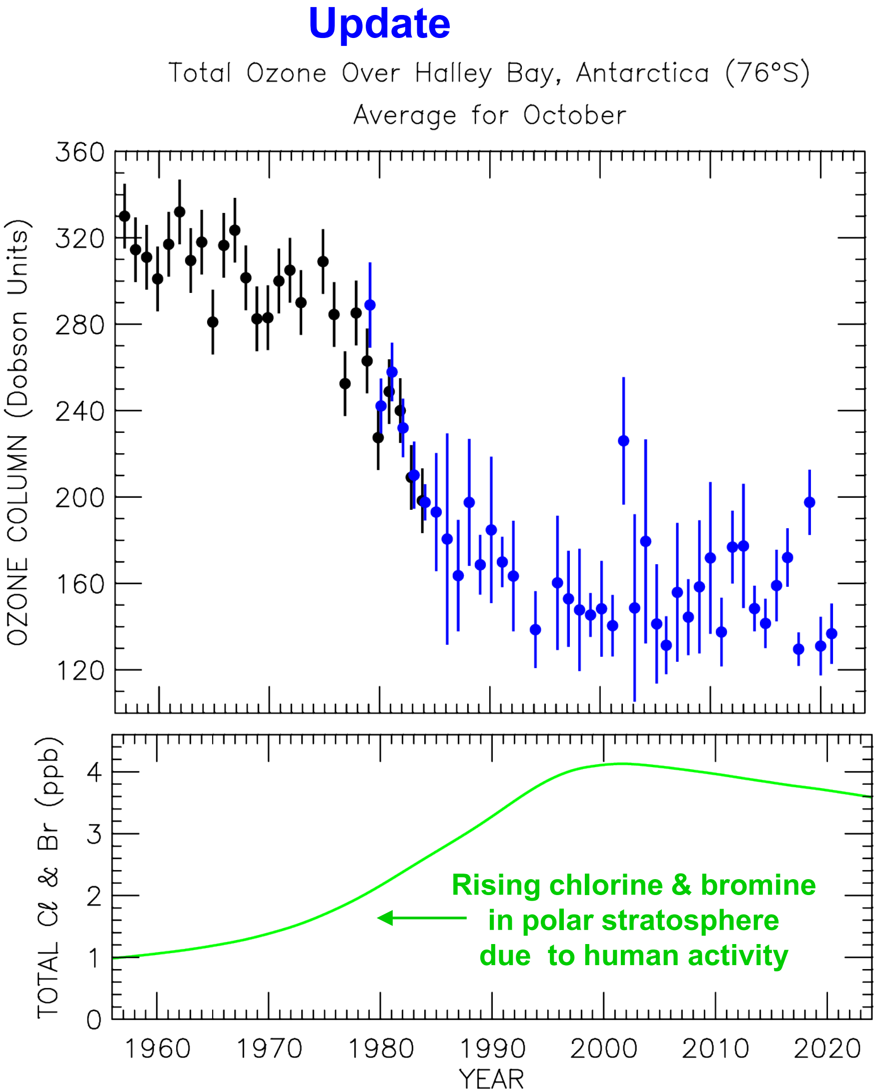
Fourth chart expresses abundance of ozone concentration, or ozone density, or $[O_3]$, in units of molecules / cm^3

Earth's Atmosphere – Effect of Humans

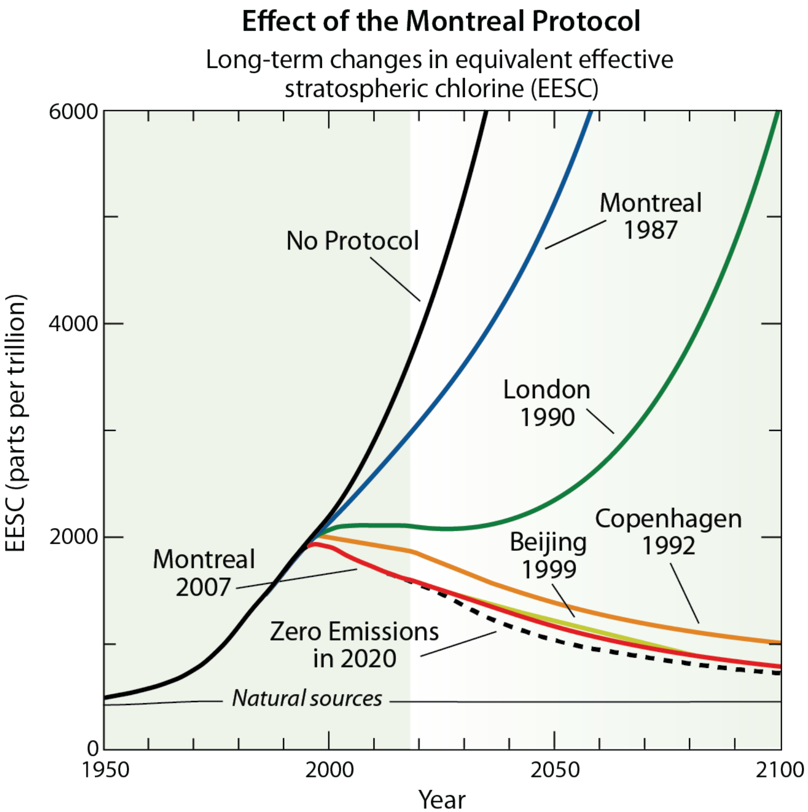
Stratospheric Ozone – shields surface from solar UV radiation



After Farman *et al*., Large losses of total ozone in Antarctica reveal Seasonal ClOx/NOx interaction, Nature, 315, 207, 1985.



And Atmospheric Levels of these Pollutants are Declining



CFCs: Chlorofluorocarbons

Contain some combination of chlorine, fluorine, and at least one carbon. Freons are a trade name for CFCs.

Bromocarbons:

Contain bromine, perhaps chlorine, and at least one carbon. Halons are a trade name for bromocarbons.

HCFCs: Hydro-chlorofluorocarbons

Same as CFCs, except one or more hydrogen has replaced a chlorine.

HFCs: Hydrofluorocarbons

Contain some combination of hydrogen, fluorine, and carbon. **These gases do not contain any bromine or chlorine, and hence pose no damage to the ozone layer.** Some HFCs are potent GHGs.

EESC: Equivalent, effective stratospheric chlorine. Reflects combined influence of chlorine and bromine on ozone, via a simple formula: [Chlorine] + 60 × [Bromine]

Figure Q14-1, 20 QAs about the Ozone Layer

Phase out of CFCs and other Ozone Depleting Substances (ODSs)

Phase 1: CFCs & other ODSs → HCFCs

Phase 2: HCFCs → HFCs

CFCs & other ODSs

CFC-11
CFC-12
CFC-113
CFC-114
CFC-115
CCl_4
CH_3CCl_3

Harmful to ozone layer

HCFCs

HCFC-22
HCFC-141b
HCFC-142b

Less harmful to ozone layer

HFCs

HFC-23
HFC-143a
HFC-125
HFC-134a
etc.

But very harmful to Earth's climate

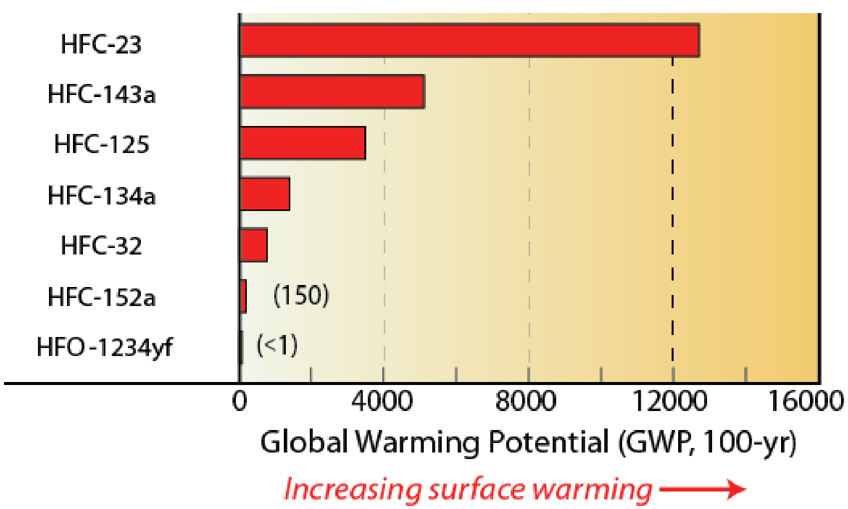


Figure Q17-3, 20 QAs about the Ozone Layer

Phase out of CFCs and other Ozone Depleting Substances (ODSs)

Phase 1 →		Phase 2 →	
CFCs & other ODSs		**HCFCs**	**HFCs**

CFCs & other ODSs

CFC-11
CFC-12
CFC-113
CFC-114
CFC-115
CCl_4
CH_3CCl_3

Harmful to ozone layer

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Less harmful to ozone layer

HFCs

HFC-23
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etc.

But very harmful to Earth's climate

Phase 3

As of 15 October 2016, future production of HFCs controlled by the Montreal Protocol, based on amendment passed in Kigali, Rwanda

http://multimedia.3m.com/mws/media/1365924O/unep-fact-sheet-kigali-amendment-to-mp.pdf

Climate Benefit of the Kigali Amendment

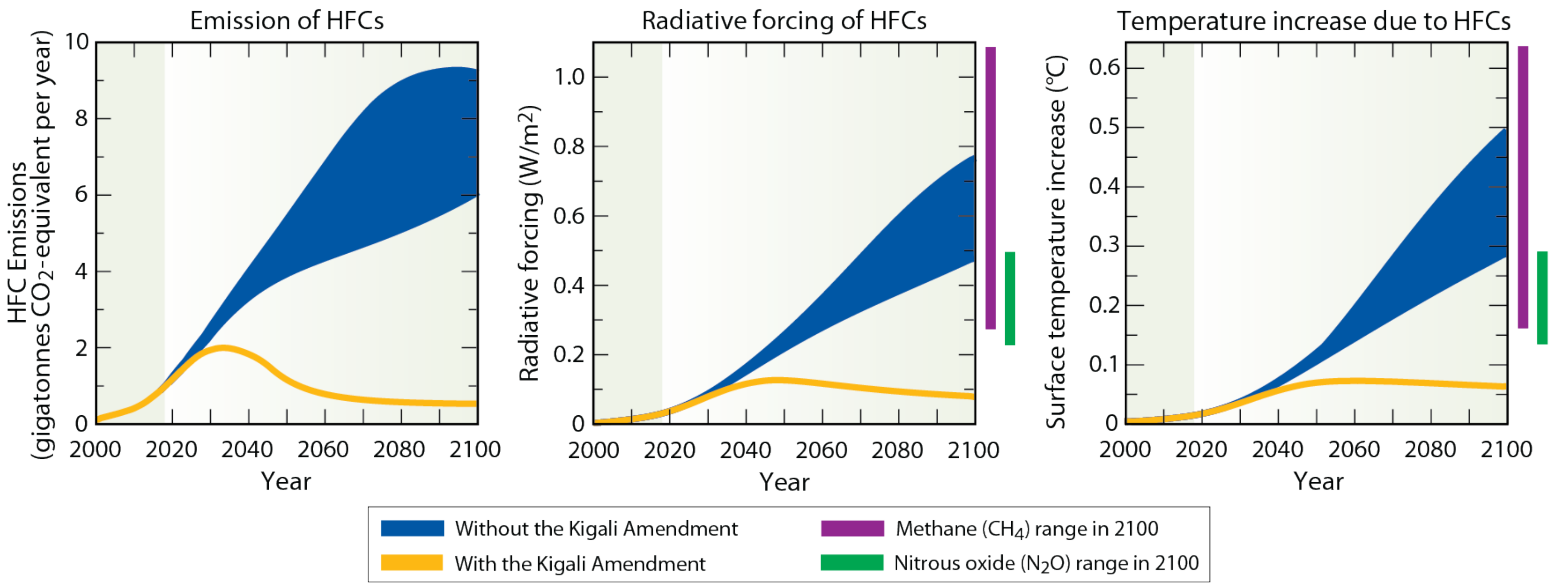

Figure Q19-2, 20 QAs about the Ozone Layer

GHG Record Over Last Several Millennia

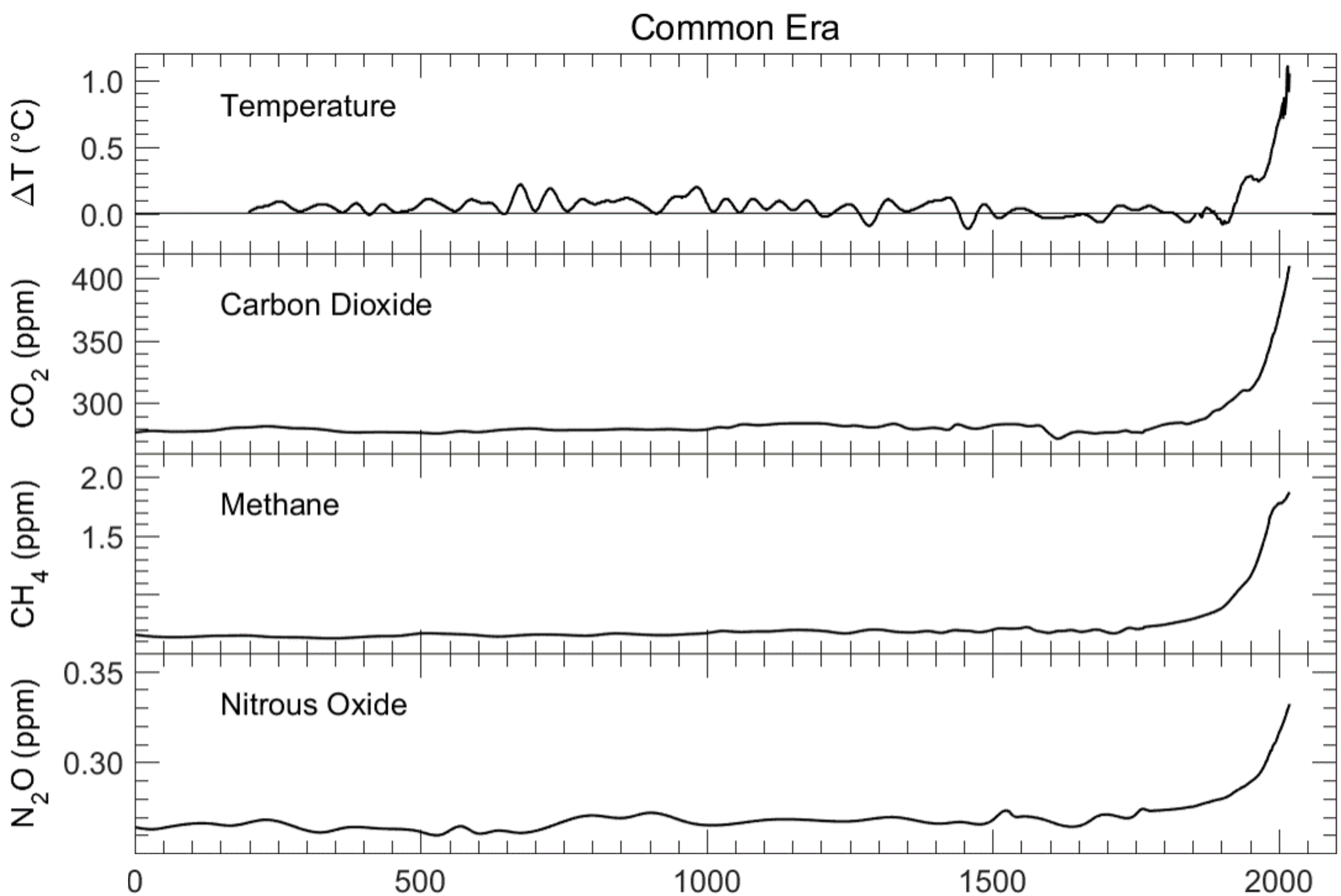

Figure 1.2, Paris Beacon of Hope (updated)

GHG Record Over Last Several Millennia

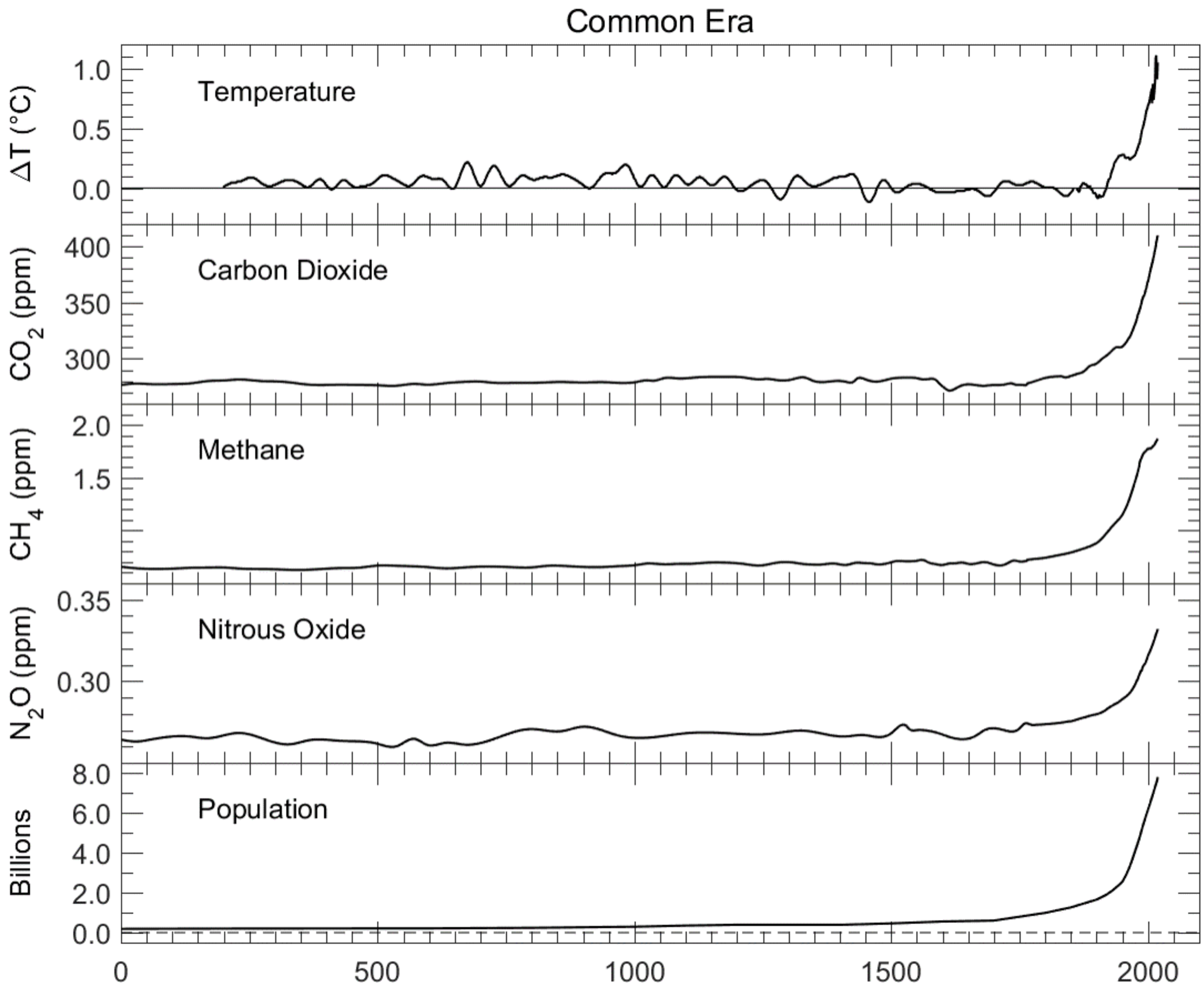

Figure 1.2, Paris Beacon of Hope (updated)

Going Back 600,000 years

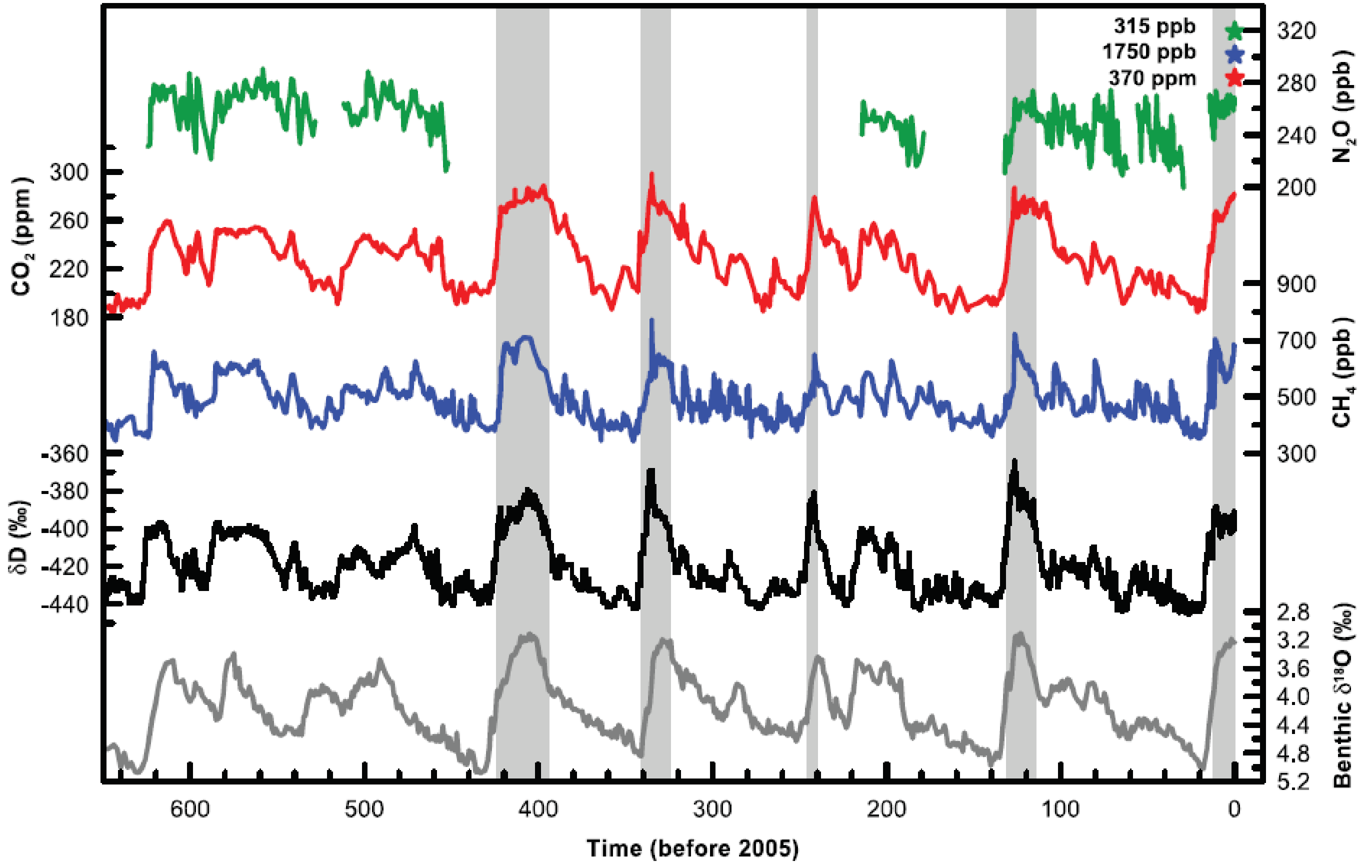

Figure 6.3. *Variations of deuterium (δD; black), a proxy for local temperature, and the atmospheric concentrations of the greenhouse gases CO_2 (red), CH_4 (blue), and nitrous oxide (N_2O; green) derived from air trapped within ice cores from Antarctica and from recent atmospheric measurements (Petit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

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

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 *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

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

GWP – Global Warming Potential

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

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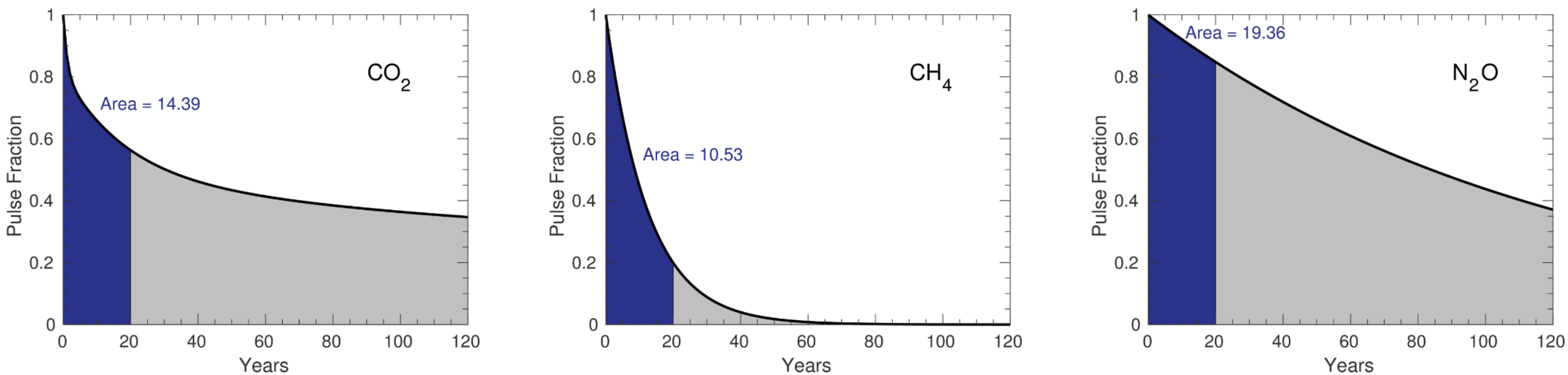
Global Warming Potentials

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



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

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

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

where all times are given in units of year

GWP – Global Warming Potential

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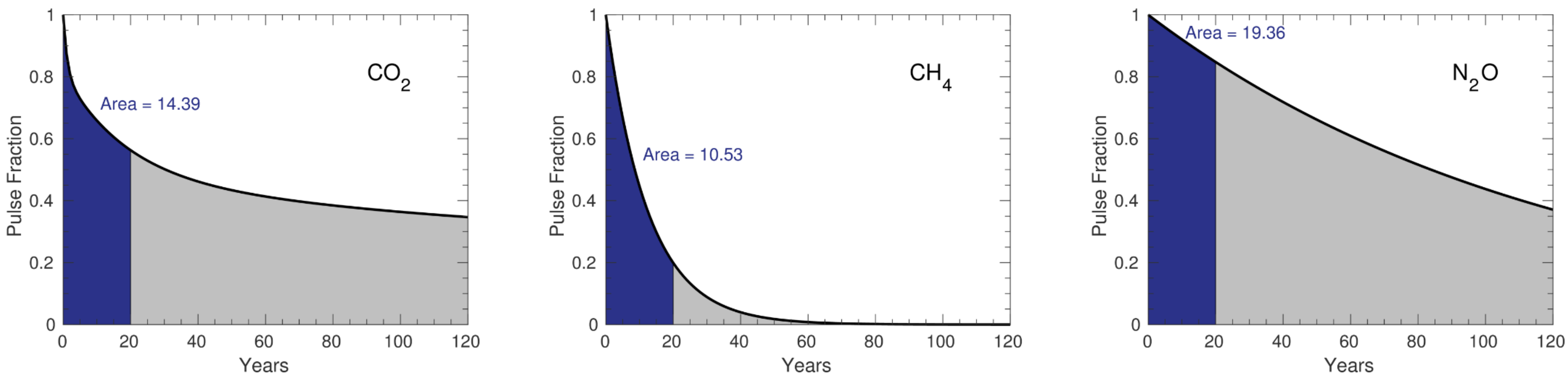
20 Year Time Horizon means time final = 20 years in these integrals



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GWP – Global Warming Potential

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

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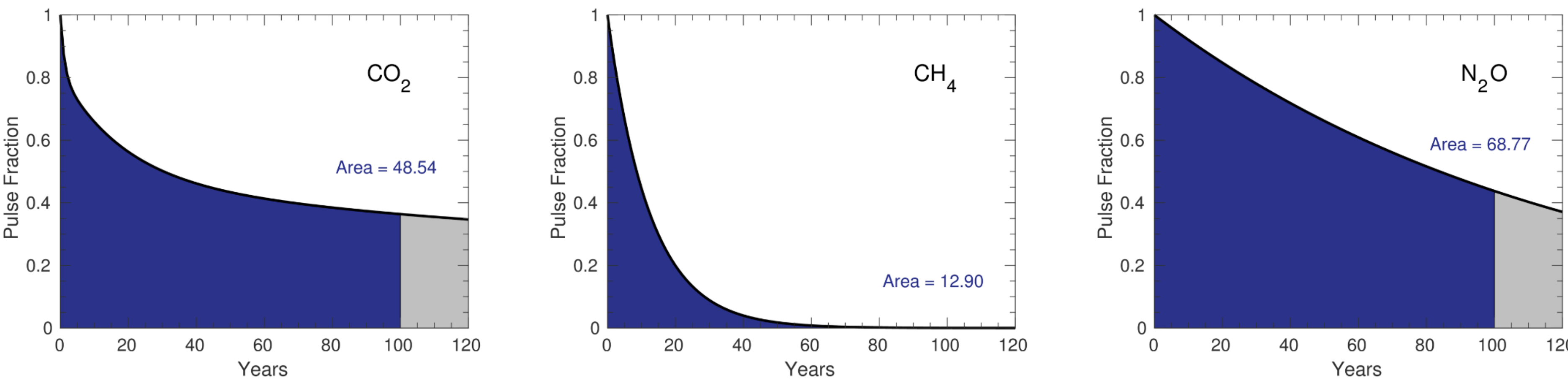

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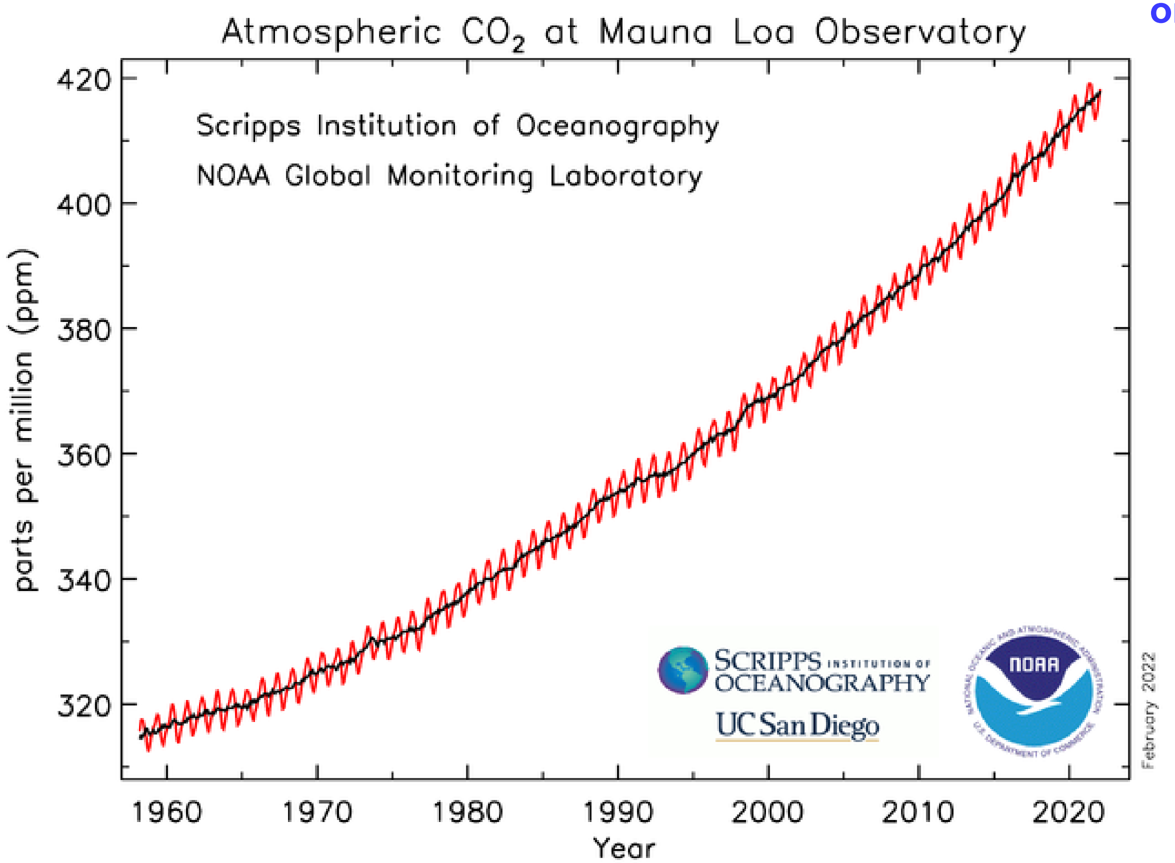
where all times are given in units of year

Modern CO_2 Record

CO_2 at MLO on 8 Feb 2021: 419.3 parts per million (ppm)
CO_2 at MLO on 8 Feb 2020: 416.0 parts per million (ppm)

ΔCO_2 = 3.3 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 ... e given is an estimate based on several r...

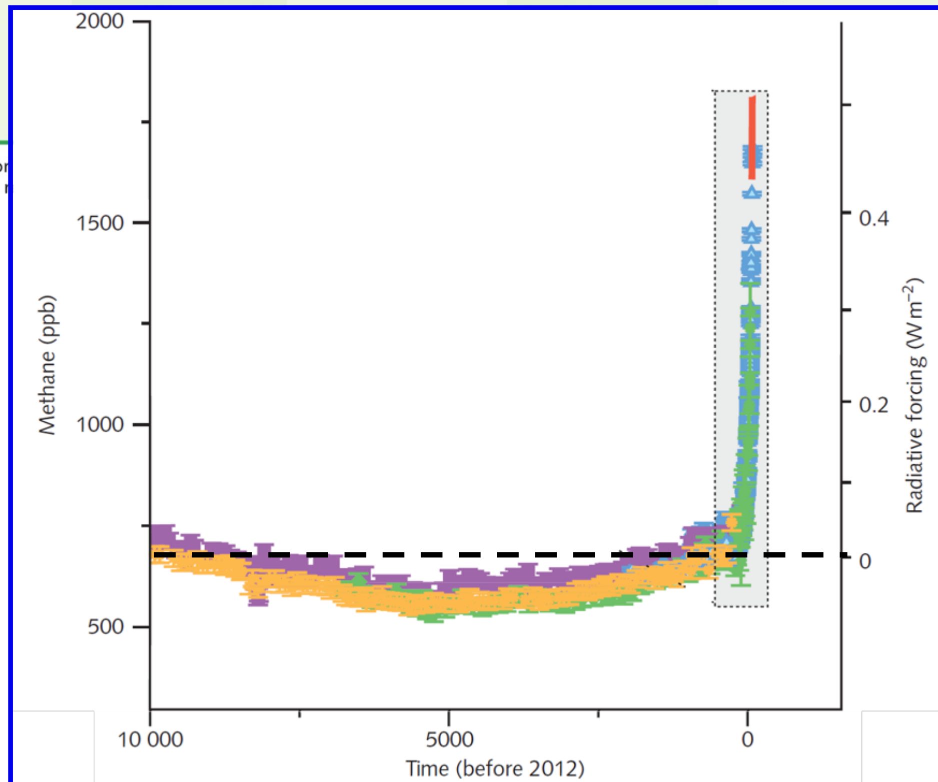


Figure 3.7, *Houghton*

Atmospheric CH_4

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

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Name and Chemical Formula	Preindustrial Concentration (1750)	Concentration in 2008	Atmospheric Lifetime (years)	Anthropogenic Sources	Global Warming Potential
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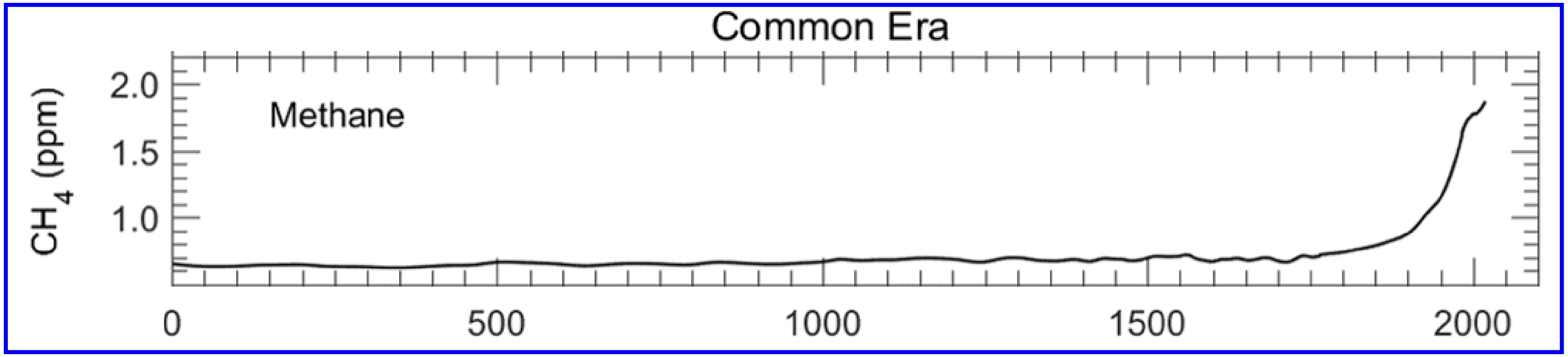
methane CH_4	700 ppb	1760 ppb	12	Rice paddies, waste dumps, livestock	21
nitrous oxide N_2O	275 ppb	322 ppb	120	Fertilizers, industrial production, combustion	310
CFC-12 CCl_2F_2	0	0.56 ppb	102	Liquid coolants, foams	8100

*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



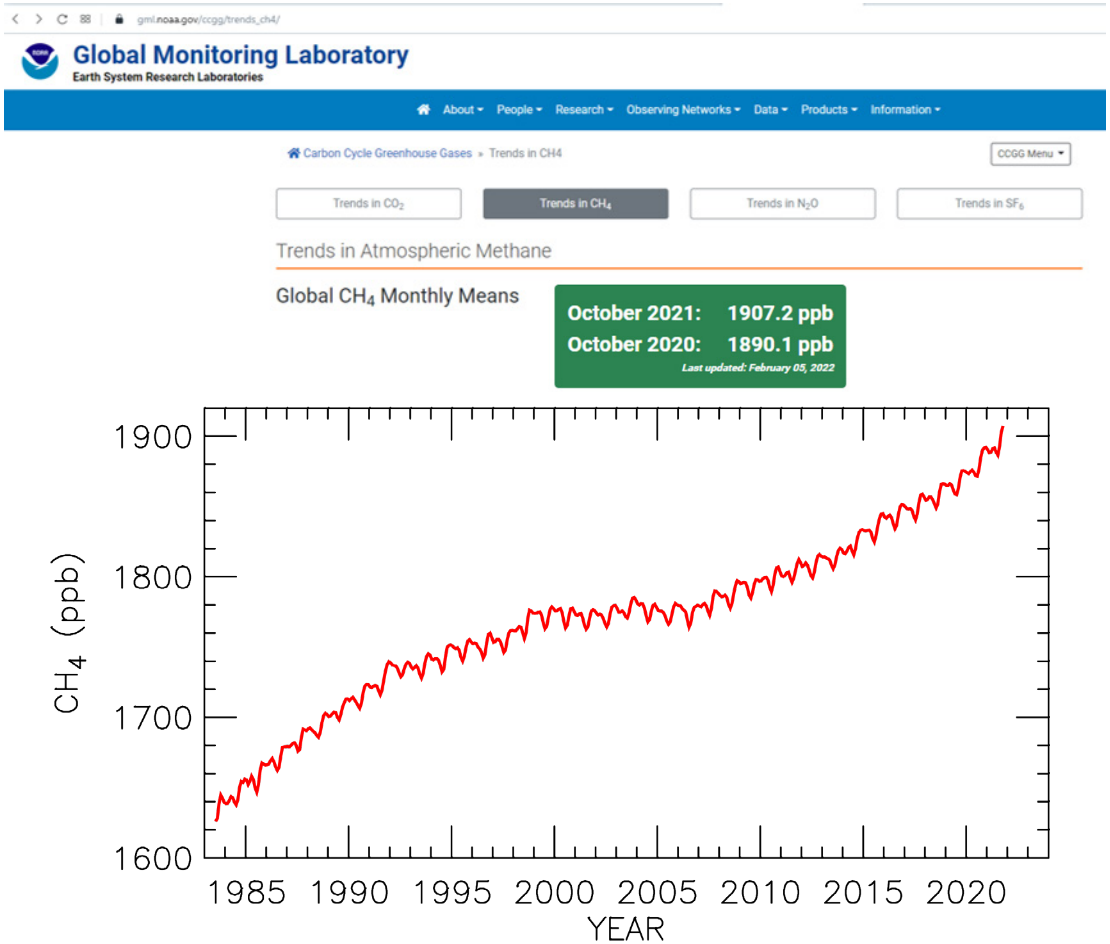
Atmospheric CH_4

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

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

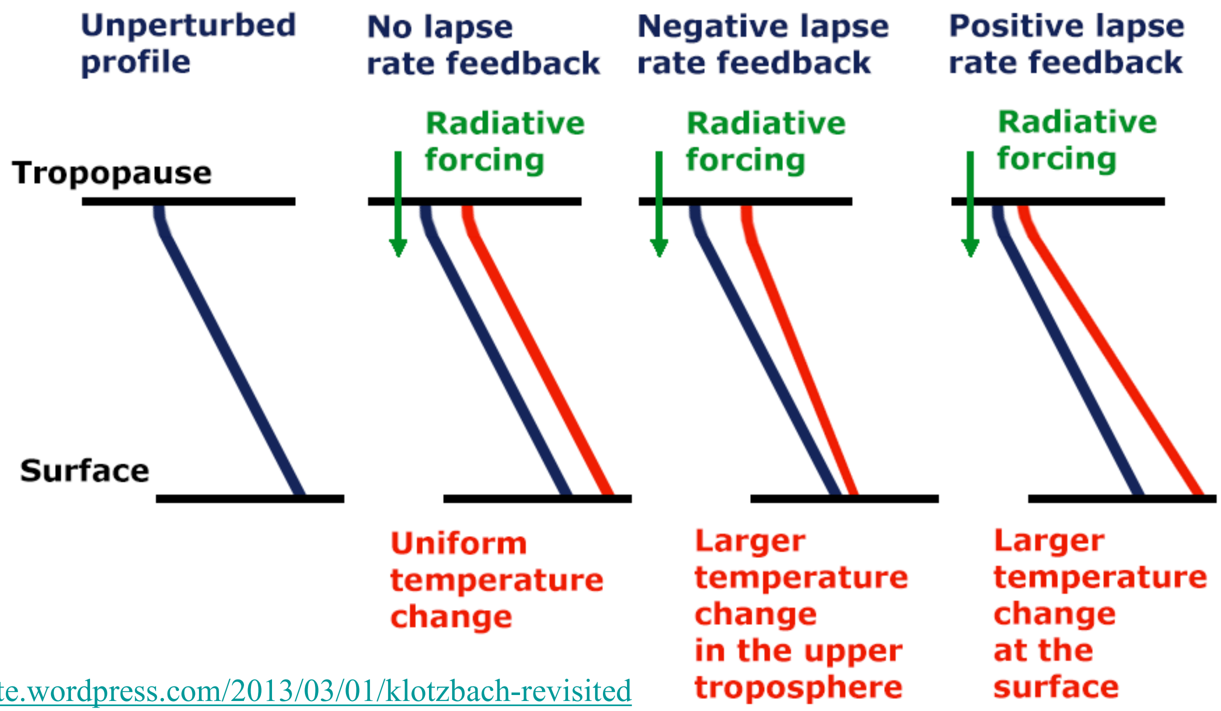
$\lambda_{BB} = 0.3\ K\ /\ W\ m^{-2}$

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

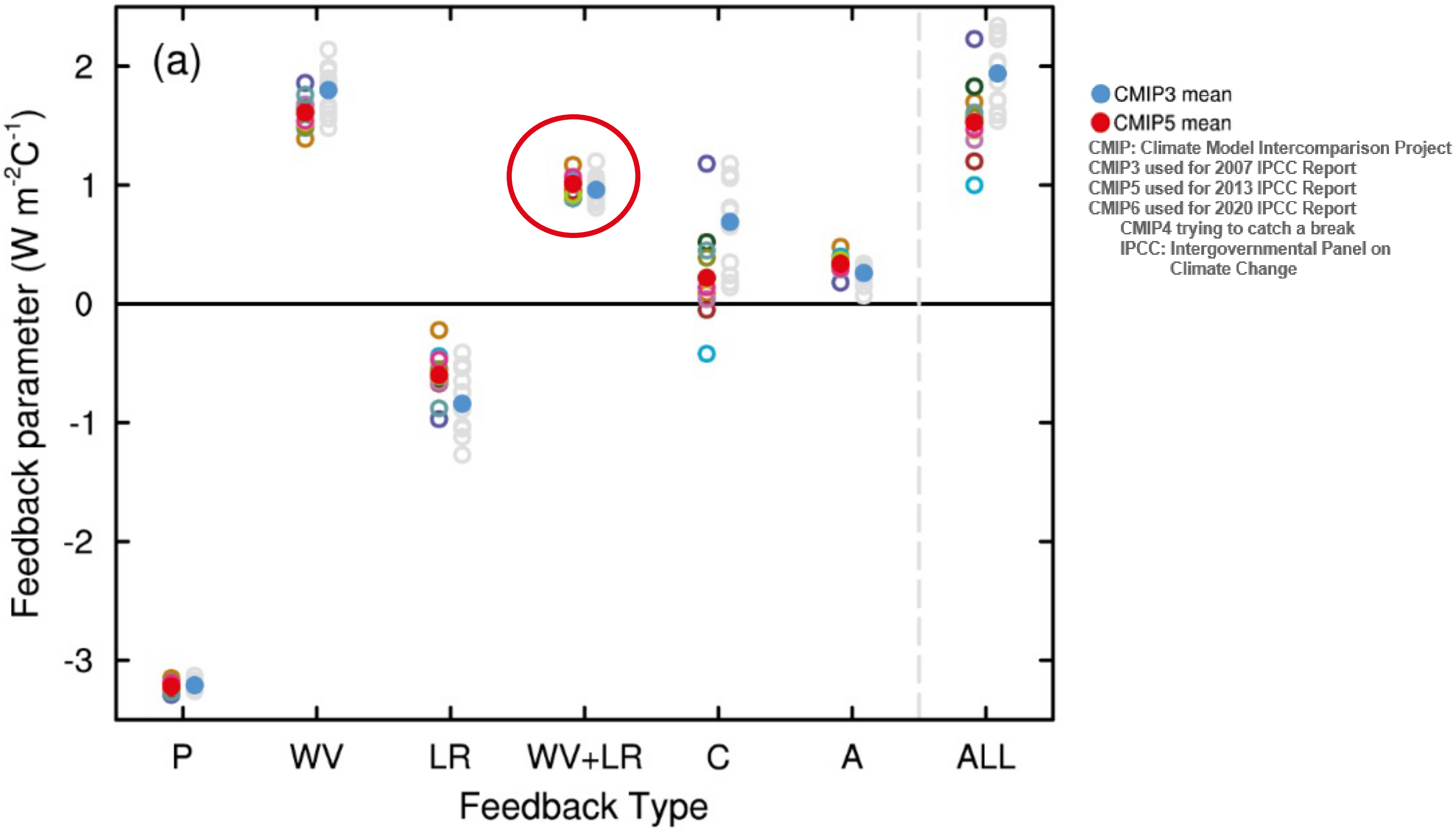


https://ourchangingclimate.wordpress.com/2013/03/01/klotzbach-revisited

- 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

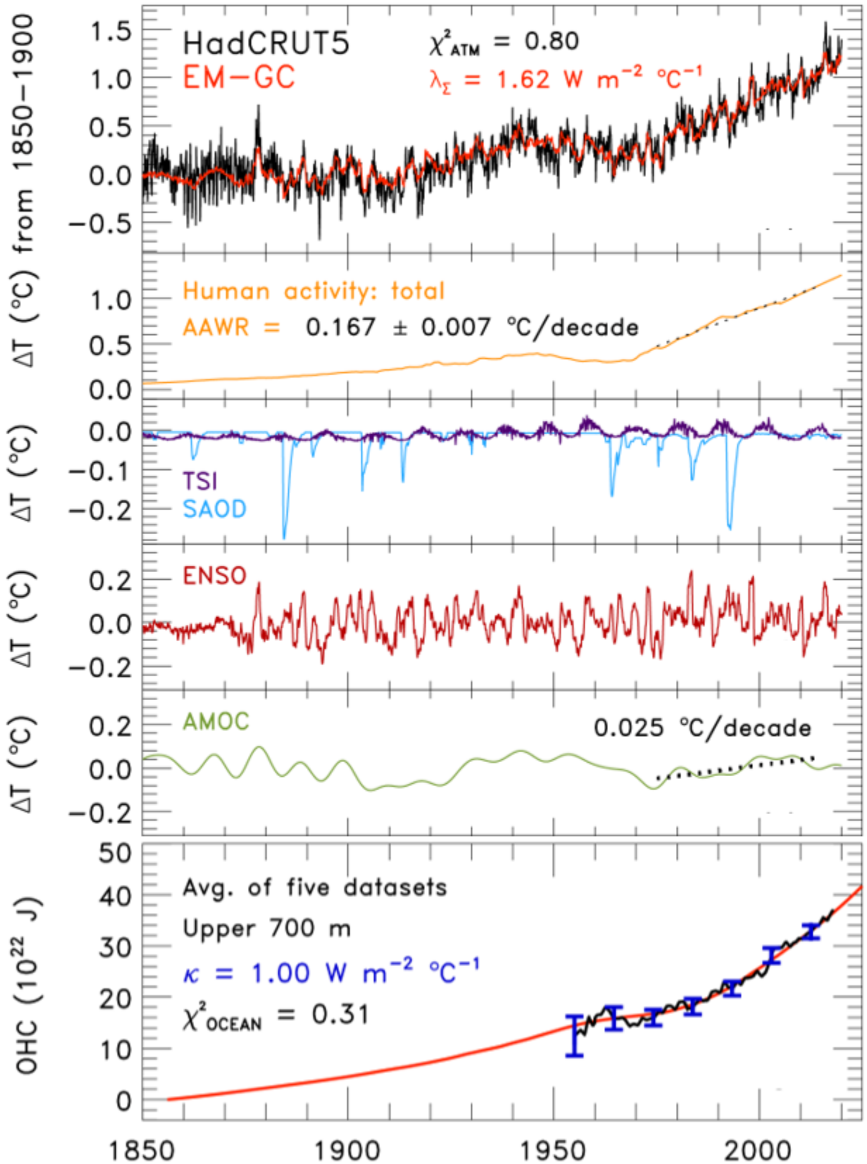
- GCMs indicate water vapor & lapse rate feedbacks are intricately linked, with the former almost certainly being positive (in response to rising GHGs), the latter almost certainly being negative, and the sum probably being positive



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

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

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



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)

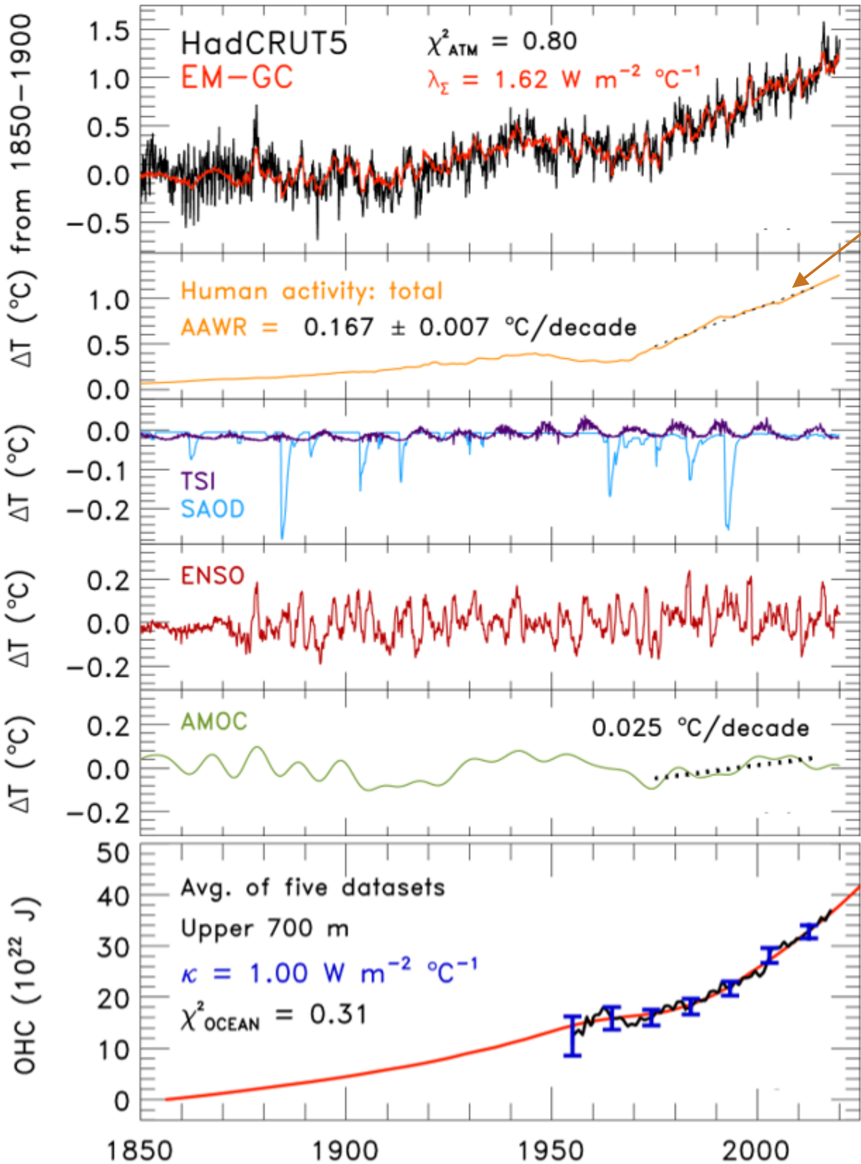
c) El Niño – Southern Oscillation (ENSO)

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



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

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

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

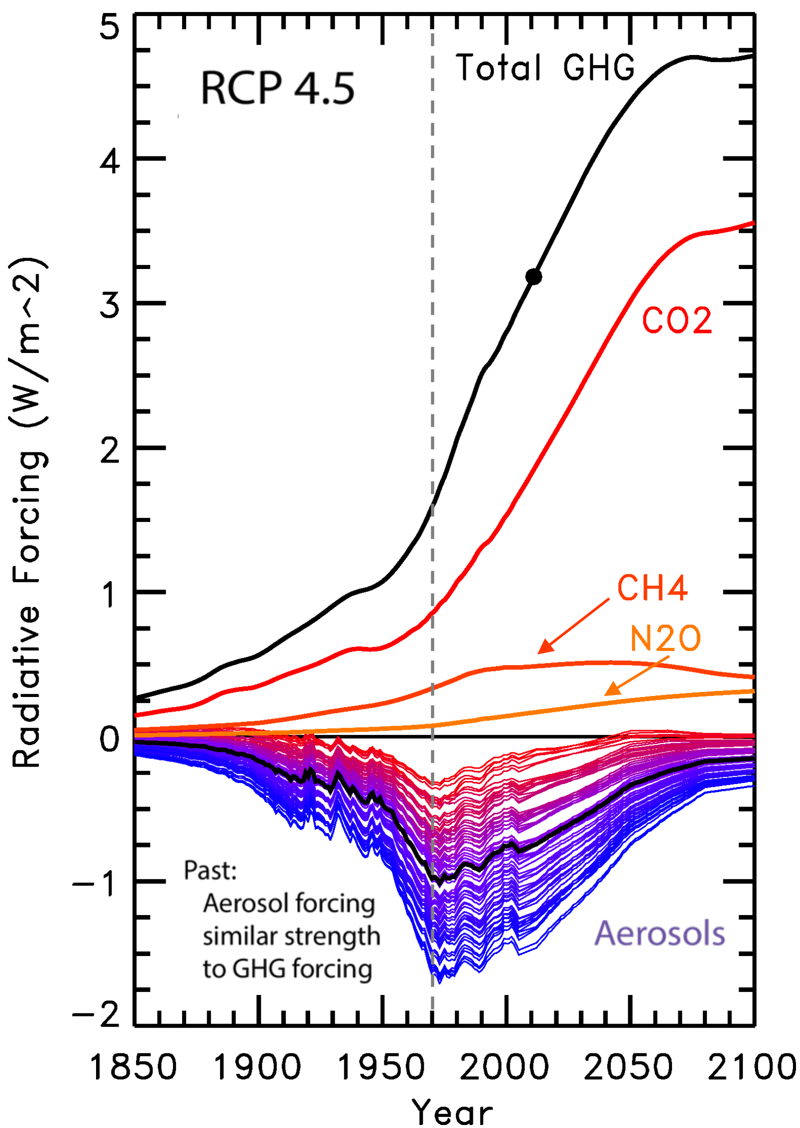
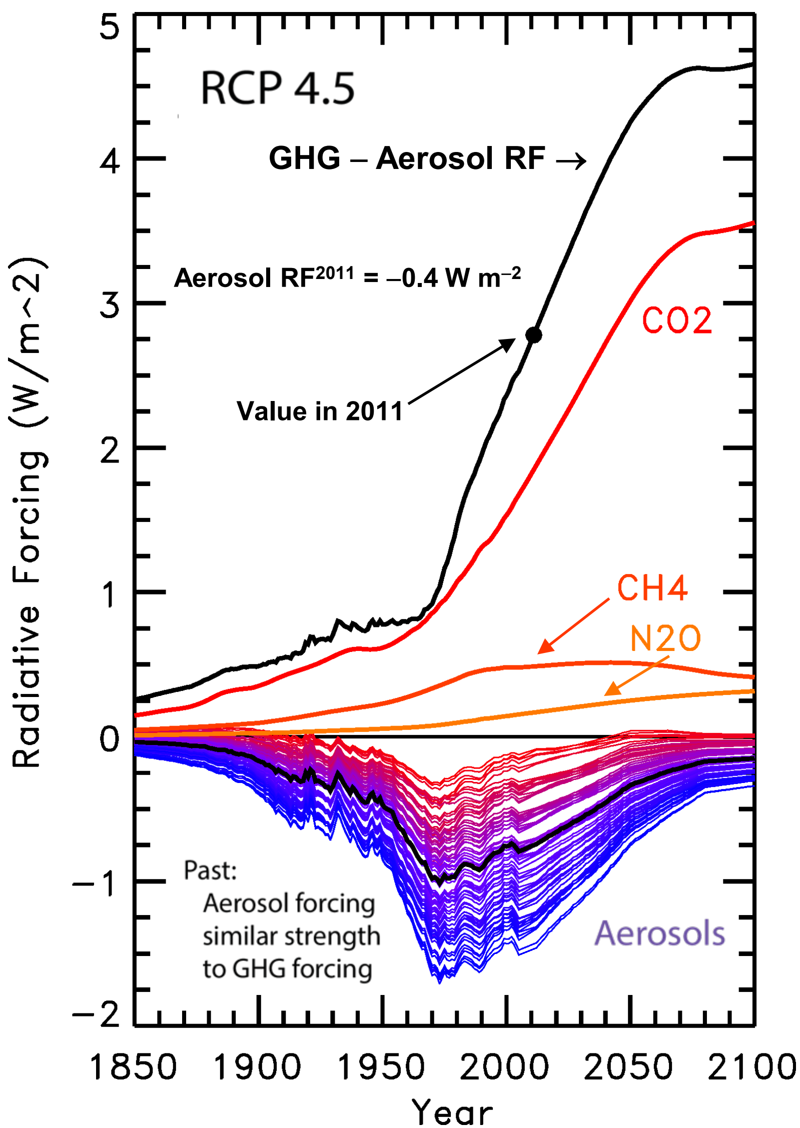


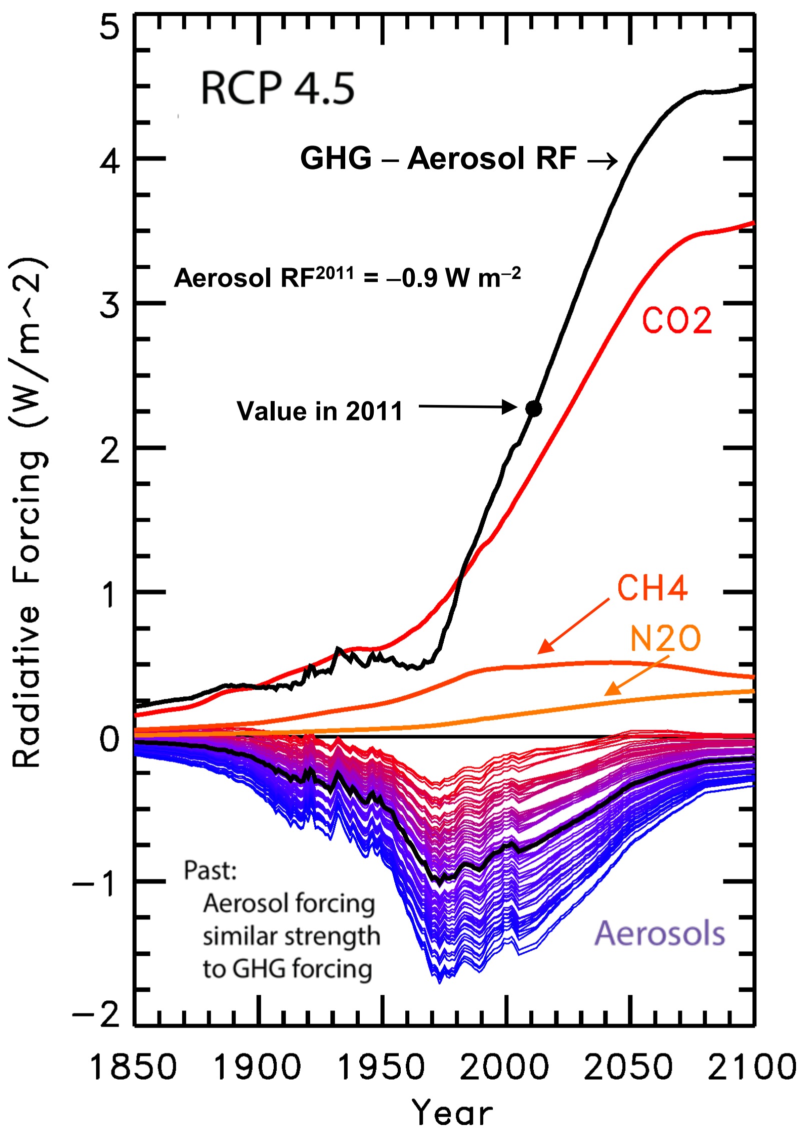
Fig 1.10, *Paris, Beacon of Hope*

Combining RF GHGs & Aerosols



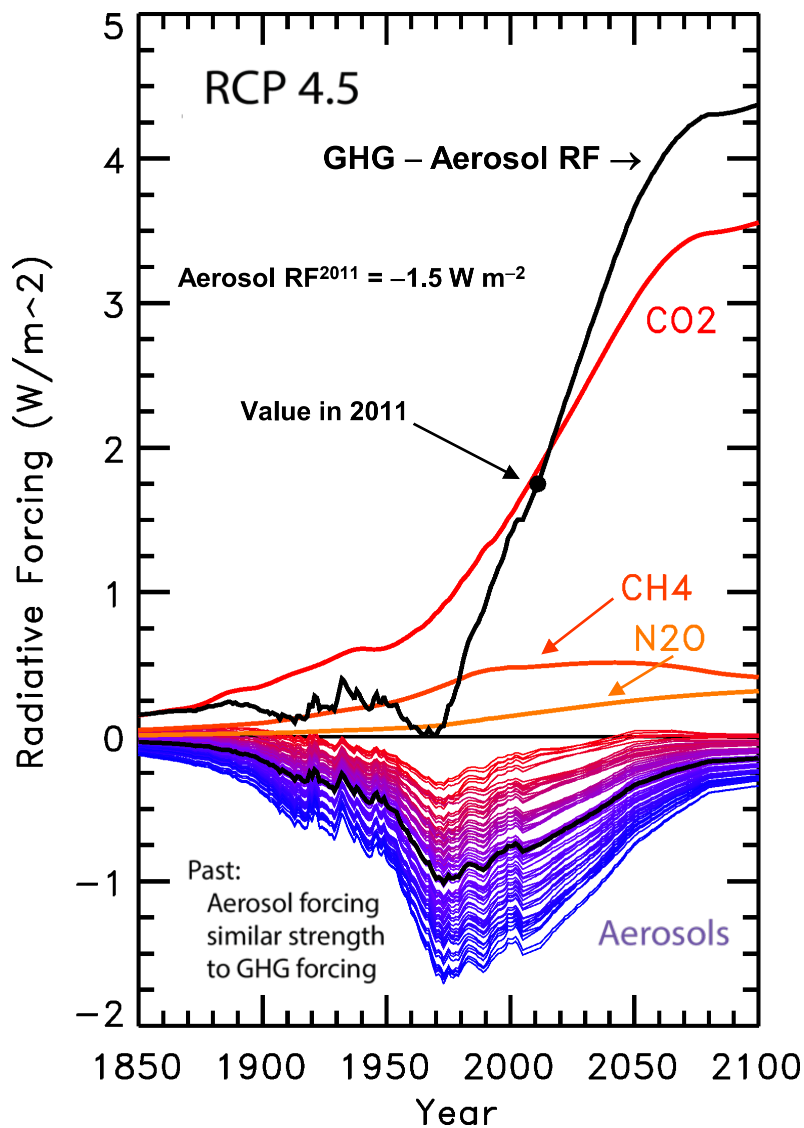
Based upon Fig 1.10, *Paris, Beacon of Hope*

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*

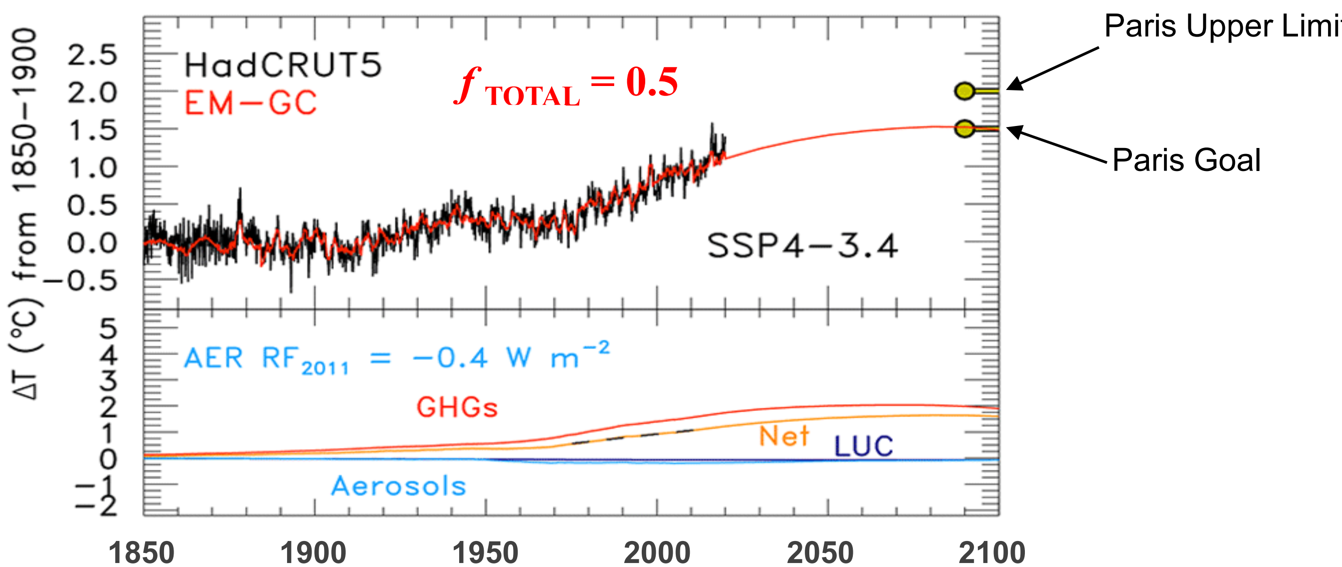
Uncertainty in RF of climate due to tropospheric aerosols is huge complication leading to fundamental uncertainty on forecasts of future global warming

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

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***.

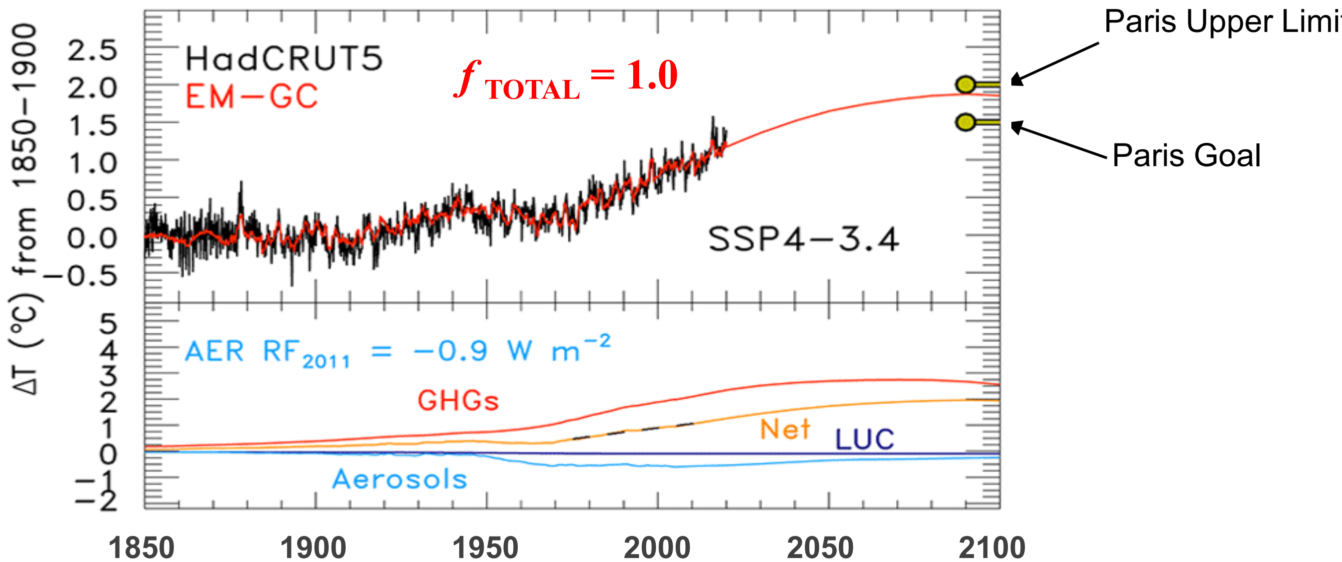
Uncertainty in RF of climate due to tropospheric aerosols is huge complication leading to fundamental uncertainty on forecasts of future global warming

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

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 **−0.9 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***.

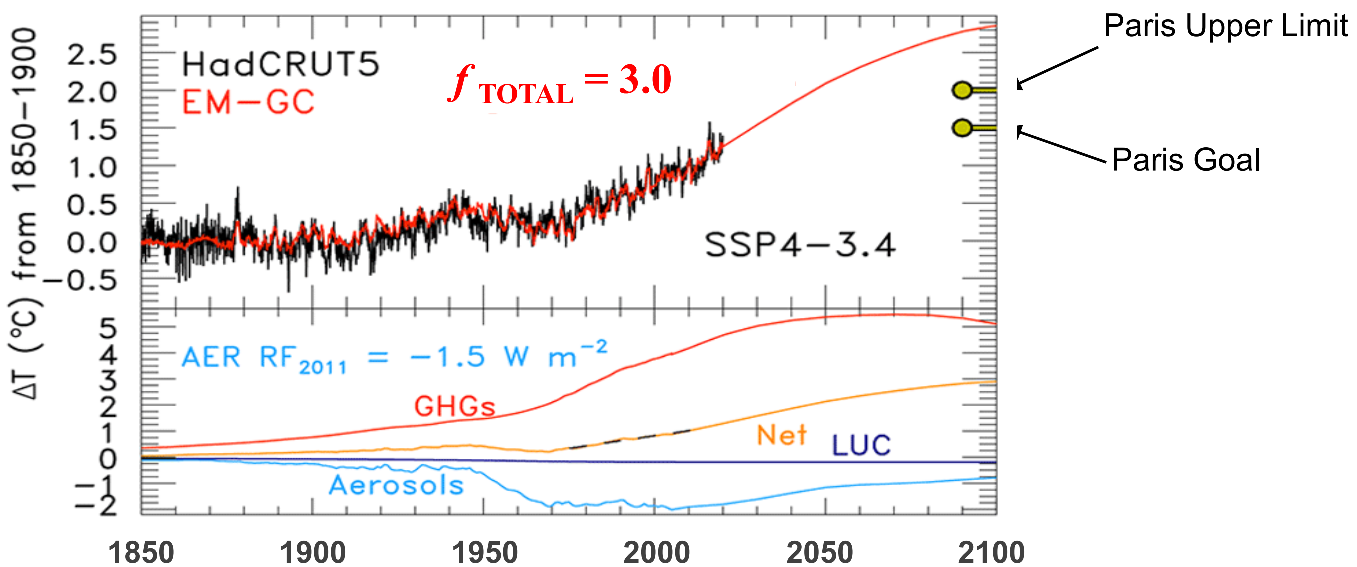
Uncertainty in RF of climate due to tropospheric aerosols is huge complication leading to fundamental uncertainty on forecasts of future global warming

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

where:

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

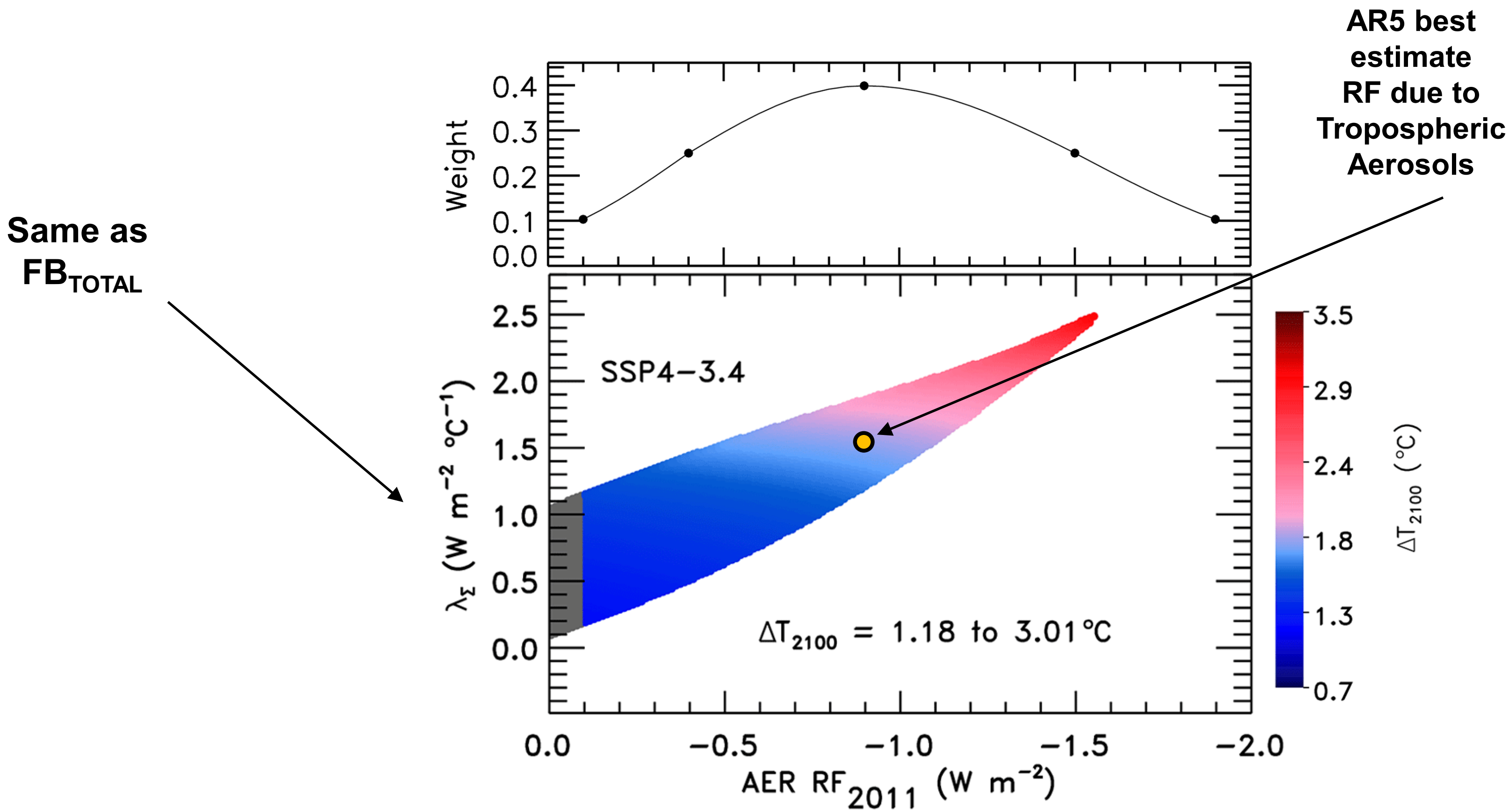
OHE = ocean heat export



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 <u>other feedbacks</u> (clouds, surface albedo) must be ***strongly positive***.

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



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

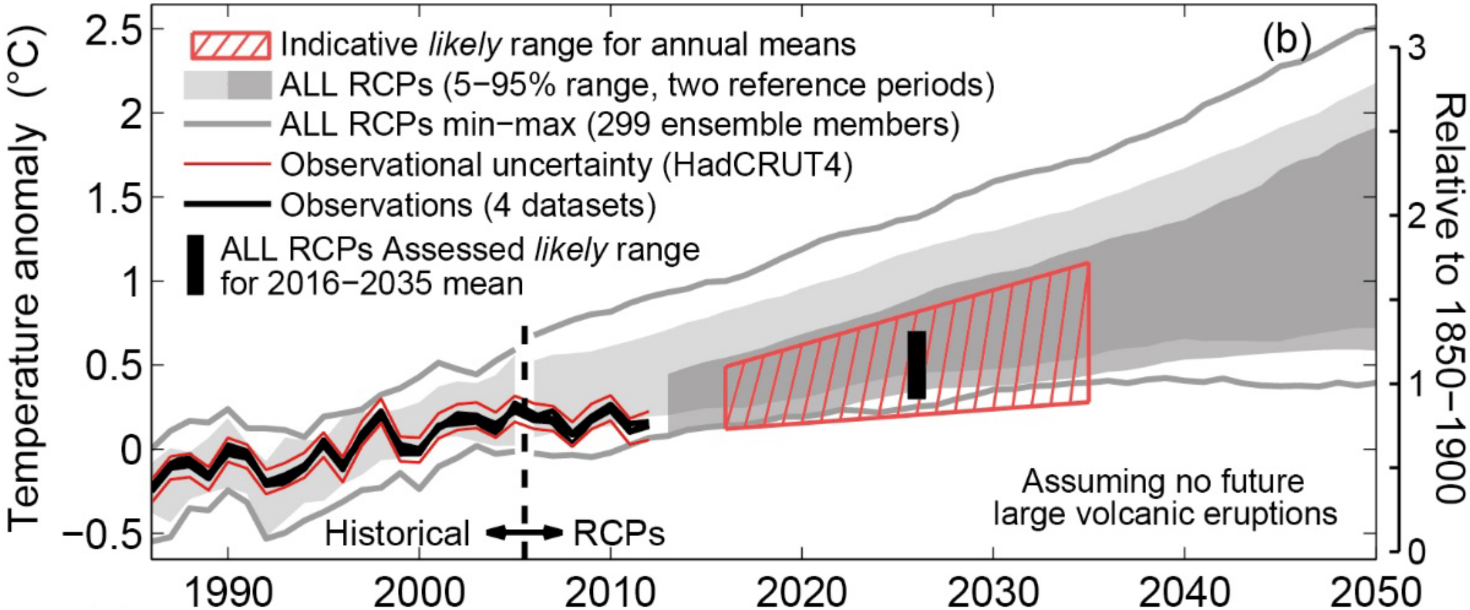
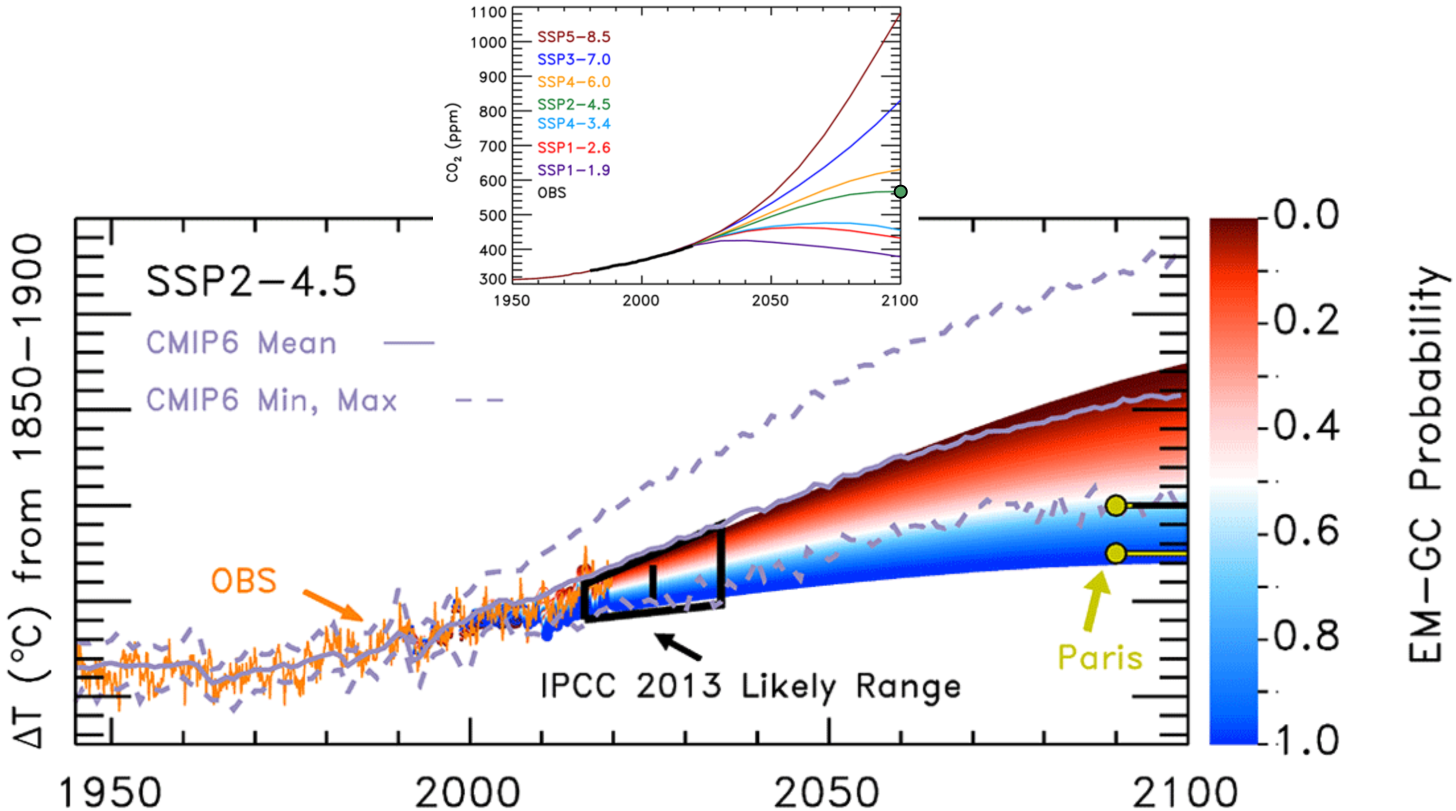


Fig 11.25b, IPCC (2013)

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

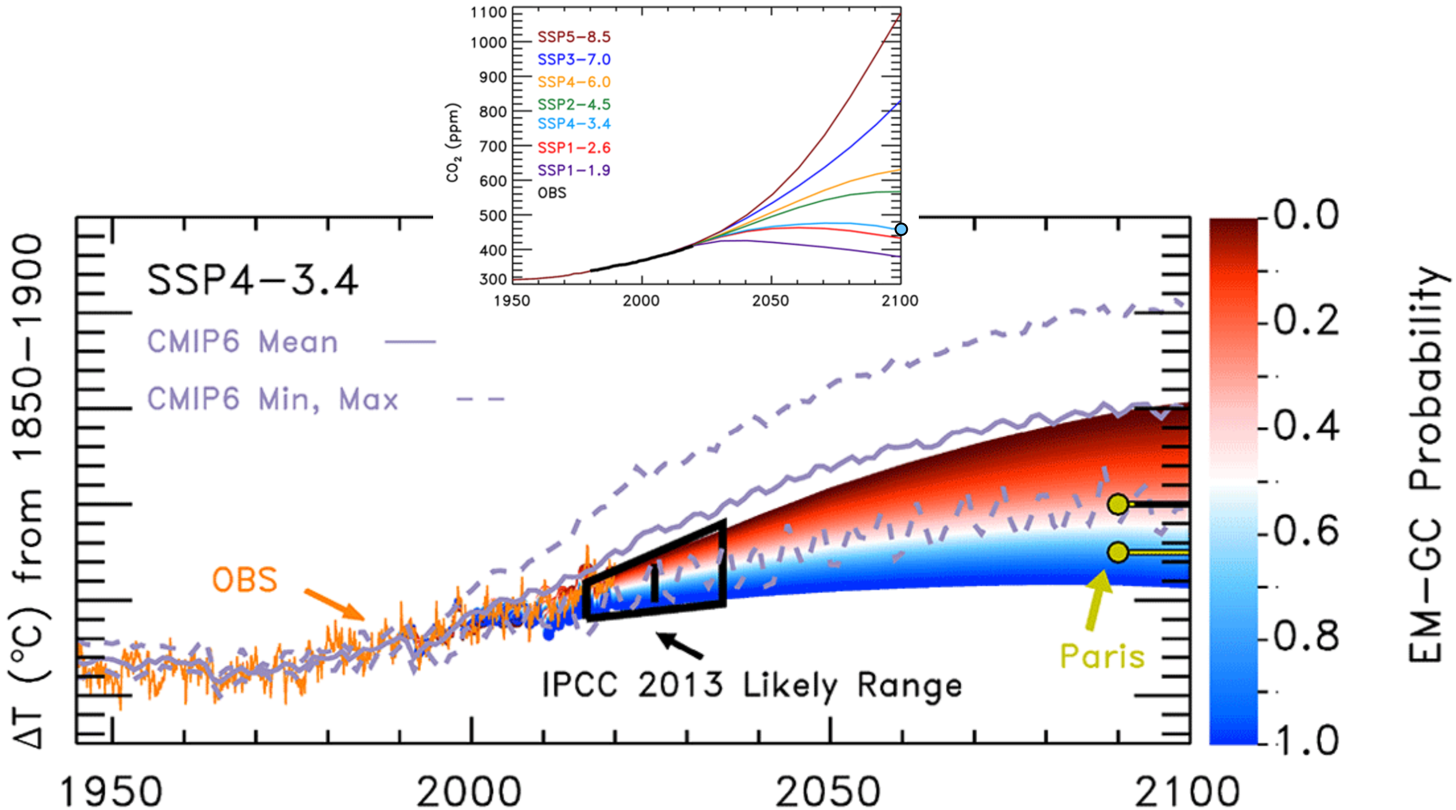


If GHGs follow SSP2-4.5, **2%** chance rise GMST stays below **1.5°C** and **33%** chance stays below **2.0°C**

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

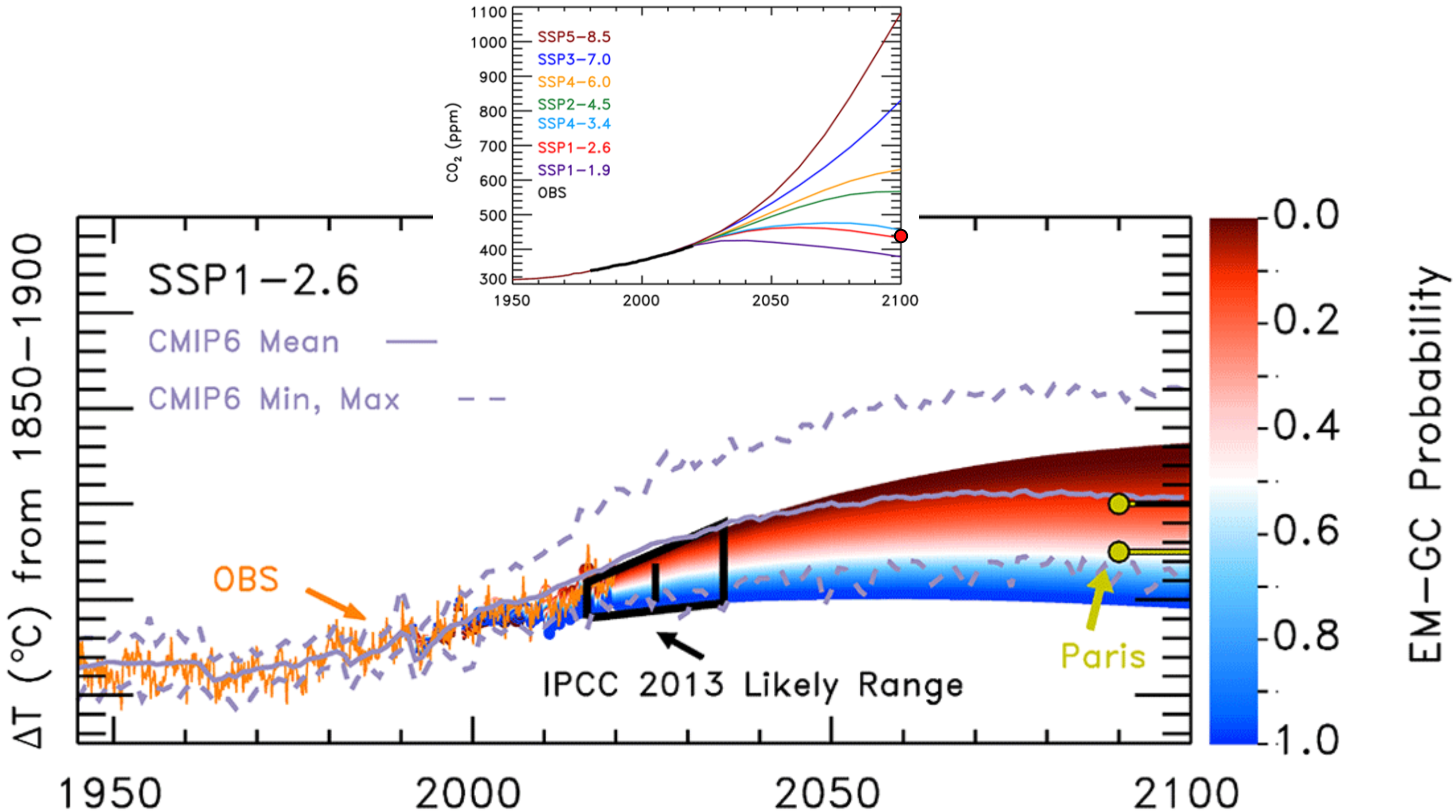


If GHGs follow SSP4-3.4, **19%** chance rise GMST stays below **1.5°C** and **64%** chance stays below **2.0°C**

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

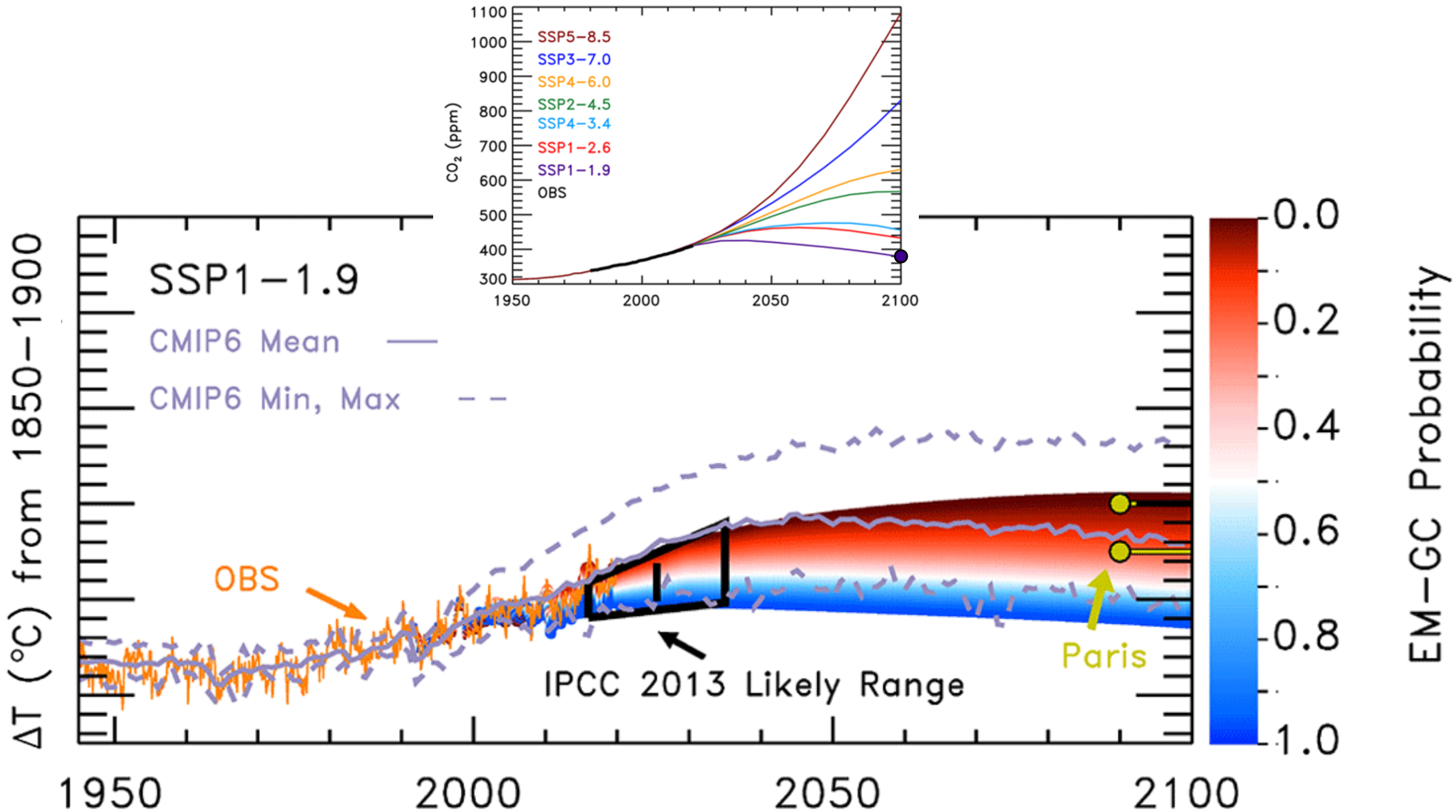


If GHGs follow SSP1-2.6, **53%** chance rise GMST stays below **1.5°C** and **86%** chance stays below **2.0°C**

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