Review for First Exam

AOSC / CHEM 433 & AOSC / CHEM 633

Ross Salawitch

Class Web Sites:
http://www2.atmos.umd.edu/~rjs/class/fall2020
https://myelms.umd.edu/courses/1291919

Review A

6 October 2020

Announcements: Class

Original announcement:

Also, the first exam which will be on-line, open book, open web, ~~that I hope you will take on 8 Oct (you'll have 75 mins time to take either 7 Oct, 8 Oct, or 9 Oct) will cover material up to Lecture 8 (today's lecture).~~

However, please note that:

a) the exam will focus on a series of questions, about one per lecture, that you can only answer properly in the limited time IF you are already familiar with the contents of each lecture;

b) there will be no calculations on the exam so, in this sense, the exam will be qualitative rather than quantitative

c) if you have been doing all of the readings, answering the ATs based on a comprehensive understanding of the readings, and retaining knowledge from the readings and exams, as solidified by consistently high scores of the learning out come quizzes, then you'll be in great shape for the first exam. On the other hand, if you have been skimming the readings, doing the bare minimum to answer the ATs, and not completing the learning outcome quizzes, you will need to impart greater effort to prepare for the exam, in order to do well. The exam will open more than a week from this moment in time ... so there is still time to prepare.

Announcements: Class

Modified announcement:

Also, the first exam which will be on-line, open book, open web, ***that everyone will take during normal class hour on Thurs, 8 Oct, from 2:00 to 3:15 pm.***

However, please note that:

a) the exam will focus on a series of questions, about one per lecture, that you can only answer properly in the limited time IF you are already familiar with the contents of each lecture;

b) there will be no calculations on the exam so, in this sense, the exam will be qualitative rather than quantitative

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Announcements: Class

Modified announcement:

Also, the first exam which will be on-line, open book, open web, *that everyone will take during normal class hour on Thurs, 8 Oct, from 2:00 to 3:15 pm.*

Details:

- Exam will open at 2:02 pm on Thurs, 8 Oct
- Exam will close at 3:17 pm on Thurs, 8 Oct
- Everyone is asked to connect to the class Zoom while conducting the exam, and have video running solely so that I can see you are "alone"
- Welcome to use any resource (readings, lectures, notes, etc) other than ***communicating with another person***
- Exam will consist of 9 essay questions:
  - Students will answer 6 of the 9 questions
  - Questions will cover Lectures 1 to 8
  - Expected that each answer will require about 10 minutes of thought & writing
  - Questions should be sent to me through chat: if any question requires clarification, this will be announced via Zoom
  - One of the questions, **Question 9**, will be required to be answered by students in 633
  - When the exam is complete, you are asked to write ***the word "BLANK" in the text box of the 3 questions you do not answer***
  - If you have internet connectivity issues during the exam, please text me at 626-487-5643 and include a cell phone image showing "the problem"

Announcements: Class

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  - **If you have an exceptional circumstance that requires taking this exam at a different time, please let me know ASAP**

Announcements: Class

Roll call to state you understand exam will be taken on ELMS during regular class time on Thurs, with your Zoom video running (fine to mute), and that you should text Ross at 626-487-5643 if you have internet connection issues, you should send a chat to Ross if you have questions during the exam, and that the exam is open book, open web, open everything except no contact with another person during the exam.

Student Name
Emma B AOSC433-0101
Nancy C CHEM433-0101
Ciara D AOSC433-0101
Ehiremen E CHEM633-0101
Endre F CHEM633-0101
Heather F AOSC433-0101
Nicholas F CHEM633-0101
HyunGee H CHEM433-0101
Michael H AOSC433-0101
Rachel K AOSC433-0101
Madeline L CHEM633-0101
Kishalay M CHEM633-0101

Student Name
Kotiba M AOSC633-0101
Jeffrey M CHEM433-0101
Malgorzata P CHEM433-0101
Michael R CHEM633-0101
Akanksha S AOSC633-0101
Stuart S CHEM633-0101
Nathaniel S AOSC433-0101
William Jay S AOSC433-0101
Pierce V CHEM633-0101
Alice W CHEM433-0101
Cindy X CHEM433-0101
Chencheng Z CHEM433-0101

Announcements: Outside of Class

1) Thurs, 8 Oct : AOSC Weekly Seminar (3:30 pm)

Dr. Jiwen Fan

Physical factors impacting convective storms and weather hazards

Deep convective clouds play a crucial role in atmospheric circulation, energy, and water cycle of our climate system. The extreme form of such storms produces weather hazards such as large hail, damaging winds and/or tornadoes, and torrential rainfall, causing significant property damages and economic losses. There is a large gap in our fundamental understanding of environmental factors impacting storm intensity, precipitation, and associated hazards. In particular, how aerosols from various sources modify these storms is still controversial. In this talk, I will present our efforts in understanding physical factors that impact storm intensity, extreme precipitation, and hailstones associated with:

(1) land cover and anthropogenic aerosol changes and

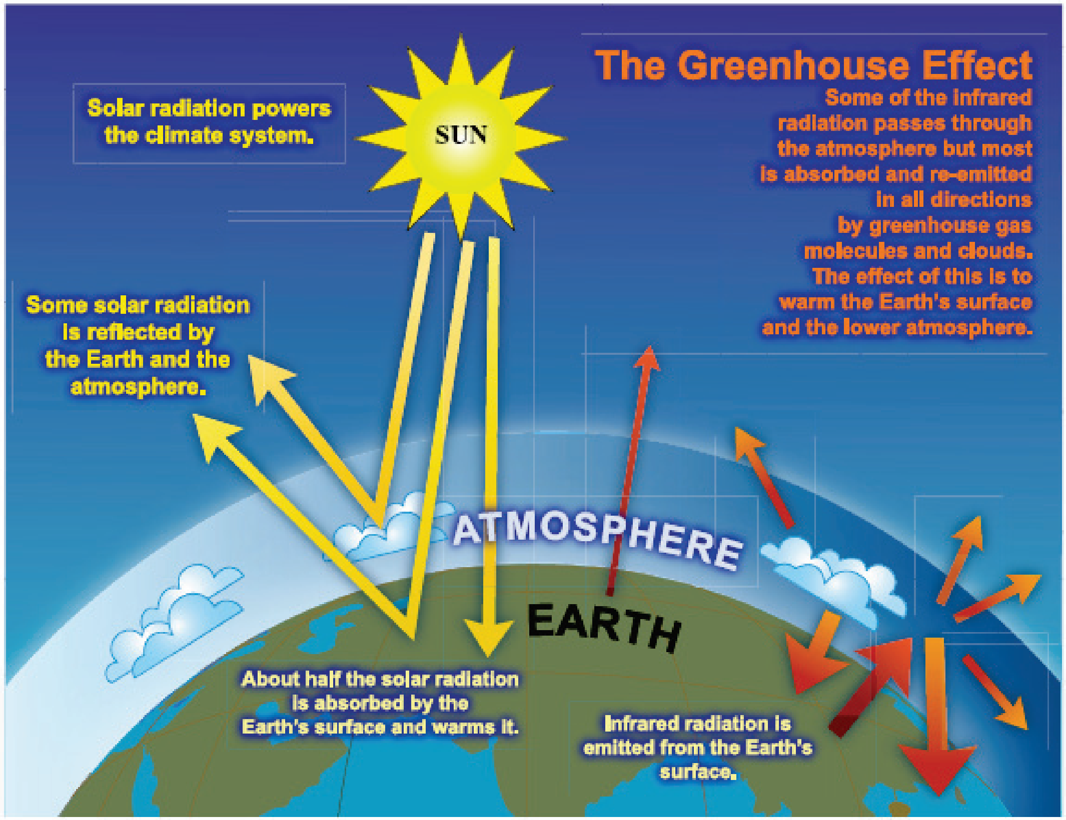
(2) anthropogenic warming

I will focus on the understandings mainly gained from process-level studies with both advanced observations and high-resolution model simulations. The challenges in observing and modeling such deep convective clouds and their interactions with environmental factors will be discussed.

https://aosc.umd.edu/seminars/department-seminar

Email Joseph Knisely at jknisely@umd.edu for Zoom connection info

Greenhouse Effect

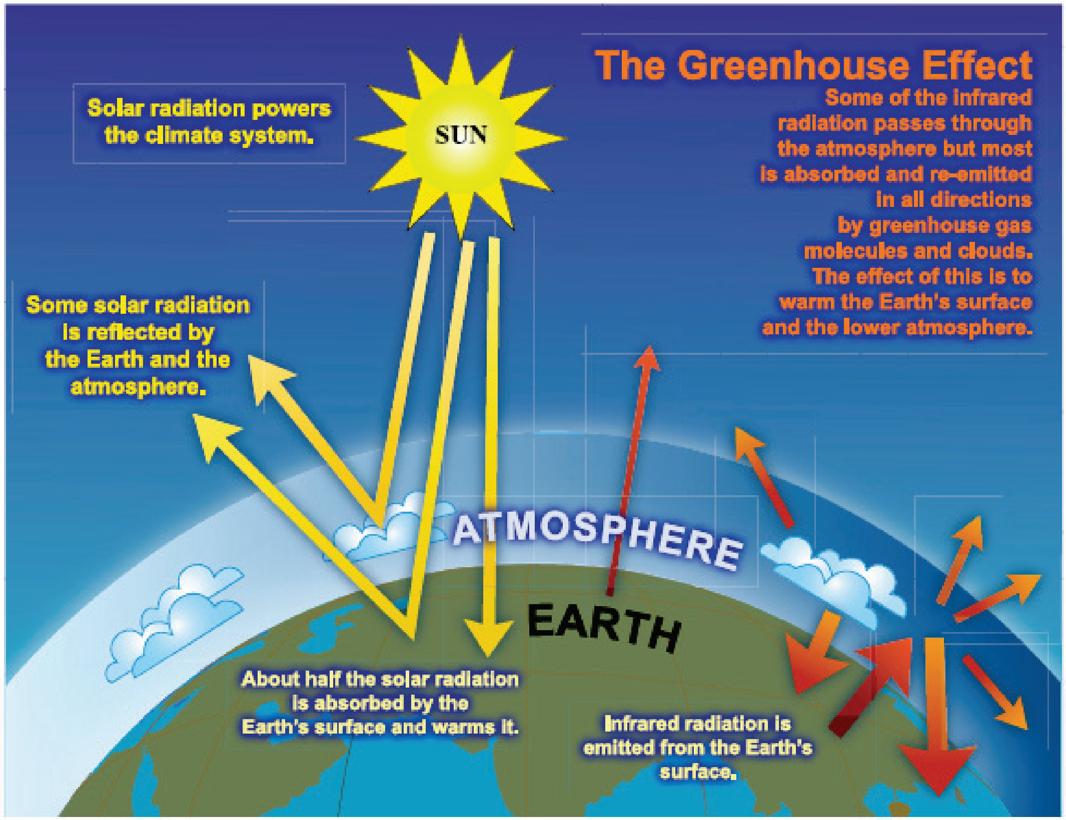


FAQ 1.3, Figure 1. *An idealised model of the natural greenhouse effect. See text for explanation.*

Question 1.3, IPCC, 2007

What is the most important greenhouse gas (GHG) ?

Greenhouse Effect

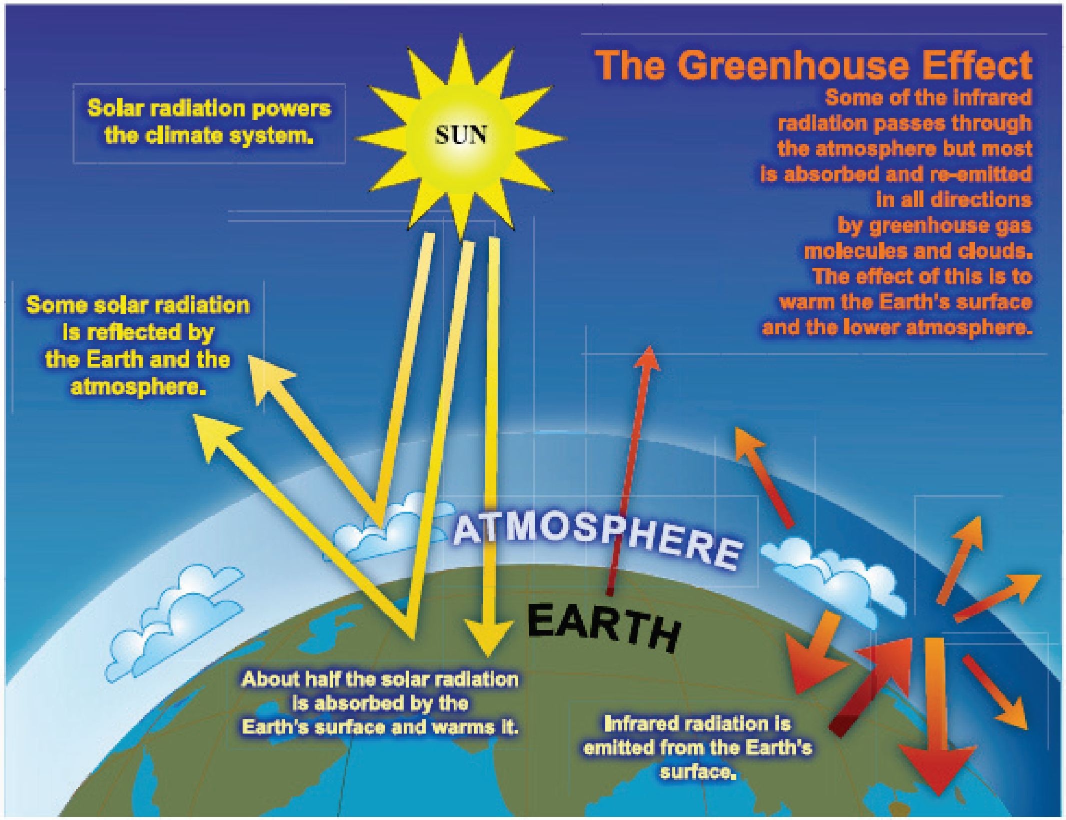


FAQ 1.3, Figure 1. *An idealised model of the natural greenhouse effect. See text for explanation.*

Question 1.3, IPCC, 2007

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

Greenhouse Effect



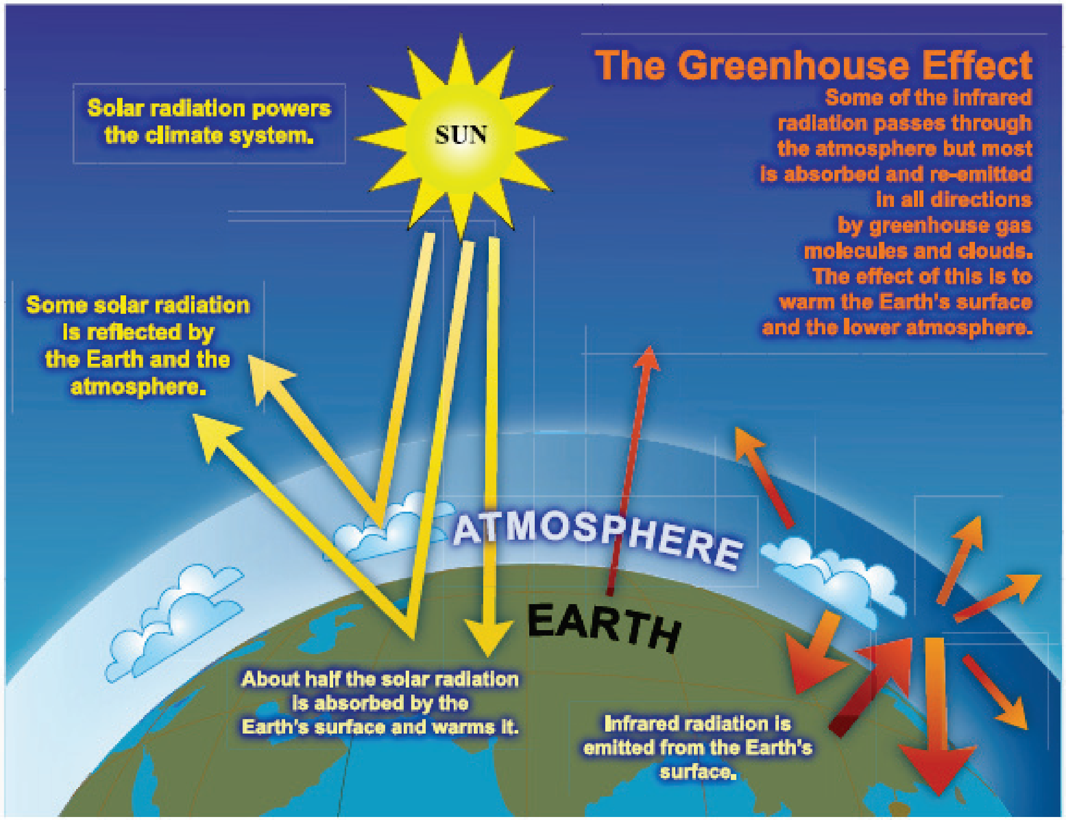
FAQ 1.3, Figure 1. *An idealised model of the natural greenhouse effect. See text for explanation.*

Question 1.3, IPCC, 2007

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

Second most important ?

Greenhouse Effect



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Question 1.3, IPCC, 2007

What is the most important *<u>anthropogenic</u>* greenhouse gas (GHG) ?

Second most important ?

Third ?

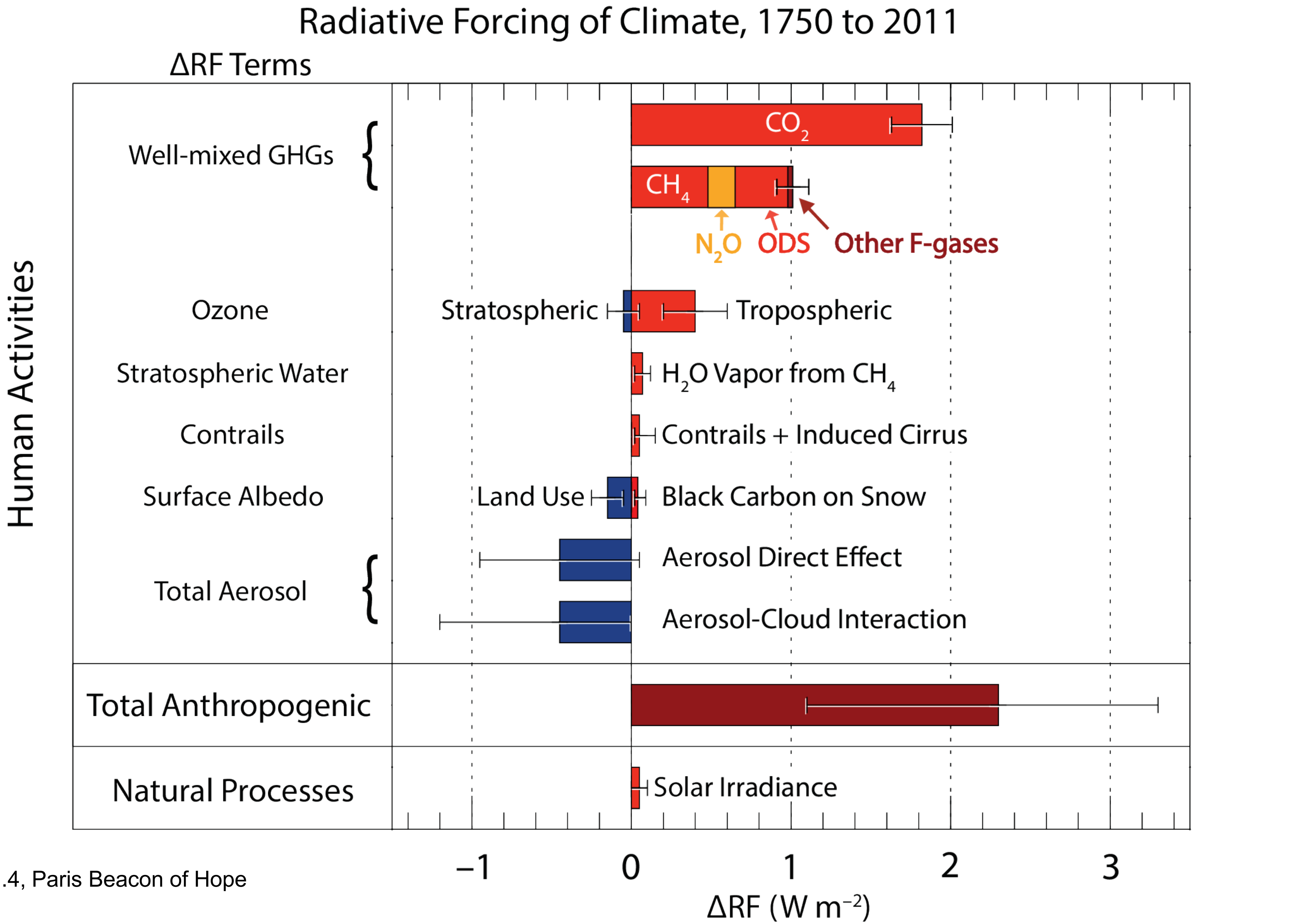
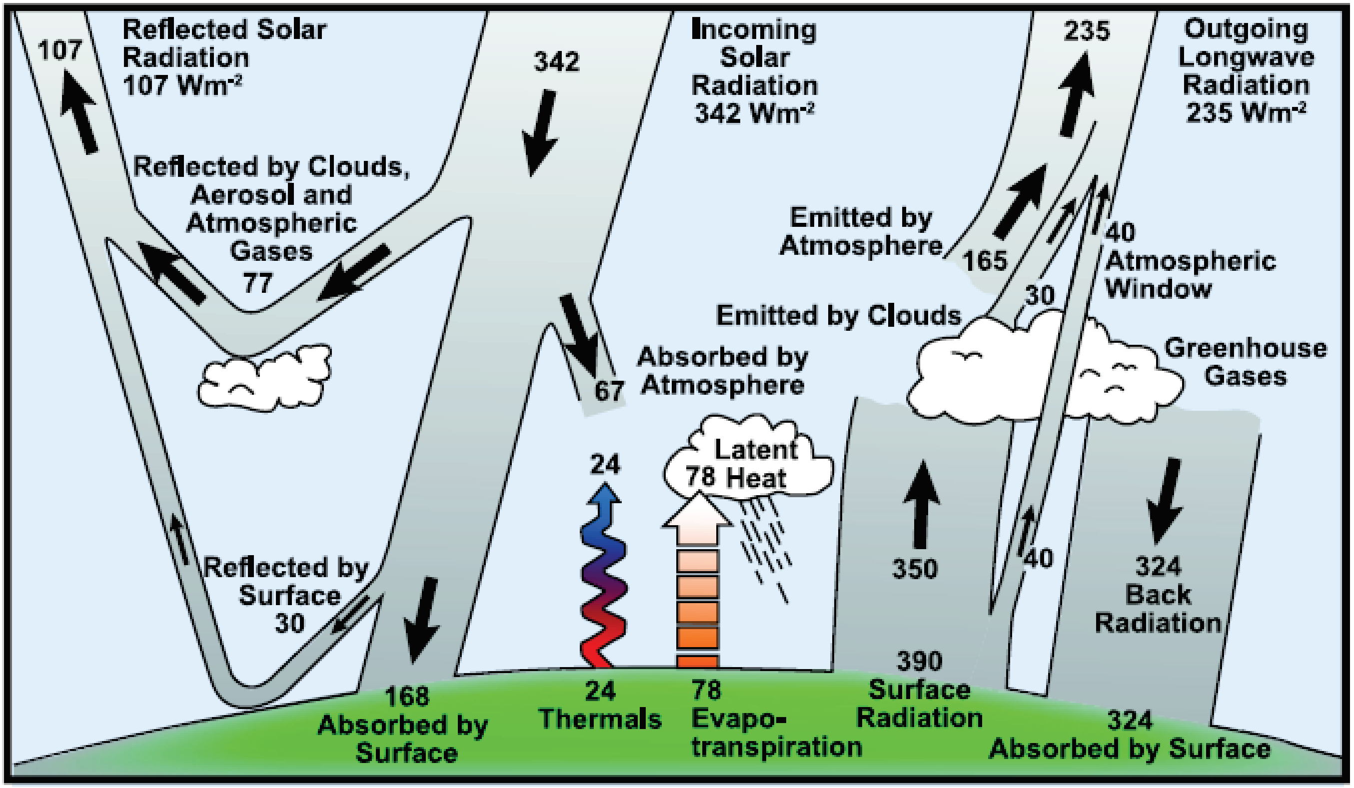


Figure 1.4, Paris Beacon of Hope

Radiative Forcing

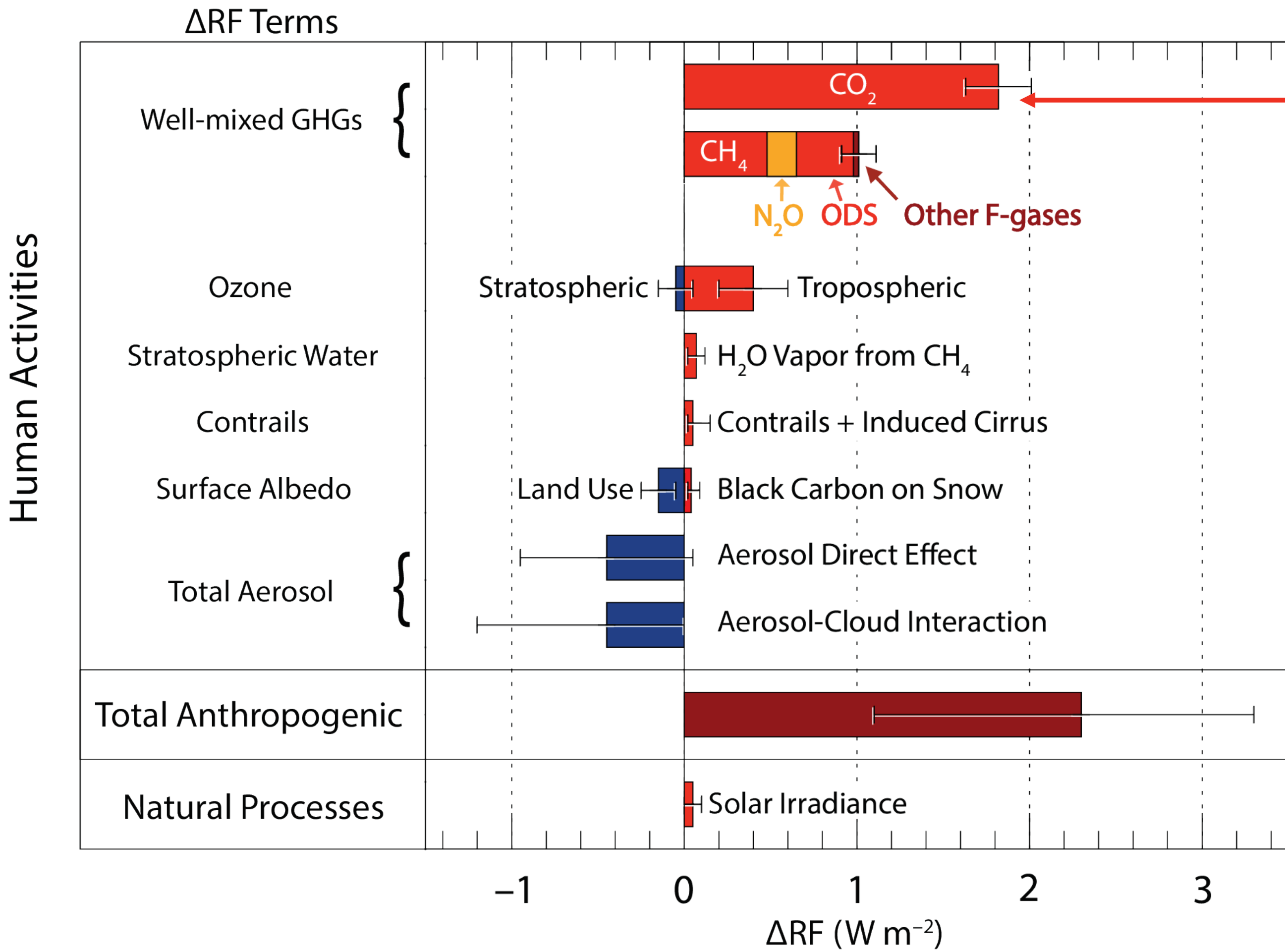


FAQ 1.1, Figure 1. *Estimate of the Earth's annual and global mean energy balance. Over the long term, the amount of incoming solar radiation absorbed by the Earth and atmosphere is balanced by the Earth and atmosphere releasing the same amount of outgoing longwave radiation. About half of the incoming 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 2011

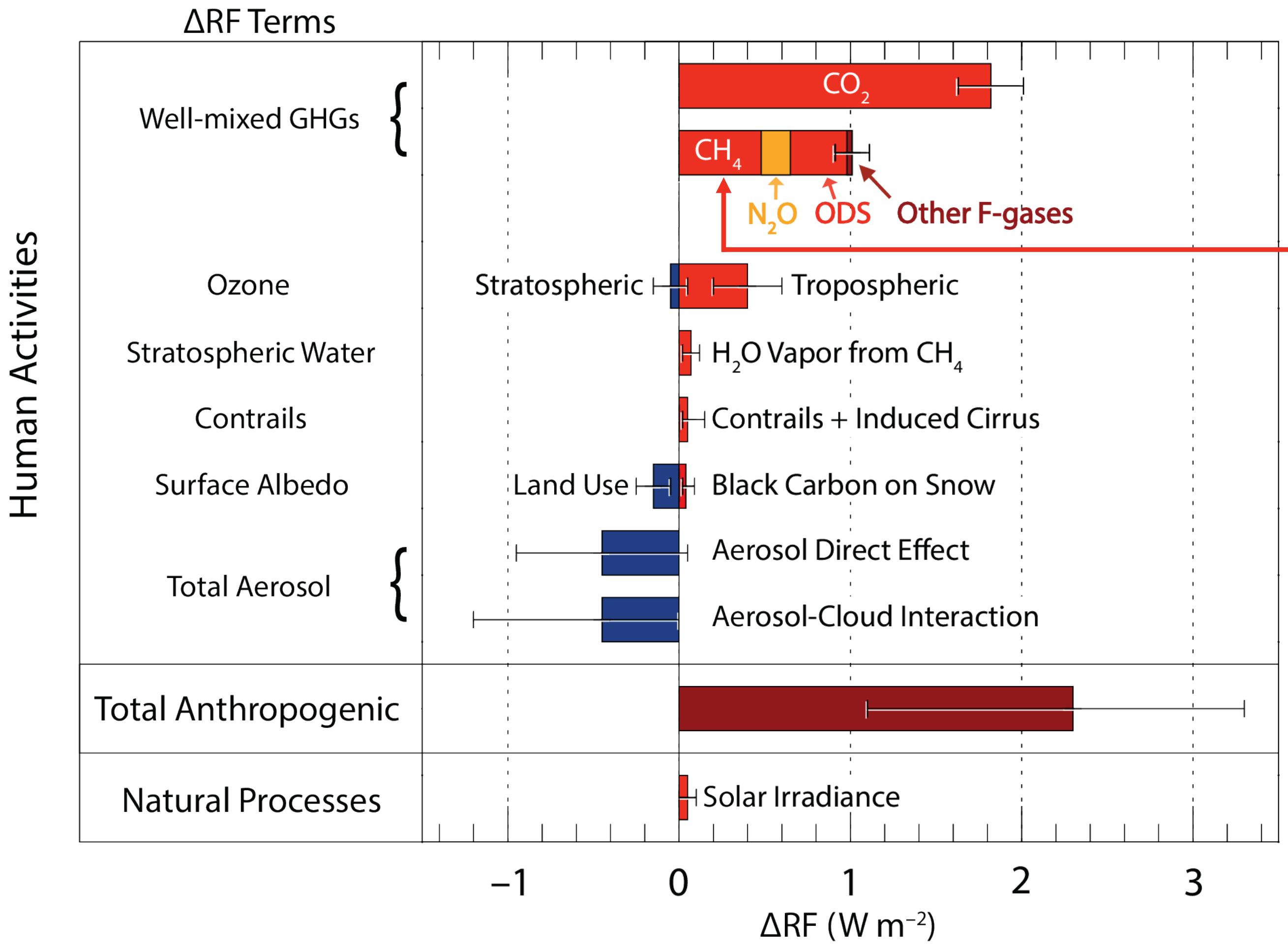


CO_2 is dominant anthropogenic (human) greenhouse gas (GHG). Once released, CO_2 persists in the atmosphere for hundreds of years.

Between 1750 and 2011, the rise in atmospheric CO_2 caused RF of climate to rise by 1.8 W m^{-2}

Figure 1.4, Paris Beacon of Hope

Radiative Forcing of Climate, 1750 to 2011



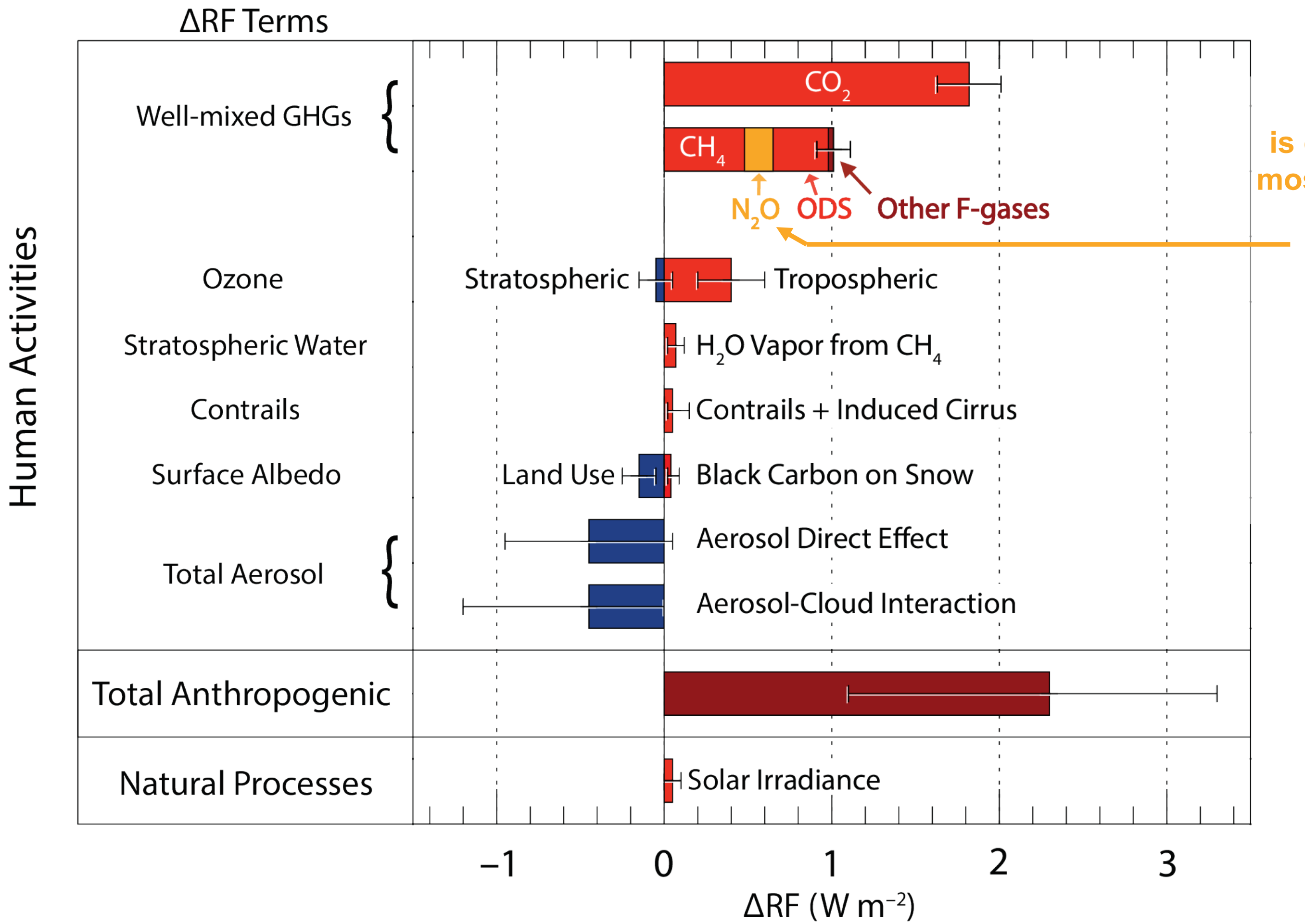
Methane (CH_4) is the 2nd most important human GHG. Once released, CH_4 persists in the atmosphere for <u>about decade</u>.

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

Between 1750 and 2011, the rise in atmospheric CH_4 caused RF of climate to rise by 0.48 W m^{-2}

Figure 1.4, Paris Beacon of Hope

Radiative Forcing of Climate, 1750 to 2011



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.

Figure 1-4, Paris Beacon of Hope

Radiative Forcing of Climate, 1750 to 2011

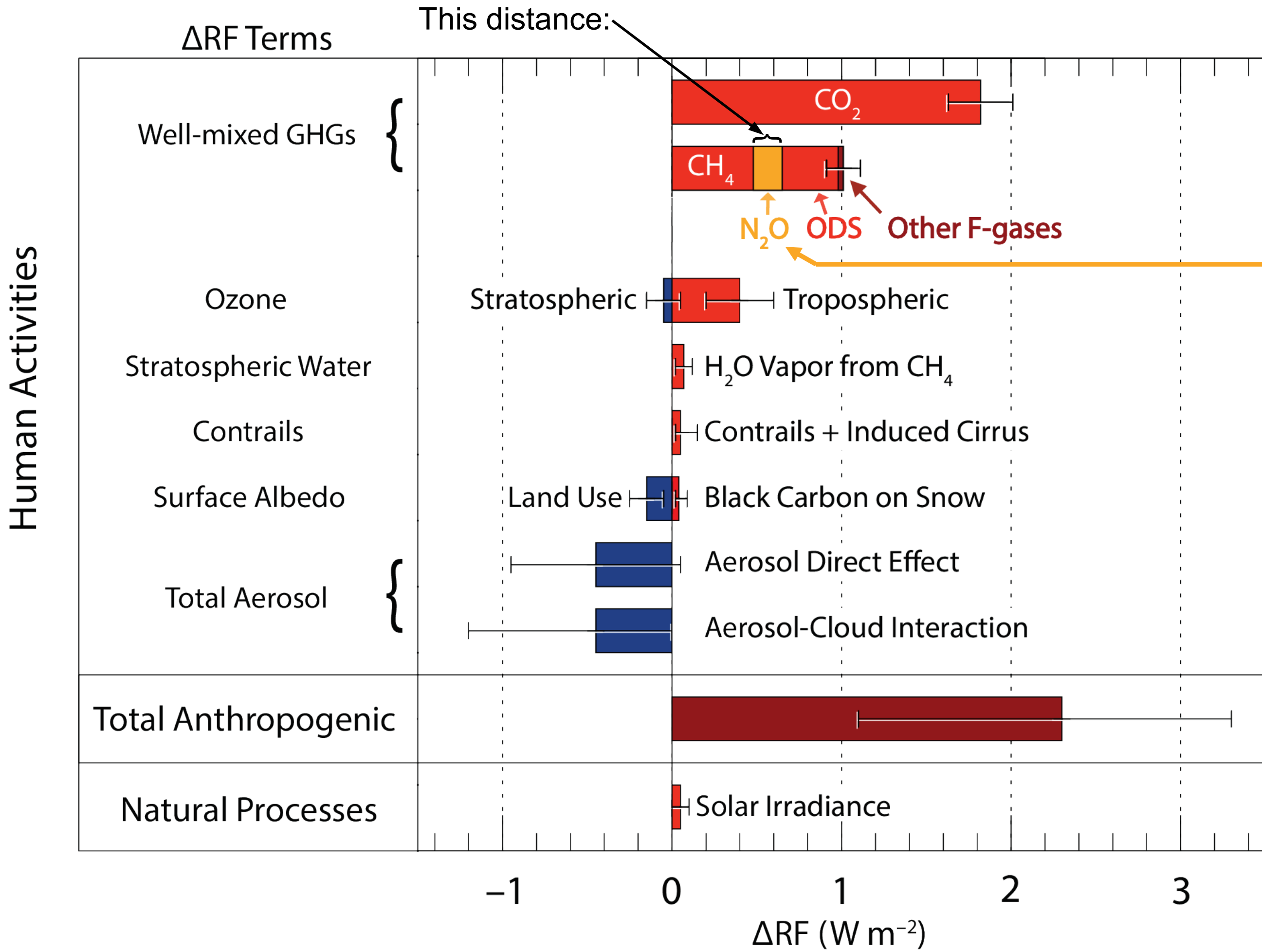


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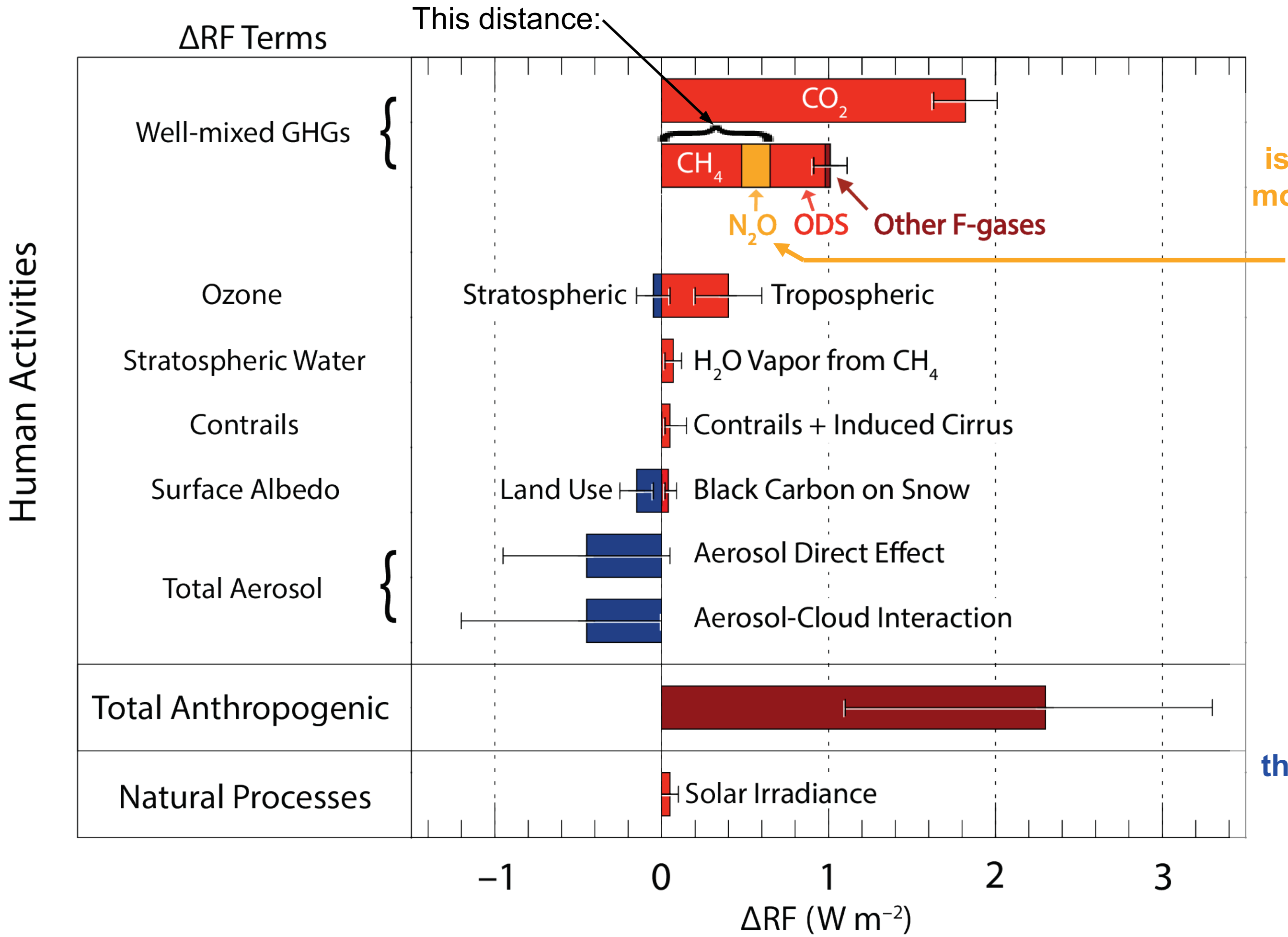
Figure 1-4, Paris Beacon of Hope

Radiative Forcing of Climate, 1750 to 2011



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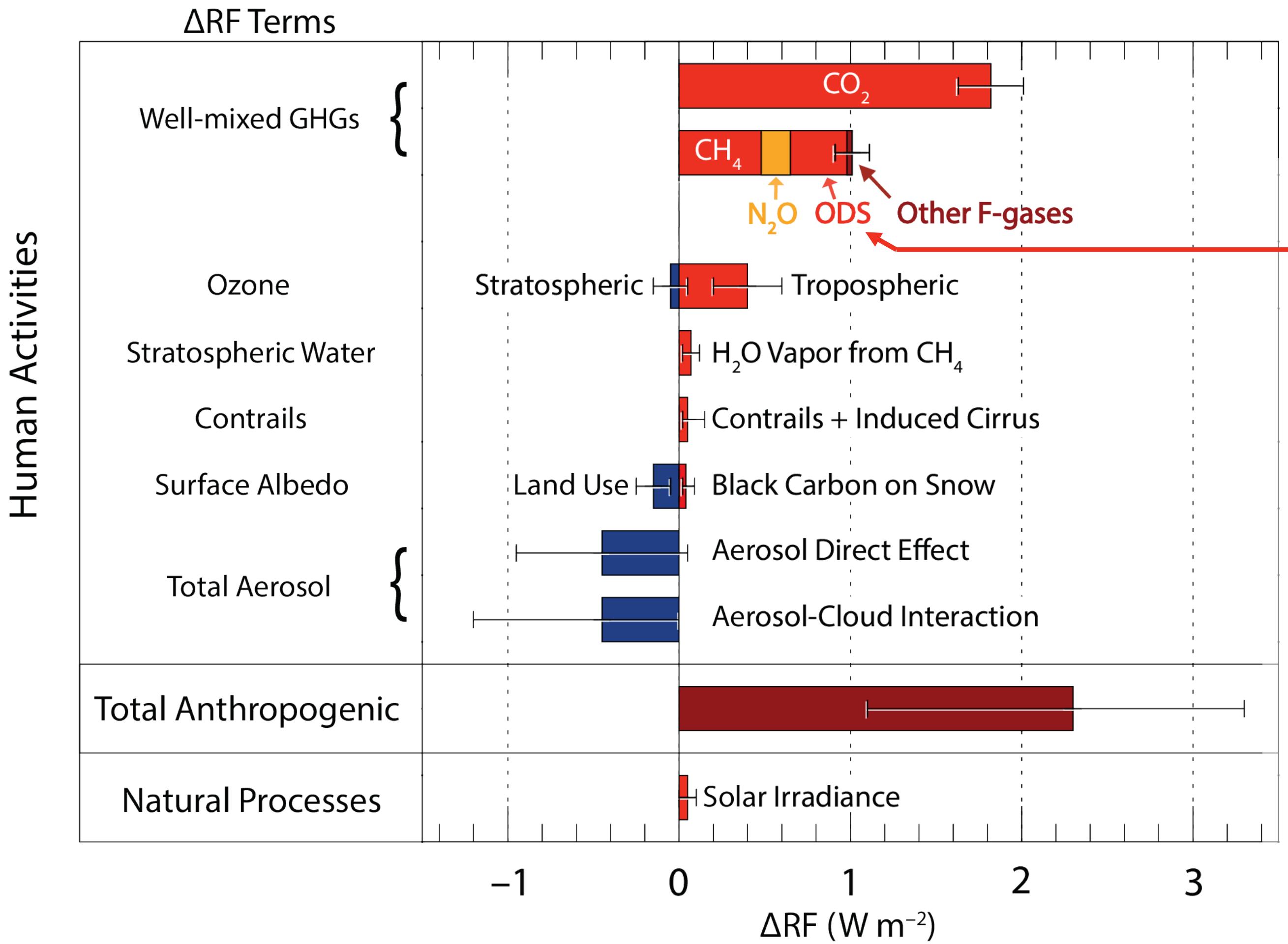
On either a per molecule or a per mass basis, N_2O causes 264 times more warming than CO_2 over a 20-yr time horizon.

Between 1750 and 2011, the rise in atmospheric N_2O caused RF of climate to rise by 0.17 W m^{-2}

The rise in RF of climate due to both CH_4 and N_2O was about 35% of the the rise in RF of climate due to CO_2

Figure 1-4, Paris Beacon of Hope

Radiative Forcing of Climate, 1750 to 2011



CFCs and other ozone depleting substances (ODS) also act as GHGs.

Between 1750 and 2011, the rise in ODS caused RF of climate to rise by 0.33 W m^{-2}

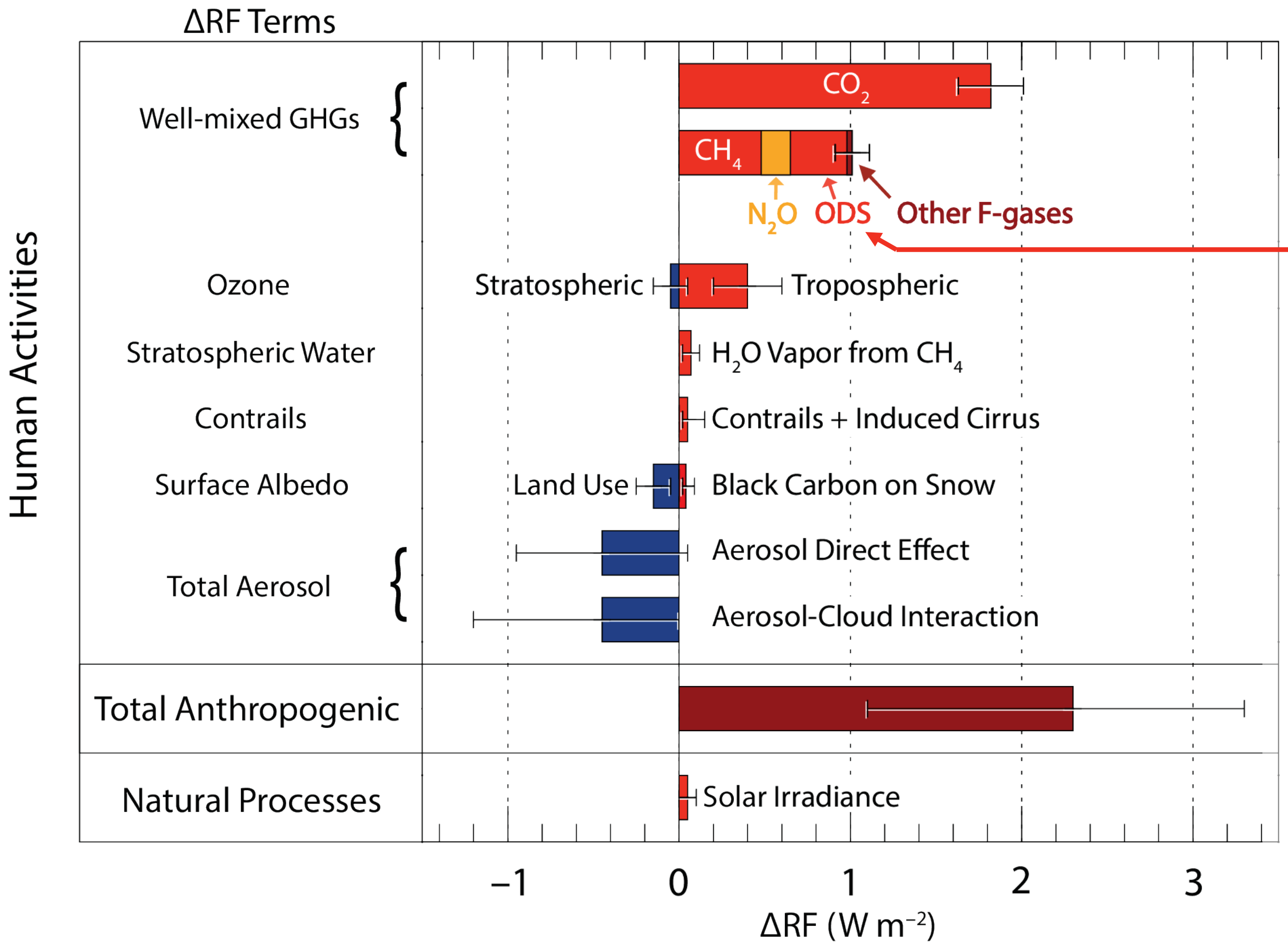
The rise in RF of climate due to CH_4, N_2O, and ODS was *about half* of the the rise in RF of climate due to CO_2

Industrial production of CFCs and other ODS was banned by the ________ ________

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

Figure 1-4, Paris Beacon of Hope

Radiative Forcing of Climate, 1750 to 2011



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The rise in RF of climate due to CH_4, N_2O, and ODS 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 1-4, Paris Beacon of Hope

Ozone in the Atmosphere

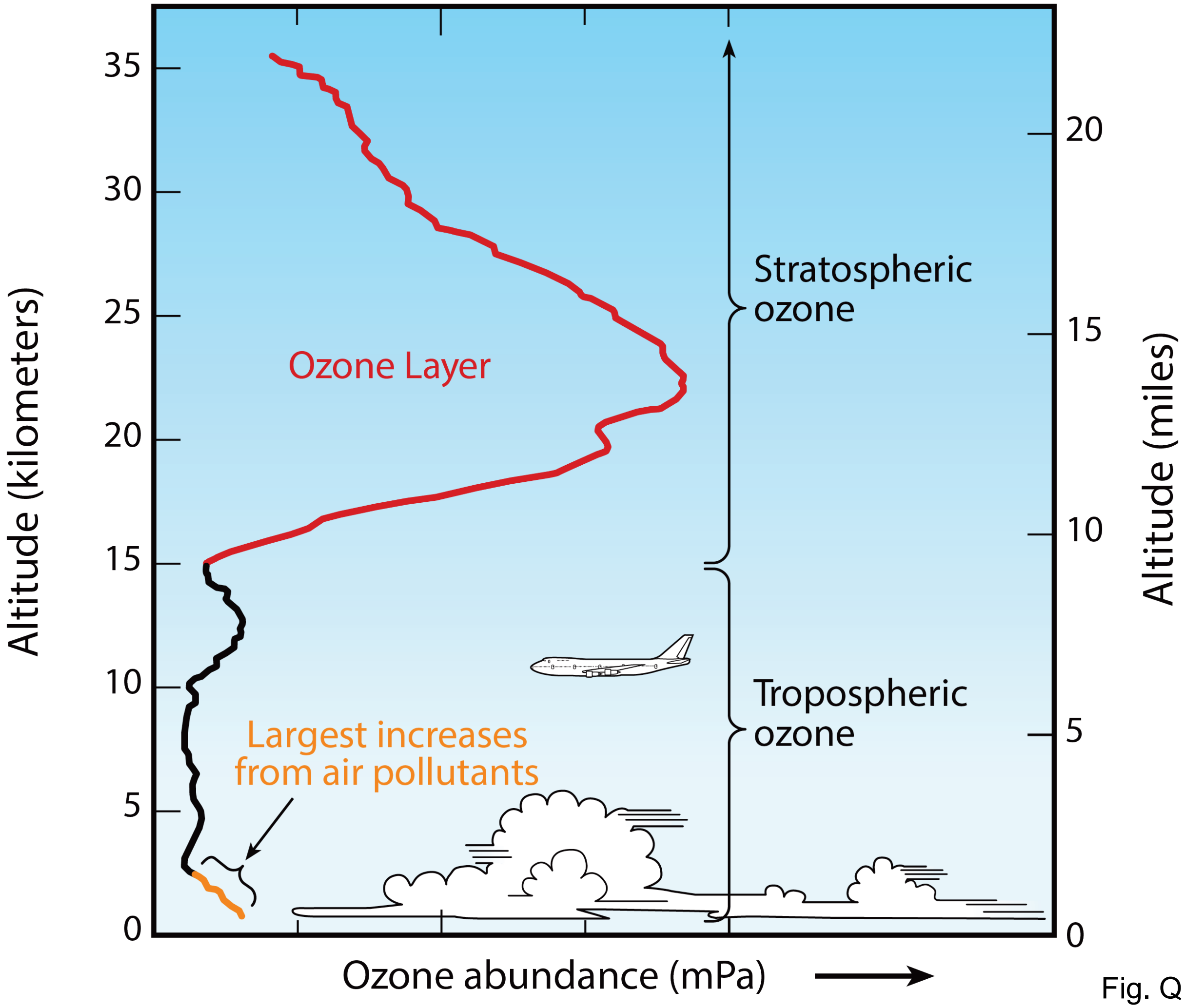
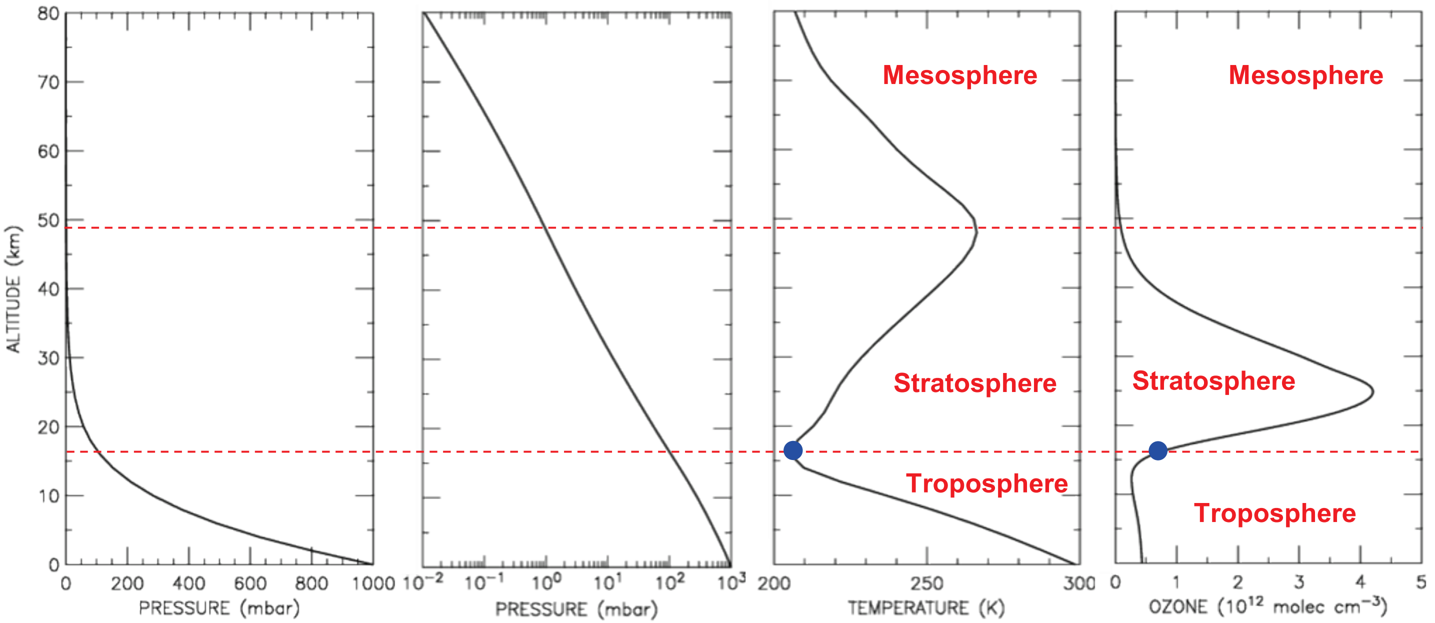


Fig. Q1-2
20 QAs about the Ozone Layer

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

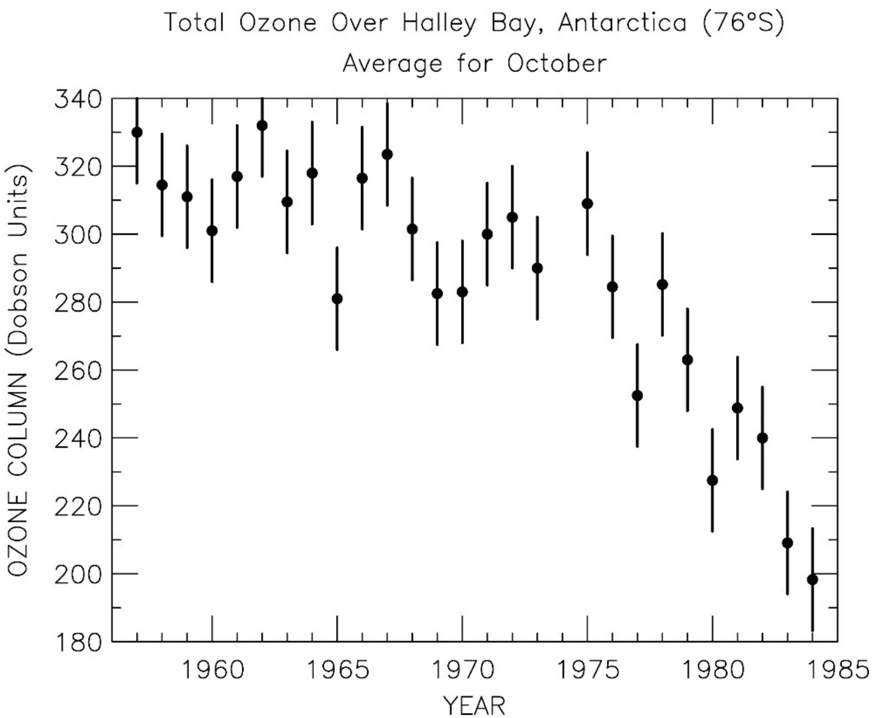


•T falls wrt increasing altit until the tropopause, then rises wrt altit until the stratopause, then falls wrt to rising altitude

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

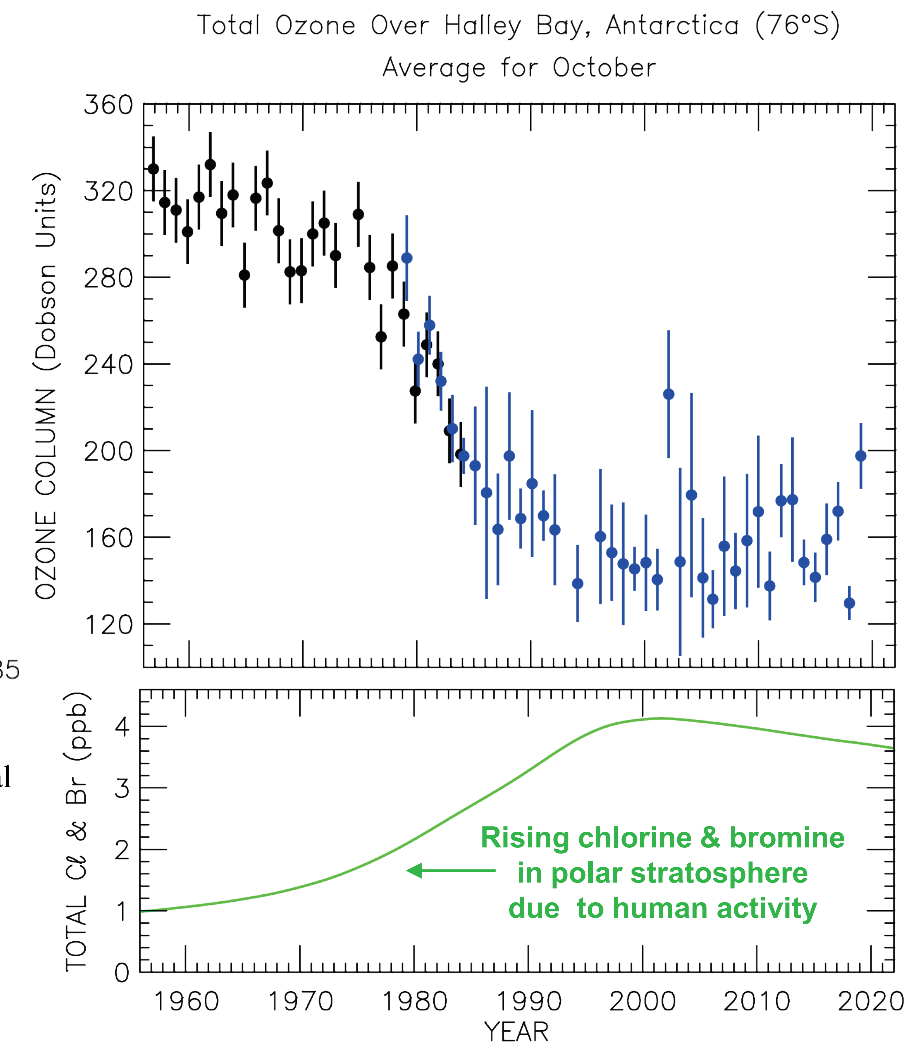
Earth's Atmosphere – Effect of Humans

Stratospheric Ozone – shields surface from solar UV radiation

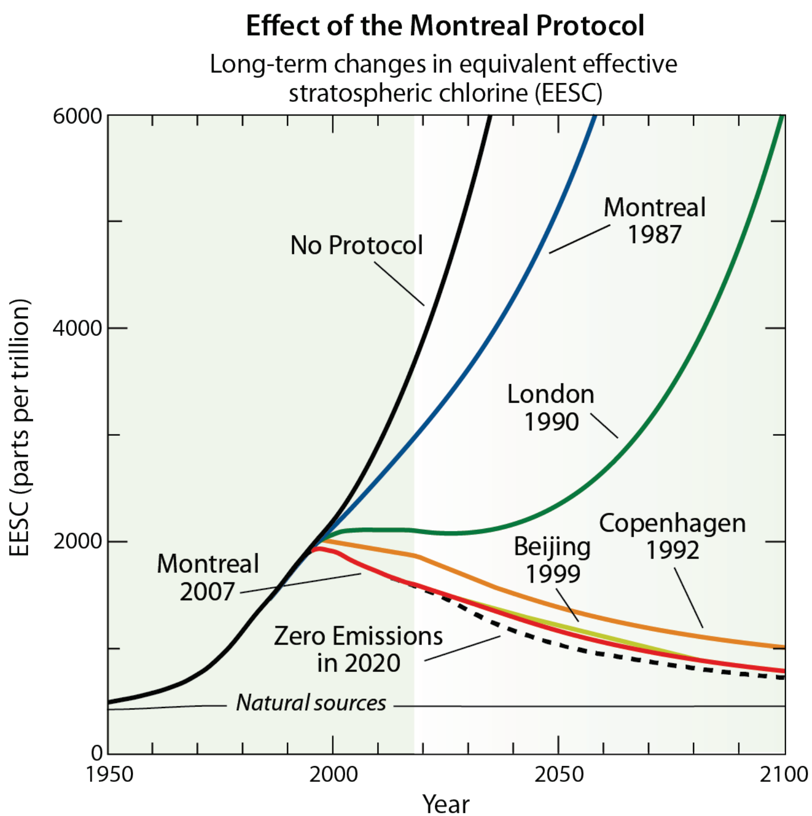


After Farman *et al*., Large losses of total ozone in Antarctica reveal Seasonal ClOx/NOx interaction, Nature, 315, 207, 1985.

Update



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)

CFCs & other ODSs	Phase 1 ⇒	HCFCs	Phase 2 ⇒	HFCs
CFC-11 CFC-12 CFC-113 CFC-114 CFC-115 CCl_4 CH_3CCl_3		HCFC-22 HCFC-141b HCFC-142b		HFC-23 HFC-143a HFC-125 HFC-134a etc.
Harmful to ozone layer		**Less harmful to ozone layer**		**Pose no risk to ozone layer, since no Cl or Br**

See http://www.atmos.umd.edu/~rjs/class/spr2020/supplemental_readings/Naming_Convention_for_CFCs_Halons.pdf
for a guide to CFC naming convention

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

CFCs & other ODSs	Phase 1 →	HCFCs	Phase 2 →	HFCs
CFC-11		HCFC-22		HFC-23
CFC-12		HCFC-141b		HFC-143a
CFC-113		HCFC-142b		HFC-125
CFC-114				HFC-134a
CFC-115				etc.
CCl_4				
CH_3CCl_3				
Harmful to ozone layer		**Less harmful to ozone layer**		**But very harmful to Earth's climate**

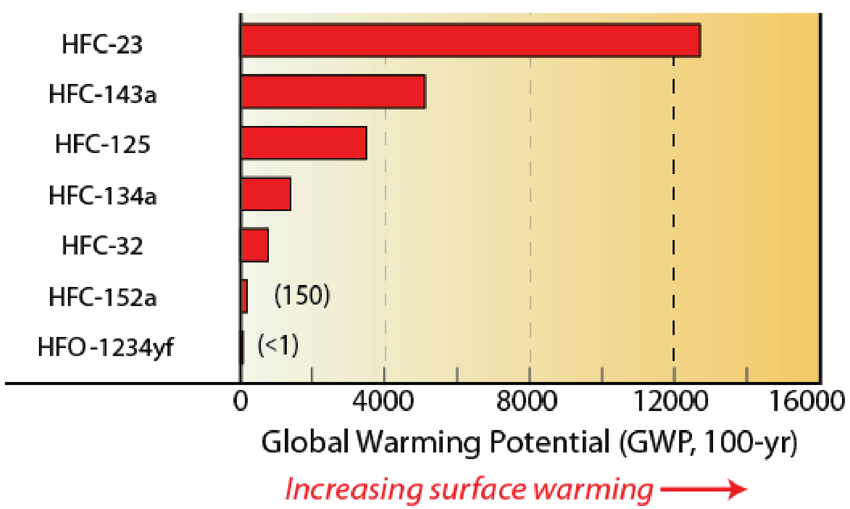


Figure Q17-3, 20 QAs about the Ozone Layer

Kigali Amendment

Tina Birmpili, Ozone Secretariat

PhD in Environmental Management and Economics from *Imperial College of Science, Technology and Medicine*, London.

As of 1 January 2019, the future production of HFCs is controlled by the Montreal Protocol, based on amendment passed in Kigali, Rwanda in Fall 2017, hosted by Rwanda's Minister of Environment Vincent Biruta and Canada's Minister of Environment and Climate Change Catherine McKenna.

"Ozone Secretariat Executive Secretary Tina Birmpili added: "2017 marks the 30th anniversary of the Protocol's life and there is no better way to celebrate this anniversary than by seeking country support to ratify the Kigali Amendment and build on the next 30 years."

https://ozone.unep.org/unga-high-level-event-ratification-kigali-amendment

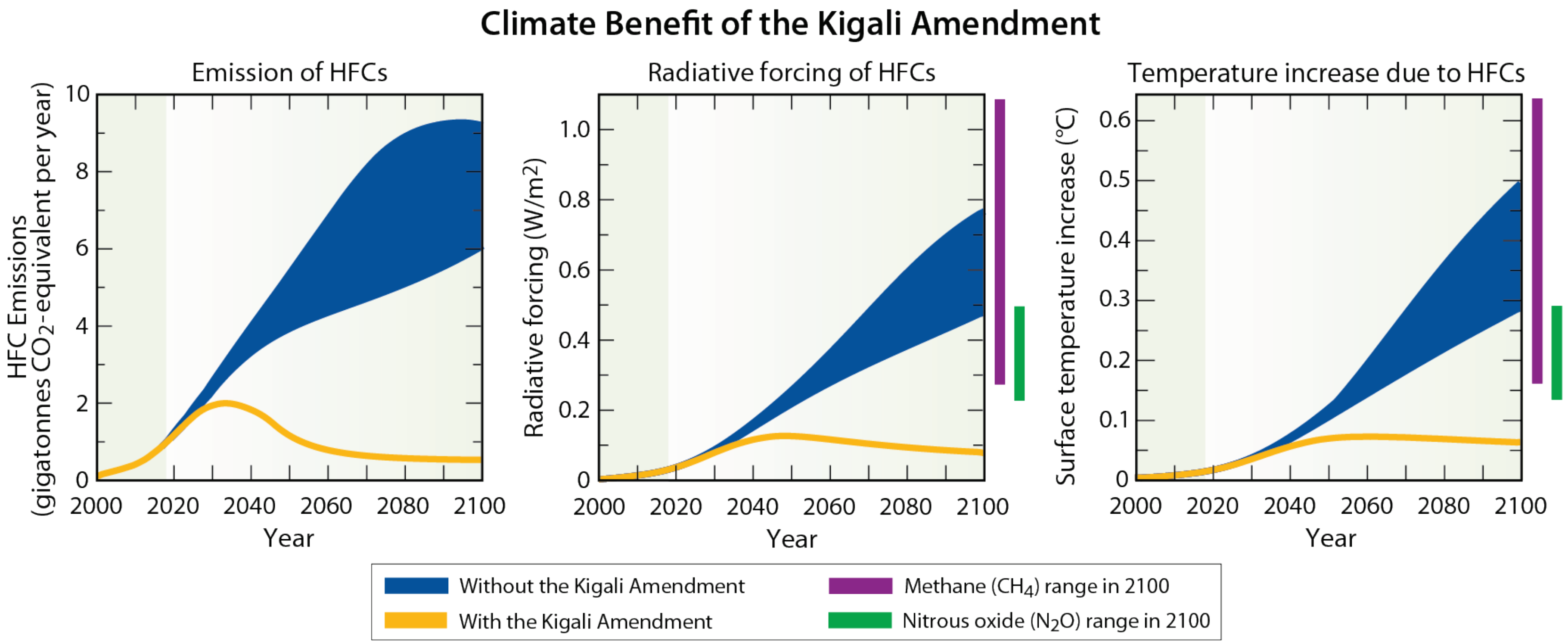
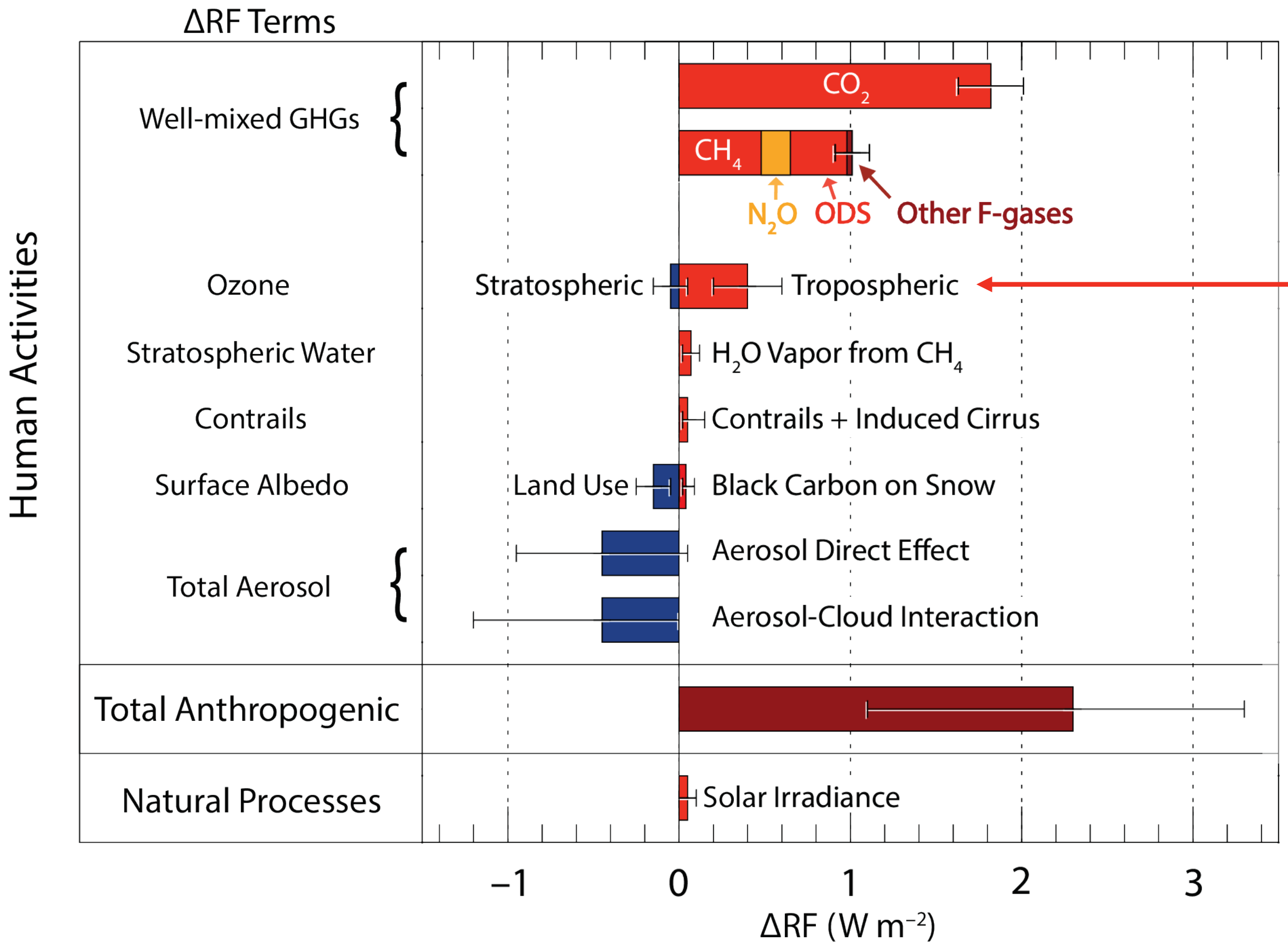


Figure Q19-2, 20 QAs about the Ozone Layer

Radiative Forcing of Climate, 1750 to 2011



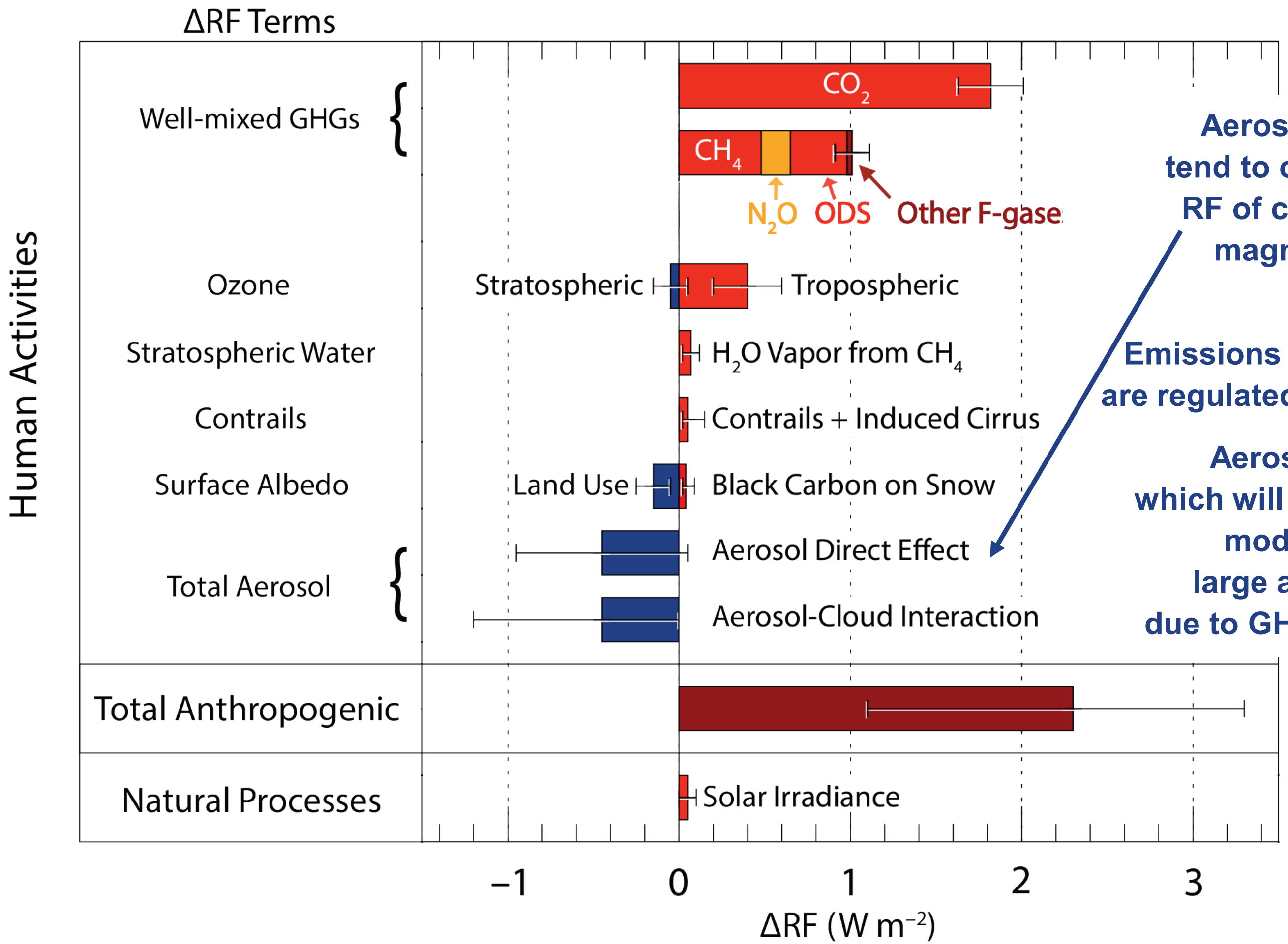
Ozone (O_3) acts as a GHG.

Between 1750 and 2011, the rise in tropospheric O_3 caused RF of climate to rise by 0.40 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 1-4, Paris Beacon of Hope

Radiative Forcing of Climate, 1750 to 2011



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 1-4, Paris Beacon of Hope

Earth's Climate History

Accordion-like unraveling of Earth's climate and CO_2

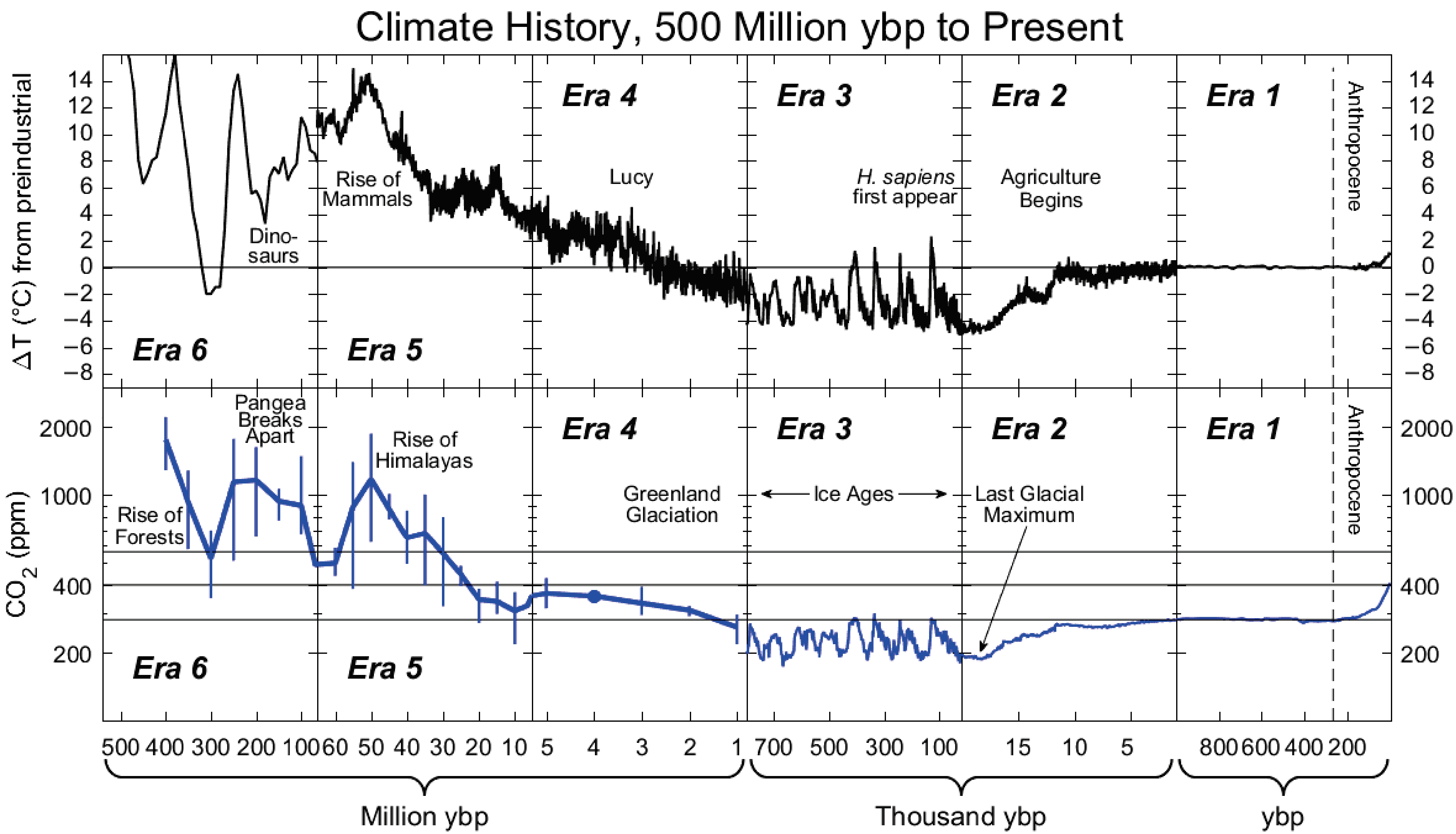


Fig 1.1, *Paris Beacon of Hope*

Going Back 600,000 years

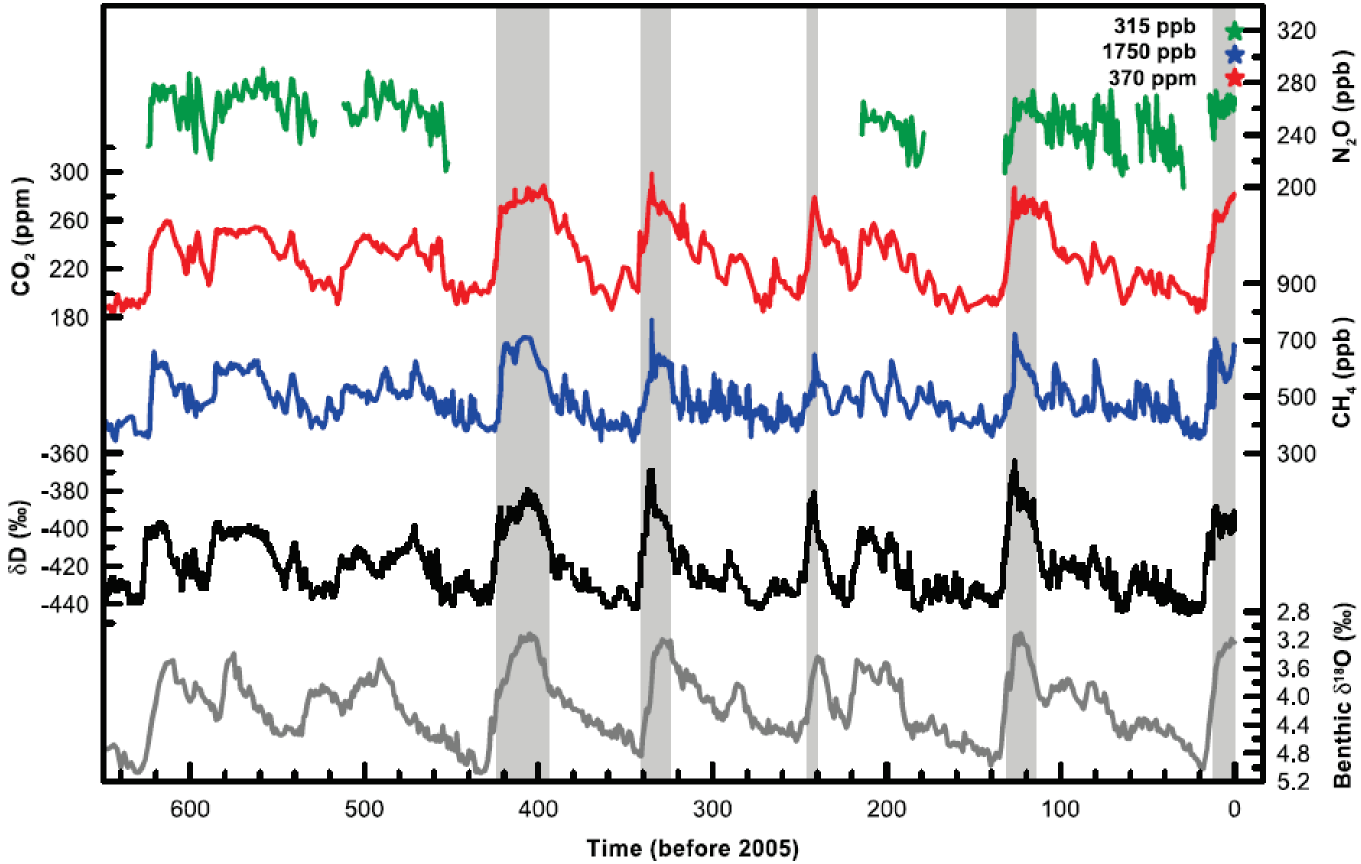


Figure 6.3. *Variations of deuterium (δD; black), a proxy for local temperature, and the atmospheric concentrations of the greenhouse gases CO_2 (red), CH_4 (blue), and nitrous oxide (N_2O; green) derived from air trapped within ice cores from Antarctica and from recent atmospheric measurements (Petit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

GHG Record Over Last Several Millennia

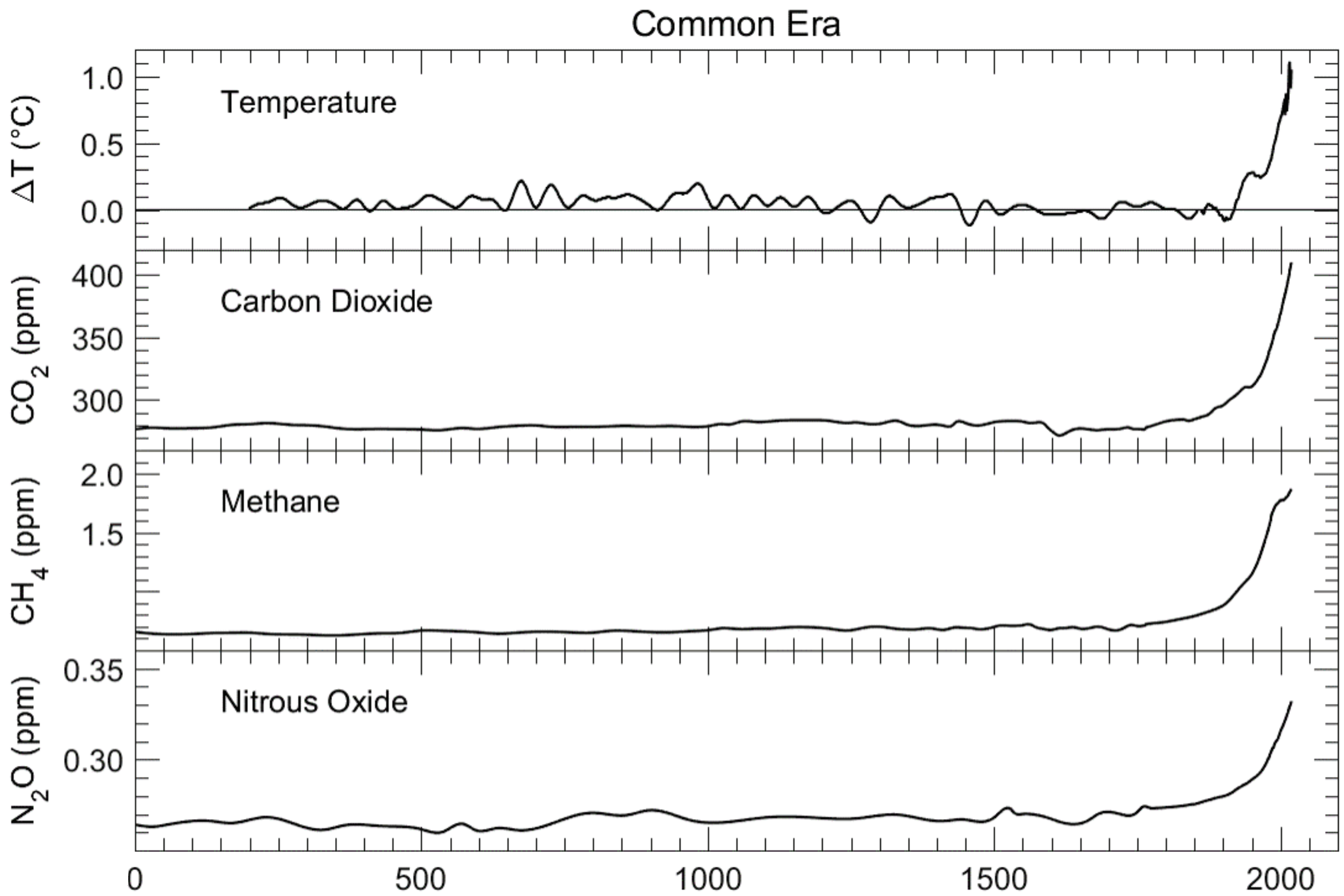


Figure 1.2, Paris Beacon of Hope (updated)

GHG Record Over Last Several Millennia

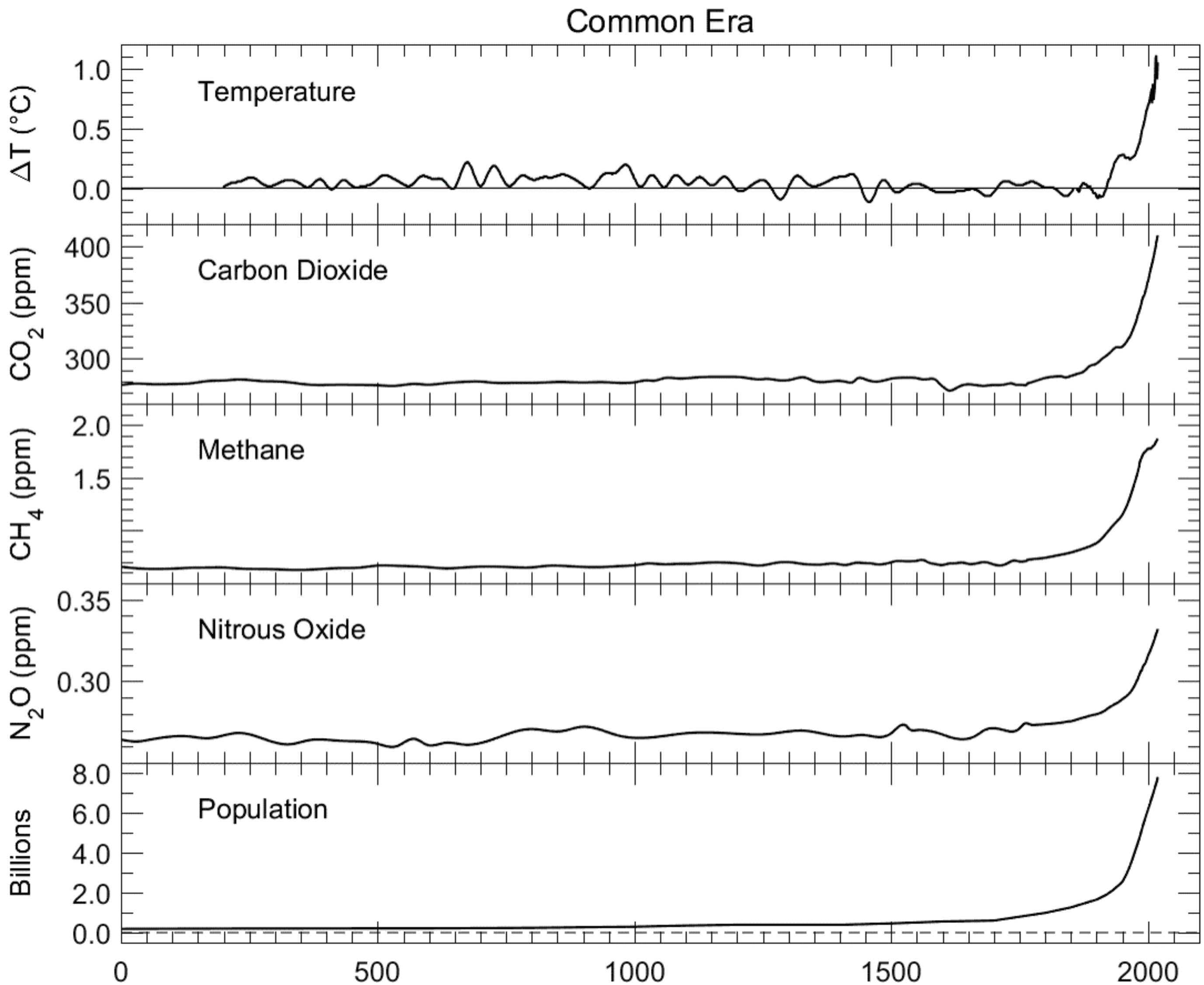


Figure 1.2, Paris Beacon of Hope (updated)

GWP – Global Warming Potential

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

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

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

GWP – Global Warming Potential

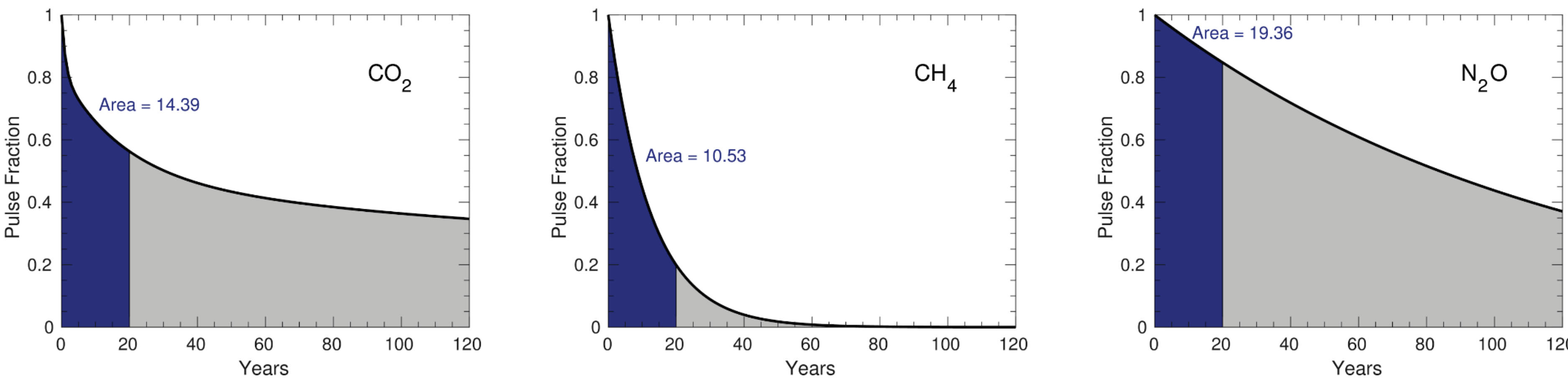
Table 1-1, Paris Beacon of Hope

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

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

GHG	IPCC (1995)	IPCC (2001)	IPCC (2007)	IPCC (2013)
100 Year Time Horizon				
CH_4	21	23	25	28, 34*
N_2O	310	296	298	265, 298*
20 Year Time Horizon				
CH_4	56	62	72	84 86*
N_2O	280	275	289	264 268*
*Allowing for carbon cycle feedback				

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

Table 1-1, Paris Beacon of Hope

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

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

GHG	IPCC (1995)	IPCC (2001)	IPCC (2007)	IPCC (2013)
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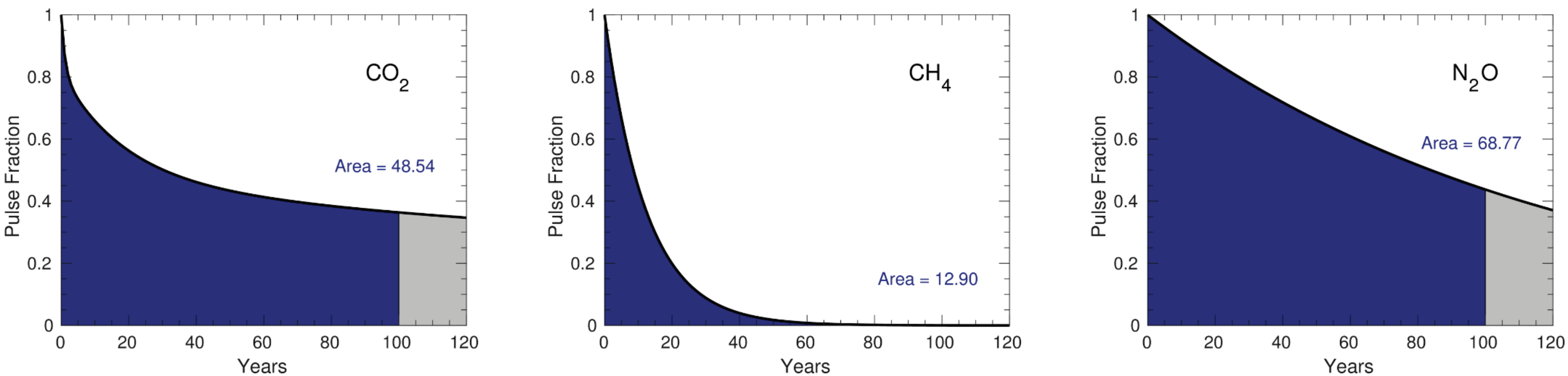
N_2O	280	275	289	264, 268*
*Allowing for carbon cycle feedback				

100 Year Time Horizon means time final = 100 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

Table 1-1, Paris Beacon of Hope

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

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

GHG	IPCC (1995)	IPCC (2001)	IPCC (2007)	IPCC (2013)
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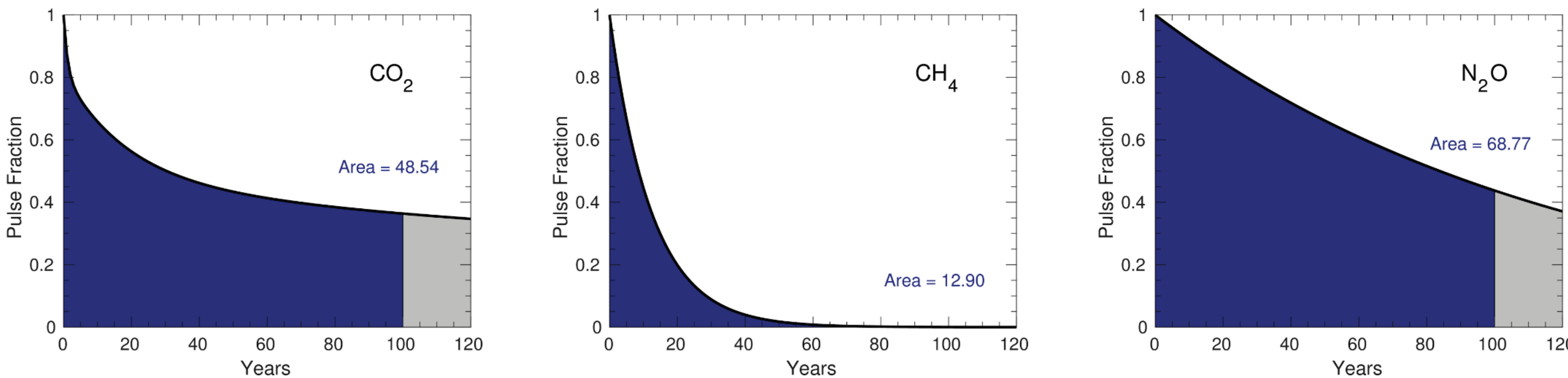
20 Year Time Horizon				
CH_4	56	62	72	84, 86*
N_2O	280	275	289	264, 268*
*Allowing for carbon cycle feedback				

These numbers (i.e., 1995, 2001, 2007, & 2013) are publication years



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

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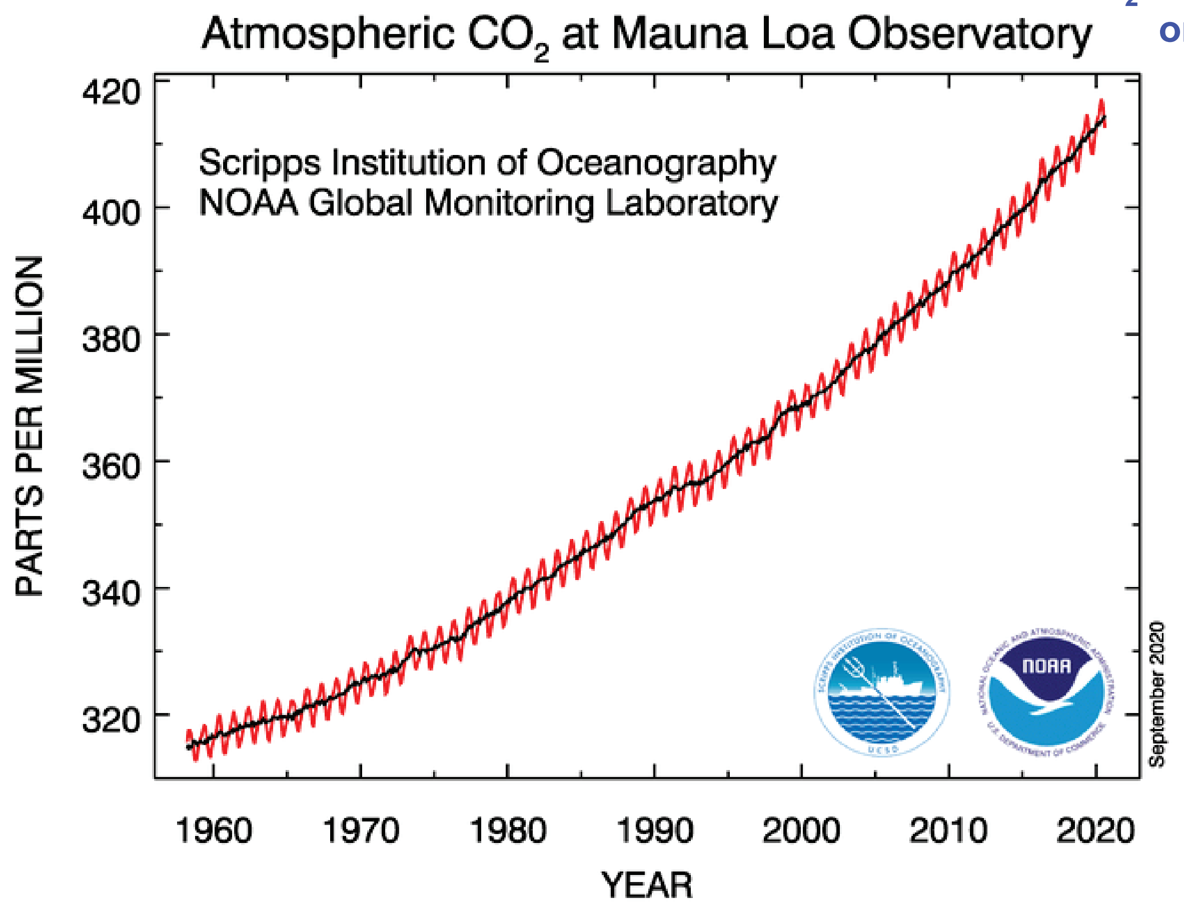
where all times are given in units of year

Modern CO_2 Record

CO_2 at MLO on 15 Sept 2020: 411.84 parts per million (ppm)
CO_2 at MLO on 14 Sept 2019: 408.12 parts per million (ppm)

ΔCO_2 = 3.71 ppm per year
or 0.91 % 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…

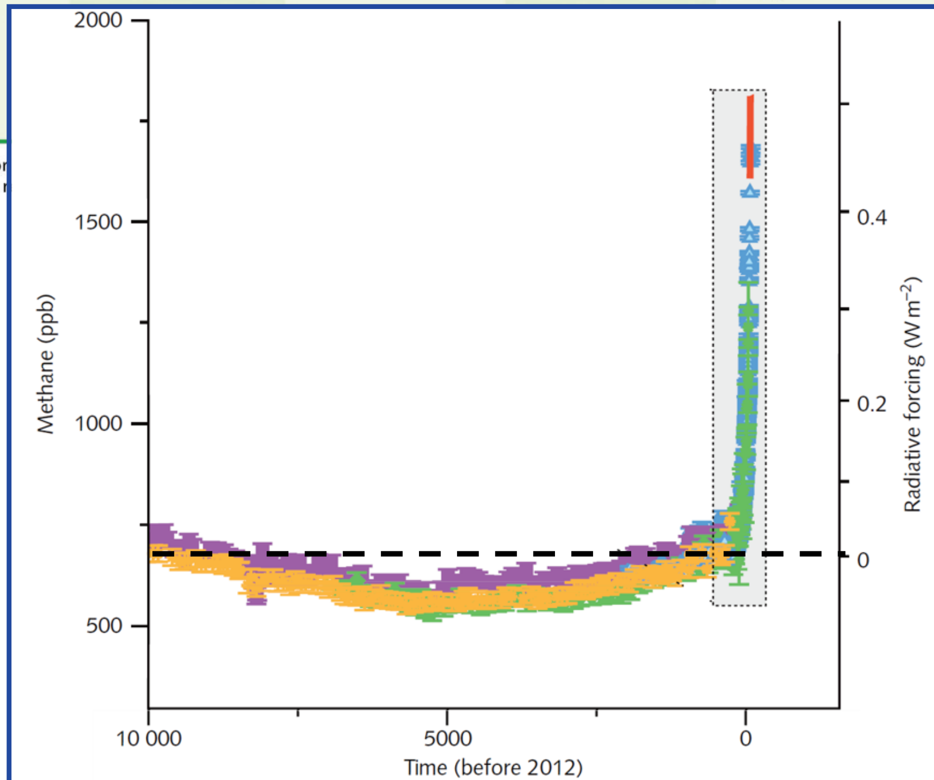


Figure 3.7, *Houghton*

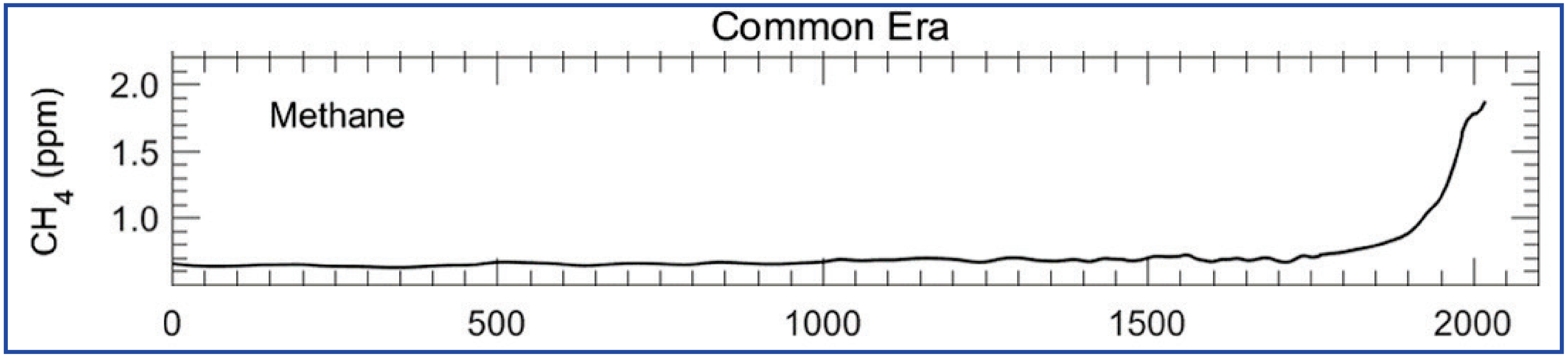
Atmospheric CH_4

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

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	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.

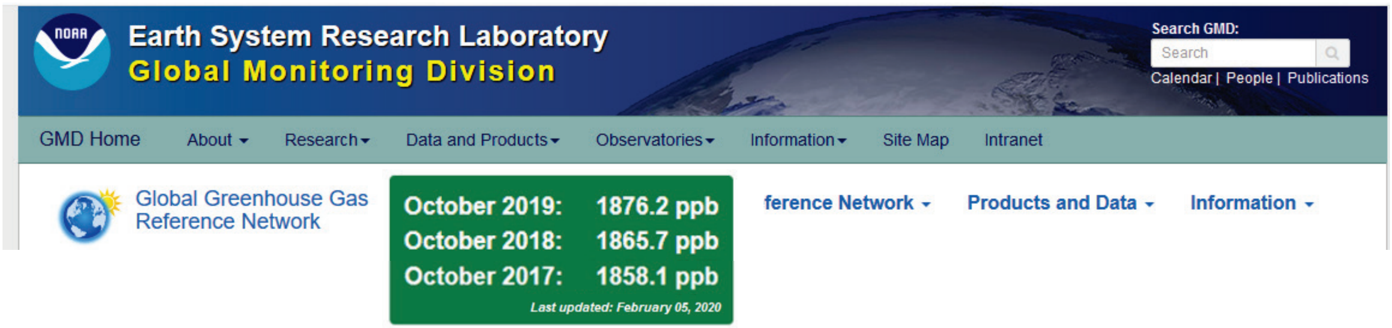


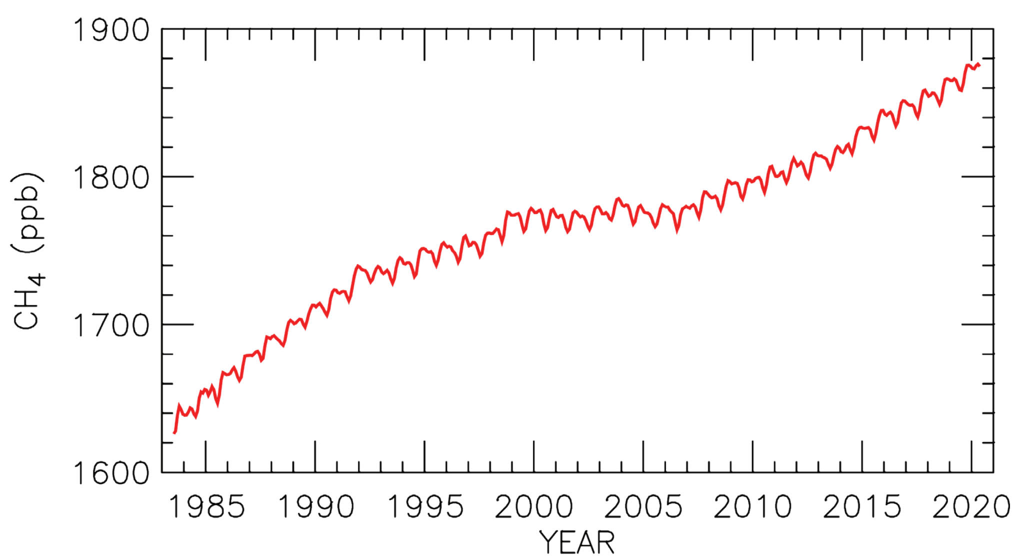
Atmospheric CH_4

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 at 1876.2 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

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

where

$\lambda_P = 0.3 \text{ K} \ / \ \text{W m}^{-2}$

OHE = Ocean Heat Export

Climate models that consider water vapor feedback find:

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

Simple Climate Model

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

where

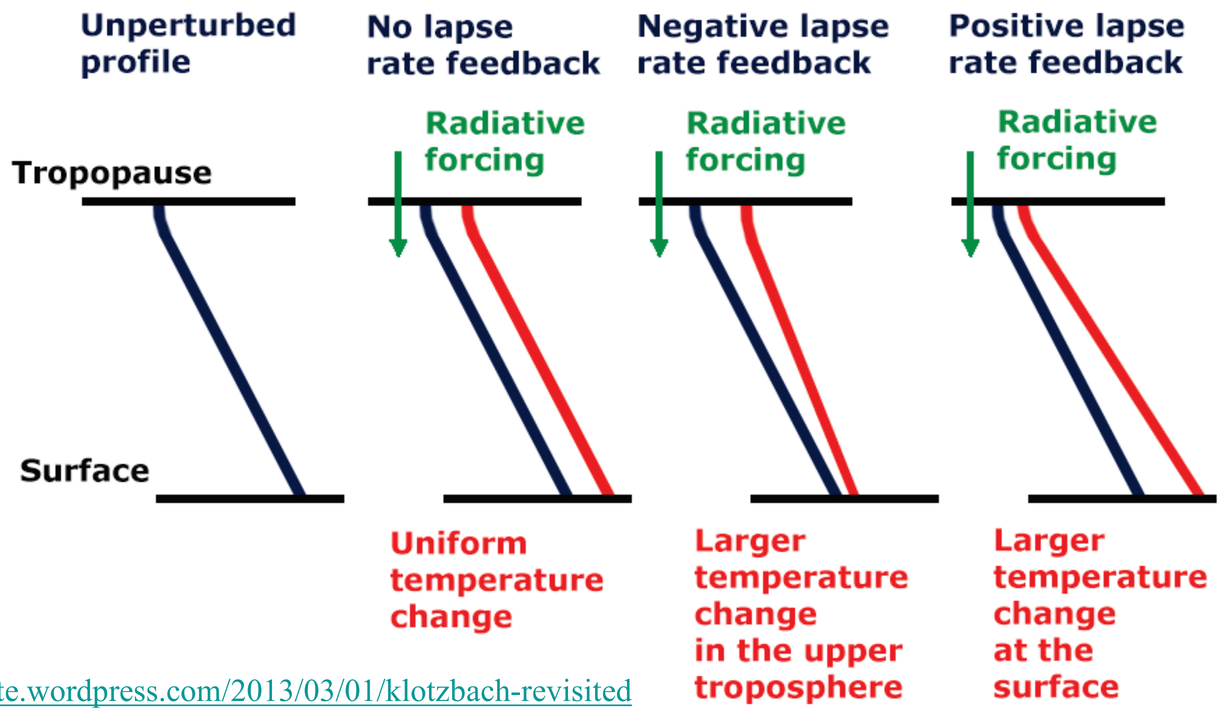
$\lambda_P = 0.3\ K \ / \ W\ m^{-2}$

OHE = Ocean Heat Export

Climate models that consider water vapor feedback & lapse rate feedback find:

$\lambda \approx 0.44\ K \ / \ W\ m^{-2}$, from which we deduce $f_{H2O\ \&\ Lapse\ Rate} = 0.45$

Lapse Rate Feedback



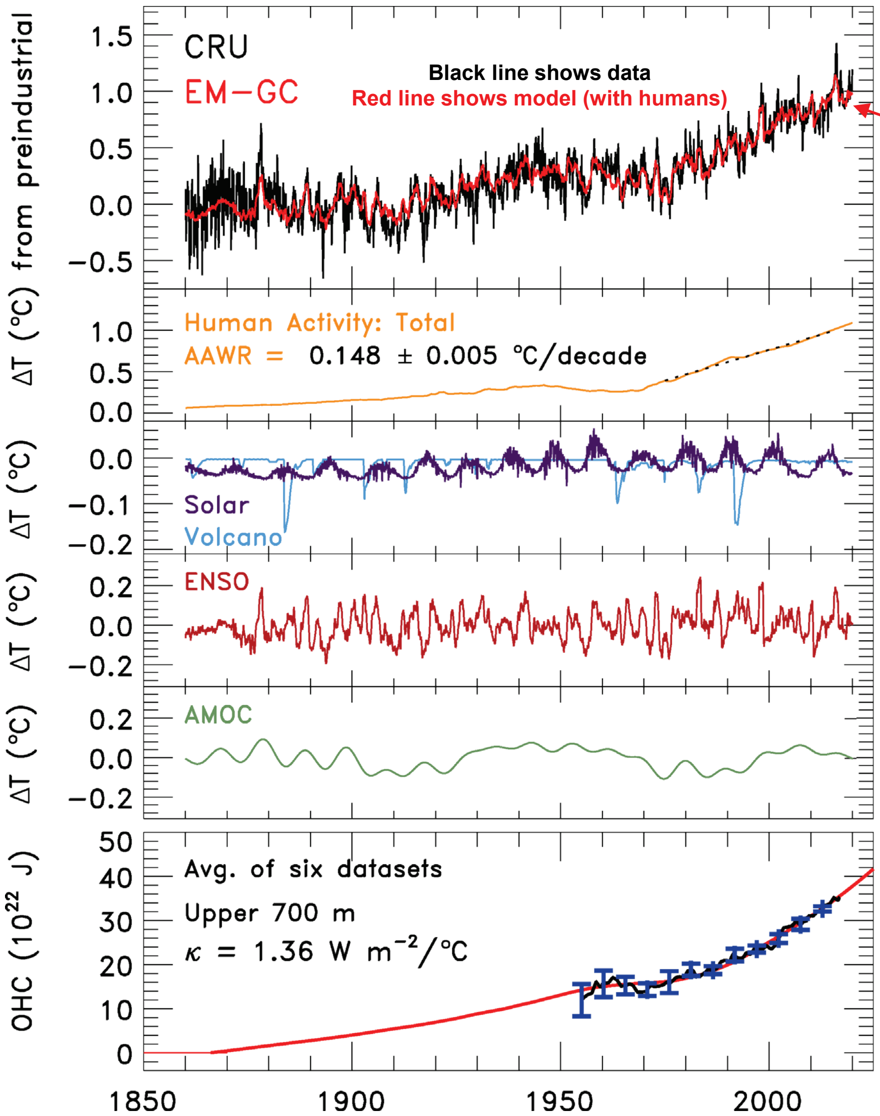
https://ourchangingclimate.wordpress.com/2013/03/01/klotzbach-revisited

- 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
- Definition of empirical lapse rate feedback has some controversy due to differences in opinion regarding proper interpretation of temperature data in UT from various Microwave Sounding Unit (MSU) instruments

Are humans responsible?



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

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

Here, $f_{TOTAL} = 0.99$

This model run assumes $\Delta F_{AEROSOLS}$ in 2011 is –0.9 W m^{-2}

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:

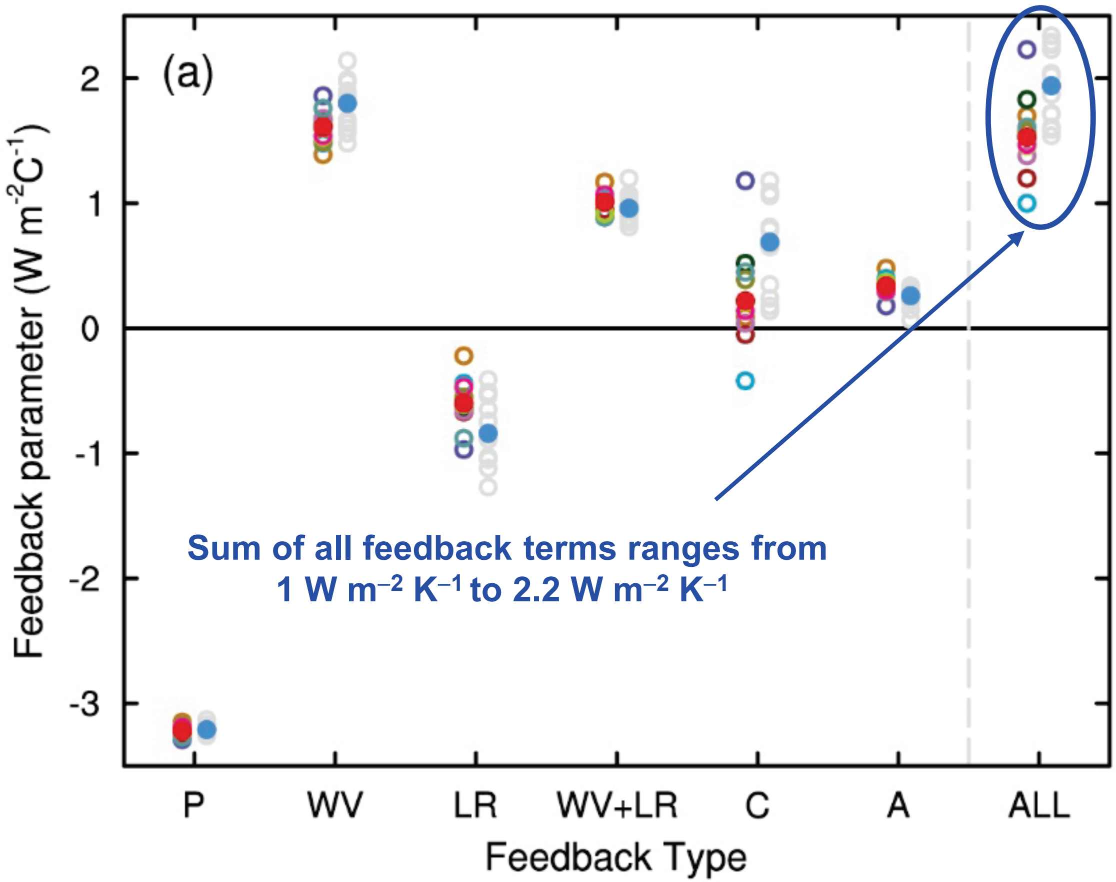
$$1 + f_{TOTAL} = \frac{1}{1 - FB_{TOTAL}\ \lambda_P}$$

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}

Lecture 2, Slide 37

Canty *et al*., 2013 https://www.atmos-chem-phys.net/13/3997/2013/acp-13-3997-2013.html
Hope *et al*., 2017 https://link.springer.com/chapter/10.1007/978-3-319-46939-3_2
as well as Hope *et al*. (2020, submitted) & McBride *et al*. (2020, submitted).
Figure provided by Laura McBride.



Low end of IPCC climate models (i.e., FB_{ALL} = **1.0 W m^{-2} K^{-1}**) implies

$f_{TOTAL} = 0.45$; i.e., all feedbacks besides water vapor & lapse rate cancel

High end of IPCC climate models (i.e., FB_{ALL} = **2.2 W m^{-2} K^{-1}**) implies

$f_{TOTAL} = 2.98$; i.e., clouds must exert a very strong positive feedback

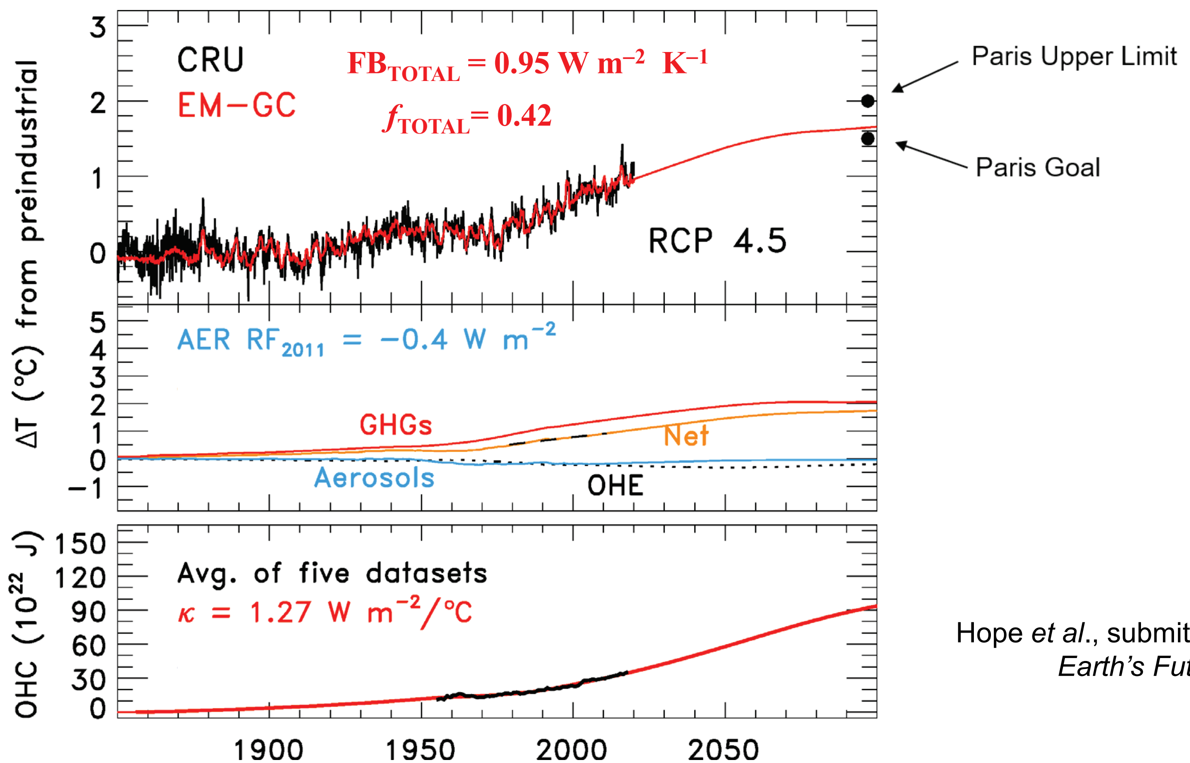
Uncertainty in RF due to aerosols is a huge complication that places a fundamental uncertainty on how well future global warming can be forecast

$$\Delta T \approx \lambda_P \,(1 + f_{TOTAL})\,\Delta RF - OHE \quad ; \qquad 1 + f_{TOTAL} = \frac{1}{1 - FB_{TOTAL}\,\lambda_P}$$

f_{TOTAL} : total feedback term (dimensionless) due to water vapor, lapse rate, clouds, etc. that directly amplifies RF

FB_{TOTAL} : sum of individual feedback terms (units W m^{-2} K^{-1}) computed using IPCC formalism

OHE : export of heat from atmosphere to world's ocean



Hope *et al*., submitted to AGU journal *Earth's Future*, 2020.

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***.

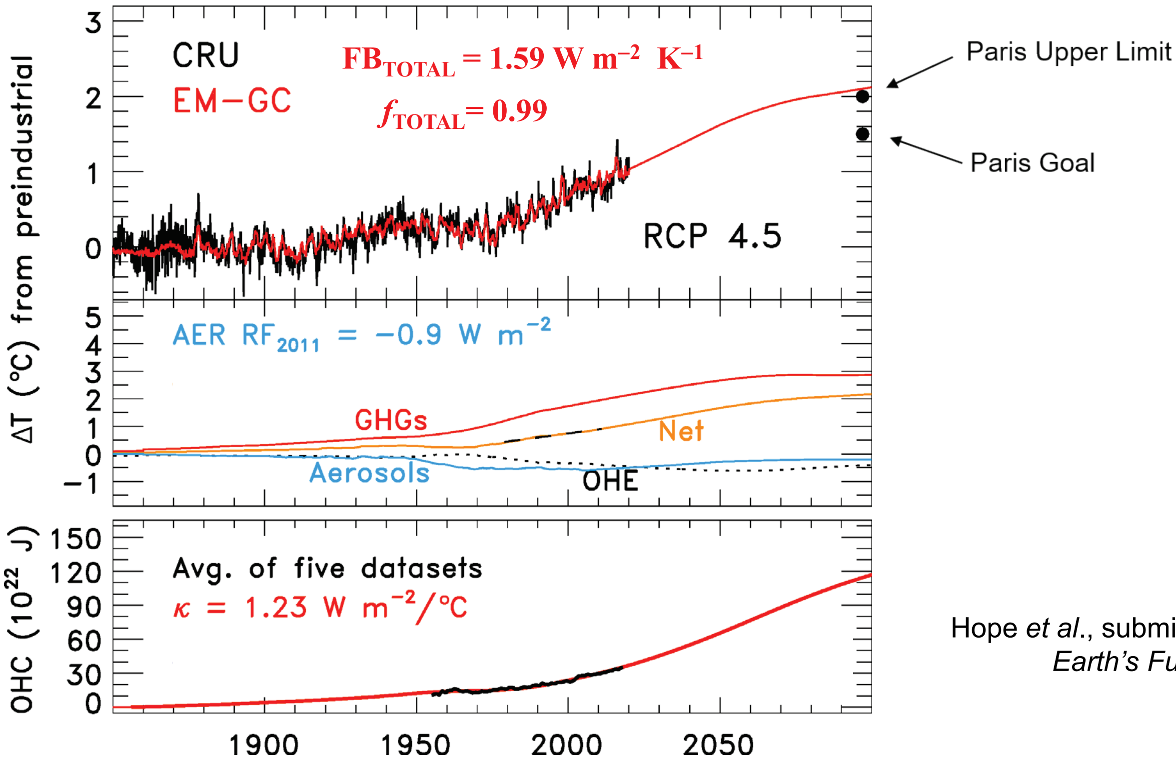
Uncertainty in RF due to aerosols is a huge complication that places a fundamental uncertainty on how well future global warming can be forecast

$$\Delta T \approx \lambda_P \, (1 + f_{TOTAL}) \, \Delta RF - OHE \quad ; \qquad 1 + f_{TOTAL} = \frac{1}{1 - FB_{TOTAL} \, \lambda_P}$$

f_{TOTAL} : total feedback term (dimensionless) due to water vapor, lapse rate, clouds, etc. that directly amplifies RF

FB_{TOTAL} : sum of individual feedback terms (units $W \, m^{-2} \, K^{-1}$) computed using IPCC formalism

OHE : export of heat from atmosphere to world's ocean



Hope *et al*., submitted to AGU journal *Earth's Future*, 2020.

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***.

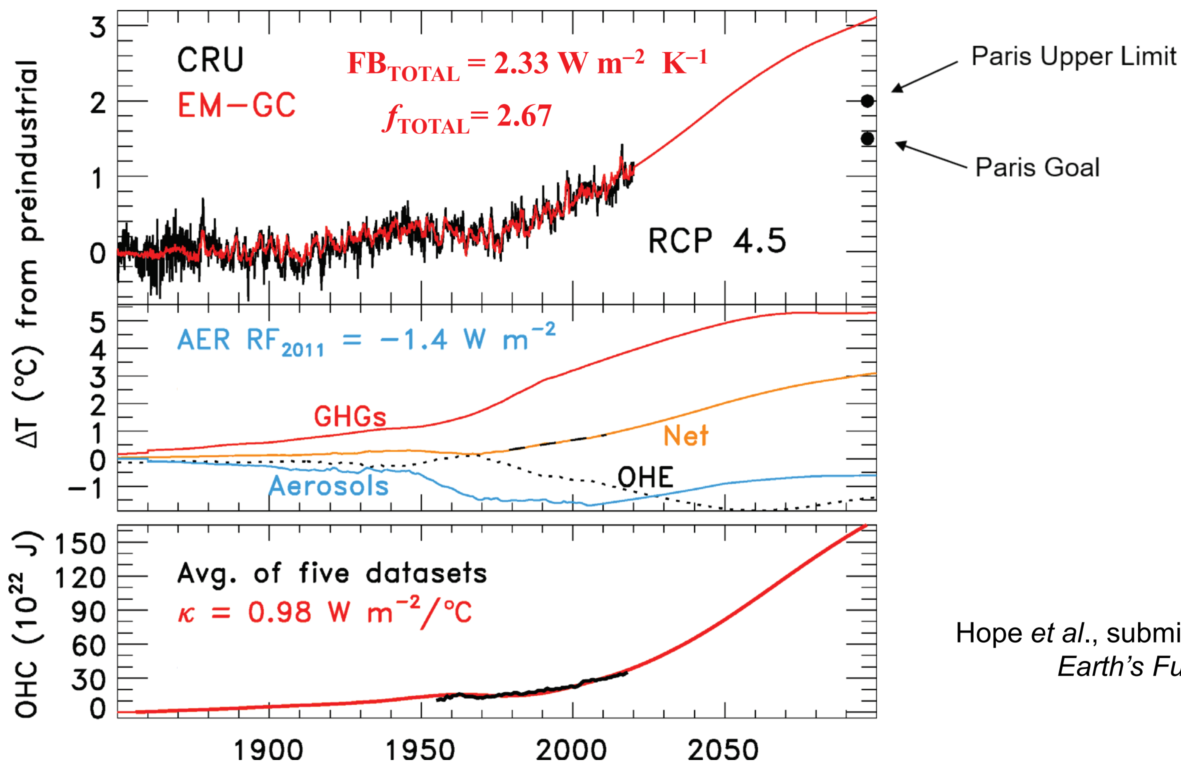
Uncertainty in RF due to aerosols is a huge complication that places a fundamental uncertainty on how well future global warming can be forecast

$$\Delta T \approx \lambda_P \,(1 + f_{TOTAL})\, \Delta RF - OHE \quad ; \qquad 1 + f_{TOTAL} = \frac{1}{1 - FB_{TOTAL}\,\lambda_P}$$

f_{TOTAL} : total feedback term (dimensionless) due to water vapor, lapse rate, clouds, etc. that directly amplifies RF

FB_{TOTAL} : sum of individual feedback terms (units $W\,m^{-2}\,K^{-1}$) computed using IPCC formalism

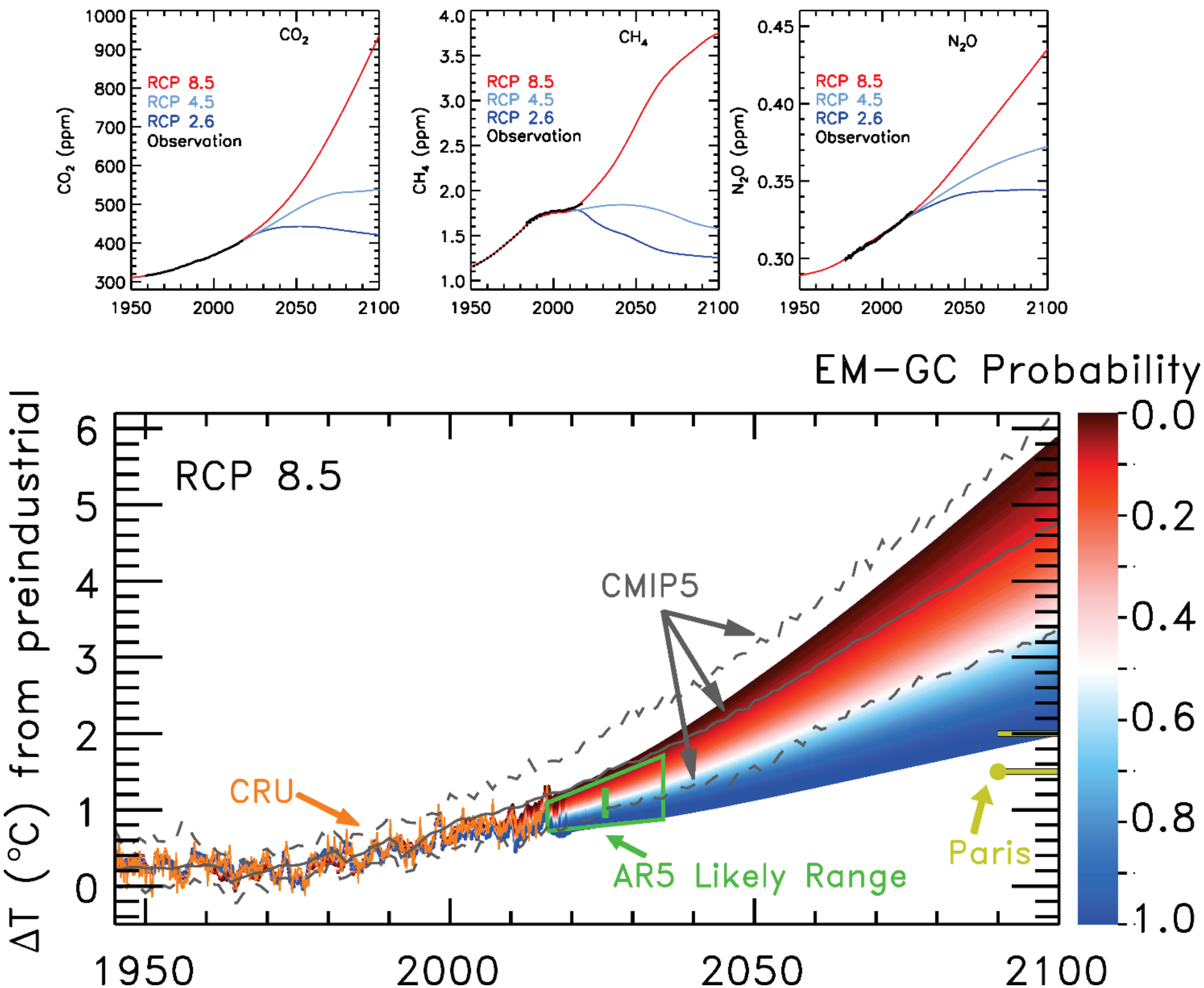
OHE : export of heat from atmosphere to world's ocean



Hope *et al.*, submitted to AGU journal *Earth's Future*, 2020.

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***.

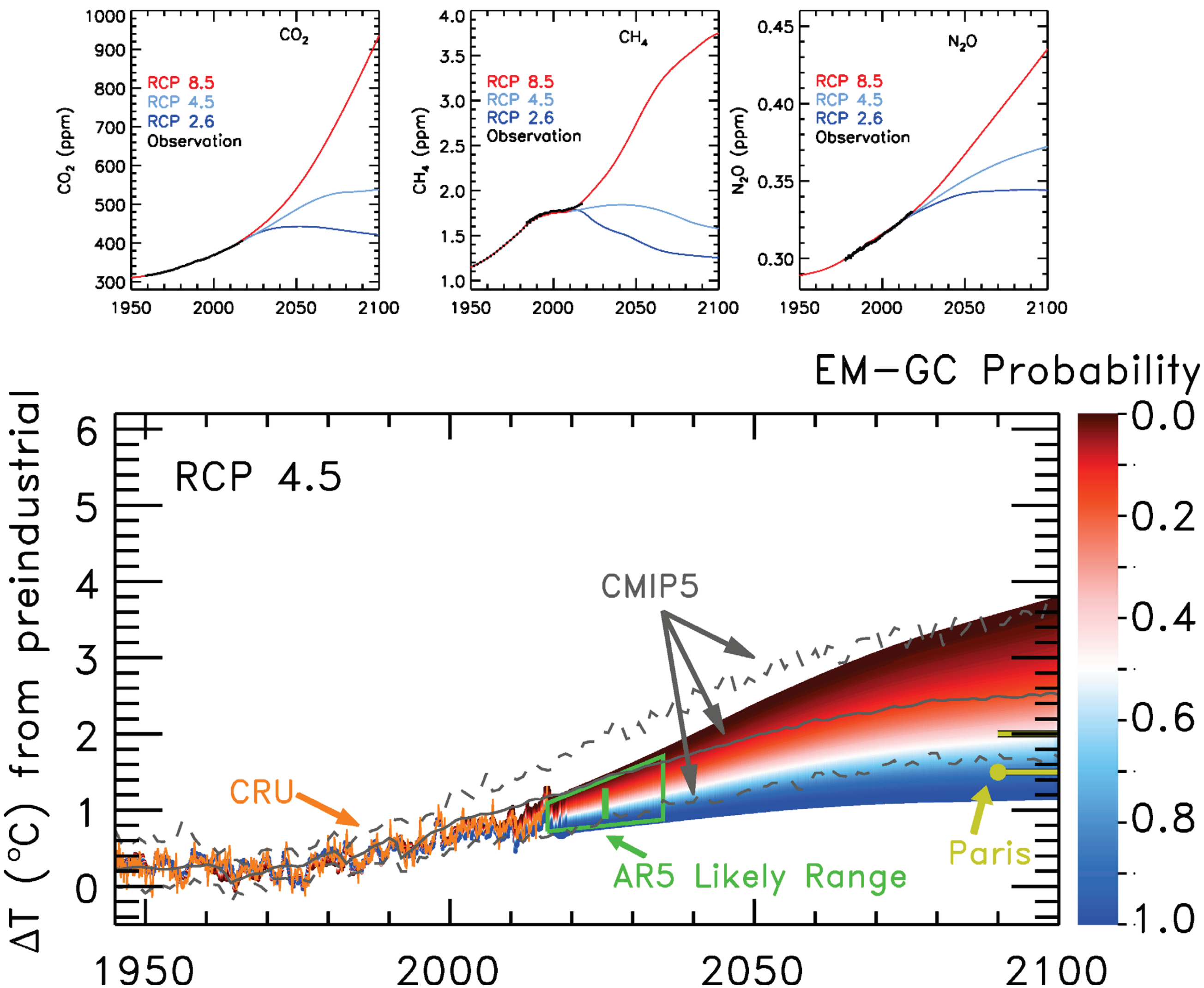
EM-GC Forecast vs CMIP5



If GHGs follow RCP 8.5, **0%** chance rise GMST stays below **1.5°C** and **0%** chance stays below **2.0°C**

Hope *et al*., *Earth's Future*, submitted, 2020.

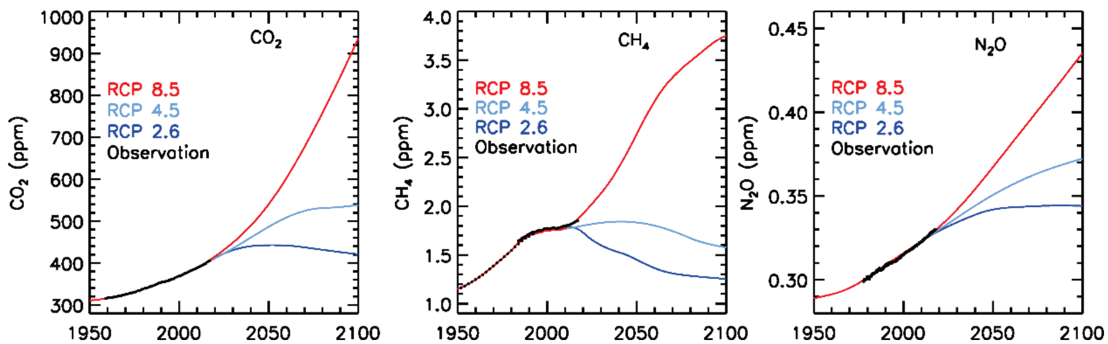
EM-GC Forecast vs CMIP5

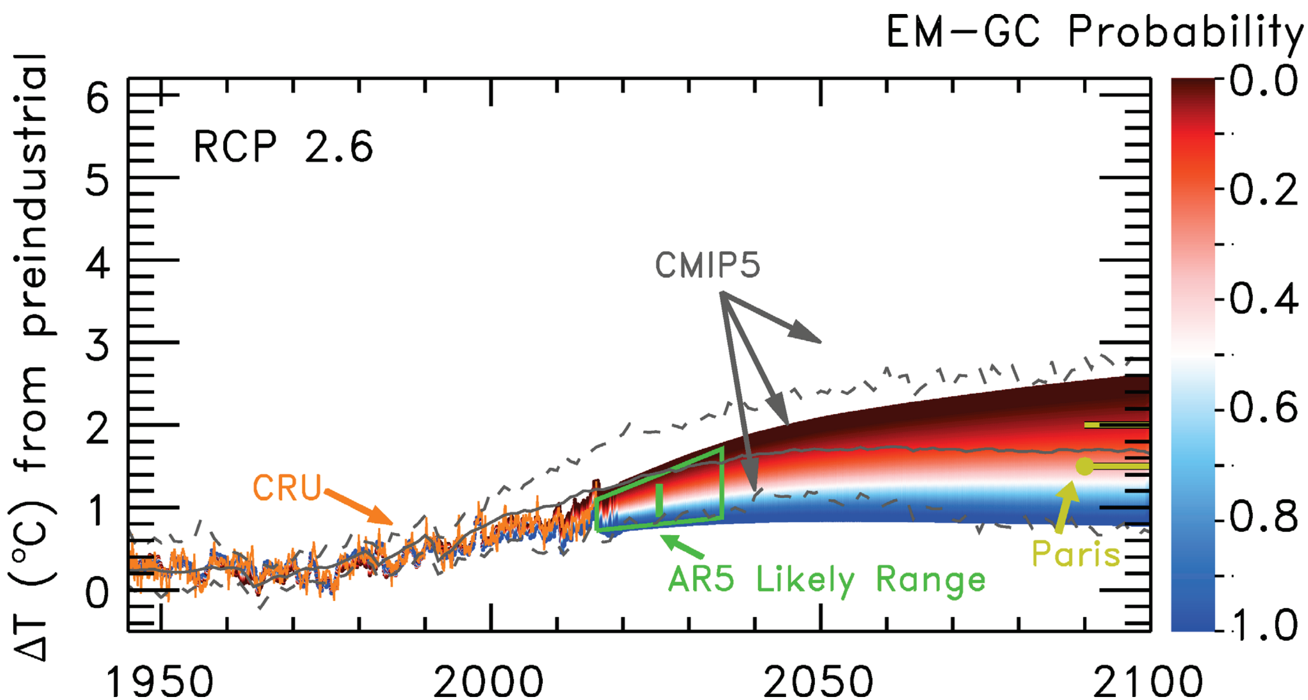


If GHGs follow RCP 4.5, **10%** chance rise GMST stays below **1.5°C** and **50%** chance stays below **2.0°C**

Hope *et al.*, *Earth's Future*, submitted, 2020.

EM-GC Forecast vs CMIP5





If GHGs follow RCP 2.6, **67%** chance rise GMST stays below **1.5°C** and **92%** chance stays below **2.0°C**

Hope *et al*., *Earth's Future*, submitted, 2020.