Radiative Forcing: **Catch-Up**

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

Goals:

- Understanding interaction between gases and IR radiation
- Radiative forcing of greenhouse gases
- Radiative forcing of aerosols

Wavenumber = 1 / Wavelength

1 μm (micron) = 10^{-6} m
1 nm (nanometer) = 10^{-9} m

Therefore, 1 μm = 1000 nm

Lecture 7: Catch-up

24 September 2020

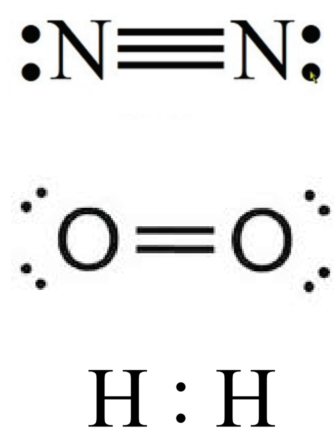
Excitation of Molecules

A greenhouse gas must have either

- naturally occurring **dipole moment**
- exhibit a **dipole moment** during vibration

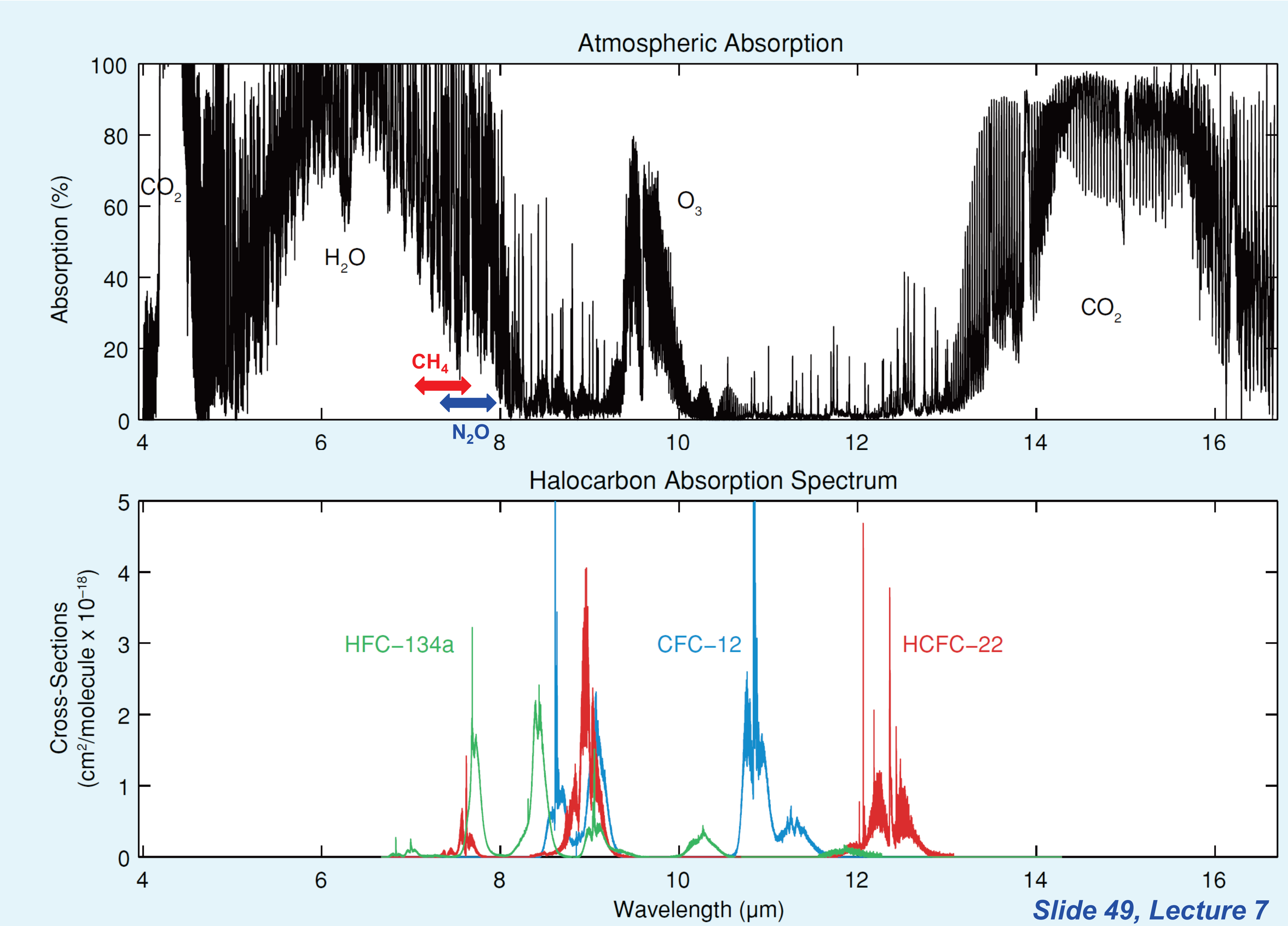
Dipole moment ⇨ product of magnitude of charges & distance of separation between charges:
i.e., a molecule is said to have a dipole moment if it has a non-zero spatial distribution of charge

No dipole moment, either naturally or during vibration, for diatomic molecules <u>of the same atoms</u>:



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

Absorption vs. Wavelength



Slide 49, Lecture 7

Overview

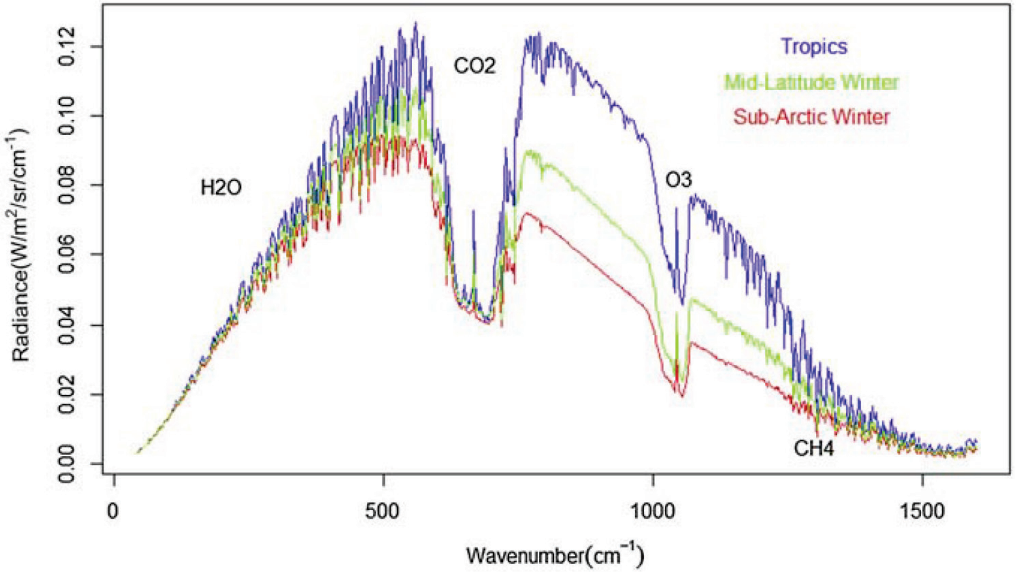


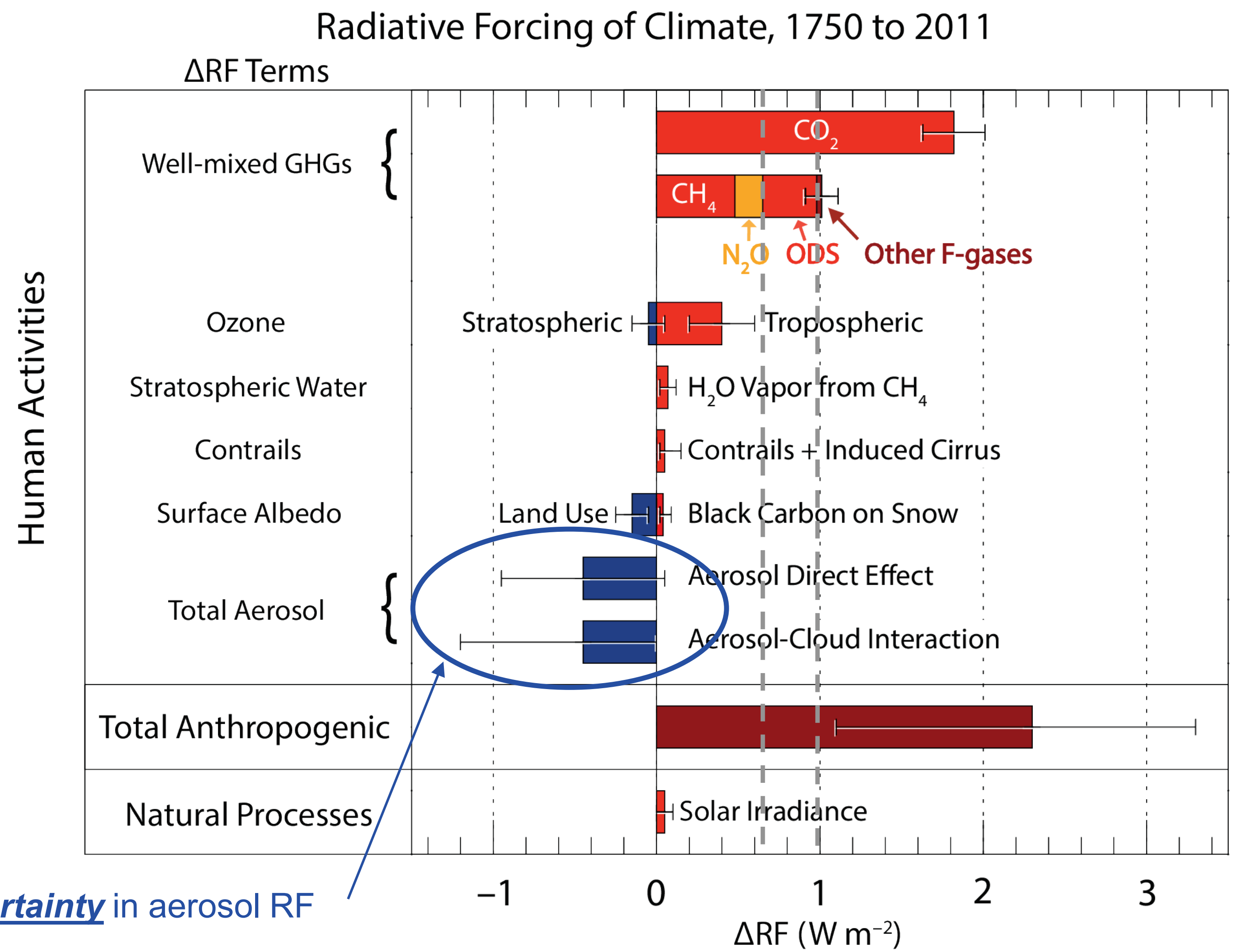
FIGURE 3.4.5 Overview of the earth's outgoing infrared radiation as a function of wave number (the inverse of wavelength) and latitude.[43] Radiances for this figure were calculated using Modtran and a web interface developed by David Archer available here: http://climatemodels.uchicago.edu/modtran/.

Kirk-Davidoff, Chapter 3.4, *Green Chemistry: An Inclusive Approach*, 2018

- GHGs prevent outgoing energy emitted from the surface from being released back into space, thereby trapping this energy and releasing it in the form of heat.
- Averaged over space and time, the Earth radiates to space an amount of energy consistent with that of a black body at 255 K.
- Some spectral regions are nearly filled (i.e., 667 cm^{-1}) whereas many others exhibit negligible attenuation of outgoing radiation.
- A newly discovered "miracle compound" with a long atmospheric lifetime will be much more damaging to Earth's climate system if it absorbs in a region that is optically open, rather than a region that is optically closed.

Slide 11, Lecture 7

ΔRF of Climate

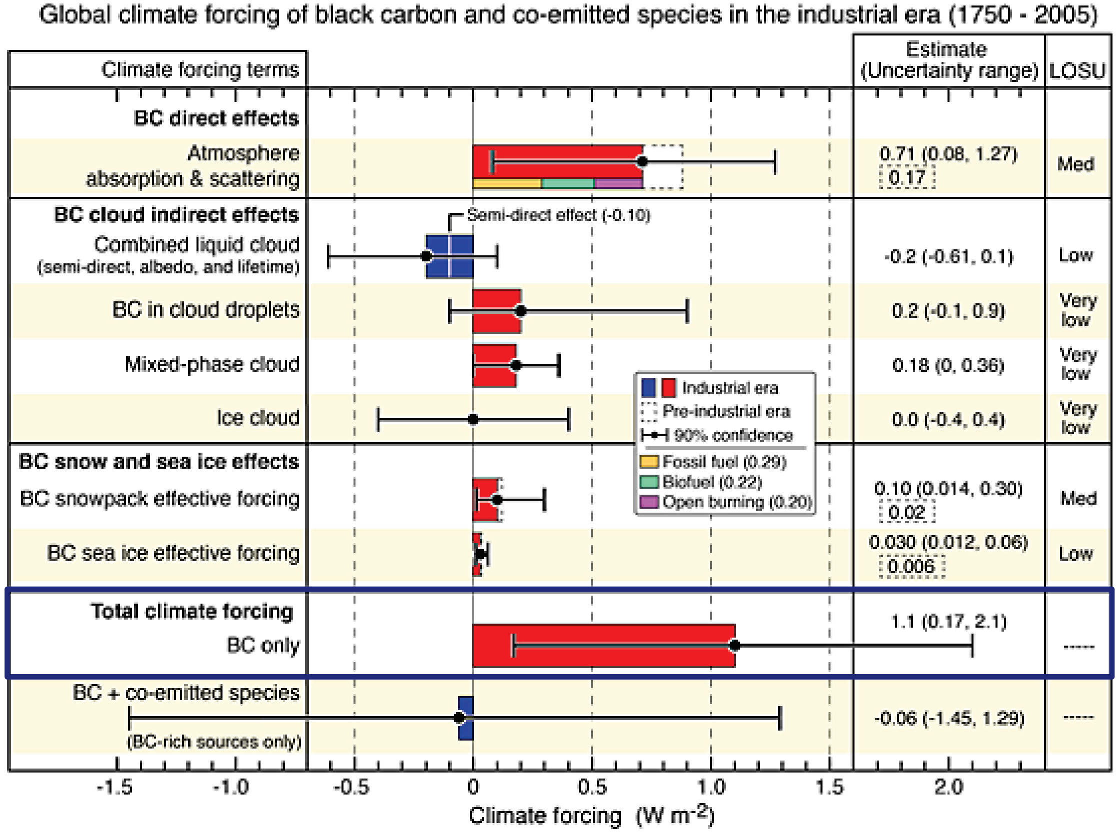


Large uncertainty in aerosol RF

- scatter and absorb radiation (**direct radiative forcing**)
- affect cloud formation (**indirect radiative forcing**)

Black Carbon Aerosols

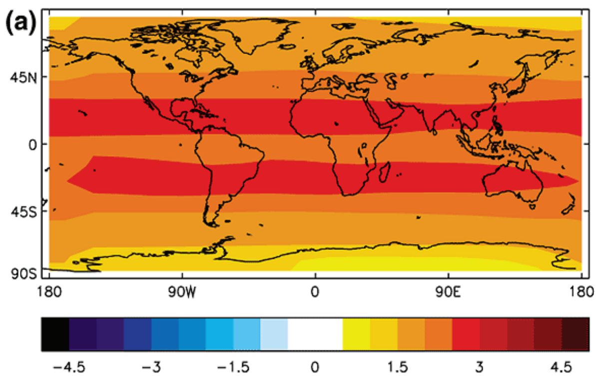
Bond *et al.*, Bounding the role of black carbon in the climate system: A scientific assessment, *JGR*, 2013



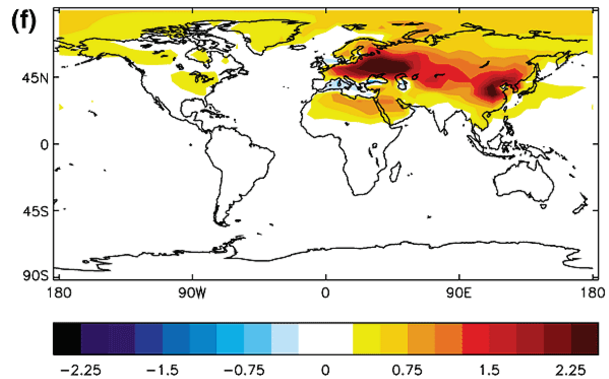
	Total Climate Forcing, Black Carbon Aerosols (W m^{-2})			
Report	IPCC (1995)	IPCC (2001)	IPCC (2007)	**IPCC (2013)**
ΔRF, BC	0.1 (0.03 to 0.3)	0.2 (0.1 to 0.4)	0.2 (0.05 to 0.35)	**0.4 (0.05 to 0.80)**

Global View

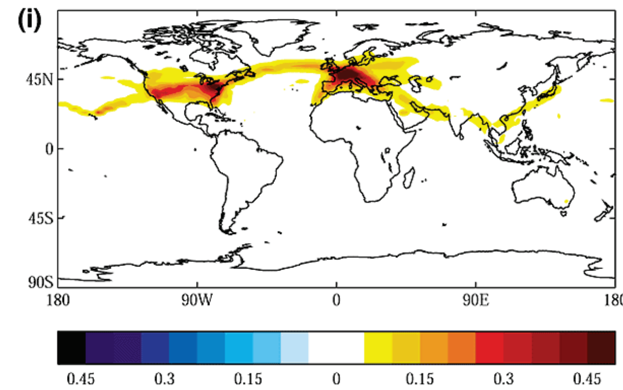
All forcings (1750-2000) are in Wm^{-2}

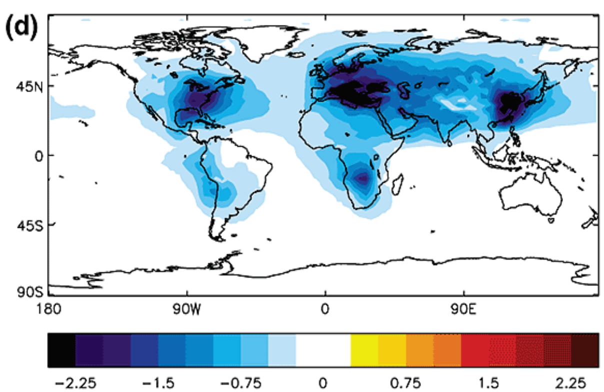


Greenhouse gases

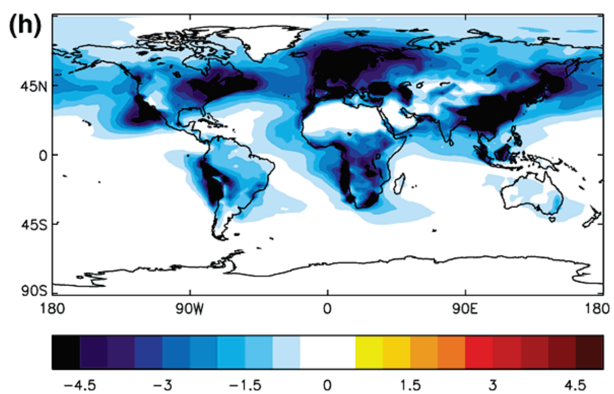


Organic and black carbon from fossil fuel burning

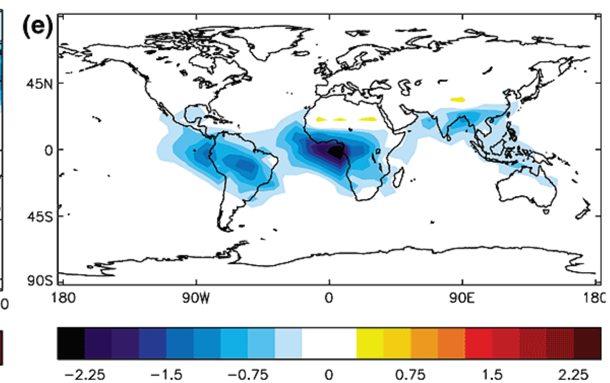




Direct effect from sulphate aerosols



Indirect effect from sulphate aerosols

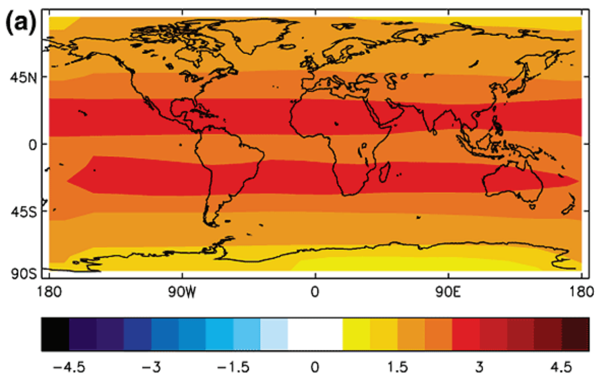


Organic and black carbon from biomass burning

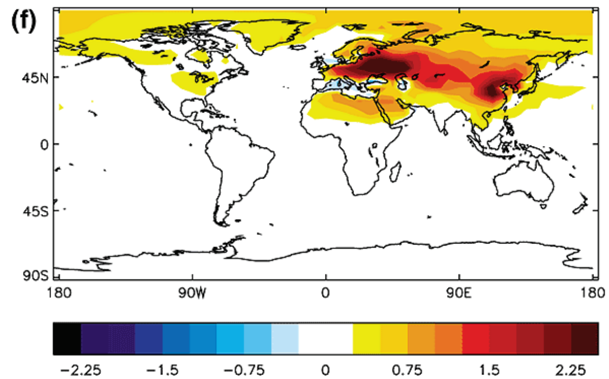
https://www.ipcc.ch/report/ar3/wg1/chapter-6-radiative-forcing-of-climate-change/

Global View

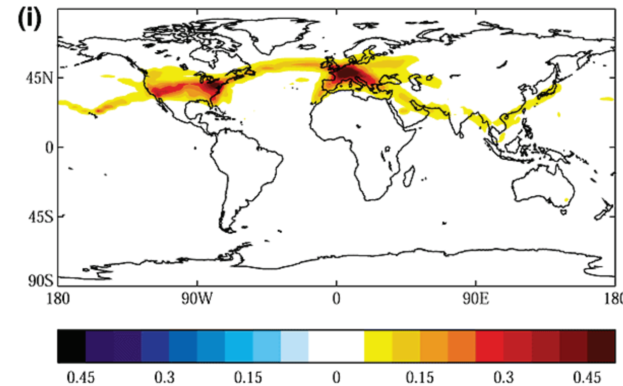
All forcings (1750-2000) are in Wm^{-2}



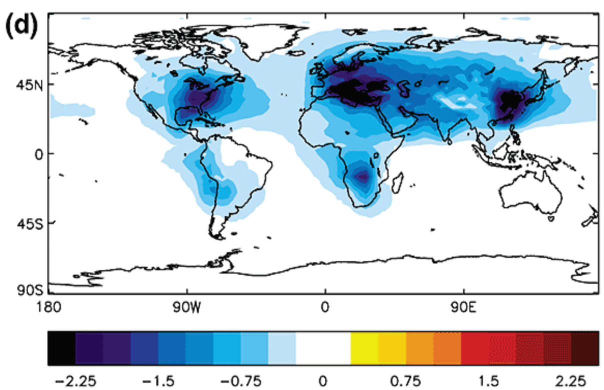
Greenhouse gases



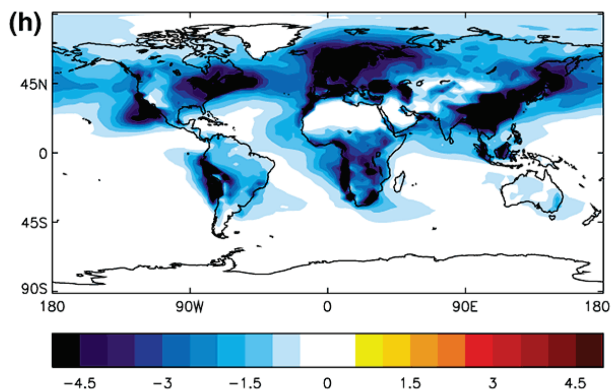
Organic and black carbon from fossil fuel burning



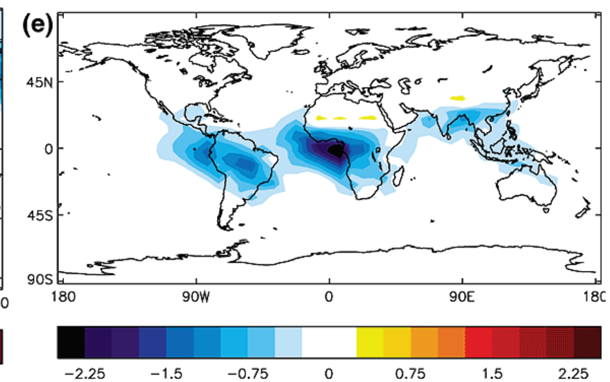
Aircraft contrails



Direct effect from sulphate aerosols



Indirect effect from sulphate aerosols

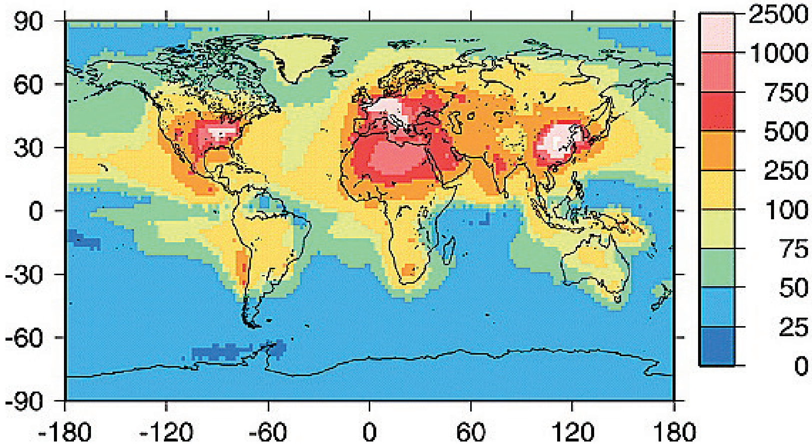


Organic and black carbon from biomass burning

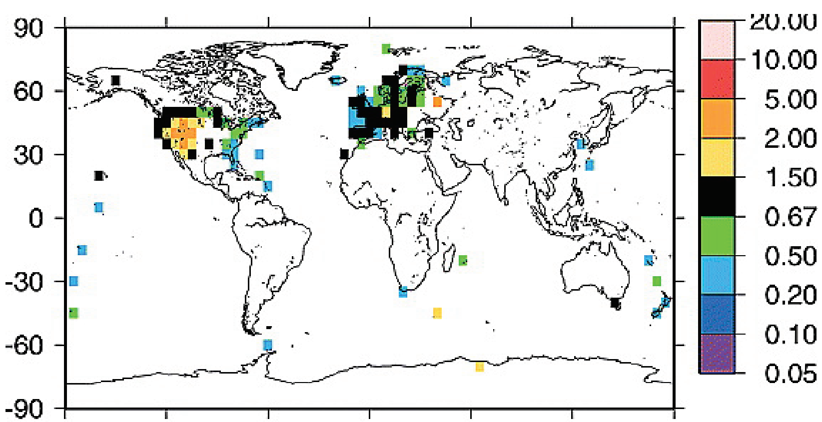
https://www.ipcc.ch/report/ar3/wg1/chapter-6-radiative-forcing-of-climate-change/

Tropospheric Sulfate Aerosols

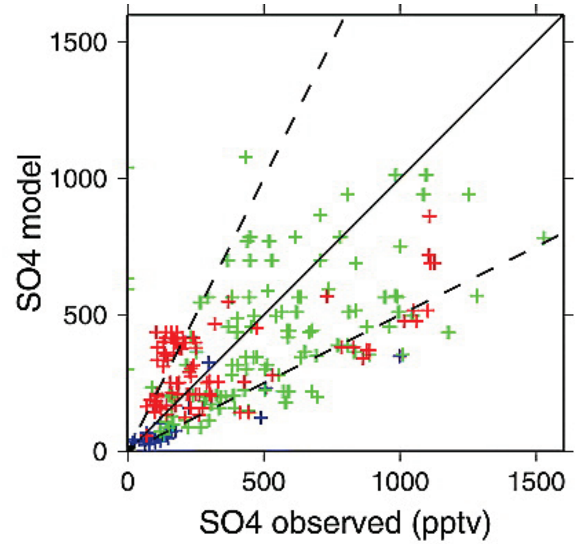
Modeled Sulfate (ppt)
Year 2000



Ratio of Modeled / Measured Sulfate



Modeled versus Measured Sulfate

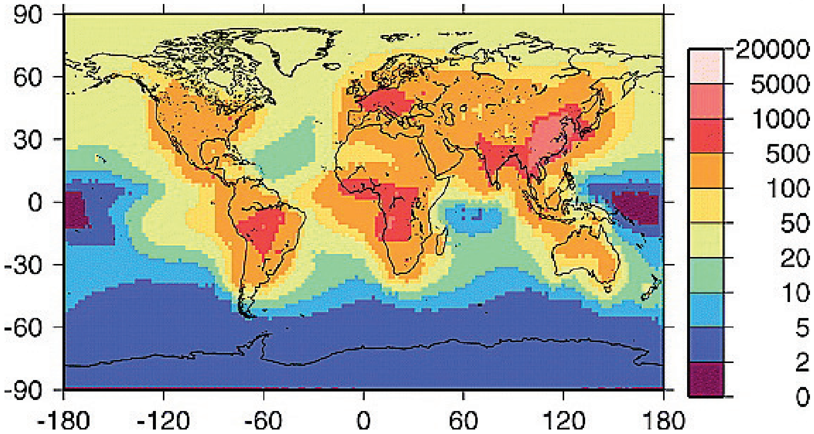


Remote sites (blue), Europe (green), & United States (red).

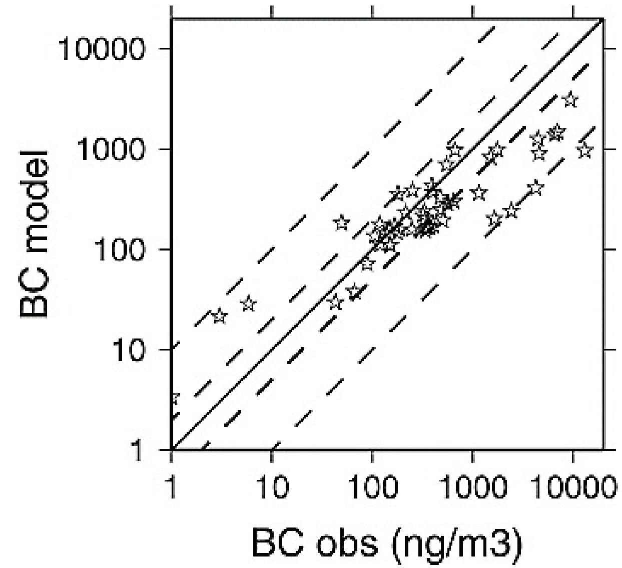
Koch *et al., JGR,* 2007
https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2005JD007024

Tropospheric Sulfate Aerosols

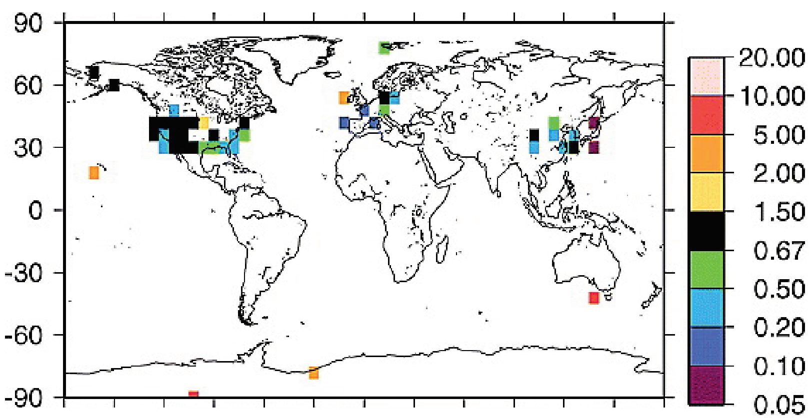
Modeled Black Carbon (ng m^{-3})
Year 2000



Modeled versus Measured Black Carbon



Ratio of Modeled / Measured Black Carbon

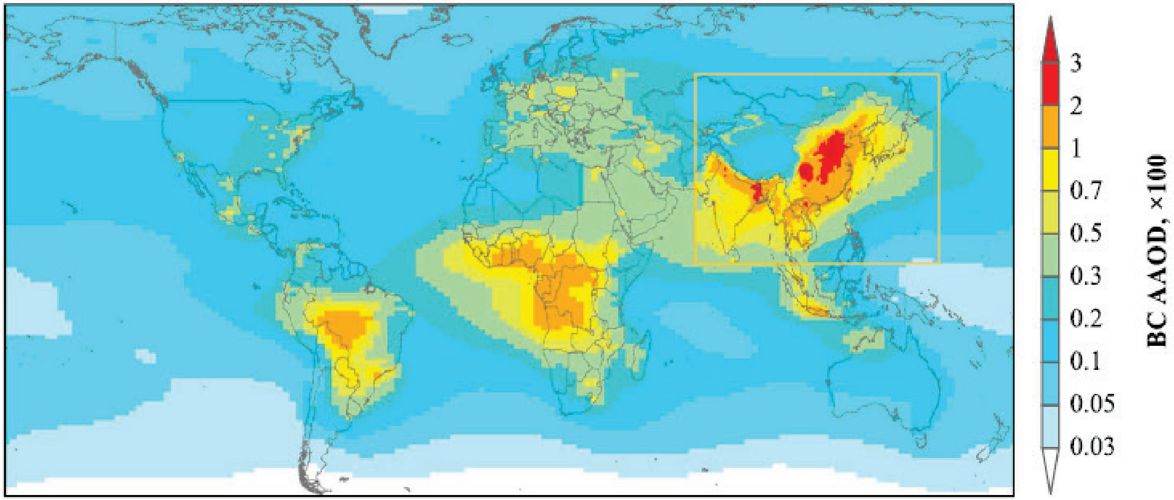


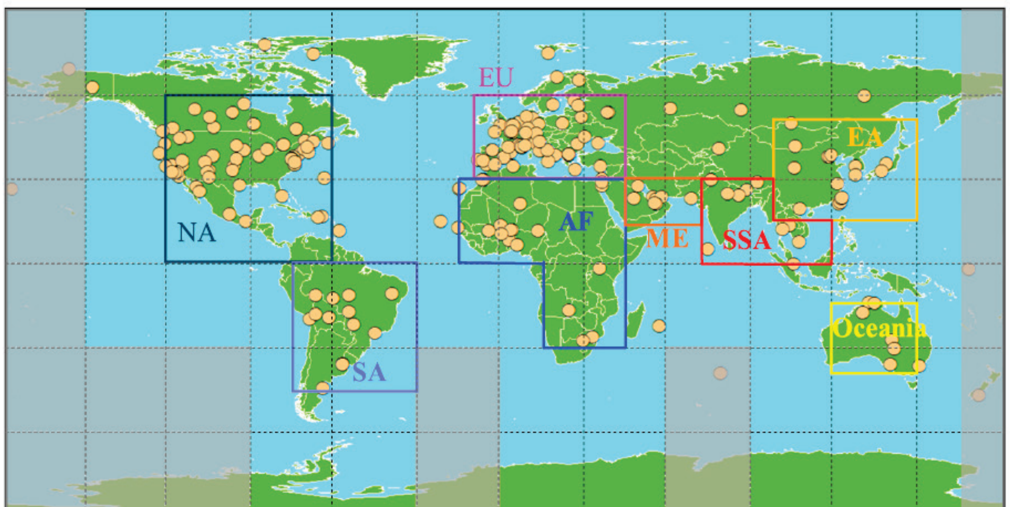
Koch *et al.*, *JGR*, 2007

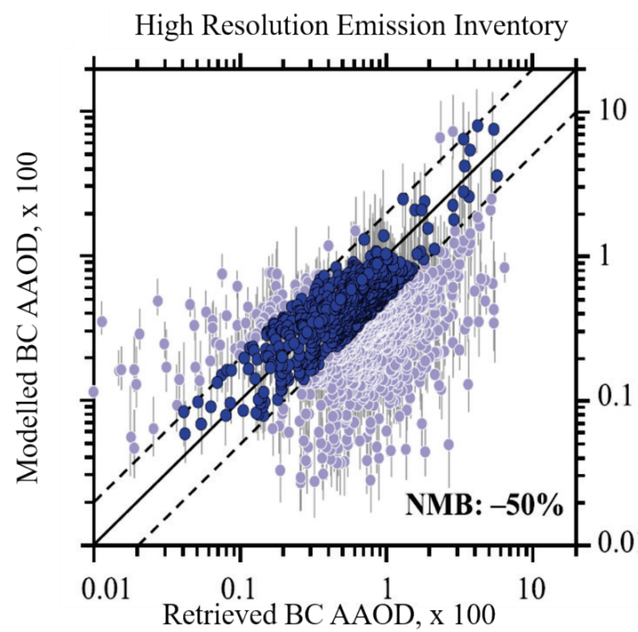
https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2005JD007024

Black Carbon Aerosols

Simulated Black Carbon Aerosol Absorption Optical Depth (AAOD) at 900 nm for year 2007



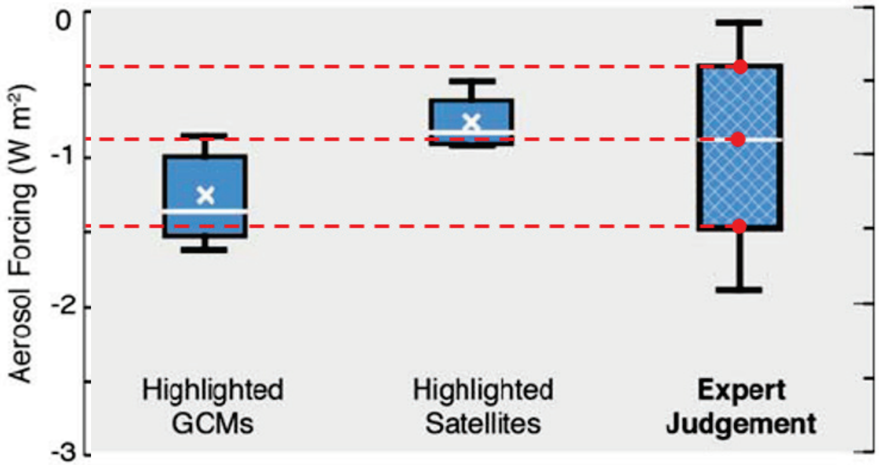




Wang et al., *JGR,* 2016

https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2015JD024326

Tropospheric Aerosol RF:
1750 to 2011



Box & Whisker Plots:
mean (X), median (middle line)
17th and 83th percentiles
(likely range; boundaries)
5th and 95th percentiles (whiskers)

Figure 7.19B, IPCC 2013

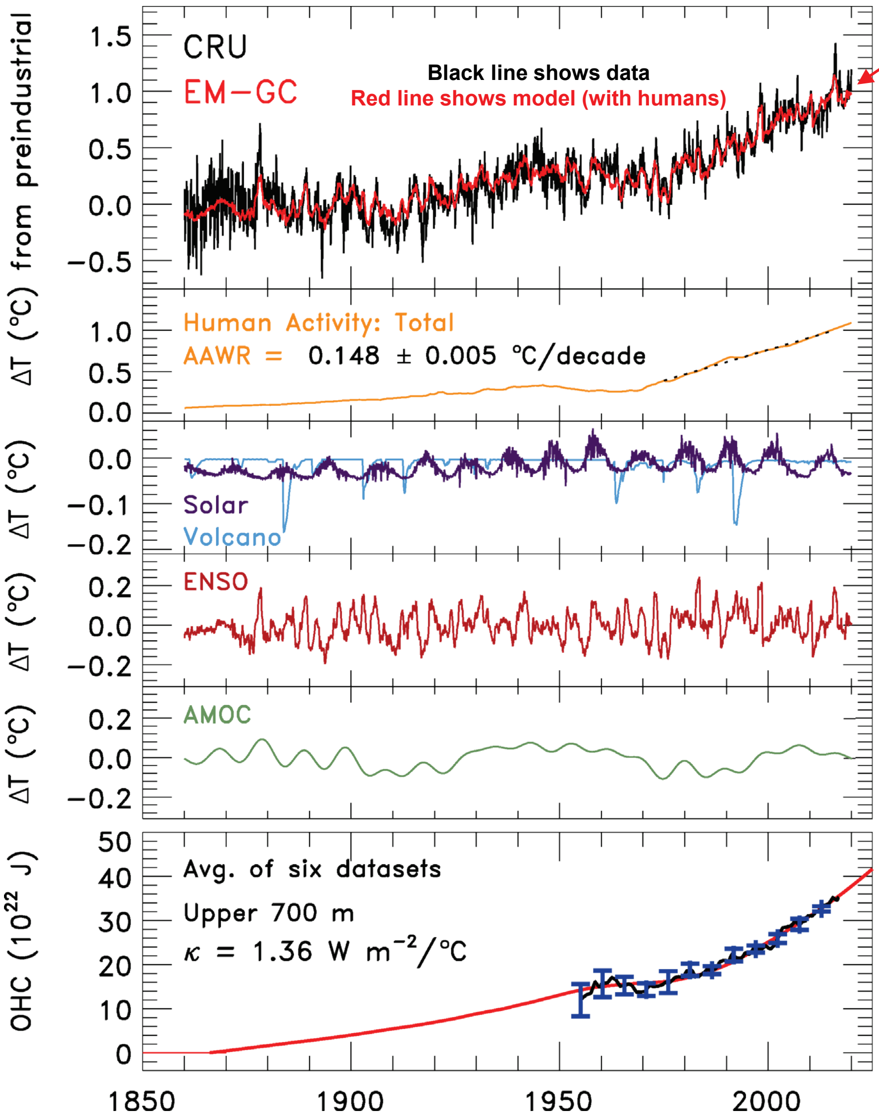
ΔRF_{2011} GHGs ≈ 3.2 W m^{-2} ⇨ climate change is complex but this quantity is ***well known***

ΔRF_{2011} Aerosols: best estimate is –0.9 W m^{-2}, probably between –0.4 W m^{-2} and –1.5 W m^{-2};
could be between –0.1 W m^{-2} and –1.9 W m^{-2}

Large uncertainty in aerosol RF

- scatter and absorb radiation (**direct radiative forcing**)
- affect cloud formation (**indirect radiative forcing**)

Are humans responsible?



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

where:

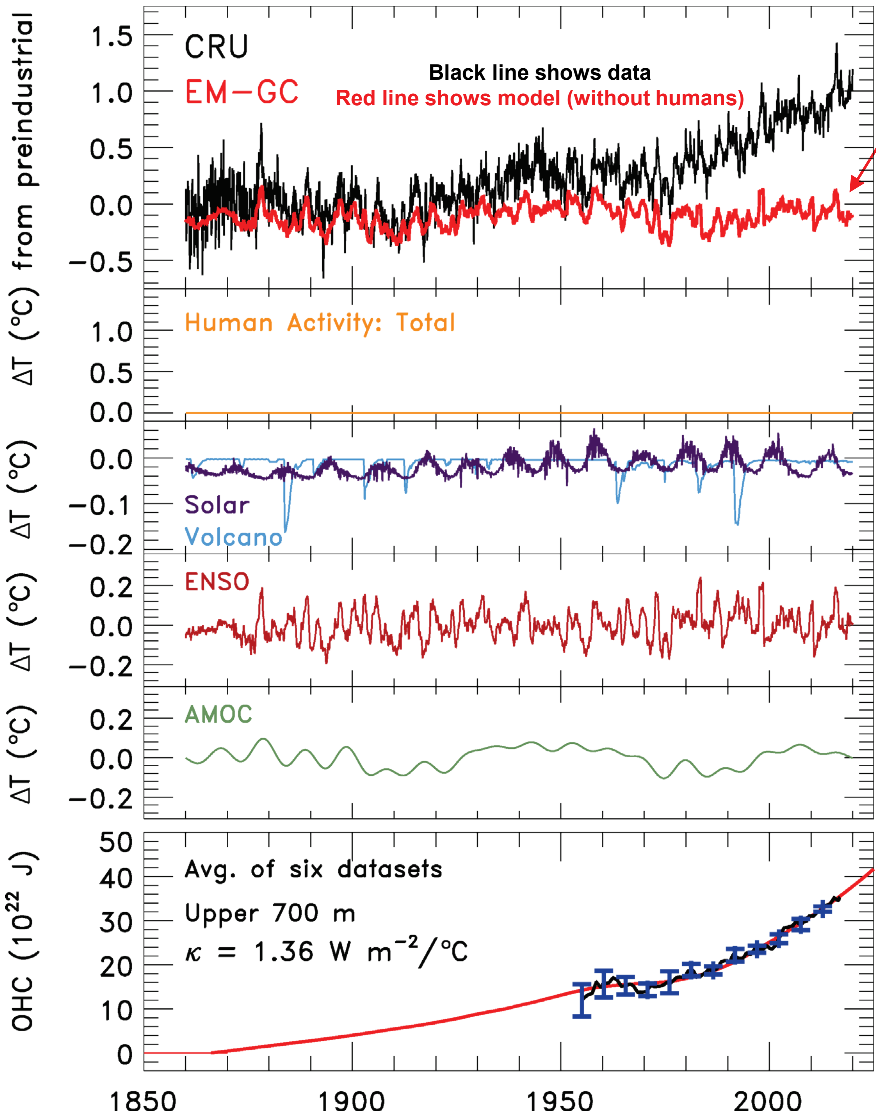
- i denotes month
- $\lambda_p = 3.2\ \mathrm{W\ m^{-2}\,{}^\circ C^{-1}}$
- $1+\gamma = \{1 - \lambda_\Sigma/\lambda_p\}^{-1}$
- GHG RF = RF due to all anthropogenic GHGs
- LUC RF = RF due to Land Use Change
- Aerosol RF = RF due to Tropospheric Aerosols
- SOD = Stratospheric Optical Depth
- TSI = Total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

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

Slide 37, Lecture 2

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.

Are humans responsible?



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

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~~GHG RF = RF due to all anthropogenic GHGs~~

~~LUC RF = RF due to Land Use Change~~

~~Aerosol RF = RF due to Tropospheric Aerosols~~

SOD = Stratospheric Optical Depth

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ENSO = El Niño Southern Oscillation

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~~Q_{OCEAN} = Ocean heat export =~~

~~$\kappa(1+\gamma)\{\Delta T_{MDL\,i} - \Delta T_{OCEAN\ SURFACE\,i}\}$~~

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Slide 38, Lecture 2

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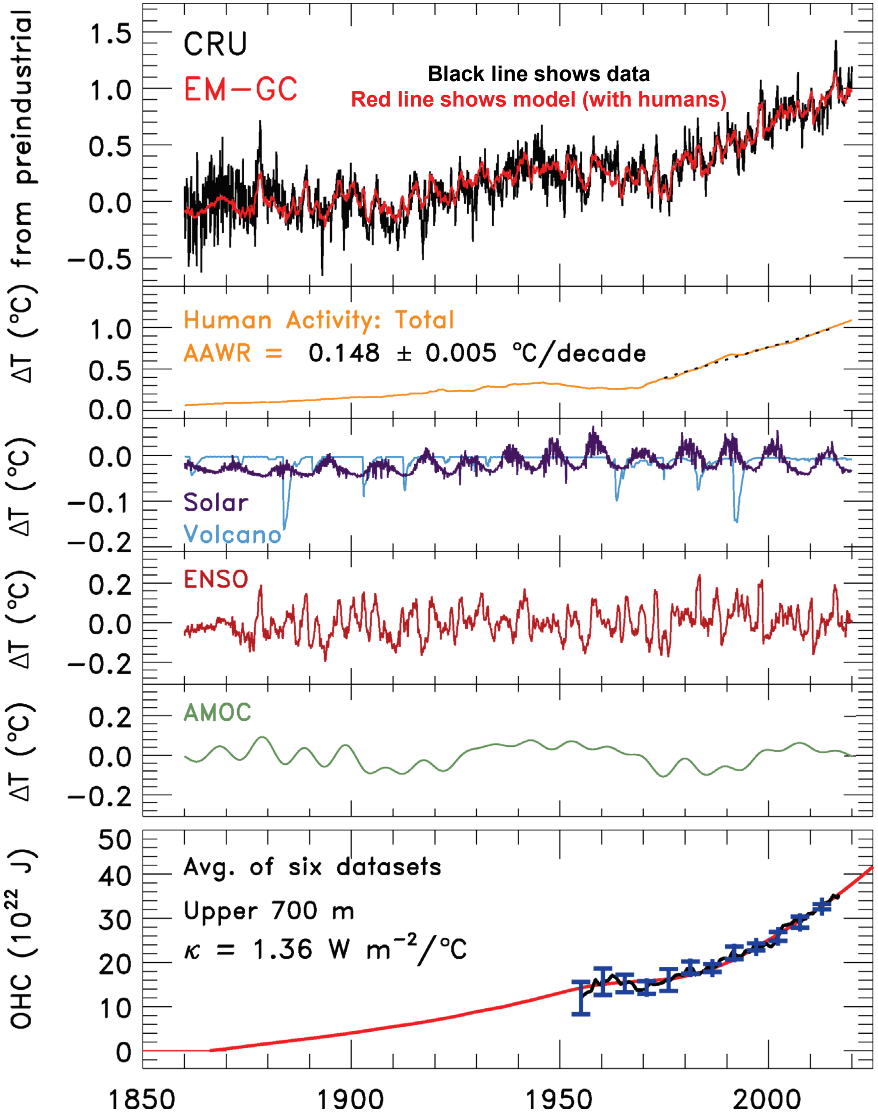

Global warming is caused by CO_2, the greatest waste product of modern society, as well as CH_4, N_2O, and other GHGs.

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

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

Slide 39, Lecture 2

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
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Question 4, AT07

Explain in a paragraph, based on the material in Section 1.2.3.6 of *Paris Climate Agreement: Beacon of Hope*, why the uncertainty in the RF of climate due to tropospheric aerosols complicates future projections of global warming.

The uncertainty in the RF of climate due to tropospheric aerosols complicates future projections of global warming because there's no clear, established numerical values for both changes in RF by anthropogenic aerosols and changes in RF by the effect of aerosols on clouds.

This issue is best illustrated by considering two possible scenarios on the influence of anthropogenic aerosols and the effects of aerosols on clouds affecting the change in RF.

Scenario one features black carbon aerosols exerting high, positive change in RF and nearly off-setting the cumulative, negative change in RF by sulfate , organic carbon, and the effect of aerosols on clouds, thus warming the climate.

Scenario two depicts black carbon aerosols exerting much lower RF, not nearly enough to off-set the total negative change in RF by sulfate, organic carbon, and the effect of aerosols on cloud, thus cooling the climate.

The contrast in a projection of global warming between these two scenarios is enormous, which highlights the scientific importance of the uncertainty in the RF of climate due to tropospheric aerosols.

Combining RF GHGs & Aerosols

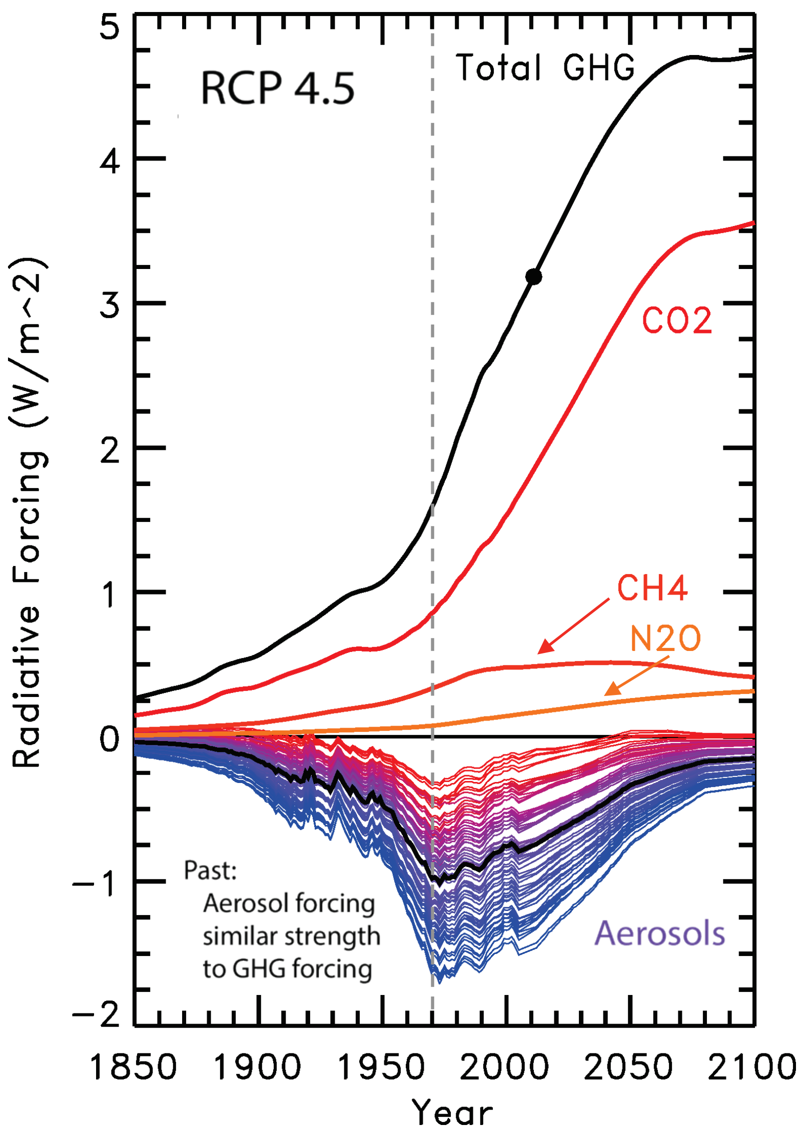
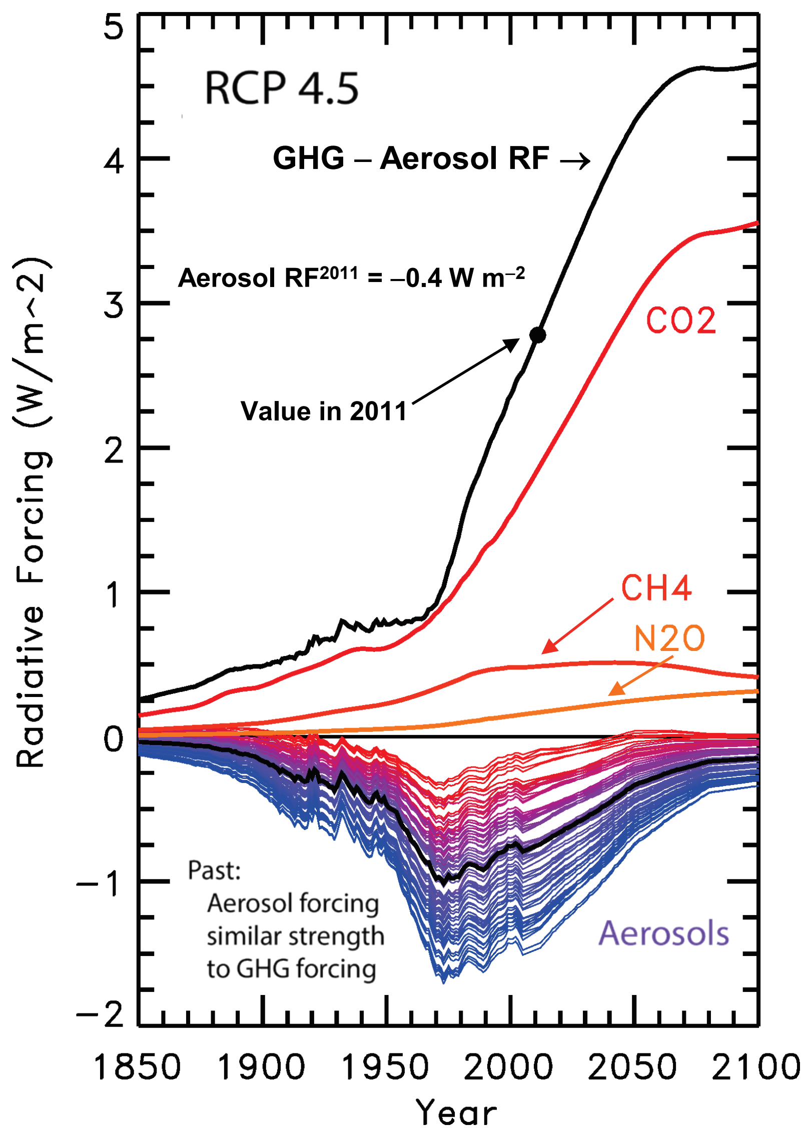


Fig 1.10, *Paris, Beacon of Hope*

Combining RF GHGs & Aerosols



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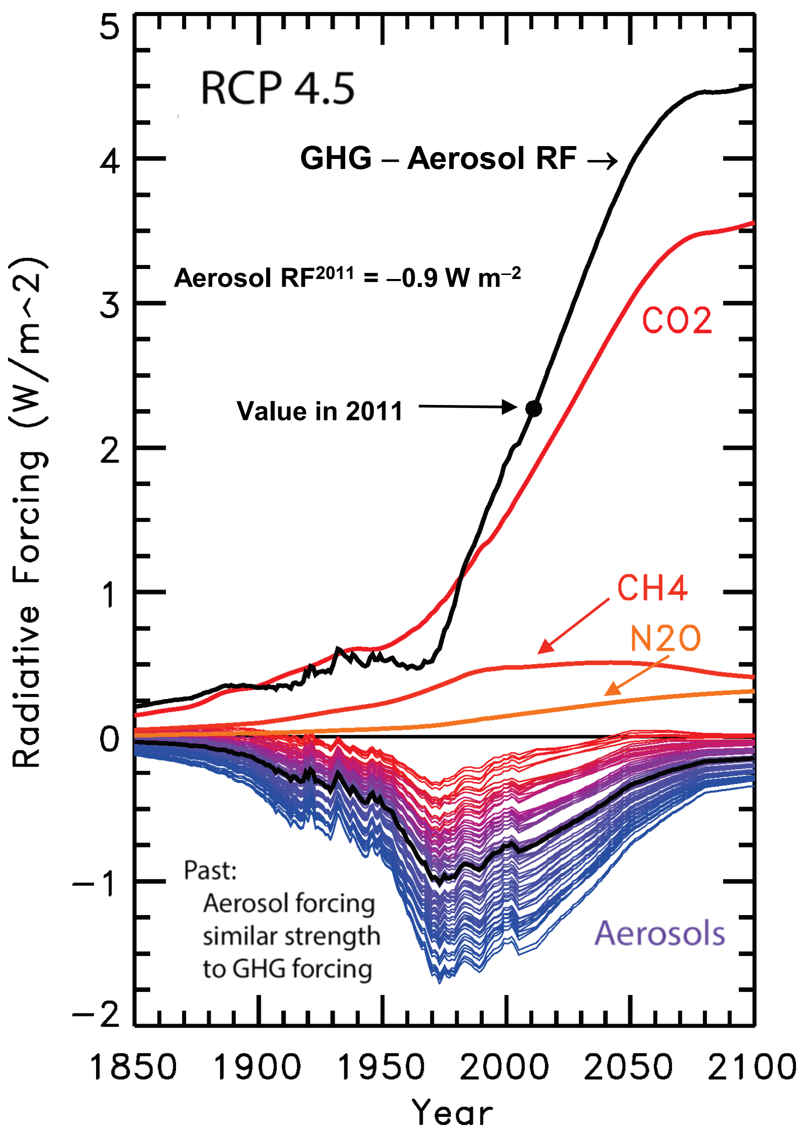

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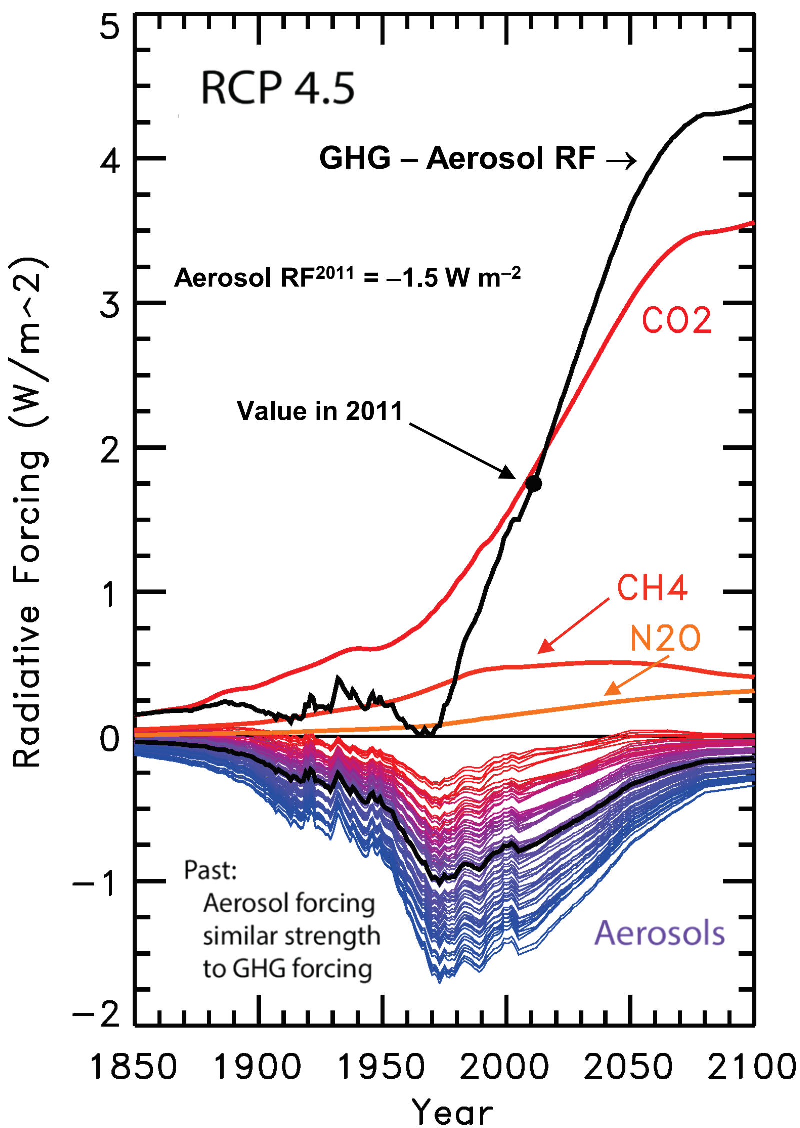

Fig 1.10, *Paris, Beacon of Hope*

Time to get quantitative:
how do changes in radiative forcing affect temperature?

Let's relate a change in temperature to a change in radiative forcing:

$$\Delta T = \lambda \, \Delta F$$

λ is the *climate sensitivity factor* in units of $\frac{K}{W/m^2}$

For an ideal blackbody: $F = \sigma \, T^4$

$$\frac{dF}{dT} = 4 \, \sigma \, T^3$$

We write:

$\lambda_{ACTUAL} = \lambda_P \, (1+f_{H2O})$

where f_{H2O} is the H_2O feedback

Here, $f_{H2O} \approx 1.08$

Above equation can be re-arranged to yield:

$$\Delta T \approx \frac{1}{4 \, \sigma \, T^3} \, \Delta F$$

So: $$\lambda = \frac{1}{4 \, \sigma \, T^3}$$

Slide 61, Lecture 3

Time to get quantitative:
how do changes in radiative forcing affect temperature?

Let's relate a change in temperature to a change in radiative forcing:

$$\Delta T = \lambda \, \Delta F$$

λ is the *climate sensitivity factor* in units of $\dfrac{K}{W/m^2}$

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$$\frac{dF}{dT} = 4 \, \sigma \, T^3$$

Above equation can be re-arranged to yield:

$$\Delta T \approx \frac{1}{4 \, \sigma \, T^3} \Delta F$$

So: $$\lambda = \frac{1}{4 \, \sigma \, T^3}$$

We write:

$\lambda_{ACTUAL} = \lambda_P \, (1 + f_{H2O+Lapse\ Rate})$

where $f_{H2O+Lapse\ Rate}$ is the combined effect of the H_2O and Lapse Rate feedbacks

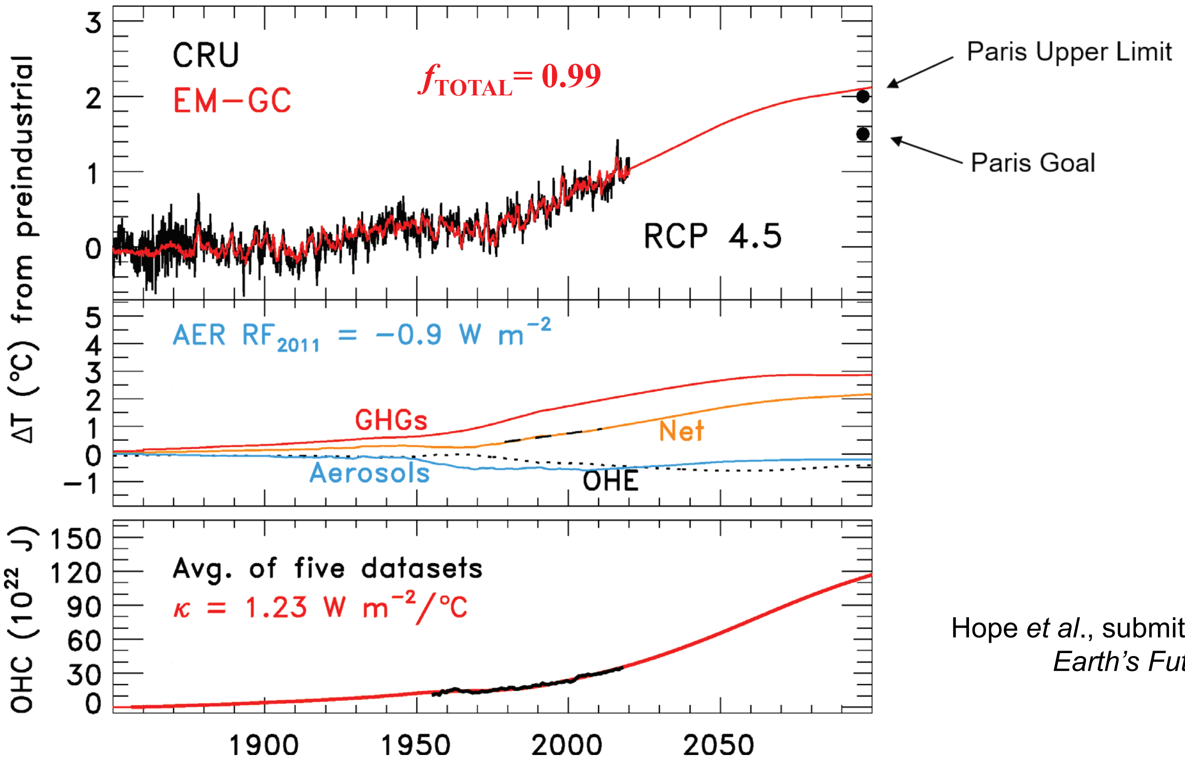
Here, $f_{H2O+LapseRate} \approx 0.45$

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

$$\Delta T \approx \lambda_{BB} \, (1+f_{TOTAL}) \, \Delta RF - OHE$$

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

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



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

$$\Delta T \approx \lambda_{BB} \, (1+f_{TOTAL}) \, \Delta RF - OHE$$

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

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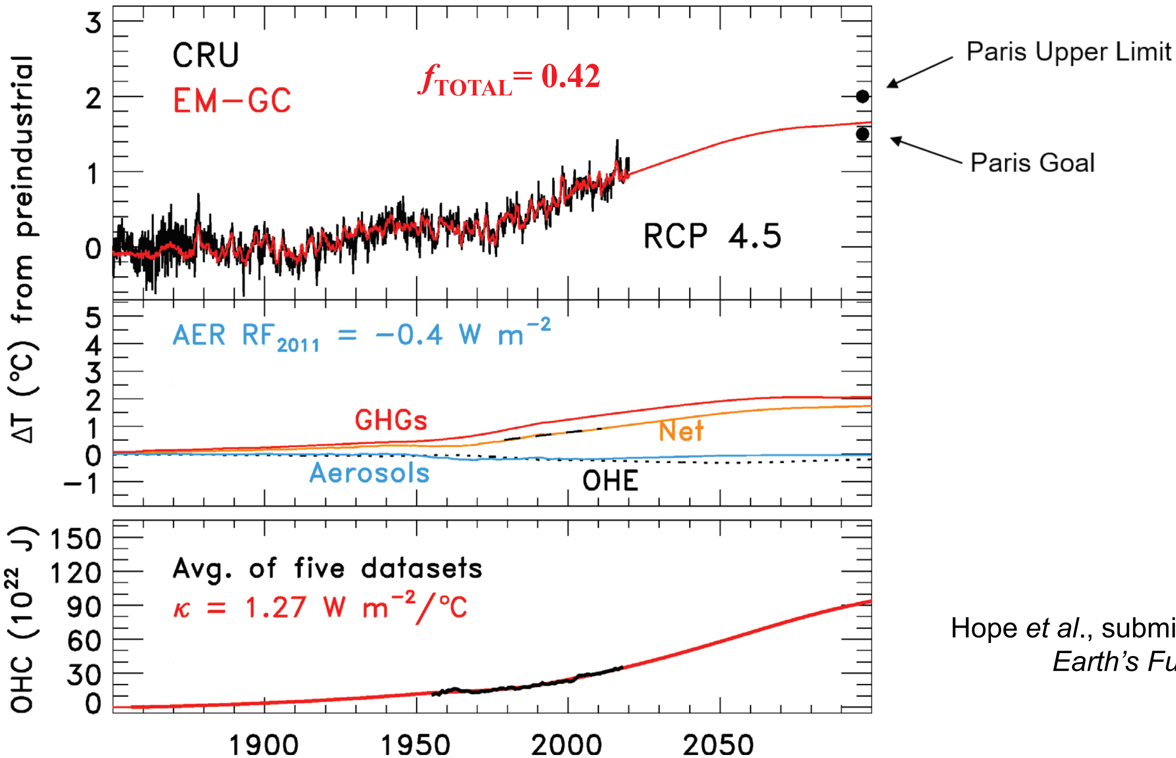


Hope *et al*., submitted to AGU journal *Earth's Future*, 2020.

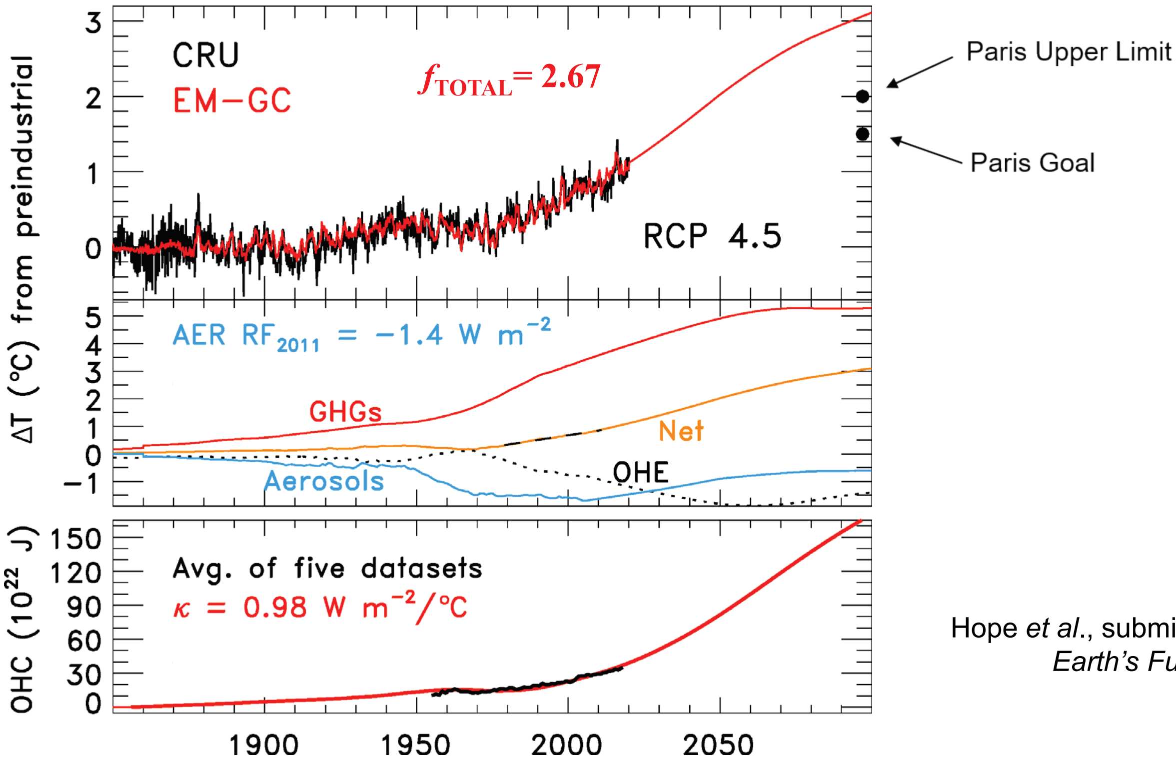
We assume that whatever value of climate feedback is inferred from the climate record will persist into the future. For Aerosol RF in 2011 of **−0.4 W m⁻²** & assuming best estimate for H_2O and Lapse Rate feedback is correct, this simulation implies sum of <u>other feedbacks</u> (clouds, surface albedo) 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

$$\Delta T \approx \lambda_{BB} (1+f_{TOTAL}) \Delta RF - OHE$$

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

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



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***.