Radiative Forcing

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

24 September 2020

Announcements

- Problem Set #2 due Fri, 2 Oct, 5 pm
  - Has been posted
  - Slightly different assignment for students enrolled in 433 & students enrolled in 633

09/24	Radiative Forcing	Chemistry in Context, Sec 2.4, 2.5, 2.6, 3.3 & 3.4 (14 pages) Paris Beacon of Hope Sec 1.2 (intro), 1.2.1 (please review), & 1.2.3.6 (8 pages)	AT 7	Lecture 7 2020 Zoom Video		Green Chemistry, Chapter 3.4 (Sections 3.4.4.1 to 3.4.4.4 provide a nice mathematical complement to the lecture material) Myhre *et al.*, *GRL*, 1998 Bera *et al.*, *JPC*, 2009	Quiz 7
09/29	Modeling Earth's Climate: Water Vapor, Aerosol, Cloud, & Albedo Feedbacks	Chemistry in Context, Sec 3.9 (6 pages) Houghton, pg 105-116	AT 8	Lecture 8 2020 Zoom Video		Bony et al., 2006	Quiz 8
10/01	Consequences of Climate Change	Chemistry in Context, Sec 3.10 (5 pages) Forbes Article	No AT	Lecture 9 2020 Zoom Video		Union of Concerned Scientists Climate Reality Project Climate Change and Disease NY Times, Bangladesh NY Times, Kiribati	No Quiz
10/02					**Problem Set 2 due today at 5 pm:** **433 Students** **633 Students**		

http://www2.atmos.umd.edu/~rjs/class/fall2020

Announcements: Outside of Class

1) Thurs, 24 Sept : AOSC Weekly Seminar (today @ 3:30 pm)

Professor Nicole Riemer, University of Illinois

Aerosol Mixing State: Synthesizing Measurements and Models

Atmospheric aerosols are complex mixtures of different chemical species, and individual particles exist in many different shapes and morphologies. These characteristics contribute to the aerosol mixing state, which continuously evolves in the atmosphere.

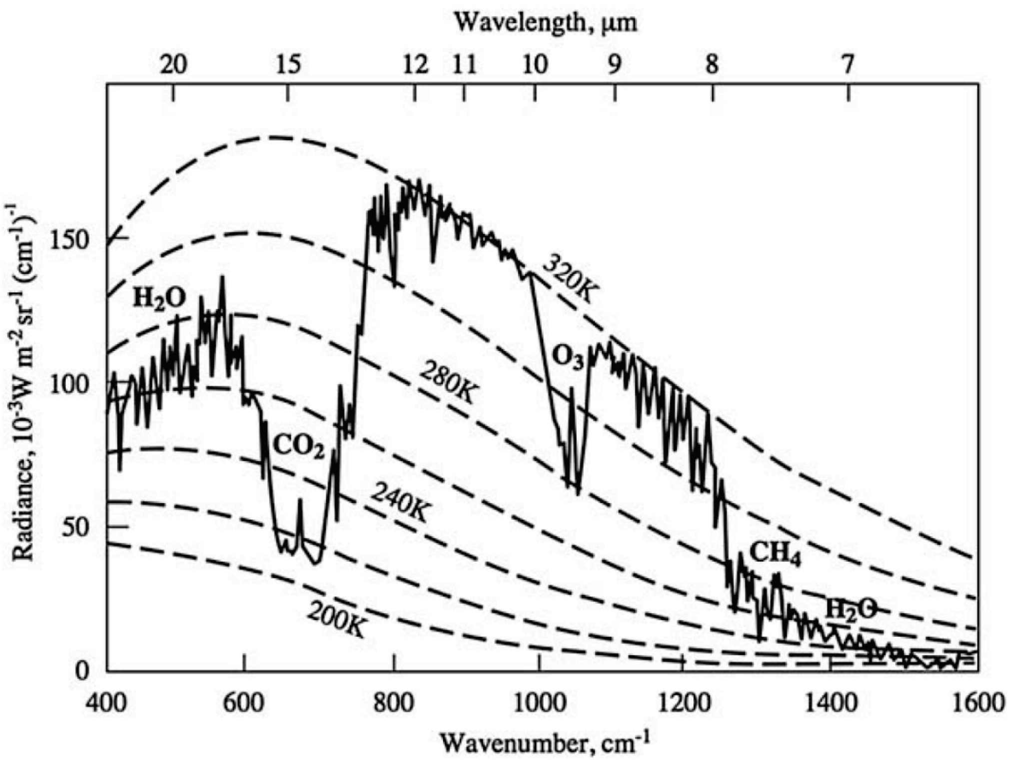
Atmospheric models have become sufficiently complex to incorporate aspects of aerosol mixing state in their predictions. Concurrently, sophisticated measurement techniques have been developed to probe various physicochemical properties of particles. However, there is no single instrument that can characterize all aspects of aerosol mixing state, and it has proven challenging to quantitatively compare measured mixing state attributes with mixing state predictions.

This talk will present a framework to synthesize a picture of the ambient aerosol from models and observations and identify current gaps in this endeavor. We will focus on suitable metrics to quantify mixing state, sampling strategies to determine these metrics that are accessible for both models and observations, and modeling strategies to scale up detailed modeling results on the particle scale to global predictions of mixing state.

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

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

Overview



Hanel *et al*., JGR, 1972:

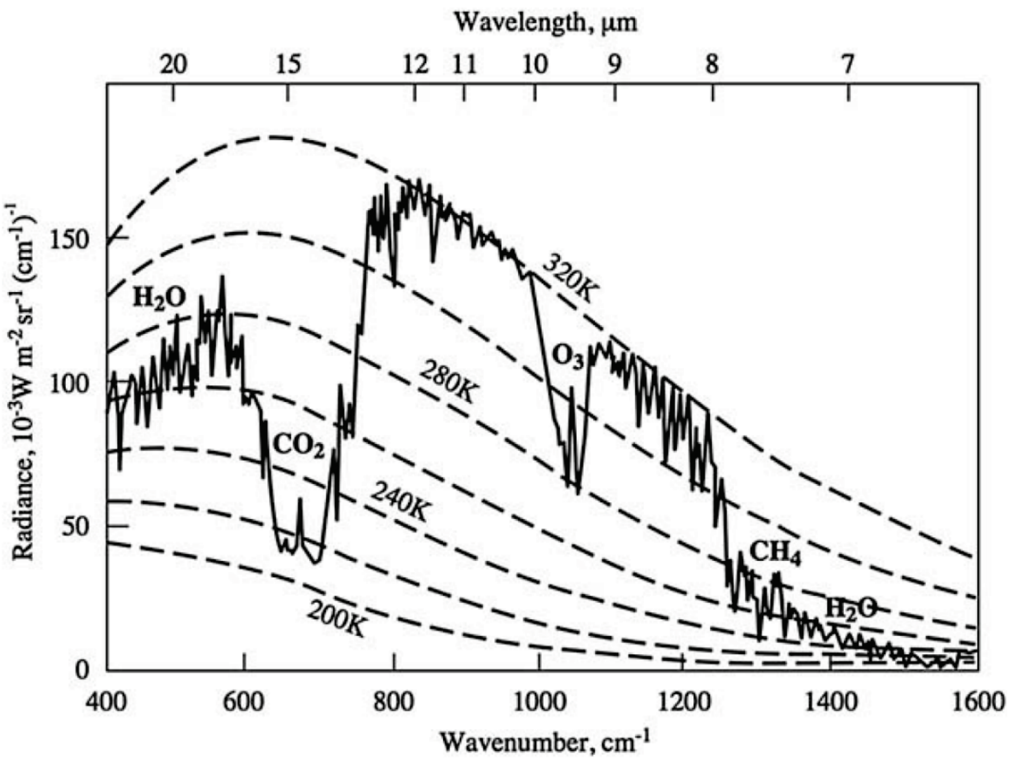
https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/JC077i015p02629

Viewed from space and averaged over space and time, Earth emits ~238 W/m^2 of thermal radiation between wavelengths of 5 and 50 μm.

The terrestrial emission spectrum matches that of a combination of blackbody spectra of temperatures between 220 and 320K.

The four most important gases that absorb terrestrial radiation (H_2O, CO_2,CH_4, O_3) are noted.

Overview

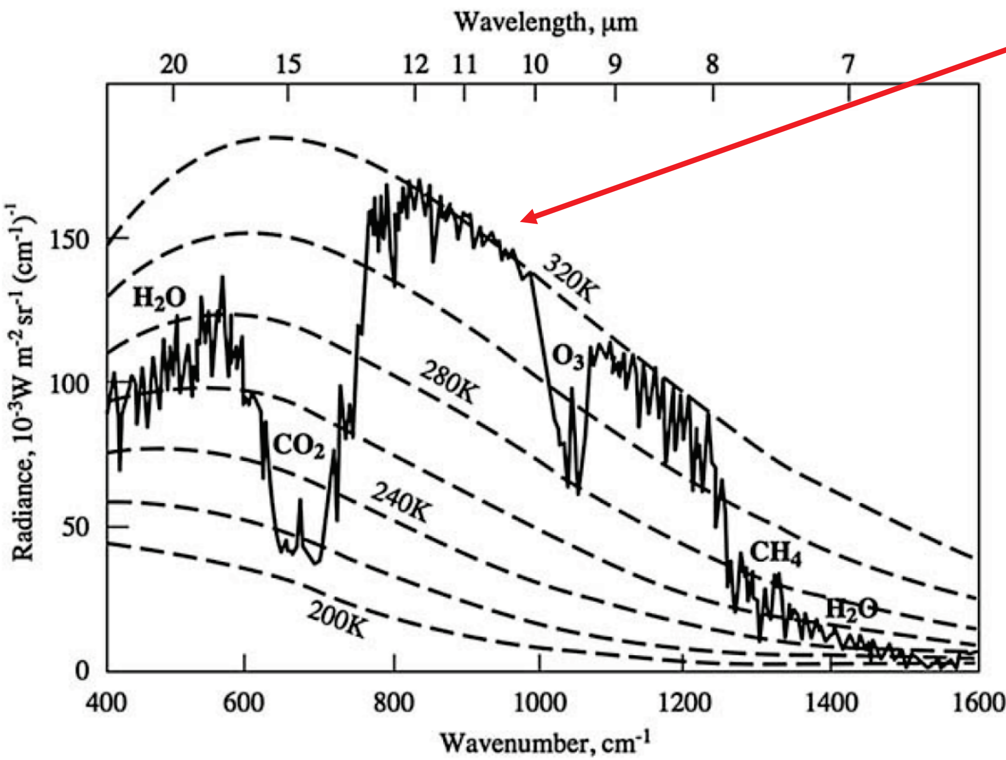


Hanel *et al*., JGR, 1972:
https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/JC077i015p02629

Wavenumber = 1 / Wavelength

$1 / 1600\ \text{cm}^{-1} = 6.25\times10^{-4}\ \text{cm} = 6.25\times10^{-6}\ \text{m} = 6.25\ \mu\text{m}$
$1 / 400\ \text{cm}^{-1} = 2.50\times10^{-3}\ \text{cm} = 2.50\times10^{-5}\ \text{m} = 25.0\ \mu\text{m}$

Overview



320 K = 47°C = 116.6°F
where was this image acquired?

Hanel *et al*., JGR, 1972:
https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/JC077i015p02629

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Overview

News & Blogs

CATEGORY 6™ | NEW STORIES | INFOGRAPHICS | POSTERS

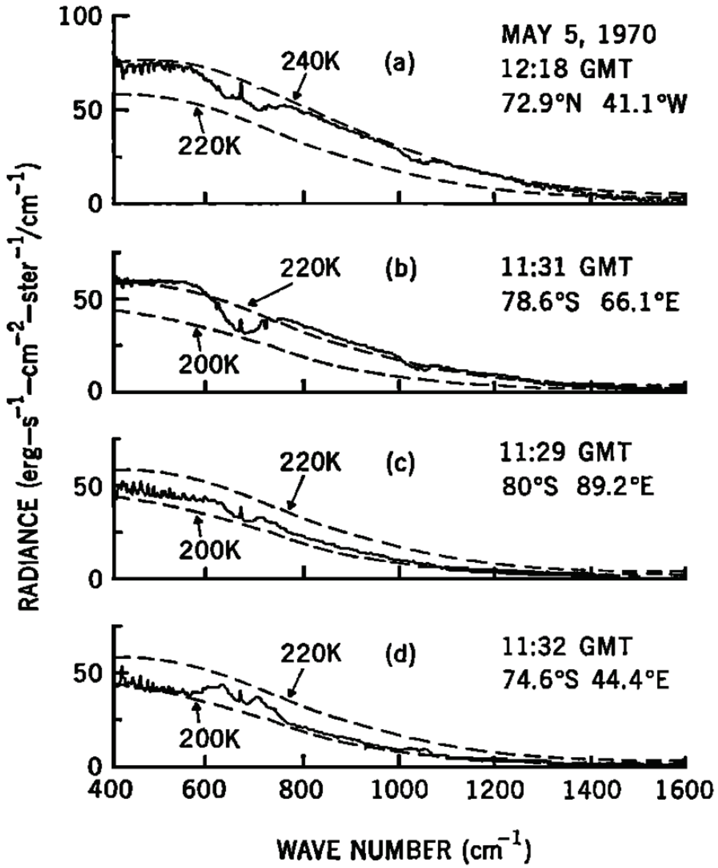
Africa's Hottest Reliably Measured Temperature on Record: 124.3°F on Thursday in Algeria

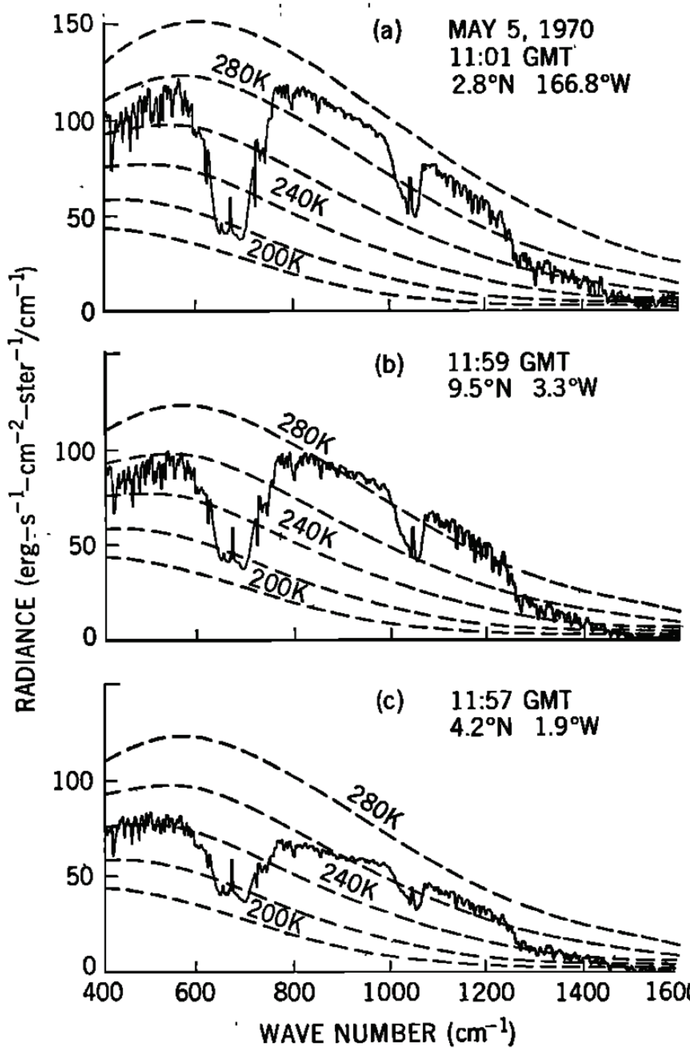
Dr. Jeff Masters · July 6, 2018, 8:08 AM EDT

A historic heat wave in northern Africa on Thursday, July 5, brought Africa its hottest reliably measured temperature on record: 124.3°F (51.3°C), at Ouargla, Algeria. Ouargla (population 190,000) is the capital city of Ouargla Province in the Algerian Sahara Desert, at an elevation of 719 feet (219 meters).

Location of Ouargla, Algeria, indicated by red marker. (Google)

https://www.wunderground.com/cat6/Africas-Hottest-Reliably-Measured-Temperature-Record-1243F-Thursday-Algeria
https://www.washingtonpost.com/news/capital-weather-gang/wp/2018/07/06/africa-may-have-witnessed-its-all-time-hottest-temperature-thursday-124-degrees-in-algeria





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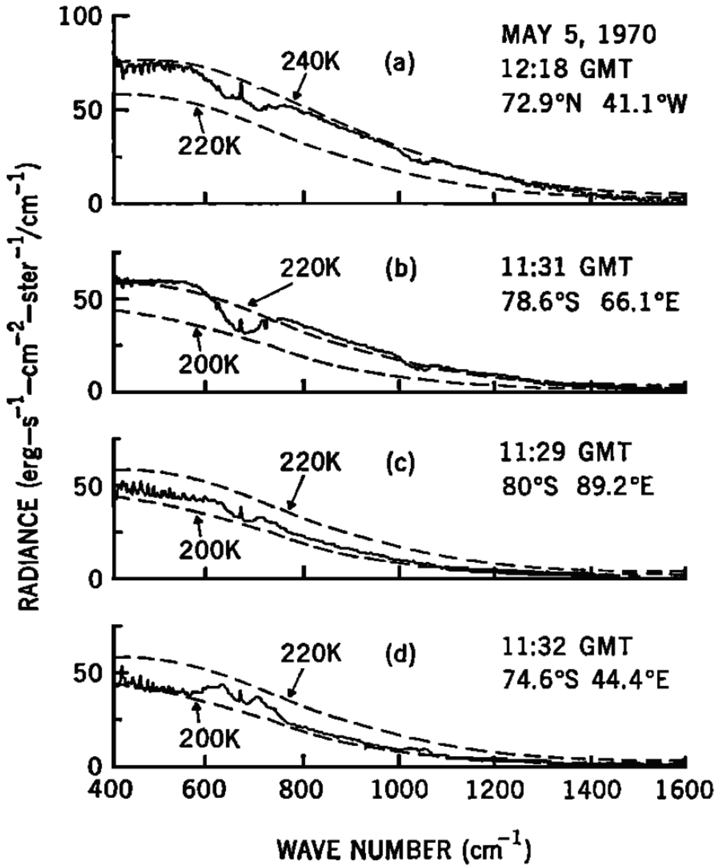
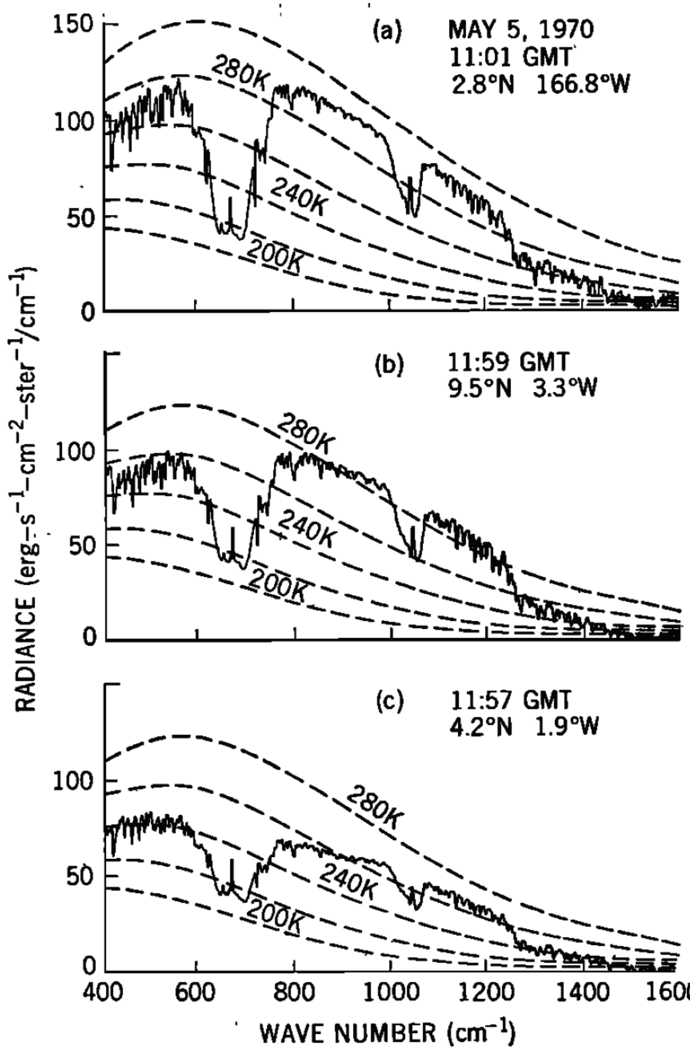


Fig. 12. Examples of polar spectra. The spectrum in *a* was obtained over Greenland; the spectra in *b*, *c*, and *d* were obtained over Antarctica.



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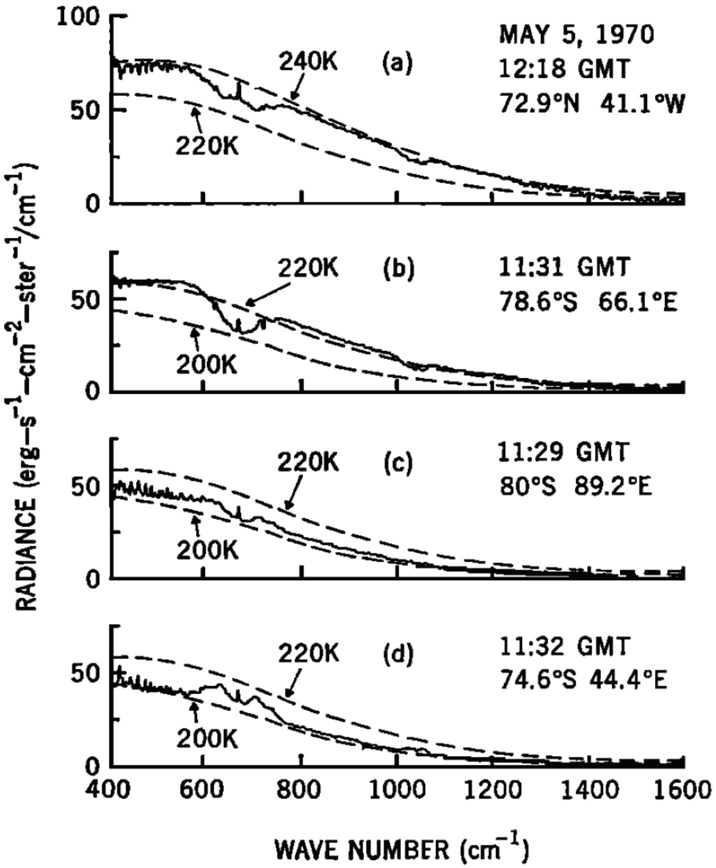

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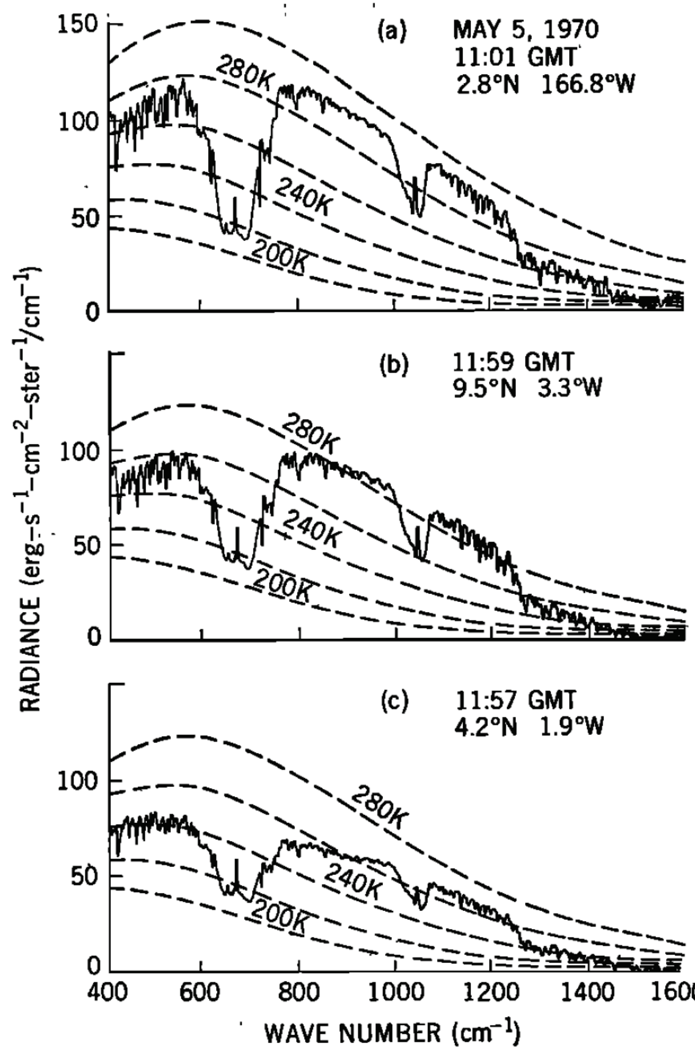


Fig. 13. Sample spectra illustrating effects of clouds in the window region of 800 to 1000 cm^{-1}. In this spectral region, a pronounced departure from a blackbody curve is noted in *b* and *c* in contrast to the spectra shown in Figure 14, for example.

Hanel *et al*., JGR, 1972: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/JC077i015p02629

Overview

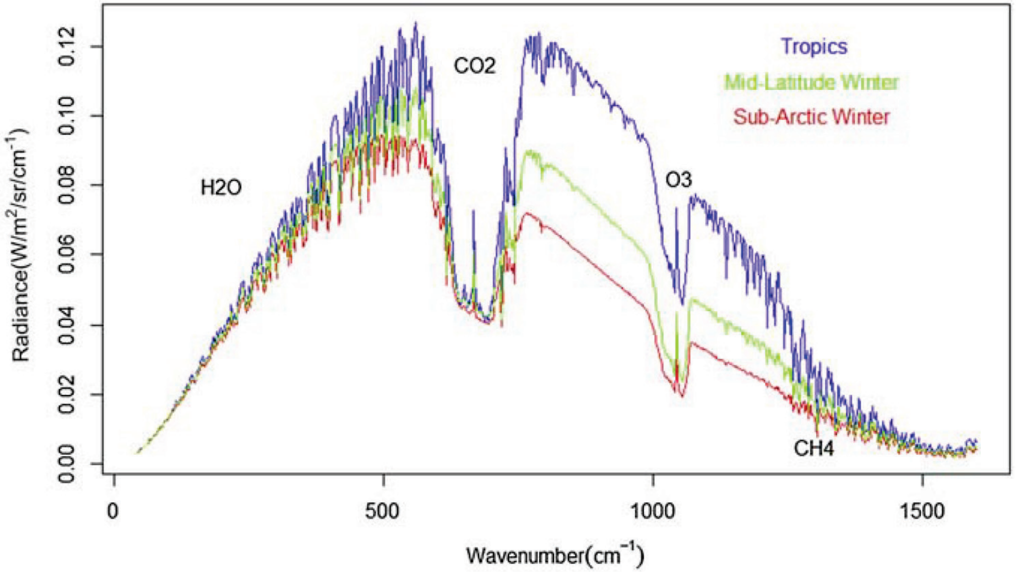


FIGURE 3.4.5 Overview of the earth's outgoing infrared radiation as a function of wave number (the inverse of wavelength) and latitude.[43] Radiances for this figure were calculated using Modtran and a web interface developed by David Archer available here: http://climatemodels.uchicago.edu/modtran/.

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 _____, rather than a region that is _____.

Global Warming Potential

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.

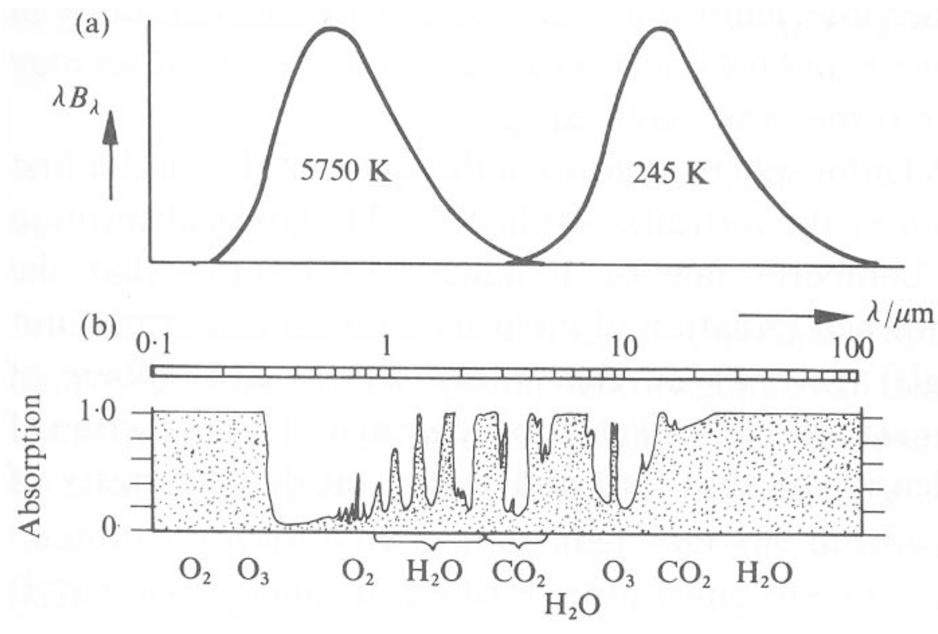
Chapter 3, *Chemistry in Context*

100 year time horizon

Some GHGs are much more effective than others, in terms of GWP (i.e., perturbation of RF per mass)

Atmospheric Radiation

- Solar irradiance (downwelling) at top of atmosphere occurs at wavelengths between ~200 and 2000 nm (~5750 K "black body" temperature)
- Thermal irradiance (upwelling) at top of the atmosphere occurs at wavelengths between ~5 and 50 μm (~245 K "black body" temperature for Earth's atmosphere)



Panel (a): Curves of black-body energy versus wavelength for 5750 K (Sun's approximate temperature) and for 245 K (Earth's mean temperature). The curves are drawn with equal area since, integrated over the entire Earth at the top of the atmosphere, the solar (downwelling) and terrestrial (upwelling) fluxes must be equal.

Panel (b): absorption by atmospheric gases for a clear vertical column of the atmosphere (1.0 represents complete absorption).

From Houghton, *Physics of Atmospheres*, 1991

- Absorption and photodissociation in the UV occurs due to changes in the electronic state (orbital configuration of electrons) of molecules
- Absorption and re-emission in the IR occurs due to changes in vibrational and rotational states of molecules with electric dipole moments

Atmospheric Radiation

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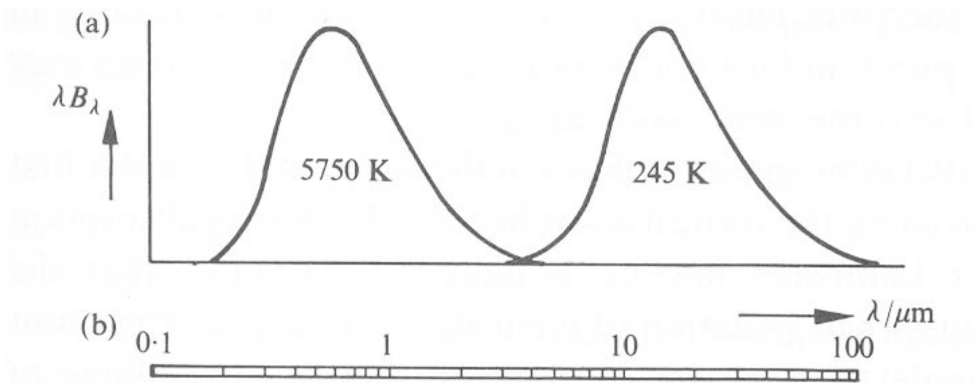

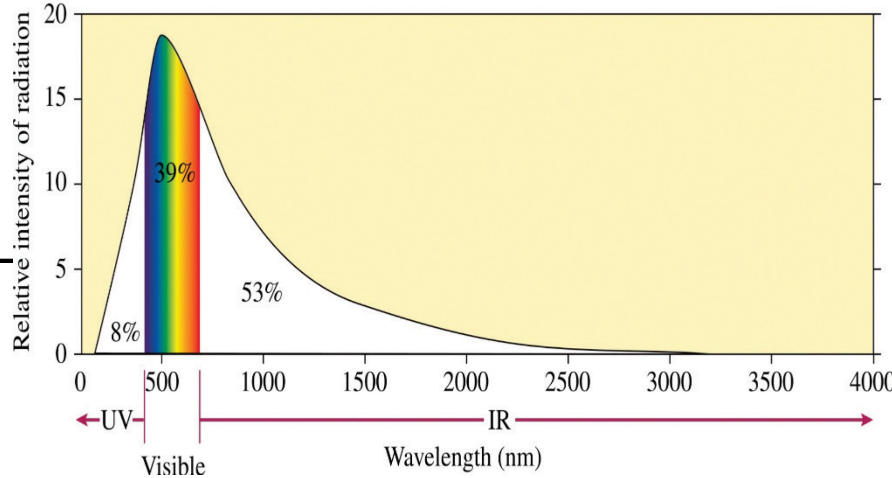

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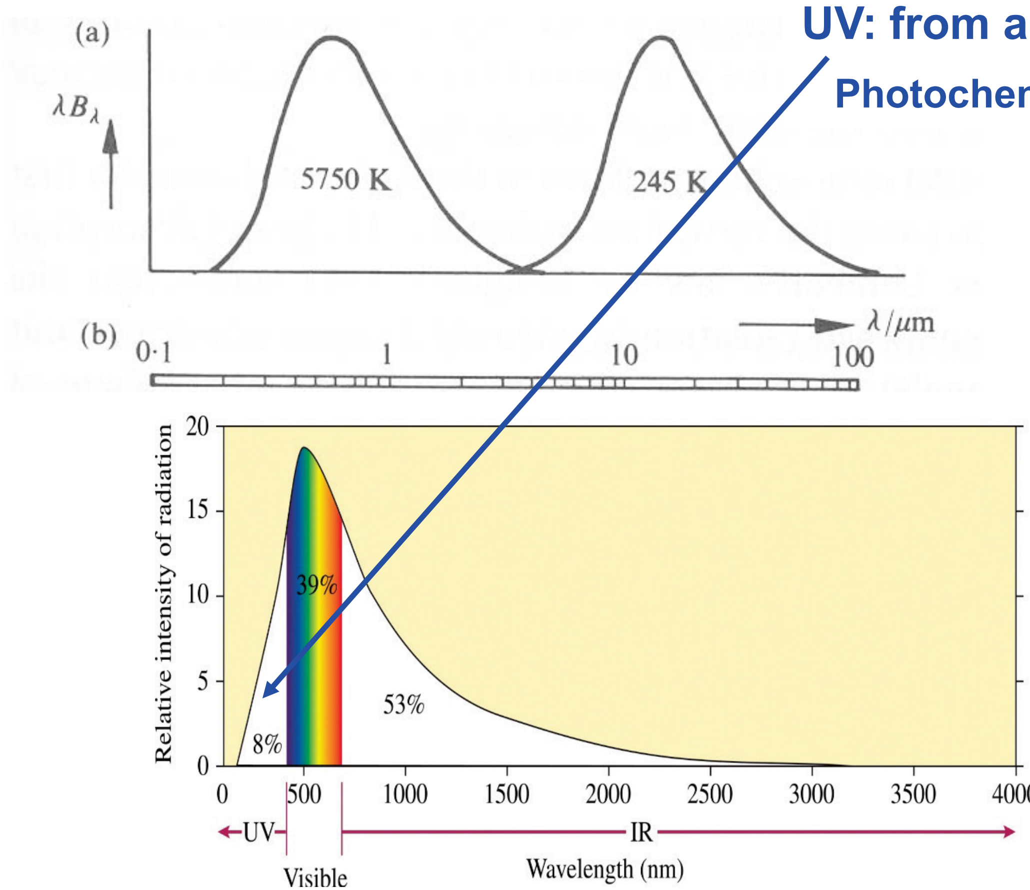
UV: from about 200 to 400 nm

Photochemistry: Second unit of class



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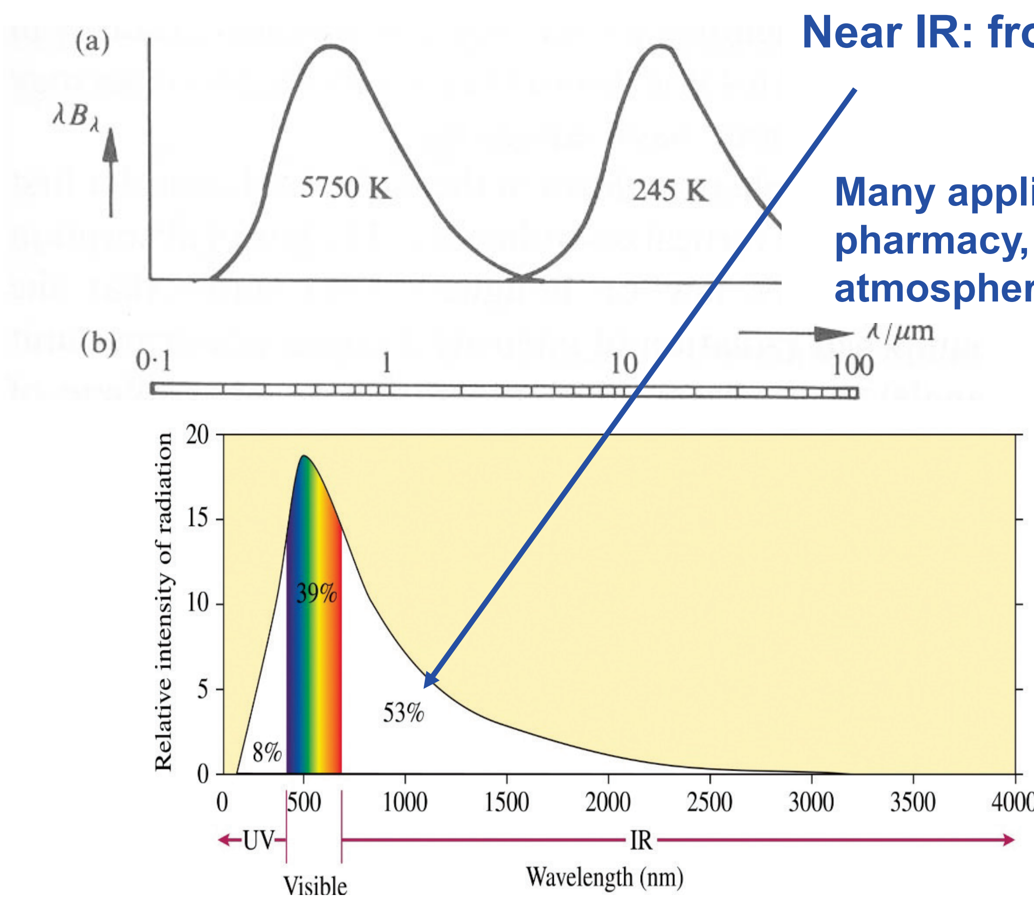

Near IR: from about 0.8 to 2.5 μm or 800 to 2500 nm

Many applications in astronomy, agriculture, pharmacy, and remote sensing of Earth's atmosphere.

Atmospheric Radiation

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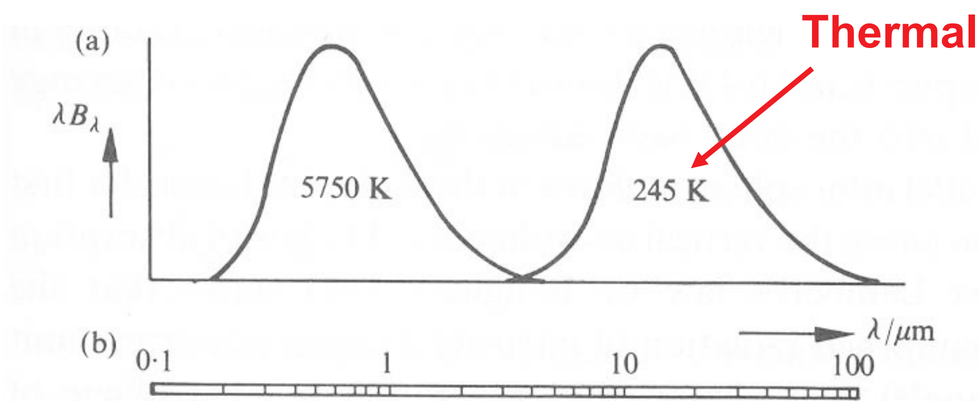
Thermal IR: from about 5 to 50 μm



Radiation & Molecules

Radiation can induce photo-dissociation (March 10 lecture), vibration, and rotation of molecules.

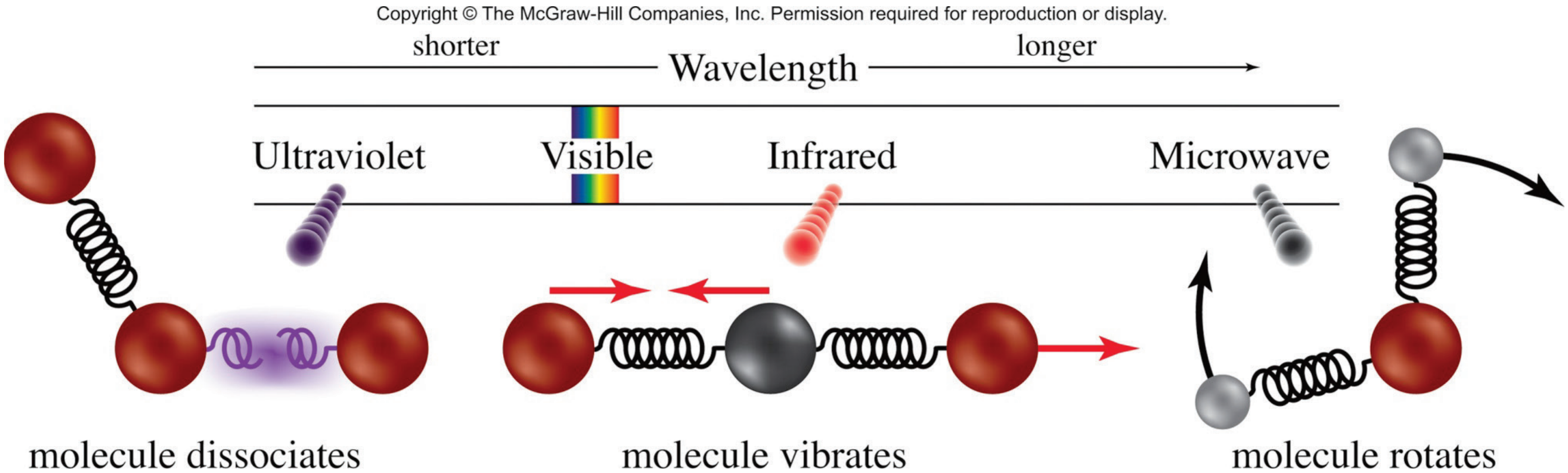


Fig 3.19, Chemistry in Context

Radiation & Molecules

Radiation can induce photo-dissociation (March 10 lecture), **vibration**, and rotation of molecules.

Thermal IR radiation is not energetic enough to break molecular bonds (i.e., photo-dissociate). Upon absorption, thermal IR will increase the vibrational energy of a molecule

CO_2 (linear molecule) has 4 vibrational modes (see below): for molecules vibrational frequencies are quantized. That is, only certain energies for the system are allowed. Most importantly, only photons with certain wavelengths (energies) will excite molecular vibrations.

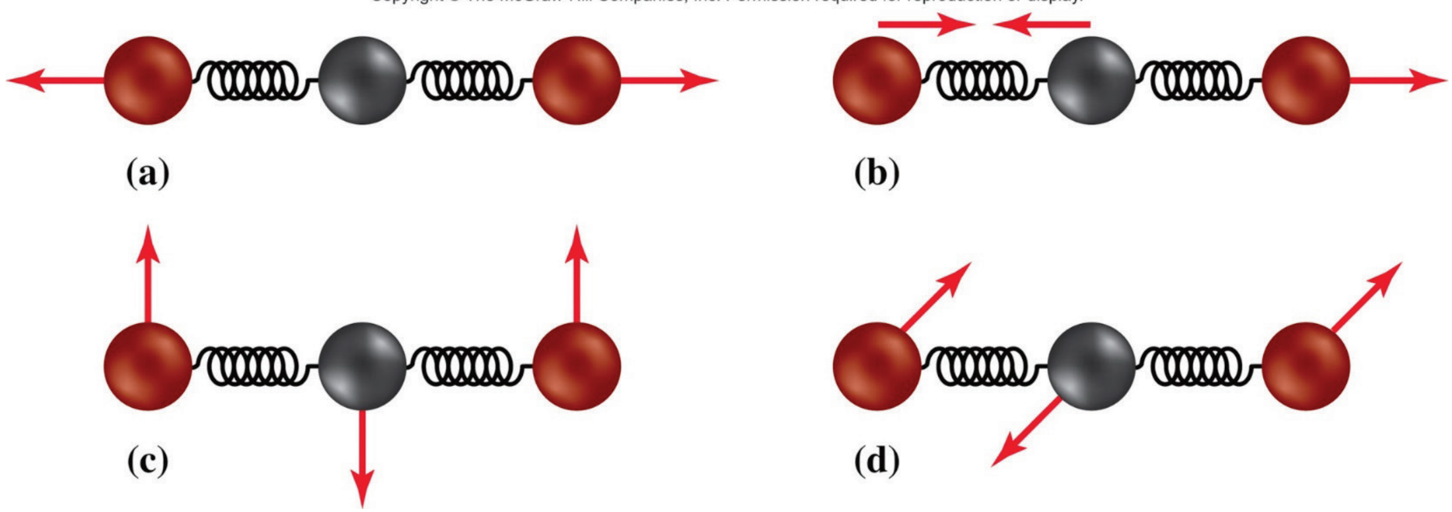


Fig 3.16, Chemistry in Context

Radiation & Molecules

Radiation can induce photo-dissociation (Oct 15 lecture), **vibration**, and rotation of molecules.

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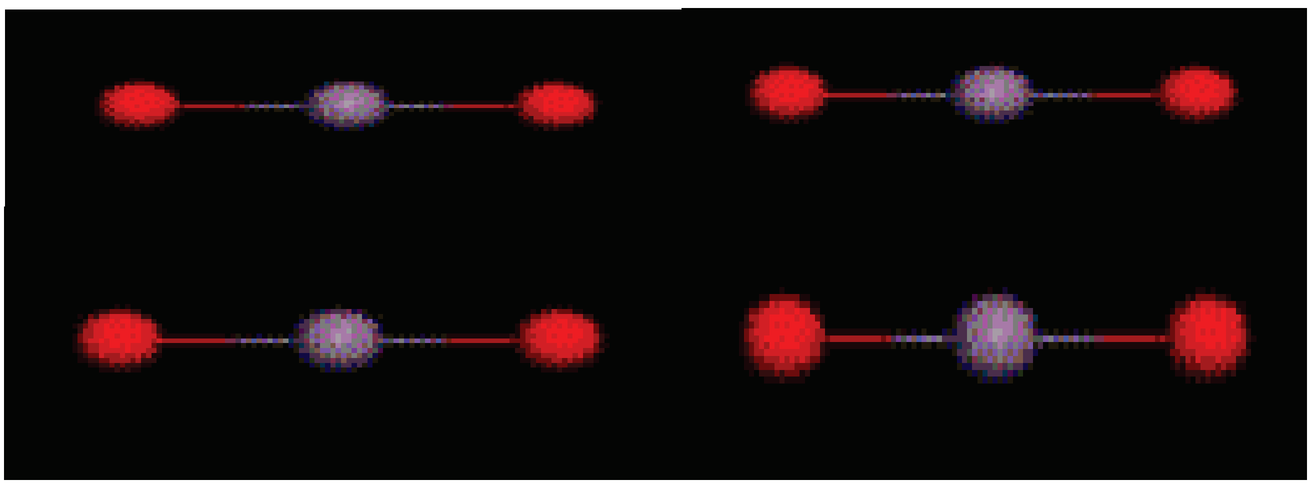

http://science.widener.edu/svb/ftir/ir_co2.html

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

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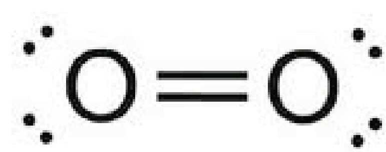
No dipole moment, either naturally or during vibration:



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CO_2 has ho natural dipole moment

$O^- — C^+ — O^-$

DP = 0

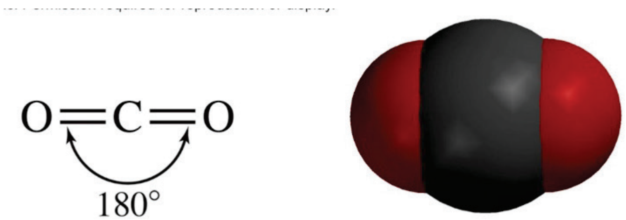

Fig 3.14, Chemistry in Context

Excitation of Molecules

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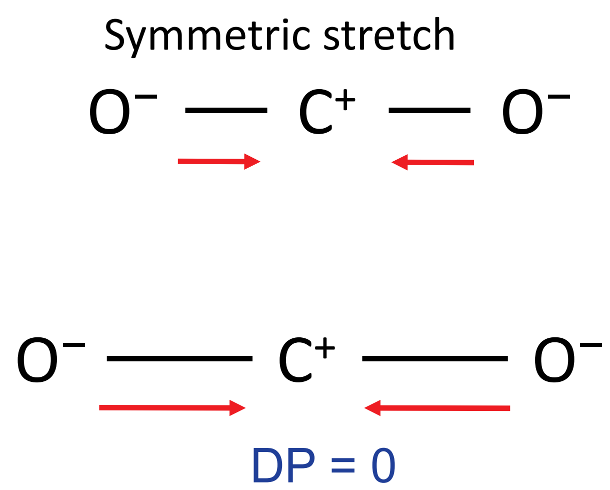
Symmetric Stretch: no dipole moment



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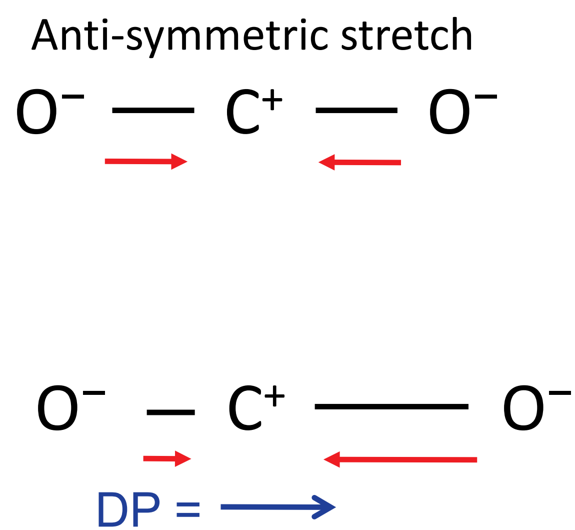
Anti-symmetric Stretch: *dipole moment*



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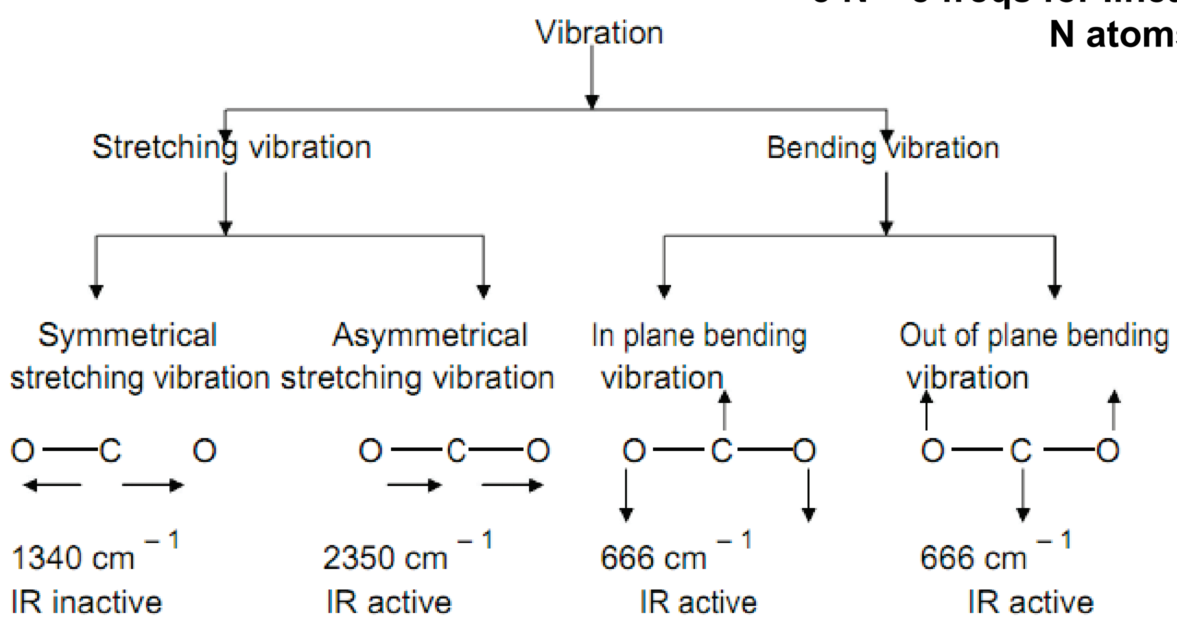
Dipole moment ⇨ product of magnitude of charges & distance of separation between charges: i.e., a molecule is said to have a dipole moment if it has a non-zero spatial distribution of charge

3 N – 5 freqs for linear molecules, N atoms: 4 freqs for CO_2

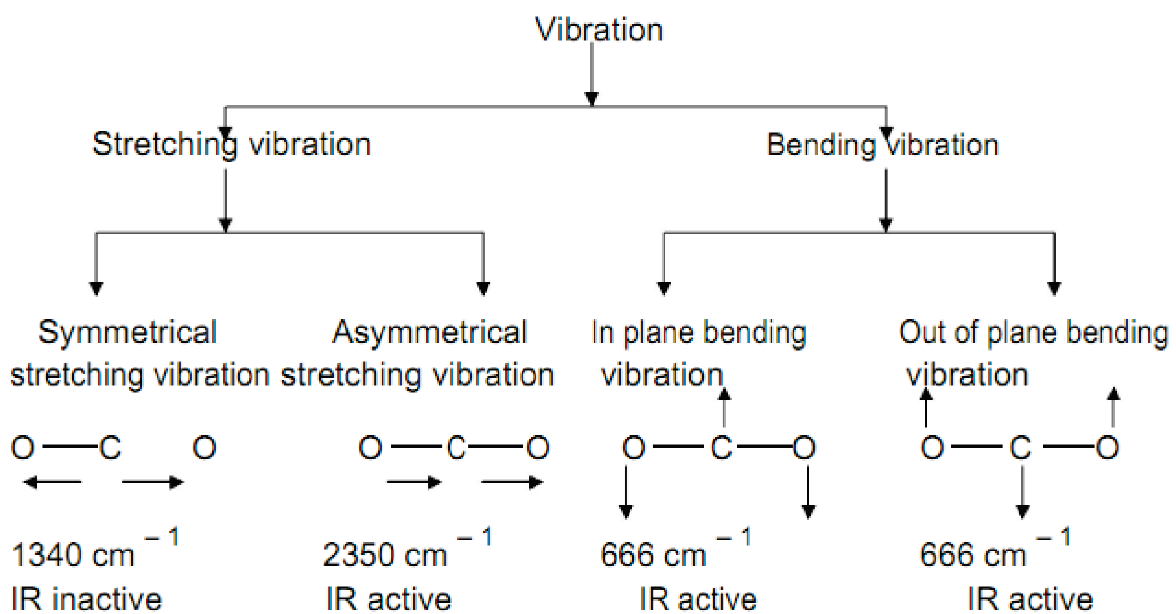


http://www.vidyarthiplus.in/2013/12/cy6151-engineering-chemistry-1.html#.VOUqai4RXIY

Excitation of Molecules

Wavenumber = 1 / Wavelength

$1 / 2350\ cm^{-1} = 4.25\times10^{-4}\ cm = 4.25\times10^{-6}\ m = 4.25\ \mu m$
$1 / 666\ cm^{-1} = 1.50\times10^{-3}\ cm = 15.0\times10^{-6}\ m = 15.0\ \mu m$



4.25 μm **15.0 μm** **15.0 μm**

http://www.vidyarthiplus.in/2013/12/cy6151-engineering-chemistry-1.html#.VOUqai4RXIY

Excitation of Molecules

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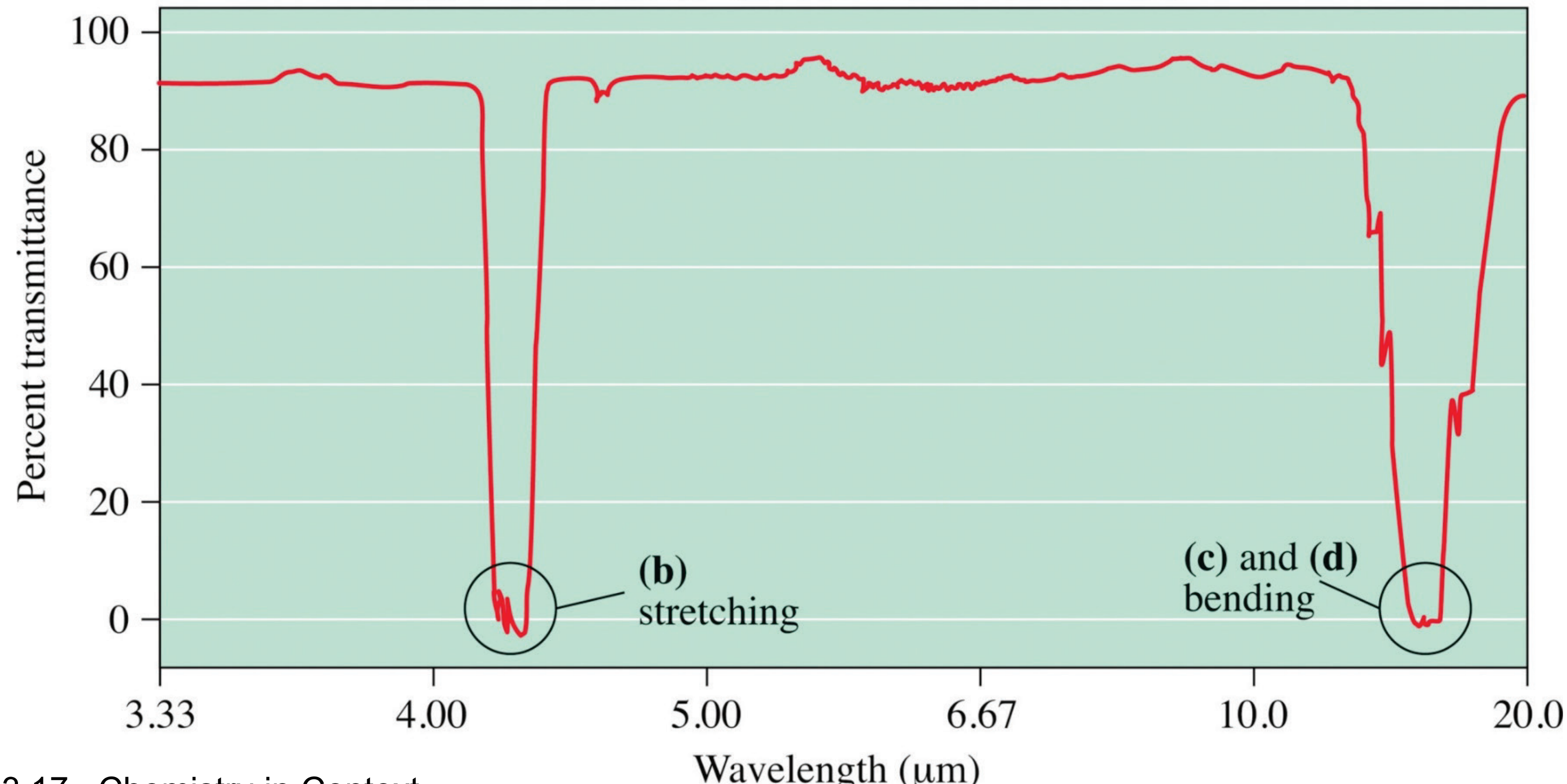

Fig 3.17, Chemistry in Context

Excitation of Molecules

Which transition involves more energy?

$E = hc / \lambda$

h (Planck's constant) = 6.62×10^{-27} erg sec; c (speed of light) = 3×10^{8} cm/sec

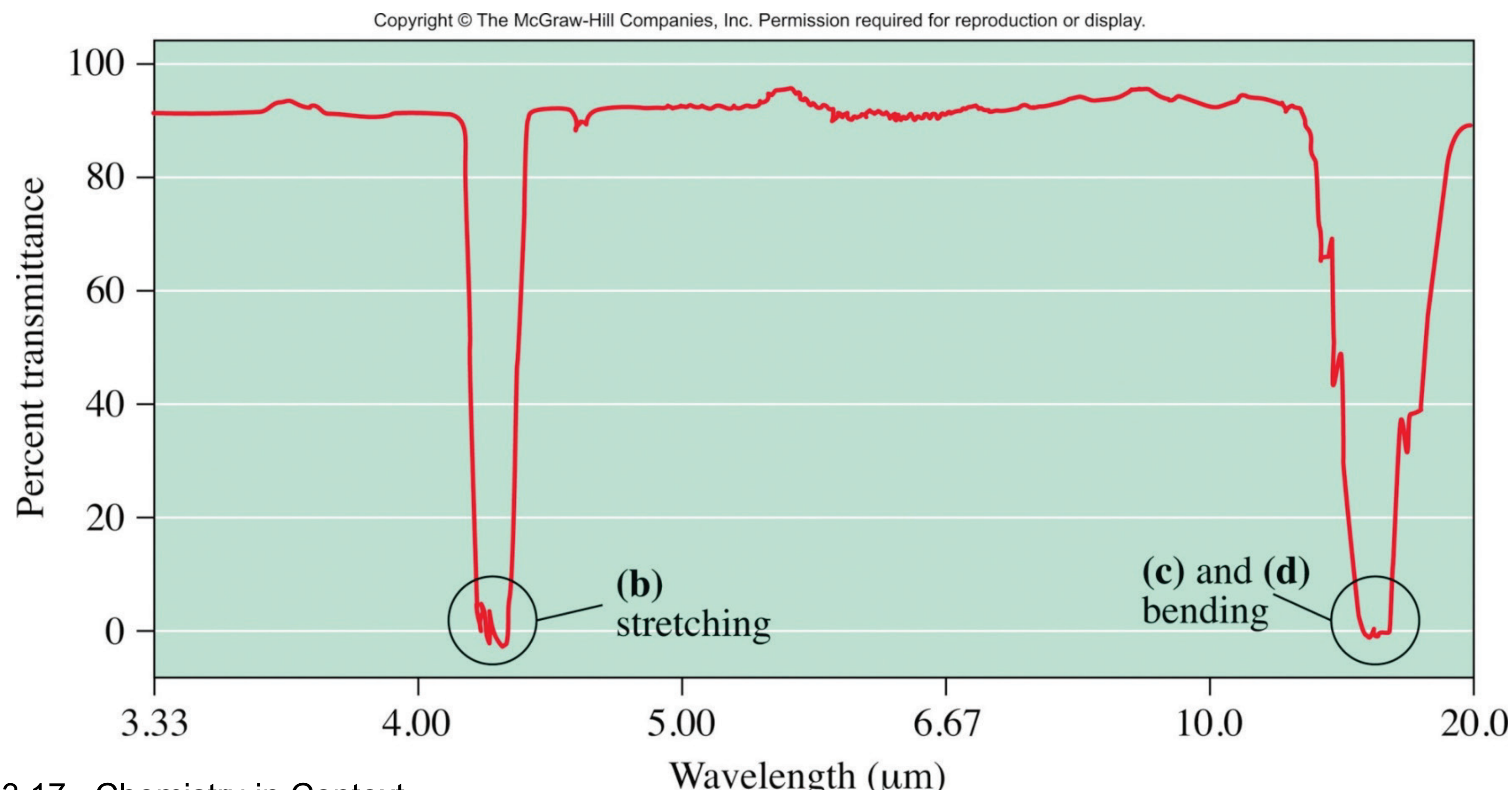

Fig 3.17, Chemistry in Context

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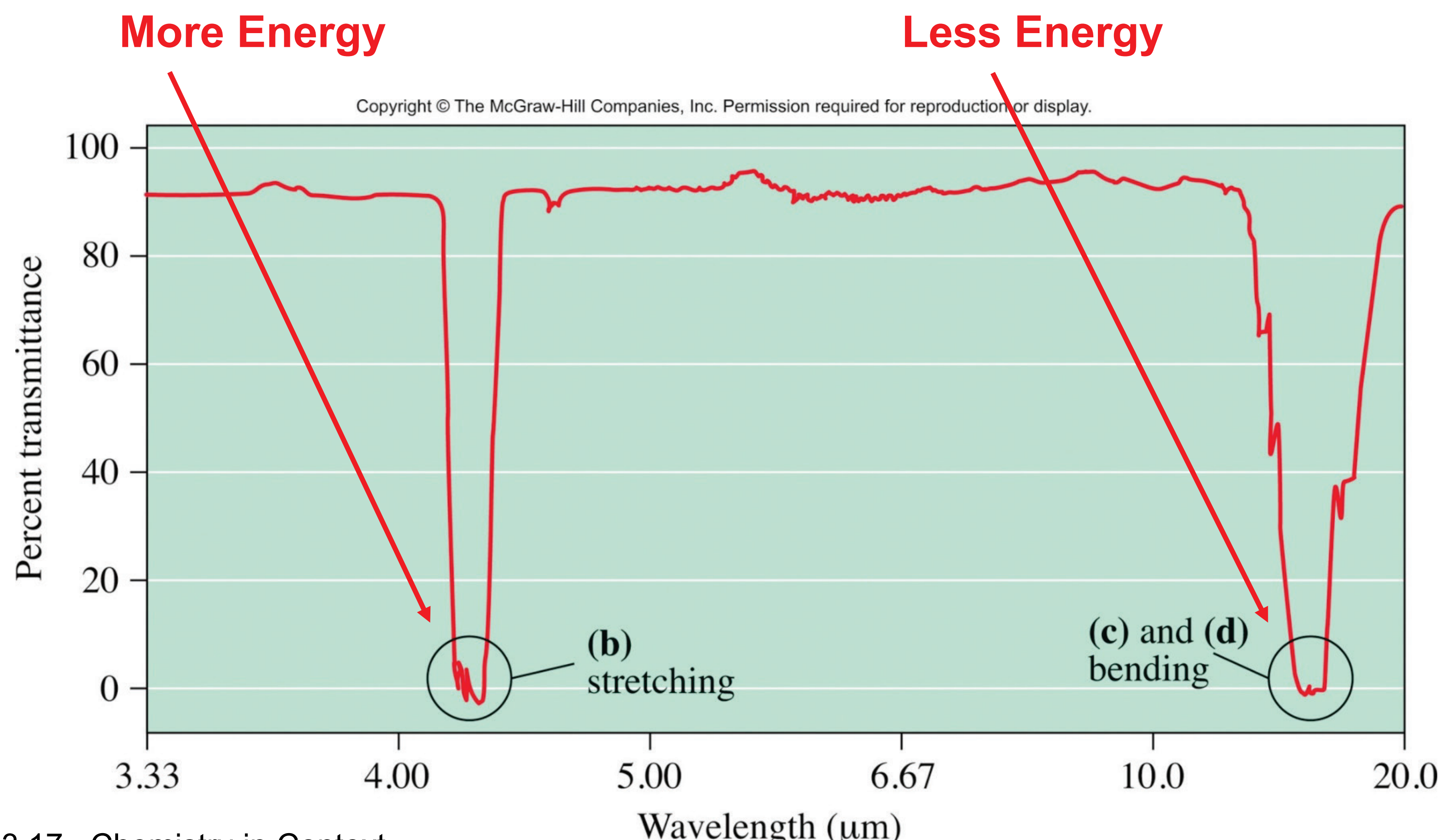

Fig 3.17, Chemistry in Context

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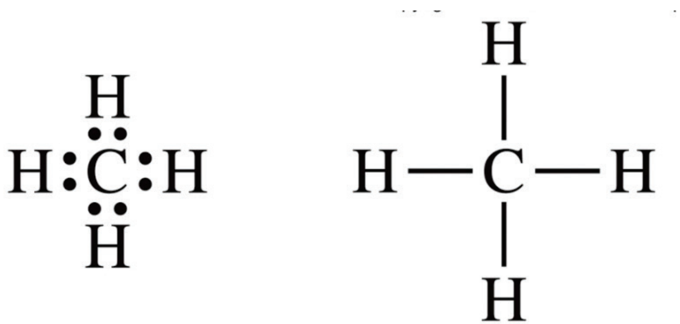
CH_4 also has no natural dipole moment: charge is uniformly distributed



Figs 3.10 & 3.11, Chemistry in Context

Excitation of Molecules

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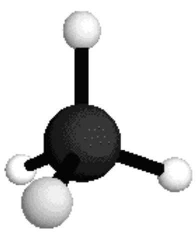
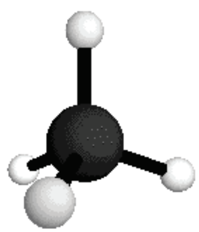
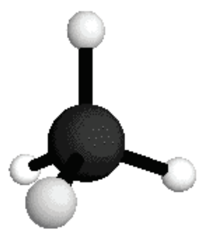
CH_4 has 4 unique vibrational modes, 2 of which interact with the IR field



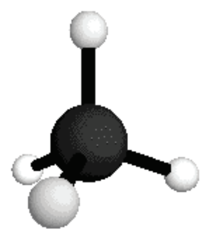
#1
3.3 μm



#2
6.3 μm



#3
3.2 μm



#4
7.6 μm

http://www2.ess.ucla.edu/~schauble/MoleculeHTML/CH4_html/CH4_page.html

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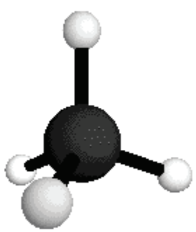
- naturally occurring **dipole moment**
- exhibit a **dipole moment** during vibration

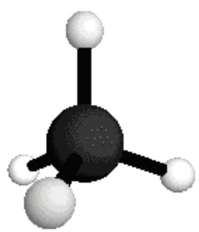
Dipole moment ⇨ product of magnitude of charges & distance of separation between charges: i.e., a molecule is said to have a dipole moment if it has a non-zero spatial distribution of charge

CH_4 has 4 unique vibrational modes, 2 of which interact with the IR field

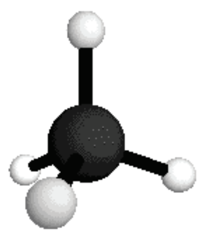
Only modes for which the C and H atoms both move are radiatively active



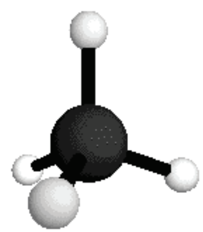
#1
3.3 μm



#2
6.3 μm



#3
[3.2 μm](http://)



#4
7.6 μm

http://www2.ess.ucla.edu/~schauble/MoleculeHTML/CH4_html/CH4_page.html

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

H_2O has a natural dipole moment (bent molecule) and absorbs in three spectral regions:

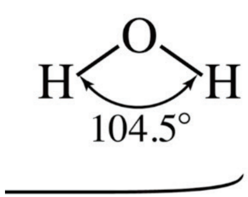
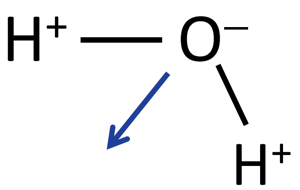


Fig 3.13, Chemistry in Context



Excitation of Molecules

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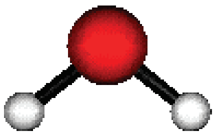
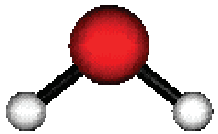


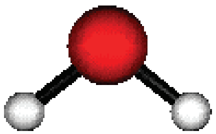
2.5 μm

Asymmetric Stretch



2.6 μm

Symmetric Stretch



6.1 μm

Bending Mode

http://www2.ess.ucla.edu/~schauble/MoleculeHTML/H2O_html/H2O_page.html

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

N_2O also has a natural dipole moment (since it is an asymmetric molecule) and also absorbs in three spectral regions:

4.5 μm

7.8 μm

17.0 μm

http://www2.ess.ucla.edu/~schauble/MoleculeHTML/N2O_html/N2O_page.html

Absorption vs. Wavelength

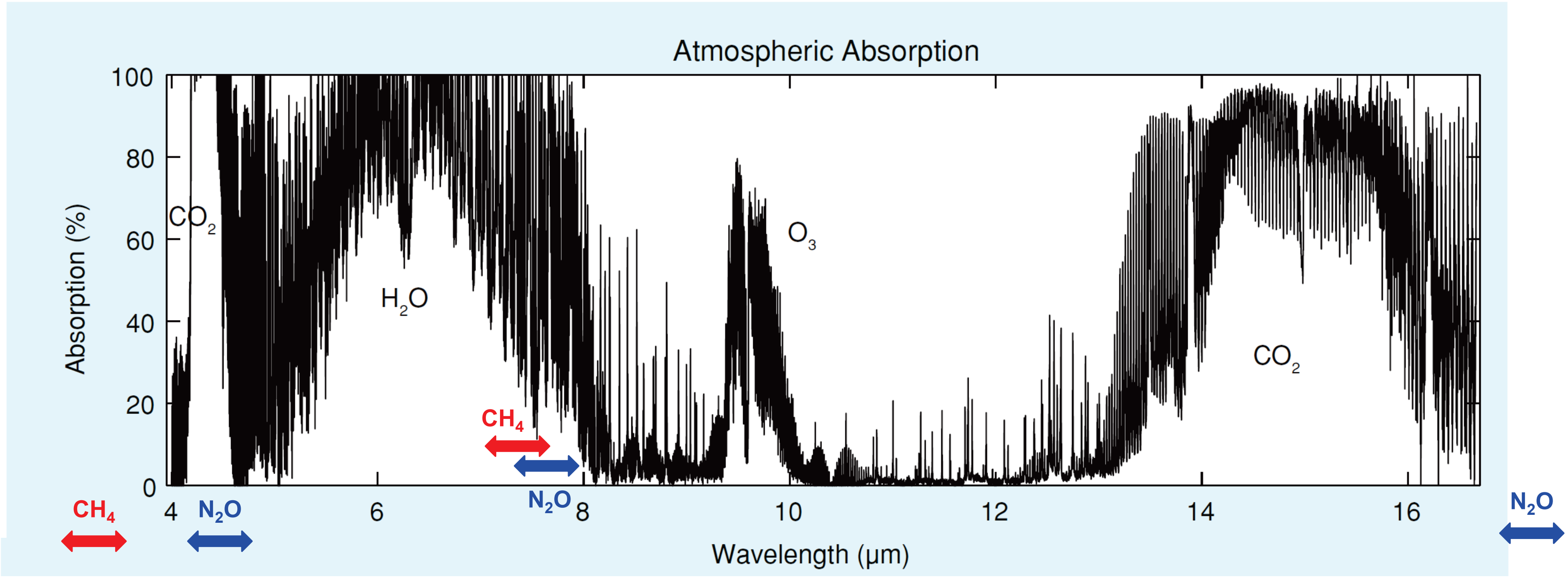


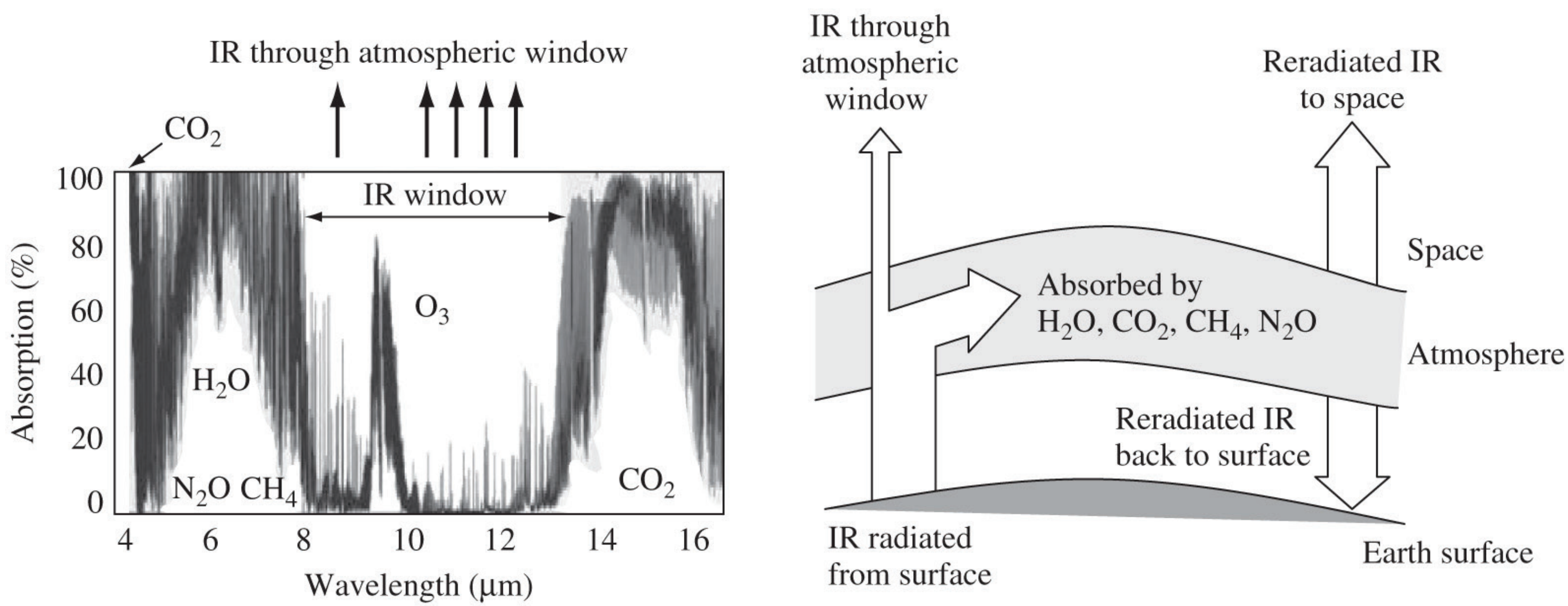
Fig 2.6, IPCC SROC (Special Report on Ozone layer and Climate), 2005
https://www.ipcc.ch/site/assets/uploads/2018/03/sroc02-1.pdf

The Greenhouse Effect

Molecules of that absorb specific wavelengths of IR energy experience different fates:

- **Some hold that extra energy for a brief time, then re-emit it in all directions as heat.**
- **Others collide with atmospheric molecules such as N_2 and O_2 and transfer the absorbed energy to those molecules, as heat**

Both processes "trap" radiation emitted by the Earth; this trapping of energy heats the lower atmosphere and surface

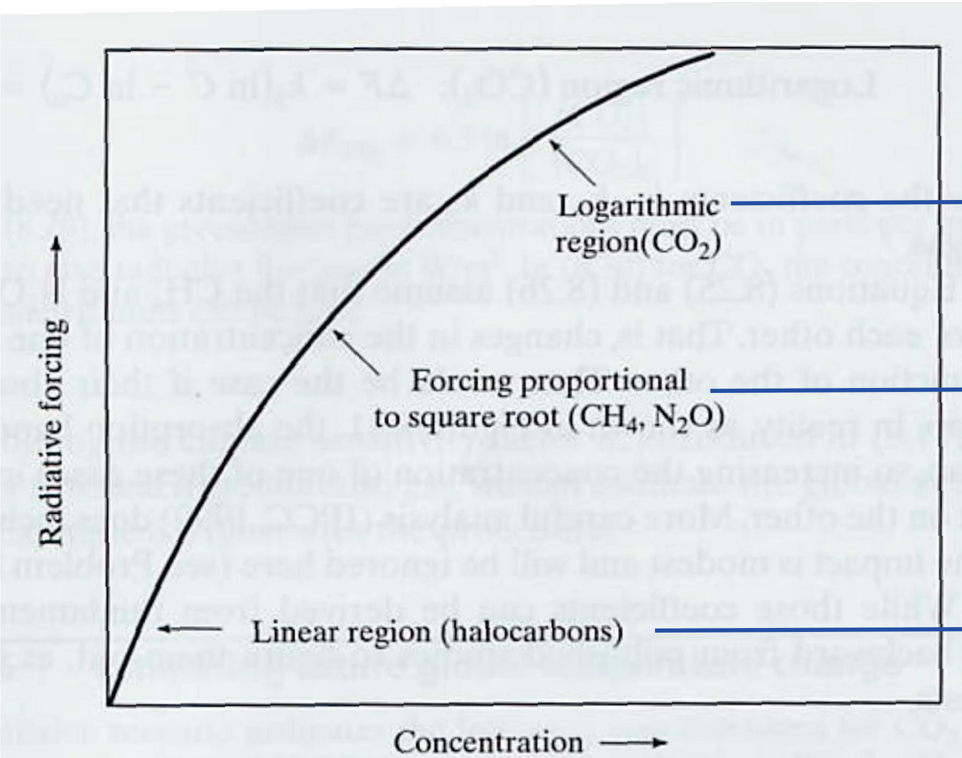


Masters, Intro. to Environmental Engineering and Science, 3d ed.

See Chapter 3.4 by Dan Kirk-Davidoff,
in *Green Chemistry: An Inclusive Approach*, 2018
in Additional Readings for a simple, differential equation description of the GHG effect based on a so-called two layer model.

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

How does RF change with concentration?



Wigley (1987)

$$\Delta RF = \alpha \ln\left(\frac{C}{C_o}\right)$$

$$\Delta RF = \alpha \left(\sqrt{C} - \sqrt{C_o}\right)$$

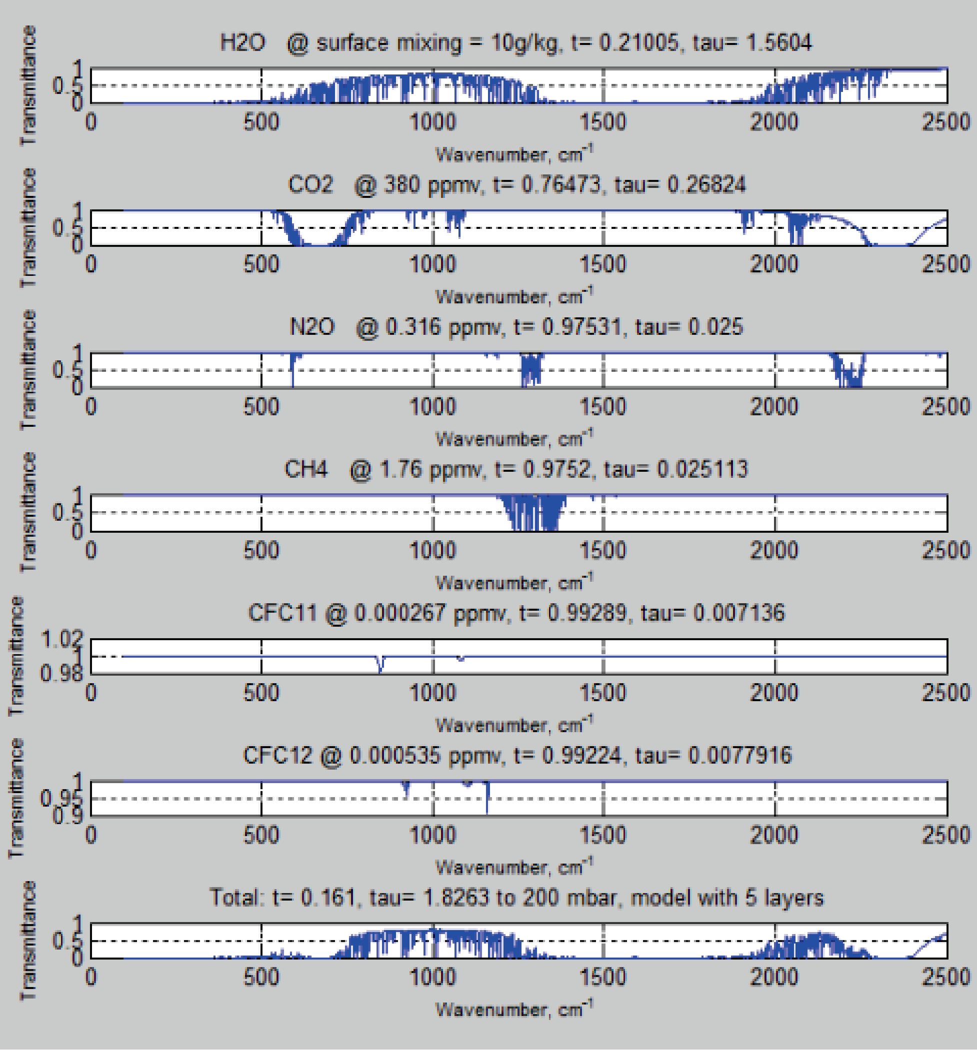
$$\Delta RF = \alpha \left(C - C_o\right)$$

Masters, Introduction to Environmental Engineering and Science, 1998

Effectiveness of a GHG depends on “saturation” of absorption band.

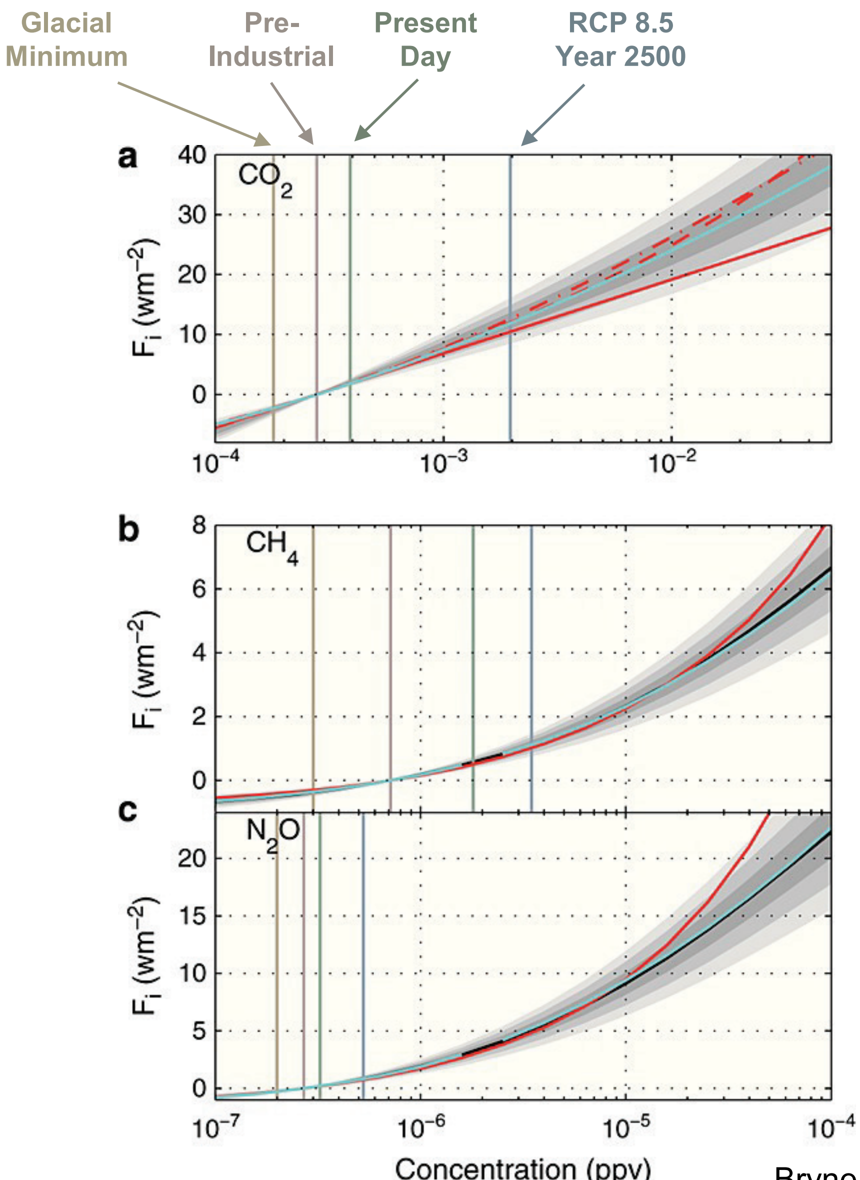
Highly saturated (most of the outgoing radiation is already absorbed) bands are less sensitive to increases in GHG concentration than partially or non saturated bands.

How does RF change with concentration?



https://www.google.com/url?sa=i&url=https%3A%2F%2Fscienceofdoom.com%2F2011%2Fpage%2F4%2F&psig=AOvVaw0YxpsuY4tcgapz8bhcYtC2&ust=1601056441281000&source=images&cd=vfe&ved=0CAIQjRxqFwoTCID7v5euguwCFQAAAAAdAAAAABAD

How does RF change with concentration?



- Black line is calculated RF using the Spectral Mapping for Atmospheric Radiative Transfer (SMART) radiative transfer code
- Light and dark grey show 1σ & 2σ uncertainties
- Cyan line is "fit" to the results
- Red lines are older fits from various IPCC and WMO/UNEP Ozone Depletion Reports

Bryne and Goldblatt, JGR, 2013
https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2013GL058456

How does RF change with concentration?

Table 8.SM.1 | Supplementary for Table 8.3: RF formulae for CO_2, CH_4 and N_2O.

Gas	RF (in W m^{-2})	Constant α
CO_2	$\Delta F = \alpha \ln(C/C_0)$	5.35
CH_4	$\Delta F = \alpha\left(\sqrt{M} - \sqrt{M_0}\right) - \left(f(M,N_0) - f(M_0,N_0)\right)$	0.036
N_2O	$\Delta F = \alpha\left(\sqrt{N} - \sqrt{N_0}\right) - \left(f(M_0,N) - f(M_0,N_0)\right)$	0.12

Notes:

$f(M, N) = 0.47 \ln[1+2.01\times10^{-5} (MN)^{0.75} + 5.31\times10^{-15} M (MN)^{1.52}]$

C is CO_2 in ppm.

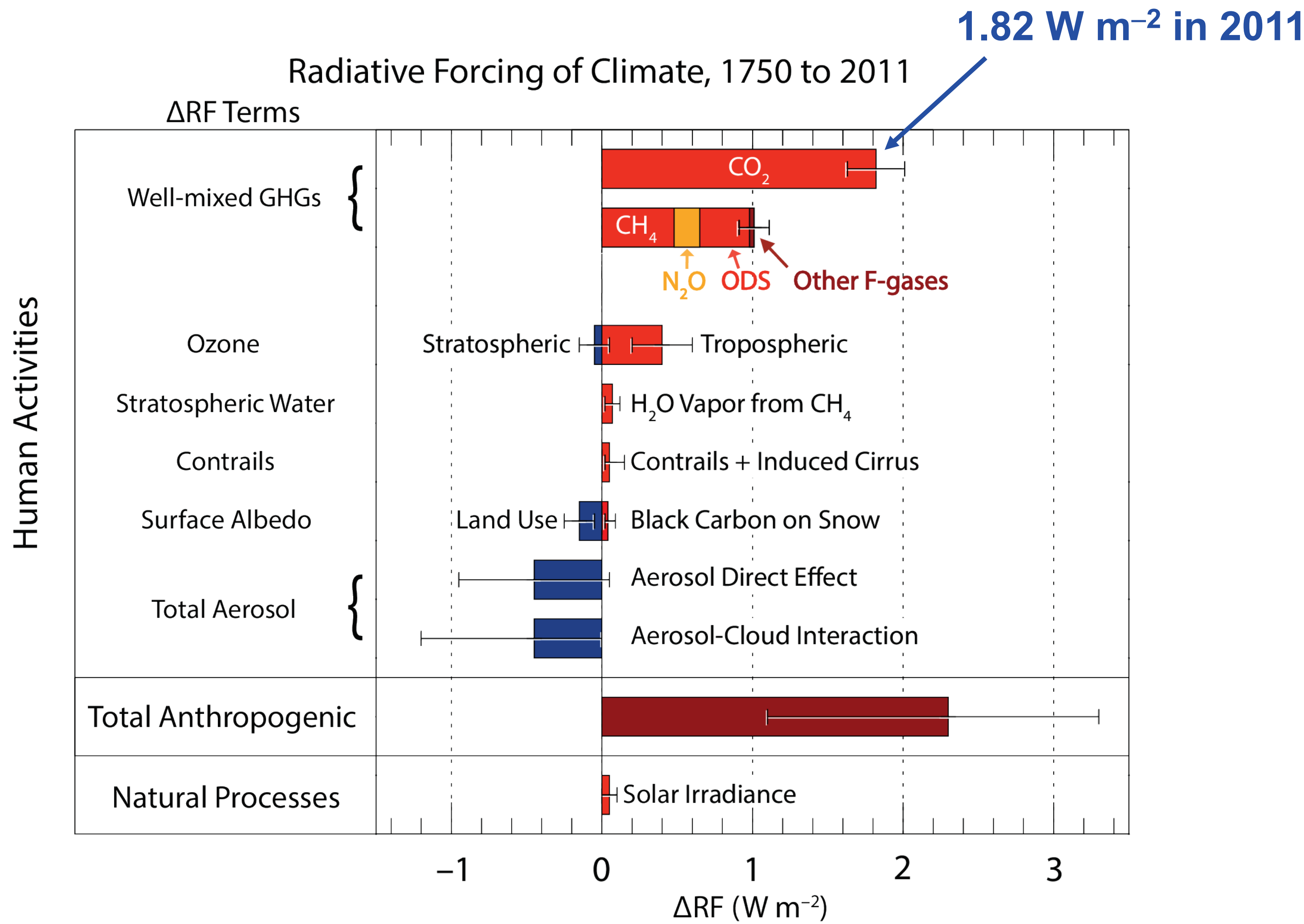
M is CH_4 in ppb.

N is N_2O in ppb.

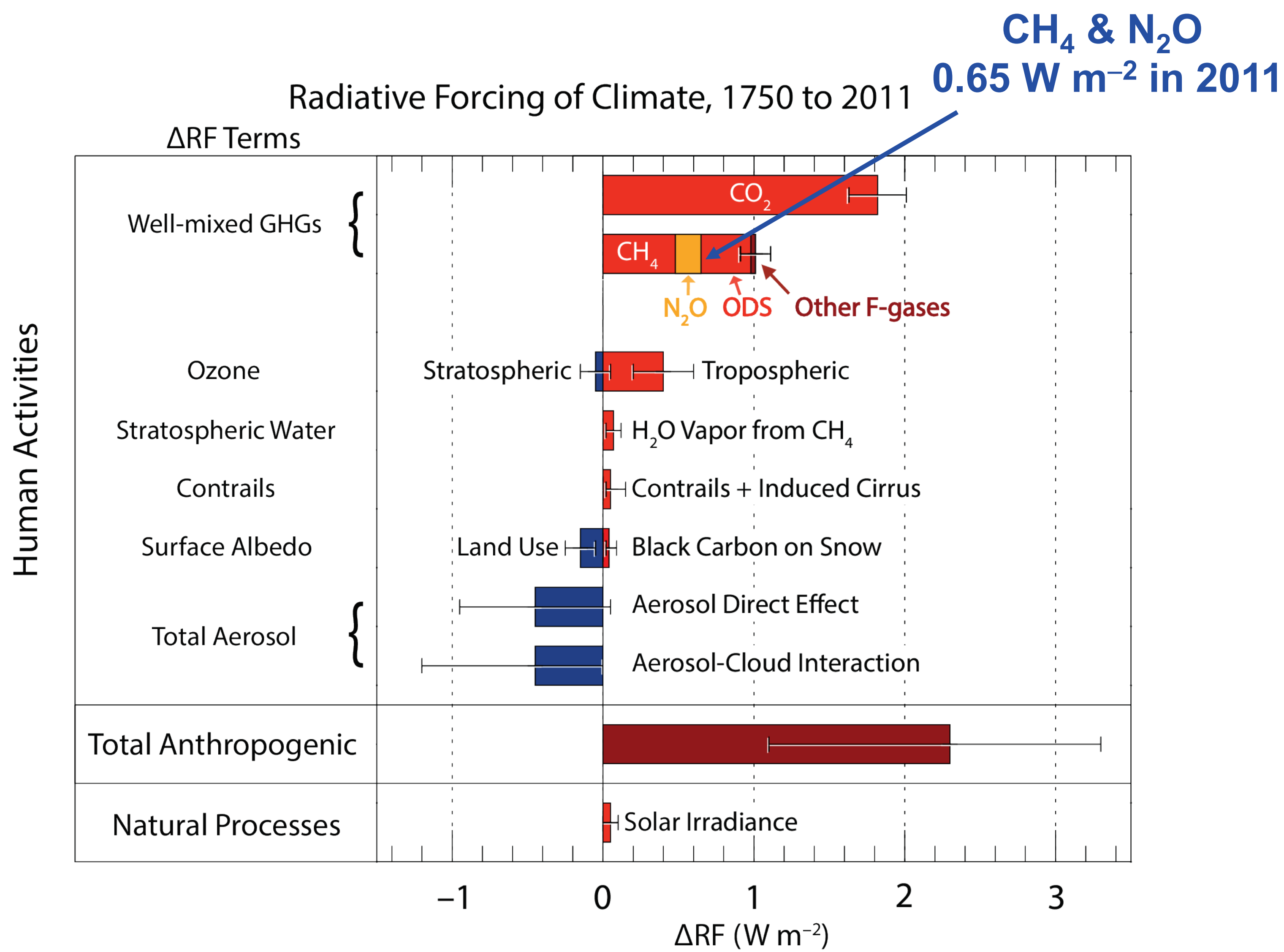
The subscript 0 denotes the unperturbed molar fraction for the species being evaluated. However, note that for the CH_4 forcing N_0 should refer to present-day N_2O, and for the N_2O forcing M_0 should refer to present-day CH_4.

IPCC Fifth Assessment Report, 2013

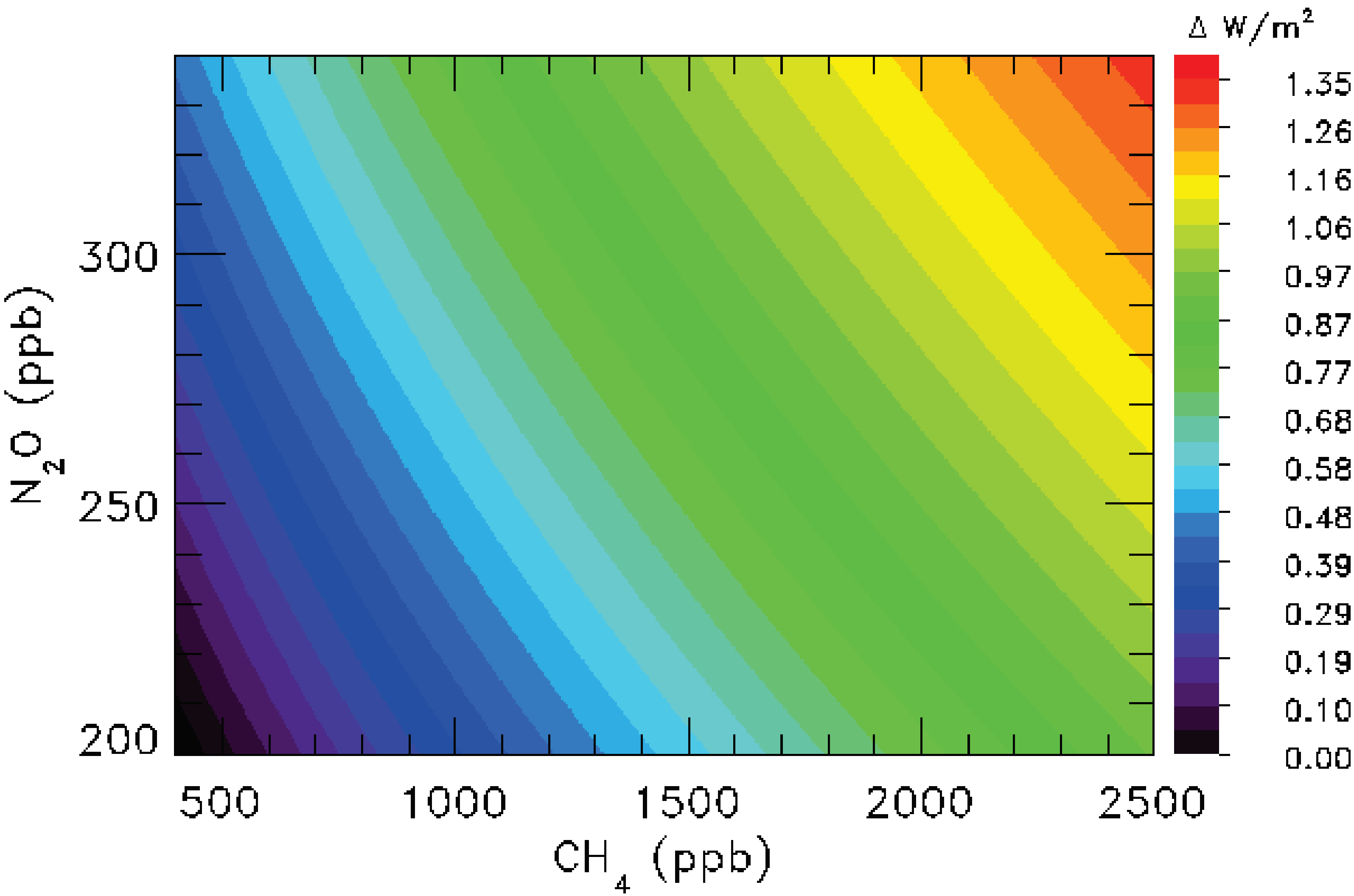
ΔRF of Climate



ΔRF of Climate

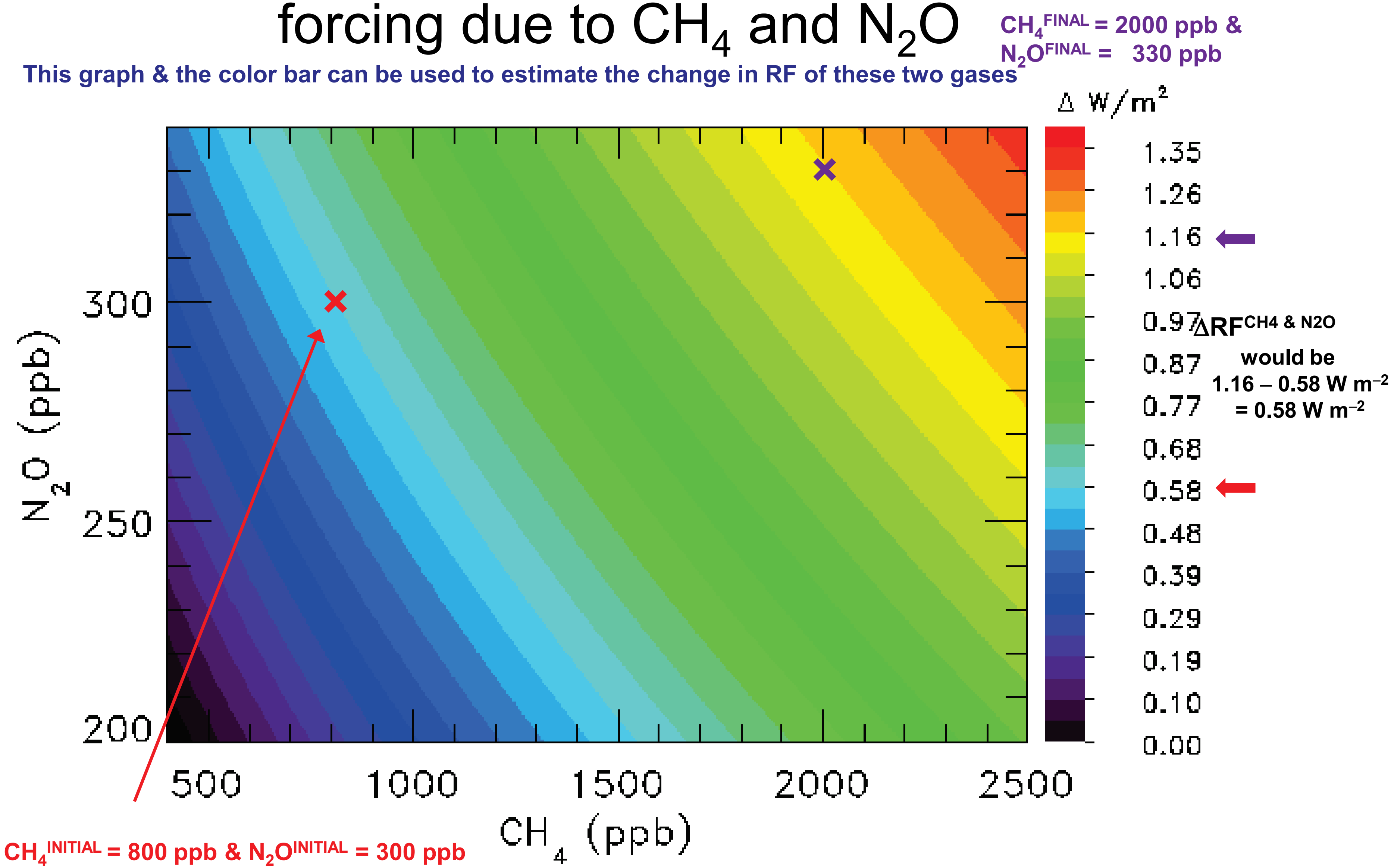


Graphical representation of surface radiative forcing due to CH_4 and N_2O



Graphical representation of surface radiative forcing due to CH_4 and N_2O

This graph & the color bar can be used to estimate the change in RF of these two gases



Absorption vs. Wavelength

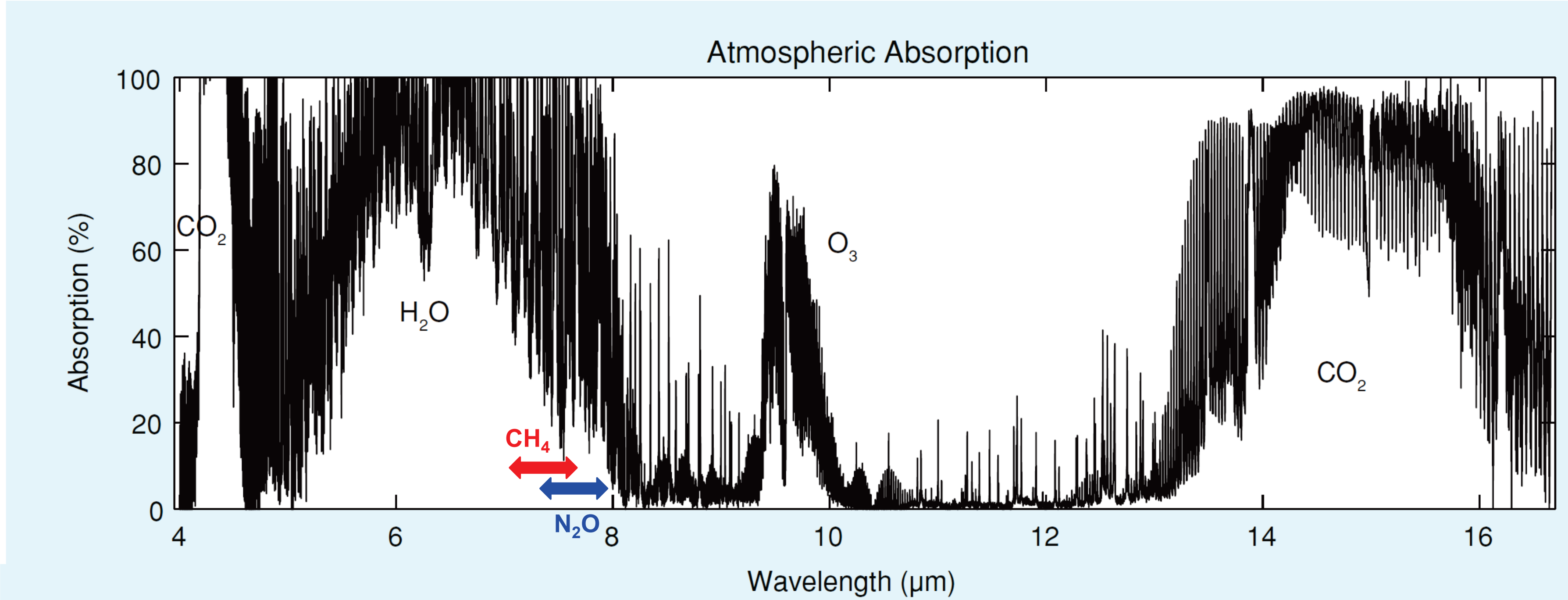
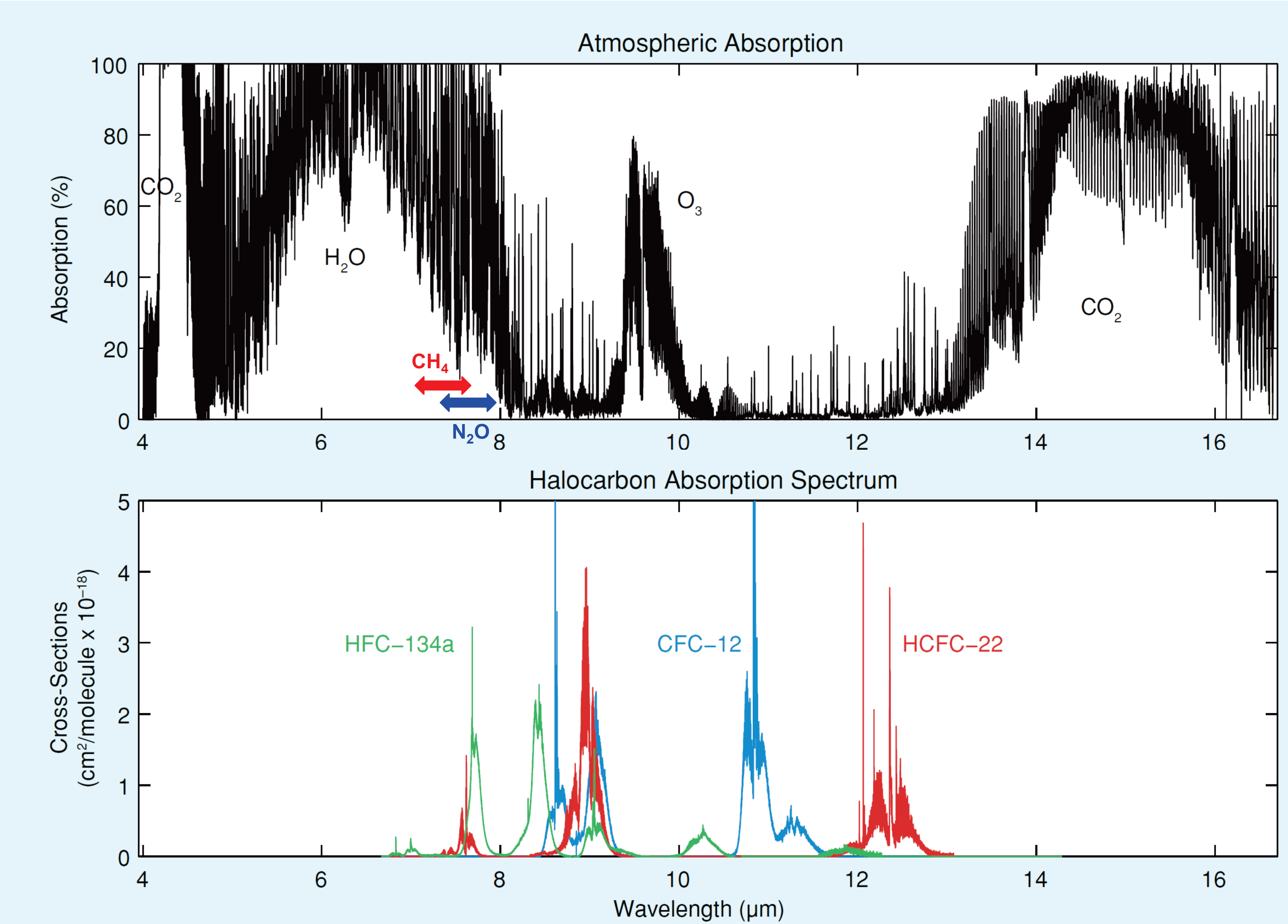


Fig 2.6, IPCC SROC (Special Report on Ozone layer and Climate), 2005
https://www.ipcc.ch/site/assets/uploads/2018/03/sroc02-1.pdf

Absorption vs. Wavelength



How does RF change with concentration?

Table 6.2: *Simplified expressions for calculation of radiative forcing due to CO_2, CH_4, N_2O, and halocarbons. The first row for CO_2 lists an expression with a form similar to IPCC (1990) but with newer values of the constants. The second row for CO_2 is a more complete and updated expression similar in form to that of Shi (1992). The third row expression for CO_2 is from WMO (1999), based in turn on Hansen et al. (1988).*

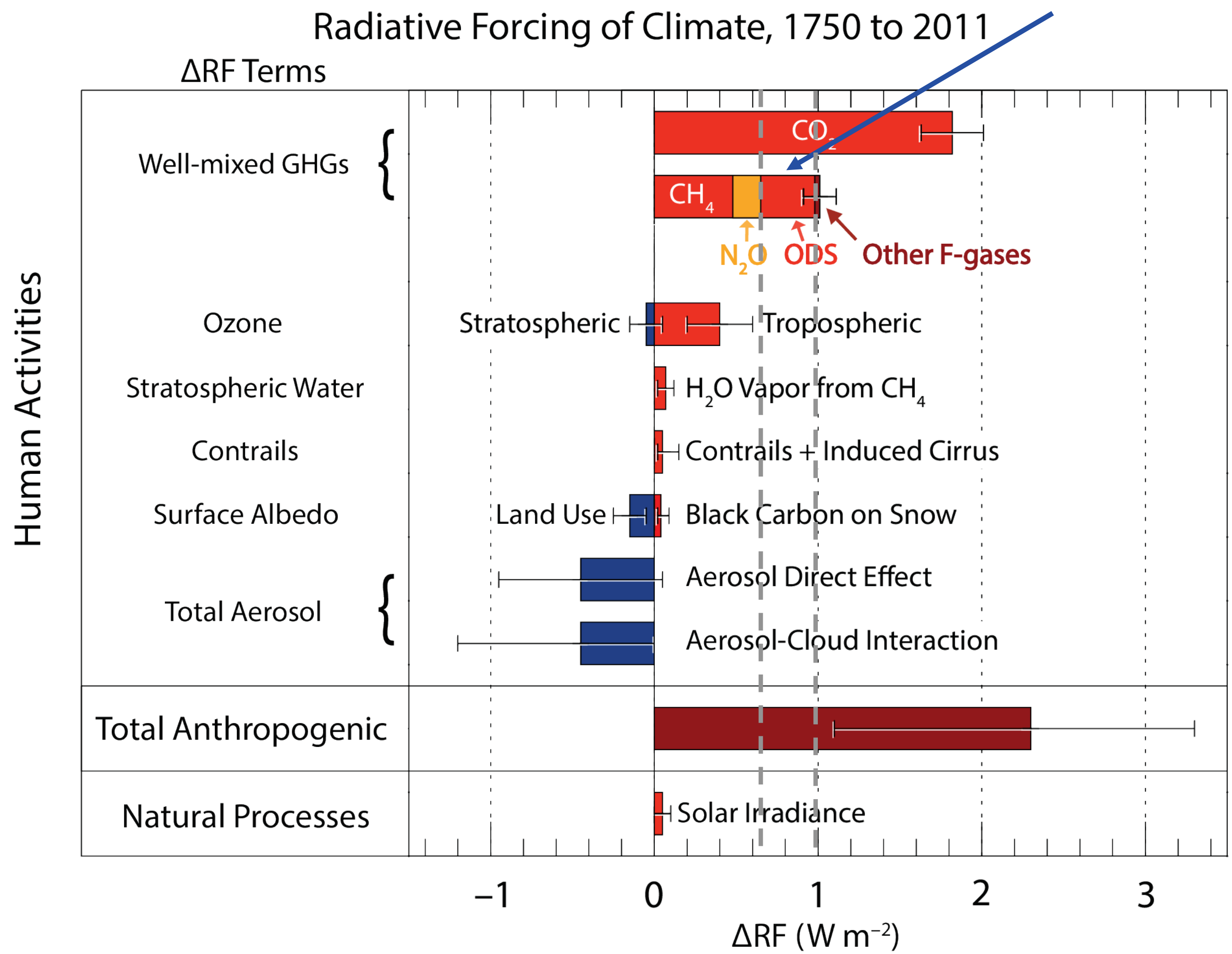
Trace gas	Simplified expression Radiative forcing, ΔF (Wm^{-2})	Constants
CO_2	$\Delta F = \alpha \ln(C/C_0)$	$\alpha = 5.35$
CH_4	Please see slide 42	
N_2O		
CFC-11a	$\Delta F = \alpha(X - X_0)$	$\alpha = 0.25$
CFC-12	$\Delta F = \alpha(X - X_0)$	$\alpha = 0.32$

C is CO_2 in ppm
M is CH_4 in ppb
N is N_2O in ppb
X is CFC in ppb
The constant in the simplified expression for CO_2 for the first row is based on radiative transfer calculations with three-dimensional climatological meteorological input data (Myhre *et al.*, 1998b). For the second and third rows, constants are derived with radiative transfer calculations using one-dimensional global average meteorological input data from Shi (1992) and Hansen *et al.* (1988), respectively.
The subscript 0 denotes the unperturbed concentration.
[a] The same expression is used for all CFCs and CFC replacements, but with different values for α (i.e., the radiative efficiencies in Table 6.7).

IPCC Third Assessment Report, 2001

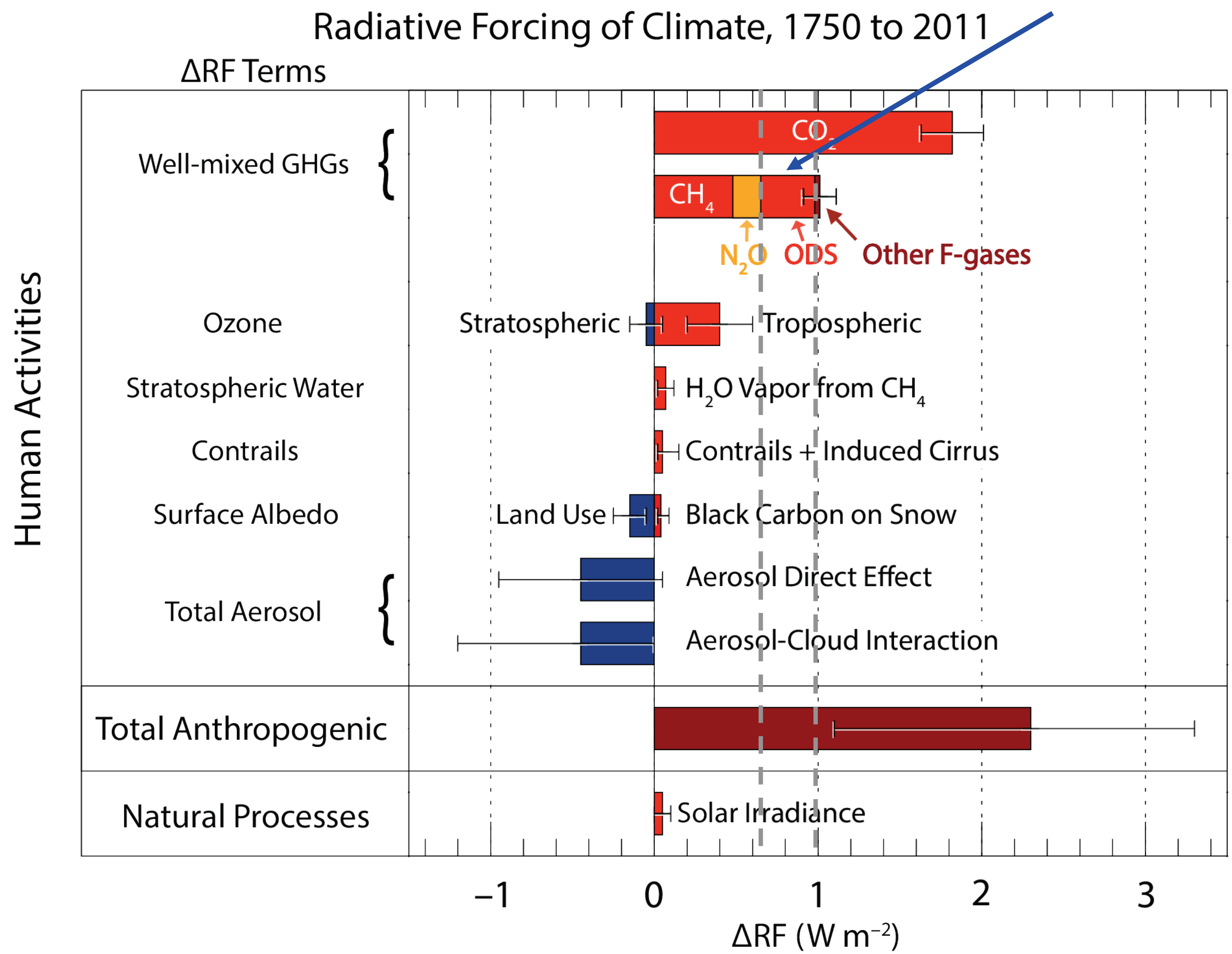
ΔRF of Climate

All Ozone Depleting Substances
0.33 W m^{-2} in 2011
CFC-11 & CFC-12 70% of total

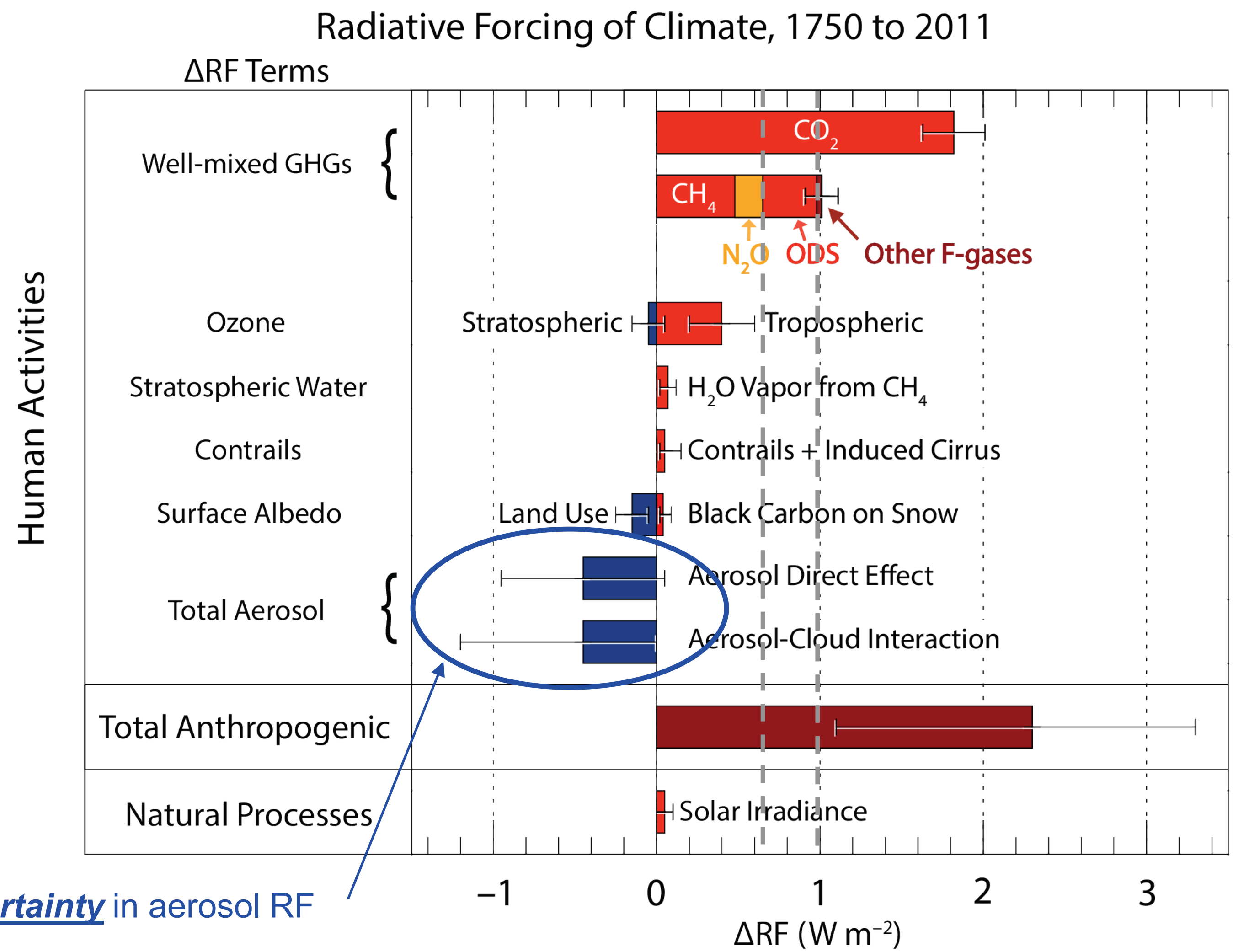


ΔRF of Climate

All Ozone Depleting Substances
0.33 W m^{-2} in 2011
CFC-11 & CFC-12 70% of total



ΔRF of Climate



Large uncertainty in aerosol RF

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

RF Due to Tropospheric Aerosols: Direct Effect

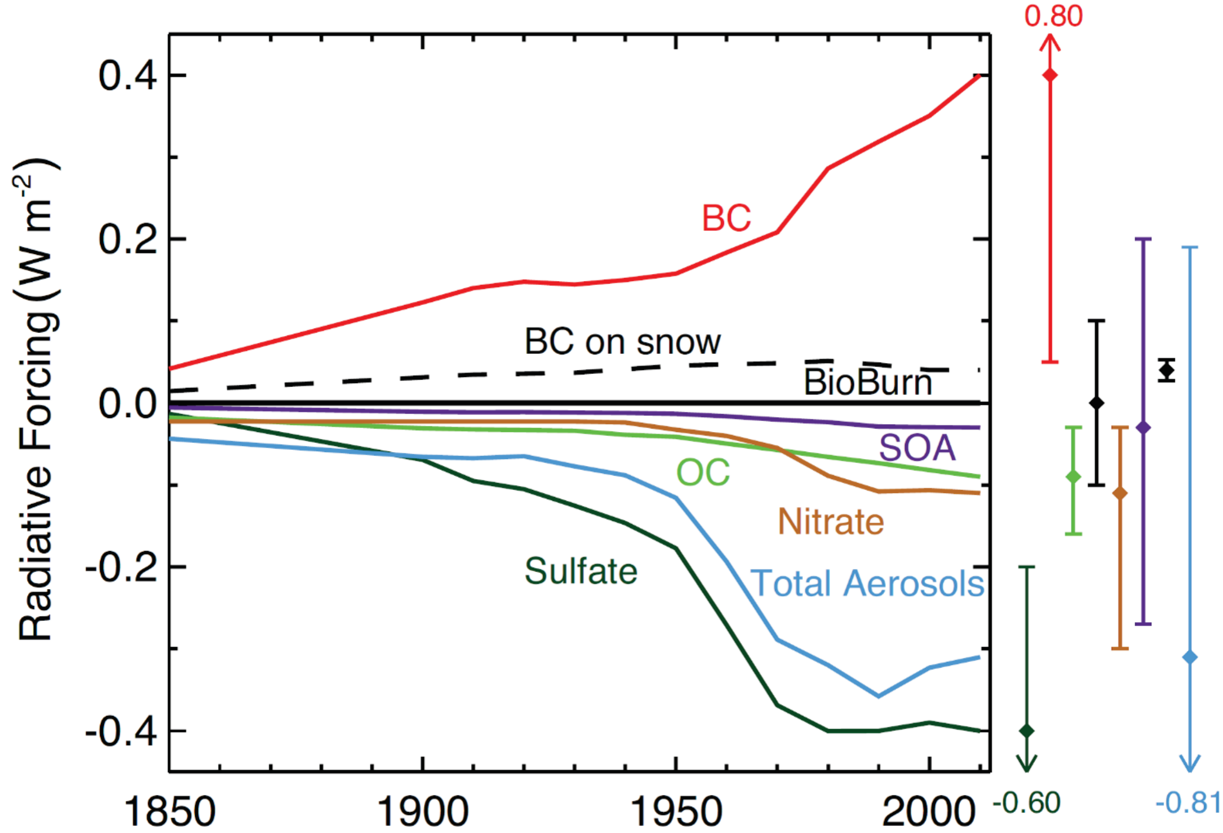


Figure 8.8 | Time evolution of RF due to aerosol–radiation interaction and BC on snow and ice.

Fig 8.8, IPCC 2013: Only Direct RF of aerosols considered here

RF Due to Tropospheric Aerosols: Indirect Effect

Indirect Effects of Aerosols on Clouds

Anthropogenic aerosols lead to more cloud condensation nuclei (CCN)
Resulting cloud particles consist of smaller droplets, promoted by more sites (CCN) for cloud nucleation
The cloud that is formed is therefore brighter (reflects more sunlight) ⇨
Twomey effect, aka 1st Indirect Effect

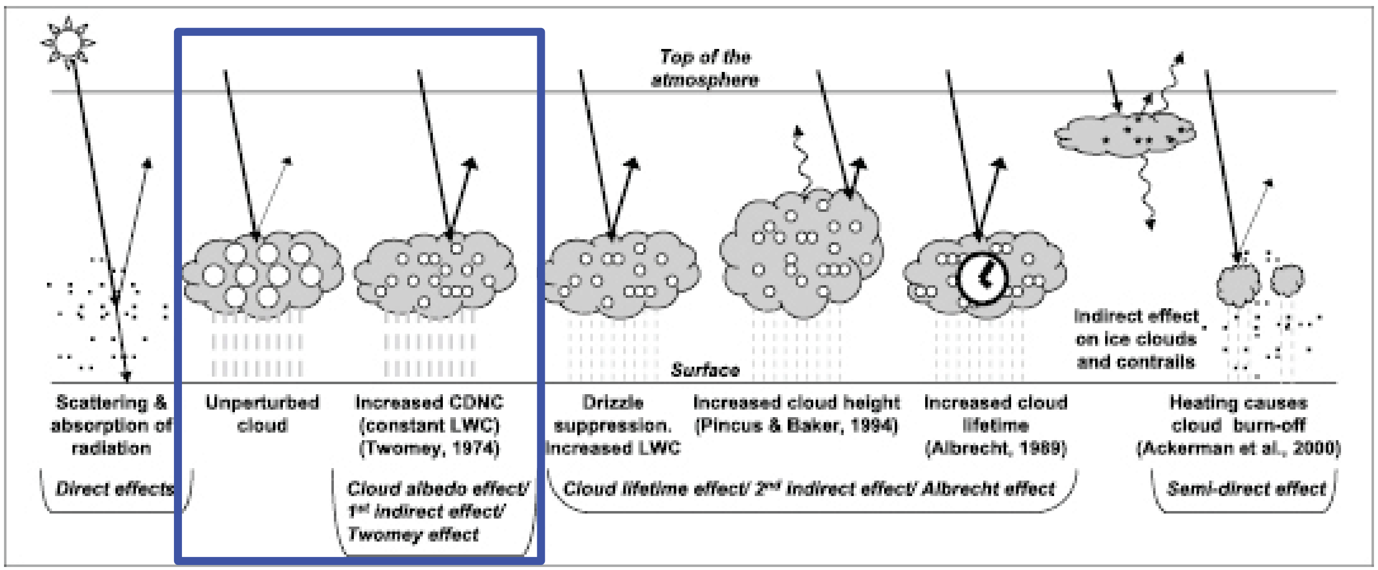


Fig 2-10, IPCC 2007

Large uncertainty in aerosol RF

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

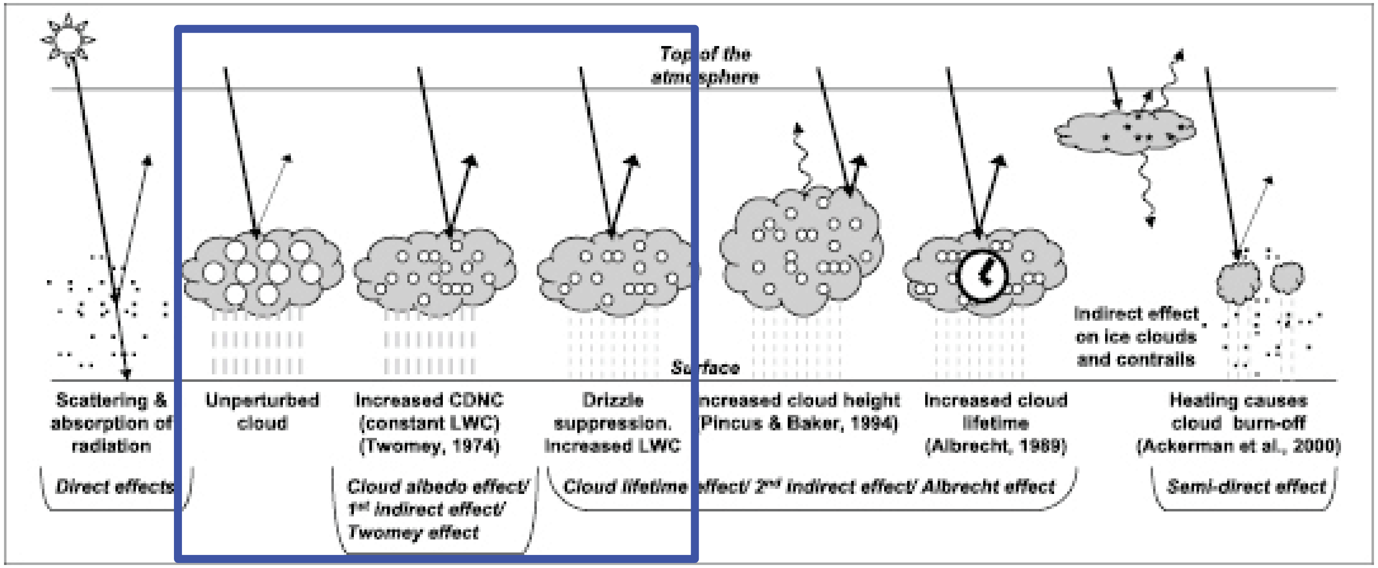
RF Due to Tropospheric Aerosols: Indirect Effect

Indirect Effects of Aerosols on Clouds

Anthropogenic aerosols lead to more cloud condensation nuclei (CCN)

Resulting cloud particles consist of smaller droplets, promoted by more sites (CCN) for cloud nucleation

The cloud that is formed is therefore brighter (reflects more sunlight) ***and*** has less efficient precipitation, i.e. is longer lived) ⇨ **Albrecht effect, aka 2nd Indirect Effect**

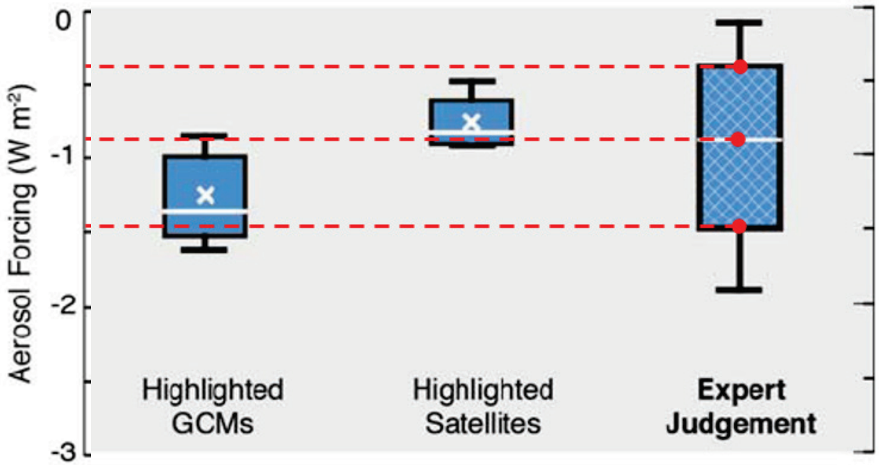


Large uncertainty in aerosol RF

Fig 2-10, IPCC 2007

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

Tropospheric Aerosol RF



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***

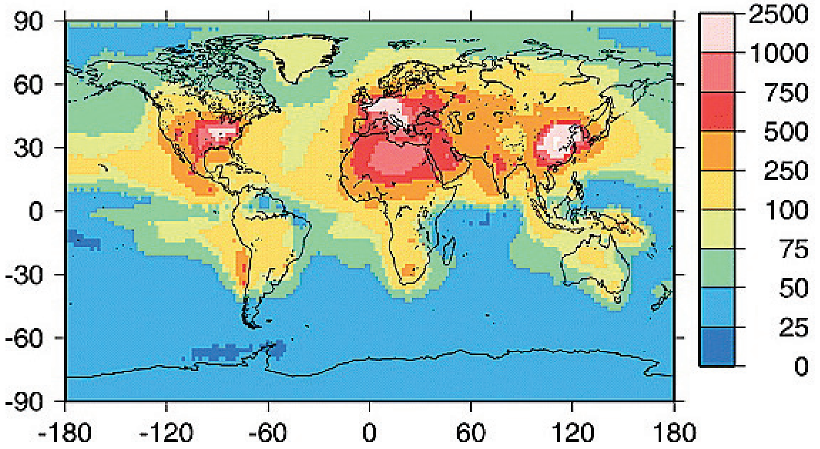
ΔRF_{2011} Aerosols: best estimate is –0.9 W m^{-2}, probably between –0.4 W m^{-2} and –1.5 W m^{-2} ;
could be between –0.1 W m^{-2} and –1.9 W m^{-2}

Large uncertainty in aerosol RF

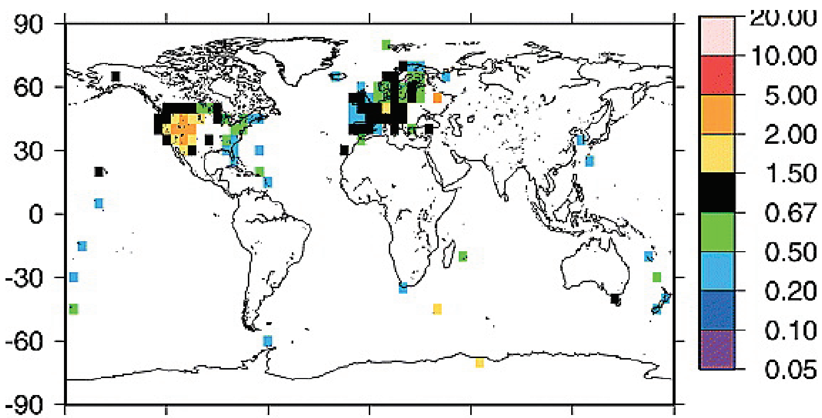
- scatter and absorb radiation (**direct radiative forcing**)
- affect cloud formation (**indirect radiative forcing**)

Tropospheric Sulfate Aerosols

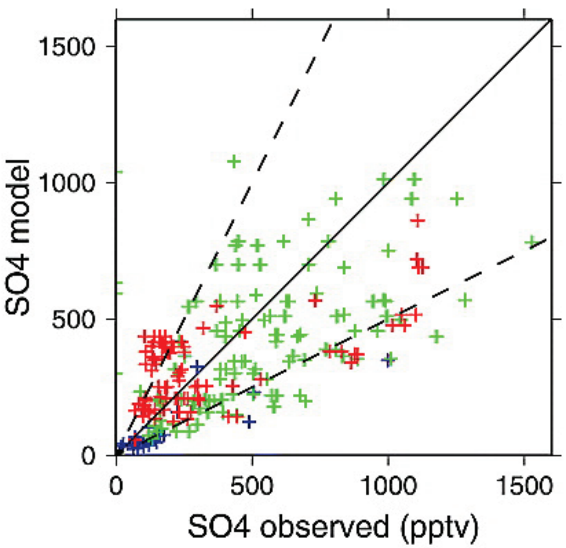
Modeled Sulfate (ppt)
Year 2000



Ratio of Modeled / Measured Sulfate



Modeled versus Measured Sulfate

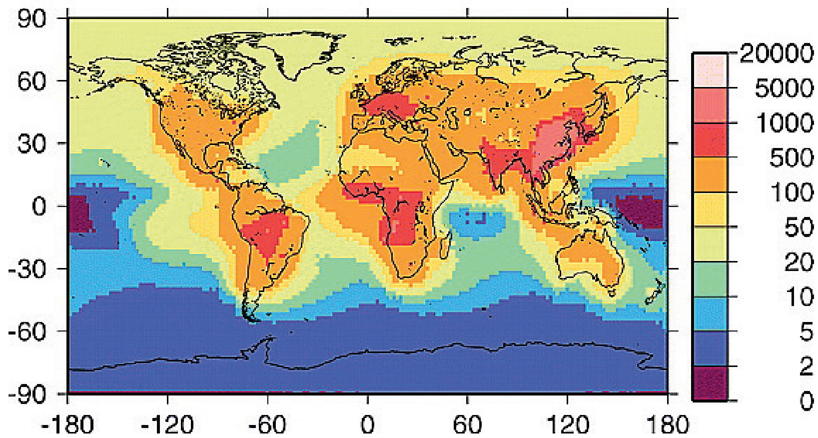


Remote sites (blue), Europe (green), & United States (red).

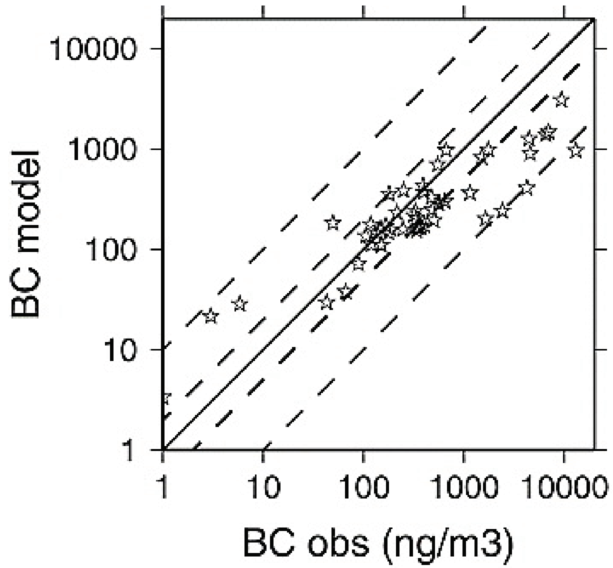
Koch *et al., JGR,* 2007
https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2005JD007024

Tropospheric Sulfate Aerosols

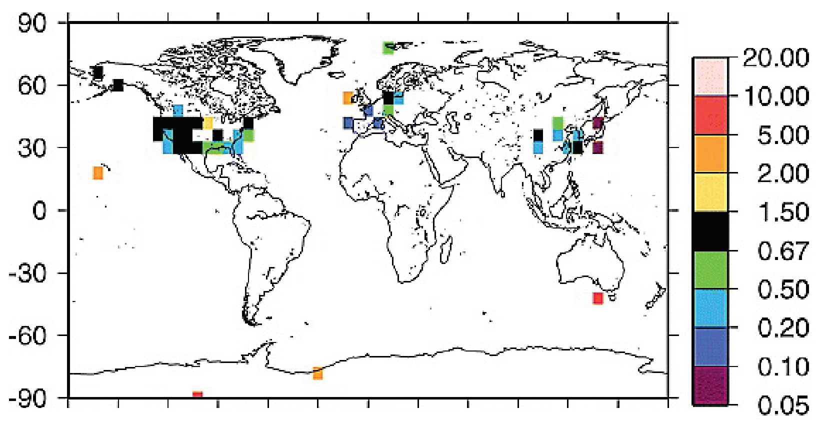
Modeled Black Carbon (ng m^{-3})
Year 2000



Modeled versus Measured Black Carbon



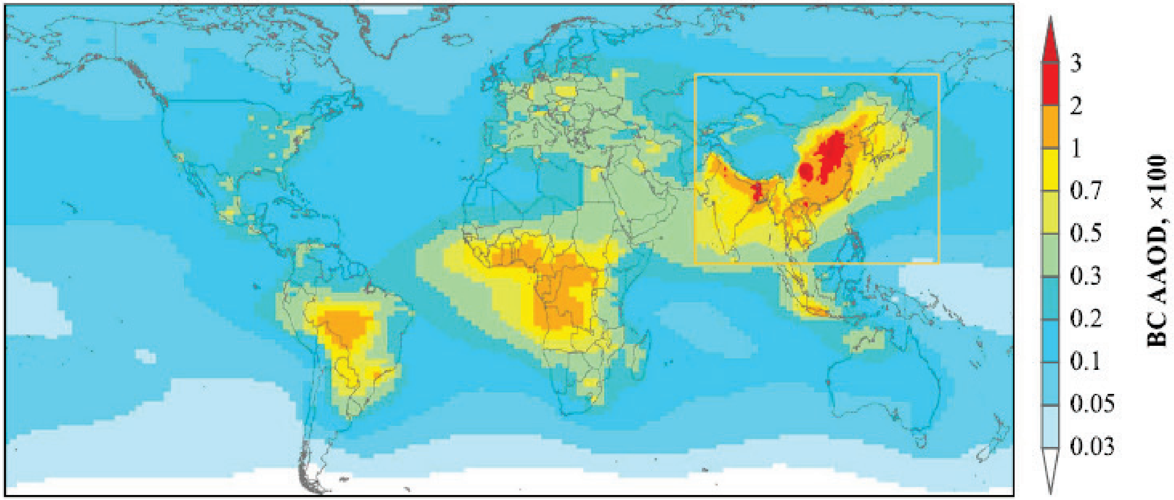
Ratio of Modeled / Measured Black Carbon

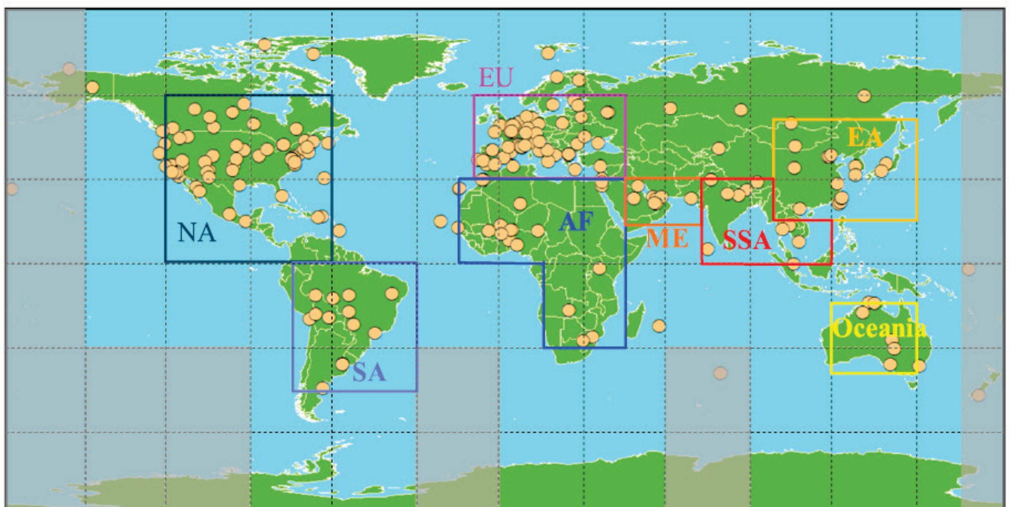


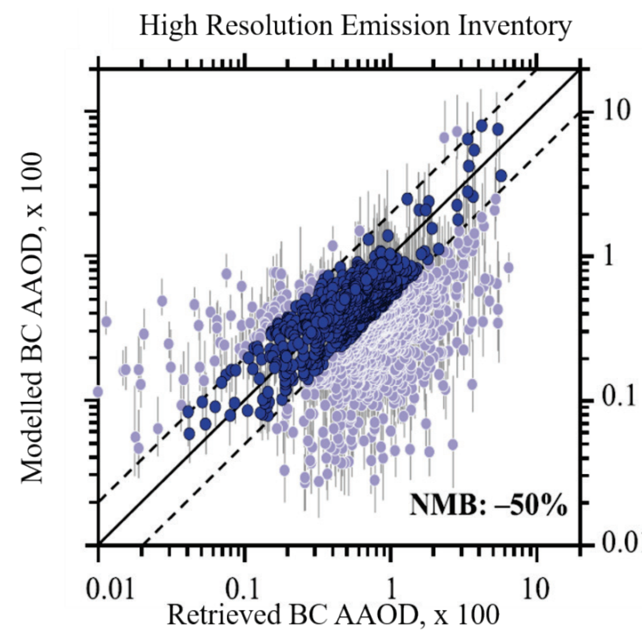
Koch *et al.*, *JGR*, 2007
https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2005JD007024

Black Carbon Aerosols

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







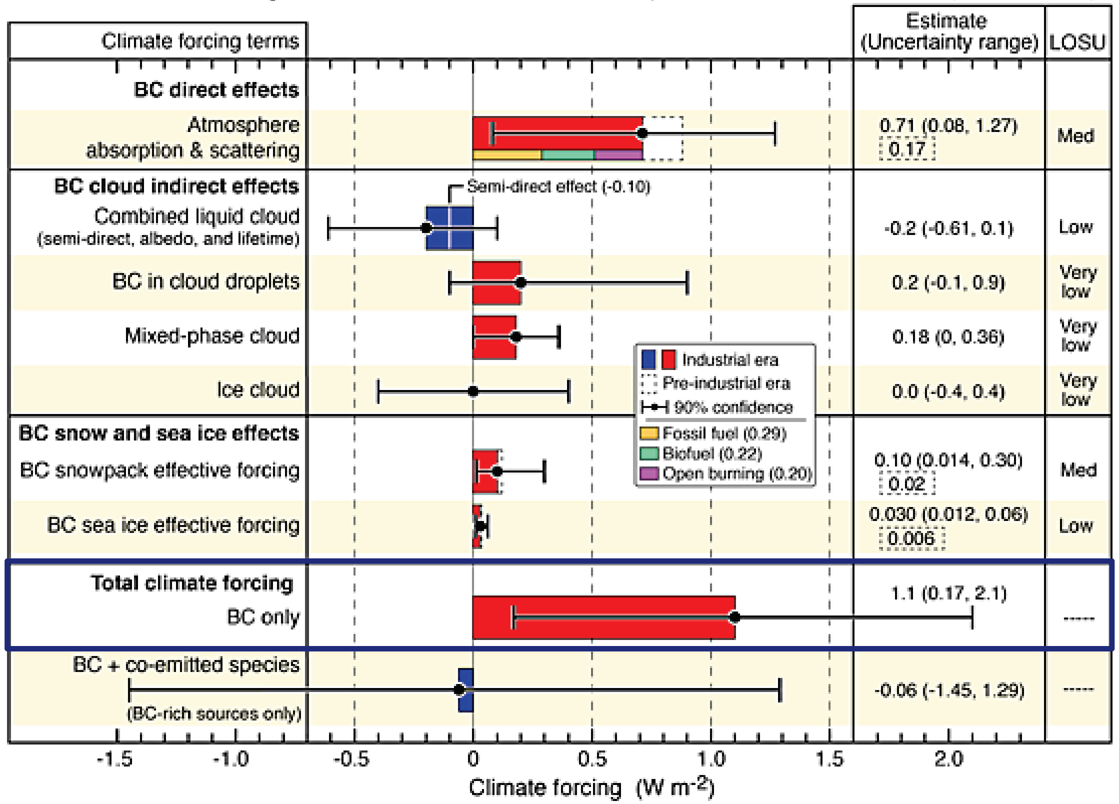
Wang et al., *JGR,* 2016

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

Black Carbon Aerosols

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

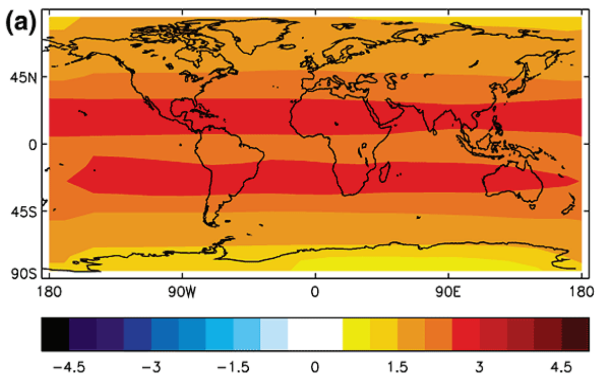
Global climate forcing of black carbon and co-emitted species in the industrial era (1750 - 2005)



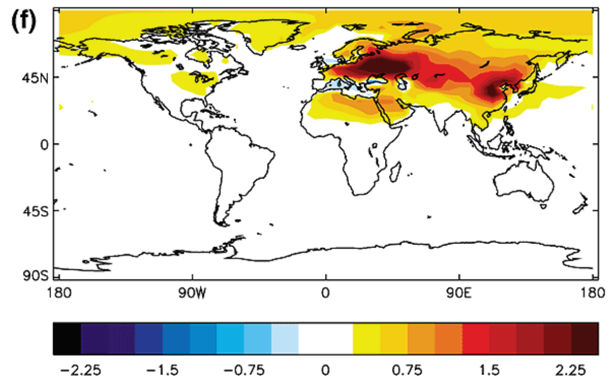
	Total Climate Forcing, Black Carbon Aerosols (W m^{-2})			
Report	IPCC (1995)	IPCC (2001)	IPCC (2007)	**IPCC (2013)**
ΔRF, BC	0.1 (0.03 to 0.3)	0.2 (0.1 to 0.4)	0.2 (0.05 to 0.35)	**0.4 (0.05 to 0.80)**

Global View

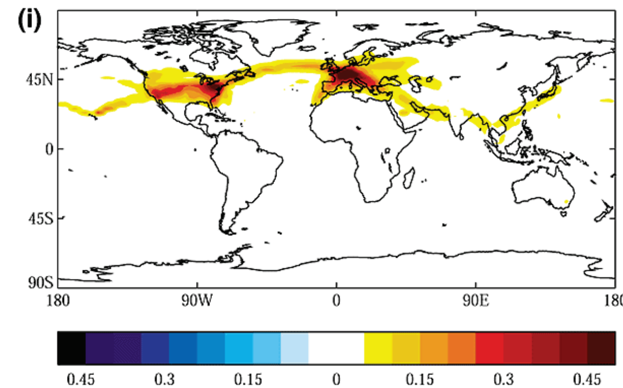
All forcings (1750-2000) are in Wm^{-2}

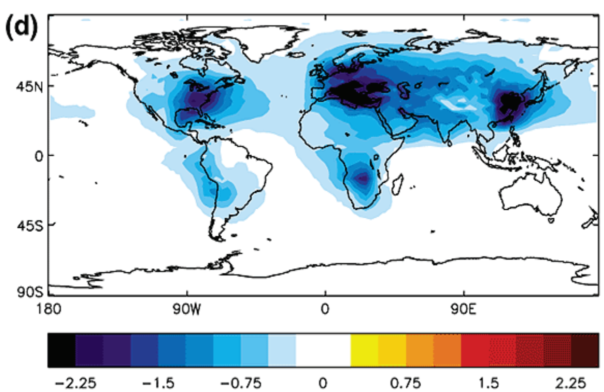


Greenhouse gases

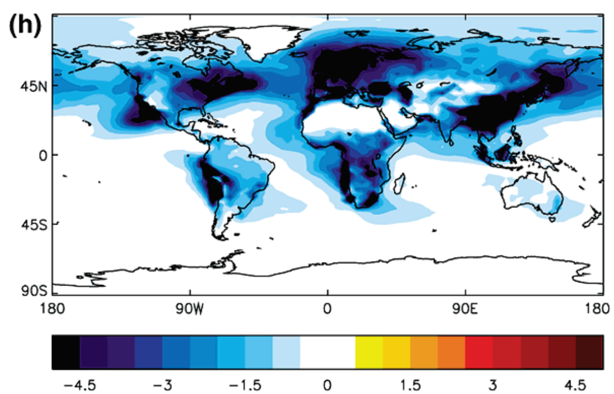


Organic and black carbon from fossil fuel burning

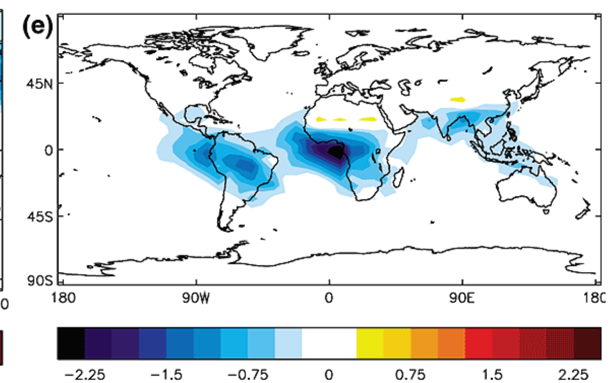




Direct effect from sulphate aerosols



Indirect effect from sulphate aerosols

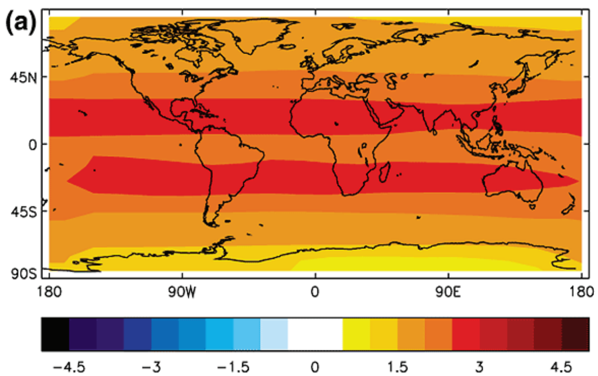


Organic and black carbon from biomass burning

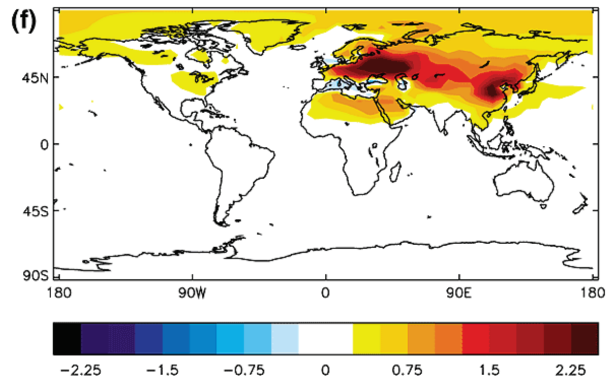
https://www.ipcc.ch/report/ar3/wg1/chapter-6-radiative-forcing-of-climate-change/

Global View

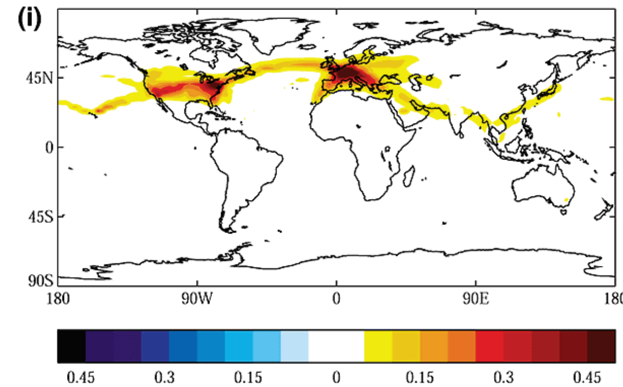
All forcings (1750-2000) are in Wm^{-2}



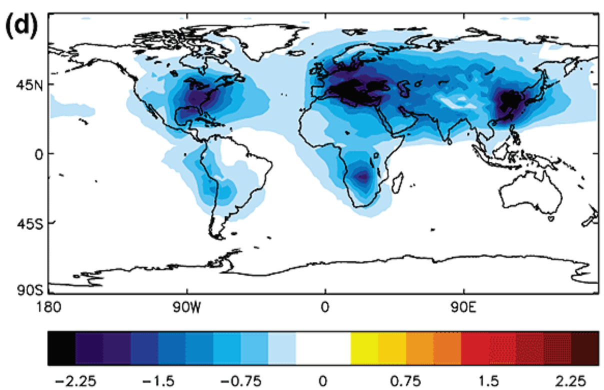
Greenhouse gases



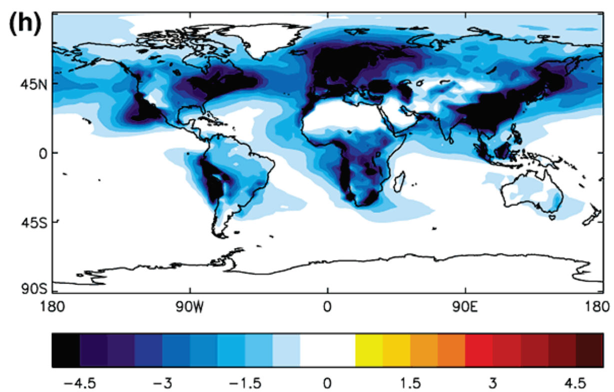
Organic and black carbon from fossil fuel burning



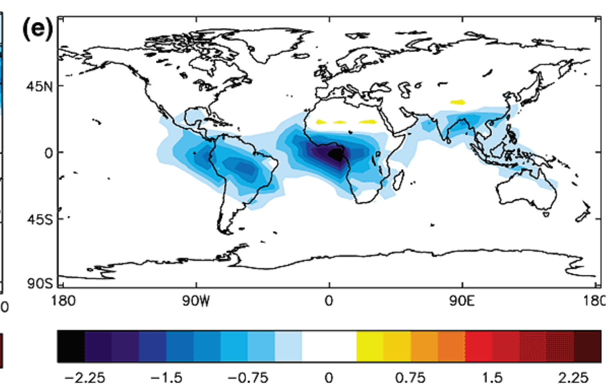
Aircraft contrails



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/

Combining RF GHGs & Aerosols

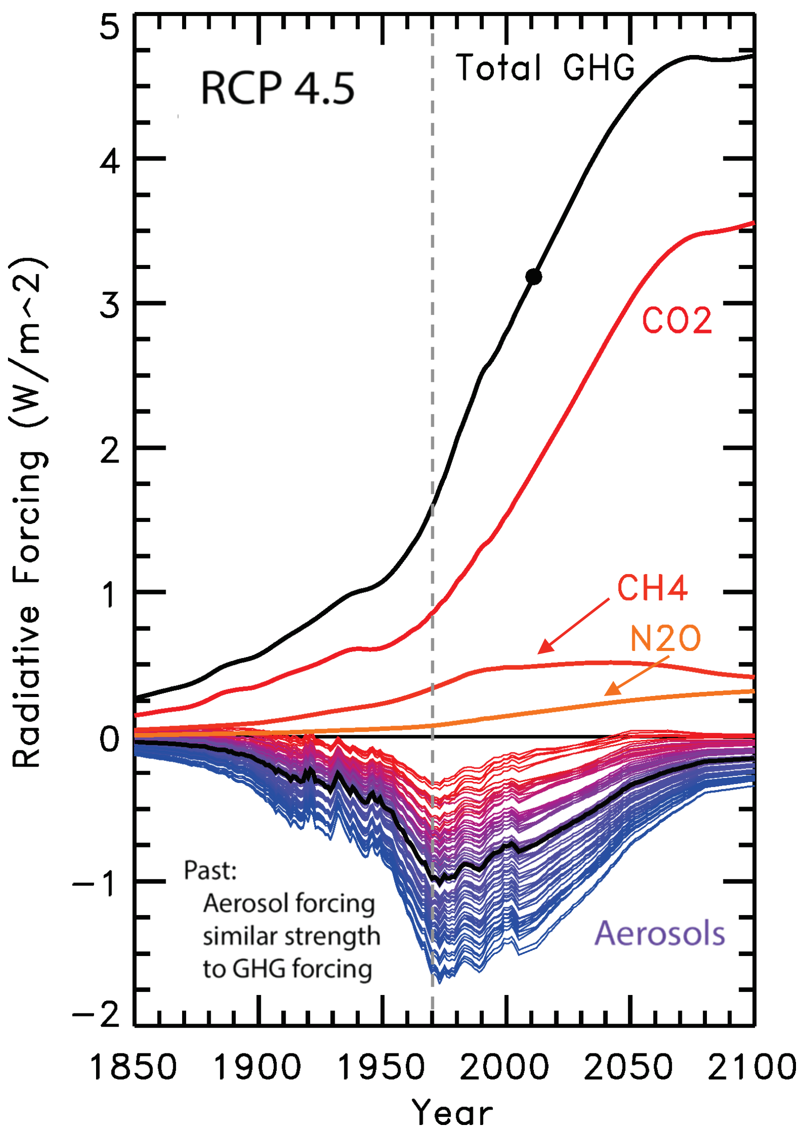


Fig 1.10, *Paris, Beacon of Hope*

Combining RF GHGs & Aerosols

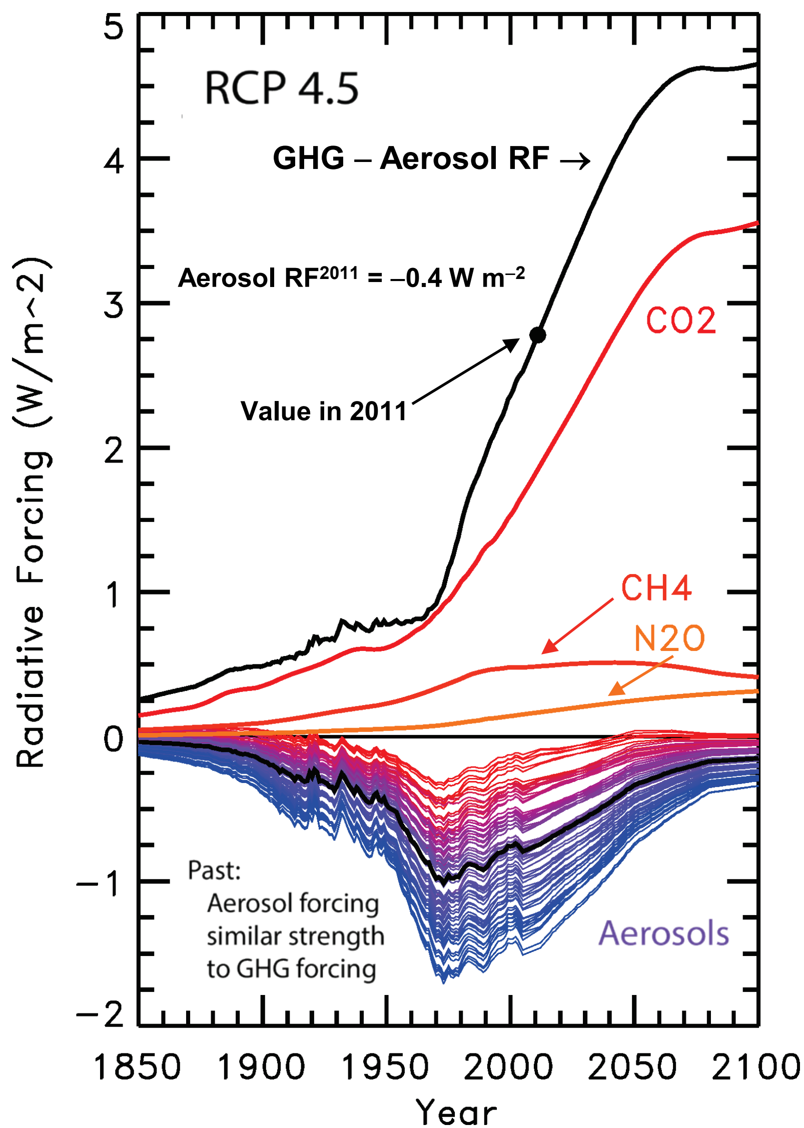


Fig 1.10, *Paris, Beacon of Hope*

Combining RF GHGs & Aerosols

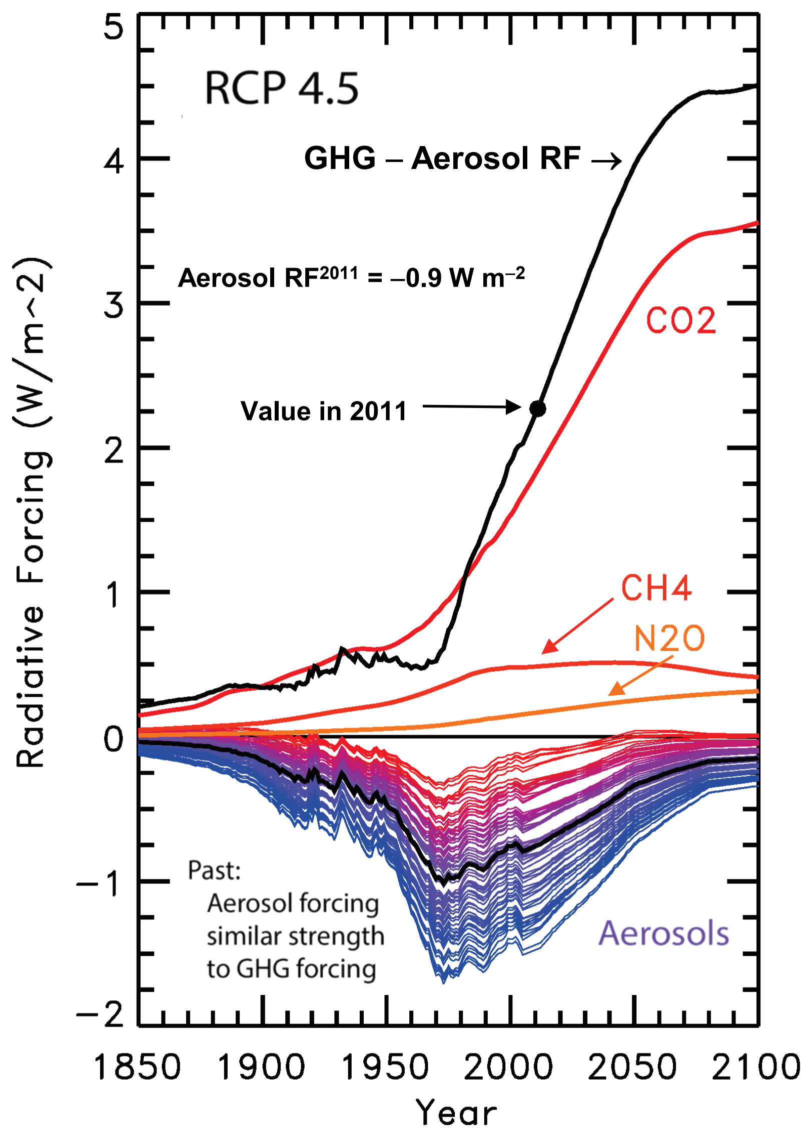


Fig 1.10, *Paris, Beacon of Hope*

Combining RF GHGs & Aerosols

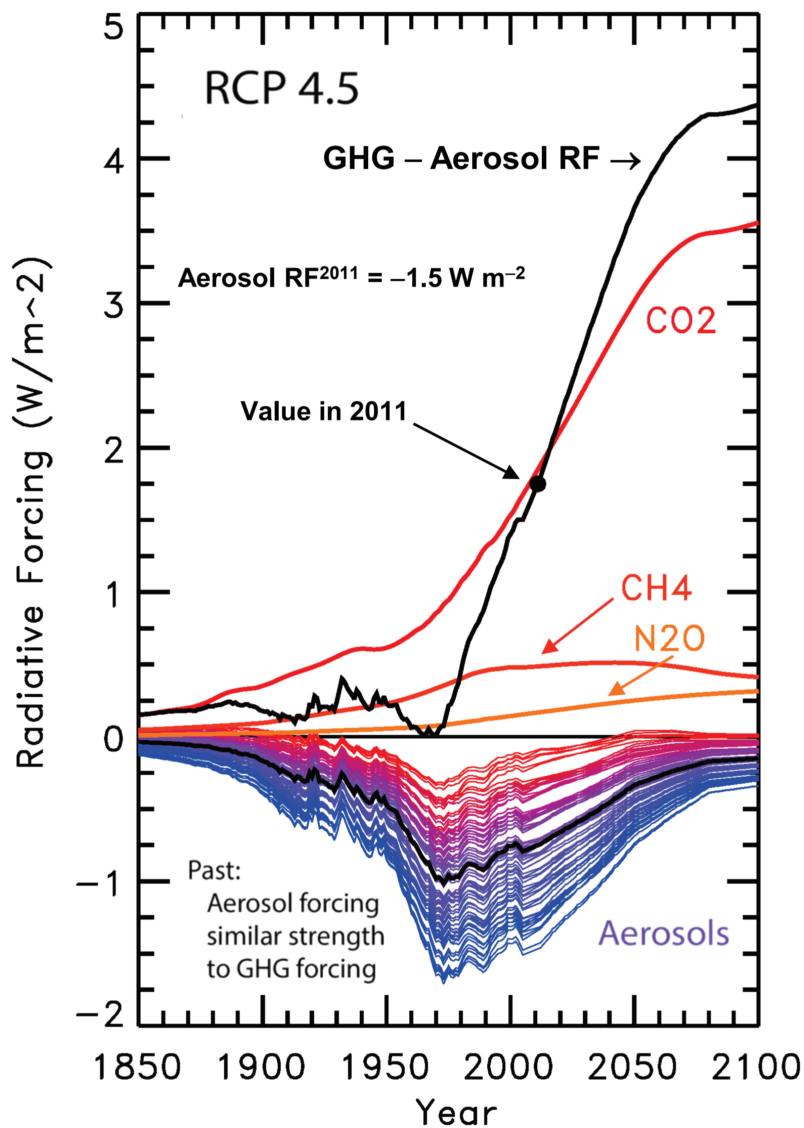
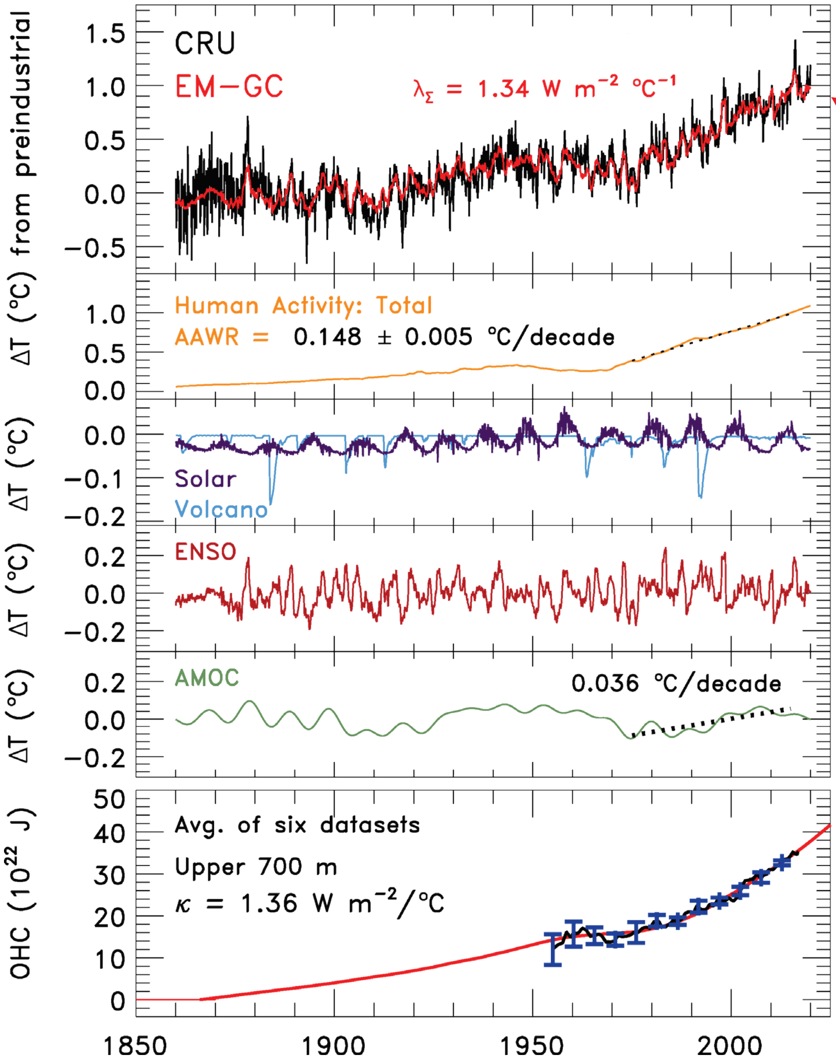


Fig 1.10, *Paris, Beacon of Hope*

Univ of Md Empirical Model of Global Climate



AAWR: Attributable Anthropogenic Warming Rate

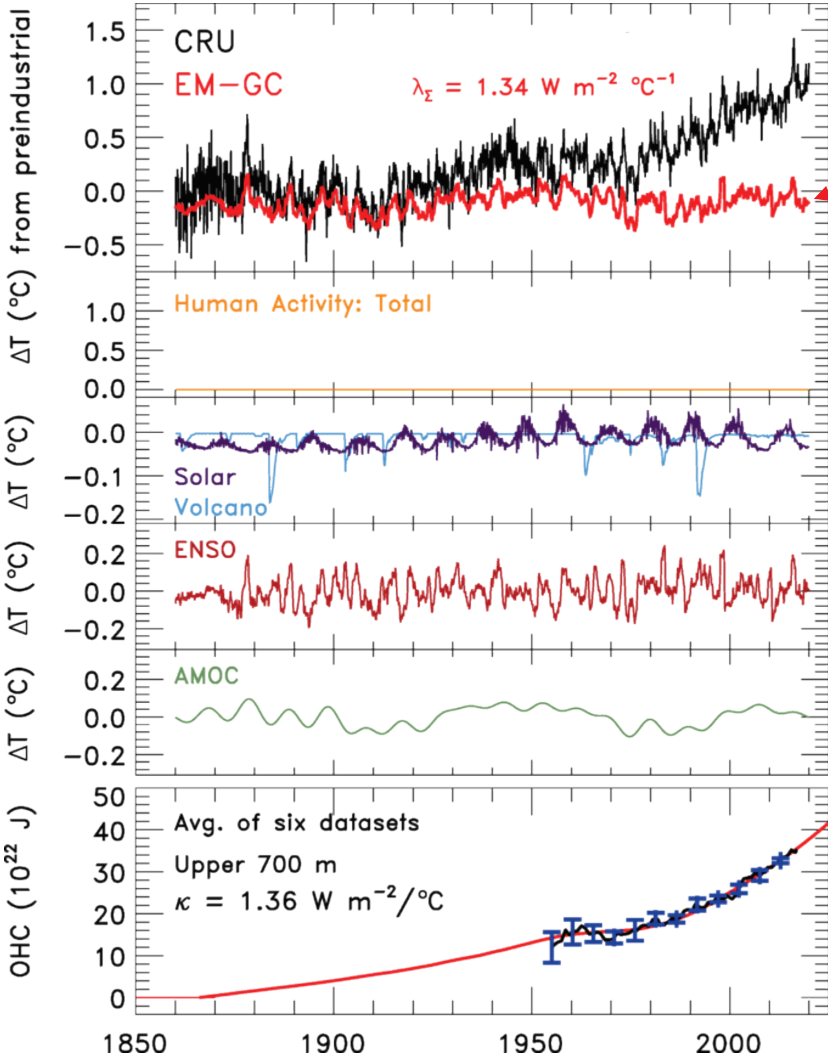
$$\Delta T_{MDL\ i} = (1+\gamma)\left(\frac{GHG\ RF_i + LUC\ RF_i + Aerosol\ RF_i}{\lambda_p}\right) + C_0 + C_1 \times SOD_{i-6} + C_2 \times TSI_{i-1} + C_3 \times ENSO_{i-2} + C_4 \times AMOC_i - \left(\frac{Q_{OCEAN_i}}{\lambda_p}\right)$$

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

Canty *et al*., ACP, 2013; Hope *et al*., Springer Climate, 2017, Hope *et al*., manuscript in preparation, 2020; McBride *et al*., manuscript in preparation, 2020.

Univ of Md Empirical Model of Global Climate



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

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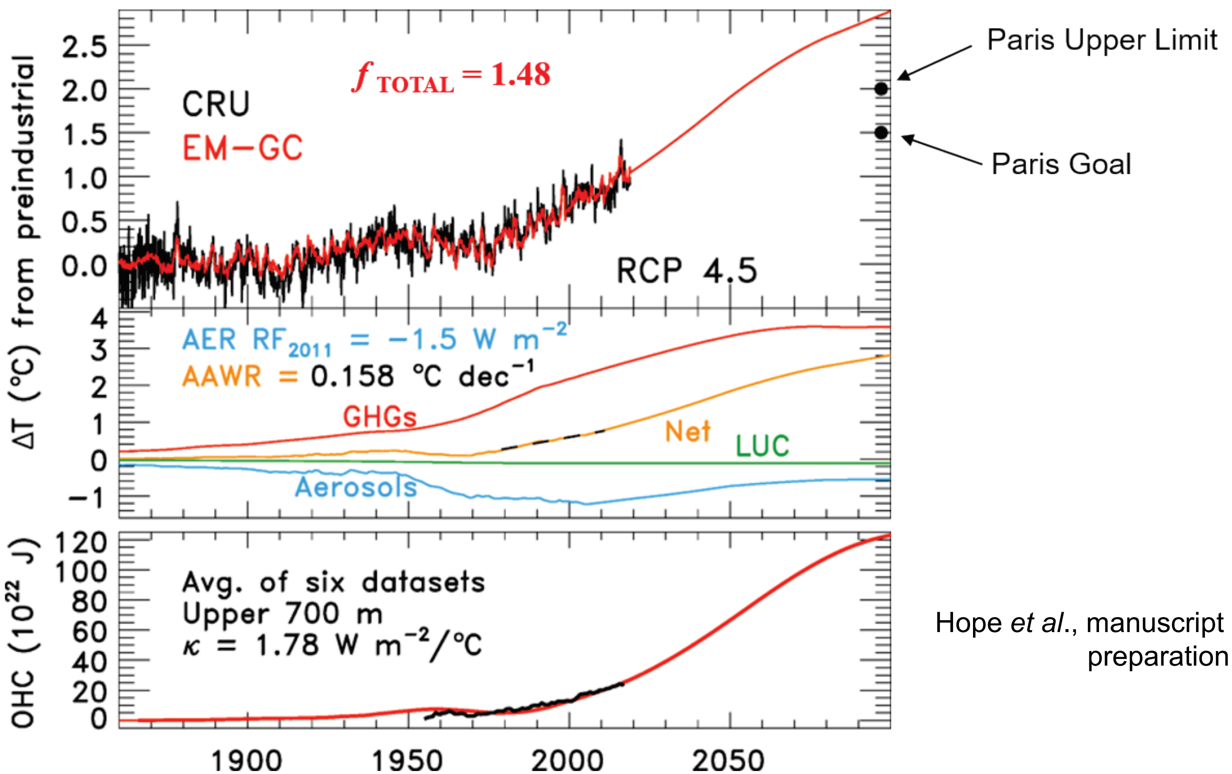
Canty *et al*., ACP, 2013; Hope *et al*., Springer Climate, 2017, Hope *et al*., manuscript in preparation, 2020; McBride *et al*., manuscript in preparation, 2020.

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*., manuscript in preparation, 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***.

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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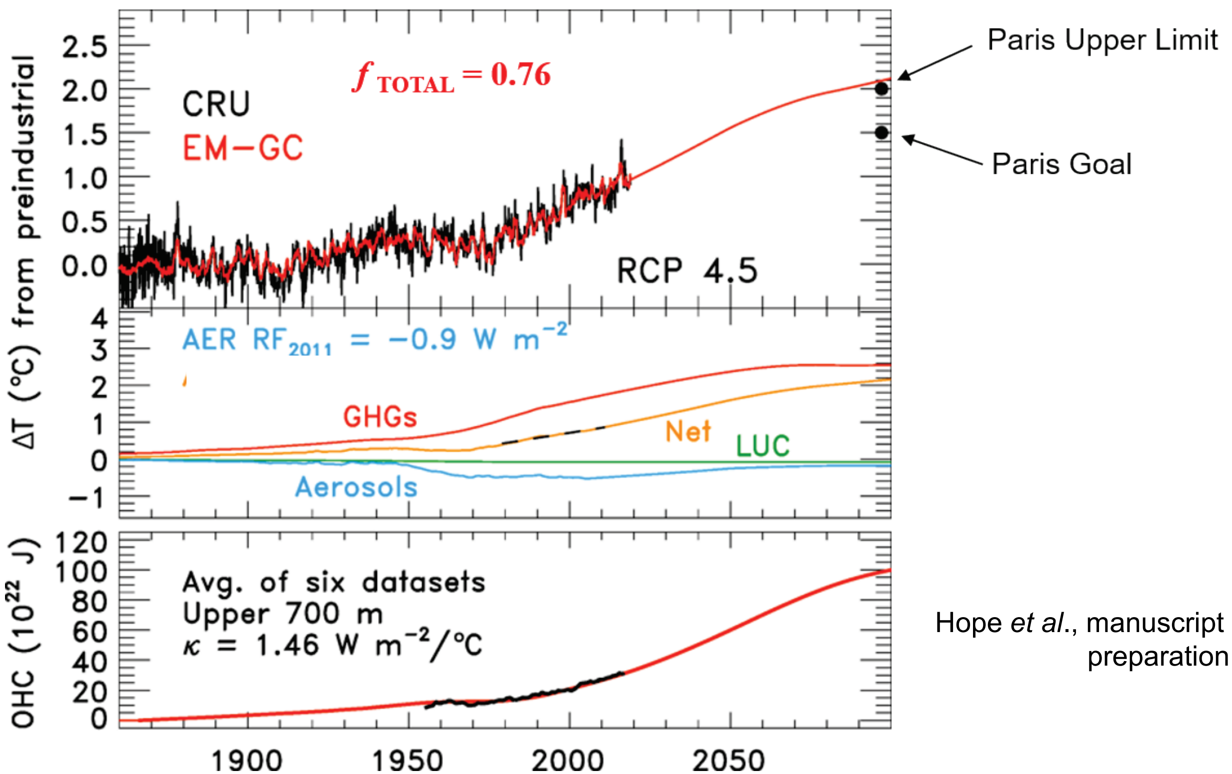


Hope *et al*., manuscript in preparation, 2020.

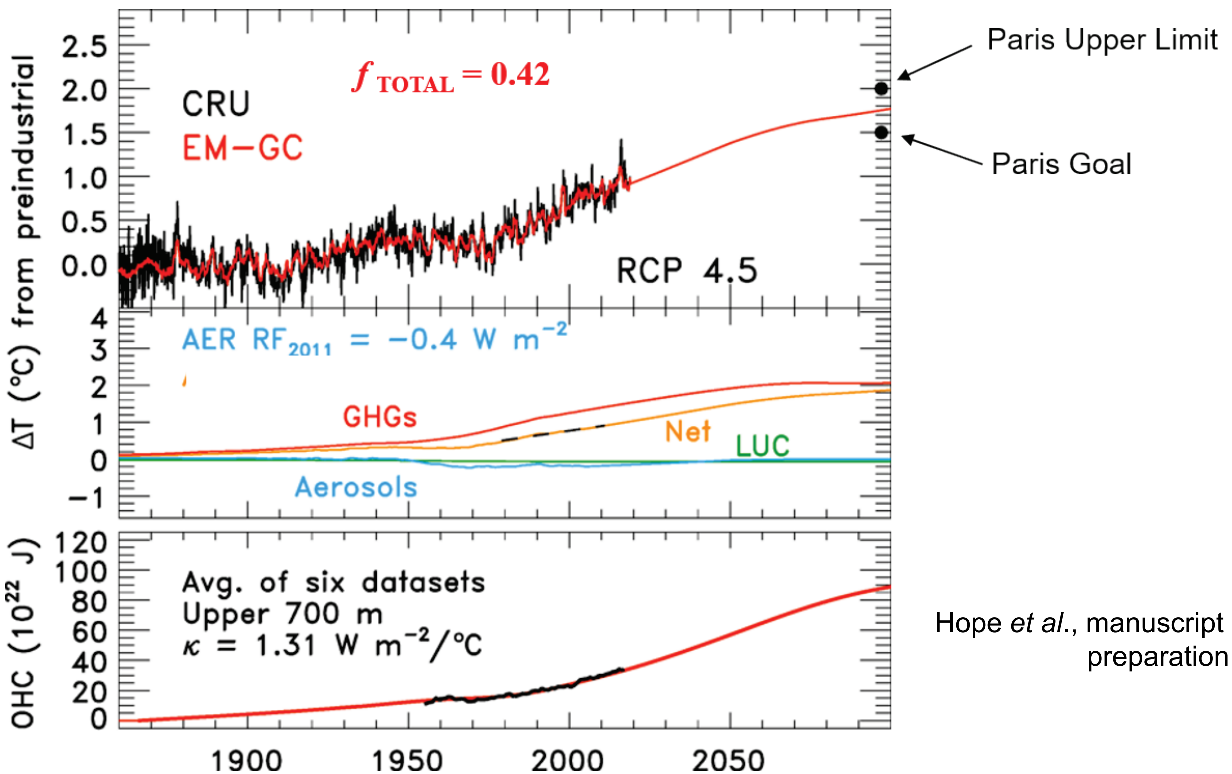
We assume that whatever value of climate feedback is inferred from the climate record will persist into the future. For Aerosol RF in 2011 of **-0.9 W m^{-2}** & assuming best estimate for H_2O and Lapse Rate feedback is correct, this simulation implies sum of <u>other feedbacks</u> (clouds, surface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

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



Hope *et al.*, manuscript in preparation, 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***.