Radiative forcing by anthropogenic constituents

Susan Solomon
MIT/EAPS 54-1720
solos@mit.edu

What did you find most surprising about the assigned readings?

What do you think are the things that are most confusing about radiative forcing for the public? For scientists?

Earth, Atmospheric and Planetary Sciences

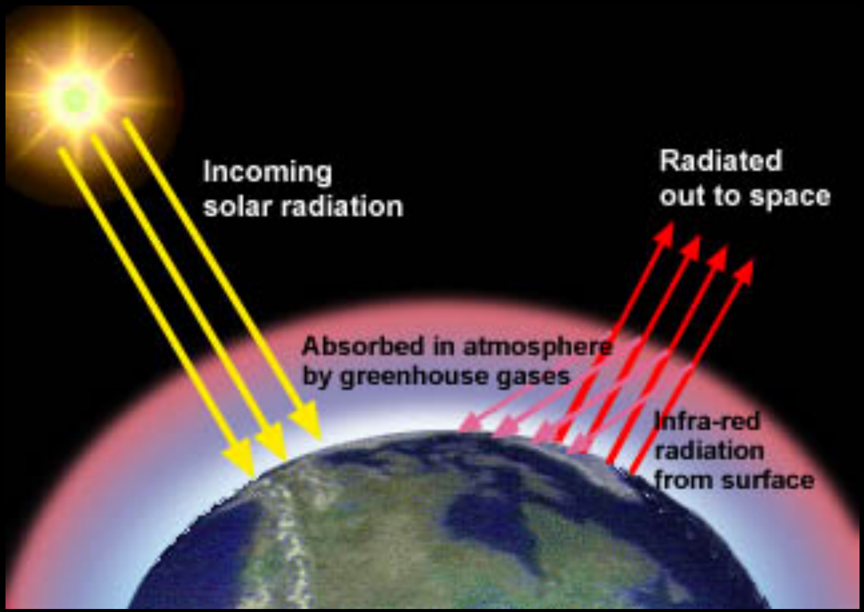
Today:

Fundamentals and definitions: radiation, the planets, RF

A stroll through key parts of the IPCC radiative forcing diagram

A few words on ‘adjusted forcing’

Comparing carbon dioxide to other RF agents



Like the sun, the Earth also emits radiation. It is much cooler than the sun, though, so it emits in the infrared, just like a person, a cat, or any other body. Some of that infrared energy may be absorbed by molecules in the atmosphere, affecting the global energy balance.

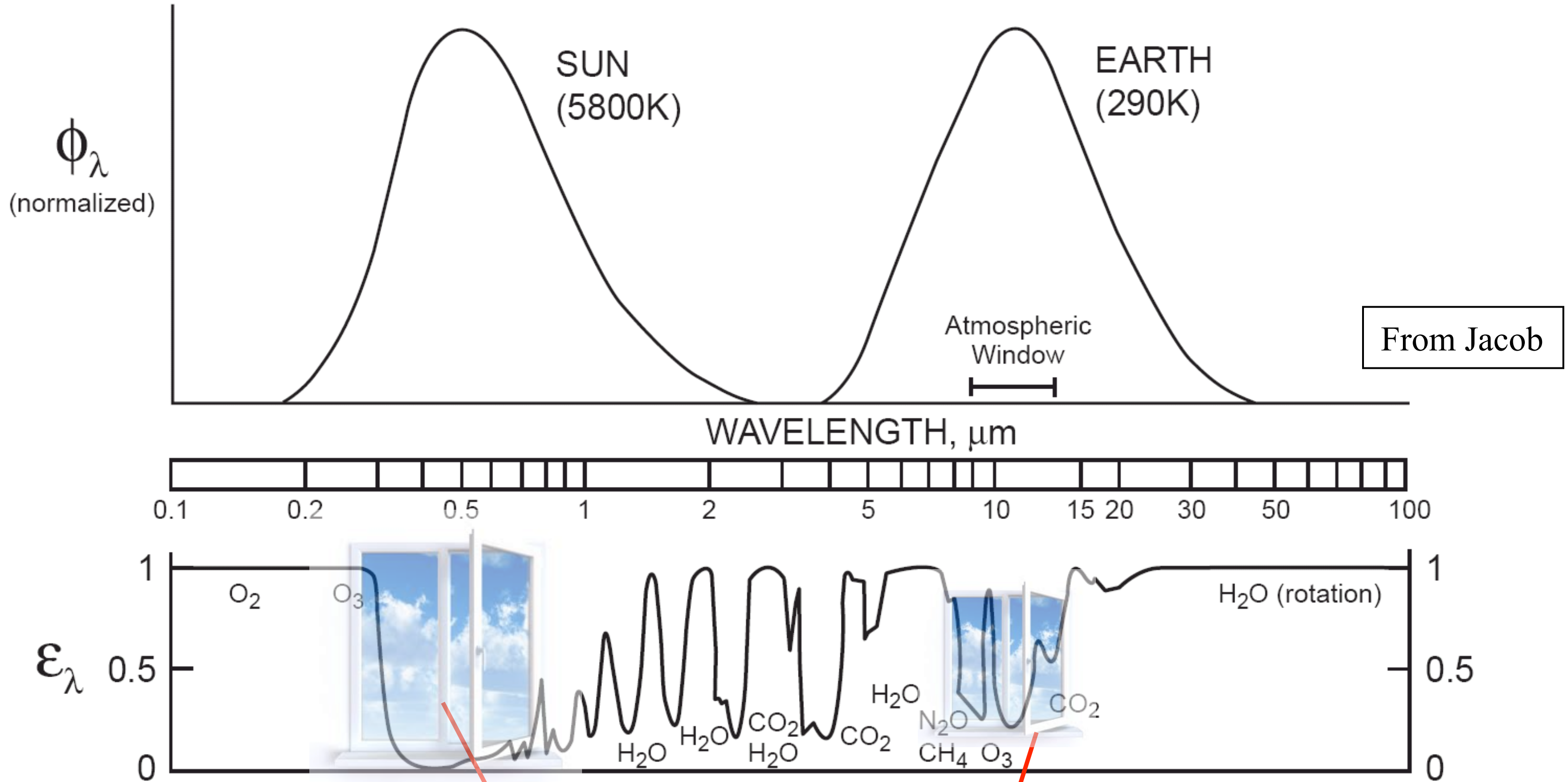


Figure 7-11 Efficiency of absorption of radiation by the atmosphere as a function of wavelength. Major absorbers are identified.

- Transparent in visible and atmospheric window
- Also e.g. @ 4 μm, no light there so we don't care!

Potential Greenhouse Gases

- Four factors for a greenhouse gas to be important:
  - Strong absorption cross section
  - Large enough concentration
- H_2O 60%, CO_2 26%, O_3 8%

In addition….human inputs

- Absorb in the atmospheric window, absorb strongly per pound even if not many pounds

- Have fairly long lifetimes

- Enhanced greenhouse effect:
  - N_2O, CH_4, O_3, CFCs, HCFCs, HFCs, SF_6

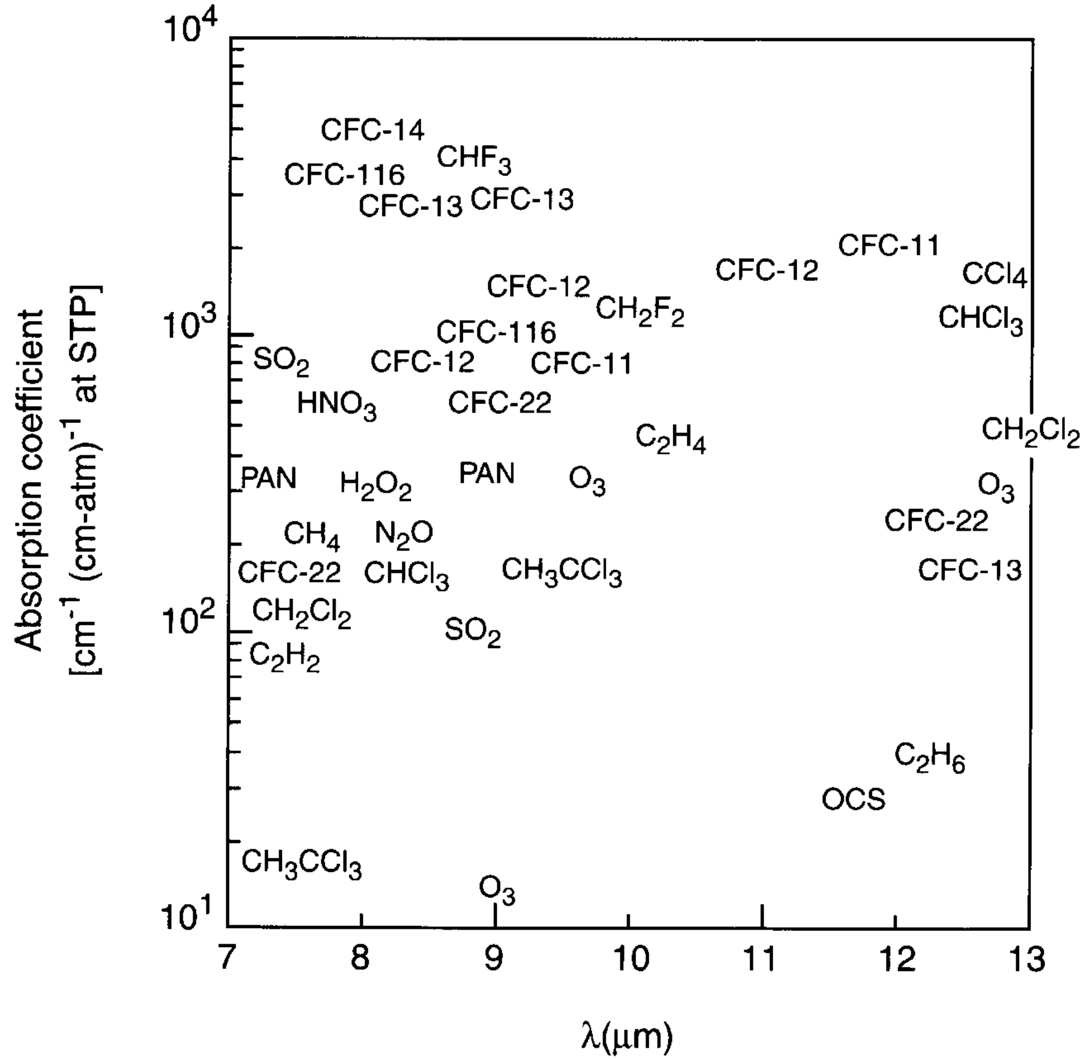
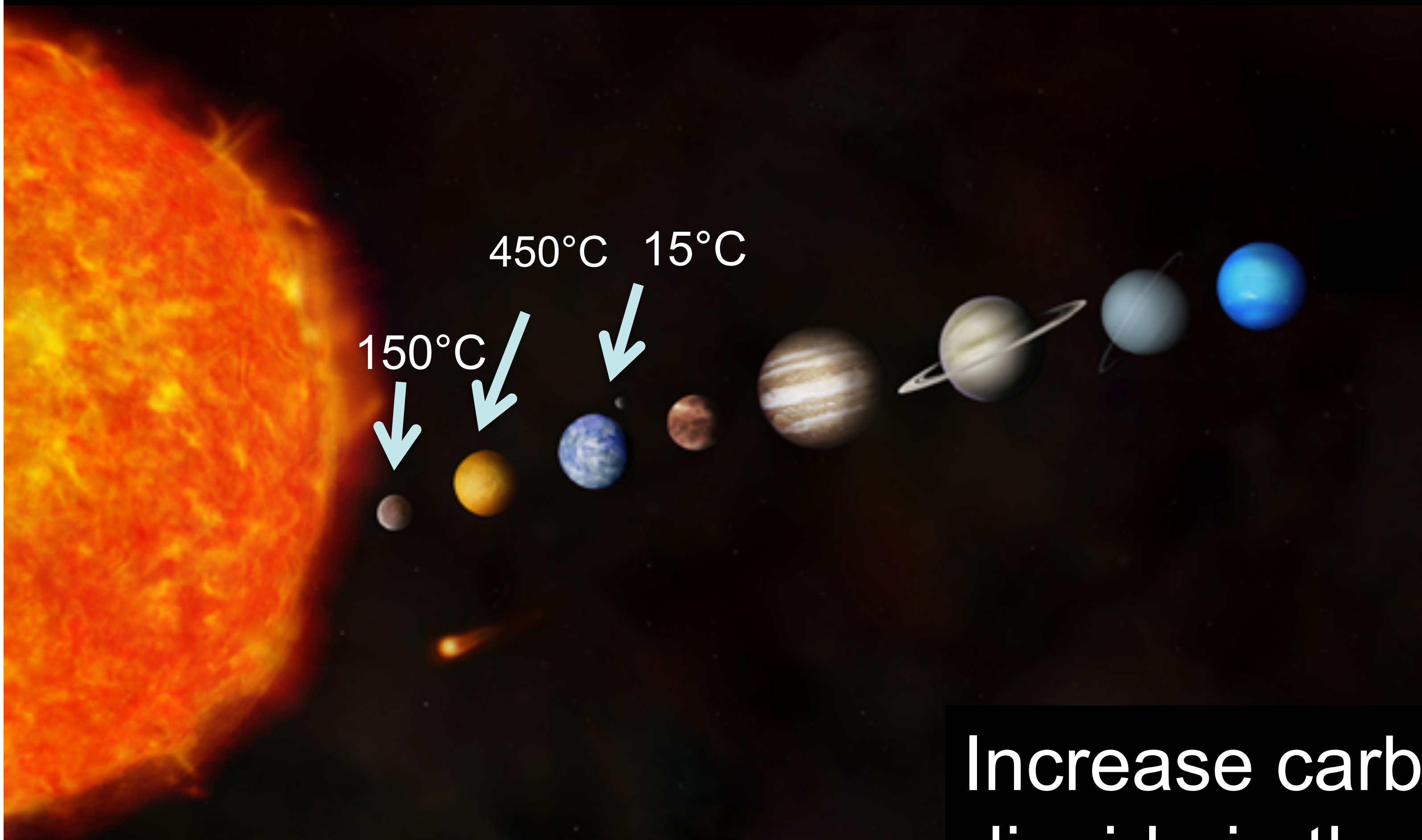


FIGURE 14.10 Intrinsic infrared absorption band strengths of some potential greenhouse gases in the atmospheric "window" (from Ramanathan, 1988a, 1988b).

From F-P&P

Do Greenhouse Gases Really Warm a Planet?

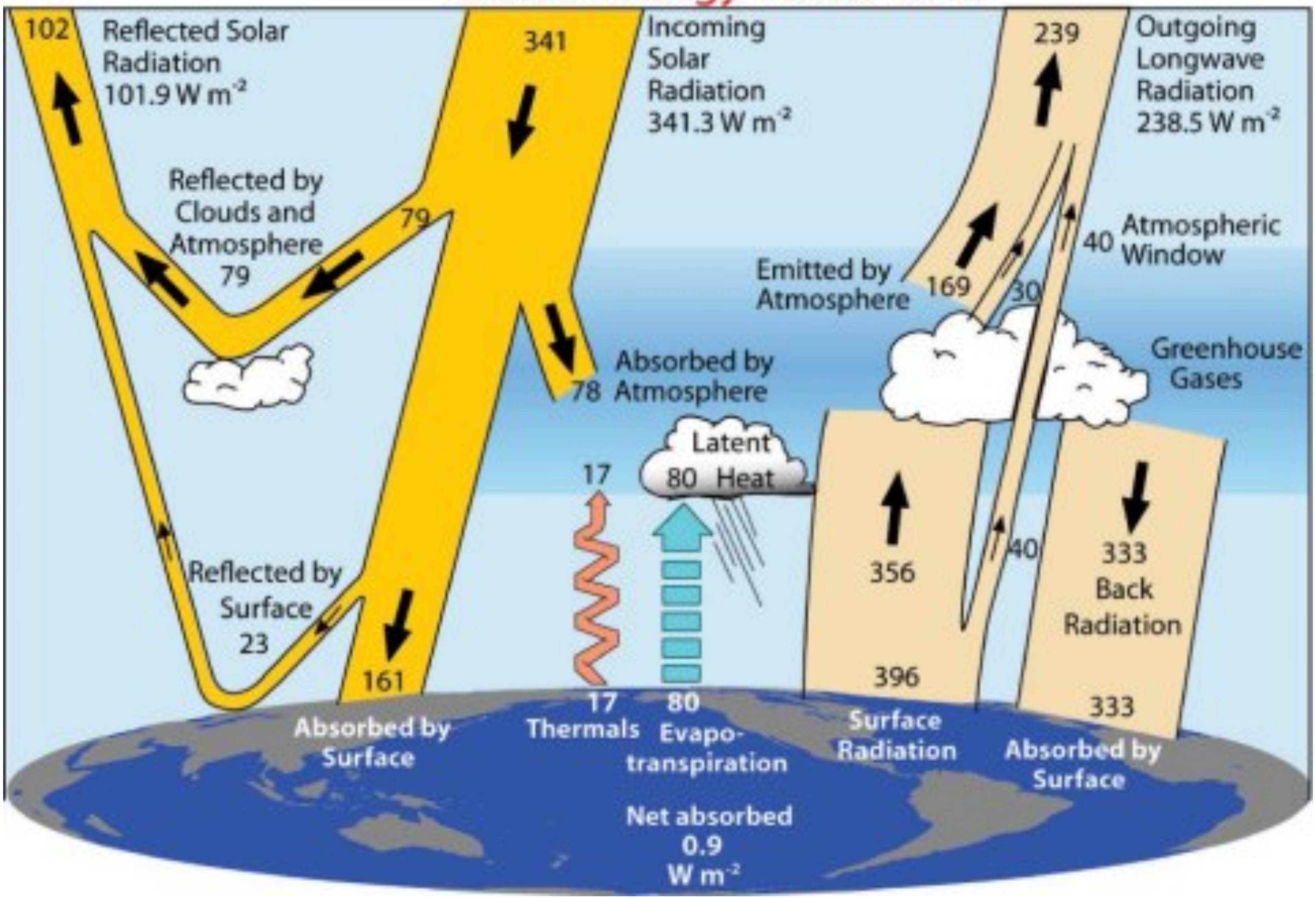


Venus atmosphere = mostly carbon dioxide and sulfuric acid

Earth atmosphere = mostly nitrogen and oxygen, a little bit of carbon dioxide

Increase carbon dioxide in the Earth's atmosphere?

Global Energy Flows W m^{-2}



Radiative Forcing (*F*)

- *F*: change in radiation @ tropopause due to increase in a greenhouse gas
  - Use the tropopause because surface + troposphere are tightly coupled by convection and mixing

- Climate change per unit RF?
  - Use average surface T as proxy for climate

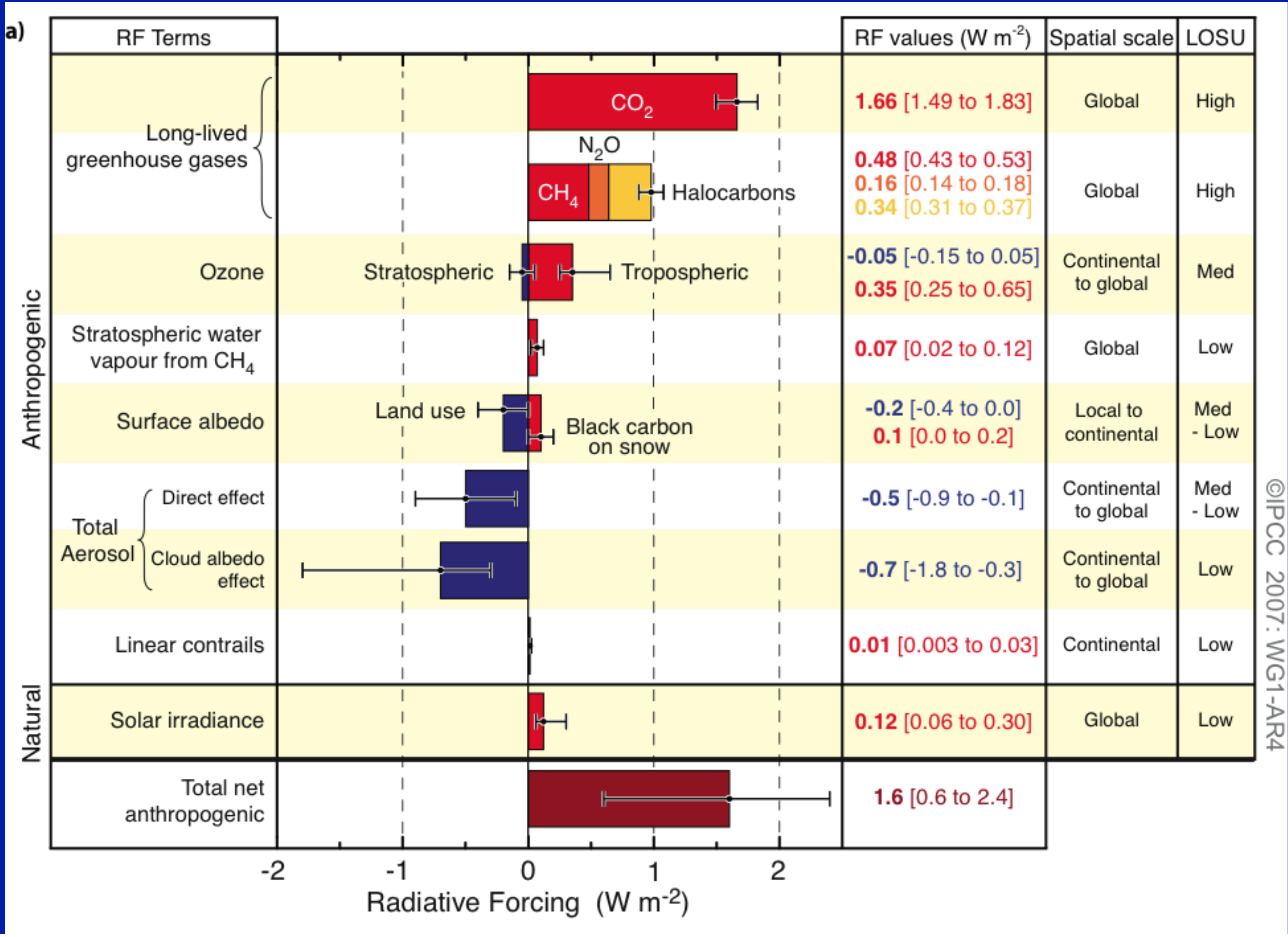
$$\boxed{\Delta T = \lambda F}$$

  - λ: *climate sensitivity*, K / (W/m^{-2});

  - also can be expressed as K for doubled CO2

Radiative forcing: change in energy balance

Used to compare different drivers of climate change

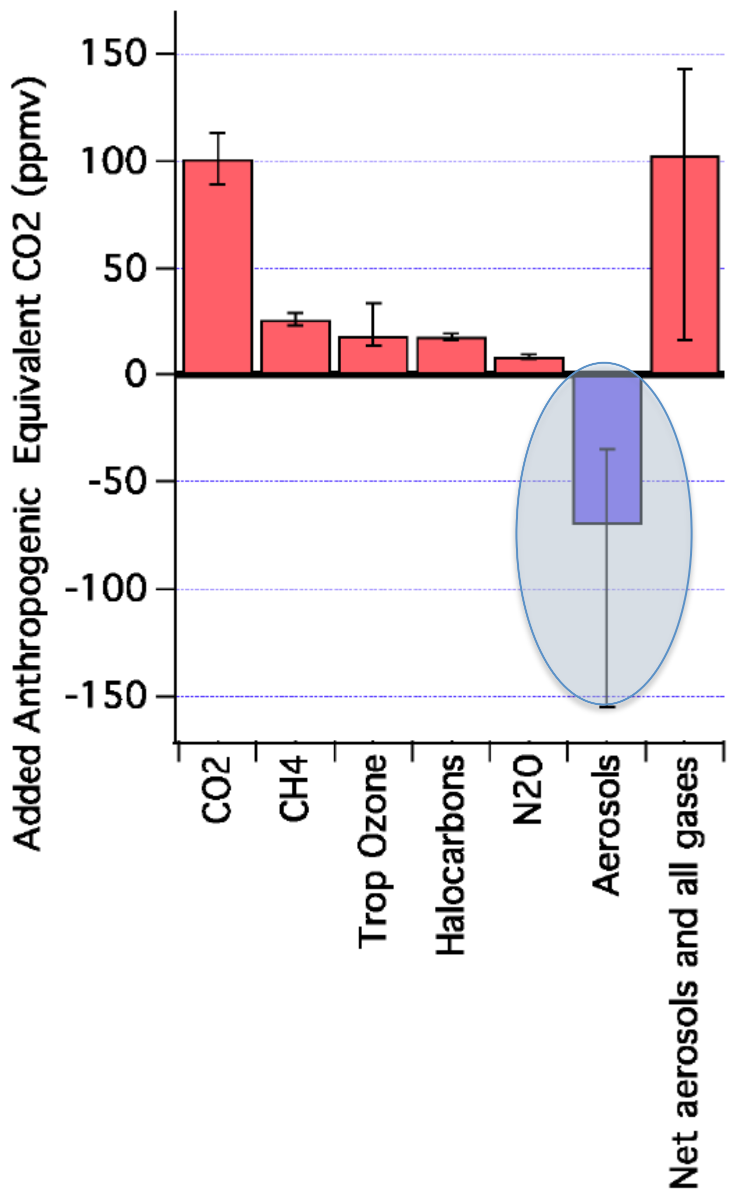


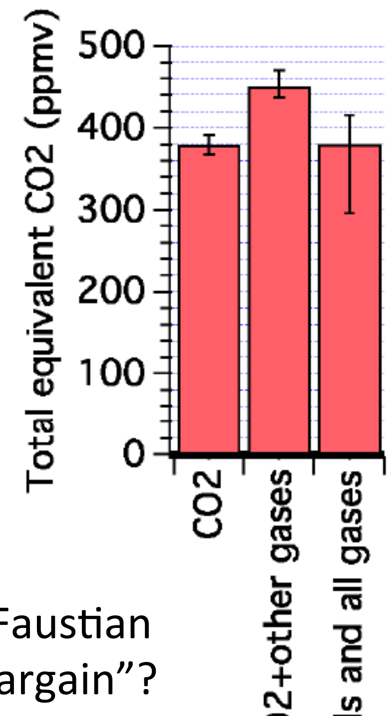
What equivalent carbon dioxide concentration would be represented by the various forcings?

The fraction due to manmade carbon dioxide is more than half now, and is expected to grow to >80% by 2100.

Best estimates of both CO2 and total CO2 equivalent concentrations happen to be ≈390 ppmv.

Organic aerosols?
Other uncertainties?





"Faustian Bargain"?

Many different long-lived greenhouse gases are known to be changing: carbon dioxide, methane, chlorofluorocarbons, and nitrous oxide.

….And more

Mauna Loa Observatory

CO_2 Atmospheric Increase: 1958 on

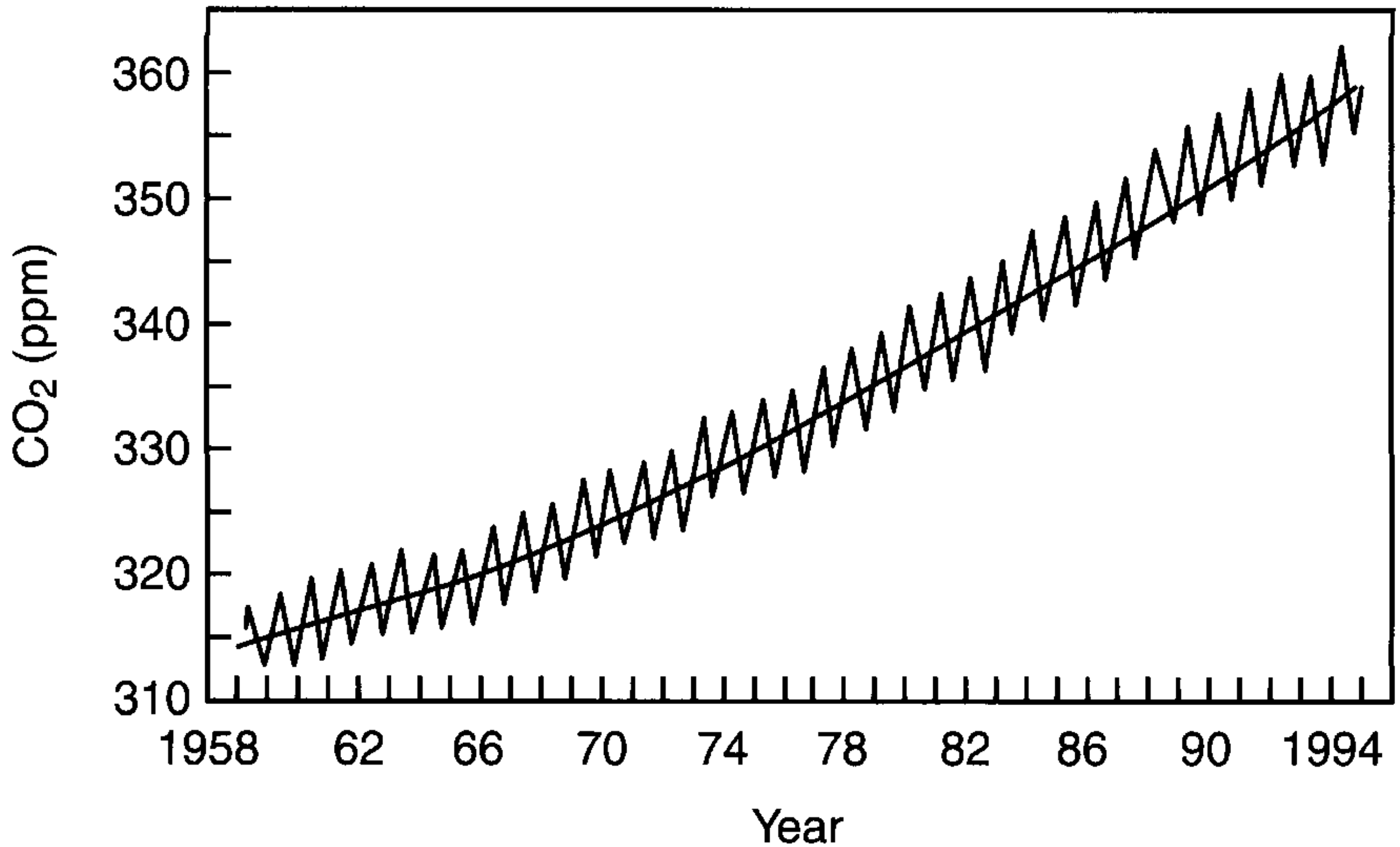
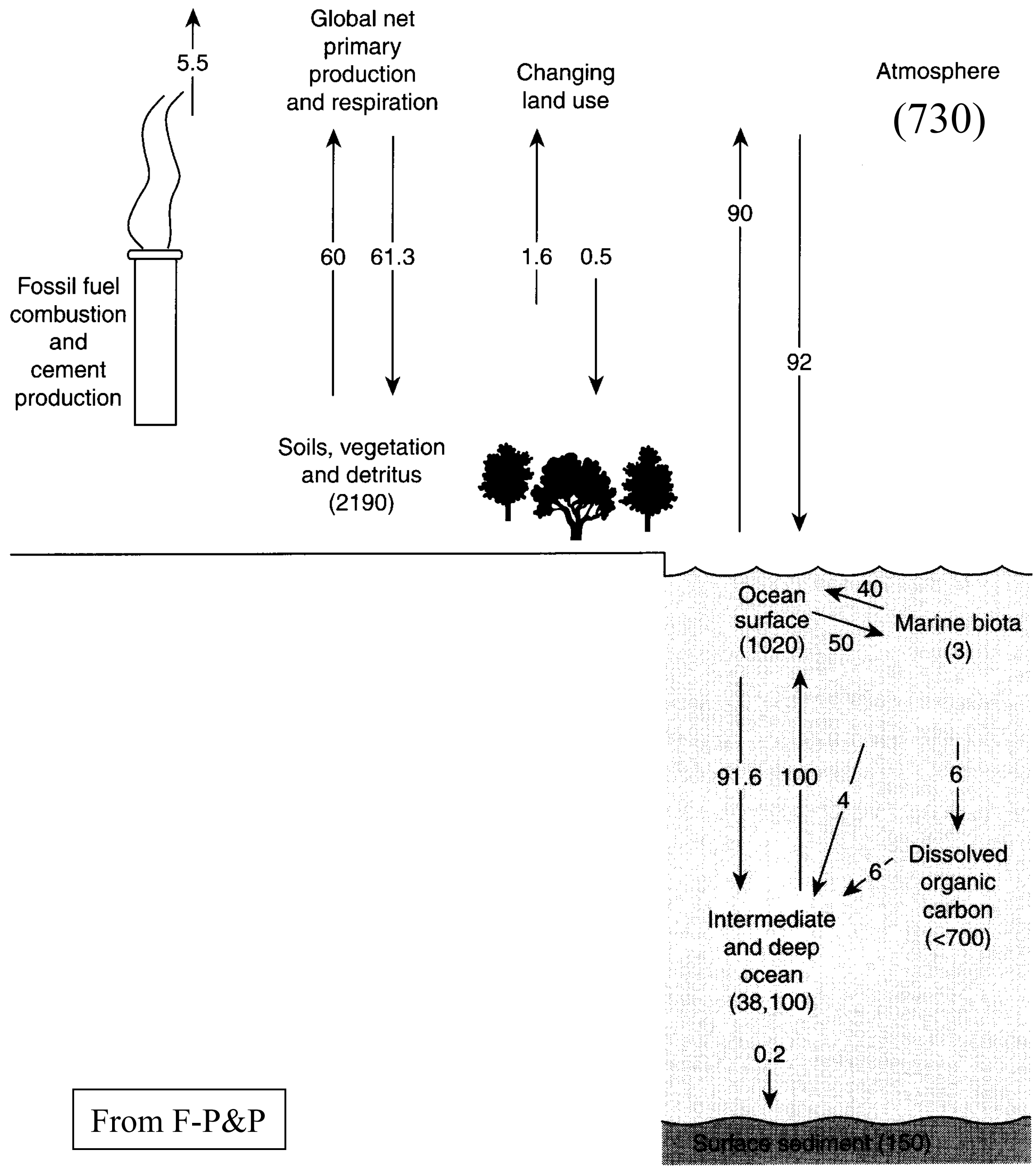


FIGURE 14.12 Measured CO_2 concentrations at Mauna Loa, Hawaii, from 1958 to 1994. The line represents the atmospheric CO_2 expected if 55.9% of the cumulative emissions of CO_2 from fossil fuel combustion and cement production remained in the atmosphere (adapted from Keeling *et al.*, 1995).

From F-P&P

C Cycle

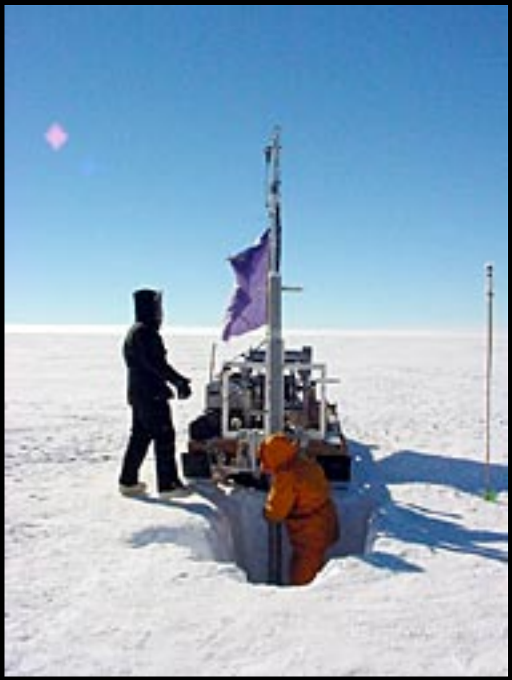
- Very large fluxes between atmosphere and soils / oceans
- Oceans are the long-term reservoir
  - From Henry's law + HCO_3^- + CO_3^{2-}
  - Lowering ocean pH
  - Limited by ocean mixing => long timescales

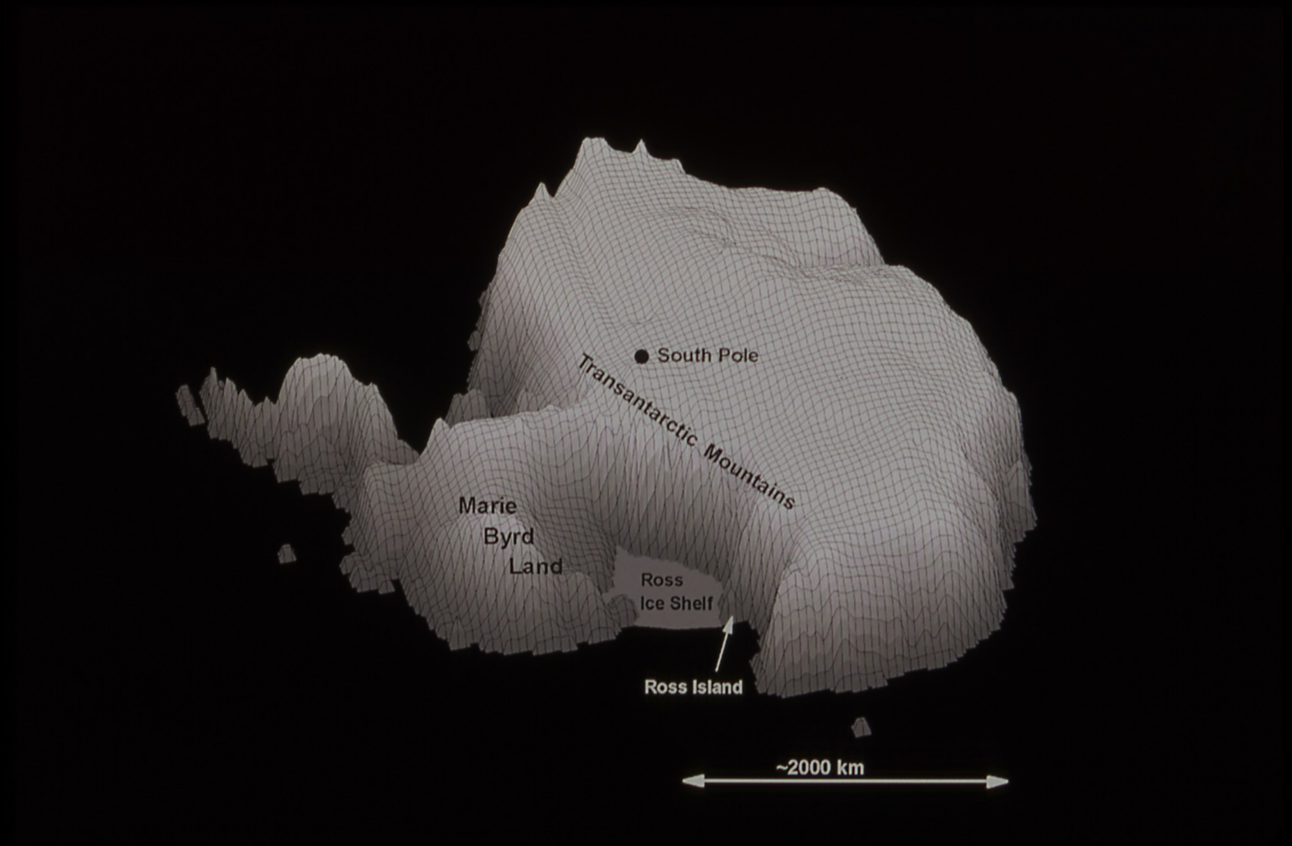


From F-P&P

FIGURE 14.11 Summary of global carbon cycle. Amount (in gigatons of C = 10^9 metric tons = 10^{15} g of C). Reservoirs are shown in parentheses, and fluxes (gigatons of C per year) are indicated by arrows. Note that the time scales associated with the various processes vary (adapted from IPCC, 1996).

The polar ice caps carry the history of the Earth's atmosphere over millions of years, in the form of bubbles trapped in the ice.

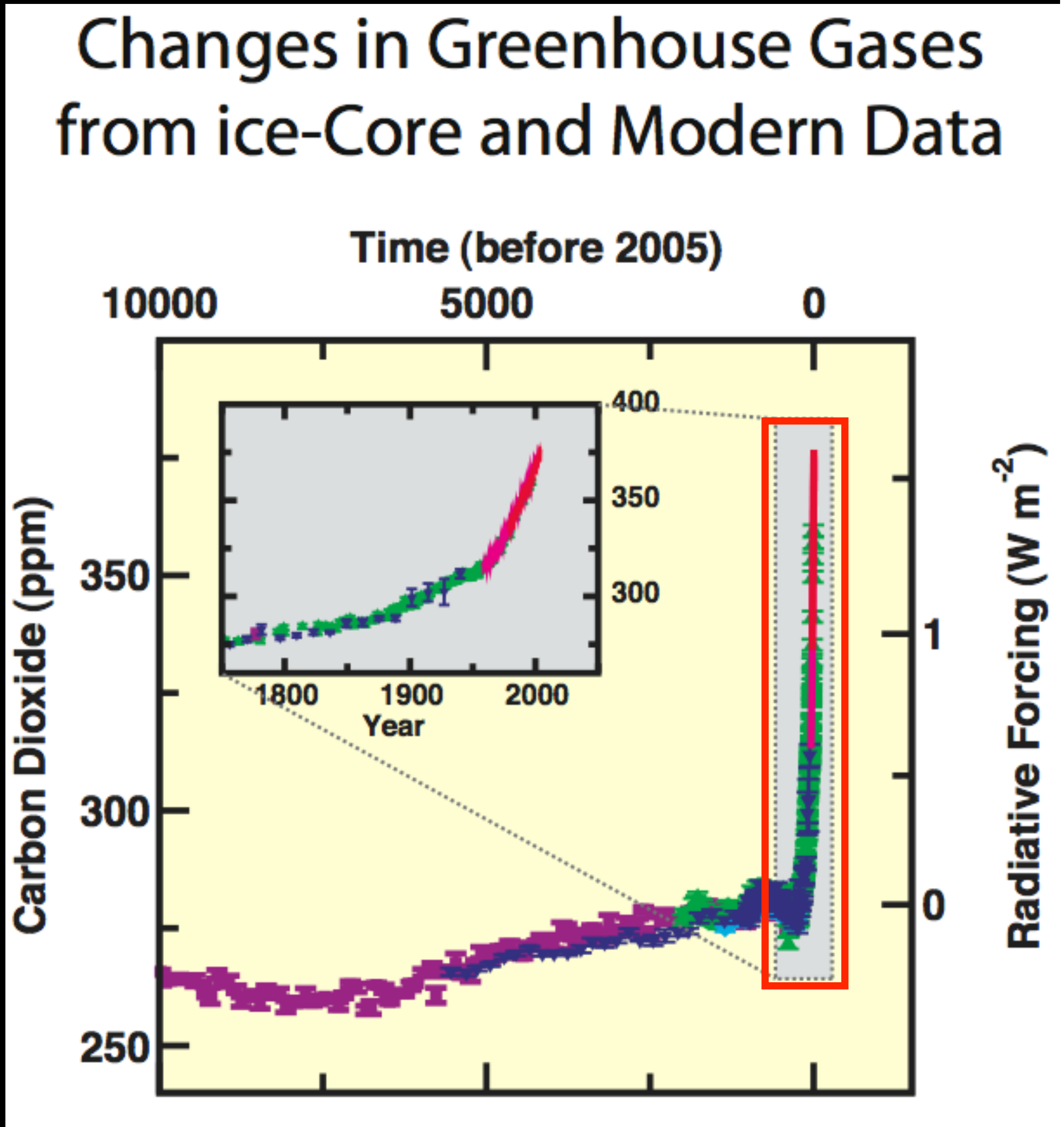




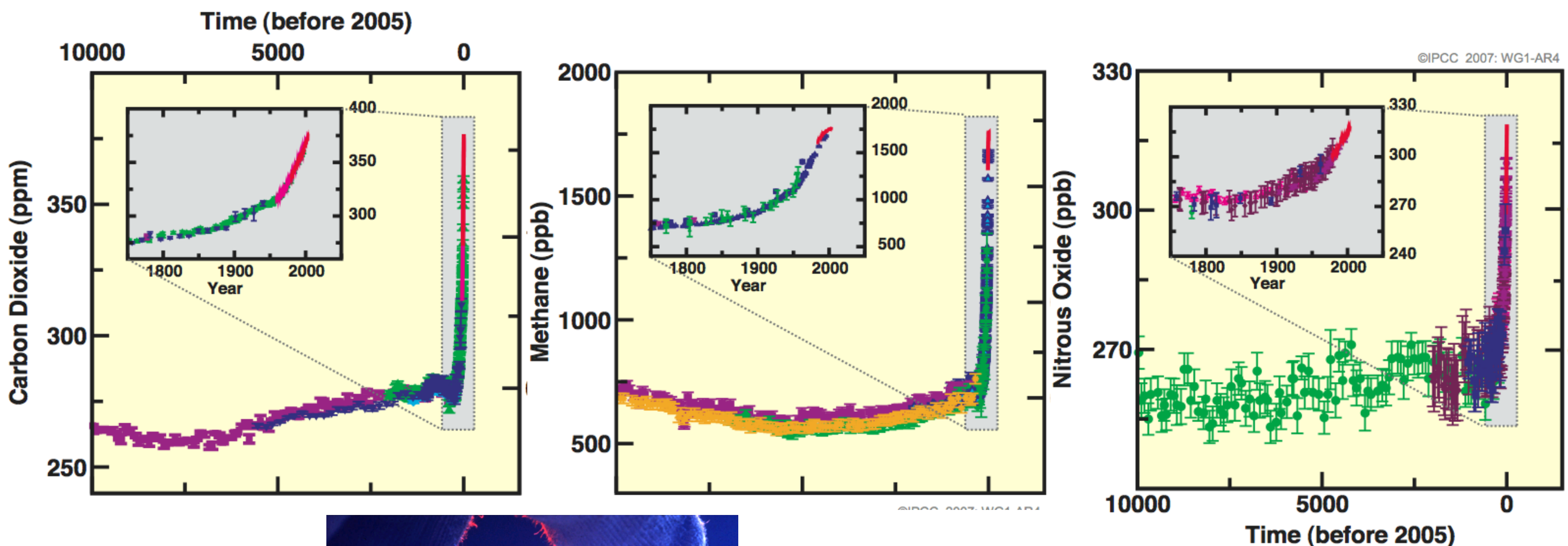
Human and Natural Drivers of Climate Change: Unprecedented [IPCC, 2007]

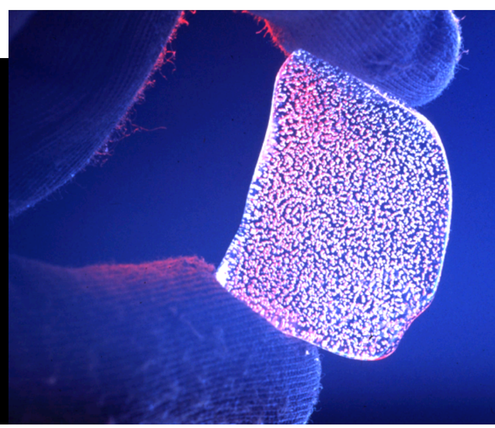
- CO_2 is a greenhouse gas, critical to the energy budget of the planet.

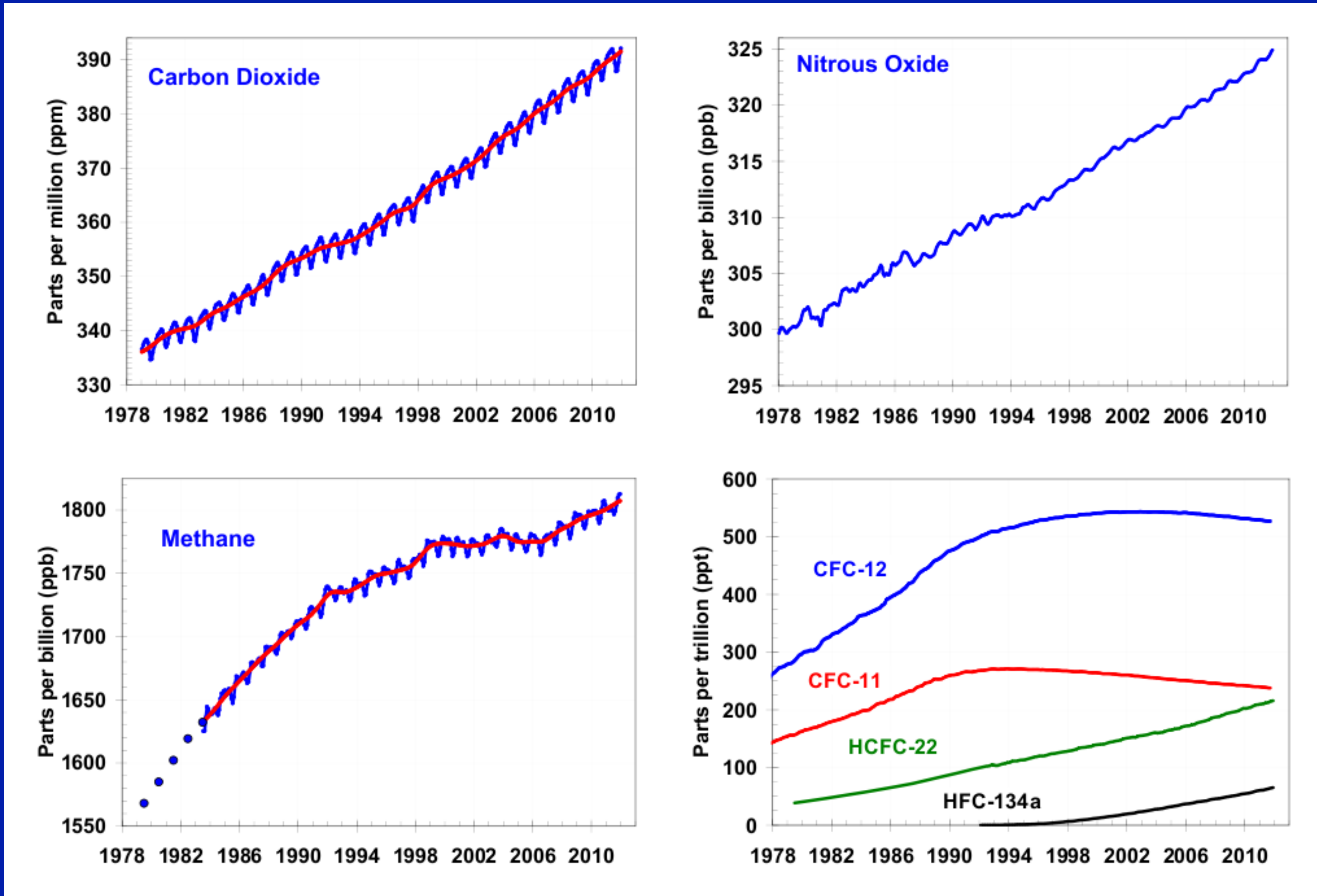
- Dramatic rise of CO_2 in the industrial era, changing that energy budget, and ‘forcing’ the climate in a new way not experienced in many thousands of years.



The current concentrations of two other greenhouse gases and their rates of change are also unprecedented.



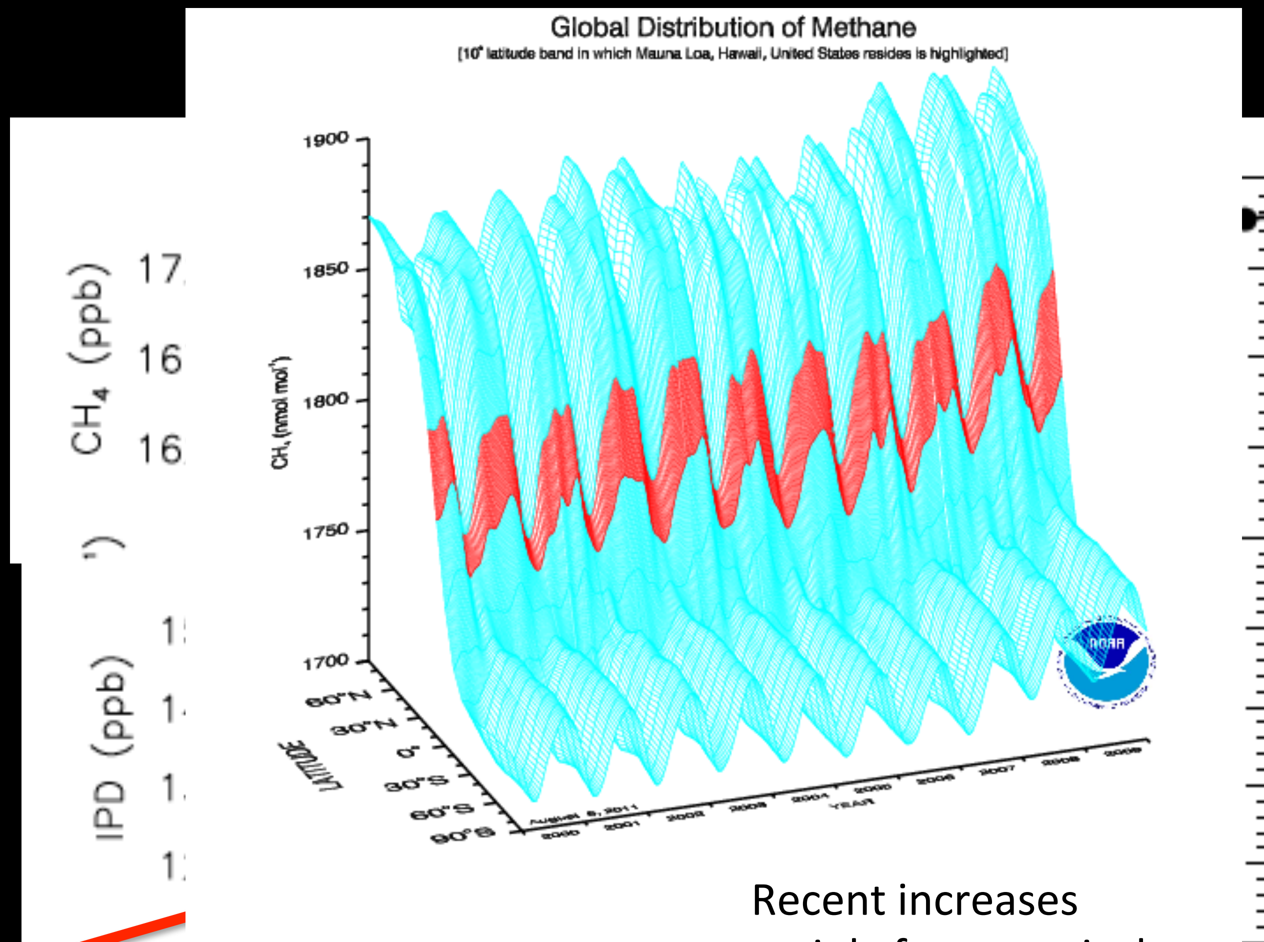




What is happening and why to methane - the world's number two warming agent? At times, constancy… implies no further increases in total emissions…. But why?

Recent Changes in Methane

But….Nature in Aug 2011…..One study uses ethane (purely fossil) to back up the view that FF efficiency contributed to uptick, while another uses ΔC13 to argue that biogenic source changes linked to fertilizers were dominant…..



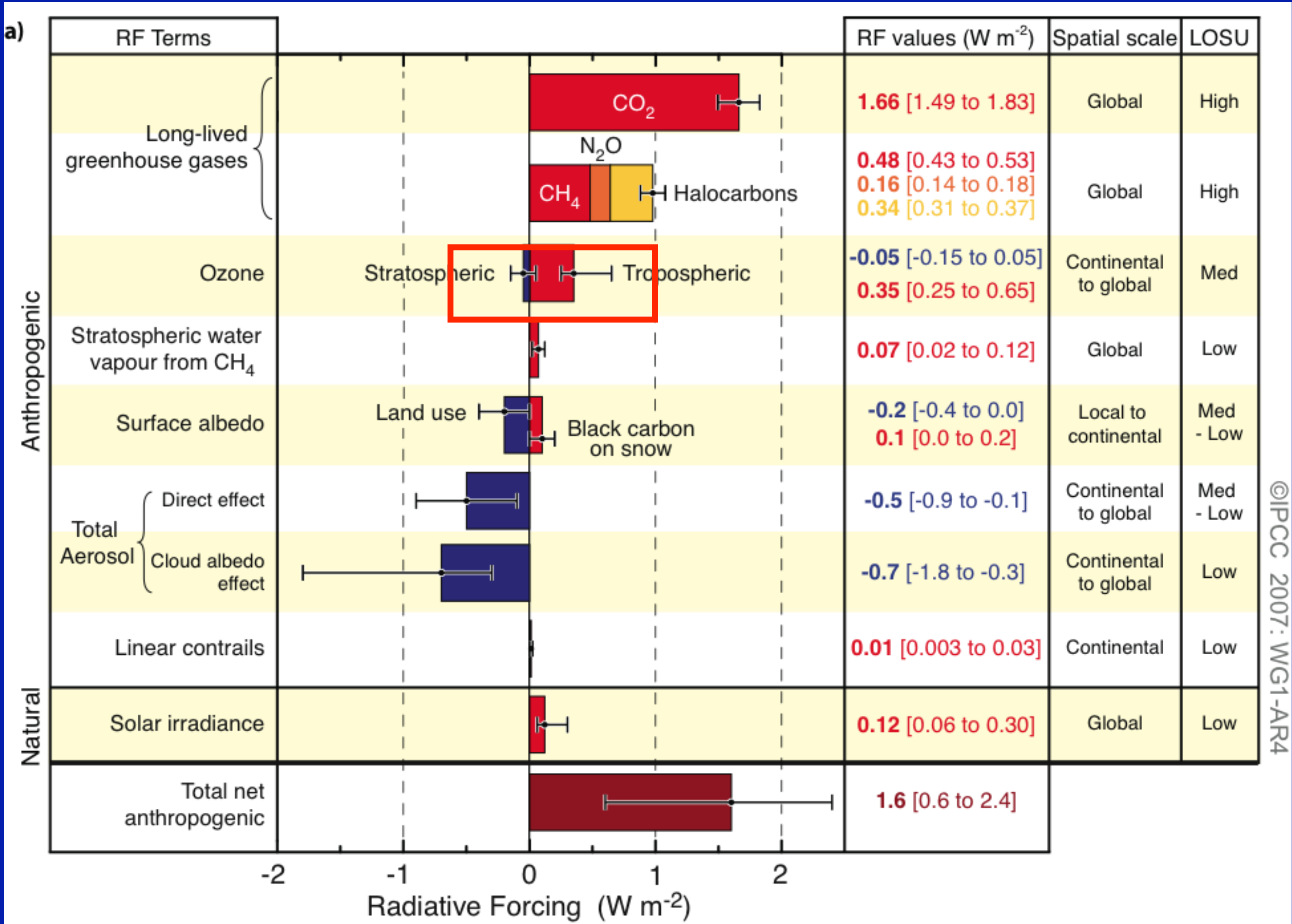
Recent increases mainly from tropical and polar wetlands.

Note changes in trends since the collapse of the Soviet Union (less release from mining)

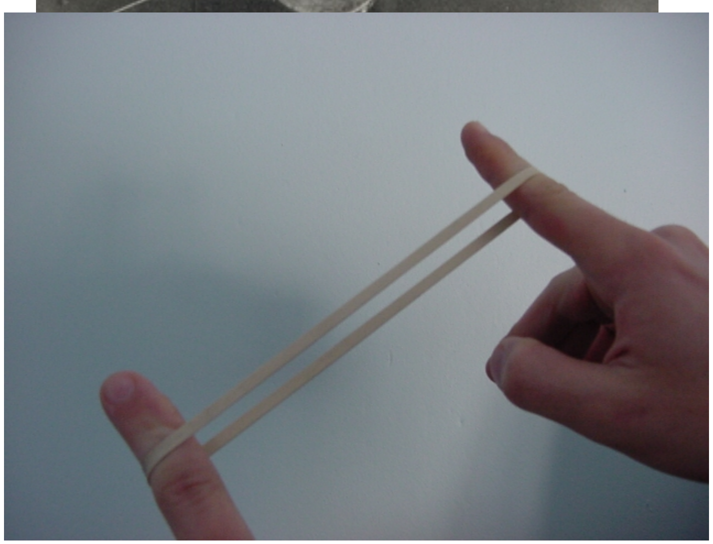
Dlugocencky et al., GRL, 2003; 2009.

Radiative forcing: change in energy balance

Used to compare different drivers of climate change



The discovery of smog ozone



Ozone Formation in Photochemical Oxidation of Organic Substances

A. J. HAAGEN-SMIT AND C. E. BRADLEY
California Institute af Technology, Pasadena 4, Calif.
M. M. FOX
Los Angeles County Air Pollution Control District, Los Angeles 58, Calif.

TABLE III. OZONE FORMATION CALCULATED FROM RUBBER CRACKING WITH ORGANIC COMPOUNDS, NITROGEN OXIDES, AND SUNLIGHT

Test Material	Concn., P.P.M. (V/V)	Nitrogen Oxides, P.P.M. (V/V)	Flask Volume, L.	Exposure Time, Min.	Av. Rate of Ozone Formation, P.P.M./Hour
Isobutane	1	0.4	2	180	0.2
n-4-Nonene	0.1	0.4	2	180	0.2
Mesitylene	1	0.4	2	240	0.9
Ketene	1	0.4	2	120	0.9
Diethyl carbinol	1	0.4	2	240	0.9
Methyl propyl carbinol	1	0.4	2	180	0.5
n-Butyraldehyde	0.1	0.4	2	210	0.4
n-Butyraldehyde	1	0.4	2	180	0.5

Smog Chemistry: CO oxidation

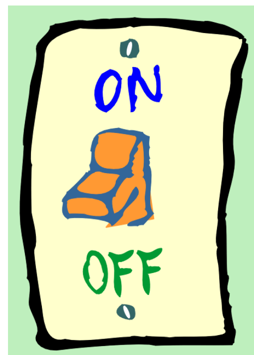
Clean (low NOx)

$CO + OH \text{-->} CO_2 + H$
$H + O_2 + M \text{-->} HO_2 + M$
$\boxed{HO_2 + O_3 \text{-->} OH + 2\,O_2}$

$CO + O_3 \text{-->} CO_2 + O_2$

Net ozone *destruction*

(but note: CO does not directly react with O_3)



Polluted (with NOx)

$CO + OH \text{-->} CO_2 + H$
$H + O_2 + M \text{-->} HO_2 + M$
$\boxed{HO_2 + NO \text{-->} NO_2 + OH}$
$NO_2 + h\nu \text{-->} NO + O$
$O + O_2 + M \text{-->} O_3 + M$

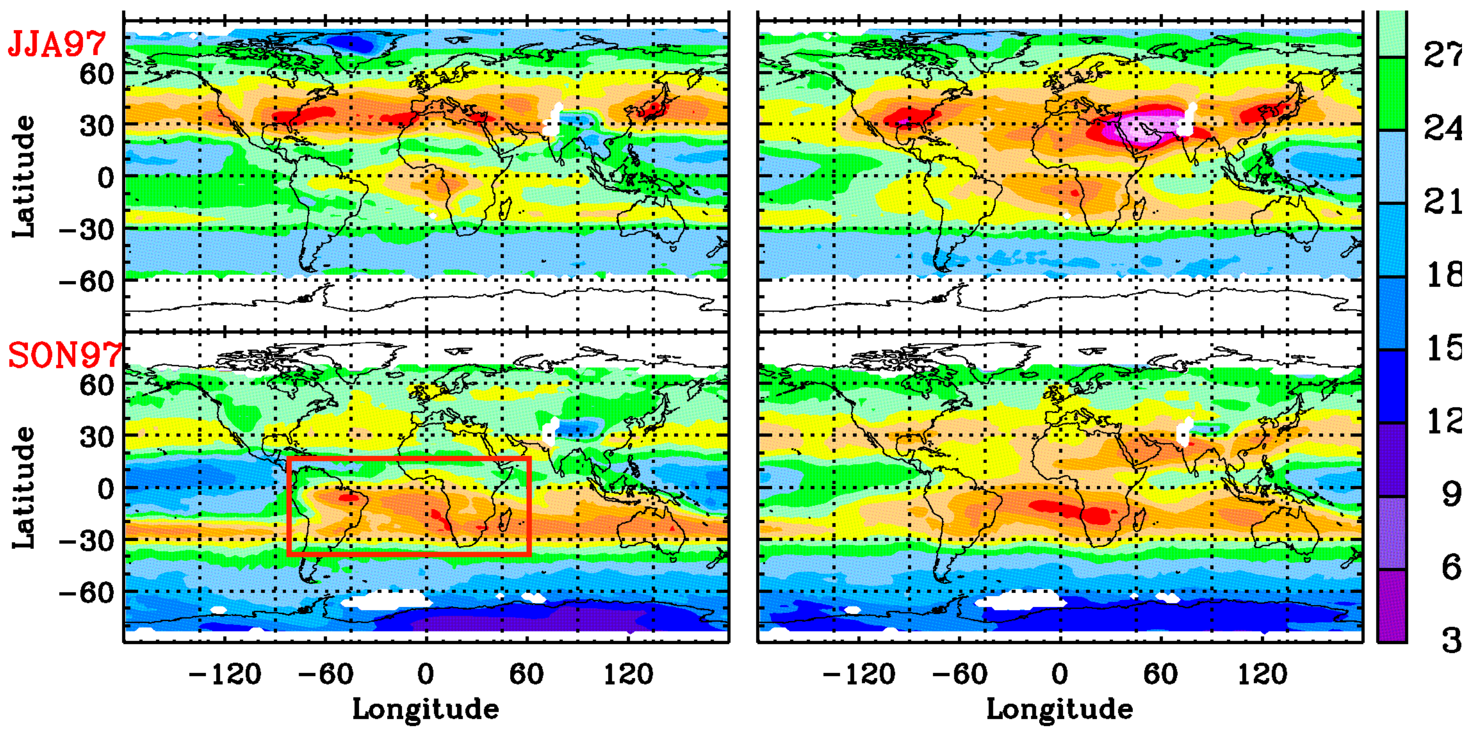
$CO + 2O_2 \text{-->} CO_2 + O_3$

Net ozone *production*

(note: CO is still oxidized to CO_2)

So if NOx or CO increase, ozone should increase based on these rx. Only a small amount of NO is needed → transport of anthropogenic ozone and significant RF.

Satellite observations of tropospheric ozone



Biomass burning and industrial…..

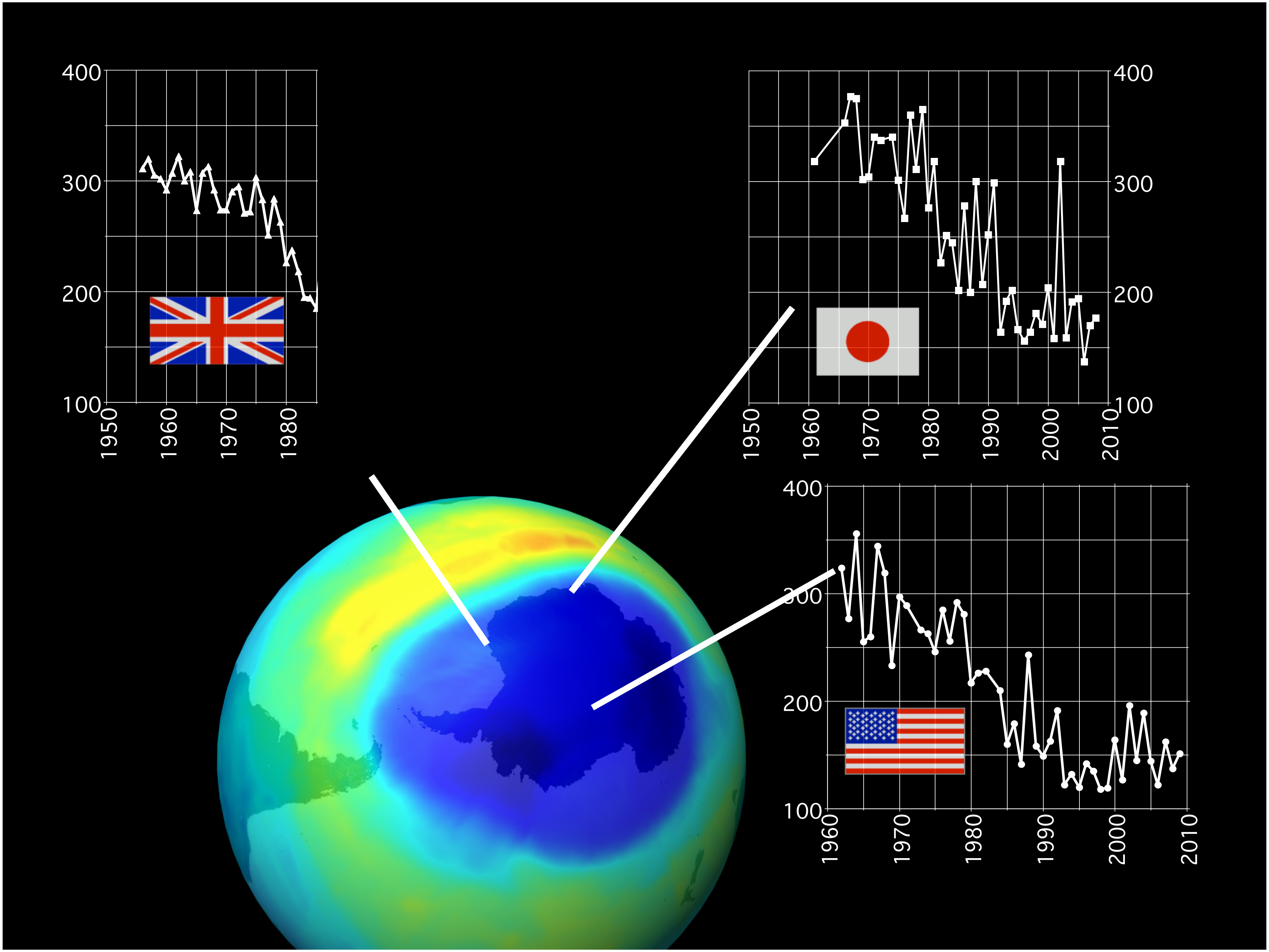
Data

Model

POPULATION OF CITIES WITH 10 MILLION INHABITANTS OR MORE, 1950, 1975, 2000 AND 2015
(*in millions*)

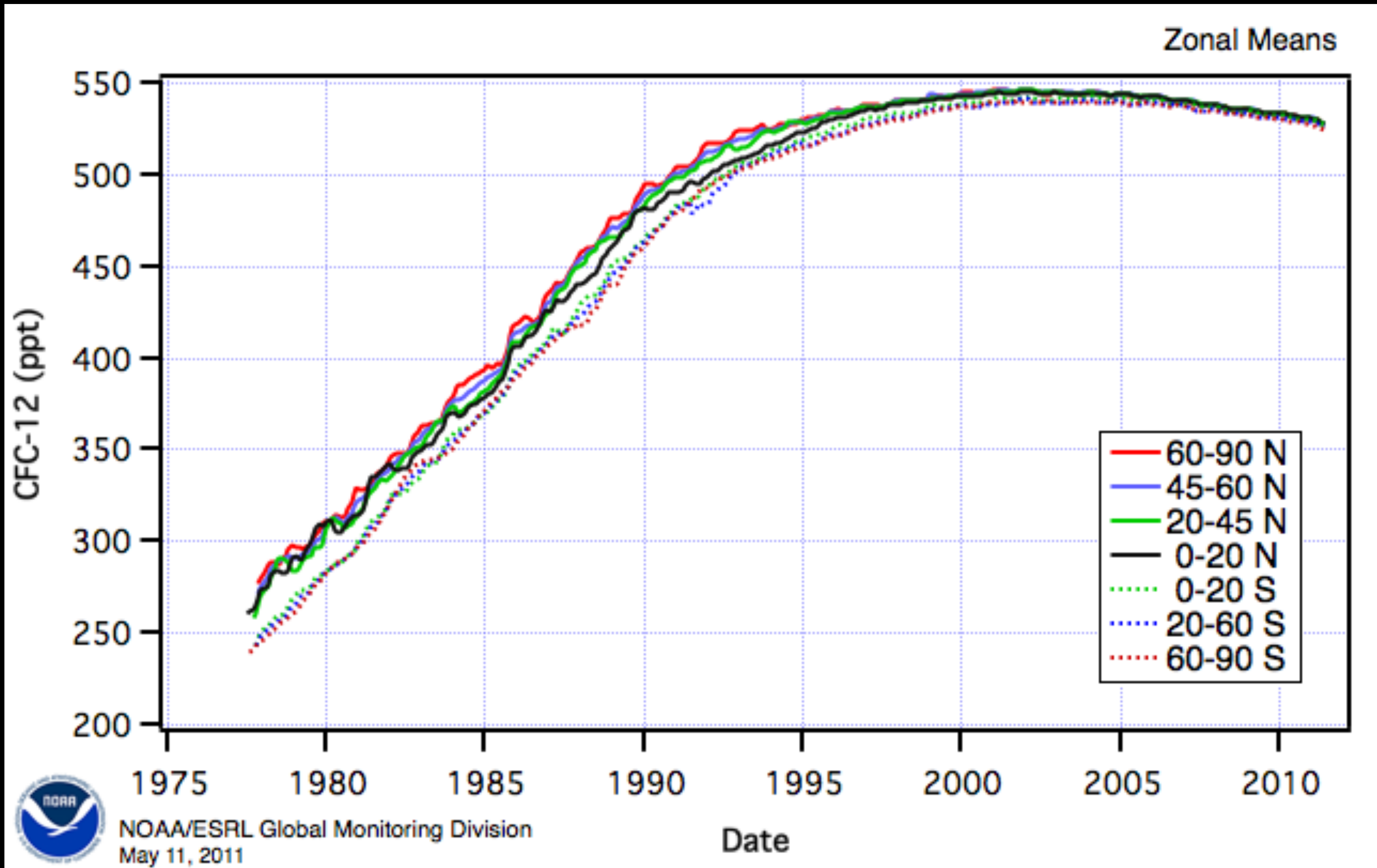
City	1950	City	1975	City	2000	City	2015
1 New York	12.3	1 Tokyo	19.8	1 Tokyo	26.4	1 Tokyo	26.4
		2 New York	15.9	2 Mexico City	18.1	2 Bombay	26.1
		3 Shanghai	11.4	3 Bombay	18.1	3 Lagos	23.2
		4 Mexico City	11.2	4 Sao Paulo	17.8	4 Dhaka	21.1
		5 Sao Paulo	10.0	5 New York	16.6	5 Sao Paulo	20.4
				6 Lagos	13.4	6 Karachi	19.2
				7 Los Angeles	13.1	7 Mexico City	19.2
				8 Calcutta	12.9	8 New York	17.4
				9 Shanghai	12.9	9 Jakarta	17.3
				10 Buenos Aires	12.6	10 Calcutta	17.3
				11 Dhaka	12.3	11 Delhi	16.8
				12 Karachi	11.8	12 Metro Manila	14.8
				13 Delhi	11.7	13 Shanghai	14.6
				14 Jakarta	11.0	14 Los Angeles	14.1
				15 Osaka	11.0	15 Buenos Aires	14.1
				16 Metro Manila	10.9	16 Cairo	13.8
				17 Beijing	10.8	17 Istanbul	12.5
				18 Rio de Janeiro	10.6	18 Beijing	12.3
				19 Cairo	10.6	19 Rio de Janeiro	11.9
						20 Osaka	11.0
						21 Tianjin	10.7
						22 Hyderabad	10.5
						23 Bangkok	10.1

UN, World Urbanization Prospects
The 2002 Revision



400
300
200
100
1950
1960
1970
1980
400
300
200
100
1950
1960
1970
1980
1990
2000
2010
400
300
200
100
1960
1970
1980
1990
2000
2010

Is the Montreal Protocol Working? Definitely.



http://www.esrl.noaa.gov/gmd/hats/

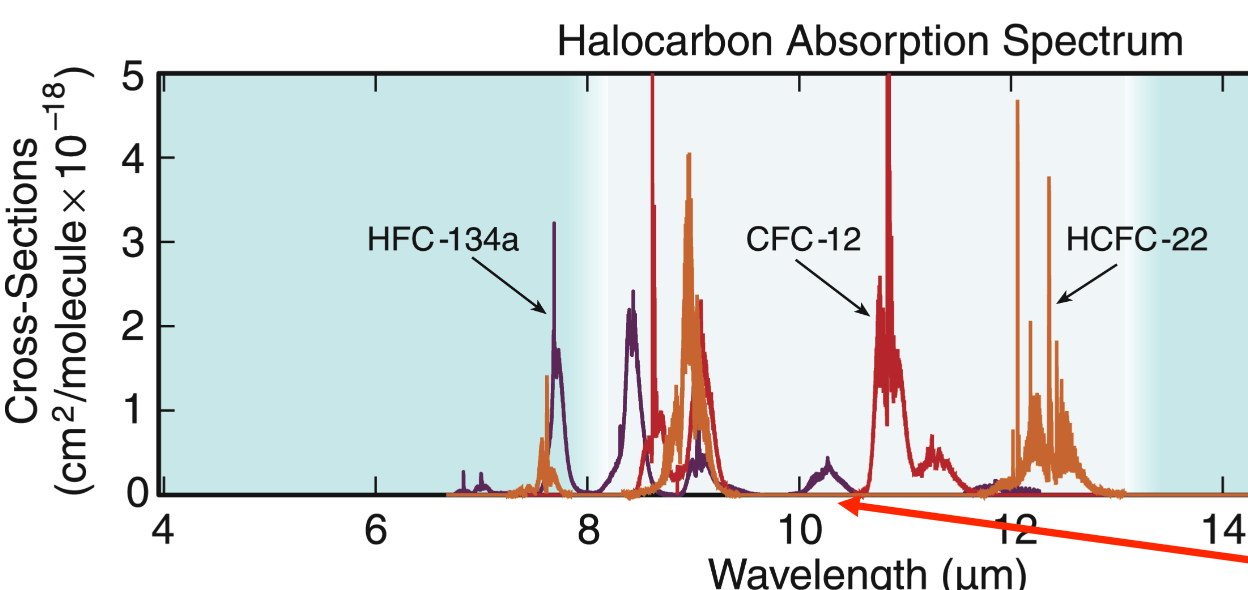
- NH, SH differences
- Lifetimes of gases, global trends
- Many decades to really 'recover'

CFCs are strong absorbers of infrared light, and *directly* contribute to global warming {CFC physics}

Greenhouse Effect Due to Chlorofluorocarbons: Climatic Implications

Abstract. *The infrared bands of chlorofluorocarbons and chlorocarbons enhance the atmospheric greenhouse effect. This enhancement may lead to an appreciable increase in the global surface temperature if the atmospheric concentrations of these compounds reach values of the order of 2 parts per billion.*

Ramanathan, Science, 1975.



Atmospheric 'window'

GWP-Weighted Emissions

Combined CO_2-eq from halocarbons:

~7.5 Gt near 1990, about 33% of that year's CO_2 emissions from global fossil fuel burning.

2002 breakdown:

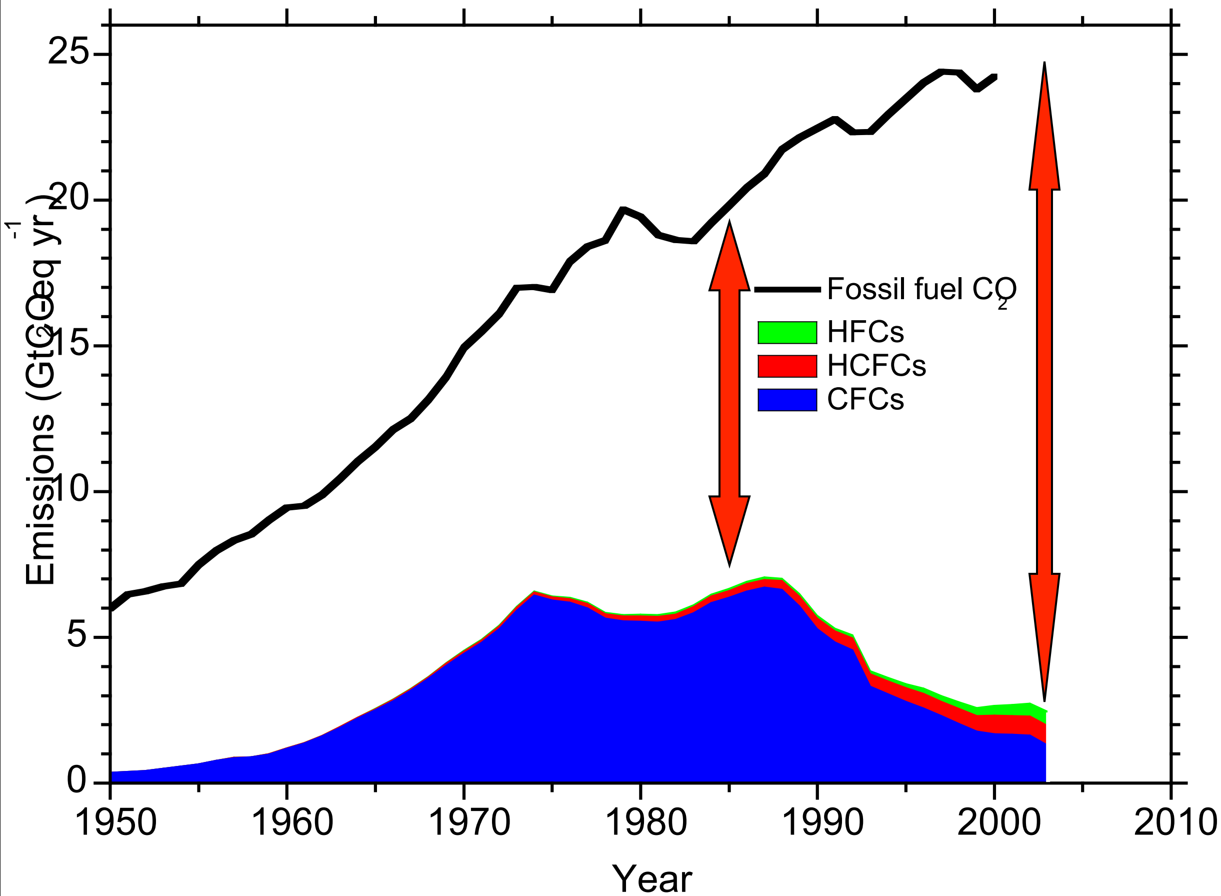
1.5-1.9 Gt for CFCs;

0.53-0.56 Gt for HCFCs;

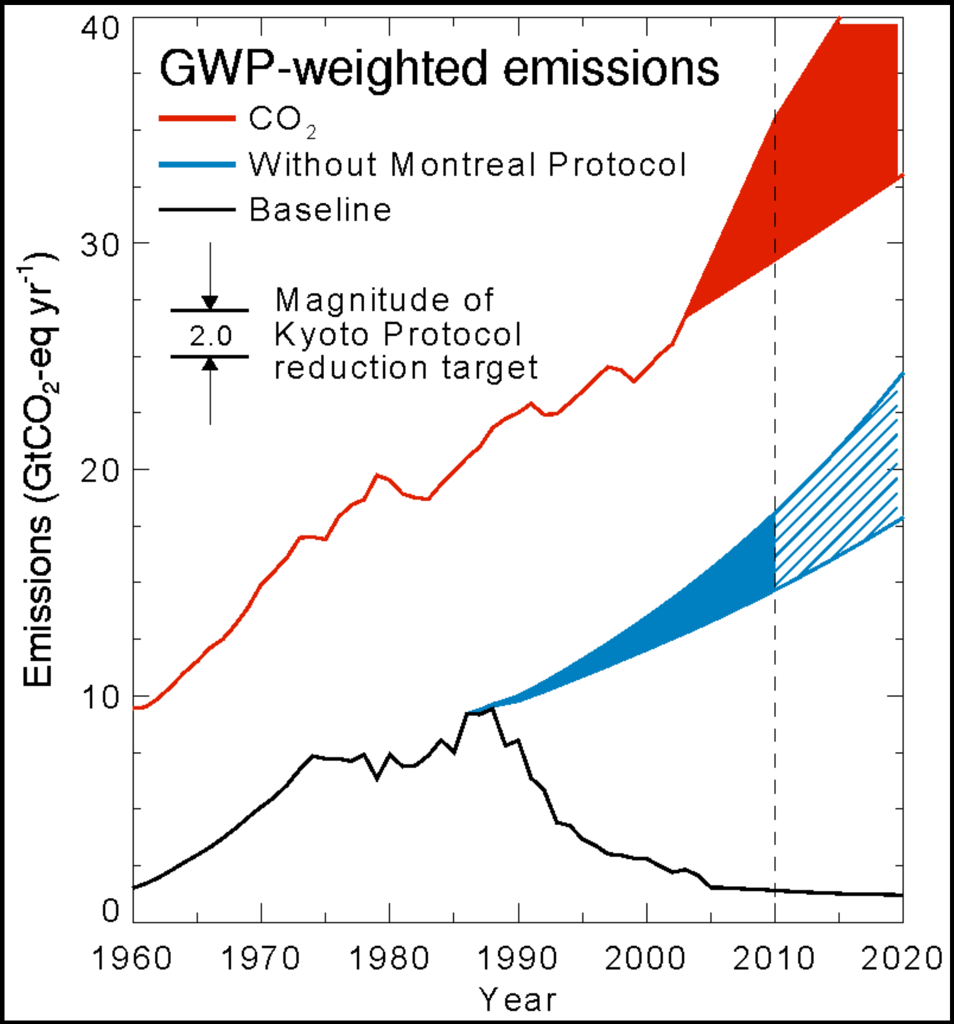
0.36 Gt for HFCs

Source:

IPCC (2005) Special Report on Safeguarding the Ozone Layer and the Global Climate System



Benefits of Montreal Protocol for Climate



Velders et al., PNAS, 2007

CO_2 emissions

World avoided by the Montreal Protocol?

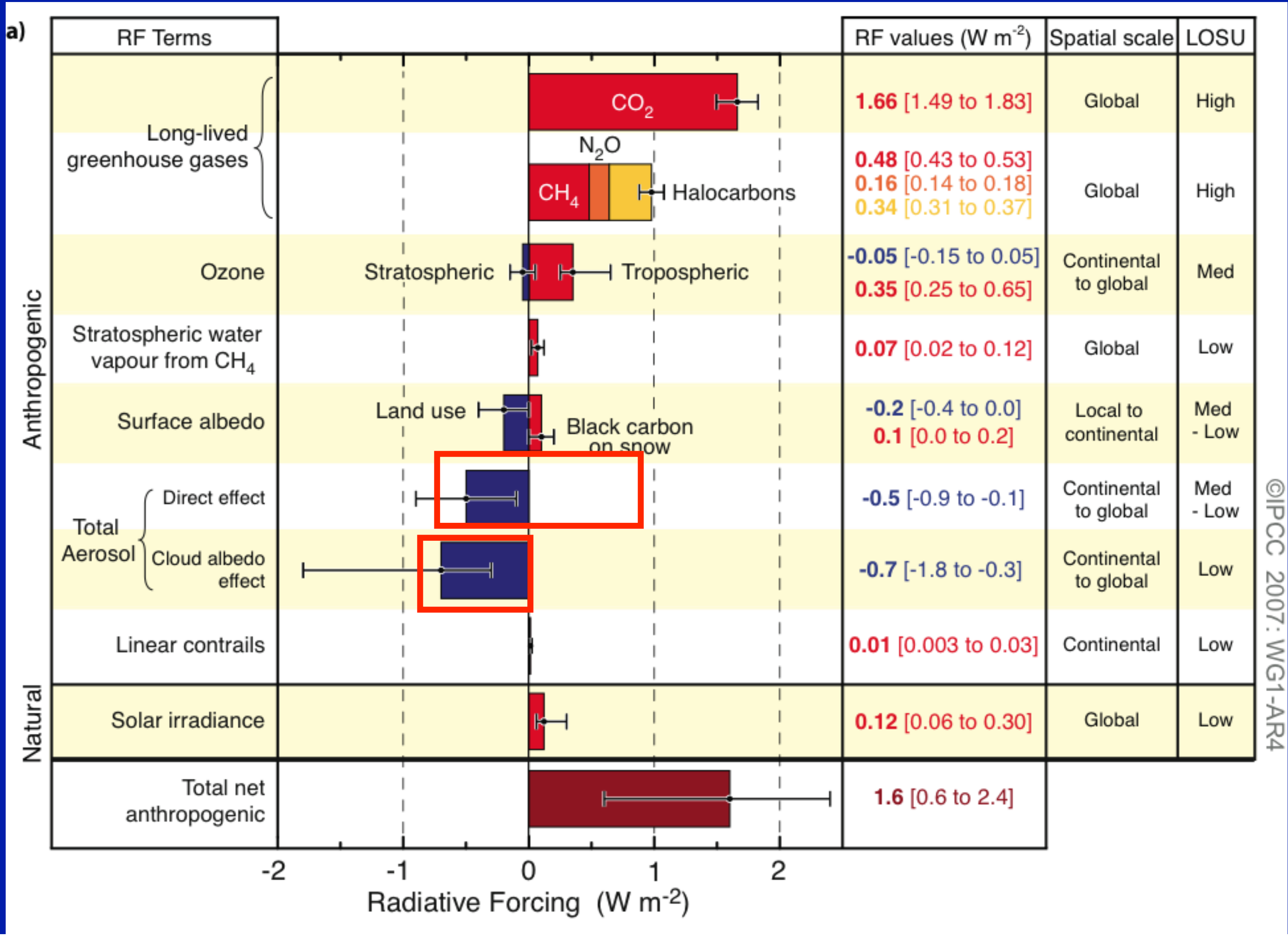
Reduction Montreal Protocol of ~11 $GtCO_2$-eq/yr

➔ 5-6 times global Kyoto target!!

What about HFCs?

Radiative forcing: change in energy balance

Used to compare different drivers of climate change



Most of the forcings due to human activity act to warm the planet.

However, some human activities can produce aerosols, which can reflect radiation to space and can modify clouds, which can cool the planet.

The net effect of human activities is therefore the sum of warming and cooling terms, and each has uncertainty.

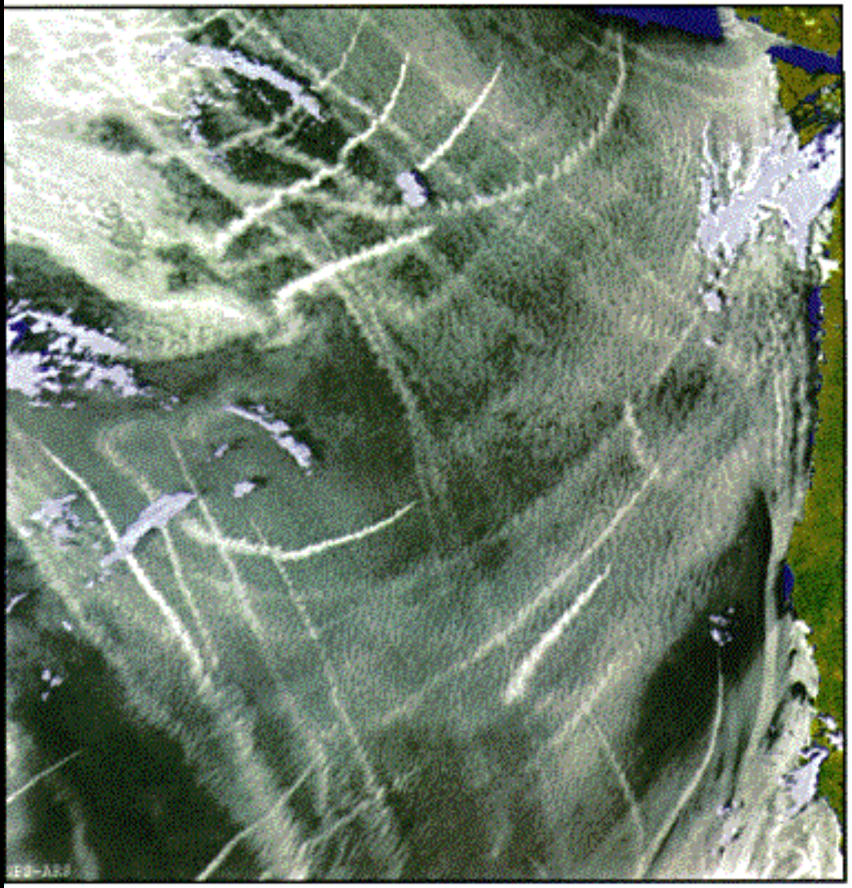


Figure 1: Ship tracks off the coast of Washington

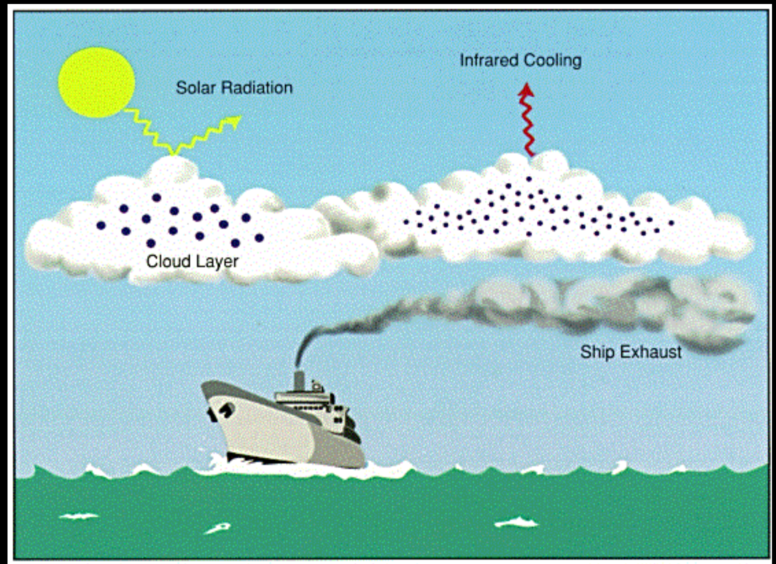
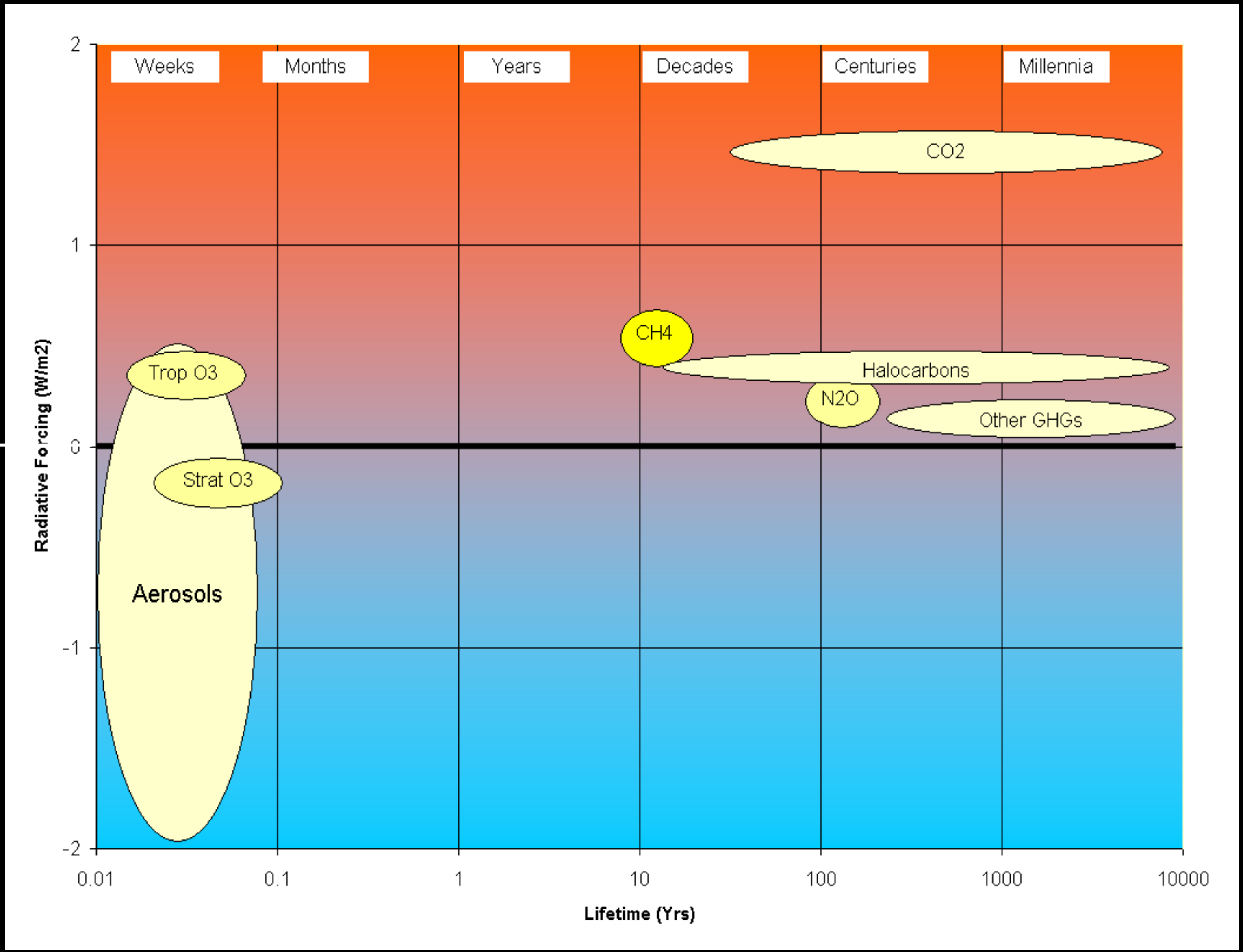


Figure 2: Illustration depicting the effects of aerosols from ship exhaust on cloud reflectivity

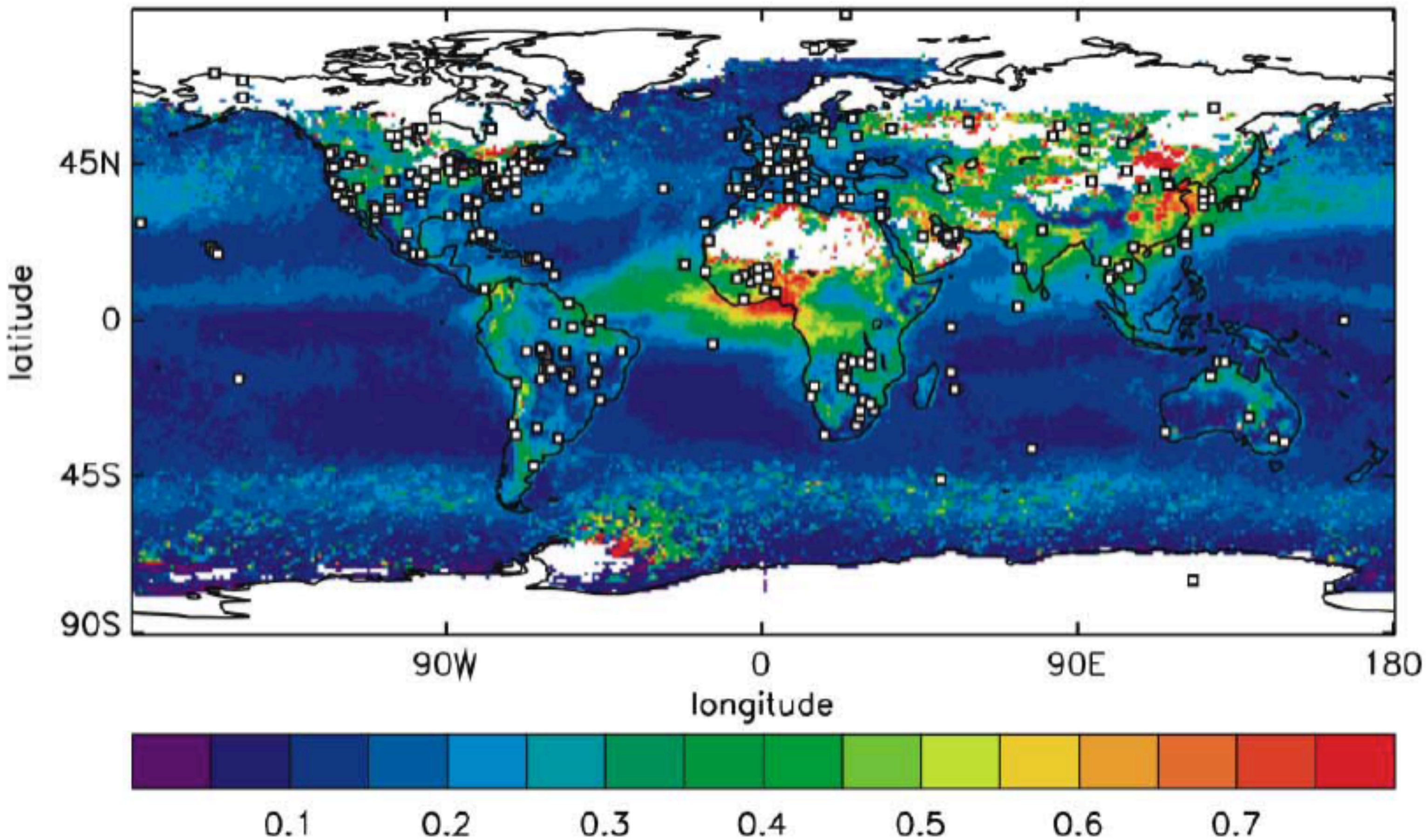
The lifetimes and magnitudes of forcings

Many key warming agents live for decades or more

All known cooling agents are short-lived



Total aerosol optical depth (natural+anthropogenic components) at mid-visible wavelength, from satellite instruments [Figure TS-4 (top)]

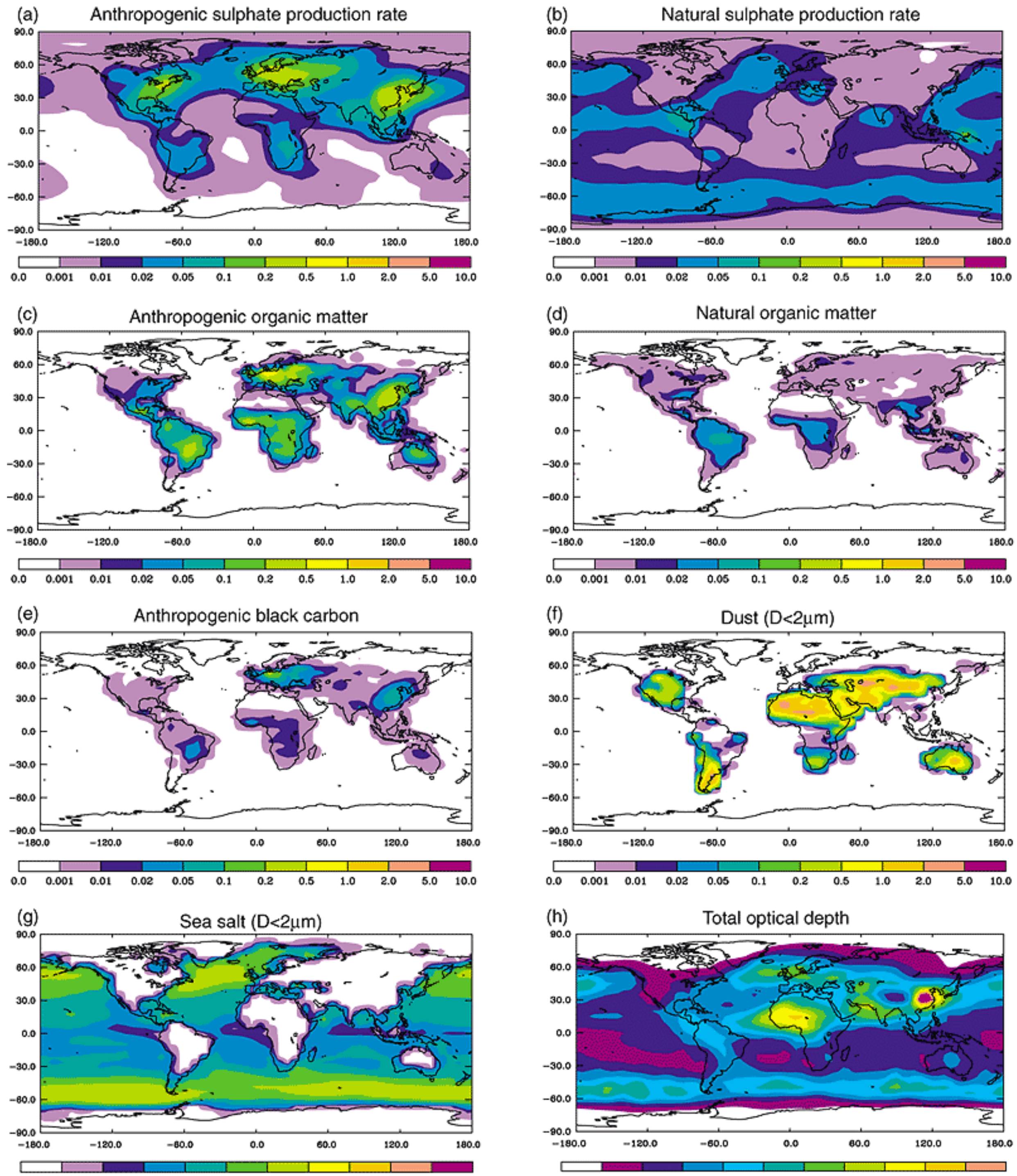


- **Observations reveal the presence and provide quantitative aspects.**
- **Aerosol transport-forcing models better tested and constrained.**

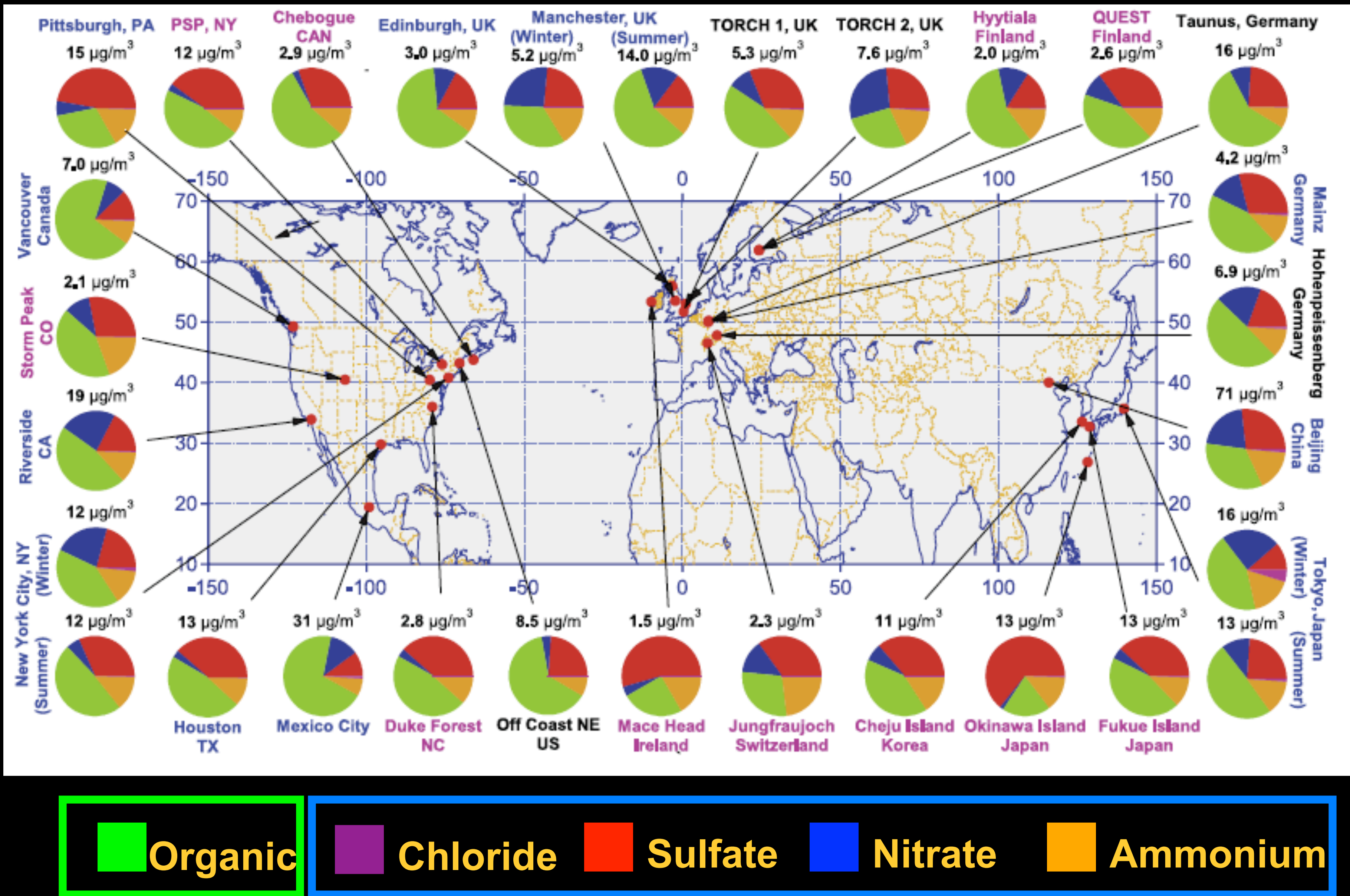
➔Much improved estimate of the total Aerosol Direct Radiative Forcing.

➔What about breakdown by component? Indirect? Future projections?

Aerosol production rates for most important aerosol types



From IPCC 2001 http://www.grida.no/climate/ipcc_tar/wg1/fig5-2.htm



Zhang et al. 2007

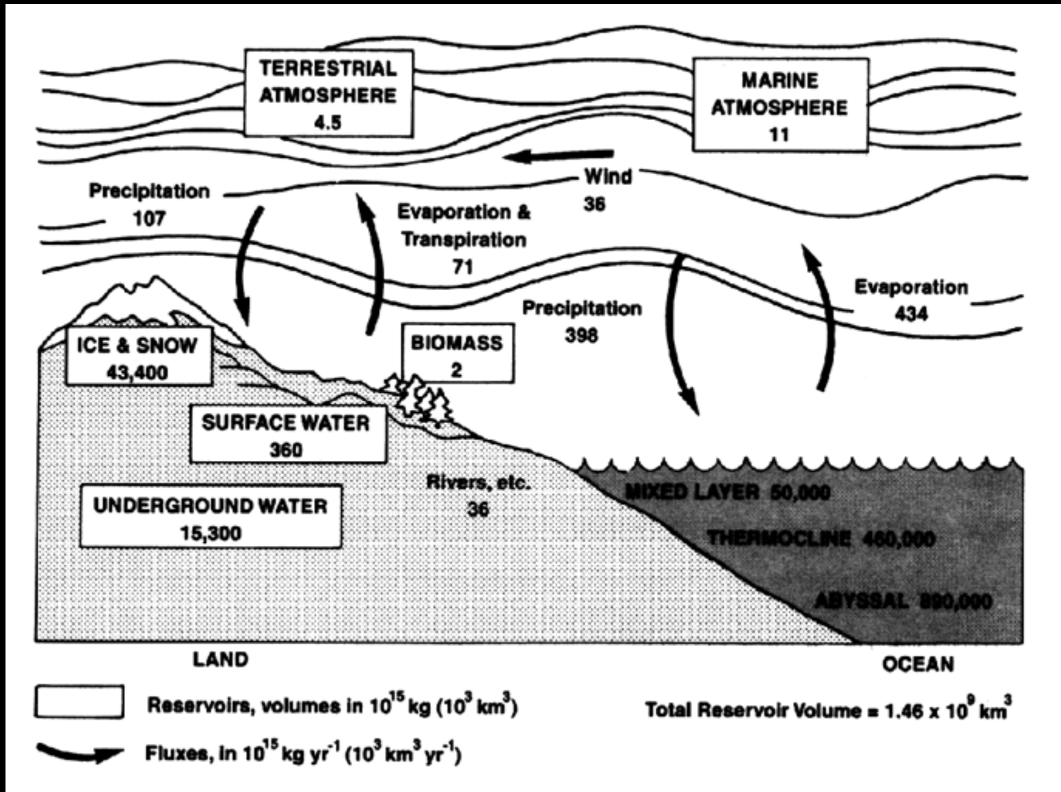
Much more organic material than expected

Aerosol Effects

- Very uncertain because of
  - Short lifetime
  - Very incomplete data
  - Great complexity of sizes & compositions
- "Direct effect"
  - Aerosols scatter sunlight back to space => cooling
    - Black carbon absorbs => warming
  - Most efficient when $d_p \sim \lambda$ (submicron aerosols)
  - Same physics that cause visibility degradation
  - All aerosol constituents participate in scattering
    - If they absorb water, they scatter more

Aerosol “Indirect” Effects

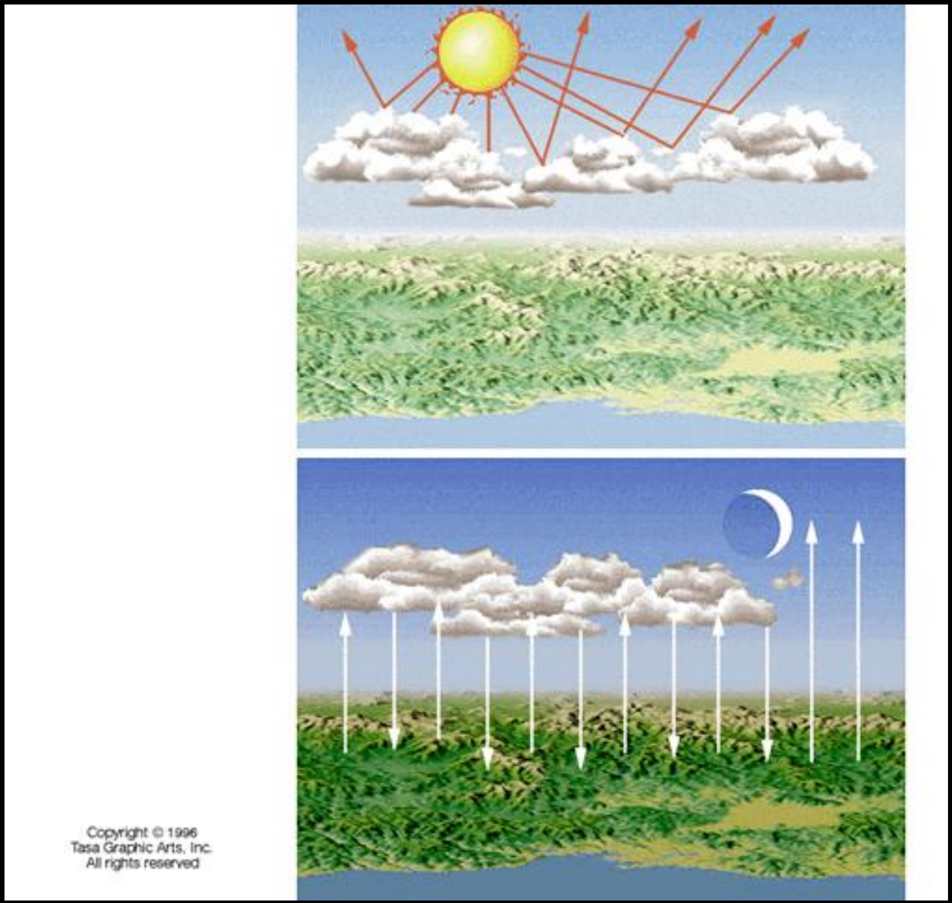
- Clouds are formed when water condenses on preexisting aerosol
  - Clouds both reflect and absorb large amounts of radiation
  - If aerosol changes, cloud can change….so this involves feedback of the climate system and is not the same as other forcings…
    - E.g. “Twomey effect” or “1st indirect effect”
      - More particles
      - Same H_2O
      - Smaller droplets
      - Closer to solar wavelenghts, so more scattering => cooling



Water vapor and clouds are key feedbacks to the climate system.

A hotter planet implies increased evaporation and more moisture, and water vapor, like CO_2 is a potent greenhouse gas.

This effect is not a forcing -- it's a feedback, very likely a positive feedback to climate change. But it's only one effect, and clouds are complex.



Clouds can absorb IR and warm the climate (which is warmer - cloudy nights or clear ones?).

But clouds also can reflect energy to space and can cool the climate.

Global models have a tough time simulating clouds. How do clouds influence the way modern climate will respond to the variety of forcings that are occurring?

Adjusted Forcing Versus Radiative Forcing

Indirect effects of aerosols on clouds – how to calculate them? Allow clouds to adjust? But carbon dioxide and other GHG also change clouds, so is this a feedback or a forcing?

Adjusted forcing allows for fast feedbacks in the troposphere (clouds and water vapor), with slow feedbacks such as oceans and sea ice kept fixed.

Probably will see more discussion of adjusted forcing in IPCC AR5.

Adjusted Forcing Versus Radiative Forcing

58 JOURNAL OF CLIMATE VOLUME 21

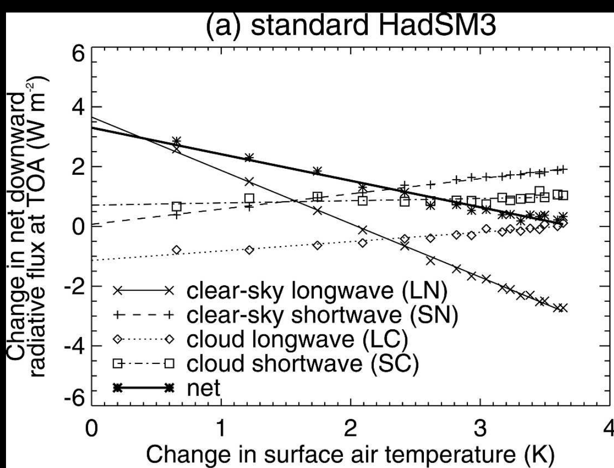
Tropospheric Adjustment Induces a Cloud Component in CO_2 Forcing

JONATHAN GREGORY

Walker Institute for Climate System Research, Department of Meteorology, University of Reading, Reading, and Hadley Centre, Met Office, Exeter, United Kingdom

MARK WEBB

Hadley Centre, Met Office, Exeter, United Kingdom



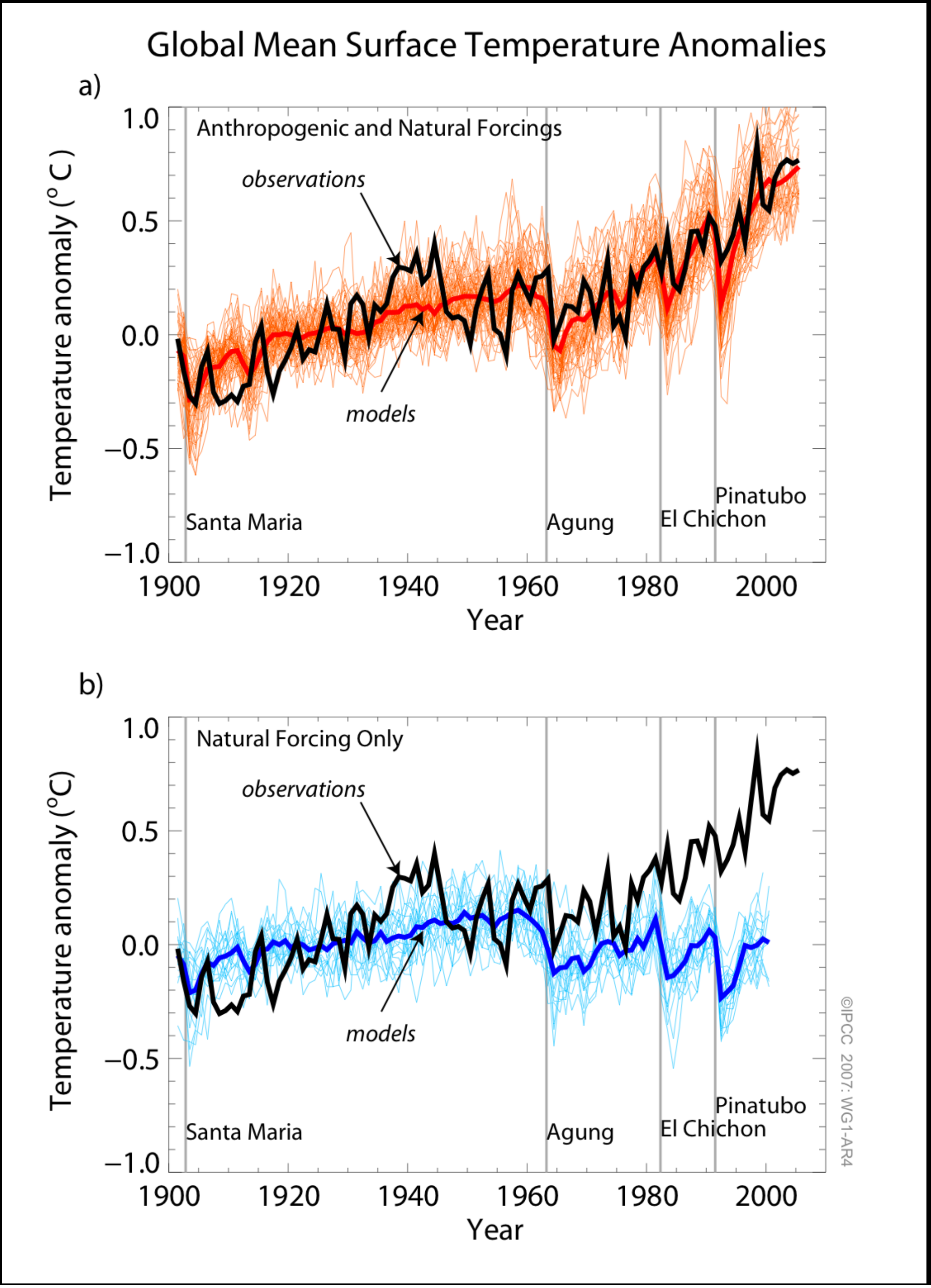
4x CO2

Extrapolate TOA back to ΔT=zero to get adjusted forcing that allows fast feedbacks only.

Attribution

- Asks whether the pattern (not absolute value) of observed changes are consistent with
- ☑ expected responses to forcings
- ☑ statistical analysis of changes in patterns in time, latitude, longitude
- ☑ inconsistent with alternative explanations (volcanoes and solar would have causing cooling….)

- **Most of the observed increase in globally averaged temperatures since the mid-20th century is very likely (>90%) due to the observed increase in anthropogenic greenhouse gas concentrations**



Forcing is the driver for much of climate change. Attribution of climate change relies on knowledge of forcing factors.

Carbon is king of climate change.

Any Questions?