PCC 588 - January 6 and 8 2009

Winter 2009: ATMS/OCN/ESS 588 The Global Carbon Cycle and Greenhouse Gases

T,Th 12:00-1:20 pm OSB 425

Course Goals

The course focuses on factors controlling the global cycle of carbon and the greenhouse gases (CO_2, CH_4, N_2O, O_3 and halocarbons).

- Abundance and distribution of carbon and greenhouse gases
- Physical, chemical and biological mechanisms that control ocean-atmosphere and terrestrial-atmosphere exchange of carbon and greenhouse gases
- The geologic evidence for climate change linked to greenhouse gases
- The fate of anthropogenic greenhouse gases, their impact on climate and strategies for sequestration of anthropogenic gases

Course Structure

- Greenhouse gases and radiative forcing (1.5 week)
- Non-CO_2 greenhouse gases and aerosols (2 weeks)
- Carbon cycle: past, present, future (2.5 weeks)
- Anthropogenic perturbation to C-cycle (1.5 week)
- Geoengineering solutions (1 week)
- Class presentations (1 week)

3 Problem sets (30%); Midterm exam (25%); Participation in class and during paper discussions (15%); Term paper & oral presentation (30%)

The IPCC Reports

• Intergovernmental Panel on Climate Change (IPCC) established in 1988 by WMO and UNEP

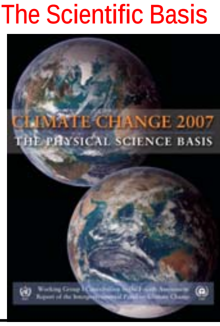
→assess available scientific and socio-economic information on climate change and its impacts and on the options mitigation and adaptation

• Report every 5 years: 1991, 1996, 2001, and 2007

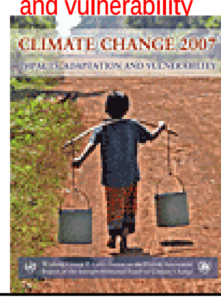
• Compiled by hundreds of scientists, reviewed by scientists, governments and experts: consensus document

http://www.ipcc.ch/ipccreports/assessments-reports.htm

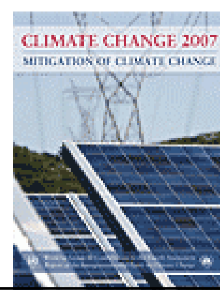
The Scientific Basis



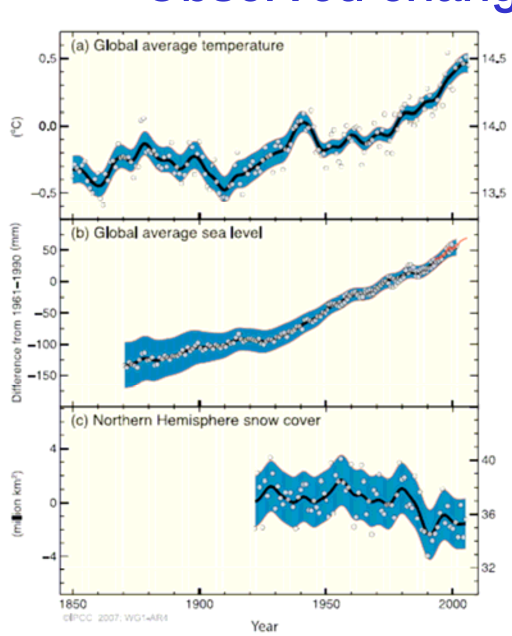
Impacts, Adaptation and vulnerability



Mitigation

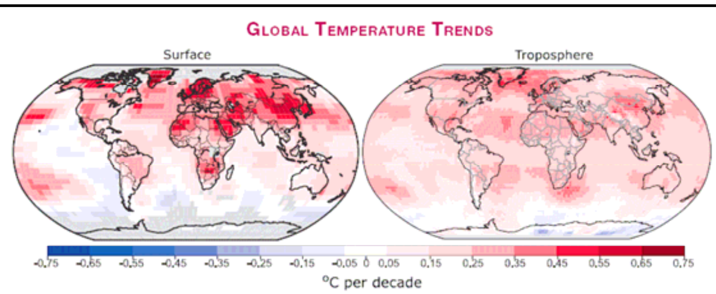


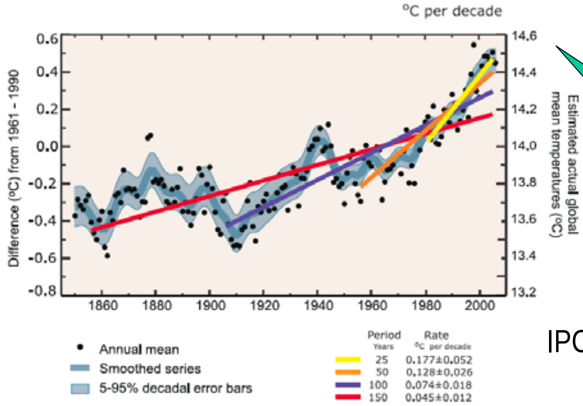
Observed changes in climate



"Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air temperatures, widespread melting of snow and ice, and rising average sea level."

IPCC 2007, Summary for Policymakers (SPM)



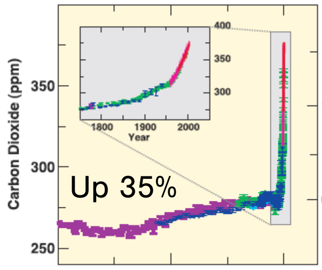


11 of the last 12 years rank among the 12 warmest years on record

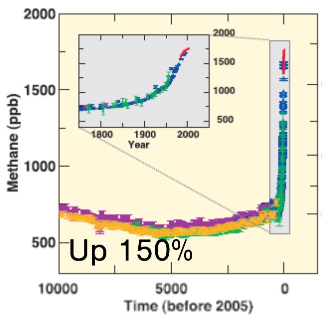
IPCC, 2007, Tech. Sum. (TS)

Global temperature increase: *0.74°C (1906-2005)*

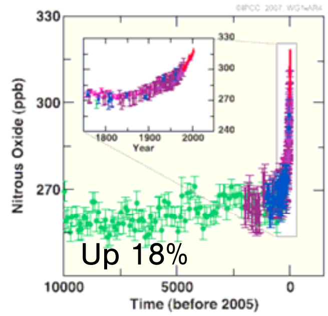
Human drivers of climate change



CO_2
Fossil fuels + land use change



CH_4
Fossil fuel use + agriculture



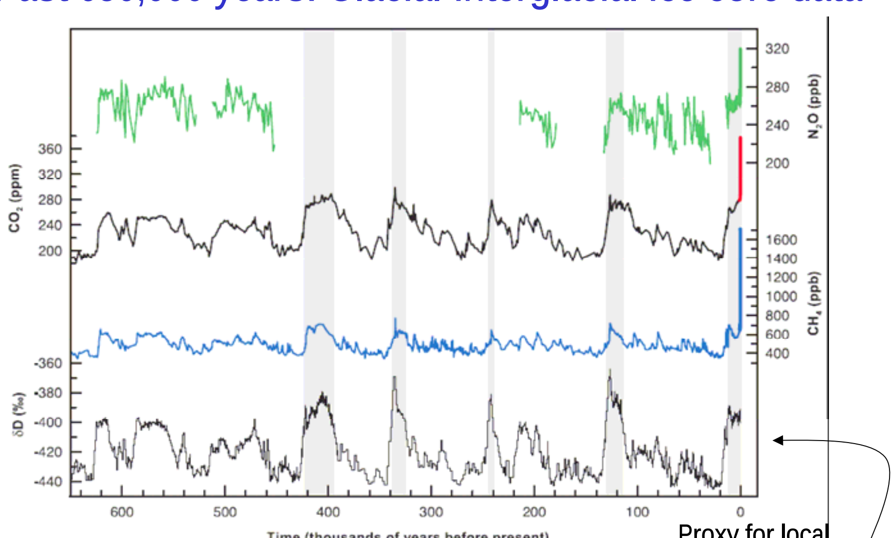
N_2O
agriculture

CO_2, CH_4 and N_2O Concentrations

- far exceed pre-industrial values
- increased markedly since 1750 due to human activities

IPCC, SPM, 2007

Past 650,000 years: Glacial-interglacial ice core data



Proxy for local temperature

IPCC, TS (2007)

Today and Thursday: From greenhouse gases to climate change …

- The climate system: what controls the temperature of the Earth?
- Greenhouse effect.
- Radiative forcing. Global warming potential. CO_2-equivalent emissions.
- Relating radiative forcing to temperature changes.

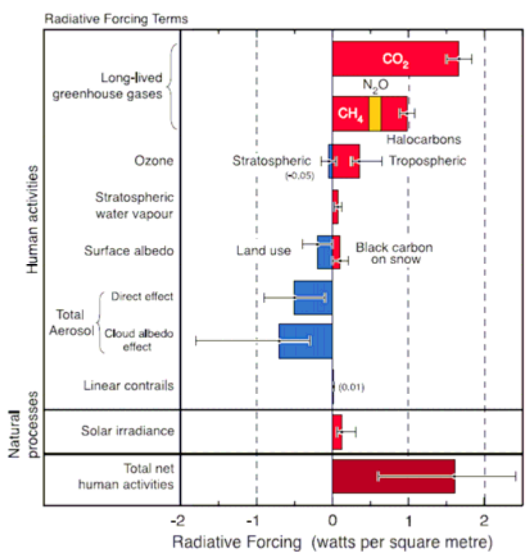
Reading for this week (will be on class web site):
IPCC WG1 Summary for Policymakers (2007)→ in-class discussion next Tues!
http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-spm.pdf

For more information:

** IPCC WG1 Technical Summary (2007)*

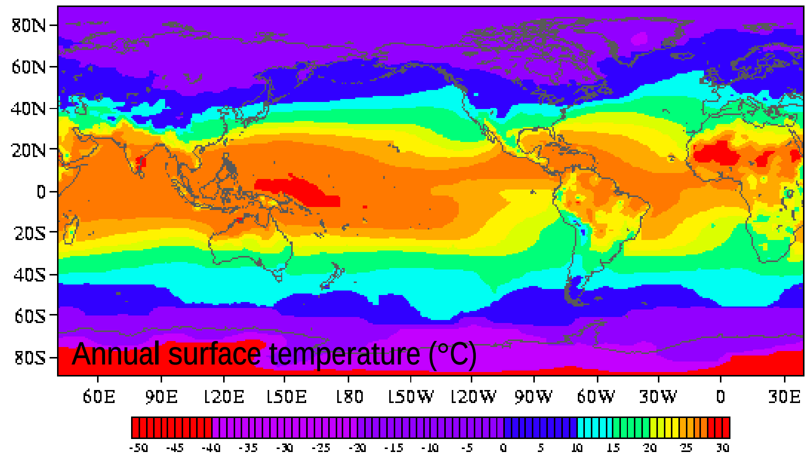
** Radiation tutorial/refresher: Chapter 7 in Jacob's "Introduction to Atmospheric Chemistry"*

Human Impacts on the Climate System
Radiative forcing of climate between 1750 and 2006



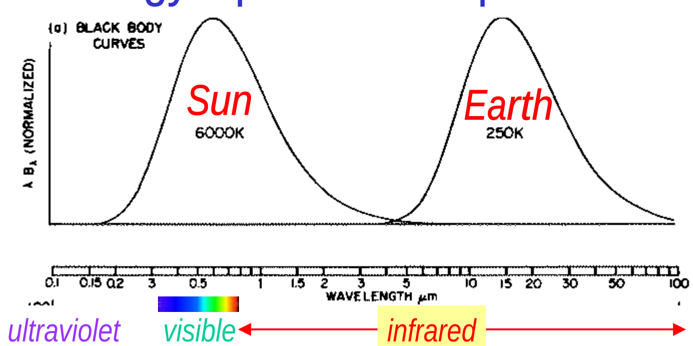
IPCC, Chap 2

Global Temperature



• Annual and global average temperature ~ 15°C, i.e. 288 K

Energy Inputs and Outputs



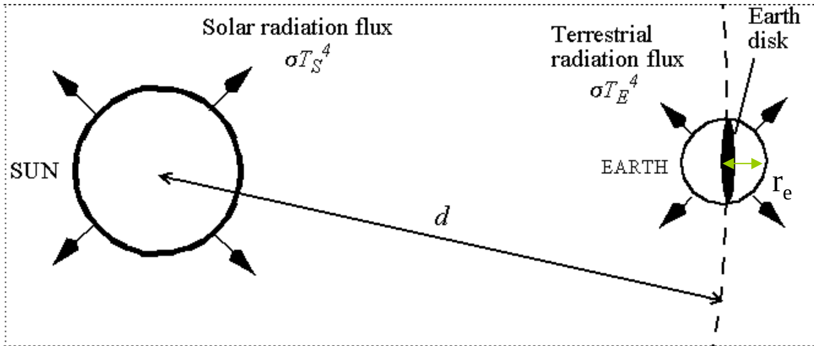
• Both Sun and Earth behave as blackbodies (absorb 100% incident radiation; emit radiation at all wavelengths in all directions)

• Earth receives energy from sun in the form of shortwave radiation with peak in the visible (λ = 0.4 - 0.7 μm)

• Earth emits energy to space in the form of longwave radiation in the infrared (λ = 5-20 μm) → function of Earth's temperature

Total Solar Radiation Received By Earth

- Solar constant for Earth: F_s=1368 W m^{-2} (Note: 1 W = 1 J s^{-1})



- Solar radiation received top of atmosphere unit area of sphere = (1368) x (π r_e^2)/(4 π r_e^2) = 342 W m^{-2}

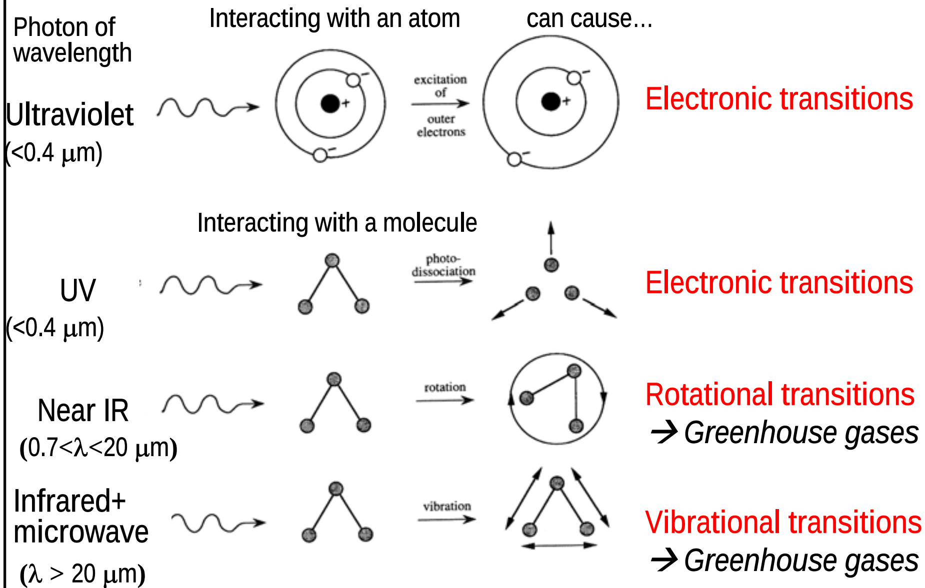
A No-Atmosphere Earth

- Assume 30% of incoming solar energy is reflected by surface (albedo of surface = 0.3)
- Energy absorbed by surface = 70% of 342 W m^{-2} = 239.4 W m^{-2}
- Balanced by energy emitted by surface
- Stefan-Boltzmann law: Energy emitted = σT^4 ;(σ=5.67 x 10^{-8} W m^{-2} K^{-4})
- 239.4 W m^{-2} = σT^4 → T = 255 K (-18°C)

  → much less than average temperature of 288 K (15°C)
- What is missing?

  → Absorption of terrestrial radiation by the atmosphere

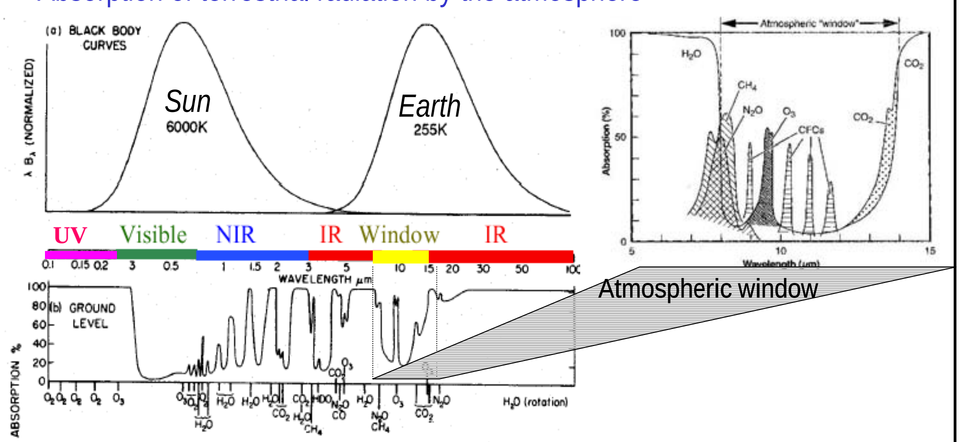
Interactions between radiation and atoms or molecules



Philander, Is the temperature rising? 1998.

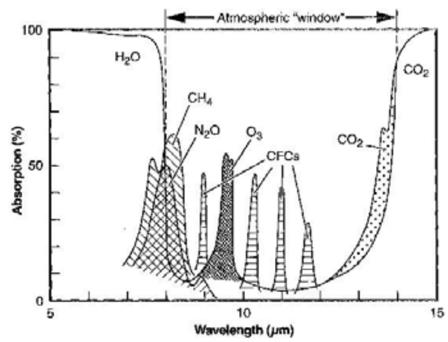
Greenhouse Effect:

Absorption of terrestrial radiation by the atmosphere



Goody & Yung, 1989

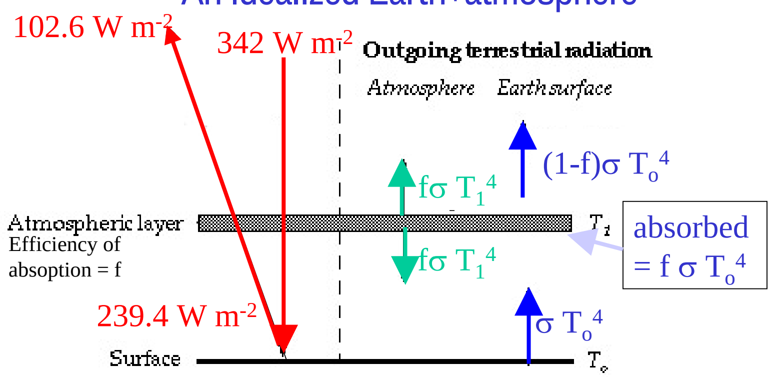
Absorption of terrestrial infrared radiation by greenhouse gases such as H_2O, CO_2, O_3, CH_4, N_2O, CFCs keeps the Earth's surface warmer than would be the case if there were no atmosphere



Not all molecules are equal…

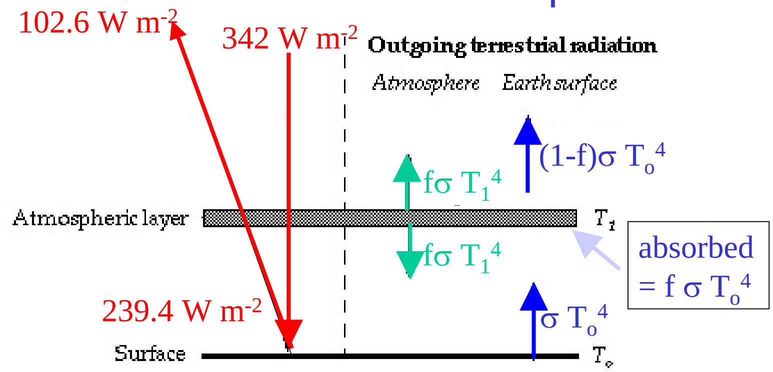
Question:
Consider CO_2, CH_4, N_2O, O_3, and CFCs: on a per molecule basis, which do you expect to be most effective at absorbing infrared radiation? Least effective? Why?

An Idealized Earth+atmosphere



- Solar radiation at surface = 70% of 342 W m^{-2} = 239.4 W m^{-2}
- Infrared flux from surface = σT_o^4
- Absorption of infrared flux by atmosphere = $f \sigma T_o^4$
- Kirchhoff's law: efficiency of absorption = efficiency of emission
- IR flux from atmospheric layer = $f \sigma T_1^4$ (up and down)

Radiation Balance Equations



- Balance at top of atmosphere

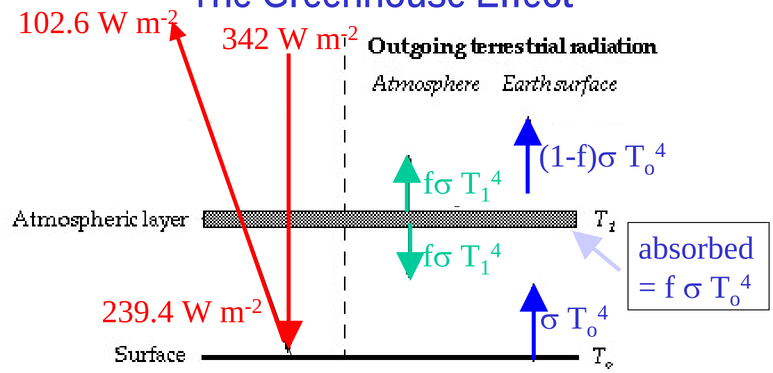
$$f \sigma T_1^4 + (1-f) \sigma T_o^4 = 239.4$$

- Balance for atmospheric layer

$$f \sigma T_1^4 + f \sigma T_1^4 = f \sigma T_o^4$$

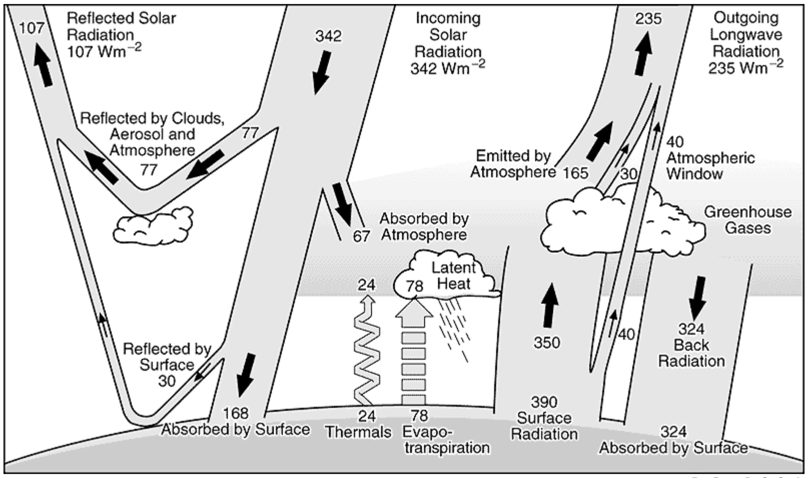
→ Solve for T_o and T_1

The Greenhouse Effect



- For f=0.77, T_o=288 K and T_1=242 K (33 K warmer than the no-atmosphere case)
- As f increases, T_o and T_1 increase
- Greenhouse gases → gases that affect f (absorption efficiency of atmos.)
- Earth has a natural greenhouse effect; human activities enhance effect

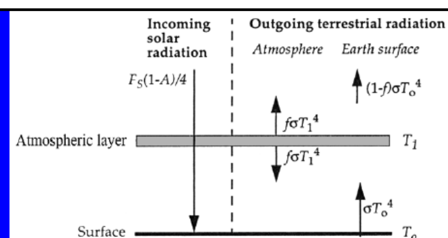
Energy Balance on Earth



IPCC, 2001

What are the differences between this picture and our simple model?

Sequence of Increasingly Complex Models



Division of atmosphere into elemental slabs

↓

"Gray atmosphere" model → Exponential decrease in temperature $T_{TOP} \sim 210$ K

Resolution of spectral absorption into lines and "band models"

↓

Spectrally resolved radiative models

Inclusion of buoyancy, convection, energy balance

↓

Radiative-convective models

Global, three-dimensional equations for conservation of energy, mass and momentum

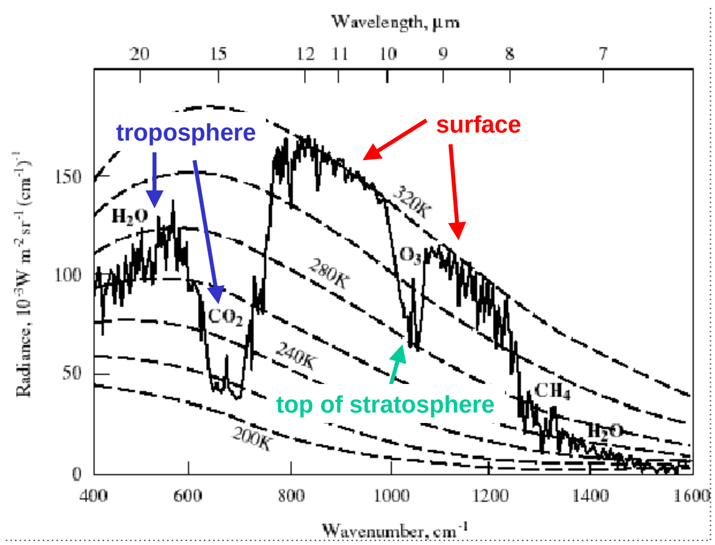
↓

General circulation models

The ultimate models for climate research

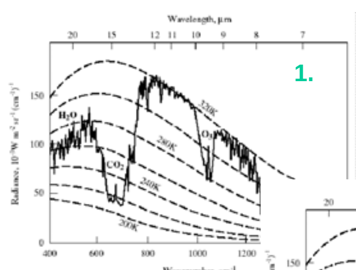
TERRESTRIAL RADIATION SPECTRUM FROM SPACE: composite of blackbody radiation spectra for different *T*

Scene over Niger valley, N Africa

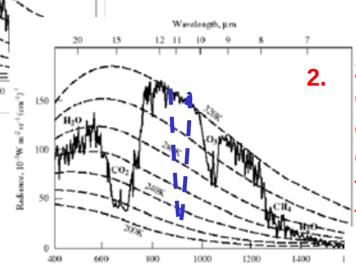


How does the addition of a greenhouse gas warm the earth?

Example of a GHG absorbing at 11 µm

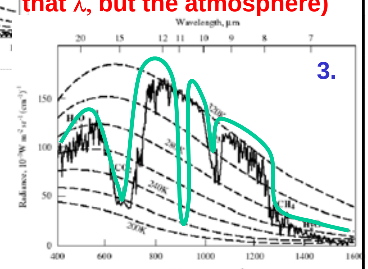


1. Initial state



2. Add to atmosphere a GHG absorbing at 11 µm; emission at 11 µm decreases (we don't see the surface anymore at that λ, but the atmosphere)

3. At new steady state, total emission integrated over all λ's must be conserved
⇨ Emission at other λ's must increase
⇨ The Earth must heat!



Concept of Radiative Forcing

Measure of the climatic impact of a greenhouse gas or other forcing agent

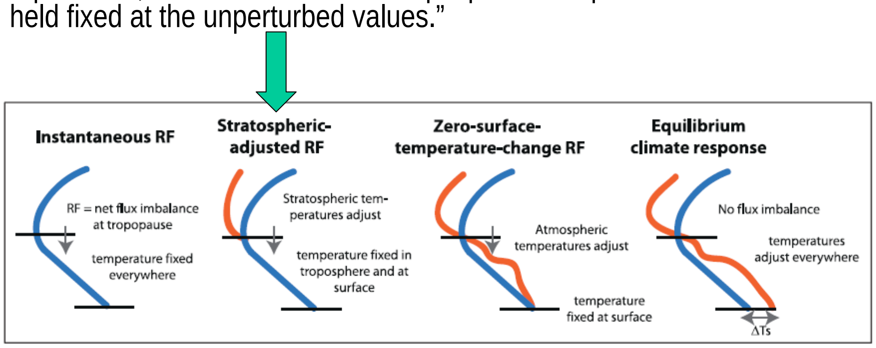
• Radiative forcing = change in radiation balance (flux in minus out) at the top of the atmosphere due to a change in amount of greenhouse gas before the system relaxes to equilibrium. ΔF (W m^{-2})

• Consider atmosphere in radiation balance:

➢ If concentration of a greenhouse gas increases and nothing else changes → outgoing terrestrial radiation decreases

IPCC definition of radiative forcing

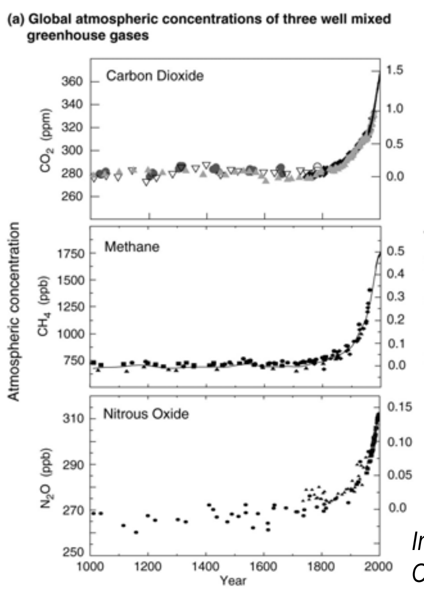
• IPCC definition
"The radiative forcing of the surface-troposphere system due to the perturbation in or the introduction of an agent (say, a change in greenhouse gas concentrations) is the change in net (down minus up) irradiance (solar plus long-wave; in Wm^{-2}) at the tropopause AFTER allowing for stratospheric temperatures to readjust to radiative equilibrium, but with surface and tropospheric temperatures and state held fixed at the unperturbed values."



Why is radiative forcing useful?

- Simple measure to quantify and rank the many different influences on climate change.
- Robust. can be calculated with some accuracy
- Additive (globally/regionally/locally)
- Is used to calculate surface temperature changes, but avoids issue of climate sensitivity
- Near-quantitative comparison of anthropogenic forcing agents

Radiative forcing calculations



Simplified expressions for RF calculations

Gas	Radiative forcing
CO_2	$F = f(c) - f(c_o)$, where $f(c) = 4.996 \ln (c + 0.0005c^2)$
CH_4	$F = 0.0406(\sqrt{m} - \sqrt{m_o}) - [g(m, n_o) - g(m_o, n_o)]$
N_2O	$F = 0.136(\sqrt{n} - \sqrt{n_o}) - [g(m_o, n) - g(m_o, n_o)]$, where $g(m, n) = 0.5 \ln [1 + 2 \times 10^{-5}(mn)^{0.75}]$
CFC-11	$F = 0.264(x - x_o)$
CFC-12	$F = 0.323(y - y_o)$

c, CO_2 (ppm); m, CH_4 (ppb); n, N_2O (ppb); x/y, CFC-11/12 (ppb).

Table from Hansen et al., PNAS, vol. 97 (18), 9875-9880, 2000

Intergovernmental Panel on Climate Change (IPCC), 2001.

Human Impacts on the Climate System
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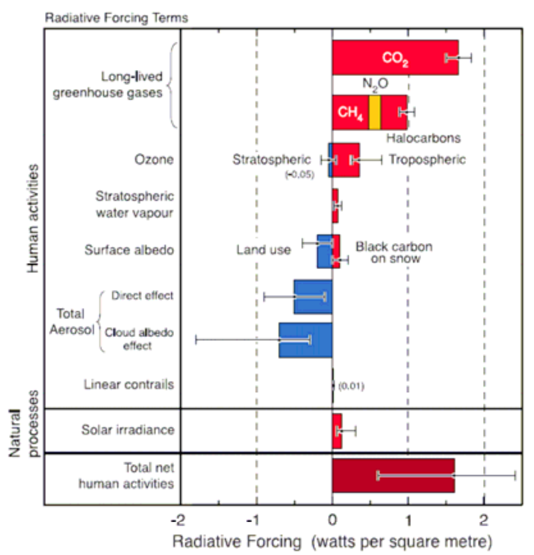


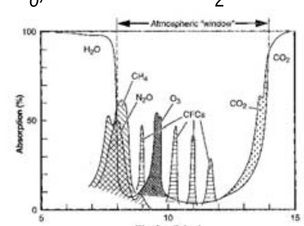
Radiative forcing gives first-order estimate of the relative climatic forcing of anthropogenic gases, aerosols, land-use change

IPCC, Chap 2

GLOBAL WARMING POTENTIAL (GWP): foundation for climate policy

- The GWP measures the integrated radiative forcing over a time horizon Δt from the injection of 1 kg of a species X at time t_o, relative to CO_2:

$$GWP = \frac{\int_{t_o}^{t_o+\Delta t} \Delta F_{1\text{ kg X}}\, dt}{\int_{t_o}^{t_o+\Delta t} \Delta F_{1\text{ kg CO}_2}\, dt}$$



Gas	Mixing ratios (ppm) in 2005	Lifetime (years)	GWP for time horizon 20 years	100 years	500 years
CO_2	379	~200	1	1	1
CH_4	1.774	12	72	25	7.6
N_2O	0.319	114	289	298	153
CFC-12 (CF_2Cl_2)	0.000538	100	11,000	10,900	5,200
SF_6	0.0000056	3200	16,300	22,800	32,600

CO_2 equivalent emissions

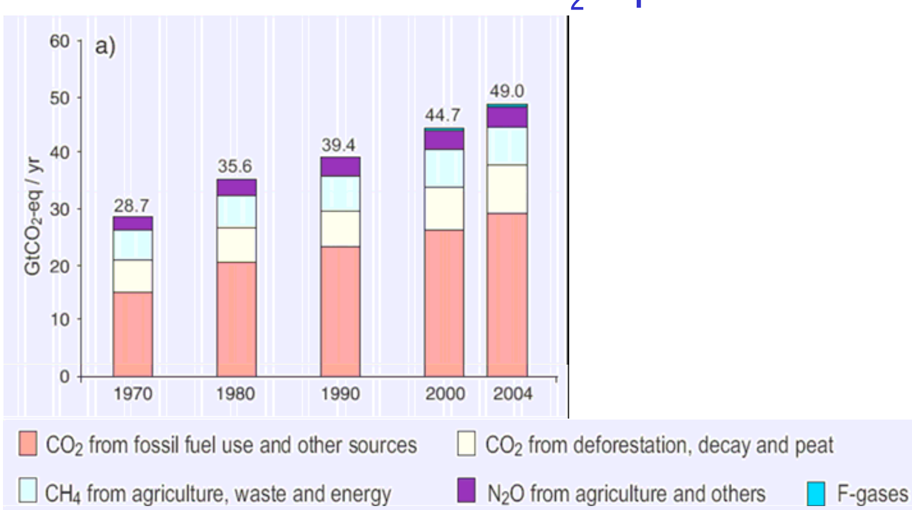
- Amount of CO_2 that would have the same radiative forcing as an emitted amount of a GHG for a 100 year horizon

= time integrated radiative forcing

- Example: Emitting 1 million ton of CH_4 (GWP(100 years) = 25) is the same as emitting 25 million tons of CO_2 or 25 Gt CO_2-equivalent.

- Question: are the impacts really the same?

Global anthropogenic GHG emissions in terms of CO_2-eq



IPCC, WGIII Mitigation, TS (2007)

Radiative Forcing and Temperature Change

• Response of system to energy imbalance: → T_0 and T_1 increase
→ may cause other greenhouse gases to change
→ T_0 and T_1 may increase or decrease depending on internal climate *feedbacks*
→ Δf → ΔT → etc… → Ultimately, the system gets back in balance

• Radiative forcing is only a measure of initial change in outgoing terrestrial radiation

• How do we relate radiative forcing to temperature change?

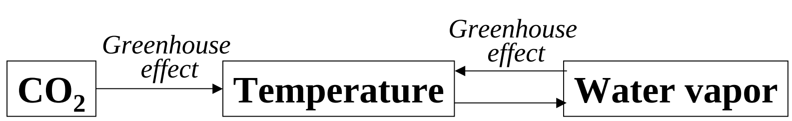
$$\Delta T_0 = \lambda \, \Delta F,$$

ΔT_0: Surface Temperature change (°C)
ΔF: Radiative forcing (W/m^2)
λ : Climate sensitivity (°C per W/m^2)

•Climate models (GCMs) indicate that λ ranges from 0.3 to 1.4 °C per W/m^2. On average $\lambda \sim 0.75$ °C per W/m^2

Feedbacks

• **water vapor feedback:** positive.



• **ice-albedo feedback:** positive.
• **cloud feedbacks:** positive or negative? potentially large
(clouds can reflect solar radiation or absorb IR radiation depending on their height, thickness and microphysical properties)

• **land surface feedback:** positive (deforestation and hydrological cycle)

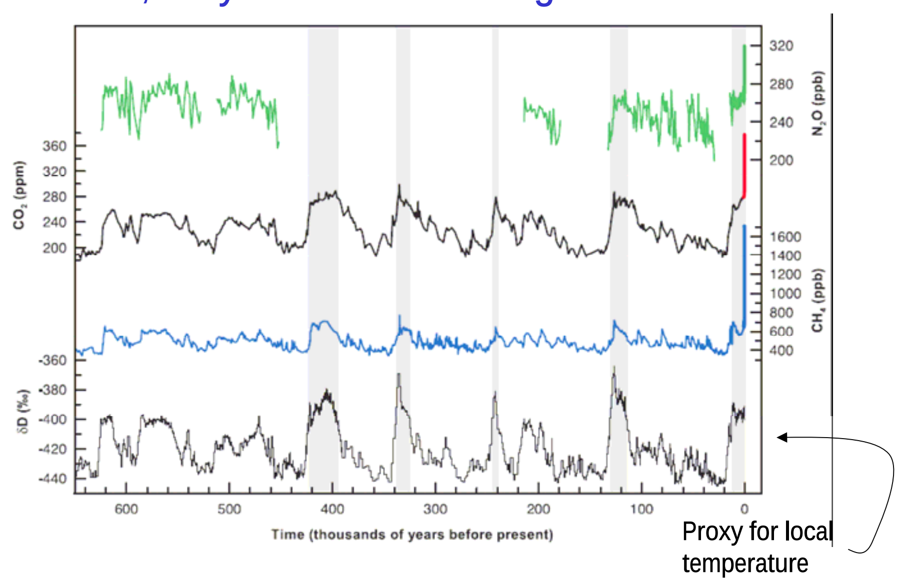
Climate response to a doubling of CO_2

Solar (S) and longwave (L) radiation in Wm^{-2} at the top of the atmosphere

S	L	S	L	S	L	S	L
235	235	235	231	235	235	235	235

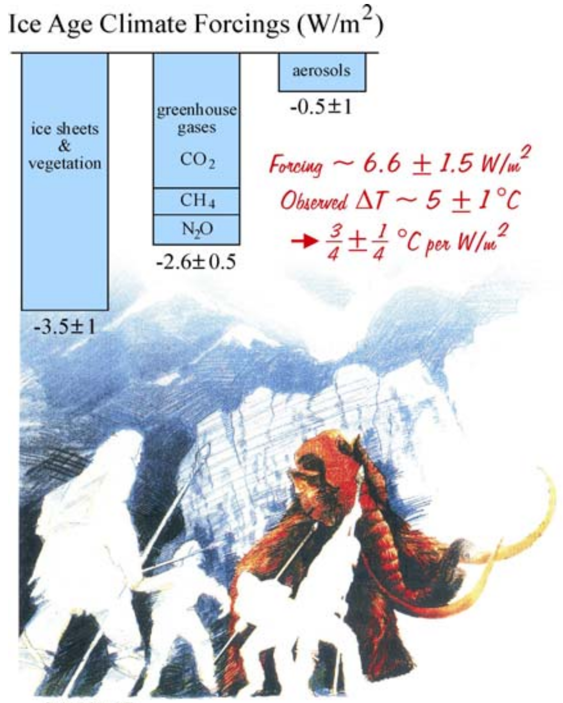
T = -18°C	CO_2 x 2 ΔF ~ 4 Wm^{-2}	CO_2 x 2	CO_2 x 2 + Feedbacks: H_2O (+60%) Ice/Albedo (+60%) Clouds?
T_S = 15°C	T_S = 15°C	ΔT_S ~ 1.2°C	ΔT_S ~ 3°C

Past 650,000 years: Glacial-interglacial ice core data



IPCC, TS (2007)

Ice Age Forcings Imply Global Climate Sensitivity ~ ¾°C per W/m².



Source: Hansen et al., *Natl. Geogr. Res. & Explor.,* **9***,* 141, 1993.