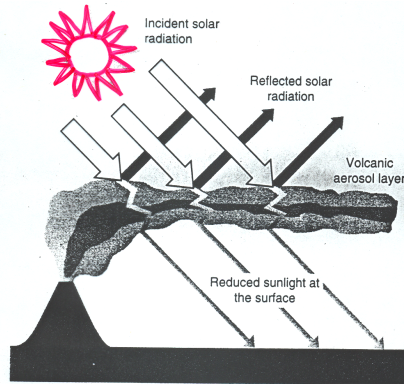
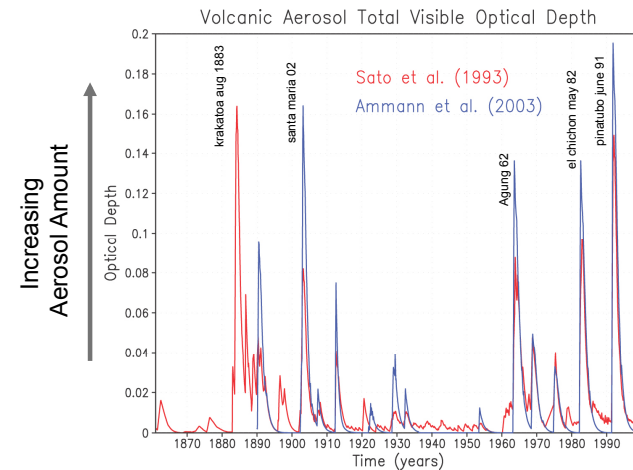


Mechanism of Volcanic Perturbation

- Sulphate particles in the stratosphere reflect sunlight, hence increase the planetary albedo
- Process is well understood but ...
 - Amount of sunlight scattered depends greatly on size and amount of aerosol particles
 - The global monitoring of aerosols began in ~1980
- Hence, the history of the amplitude of the ‘forcing’ before 1980 is poorly known



Major Volcanic Eruptions in the past



Estimates from two different groups

IPCC 2007 Fig 2.18

Volcanic Eruptions and Global Temperature

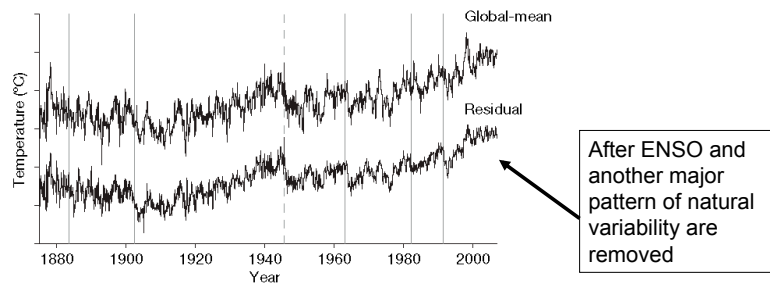
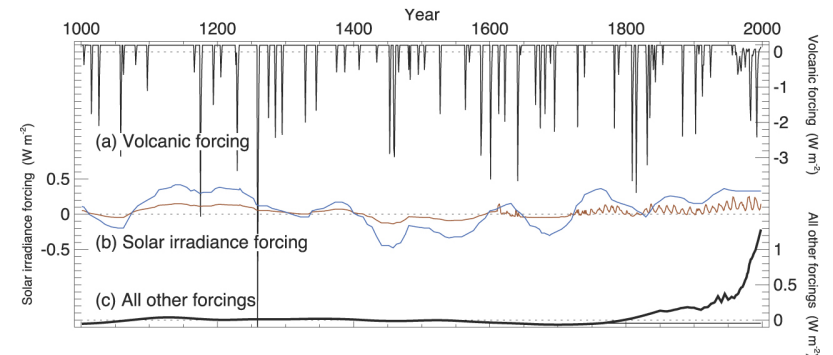


Figure 2 | The original (that is, unfiltered) and residual global-mean temperature time series duplicated from Fig. 1. The solid vertical lines denote volcano eruption dates: from left to right, Mts Krakatoa, Santa Maria, Agung, El Chichón and Pinatubo. The dashed vertical line denotes the month of August 1945. Vertical axis shows temperature anomalies; tickmarks indicate steps of 0.5°C.

- Suggestion that the typical large volcano can cool the planet by ~0.3°C for about a year or so

Thompson et al 2008

Major Volcanic Eruptions in the past



Estimates of forcing amplitude are highly uncertain because amount and size of aerosol lofted is only crudely estimated



Mt. Rinjani, Indonesia 1258

IPCC 2007 Fig 6.14

Climate Variability and Climate Change

1. Definitions

- The Climate System; Natural and Forced Variability

2. Natural Variability

- North Atlantic Oscillation, El Nino/Southern Oscillation

3. Forced Change (natural)

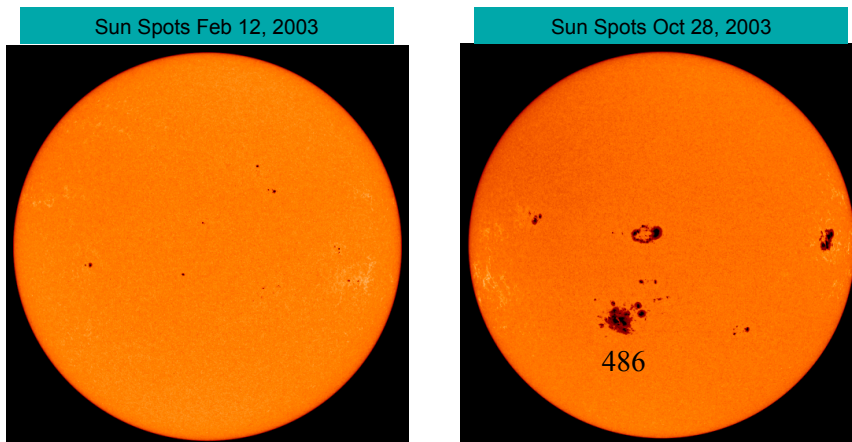
- Volcanic Eruptions (scattering particles)
- Changes in the Solar Luminosity

4. Forced Change (human)

- Burning of fossil fuels (increasing GH gases)
- Burning of biomass (scattering particles)

Forced Change: Changes in the Sun's output

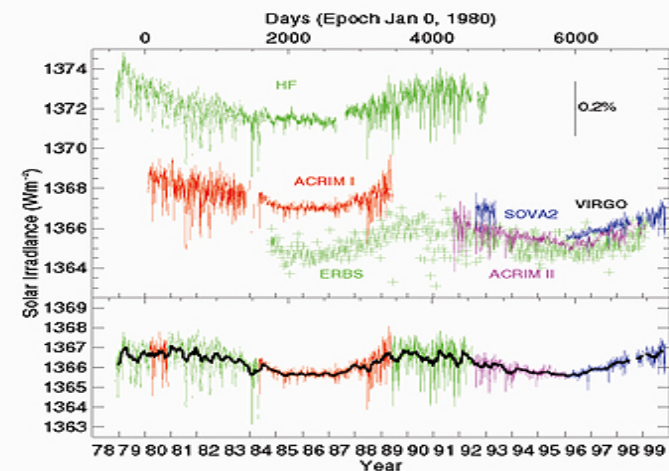
- Sunspots are associated with a small *increase* in energy coming from the Sun
 - Sunspot numbers vary (11 year cycle, and other poorly understood time scales)
- We have direct estimates of the change in insolation since 1978
 - The solar constant varies by +/- 0.05% over the sunspot cycle, or about +/- 0.5W/m², or about +/-0.125 W/m² averaged over the whole Earth
- Changes are too small to explain correlated variability in global temperature (so proponents of solar forcing offer exotic ideas -- often involving cosmic rays and clouds -- to amplify the impact):
 - Expect ~0.05°C changes in global temperature



"one of the most powerful solar flares in years... erupted from sunspot 486."

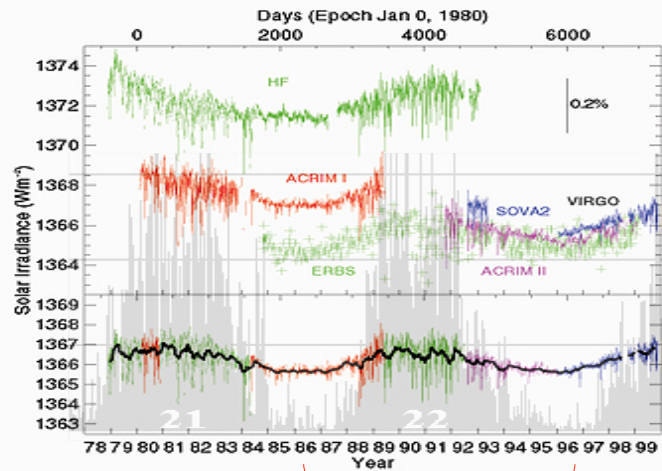
www.spaceweather.com

The Solar Constant



Direct measurements of Solar luminosity since 1978

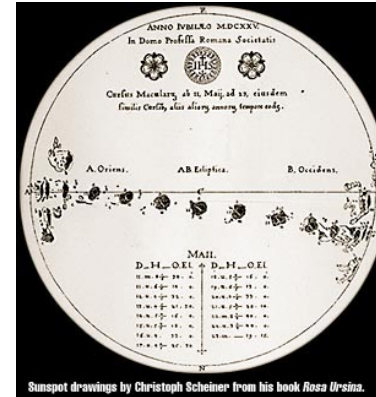
The Solar Constant



Sunspot cycle #22

Sunspot observations

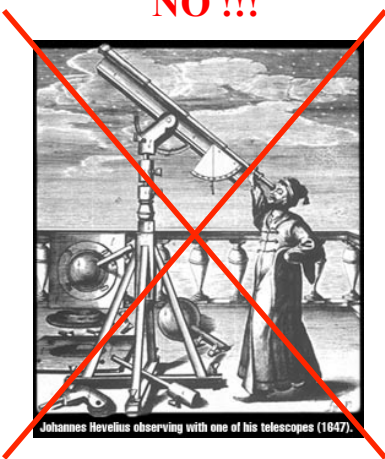
25 BC: First sunspot records in China
 1611: Sunspots discovered by Europeans (with telescopes)



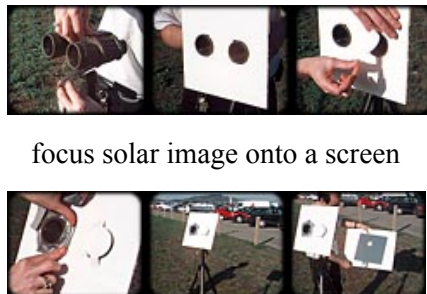
An image of the region around a sunspot. The mottled appearance is due to turbulent eruptions at the surface of the sun.

How to view sunspots

NO !!!



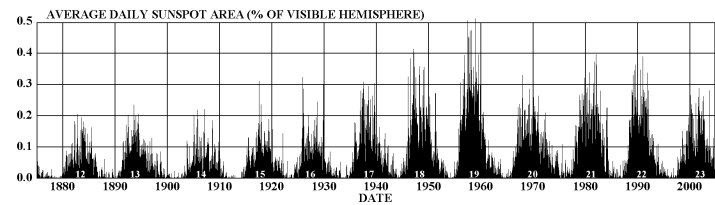
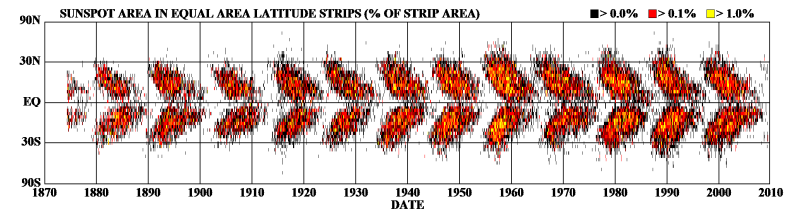
Yes



focus solar image onto a screen

Sunspot Evolution

DAILY SUNSPOT AREA AVERAGED OVER INDIVIDUAL SOLAR ROTATIONS

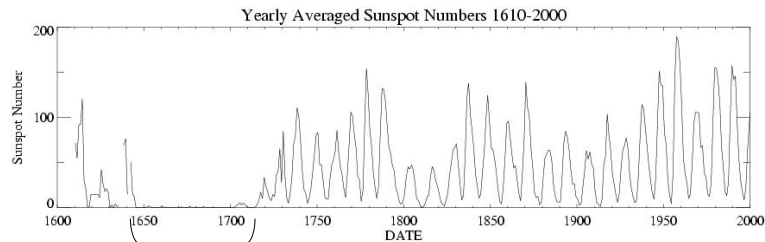


<http://science.msc.nasa.gov/solpod/solar/images/bbf.gif>

NASA/SSSTC/HATHAWAY 2004/11

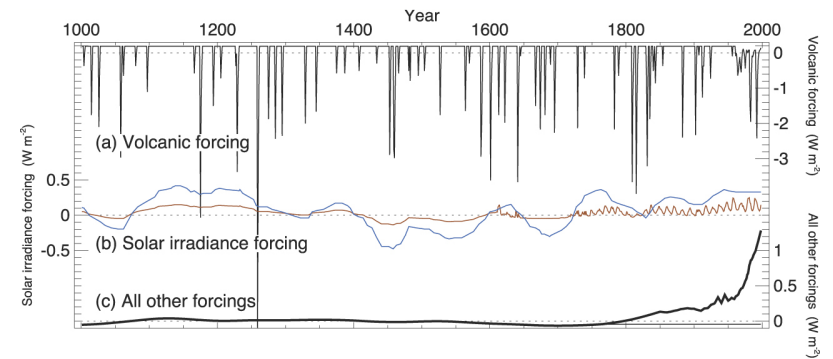
Cycle is on average 10.55 yrs (range is 9 to 14 yr)

Sunspot Numbers



Maunder Minimum in Sunspots
(Also the time of the "Little Ice Age" in Europe)
Coincidence?

The Solar Constant in the past



History of Sun's luminosity is revised downward (to brown curve)

Estimate comes from: (i) extrapolating direct insolation-sunspot number relationship; (ii) modeling of the solar magnetic flux; ^{14}C and ^{10}Be measurements in trees (cosmogenic flux); (iii) observing range of luminosity in other Sun-like stars.

IPCC 2007 Fig 6.14

Climate Variability and Climate Change

1. Definitions

- The Climate System; Natural and Forced Variability

2. Natural Variability

- North Atlantic Oscillation, El Niño/Southern Oscillation

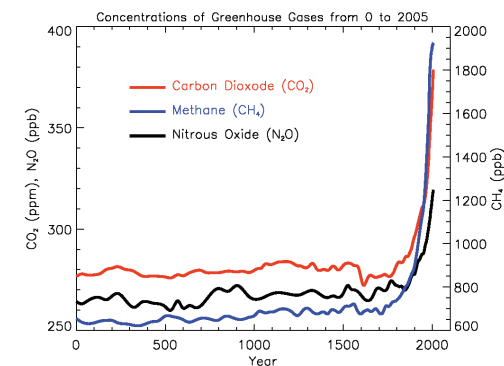
3. Forced Change (natural)

- Volcanic Eruptions (scattering particles)
- Changes in the Solar Luminosity

4. Forced Change (human)

- Burning of fossil fuels (increasing GH gases)
- Burning of biomass (scattering particles)

Forced Change: Three Important GH gases influenced by human activity



FAQ 2.1, Figure 1. Atmospheric concentrations of important long-lived greenhouse gases over the last 2,000 years. Increases since about 1750 are attributed to human activities in the industrial era. Concentration units are parts per million (ppm) or parts per billion (ppb), indicating the number of molecules of the greenhouse gas per million or billion air molecules, respectively, in an atmospheric sample. (Data combined and simplified from Chapters 6 and 2 of this report.)

IPCC 2007

Forced Change: Three Important GH gases influenced by human activity

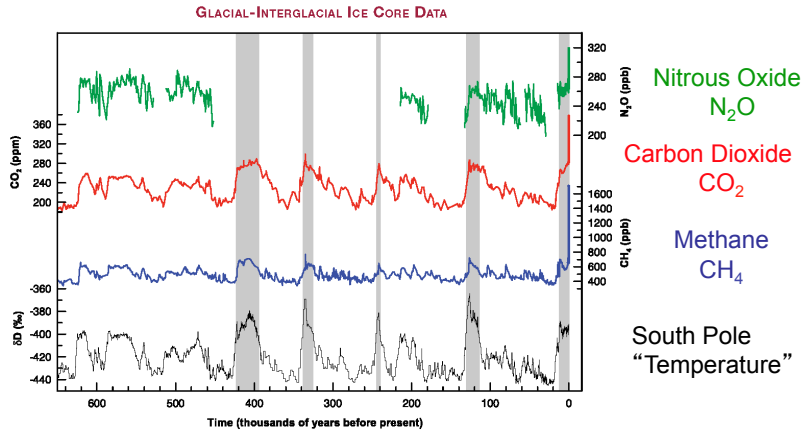
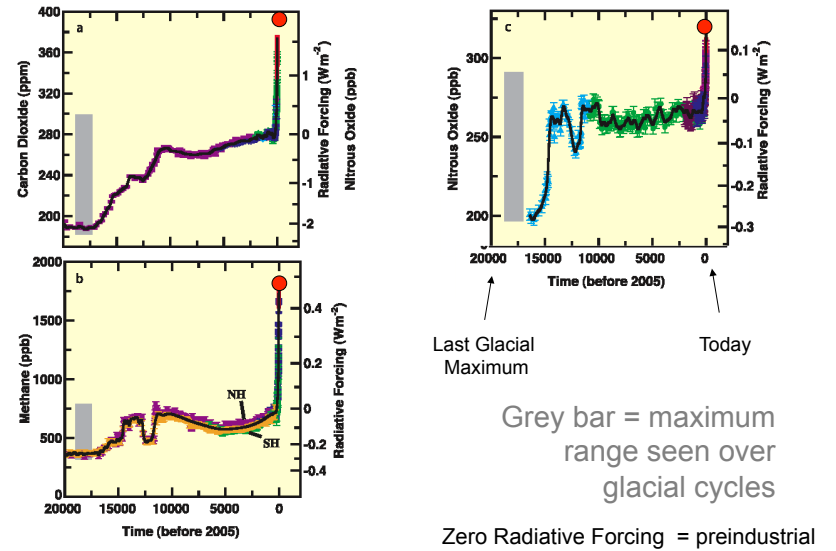
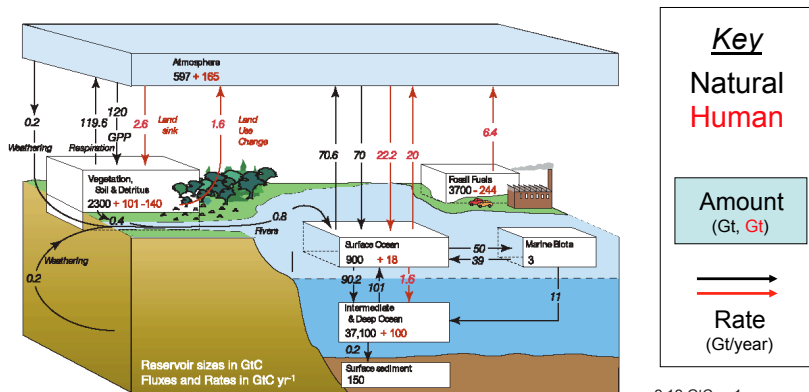


Figure TS.1. Variations of deuterium (δD) in antarctic ice, which is a proxy for local temperature, and the atmospheric concentrations of the greenhouse gases carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) in air trapped within the ice cores and from recent atmospheric measurements. Data cover 650,000 years and the shaded bands indicate current and previous interglacial warm periods. (Adapted from Figure 6.3)

Human Forcing: Changes in GH gases



The Carbon Cycle is complex

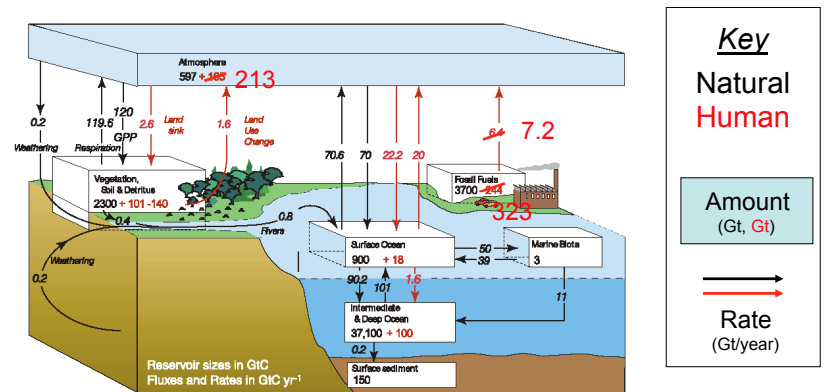


2.12 GtC = 1 ppm
1 Gt = billion tonnes

Where is the carbon *circa 1990AD*?

Ocean (non-biota) 38,150 + 118 Gt
Land Biosphere 2300 - 39
Fossil Fuels 3700 - 244
Ocean Biota 3
Atmosphere 600 + 165
Rocks gobs

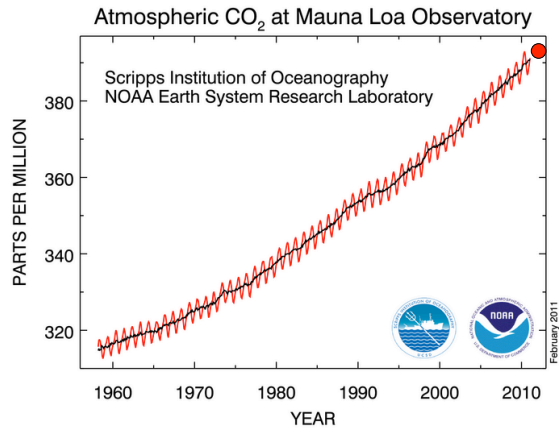
The Carbon Cycle is complex



Where is the carbon *circa 1990AD 2005AD*?

Ocean (non-biota) 38,150 + ~~118~~ + 145
Land Biosphere 2300 - ~~39~~ - 28
Fossil Fuels 3700 - ~~244~~ - 323
Ocean Biota 3
Atmosphere 600 + ~~165~~ + 213
Rocks gobs

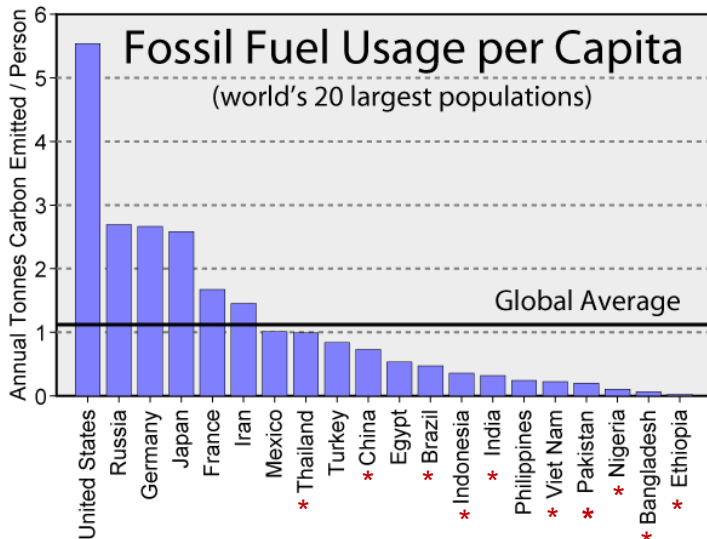
Atmospheric Carbon Dioxide



- Carbon Dioxide is increasing because of burning fossil fuels (85%) and deforestation (15%)
 - 25% increase in the past 50 years; 10% increase since 1991.

Fun Facts about CO₂

- Since Industrial revolution
 - 75% of carbon emission is due to fossil fuel burning and cement production; 25% due to land use.
- Today's emissions (2012): total 9.5 Gt/yr
 - 85% (8Gt/yr) due to fossil fuel and cement
 - 15% (1.5 Gt/yr) due to land use
- CO₂ in the atmosphere has increased:
 - About 10% since 1991;
 - 25% over the past 50 yrs;
 - 40% increase since the beginning of the industrial revolution
- Today: About 1/2 of what is emitted by humans stays in the atmosphere
 - the other half goes into ocean (2.7 Gt/yr) and land (2.2 Gt/yr)



* = Countries most affected by Global Warming

How do we know the increase in CO₂ is due to human activity?

- Inventory industry and government: how much coal and oil is sold each year?
- Look at isotopes of carbon in the atmosphere carbon dioxide
 - Cosmic rays create a little bit of C¹⁴ in the atmosphere, and plants take this in along with lots of normal carbon (C¹²)
 - Fossil fuels have no C¹⁴ because it is old (all C¹⁴ has decayed to N¹⁴; half life 5370yrs)
 - So adding CO₂ to the atmosphere from burning fossil fuels will cause the atmospheric C¹⁴/C¹² ratio to decrease over time.
- Look at how oxygen in atmosphere has change
- Inventory industry: how much cement is produced each year?

Human Forcing: Carbon Dioxide

Sources and Sinks of Carbon to the Atmosphere

	1980s	1990s	2000-2005	2010
Atmospheric increase	3.3 ± 0.1	3.2 ± 0.1	4.1 ± 0.1	4.6
Fossil carbon dioxide emissions	5.4 ± 0.3	6.4 ± 0.4	7.2 ± 0.3	8.0
Net ocean-to-atmosphere flux	-1.8 ± 0.8	-2.2 ± 0.4	-2.2 ± 0.5	-2.7
Net land-to-atmosphere flux	-0.3 ± 0.9	-1.0 ± 0.6	-0.9 ± 0.6	-2.2
<i>Partitioned as follows</i>				
Land use change flux	1.4 (0.4 to 2.3)	1.6 (0.5 to 2.7)	NA	1.5
Residual land sink	-1.7 (-3.4 to 0.2)	-2.6 (-4.3 to -0.9)	NA	(-3.7)

³ Fossil CO₂ emissions include those from the production, distribution and consumption of fossil fuels and from cement production. Emission of 1 GtC corresponds to 3.67 GtCO₂.

⁴ As explained in Section 7.3, uncertainty ranges for land use change emissions, and hence for the full carbon cycle budget, can only be given as 65% confidence intervals.

Units are Giga tonnes of Carbon per year

(1 Gt = 10⁹ tonnes; 1 tonne = 2200 lbs)

Human input (burning of fossil fuel) is increasing

Human Forcing: Carbon Dioxide

Sources and Sinks of Carbon to the Atmosphere

	Overall Gain (1750-2005)	Overall Rate (1750-2005)	Rate (2000-2005)
Emission (Fossil Fuel & Cement) + Land Use	323 +160 Gt	1.3+0.7 Gt/year	7.2 FF +1.6 (land use) Gt/year
In Atmosphere	213 Gt	0.8	4.1
In Ocean	145 Gt	0.5	2.2
In Land	125 Gt	0.4	2.5

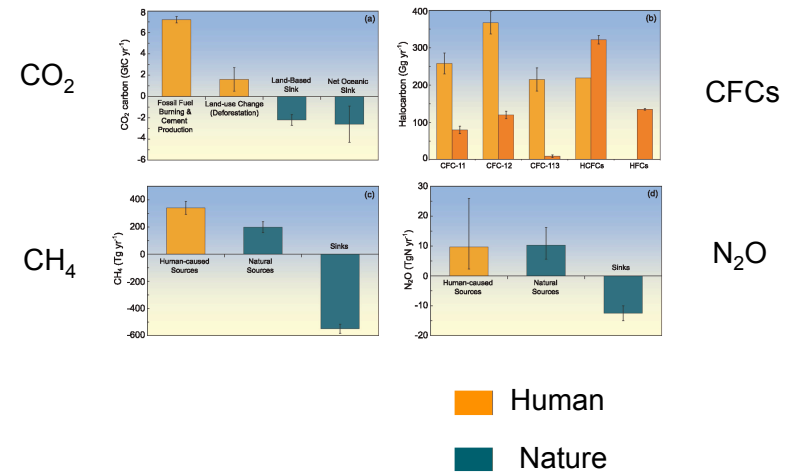
Amount presently in atmosphere: ~ 835 Gt

Forced Change: Three Important GH gases influenced by human activity

Gas	Human Source	Pre-Indust. Value	2005	RF in 2000 (W/m ²)
Carbon Dioxide CO ₂	Burning Fossil Fuel & Cement Production	280 ppm	379 ppm	+1.66
Methane CH ₄	Rice agriculture, livestock, landfills	700 ppb	1774 ppb	+0.48
Nitrous Oxide N ₂ O	Agriculture (fertilizer)	270 ppb	319 ppb	+0.16

Compare to solar (+/- 0.12 W/m²) or volcanic (~ -2 W/m²)

For some GH gases, some human sources are comparable to Nature's sources



Circa 2005

Human Forcing: Other GH gas changes

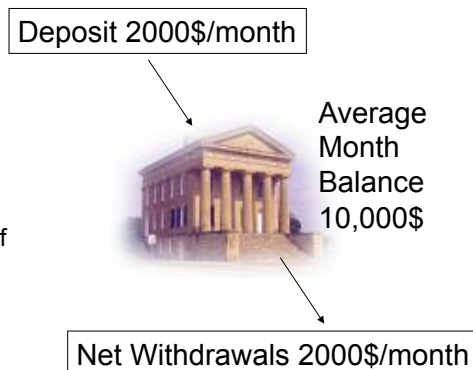
- Tropospheric Ozone (pollution and volatile organic carbon emission from planted forests): RF ~ +0.35 W/m²
- CFCs and HCFC (industrial) RF ~ + 0.35 W/m²

Tool: Residence time

- The residence time scale is the typical time it takes something to move through a reservoir when the system is in equilibrium (standard definition)
- It can also be thought of as the time it takes to see significant changes in a reservoir, if the inputs or outputs change (non-standard definition)

Tool: Residence time

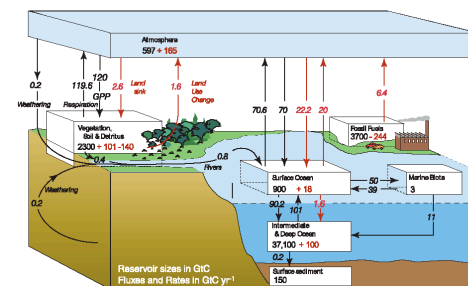
- For example, you have 10,000\$ in your bank account. You add 2000\$ per month to balance your monthly expenses of 2000\$.
- What is the residence time of a typical dollar in your bank account?



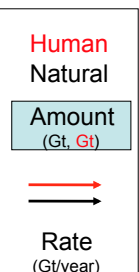
$$\text{Residence time} = 10,000\$ / (2000\$/\text{mo}) = 5 \text{ months}$$

Tool: Residence time

Residence time is a characteristic time for seeing large changes in some quantity. Another example: What is the residence time fossil fuel reservoir?



Key



$$\begin{aligned} \text{Residence time} &= \text{amount} / \text{rate of input} \\ &= 3700 \text{ Gt} / 6.4 \text{ Gt per year} = 580 \text{ yrs} \end{aligned}$$

Human Forcing: Aerosols

Human activity puts small particles in the troposphere that greatly affect the Earth's radiation balance

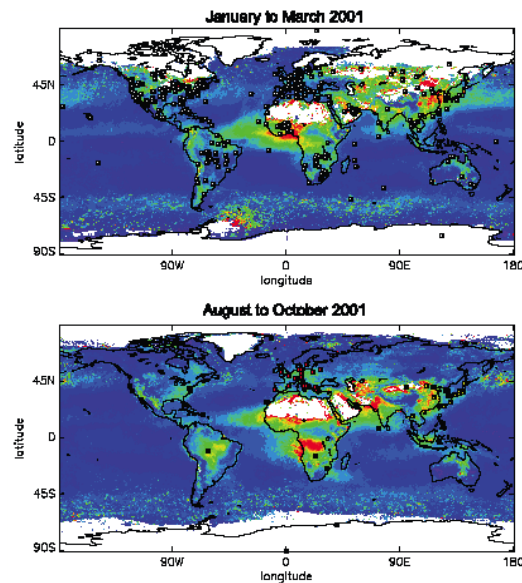
- Sulfates from the burning of coal
 - Direct effect: reflects visible light
 - Indirect effect: increases albedo of clouds
- Soot (organic and black carbon) from the burning of biomass
 - Absorbs visible light (warms atmosphere and cools surface)
- Industrial dust

Human Forcing: Aerosols

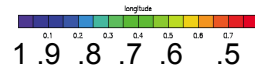
- Aerosols injected into the *troposphere* settle out quickly (about 2-5 days)
 - Mixing of air that brings it in contact with the ground
 - Scavenged by raindrops
- Hence, aerosols injected into the troposphere don't get far from the source

$$\begin{aligned} \text{Distance} &= \text{wind speed} \times \text{residence time} \\ &= 15 \text{ m/s} \times (3 \times 24 \times 60 \times 60 \text{ s}) \\ &= 4 \times 10^6 \text{ m} = 4000 \text{ km} \end{aligned}$$

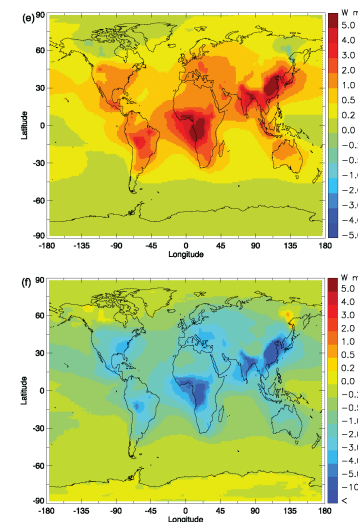
Aerosols in the atmosphere (human and natural)



Fraction of solar energy in mid-visible band reaching the surface (when no clouds are present)



Impact of Aerosols: Radiative Forcing



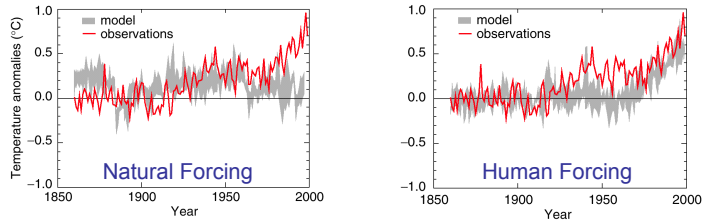
Shortwave absorbed in atmosphere by human sources of aerosols (SO_4 , black carbon)

Shortwave lost to the surface due to human sources of aerosols (SO_4 , black carbon)

Fig 2.12 of IPCC 2007 WG1

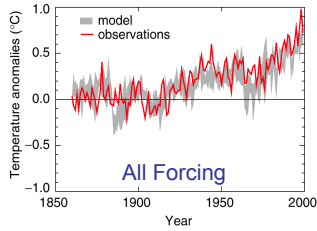
Climate Variability and Climate Change

Modeled and Observed Temperature Change 1850-2000



Natural Forcing
Sun, Volcanic

Human Forcing
Fossil Fuel and
Biomass Burning



Next: How we determine which changes are due to *natural variability* and which changes are due to *forcing (natural and human induced)*?