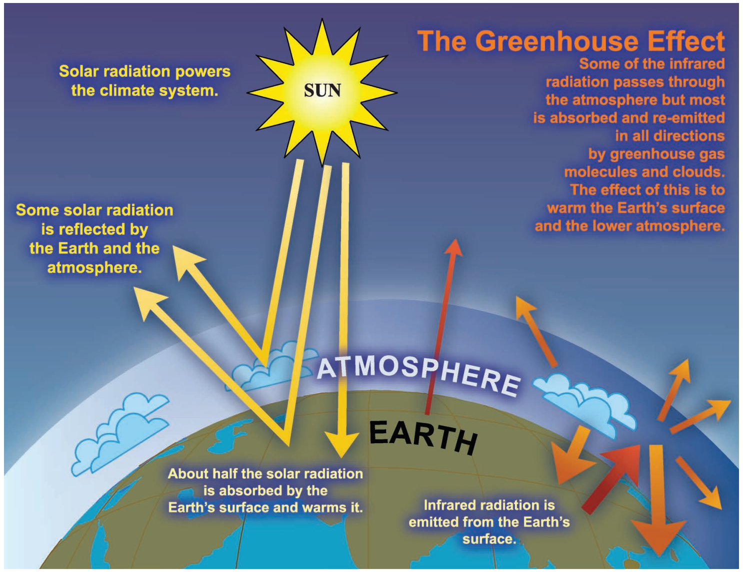
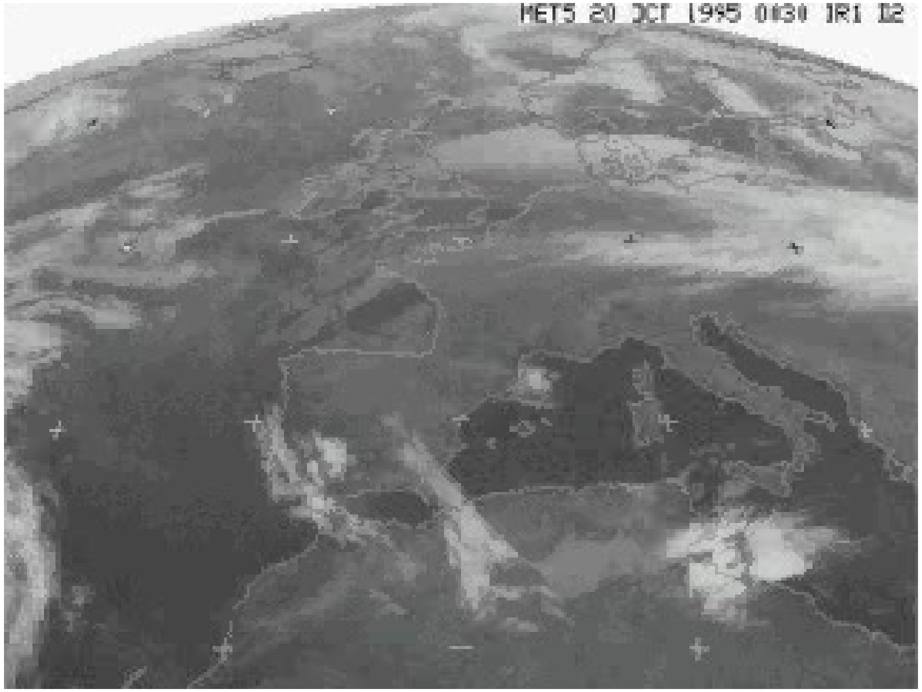
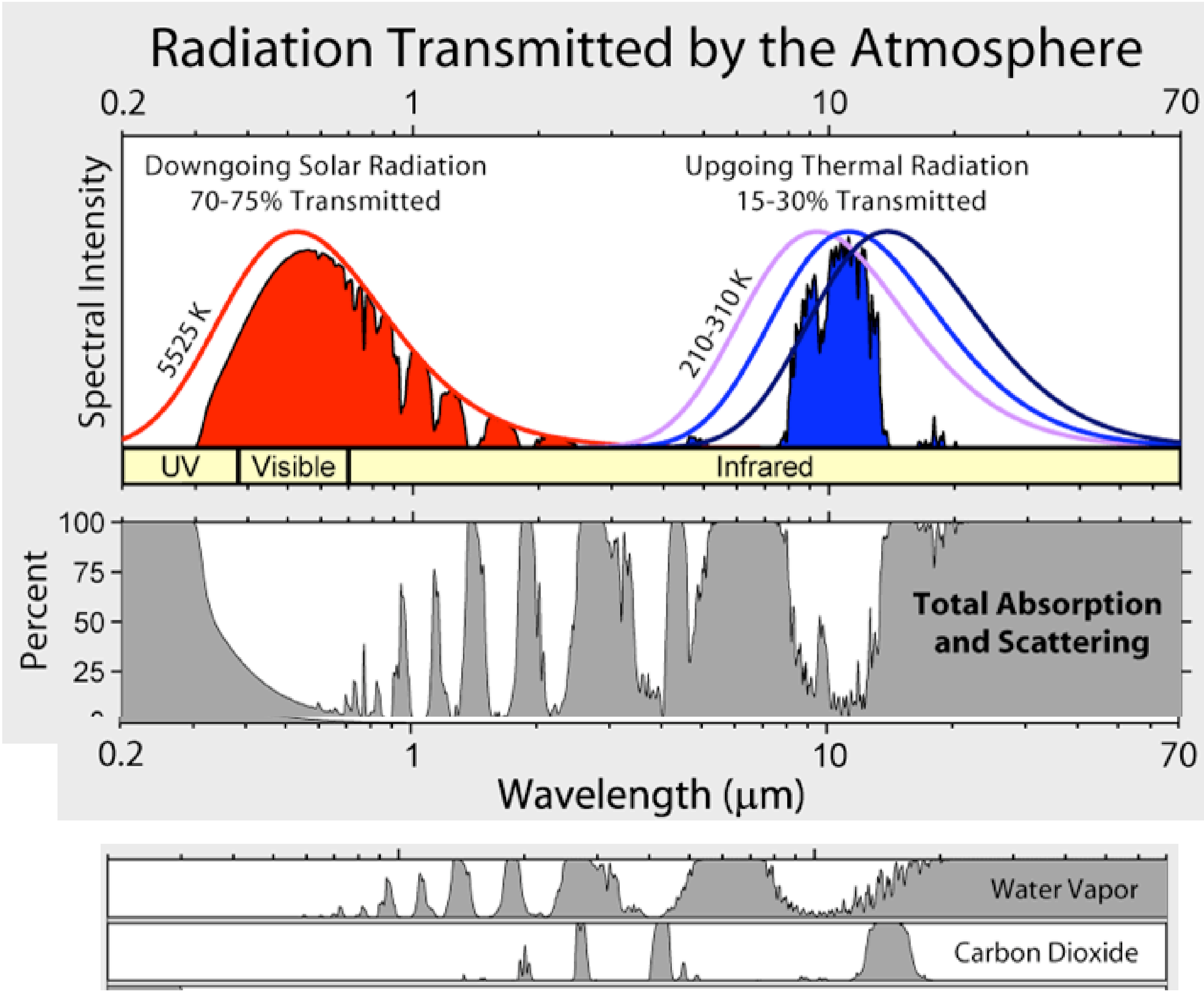
The carbon and climate problem

1. Heating from CO_2
2. Recent warming
3. Long-term effects of carbon emissions



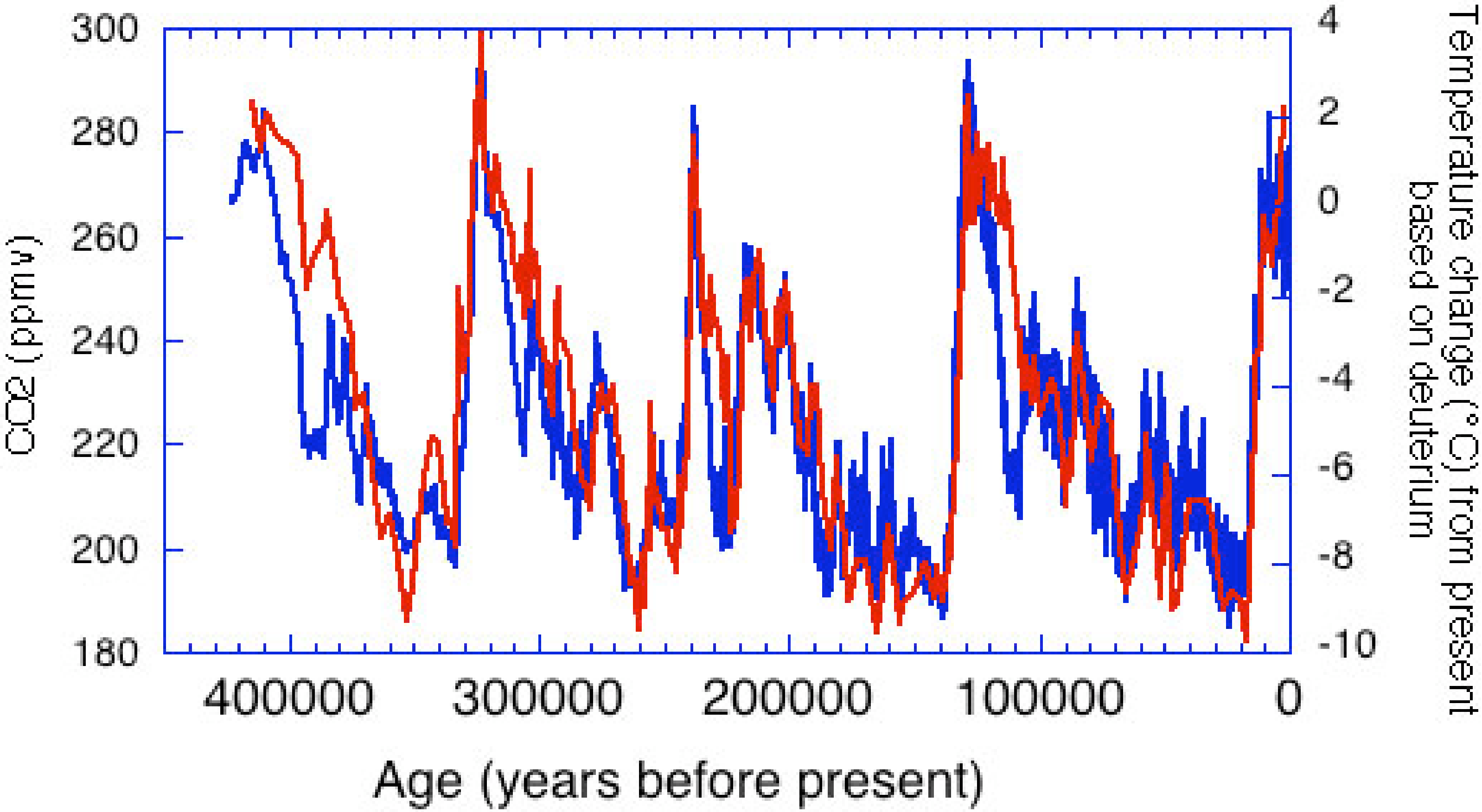




Radiation Transmitted by the Atmosphere
0.2
1
10
70
Spectral Intensity
Downgoing Solar Radiation
70-75% Transmitted
Upgoing Thermal Radiation
15-30% Transmitted
5525 K
210-310 K
UV
Visible
Infrared
Percent
100
75
50
25
Total Absorption
and Scattering
0.2
1
10
70
Wavelength (μm)
Water Vapor
Carbon Dioxide

Millennial changes

atmospheric CO_2 temperature change

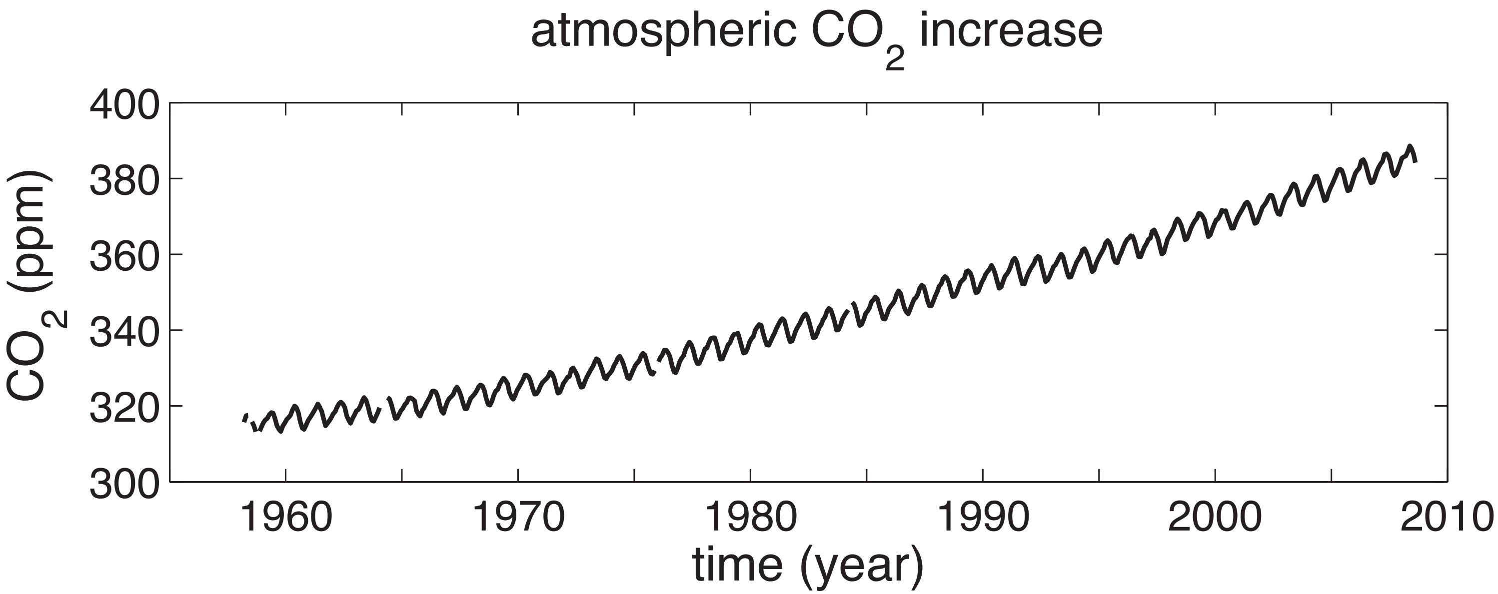


positive *correlation*
probably *positive feedback system*

http://www.ncdc.noaa.gov/paleo/globalwarming/temperature-change.html

1. Radiative heating and atmospheric CO_2

data/simple theory



Radiative forcing varies *logarithmically* with atmospheric CO_2 concentration

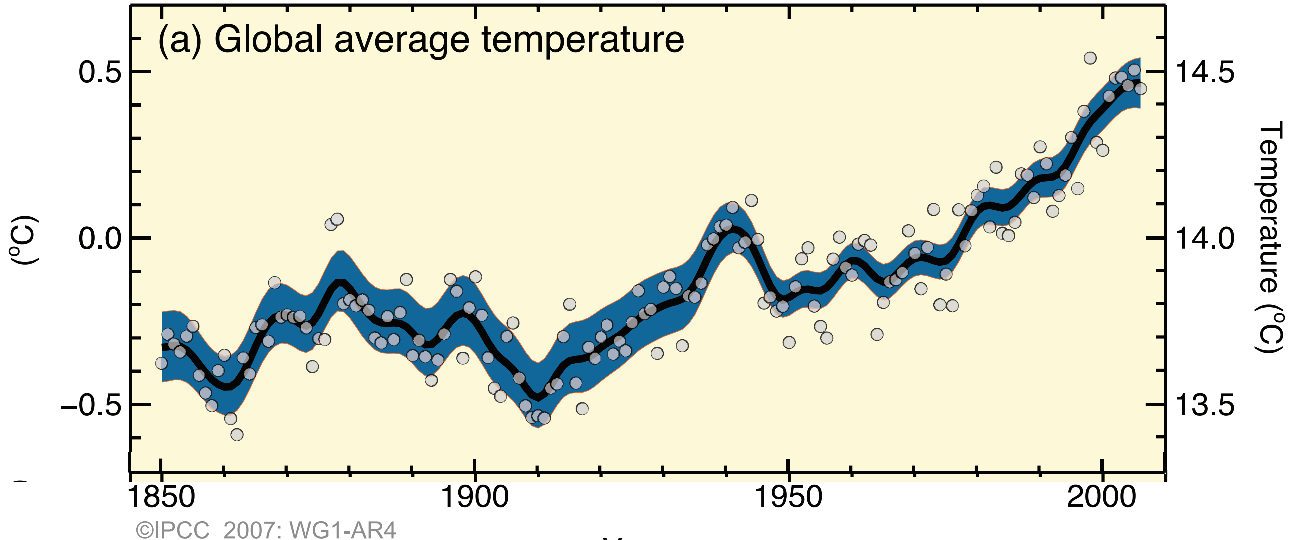
expect

- global rise in heat flux ~ 1 W m^{-2}
- ocean temperature rise ~ 0.4°C

Global warming data (from IPCC, 2007)

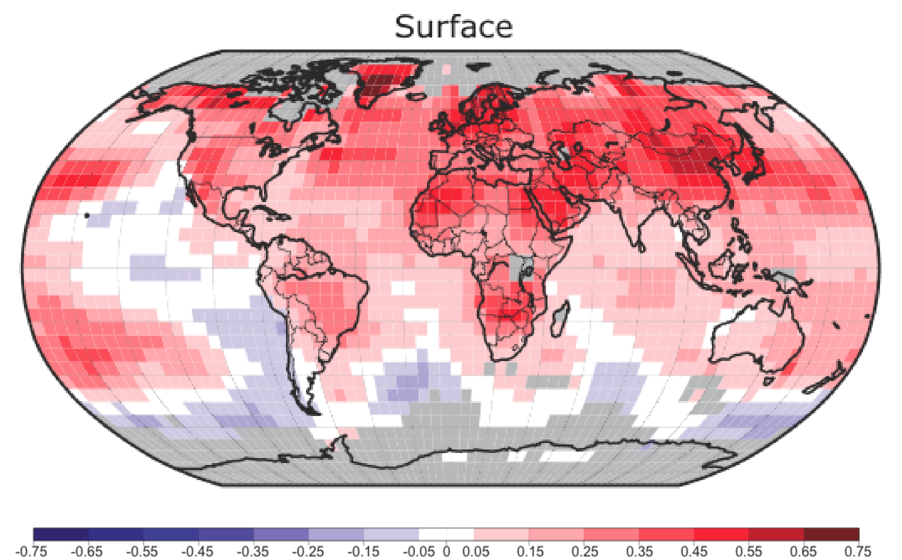
global data

global warming of 0.6°C since 1950



Surface warming since 1979:

- warming over most of globe
- land warming faster than ocean

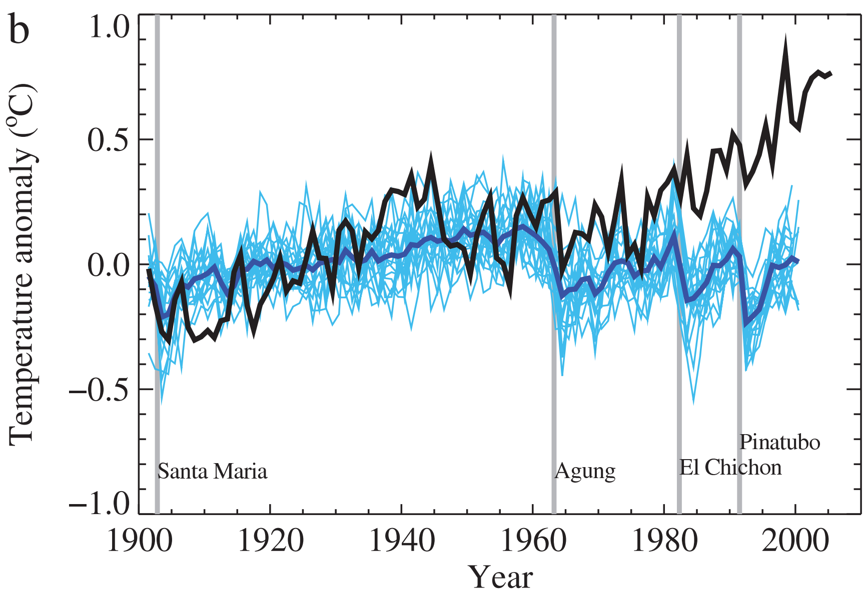


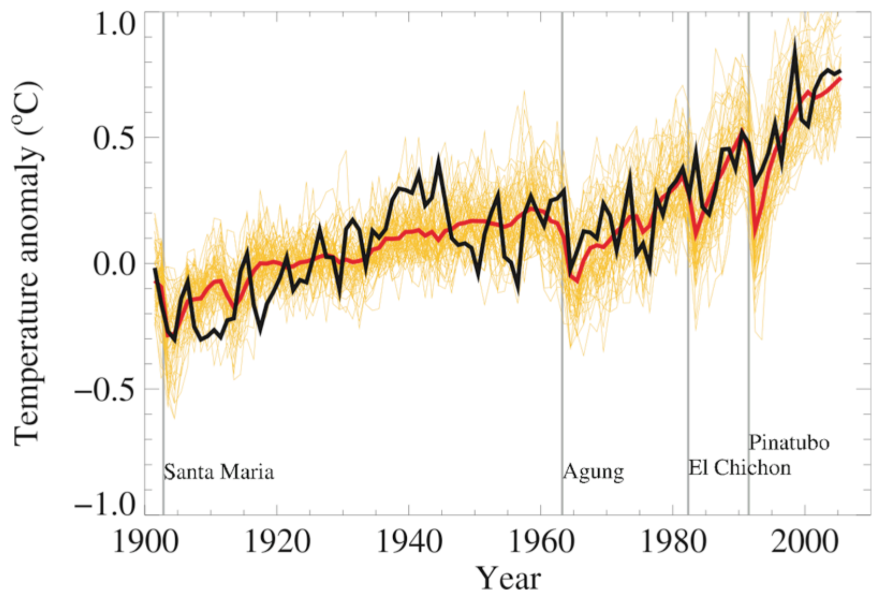
-0.75 -0.05 0.05 0.75

°C per decade

climate models

How can warming be explained?





data: black line

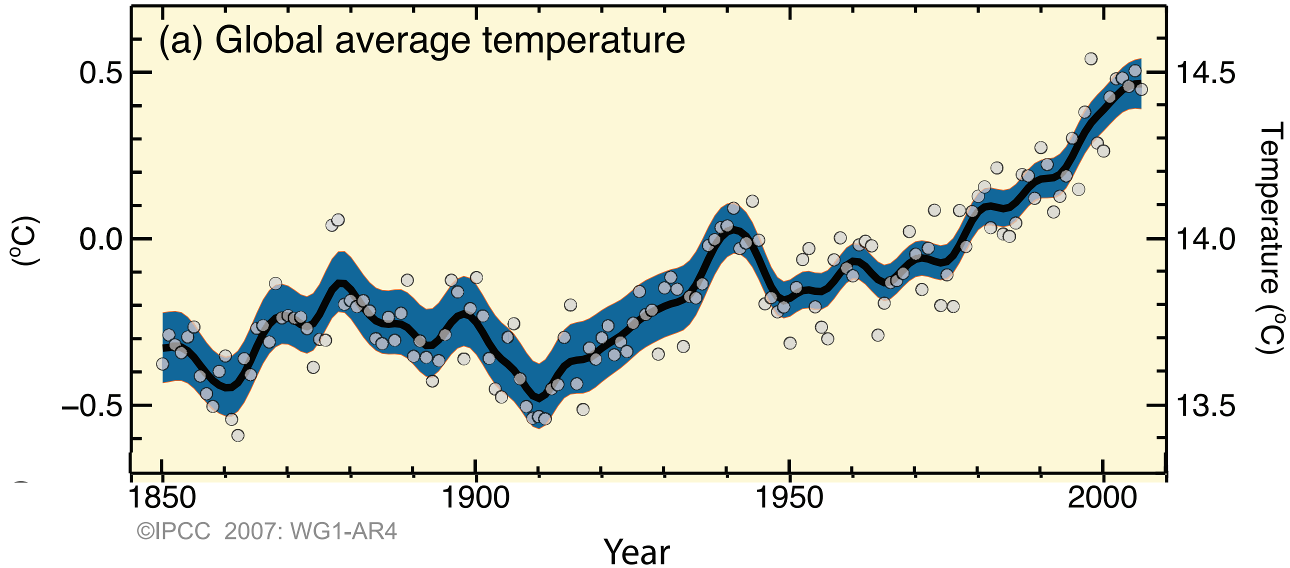
climate model with only natural forcing: blue line (19 simulations, 5 models)

climate model +anthropogenic forcing: red line (58 simulations, 14 models)

IPCC (2007)

2. Recent warming of the planet

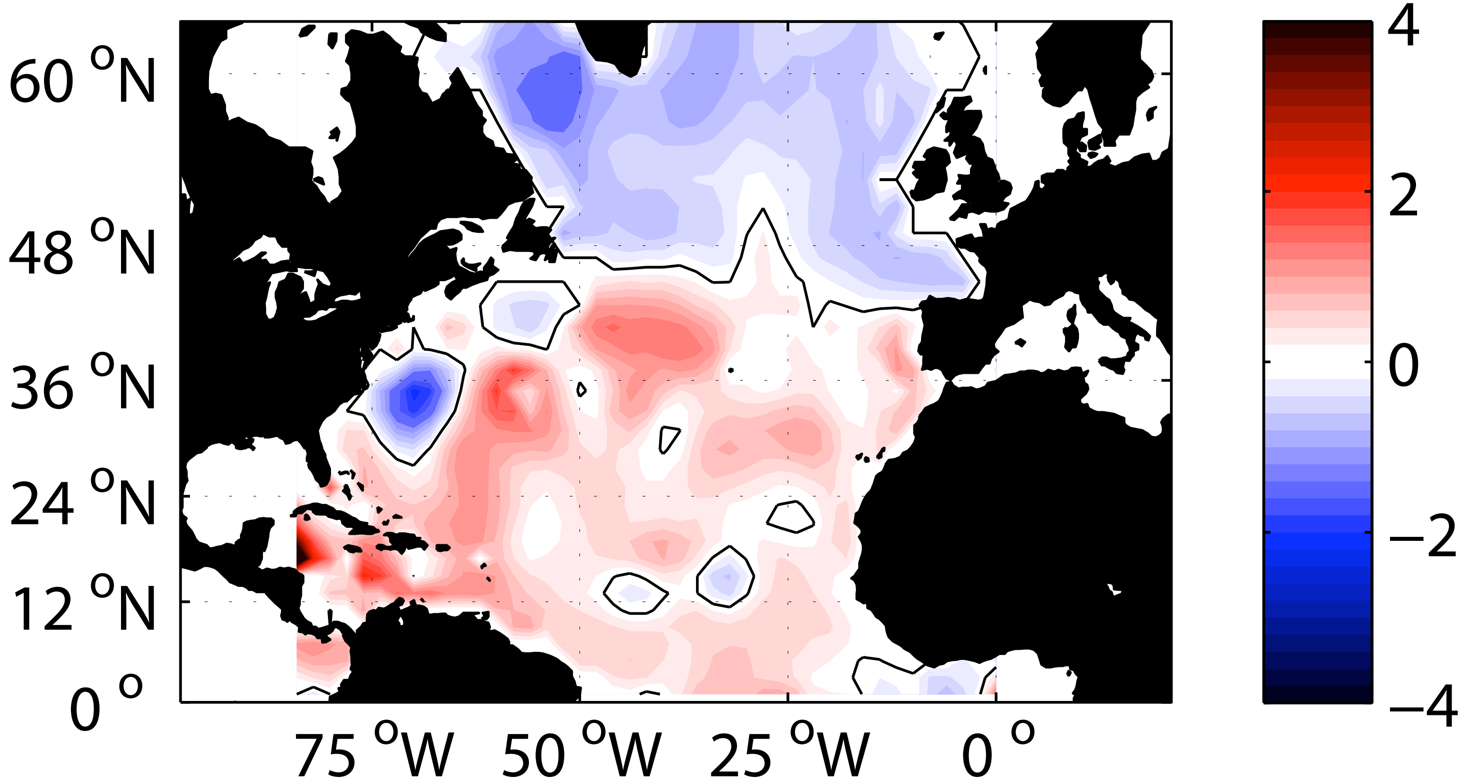
global data



- see global warming of upper ocean
- oceans have absorbed more than 80% of the heat added to the climate system (IPCC, 2007)

Ocean heat content change

data



Change in ocean heat content (10^{20}J) between 1980-2000 and 1950-1970

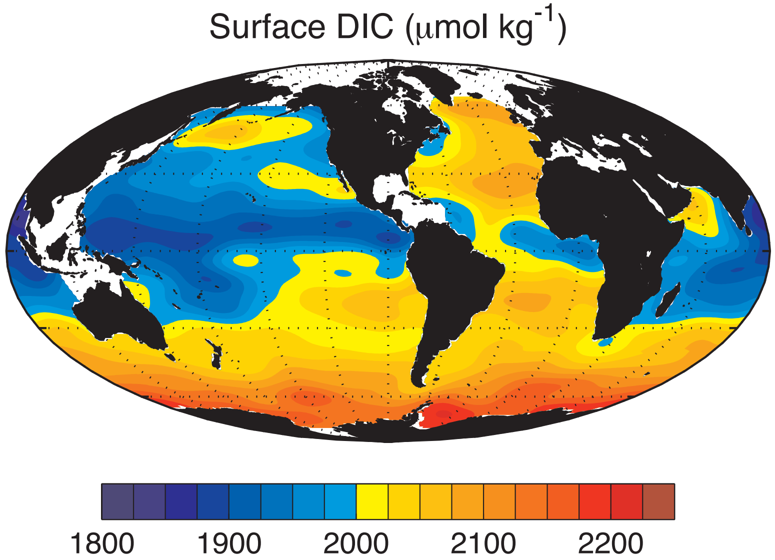
- Large regional changes ($\pm$4 W m^{-2})
- Decadal, natural variability might mask any **local** signal of greenhouse forcing

Lozier, Leadbetter, Williams et al. (2008) Science data

3. Long-term effects of carbon emissions

- Ocean holds ~ 50 as much carbon as in the atmosphere

- 1/3 of the recent industrial emissions of carbon has gone into ocean



CO_2 reacts in seawater

$$DIC = CO_2^* + HCO_3^- + CO_3^{2-}$$

Dissolved inorganic carbon

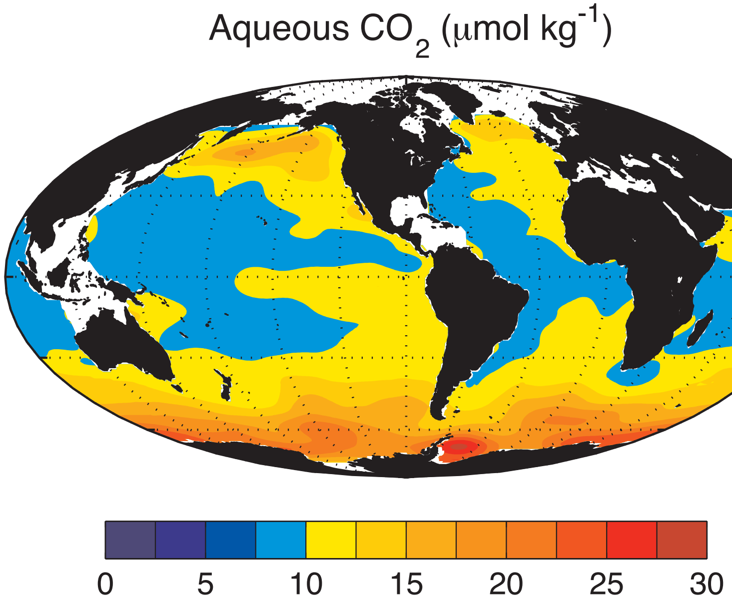
aqueous carbon dioxide (1%)

bicarbonate (90%)

carbonate (9%)

theory/
data

What is the problem?



as add more CO_2, oceans become more acidic

$$CO_2 + 2H_2O \leftrightharpoons CO_3^{2-} + 2H^+$$

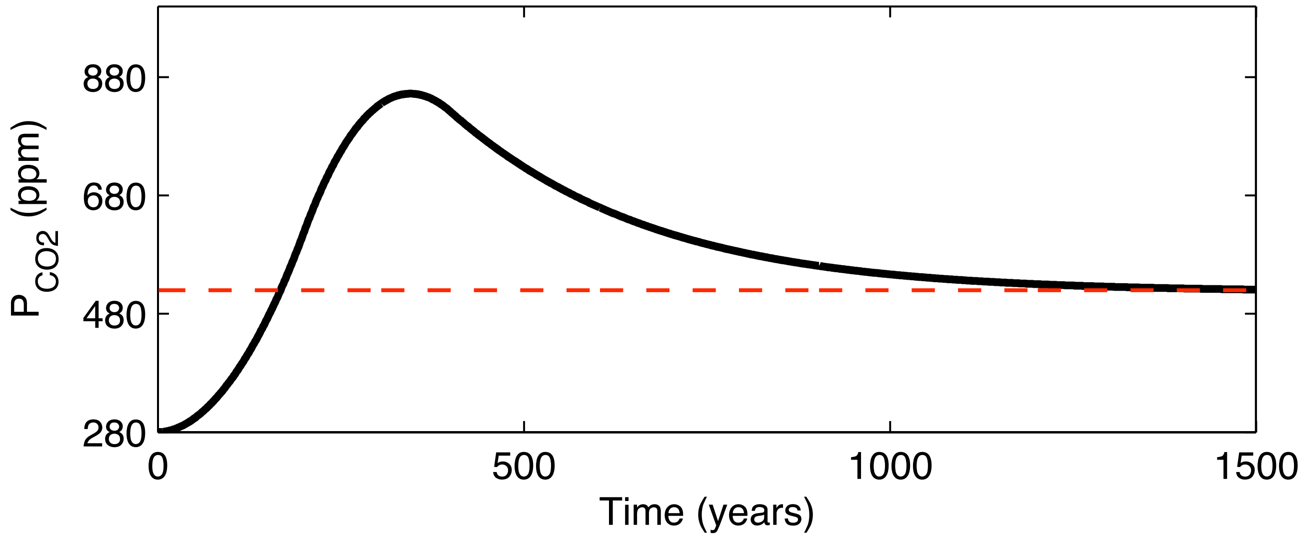
increase in H^+ ions

- more CO_2 ends up in aqueous CO_2 pool
- **inhibits** further ocean uptake
- i.e. higher fraction of emitted CO_2 stays in the atmosphere

simple model

So what happens if we burn all our fossil fuels?

atmospheric CO_2



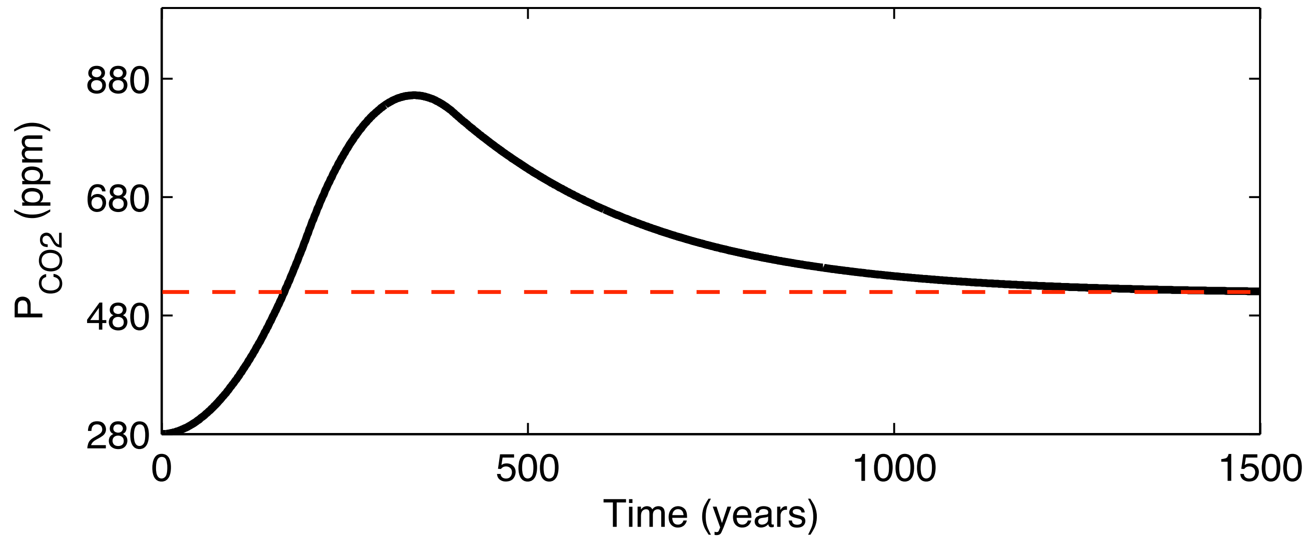
- Initial fast rise in atmospheric CO_2
- Eventually approach a steady state

final atmospheric CO_2 concentration varies *exponentially* with carbon emissions

Summary for radiative forcing

theory

• Radiative forcing varies *logarithmically* with atmospheric CO_2 concentration



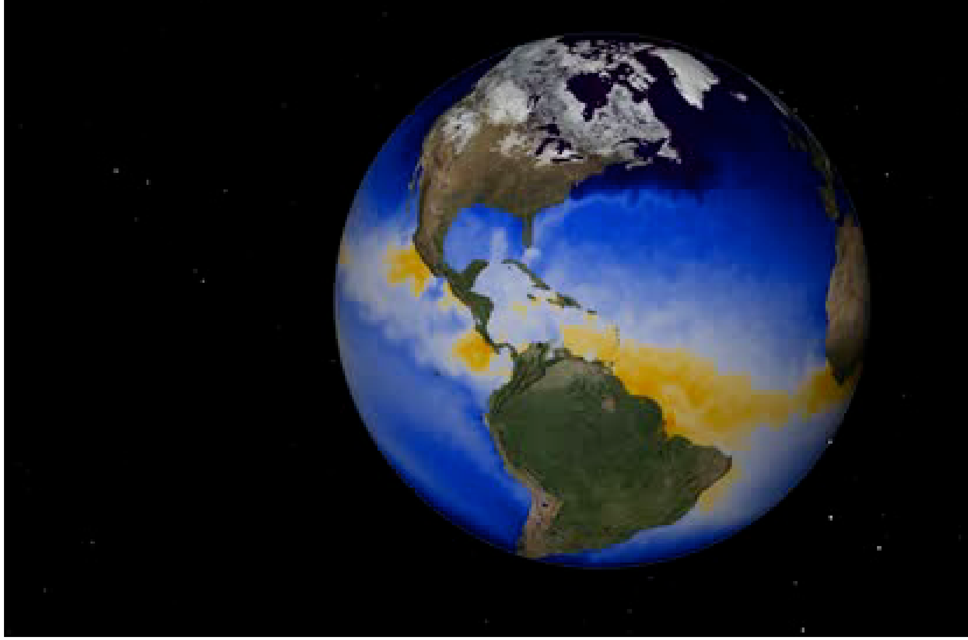
• Final, atmospheric CO_2 concentration varies *exponentially* with carbon emissions (due to ocean acidity feedback)

• Final, radiative forcing varies *linearly* with carbon emissions

emit 1000 GtC implies extra heating of 1.5 Wm^{-2} lasting for millennia

Goodwin, Williams, Ridgwell and Follows (2009) Nature Geoscience

Legacy for future generations



if release C in all conventional fossil fuels,
~ 5 x present anthropogenic heating lasting for millennia

tipping points:
Greenland ice
methane hydrates ...

Recommend

- develop carbon capture techniques
- avoid exploiting non-conventional fossil fuels (tar sands)
- develop alternative energy & non-fossil fuel alternatives

SPARE

Why does ocean partitioning change?

Reactivity of CO_2 in seawater

$$CO_2(aq) + H_2O \rightleftharpoons H_2CO_3$$

$CO_2^* = CO_2(aq) + H_2CO_3$

$$H_2CO_3 \rightleftharpoons HCO_3^- + H^+$$

$$HCO_3^- + H_2O \rightleftharpoons CO_3^{2-} + H^+$$

add more CO_2

$$CO_2 + 2H_2O \leftrightharpoons CO_3^{2-} + 2H^+$$

increase in H^+ ions

$$K_1' = [H^+]\frac{[HCO_3^-]}{[CO_2^*]}$$

dissolved CO_2 increases relative to bicarbonate
(bicarbonate increases relative to carbonate)

$$K_2' = [H^+]\frac{[CO_3^{2-}]}{[HCO_3^-]},$$

shift in partitioning,

- so more CO_2 ends up in dissolved CO_2 pool
- inhibits further ocean uptake

Change in ocean partitioning of carbon with pH