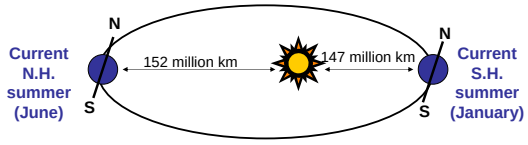
Variation of Sun-Earth Distance

Eccentricity of Earth's Orbit

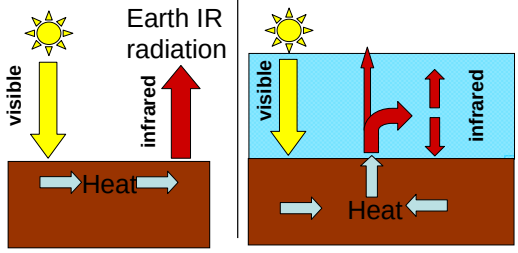


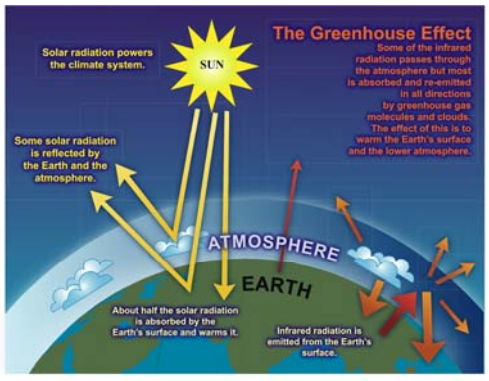
The Greenhouse Effect

no atmosphere

with atmosphere

outgoing IR radiation is absorbed and emitted back to the ground





View of Earth from Space

Why is predicting the climate so difficult?

The different effects:

- Greenhouse gases
- Clouds
- Rising temperatures

Above are not independent from another

Example:
more CO_2 ⇒ higher temperatures ⇒ more H_2O

→*stronger greenhouse effect due to H_2O*

Negative Feedback

Negative feedback

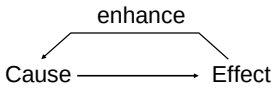
Cause ⟶ Effect

suppress

Effect suppresses cause
→ decrease effect
→ "self-regulation"

Example: warmer → more clouds → higher albedo → cooling effect (negative feedback)

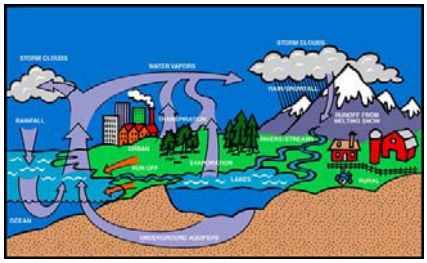
Positive Feedback



Effect enhances cause
→ increase effect
→ boom!!!

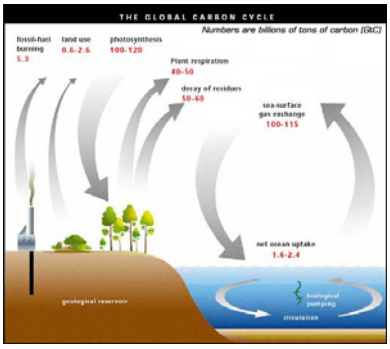
Ex: Water vapor feedback
Ex: warmer → melting land ice → lower albedo → further warming

Hydrological Cycle



from http://www.watersystems.co.nz/images/hydrologicalcycle.jpg

Carbon Dioxide (CO_2)



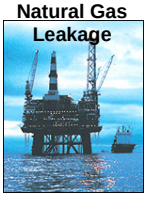
Source: http://www.esd.ornl.gov/iab/iab2-2.htm

Methane (CH_4)

Termites

Rice Paddies

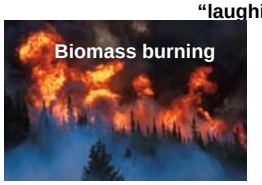
Natural Gas Leakage



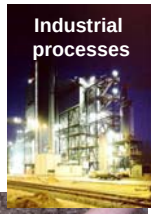
Ruminants

Nitrous Oxide, N_2O

"laughing gas"



Industrial processes



Nitrogen fertilizer

Chloroflourocarbons (CFCs), Hydrofluorocarbons (HCFCs), Perfluorocarbons (PFCs), Sulfur hexafluoride (SF_6)

Refrigeration

Aluminum smelting

Insulator for electrical equipment

Propellant

Tropospheric Ozone (O_3)

$CO + OH + O_2 \rightarrow CO_2 + HO_2$

$NO + HO_2 \rightarrow NO_2$

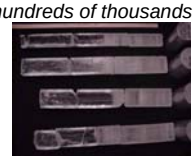
$NO_2 + hv \rightarrow NO + O$

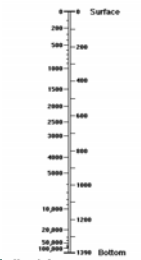
$O + O_2 \rightarrow O_3$

- ***Tree rings***: changes in growing conditions that a tree might have encountered over its lifetime (temperature and rainfall) →*hundreds of years*

- ***Pollen*** from different plant species indicate shifts in vegetation patterns that occured as a result of climate change →*millions of years*

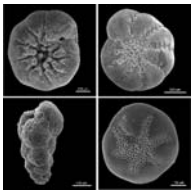
- ***Ice cores*** record information about the conditions in which the ice was formed and trap ancient air → *hundreds of thousands of years*



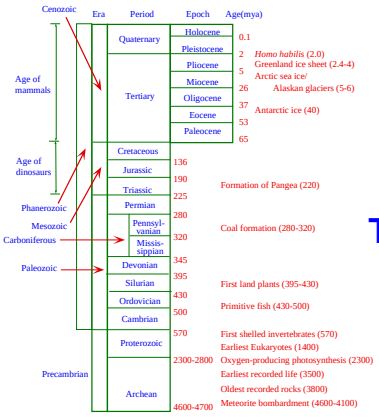


- ***Corals*** give us indications on sea surface temperature → *hundreds of thousands of years*

- Shells of marine organisms found in ***marine sediments*** tell us about past temperatures and atmospheric CO2 → *hundreds of millions of years*



- Shape of the landscape (***geomorphology***) tells us about the extent of glaciers and ice sheets and sea level in the past → *billions of years*

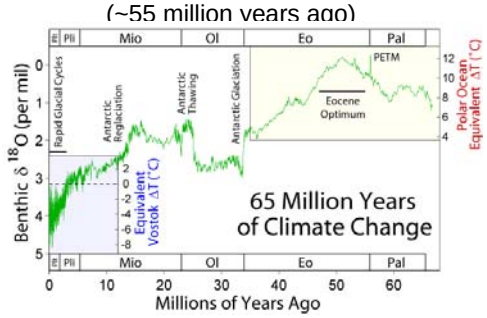


Geologic Time Scale

Figure 12.13

Paleocene-Eocene Thermal Maximum

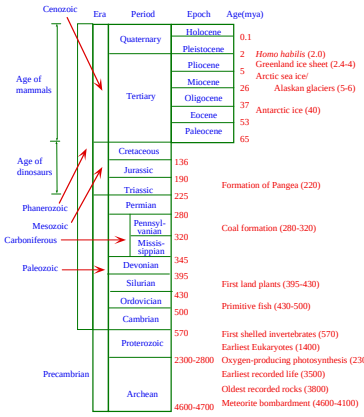
(~55 million years ago)



Rapid warming (10,000 years) lasting 100,000 years

Paleocene-Eocene Thermal Maximum

(~55 million years ago)



Geologic Time Scale

Figure 12.13

Climate History

Mid-Pliocene (~3.5 million years ago)

Configuration of continents and ocean basins close to present (good analogue for our near future?)

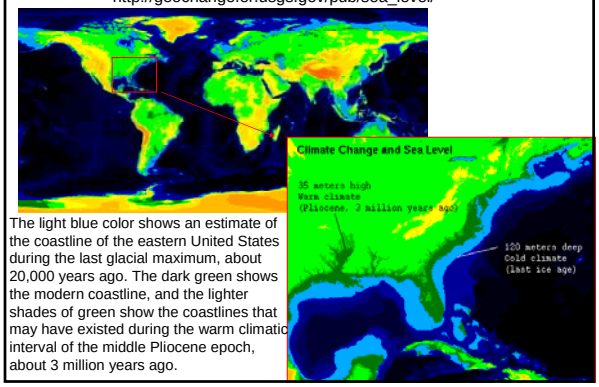
CO_2 concentrations: 360 – 400 ppm

Sea level: 15 – 25 m higher than modern

Global mean temperatures: 2 – 3° C above preindustrial

Estimated mid-Pliocene sea-level

http://geochange.er.usgs.gov/pub/sea_level/

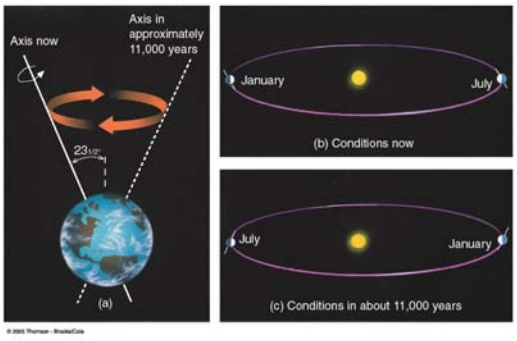


The light blue color shows an estimate of the coastline of the eastern United States during the last glacial maximum, about 20,000 years ago. The dark green shows the modern coastline, and the lighter shades of green show the coastlines that may have existed during the warm climatic interval of the middle Pliocene epoch, about 3 million years ago.

Plate tectonics

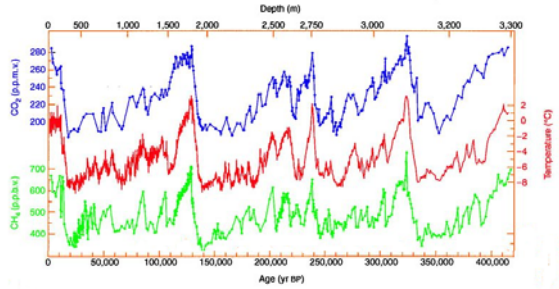
Plate tectonics

Milankovitch cycles



Climate History

Temperature and Greenhouse Gases

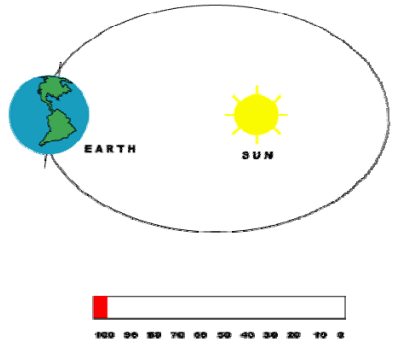


Today: CO_2 = 370 ppm

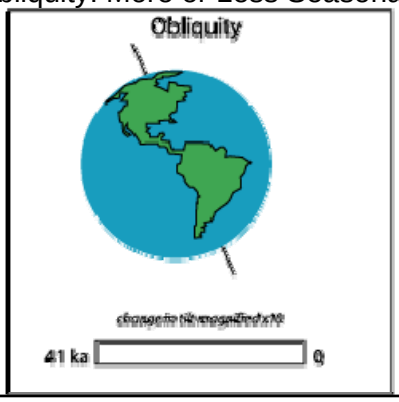
CH_4 = 1800 ppb

Petit et al., 1999

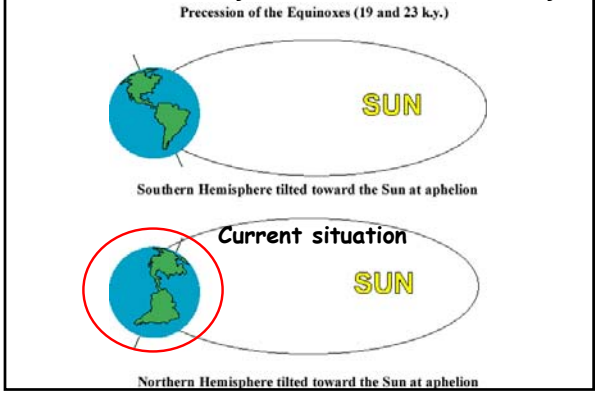
Eccentricity: More to Less Circular



Obliquity: More or Less Seasonality



Precessional Cycle: Tilt and Eccentricity

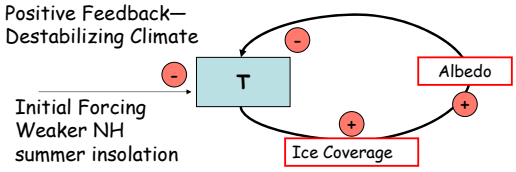


Milankovitch Cycles

Milankovitch cycles

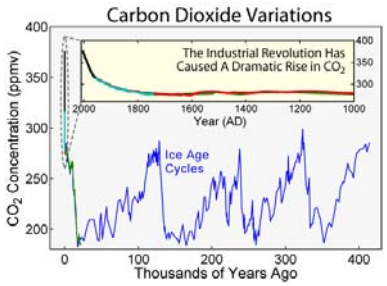
Example of how Milankovitch Cycles impact climate: NH Glaciation

Solar insolation in NH summer appears to be key maintaining glaciation. Ice sensitive to melting!

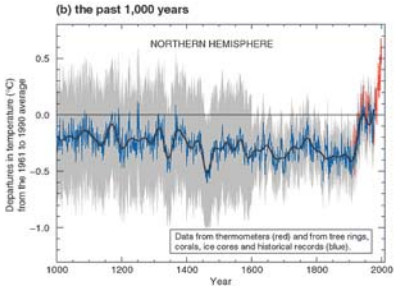


Same old ice-albedo feedback, just different initial forcing

Carbon dioxide (CO_2) variability over the past 400,000 years



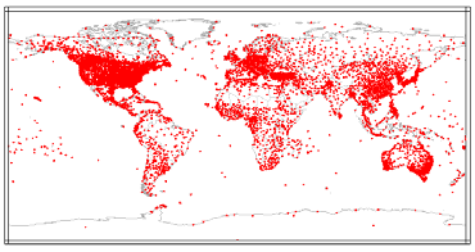
Reconstructed Temperatures in NH over last 1000 years



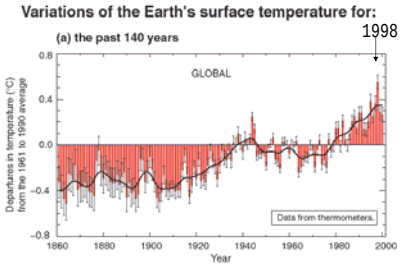
- 20th century increase largest in any century over last 1,000 years
- 1990s and 1998 warmest decade and year of the millenium

Surface Temperature Measurement Stations

GHCN v2.0 Mean Temperature Stations

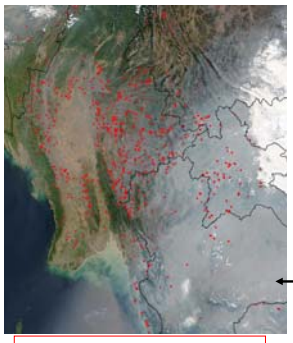


Recent Changes in Surface Temperature



- Increase in global-average surface temperature over the 20th century by about **0.6ºC**
- 1990s warmest decade and 1998 warmest year in instrumental record since 1861

Aerosols Increase Earth's Albedo



Aerosols scatter a fraction of incoming solar radiation back to space

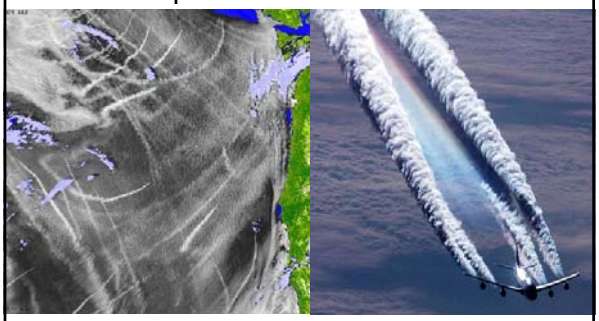
This is known as the "direct forcing" of aerosols.

Smoke particles from biomass burning in Southeast Asia appear as white haze

modis.gsfc.nasa.gov

ΔF ~ - 0.9 W/m² from *direct* effect of aerosol

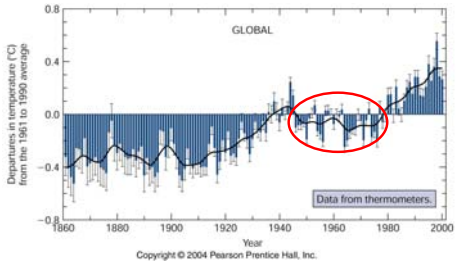
Ship Tracks and Contrails



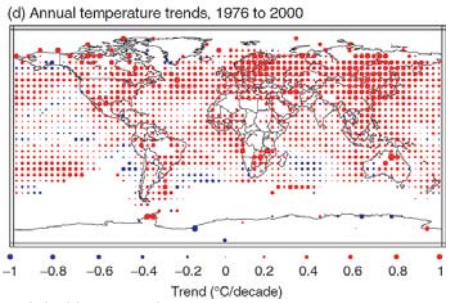
Examples of Aerosol Indirect Effects on Clouds

“Sulfate Forcing” Mid 20th Century

Aerosol direct effect thought to explain temporary hiatus in T increase

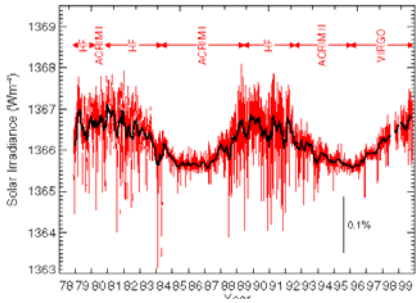


Regional pattern of warming



- Near global increase in temperatures
- Largest increases in mid- and high-latitudes over continents in Northern hemisphere

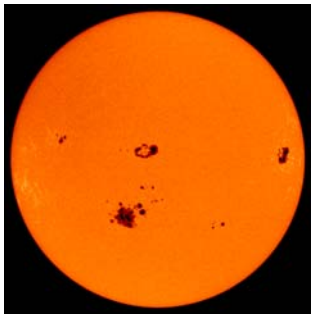
Solar output varies, but not much



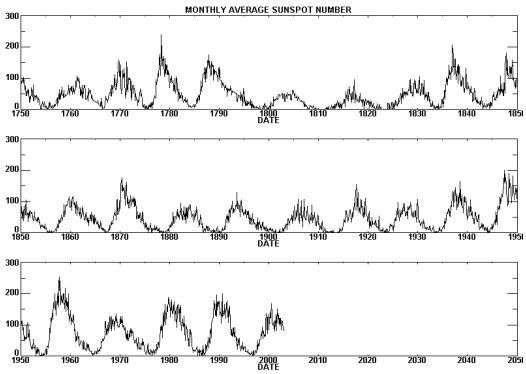
Change of solar intensity ~0.1%

Figure courtesy of NOAA National Geophysical Data Center

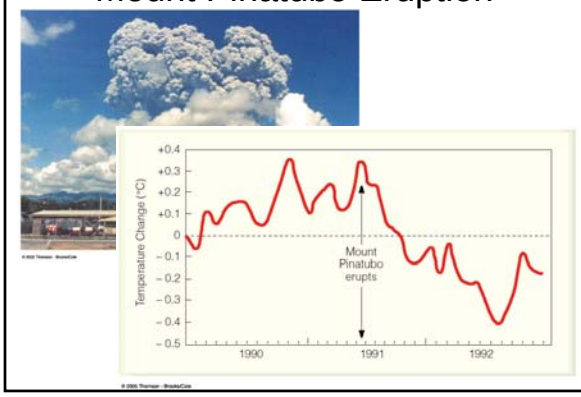
Sunspots – Cyclic Changes in Solar Output



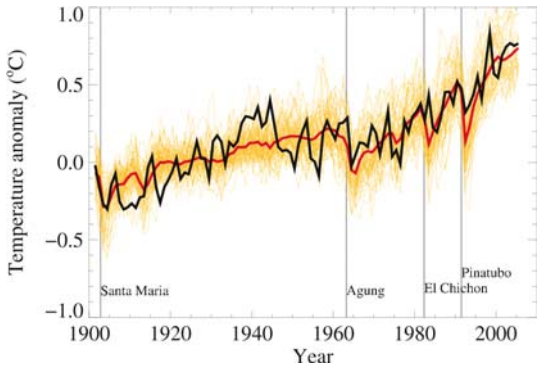
~11 year Sunspot Cycle



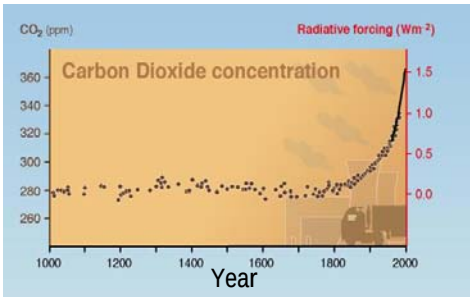
Mount Pinatubo Eruption



T Response After Major Eruptions

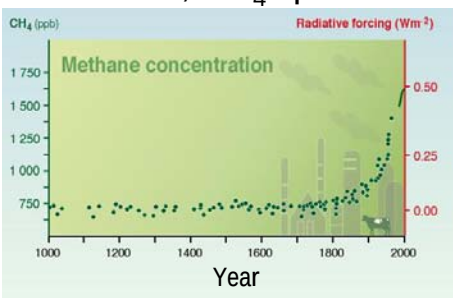


Carbon Dioxide: up 32%



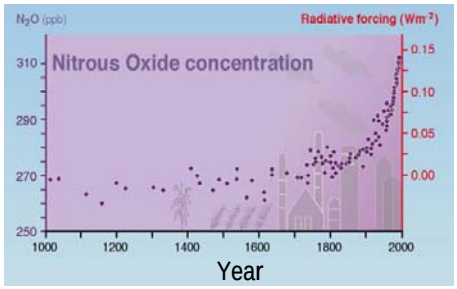
Anthropogenic sources: fossil fuel burning, deforestation

Methane, CH_4 up 150%



Anthropogenic sources: rice paddies, cows, natural gas leakage, landfills/waste, biomass burning
Natural sources: Wetlands, termites

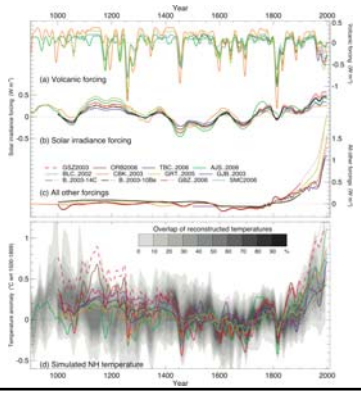
Nitrous oxide, N_2O up 15%



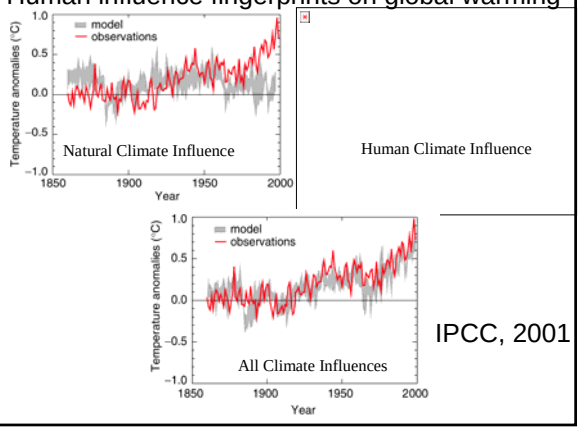
Anthropogenic sources: fertilized agriculture, biomass burning

Natural sources: Oceans, natural soils

Natural and Anthropogenic Forcings



Human influence fingerprints on global warming



IPCC, 2001

Do all Greenhouse gases have the same effect?

Global Warming Potential (GWP)

Related to amount of predicted warming from a unit increase in concentration

GWP's relative to CO_2:

$CO_2 \Rightarrow 1$

$CH_4 \Rightarrow 21$

$N_2O \Rightarrow 310$

$CFC \Rightarrow 4000\text{-}12000$

Common Myths and Misconceptions

Myths and Misconceptions (1)

"Its 70^o today, in January? Global warming is real."

"Hurricane Katrina was the strongest hurricane in decades. Global warming must be real."

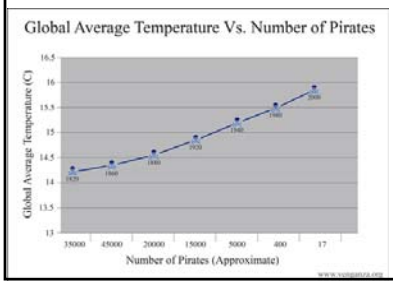
Weather Change vs. Climate

In the eye of Hurricane Katrina
Photo courtesy of Prof Bob Houze's group

- A single hurricane is an example of weather.
- An increase in the number per year or average strength is a climate problem.

Myths and Misconceptions (2)

"The decrease in pirates anti-correlates with global temperature. Thus, global warming is caused by fewer pirates (or it is causing there to be fewer pirates)."

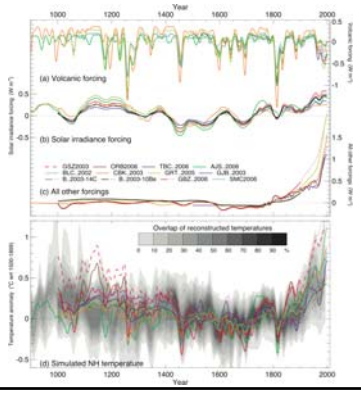


Need to have a physical explanation for correlations to be meaningful

Myths and Misconceptions (3)

"The recent warming is just part of a natural cycle."

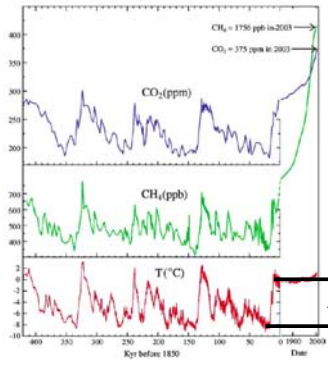
Natural and Anthropogenic Forcings



Myths and Misconceptions (4)

"Is global warming really such a big deal? A few degrees warmer seems harmless."

What difference does a few degrees make?



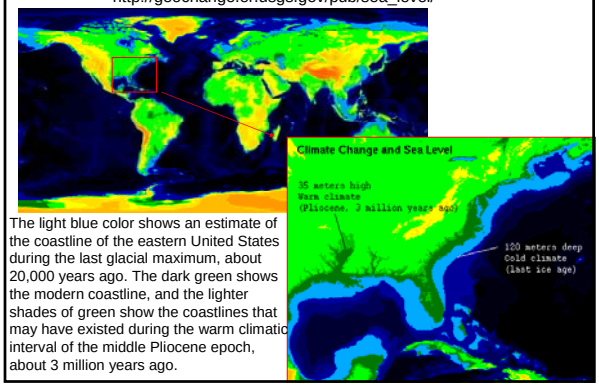
Seattle ice free

$\Delta T_{ice\text{-}no\ ice}$ ~ -5-8°

Seattle under mile of ice

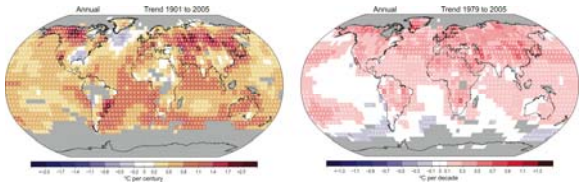
Estimated mid-Pliocene sea-level

http://geochange.er.usgs.gov/pub/sea_level/

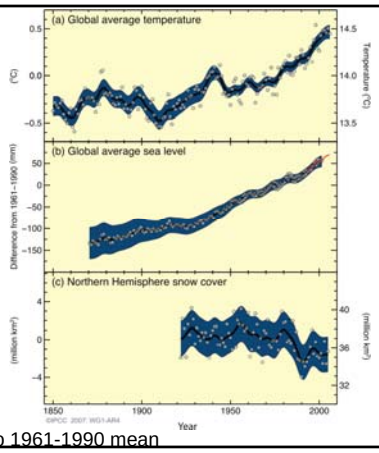


The light blue color shows an estimate of the coastline of the eastern United States during the last glacial maximum, about 20,000 years ago. The dark green shows the modern coastline, and the lighter shades of green show the coastlines that may have existed during the warm climatic interval of the middle Pliocene epoch, about 3 million years ago.

Temperature Trends

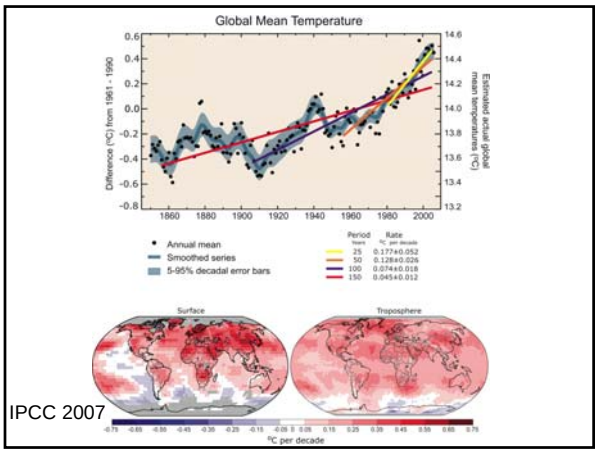


IPCC 2007

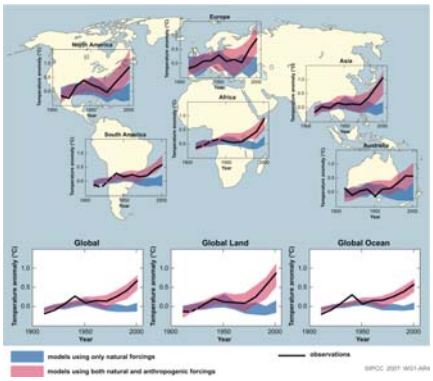


Relative to 1961-1990 mean

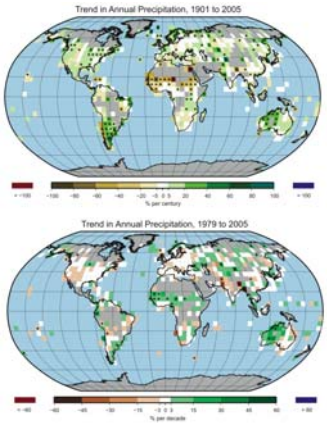
IPCC 2007



IPCC 2007

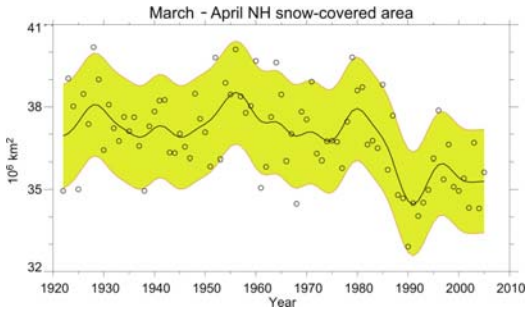


IPCC 2007



IPCC 2007

Northern Hemisphere Spring Snow Cover



IPCC 2007

Melting Glaciers

Glacier Ururashraju, Peru in 1986

1999
Glacier retreated around 500m

Glacier National Park - 1911

2000

South Cascade Glacier

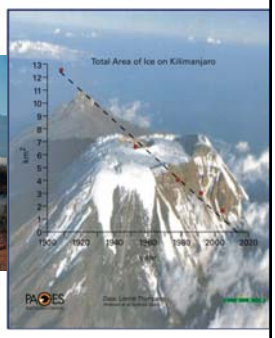
Seattle Times Nov 1 2006
"State's shrinking glaciers: Going ... going ... gone?"

1928

1966

2006

Mt. Kilimanjaro Ice Area



Changes in sea level

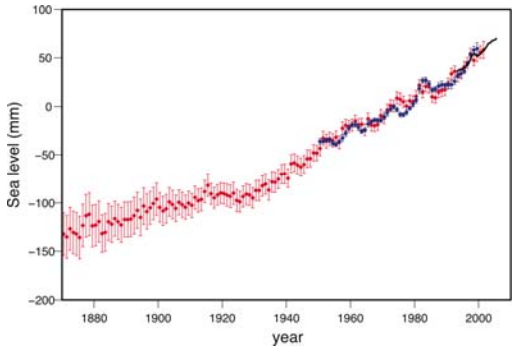
- Global average sea level rose by 0.1-0.2 meters during the 20th century (~1.5 mm/year: 10 times higher than average over last 3000 years)
- Global ocean heat content has increased

Factors causing sea-level change:

→ **Thermal expansion,** as ocean water warms it expands: main reason for change over last century and for coming few centuries

→ **Melting of ice on land** (glaciers and ice sheets): main reason for change in sea-level between glacials and interglacials (~120m since 20,000 years ago)

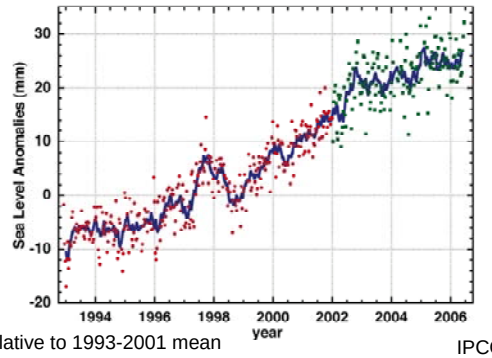
Sea-level rise



Relative to 1961-1990 mean

IPCC 2007

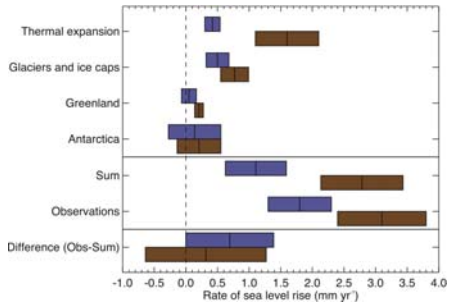
Sea-level rise



Relative to 1993-2001 mean

IPCC 2007

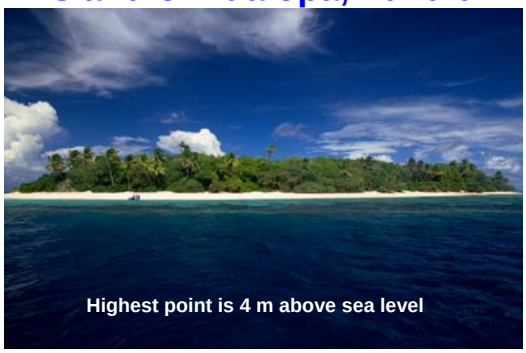
Attributing sea-level rise



1961-2003 (blue) and 1993-2003 (brown)

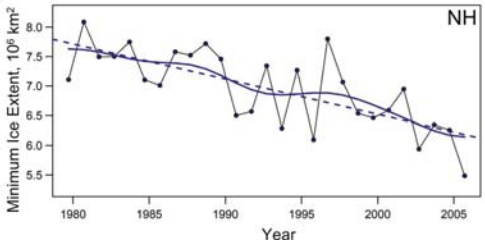
IPCC 2007

Island of Fualopa, Tuvulu



Many people on Tuvalu are now looking at migrating; indeed New Zealand has offered to take in 75 Tuvaluans every year.

Arctic Minimum Sea-Ice Extent

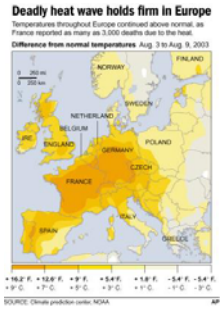


IPCC 2007

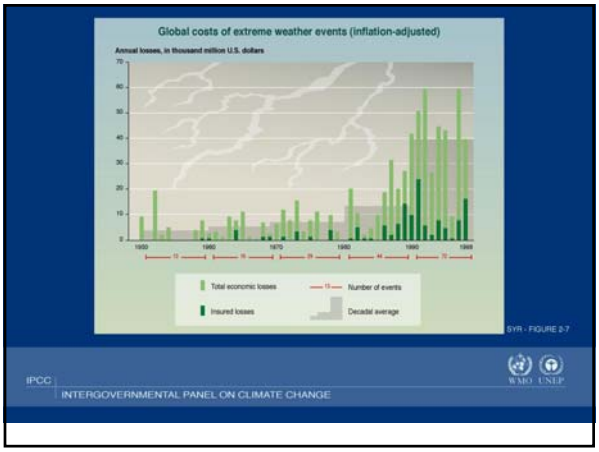
The oceans take up / release CO_2

Ocean currents redistribute heat/thermal energy

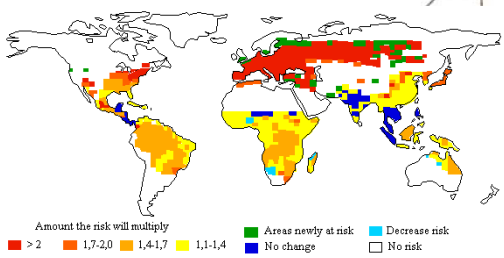
Extreme Weather Events



Hurricanes



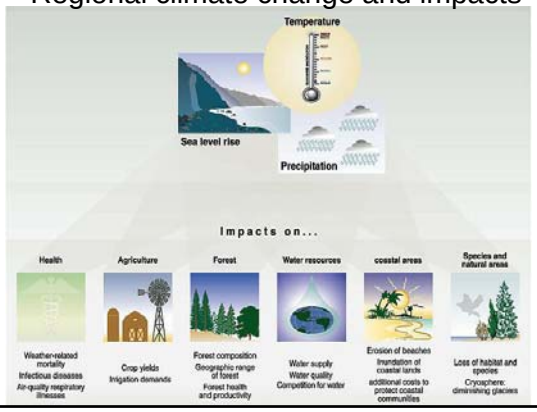
Human Health - Malaria



Prediction of Malaria Transmission rates in 2002 relative to the average risks between 1961-1990

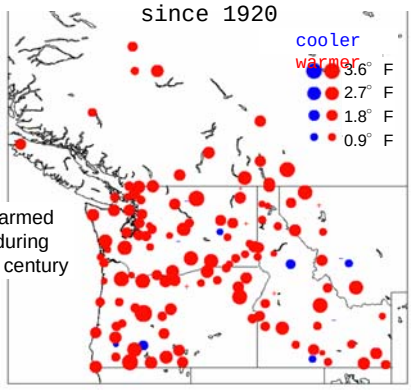
Epstein, 2000

Regional climate change and impacts



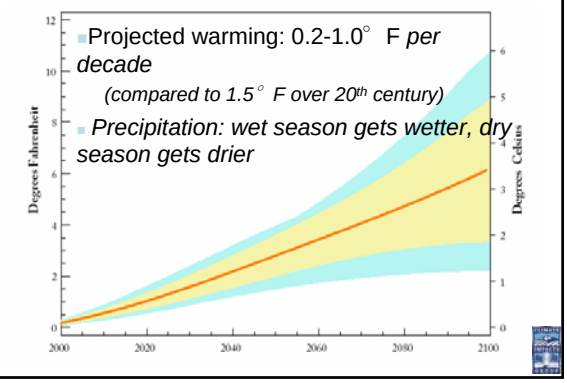
Climate change in the Pacific Northwest – past and future

Temperature trends (° F per century) since 1920

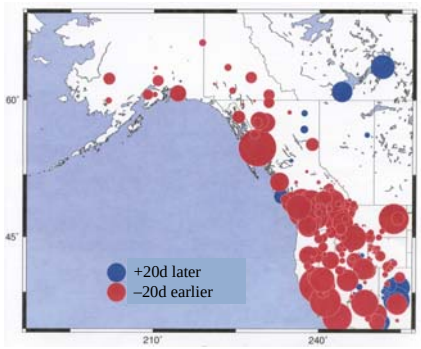


PNW warmed **+1.5 F** during the 20th century

21st Century PNW Temperature Change



Trends in timing of spring snowmelt (1948-2000)



Courtesy of Mike Dettinger, Iris Stewart, Dan Cayan

Washington's economy and natural resources are sensitive to climate changes

- we know this from experience
- the water cycle plays an especially prominent role in transmitting climate impacts into resource impacts

skiing | water supplies | hydropower
aquatic ecosystems | flooding | forests

- ***"drought" – a water supply shortage – is our region's greatest climate vulnerability***

Climate Change Policy

- 1st international negotiations to combat climate change began in 1992 at the United Nations Framework Convention on Climate Change (UNFCCC) in Rio de Janeiro, Brazil.
- Called on signatory nations to:

1. develop current and projected emissions inventories for greenhouse gases
2. Devise policies for reducing emissions
3. Promote technologies for reducing emissions

Set no mandatory limits on greenhouse gas emissions for individual nations and contains no enforcement provisions (legally non-binding)

Included provisions for updates, called protocols, that would set mandatory emissions limits

154 nations signed the UNFCCC (including the U.S.)

Kyoto Protocol (1997)

- Called on industrialized nations to reduce greenhouse gas emissions by 2008-2012 by a certain percentage relative to their 1990 emissions (for CO_2, CH_4, N_2O) or 1995 emissions (all other greenhouse gases).
- The net change in emissions would be 5.2% below 1990 levels

Percent Change in 1990 Emissions Required Under Kyoto Protocol

Country	Percent Change in Emission
Switzerland, central Europe, European Union	-8
United States	-7
Canada, Hungary, Japan, Poland	-6
Russia, New Zealand, Ukraine	0
Norway	+1
Australia	+8
Iceland	+10

Table 12.5

Percent World CO_2(g) Emissions by Country or Continent (1997)

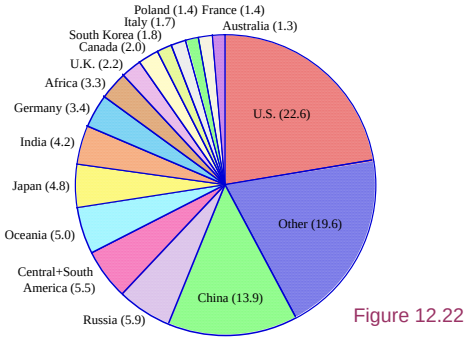


Figure 12.22

Countries can meet their Kyoto targets by:

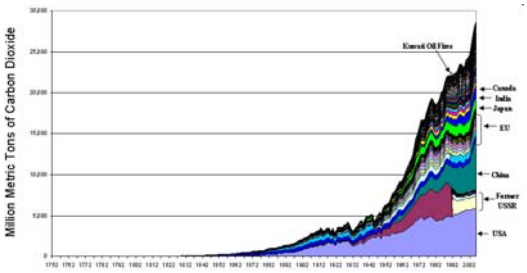
1. Reducing their own emissions and increasing their own sinks (e.g. forests)
2. Clean Development Mechanism: Financing emission-reduction projects in developing countries that are not subject to the Kyoto Protocol (e.g. planting forests, improving energy efficiency, alternative energy sources)
3. Emissions trading with other developed countries

Change in Greenhouse Gas Emissions: 1990 - 2004

Country	Change in Greenhouse Gas Emissions (excluding LULUCF)	Change in Greenhouse Gas Emissions (including LULUCF)	Treaty obligation 2008 - 2012
Germany	-17%	-18.2	-8%
Canada	+27%	+26.6%	-6%
Australia	+25%	+5.2%	+8%
Spain	+49%	+50.4%	-8%
Norway	+10%	-18.7%	+1%
New Zealand	+21%	+17.9%	0%
France	-0.8%	-6.1%	-8%
Greece	+27	+25.3	-8%
Ireland	+23%	+22.7%	-8%
Japan	+6.5	+5.2	-6%
United Kingdom	-14%	-58.8%	-8%
Portugal	+41%	+28.9%	-8%

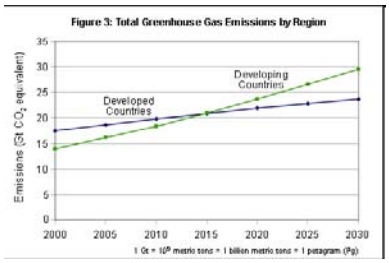
LULUCF = Land Use, Land Use Change, and Forestry

Worldwide CO_2 emissions



http://www.epa.gov/climatechange/emissions/globalghg.html

CO_2 emissions in developed and developing countries



http://www.epa.gov/climatechange/emissions/globalghg.html

Post-Kyoto: What happens next?

- Kyoto to expire in 2012
- 2009 UN conference in Copenhagen, Denmark: Goal to come up with post-2012 plan
- Resulted in (weak) “Copenhagen accord”: Actions should be taken to keep any temperature increases to below 2ºC. The document is not legally binding and does not contain any legally binding commitments for reducing CO_2 emissions.
- Copenhagen accord pledges US$30 billion to the developing world over the next three years, rising to US$ 100 billion per year by 2020, to help poor countries adapt to climate change. An agreement was also reached that would set up a deal to reduce deforestation in return for cash from developed countries.

What is happening currently in the US with respect to greenhouse gas emissions?

Emissions of CO_2 equivalents in the U.S.

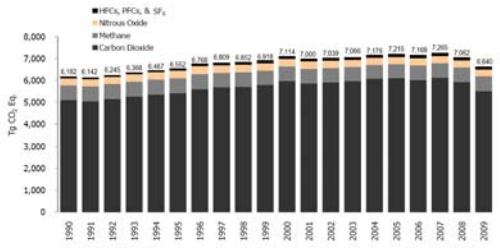


Figure 2-1: U.S. Greenhouse Gas Emissions by Gas

Recent decrease driven by 1) decrease in economic → decrease in energy consumption, and 2) fuel switching for electricity generation (price of coal increased, price of natural gas decreased).

Greenhouse gas emissions in the U.S. relative to 1990

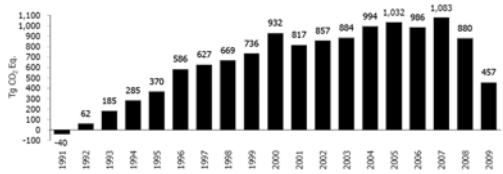


Figure 2-3: Cumulative Change in Annual U.S. Greenhouse Gas Emissions Relative to 1990

Greenhouse gas sources in the U.S. in 2009

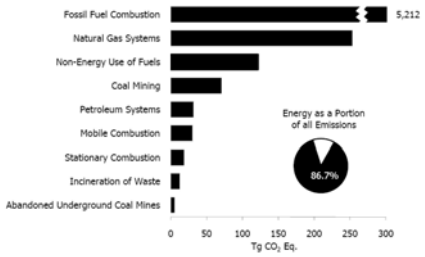


Figure 2-5: 2009 Energy Sector Greenhouse Gas Sources

2009 U.S. CO_2 emissions by sector and fuel type

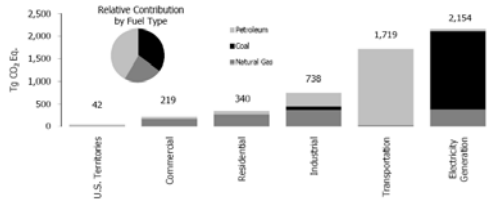


Figure 2-7: 2009 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type
Note: Electricity generation also includes emissions of less than 0.5 Tg CO_2 Eq. from geothermal-based electricity generation.

U.S. Greenhouse Gas Emissions Per Capita and Per Dollar of GDP

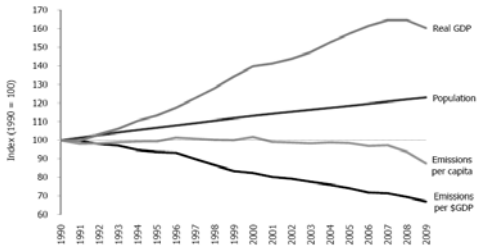


Figure 2-14: U.S. Greenhouse Gas Emissions Per Capita and Per Dollar of Gross Domestic Product

Supreme Court ruling April 2007: Massachusetts vs EPA

• U.S. Supreme Court case decided 5-4 in which twelve states and several cities of the United States brought suit against the EPA to force that federal agency to regulate carbon dioxide and other greenhouse gases as pollutants.

• The Clean Air Act requires the EPA to set emission standards for "any air pollutant" from motor vehicles or motor vehicle engines "which in his judgment cause[s], or contribute[s] to, air pollution which may reasonably be anticipated to endanger public health or welfare."

• The ruling does not force the Environmental Protection Agency to regulate auto emissions, but the agency would almost certainly face further legal action if it fails to do so.

So what is the EPA doing?

• EPA determined that CO_2 and five other greenhouse gases "endanger public health and welfare" giving the EPA a mandate to regulate ghg emissions.

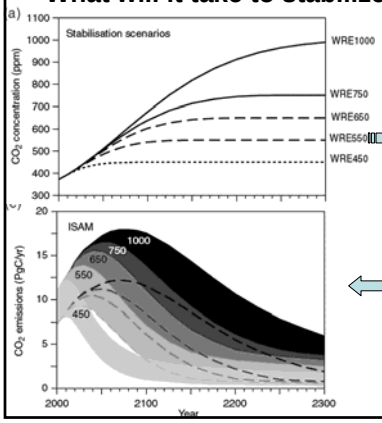
• EPA can implement new guidelines under the Clean Air Act, or wait for congress to pass more comprehensive legislation such as a "cap and trade" program (proposed legislation failed in senate in 2010)

• So, EPA will use its regulatory power to set limits on CO_2 emissions from factories, power plants and refineries (responsible for ~40% of ghg emissions) by requiring federal permits that cap ghg emissions.

How will EPA regulate greenhouse gases?

- Beginning Jan. 2, 2011, the EPA requires large new projects or plant upgrades that emit more than 75,000 tons of greenhouse gases to have a permit.
- After that, in July, the EPA will begin to include other "regulated" sources that emit more than 100,000 tons. By July 2012, it will begin to weigh smaller emitters, but none under 50,000 tons.
- House trying to block EPA from regulating greenhouse gases via federal spending legislation (as of February 18, 2011)

What will it take to stabilize CO_2 levels?



Stabilization at 550 ppm = twice pre-industrial levels

Need to start reducing emissions by 2030, and will need to drop well below current emissions by mid-22nd century