Global Warming

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Alternative Energy

February 10, 2009

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Reading for tonight: Chapter six on sustainability.

Reading for Thrusday: Chapter sixteen on energy storage.

Reading for next Tuesday: Chapter seventeen on electricity generation.

Homework due tonight.

Download homework for next Monday.

First midterm exam, Thursday, February 26.

Project proposal due Tuesday, March 3.

Outline

- Climate and weather
- Radiation balance and radiative forcing
- Global warming potentials (GWP) and equivalent CO_2 emissions
- Intergovernmental Panel on Climate Change (IPCC)
  - Fourth assessment report in 2007
- 2004 US greenhouse gas inventory

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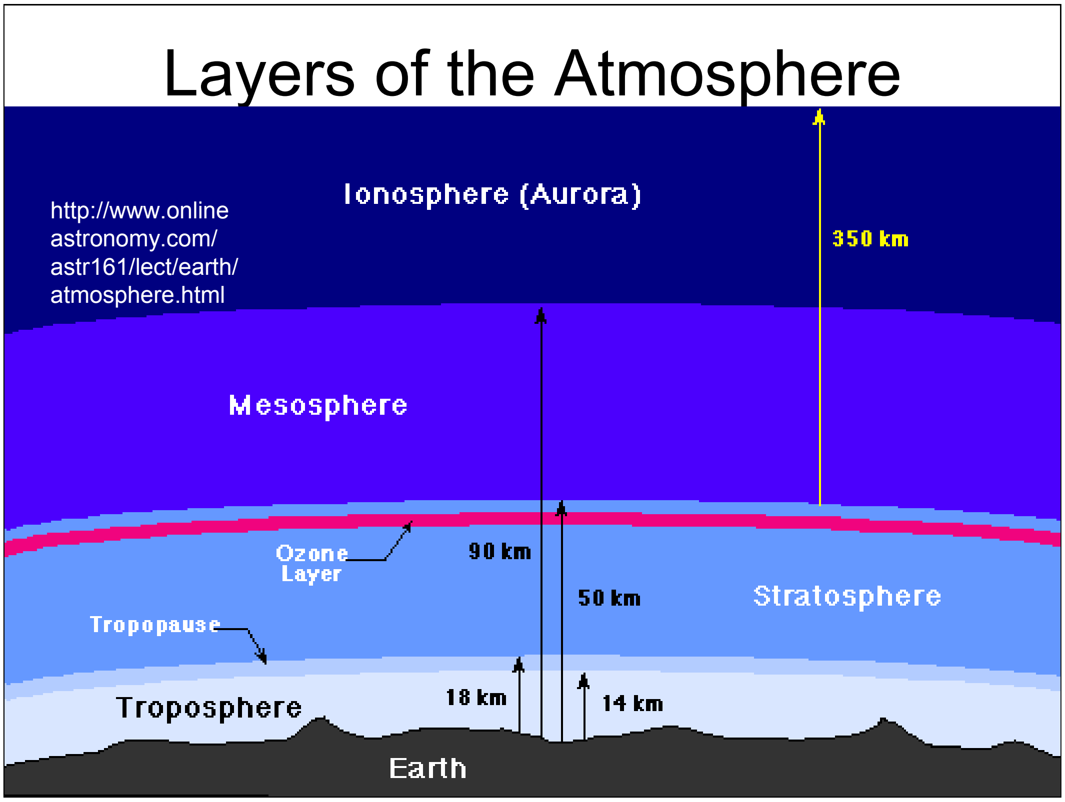
The planetary energy balance between incoming solar radiation and outgoing infrared radiation is affected by two main sources. The first is the ozone layer in the stratosphere. This layer is formed by photochemical reactions that can be disturbed by human emissions that reach there. The second is the radiation balance in the lower atmosphere (the troposphere) which can be affected by changes in the composition of various radiation absorbing species.

The intergovernmental panel on climate change (IPCC) is a UN organization that examines scientific opinion on climate change. They prepare a report, called the assessment report, every six years. The most recent one, called the Fourth Assessment Report, was issued in 2007. See http://www.ipcc.ch/ (accessed February 12, 2008)

Each report consists of three working group reports and a synthesis report summarizing the three. The working group report titles are: (1) The Physical Science Basis, (2) “Impacts, Adaptation and Vulnerability, and (3) “Mitigation of Climate Change”. Each group prepares a full report and a second report called a summary for policy makers and technical summary. These smaller reports provide a useful summary of the full report.

The synthesis report also has a full report and a summary for policy makers. That summary provides a good overview of the current considerations on global warming.



The properties of the atmosphere have been generalized in standard atmospheres by the US (published jointly by NASA, NOAA, and the US Air Force) and by the International Civil Aeronautics Organization (ICAO). Both standard atmospheres are the same up to 30 km (98,000 ft).

The base (sea-level, level 0) condition in the standard atmosphere is defined as T_0 = 15.0°C (= 59.0°F) and p_0 = 101.325 kPa (2116.22 psfa). The ideal gas equation the ideal gas law, $\rho = P/RT$ is used to find the density and ρ_0 = 1.22500 kg/m^3 (0.076474 lb$_m$/ft3). The atmosphere is then divided into layers and the temperatures in each layer is assumed to grow at a linear rate known as the lapse rate: $dT/dz = \lambda$, where the value of λ is different in each layer. (For isothermal layers, $\lambda = 0$.) The pressure is then found by integrating the equation for hydrostatic equilibrium: $dp/dz = -\rho g$, where g is the acceleration of gravity.

Combining the ideal gas equation, the lapse rate equation, and the equation for hydrostatic equilibrium gives the equation at the right for the pressure in a given layer that starts at $z = z_k$ where $p = p_k$ and $T = T_k$.

$$\frac{p}{p_k} = \left[1 + \frac{(z - z_k)\lambda_k}{RT_k}\right]^{-g/R\lambda_k}$$

References:
http://www.atmosculator.com/The%20Standard%20Atmosphere.html? and http://nssdc.gsfc.nasa.gov/space/model/atmos/us_standard.html, both accessed February 12, 2008)

Climate Issues

- Planetary energy balance
  - Greenhouse effect
  - Stratospheric ozone
- Stratospheric ozone has general agreement
  - Montreal Protocol (1987) calls for worldwide reductions in gases affecting this problem
- Most recent IPCC report on global warming very certain about effect

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The worldwide agreement on the need to reduce compounds that depleted stratospheric ozone was based on observations of greatly reduced ozone in certain seasons. The "ozone hole", 50% to 90% reduction of stratospheric ozone over the Antarctic during springtime (September through November) when the global circulation pattern isolates the stratosphere over this region. The causes of this problem are different from the problem generally addressed as global warming.

Earlier assessment reports on global warming (also known as effects of greenhouse gases or climate change) by the IPCC on the effects of human activities on global warming concluded that "the balance of evidence suggests that there is a discernible human influence on global climate,"

The third assessment report of the IPCC, published in 2001, had the following summary statement about the effect of human activities on global climate: "[I]n light of new evidence and taking into account the remaining uncertainties, most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations" (IPCC 2001).

The fourth assessment report was even more certain in attributing the effect of global warming to human activities: "Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level."(IPCC 2007)

Stratospheric Ozone

- Ground level (tropospheric) ozone is a pollutant
- Stratospheric ozone reduces UV radiation reaching planet's surface
- Cl atoms that reach the stratosphere can destroy ozone there
- Chlorofluorocarbons (CFCs) good for ground-level, bad for stratosphere
- Measured in Dobson Units (DU)

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Although ground level ozone has deleterious effects on human health, ozone in the stratosphere acts to reduce incoming solar radiation. Without this ozone the planetary energy balance would be different and the amount of high energy ultraviolet radiation would add to the intensity of the current solar radiation.

Ozone in the stratosphere has a natural cycle that is disturbed by chemicals produced from human activities. The major problem is with a class of compounds known as chlorofluorocarbons, which consist of chlorine, fluorine, and carbon atoms. These compounds are very inert and have been used as refrigerants since the 1920s. They have also found application as solvents. For several years they were a preferred alternative to traditional solvents in California because they did not react to form ozone in the troposphere.

However, because of their stability they migrated to the stratosphere where they interfered with the natural ozone cycle, removing ozone from the stratosphere. (See the chemical mechanism on the next page.)

Nitric oxide can also interfere with ozone in the stratosphere. When the idea of supersonic passenger travel was considered there was a concern that NOx emissions from SSTs flying in the stratosphere could also interfere with ozone. Fortunately for the ozone layer, SSTs did not prove an economic alternative for passenger travel.

A Dobson Unit is defined on the next notes page.

Stratospheric Photochemistry

$O_2 + h\nu \rightarrow O + O \quad \lambda < 200$ nm

$O + O_2 + M \rightarrow O_3 + M$

$O_3 + h\nu \rightarrow O_2 + O \quad \lambda \sim 200 – 300$ nm

$O + O_3 + M \rightarrow O_2 + O_2 + M$

$CF_2Cl_2 + h\nu \rightarrow CF2Cl + Cl \quad \lambda < 260$ nm

$Cl + O_3 \rightarrow ClO + O_2$

$ClO + O_3 + h\nu \rightarrow O_2 + O_2 + Cl$

$ClO + NO \rightarrow ClONO + h\nu \rightarrow NO_2 + Cl$

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The first two reactions provide for the production of ozone; the second two for the destruction of ozone. These four reactions lead to a natural equilibrium concentration of ozone in the stratosphere.

The ozone concentration peaks in a region between 20 and 30 km above the earth's surface and the concentration there is over ten times that at the earth's surface.

CFC's that reach the stratosphere can be attached by solar radiation releasing Cl atoms. These atoms can react with ozone creating a new equilibrium that reduces the normal ozone concentration by as much as 50% to 90% in the Antarctic (the so-called ozone hole.)

The Montreal protocol of 1987 as revised in 1992 calls for the complete elimination of CFCs by the beginning of 1996 in developed countries. New HFC refrigerants like R-134a have replaced older CFC refrigerants like R-11 and R-22. A copy of this protocol is available at http://www.unep.org/ozone/pdfs/Montreal-Protocol2000.pdf (accessed February 12, 2008).

In addition to refrigerants ozone depleting substances include fire suppressants known as halons and the agricultural chemical, methyl bromide.

If the all the ozone over a certain area were extracted and placed in a container at STP (0^{o}C and atmospheric pressure), the volume of that ozone, divided by the area from which it was extracted would give a height. A height of 0.01 mm is one Dobson Unit (DU).

Greenhouse Gases

- Incoming solar radiation mainly in UV and visible
- Outgoing terrestrial radiation infrared
- Atmospheric gases absorb different amounts at different wavelengths
- Greenhouse gases: CO_2, CH_4, N_2O
- Equivalent tons of carbon measure

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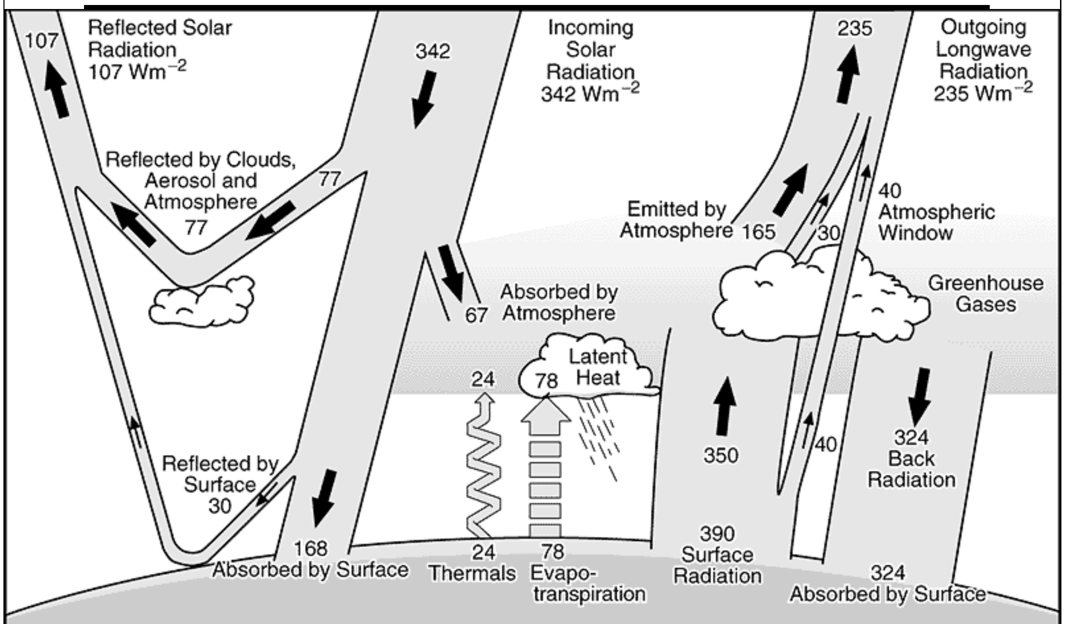
The impact of greenhouse gases has been hypothesized for many years. In particular, anthropogenic emissions of CO_2 have increased ambient CO_2 levels and continued CO_2 emissions are forecast in the future. Since CO_2 is a strong absorber of IR radiation, it will reduce the energy leaving the earth's surface as it increases.

The main concern over greenhouse gases is the uncertainty about the ultimate impact. There are may interactions to consider. For example a warmer climate will allow more water vapor in the air. This may lead to the formation of more clouds. The additional clouds will scatter more incoming radiation and absorb (and scatter) outgoing radiation.

The 2007 report by the United Nations Intergovernmental Panel on Climate Change predicted in increase in the global average temperature between 1.1^{o}C and 6.4^{o}C depending on the future emissions (possible changes in national policies to reduce green house gases) as well as the uncertainty for each emission scenario.

Reference: http://www.ipcc.ch/SPM2feb07.pdf (accessed February 8, 2007).

Radiation Balance



http://www.grida.no/climate/ipcc_tar/wg1/041.htm

Reference: http://www.grida.no/climate/ipcc_tar/wg1/041.htm

Figure 1.2: *The Earth's annual and global mean energy balance. Of the incoming solar radiation, 49% (168 Wm^{-2}) is absorbed by the surface. That heat is returned to the atmosphere as sensible heat, as evapotranspiration (latent heat) and as thermal infrared radiation. Most of this radiation is absorbed by the atmosphere, which in turn emits radiation both up and down. The radiation lost to space comes from cloud tops and atmospheric regions much colder than the surface. This causes a greenhouse effect. Source: Kiehl and Trenberth, 1997: Earth's Annual Global Mean Energy Budget, Bull. Am. Met. Soc. 78, 197-208*

Vegetation and soils at the land surface control how energy received from the Sun is returned to the atmosphere: as long-wave (infrared) radiation, or evaporating water, which consumes energy and brings water back into the atmosphere. The marine and terrestrial biospheres have a major impact influence the uptake and release of greenhouse gases. Through the photosynthetic process, both marine and terrestrial plants (especially forests) store significant amounts of carbon from carbon dioxide.

Many physical, chemical and biological interaction processes occur among the various components of the climate system on a wide range of space and time scales, making the system extremely complex. Although the components of the climate system are very different in their composition, physical and chemical properties, structure and behavior, they are all linked by fluxes of mass, heat and momentum: all subsystems are open and interrelated.

As an example, the atmosphere and the oceans are strongly coupled and exchange, among others, water vapor and heat through evaporation. This is part of the hydrological cycle and leads to condensation, cloud formation, precipitation and runoff, and supplies energy to weather systems. On the other hand, precipitation has an influence on salinity, its distribution and the thermohaline circulation. Atmosphere and oceans also exchange, among other gases, carbon dioxide, maintaining a balance by dissolving it in cold polar water which sinks into the deep ocean and by outgassing in relatively warm upwelling water near the equator.

Climate and Weather

- Weather is short term
- Climate is long-term “average weather”
  – Defined in statistical terms over time
    • Time periods range from years to centuries
    • Often use 30 years as period to analyze
  – Surface variables: temperature, precipitation, wind
- Climate change
  – Look for statistically significant changes
    • Source may be natural or anthropogenic

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Climate in a narrow sense is usually defined as the “average weather”, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period is 30 years, as defined by the World Meteorological Organization (WMO). These quantities are most often surface variables such as temperature, precipitation, and wind. Climate in a wider sense is the state, including a statistical description, of the climate system.

Climate change refers to a statistically significant variation in either the mean state of the climate or in its variability, persisting for an extended period (typically decades or longer). Climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use. The Framework Convention on Climate Change (UNFCCC), in its Article 1, defines “climate change” as: “a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods”. The UNFCCC thus makes a distinction between “climate change” attributable to human activities altering the atmospheric composition, and “climate variability” attributable to natural causes.

Climate variability

Climate variability refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all temporal and spatial scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability).

Climate and Weather II

- Climate system components
  - atmosphere
  - hydrosphere
  - cryosphere (sea ice, freshwater ice, snow, glaciers, frozen ground and permafrost)
  - land surface
  - biosphere

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The following terms are used in the IPCC reports

Climate feedback is an interaction mechanism between processes in the climate system is called a climate feedback, when the result of an initial process triggers changes in a second process that in turn influences the initial one. A positive feedback intensifies the original process, and a negative feedback reduces it.

Climate models differ in such aspects as the number of spatial dimensions, the extent to which physical, chemical or biological processes are explicitly represented, or the level at which empirical parametrizations are involved. Coupled atmosphere/ ocean/sea-ice General Circulation Models (AOGCMs) provide a comprehensive representation of the climate system.

Climate prediction is an attempt to produce a most likely description or estimate of the actual evolution of the climate in the future.

Climate projection projection of the response of the climate system to emission or concentration scenarios of greenhouse gases and aerosols, or radiative forcing scenarios, which are based on assumptions, concerning, e.g., future socio-economic and technological developments, that may or may not be realized.

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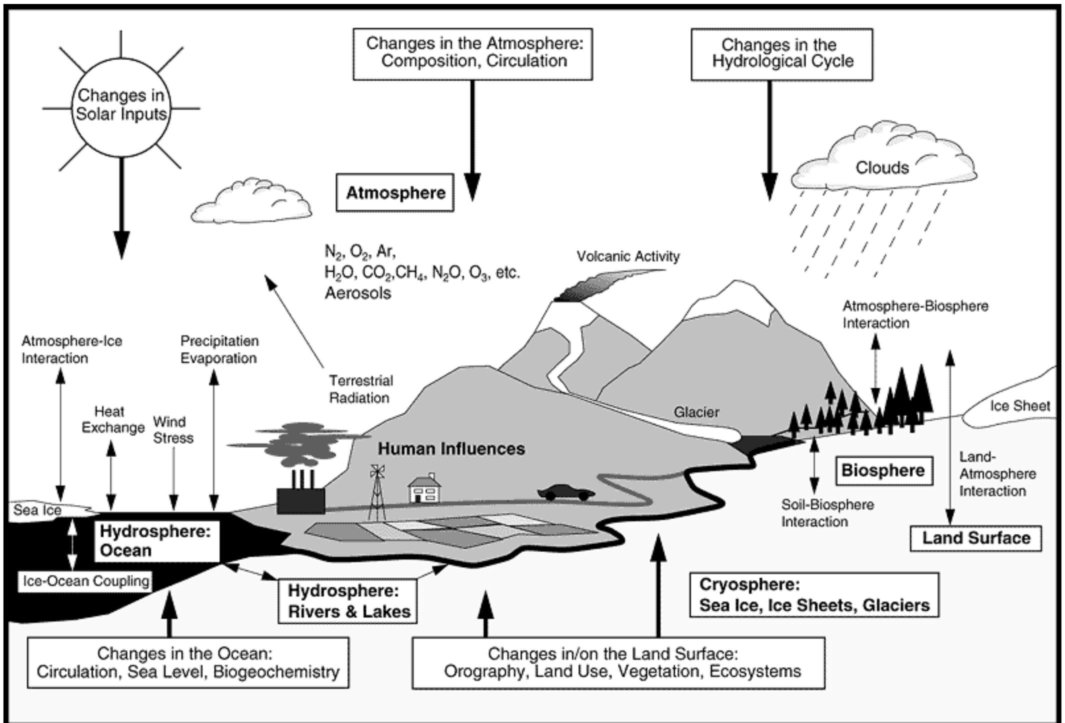

California State University Northridge http://www.grida.no/climate/ipcc_tar/wg1/fig1-1.htm 11

Reference: http://www.grida.no/climate/ipcc_tar/wg1/fig1-1.htm

The climate system is an interactive system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the land surface and the biosphere, forced or influenced by various external forcing mechanisms. The atmosphere is the most unstable and rapidly changing part of the system. Trace gases, such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and ozone (O_3), which do absorb and emit infrared radiation. Water vapor (H_2O), which is also a natural greenhouse gas has a highly variable composition, 1%. Because these greenhouse gases absorb the infrared radiation emitted by the Earth and emit infrared radiation up- and downward, they tend to raise the temperature near the Earth’s surface. Water vapor, CO_2 and O_3 also absorb solar short-wave radiation.

Ozone in the lower part of the atmosphere, the troposphere and lower stratosphere, acts as a greenhouse gas. Higher up in the stratosphere there is a natural layer of high ozone concentration, which absorbs solar ultra-violet radiation.

Solid and liquid particles (aerosols) and clouds, which interact with the incoming and outgoing radiation in a complex and spatially very variable manner. Water vapor is central to the climate and its variability and change. The hydrosphere is the component comprising all liquid surface and subterranean water, both fresh water, including rivers, lakes and aquifers, and saline water of the oceans and seas. Oceans damp vast and strong temperature changes and function as a regulator of the Earth’s climate on the longer time-scales.

The cryosphere, including the ice sheets of Greenland and Antarctica, continental glaciers and snow fields, sea ice and permafrost, derives its importance to the climate system from its high reflectivity (albedo) for solar radiation, its low thermal conductivity, its large thermal inertia and, especially, its critical role in driving deep ocean water circulation. Because the ice sheets store a large amount of water, variations in their volume are a potential source of sea level variation.

Climate and Weather III

- Climate system evolves by internal dynamics and external forcings
  - natural forcings
    - volcanic eruptions
    - solar variations
  - human-induced forcings
    - changing composition of the atmosphere
    - land-use change

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Continued from previous notes page

Climate scenarios are plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships.

Climate sensitivity refers to the equilibrium change in global mean surface temperature following a doubling of the atmospheric (equivalent) CO_2 concentration.

Climate system
The climate system is the highly complex system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the land surface and the biosphere, and the interactions between them. The climate system evolves in time under the influence of its own internal dynamics and because of external forcings such as volcanic eruptions, solar variations and human-induced forcings such as the changing composition of the atmosphere and land-use change.

Climate and Weather IV

- Climate feedback may have positive or negative effects on original process
- Climate models
  - Interaction among atmosphere, ocean, sea ice, land, called air-ocean general circulation models (AOGCM)
  - Verified by agreement with past data and used for future projections
  - Simpler models used for extensive calculations

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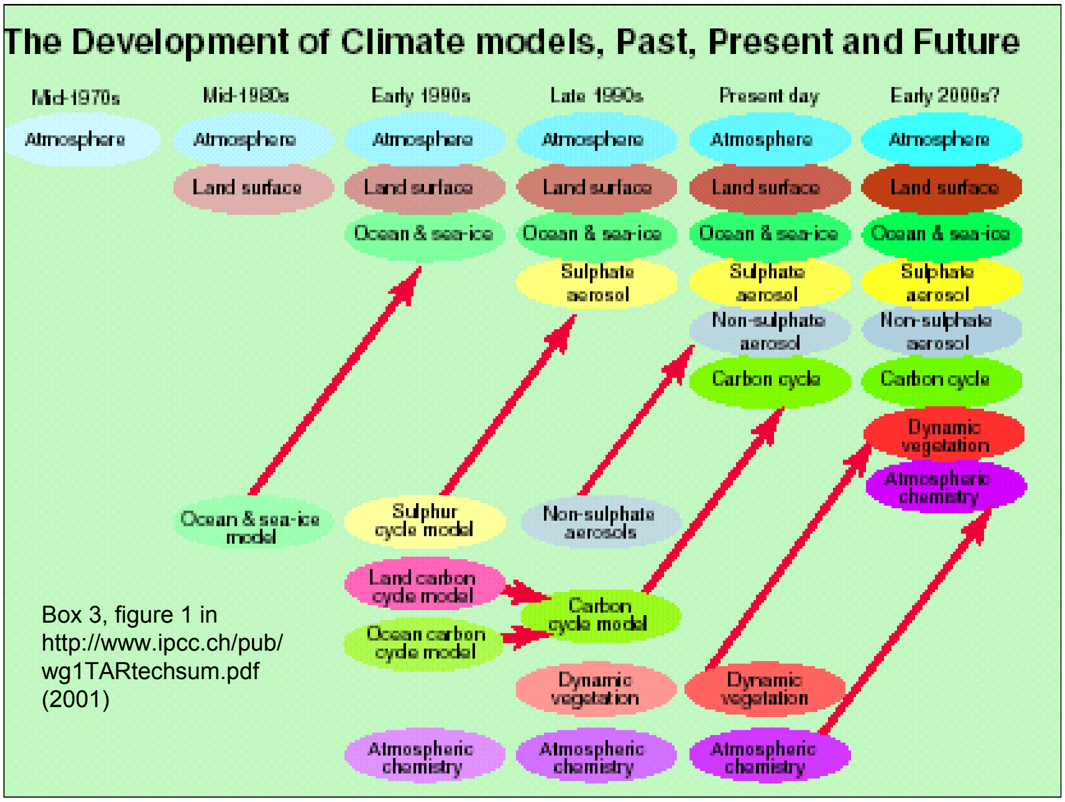
Acronyms for climate models

Air-Ocean General Circulation Models (AOGCM)

Earth System Models of Intermediate Complexity (EMIC).

Model for the Assessment of Greenhouse-Gas Induced Climate Change (MAGICC)

In IPCC assessment reports the most complex models, the AOGCMs are used to make a basic set of predictions. The simpler models are then calibrated against the results of the AOGCMs. These simpler models have “adjustable parameters” that are used in empirical treatment of phenomena that the simpler models cannot fully simulate. These adjustable parameters are modified to give the best possible agreement between the simple models and the AOGCMs before being used in more extensive calculations.



Reference: Ingergovernmental Panel on Climate Change (IPCC), *Climate Change 2001: The Sciencific Basis*, IPCC, 2001. Figure taken from technical summary available at http://www.ipcc.ch/pub/wg1TARtechsum.pdf.

The Fourth Assessment Report has a chapter on models that discusses them in great detail. That chapter points out that the most complex models have very large computing requirements and most of the work that is done in the assessment report is based on using simpler models that provide a reasonable model of the climate dynamics within a reduced computational cost. Such simpler models are required to make runs over large time periods and to make runs over various conditions to obtain probabilities.

The reference for this chapter is Randall, D.A., R.A. Wood, S. Bony, R. Colman, T. Fichefet, J. Fyfe, V. Kattsov, A. Pitman, J. Shukla, J. Srinivasan, R.J. Stouffer, A. Sumi and K.E. Taylor, 2007: Cilmate Models and Their Evaluation. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. Accessed online on February 12, 2008 at http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter8.pdf.

“Despite notable progress in improving sea ice formulations, AOGCMs have typically achieved only modest progress in simulations of observed sea ice since the TAR.” (p. 592).

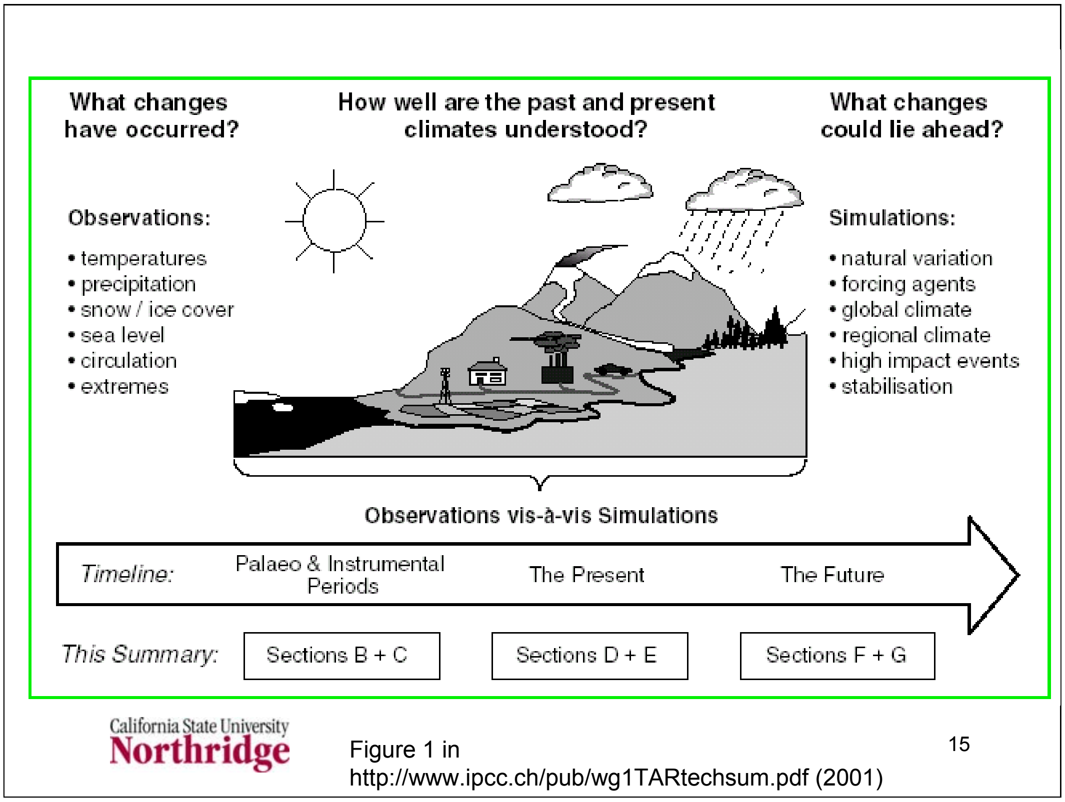


Figure: Ingergovernmental Panel on Climate Change (IPCC), *Climate Change 2001: The Sciencific Basis*, IPCC, 2001. Figure taken from technical summary available at http://www.ipcc.ch/pub/wg1TARtechsum.pdf.

From Chapter 8 of Fourth Assessment Report:

"The large-scale patterns of seasonal variation in several important atmospheric fields are now better simulated by AOGCMs than they were at the time of the TAR. Notably, errors in simulating the monthly mean, global distribution of precipitation, sea level pressure and surface air temperature have all decreased. In some models, simulation of marine lowlevel clouds, which are important for correctly simulating sea surface temperature and cloud feedback in a changing climate, has also improved. Nevertheless, important deficiencies remain in the simulation of clouds and tropical precipitation (with their important regional and global impacts)."

Climate and Weather V

- Climate projections
  - Response to scenarios of greenhouse gases and aerosols
- Climate sensitivity
  - Equilibrium change in global mean surface temperature following a doubling of the atmospheric (equivalent) CO_2 concentration.
    - Model sensitivity results on notes page

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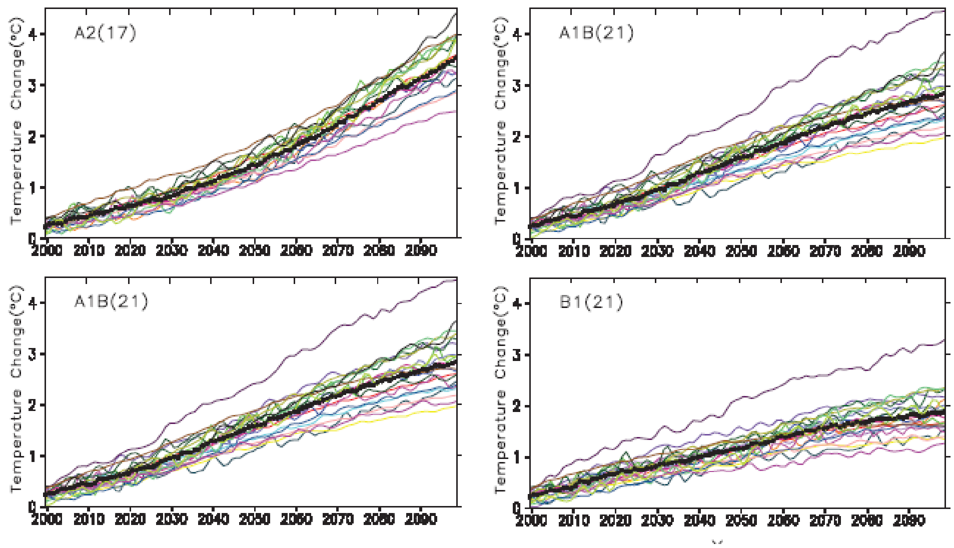
AOGCM Model	S1	S2	AOGCM Model	S1	S2
BCC-CM1	n.a.	n.a.	GISS-AOM	n.a.	n.a.
BCCR-BCM2.0	n.a.	n.a.	GISS-ER	2.7	1.5
INM-CM3.0	2.1	1.6	GISS-EH	2.7	1.6
CCSM3	2.7	1.5	IPSL-CM4	4.4	2.1
CGCM3.1(T47)	3.4	*1.9*	MIROC3.2(hires)	4.3	2.6
CGCM3.1(T63)	*3.4*	n.a.	MIROC3.2(medres)	4.0	2.1
CNRM-CM3	n.a.	1.6	MRI-CGCM2.3.2	3.2	2.2
CSIRO-MK3.0	3.1	1.4	PCM	2.1	1.3
ECHAM5/MPI-OM	3.4	2.2	UKMO-HadCM3	3.3	2.0
ECHO-G	3.2	1.7	UKMO-HadGEM1	4.4	1.9
FGOALS-g1.0	*2.3*	*1.2*	GFDL-CM2.	1 3.4	1.5
GFDL-CM2.0	2.9	1.6			

S1 is the equilibrium climate sensitivity in °C and S2 is the transient climate sensitivity, also in °C. The data are taken from http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter8.pdf. (accessed February 12, 2008) Except for results shown in italics, the results were computed using a simple model of the ocean-atmosphere coupling known as a "slab ocean". The variation in these results illustrates the uncertainties in the models.

Modeled Temperatures



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IPCC, *Climate Change2007: Working Group One Report*, Chapter 10, Intergovernmental Panel on Climate Change, 2007, Figure 10.5. Downloaded from http://www.ipccreports/ar4-wg1.htm, March 3, 2007.

This chart shows the variation in temperature foreacts from global climate models. The caption for this figure is copied below:

Time series of globally averaged (left) surface warming (surface air temperature change, °C) from the various global coupled models for the scenarios A2 (top), A1B (middle) and B1 (bottom). Numbers in parentheses following the scenario name represent the number of simulations shown. Values are annual means, relative to the 1980 to 1999 average from the corresponding 20th-century simulations, with any linear trends in the corresponding control run simulations removed. A three-point smoothing was applied. Multi-model (ensemble) mean series are marked with black dots. See Table 8.1 for model details.

Similar figures in the report, not shown here, perdict the sea level rise. These also show the kind of variation shown in the temperature predicitons.

Radiative Forcing

- Measures change in radiation due to external events
  - Change in the net vertical irradiance (W/m^2) at tropopause due to internal change or a change in the external forcing of the climate system
  - Usually radiative forcing computed after allowing for stratospheric temperatures to readjust to radiative equilibrium, but with all tropospheric properties held fixed at their unperturbed values

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http://www.grida.no/climate/ipcc_tar/wg1/518.htm

Reference: Web page for University of Reading (UK) Meteorology Department: http://www.met.rdg.ac.uk/~radiation/forcing2.html#definition

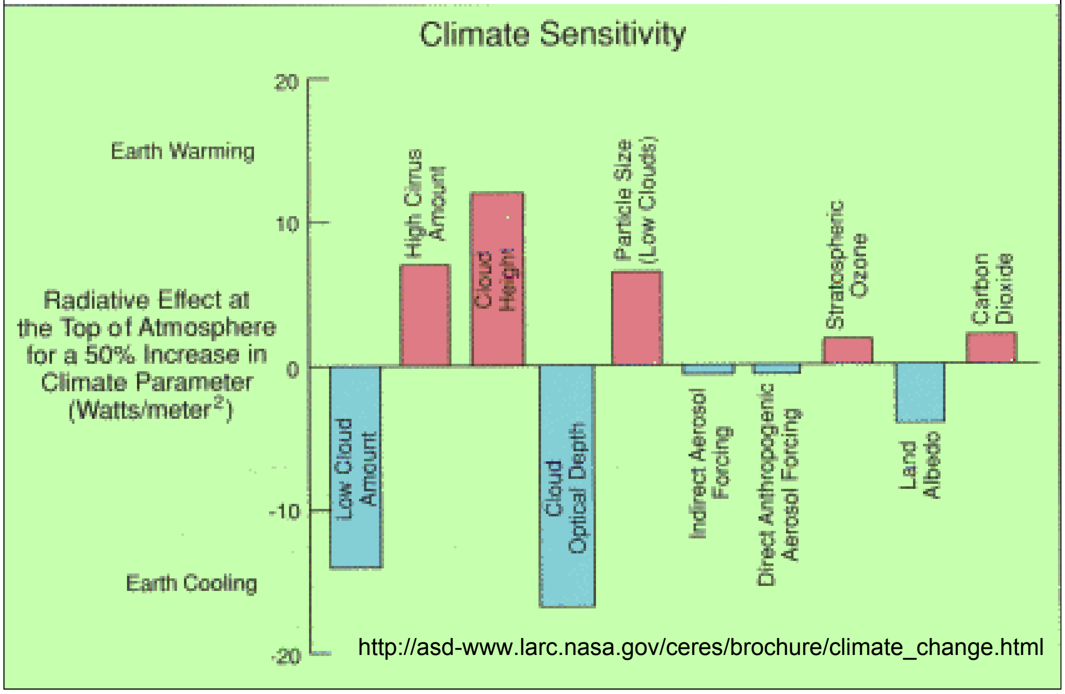
Radiative forcing (or RF) is the change in **net radiative flux** at the tropopause after the climate has been perturbed, **after allowing the stratosphere to come into equilibrium with the perturbation**. The perturbation can from a gas such as carbon dioxide, or particulate matter, such as aerosols.

The radiative forcing is calculated after the stratosphere has come into equilibrium with the perturbation because the timescale for stratospheric adjustment is **a few months**, as opposed to **decades** for the troposphere and surface. Temperature changes in the stratosphere are therefore counted as part of the forcing, and not the response. This is the reason for choosing the tropopause as the region where RF is calculated.

A positive radiative forcing implies a warming of the surface, while a negative radiative forcing implies a cooling of the surface. Most species force the climate by a magnitude of about 1 W m^2 or less.

Radiative forcing definition from http://www.grida.no/climate/ipcc_tar/wg1/518.htm
Radiative forcing is the change in the net vertical irradiance (expressed in Watts per square metre: Wm^{-2}) at the tropopause due to an internal change or a change in the external forcing of the climate system, such as, for example, a change in the concentration of carbon dioxide or the output of the Sun. Usually radiative forcing is computed after allowing for stratospheric temperatures to readjust to radiative equilibrium, but with all tropospheric properties held fixed at their unperturbed values. Radiative forcing is called instantaneous if no change in stratospheric temperature is accounted for. Practical problems with this definition, in particular with respect to radiative forcing associated with changes, by aerosols, of the precipitation formation by clouds, are discussed in the IPCC Report.

Natural "Forcing"



Reference: http://asd-www.larc.nasa.gov/ceres/brochure/climate_change.html (Last access date unknown)

This chart shows that there are a number of effects that can have a radiative forcing that gives an effect on climate. Note that the height of each bars is based on an assumed 50% increase in the parameter represented by the bar. To put this in perspective, remember that the incoming solar radiation (global and planetary average) is 342 W/m^2.

Because of the large effect of clouds some researchers have suggested that if global warming occurs it might be possible to inject chemicals into the atmosphere to increase the cloud cover to counter global warming. This is an area that is receiving more attention as concern grows that we may not be able to take enough action to reduce global warming.

Global Warming Potentials

- GWP defined as the ratio of the time-integrated radiative forcing from the instantaneous release of 1 kg of a trace substance relative to that of 1 kg of CO_2
- Measures both direct (trace substance a greenhouse gas) or indirect effects (particles affect radiation response)
- GWP-weighted emissions measured in teragrams of CO_2 equivalent

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GWP Data

• CO_2	1	CH_4	21
• N_2O	310	HFC-23	11,700
• HFC-32	650	HFC-125	2,800
• HFC-134a	1,300	HFC-143a	3,800
• HFC-152a	140	HFC-227ea	2,900
• HFC-236fa	6,300	CF_4	6,500
• C_2F	9,200	C_4F_{10}	7,000
• C_6F_{14}	7,400	SF_6	23,900

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Table ES-1 in http://epa.gov/climatechange/emissions/downloads06/06ES.pdf

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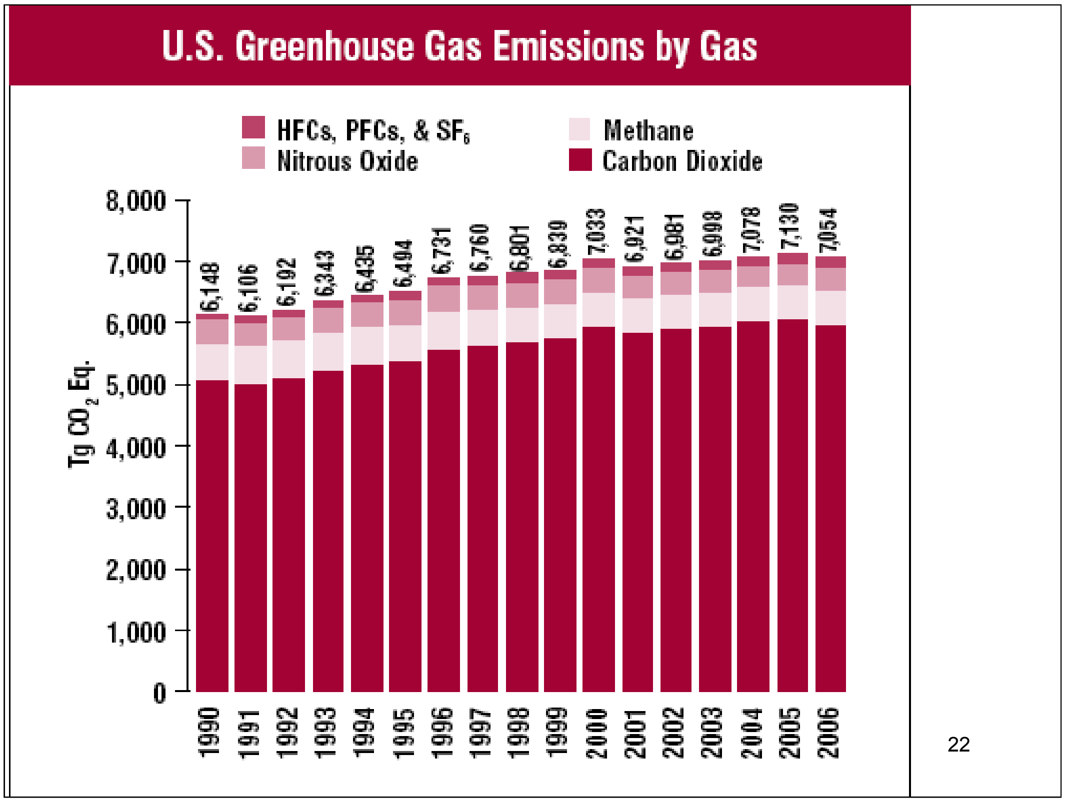
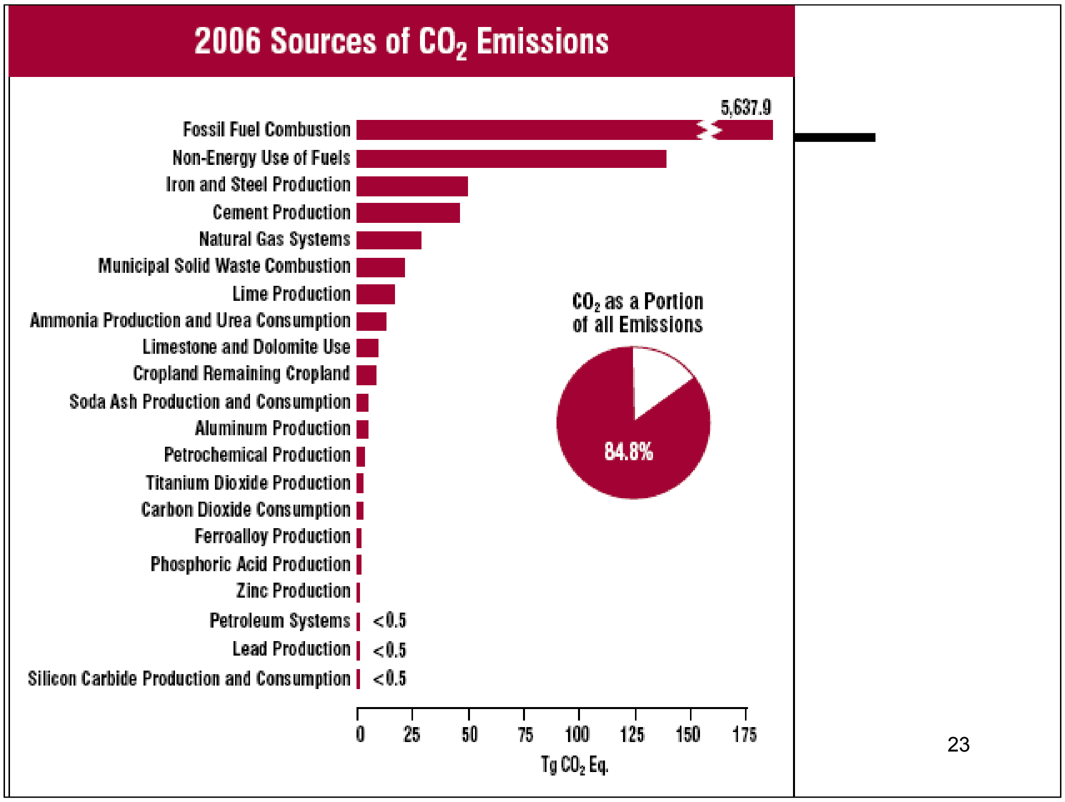


US Environmental Protection Agency, Inventory of US Greenhouse Gas Emissions and Sinks 1990-2006, April 15, 2008, Figure ES-1. http://epa.gov/climatechange/ emissions/downloads/08ES.pdf accessed February 9, 2009

In 2006 total emissions decreased for the first time since 2001. Both years with decreases are years of poor economic performance and the downturn in CO_2 emissions is due to a decrease in economic activity, including driving.

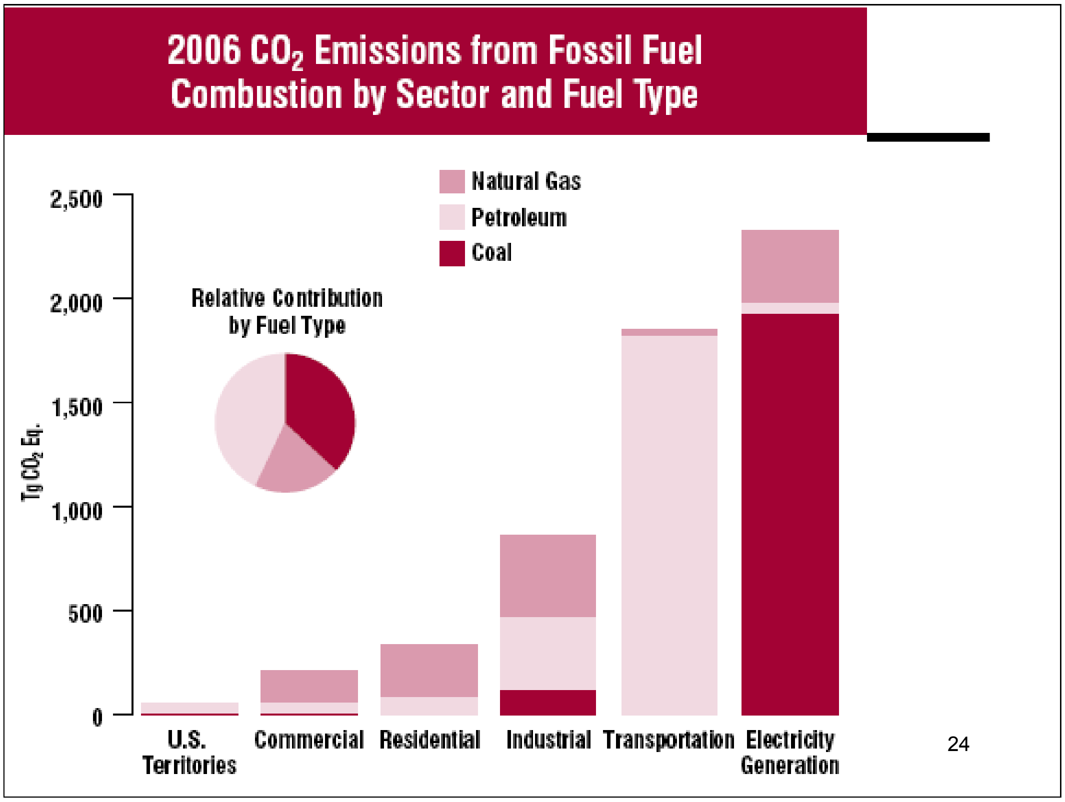
This chart illustrates the problems of trying to obtain a decrease over 1990 levels, the target of the Kyoto protocol.

http://epa.gov/climatechange/emissions/downloads/08_ES.pdfhttp://epa.gov/climatechange/emissions/downloads/08_ES.pdf



US Environmental Protection Agency, Inventory of US Greenhouse Gas Emissions and Sinks 1990-2006, April 15, 2008, Figure ES-5. http://epa.gov/climatechange/ emissions/downloads/08ES.pdf accessed February 9, 2009.

Note that the top bar – Fossil Fuel Combustion – is over 32 times longer than the total length of the horizontal axis. The components of this combustion bar are shown on a later slide.



US Environmental Protection Agency, Inventory of US Greenhouse Gas Emissions and Sinks 1990-2006, April 15, 2008, Figure ES-6. http://epa.gov/climatechange/ emissions/downloads/08ES.pdf accessed February 9, 2009.

Electricity generation has a large use of coal, which has a higher amount of CO_2 per unit heat input, compared to other fuels. This accounts for the large CO_2 production from electricity generation.

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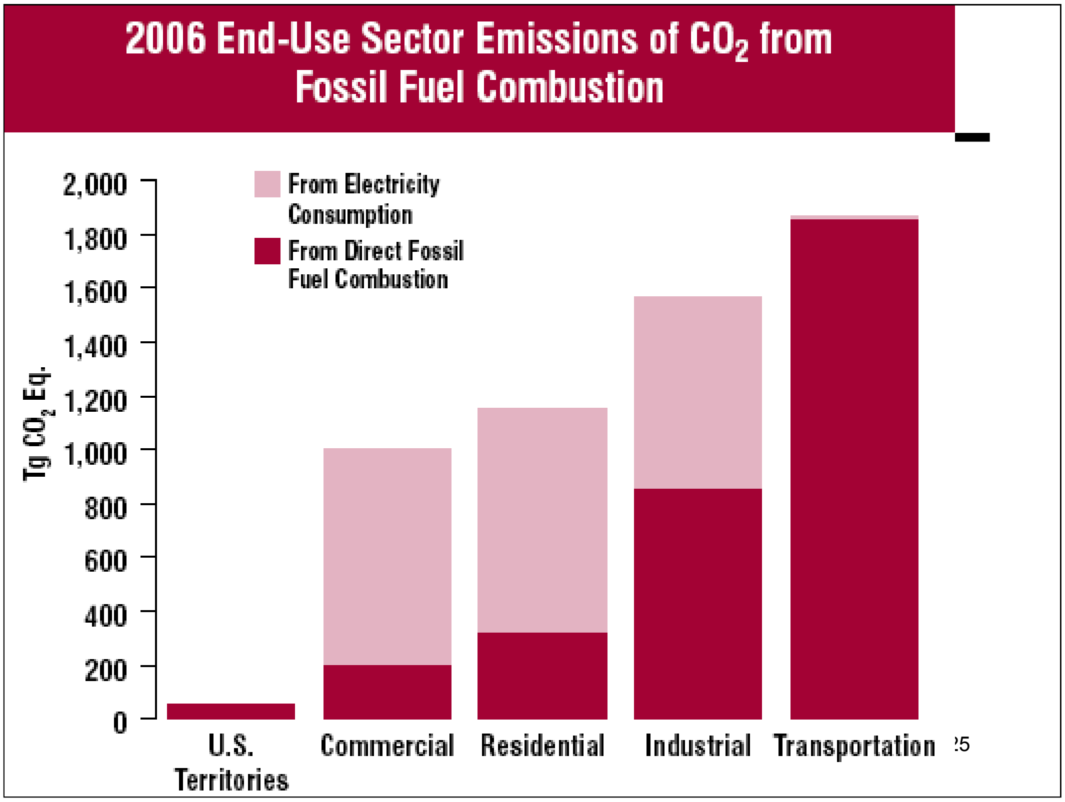
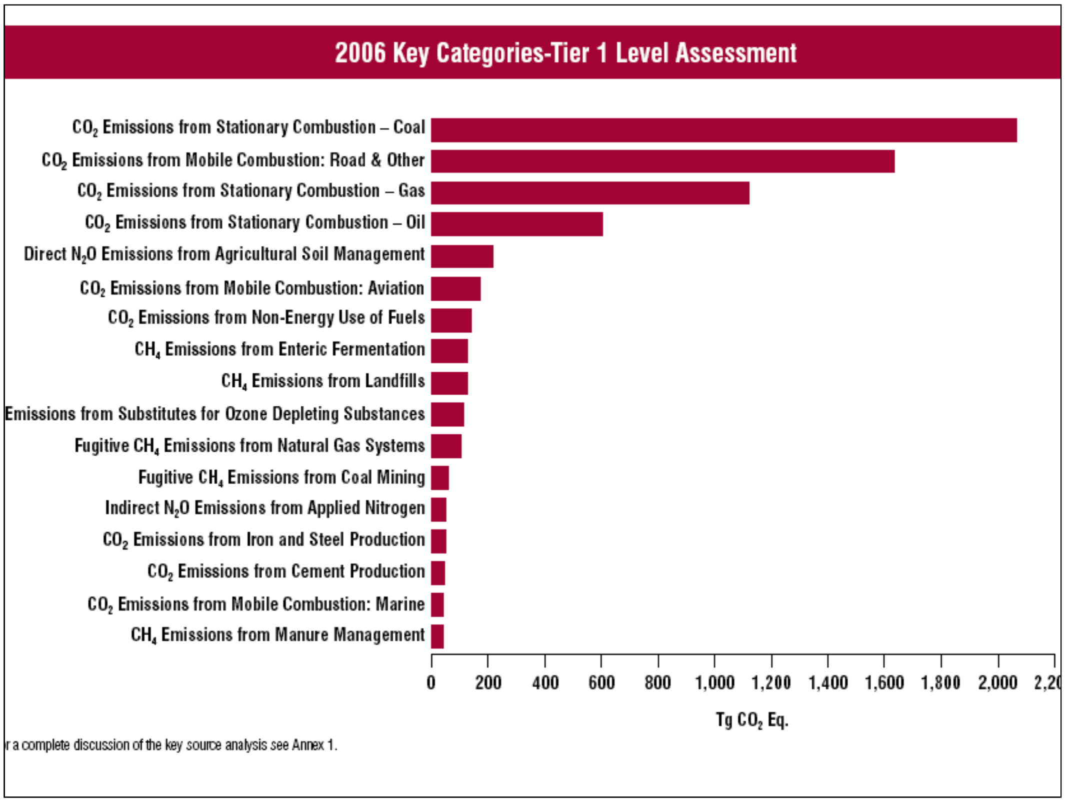
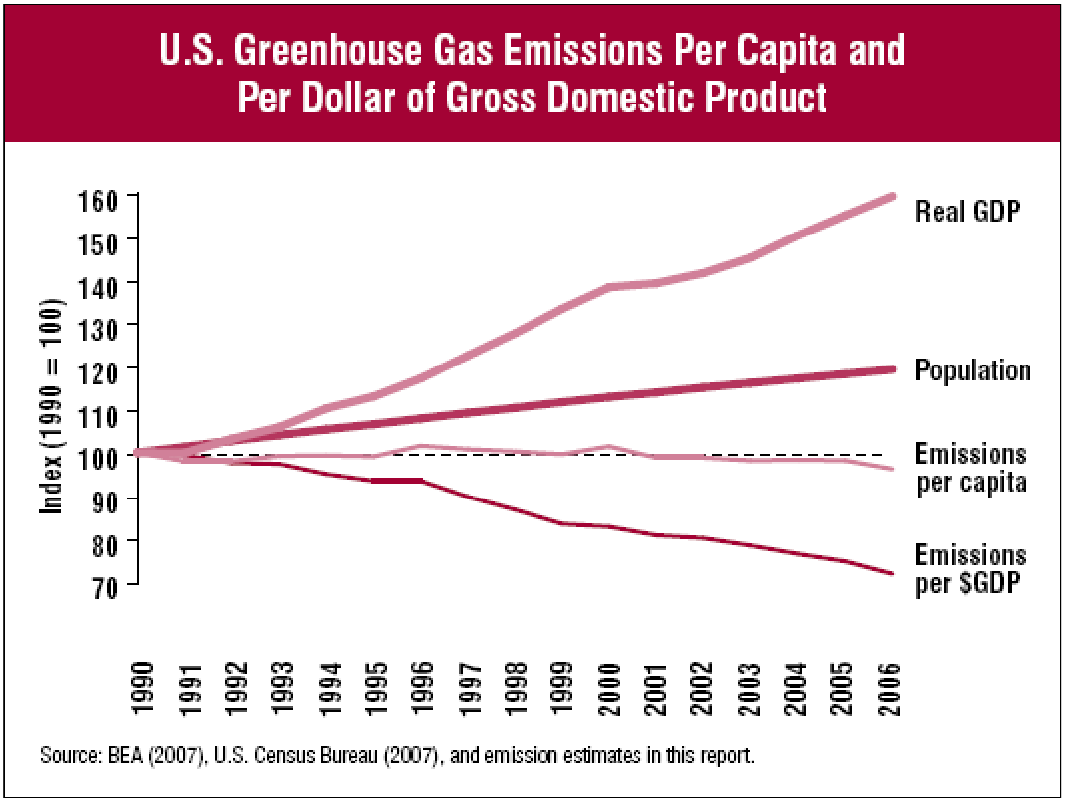


US Environmental Protection Agency, Inventory of US Greenhouse Gas Emissions and Sinks 1990-2006, April 15, 2008, Figure ES-6. http://epa.gov/climatechange/ emissions/downloads/08ES.pdf accessed February 9, 2009.

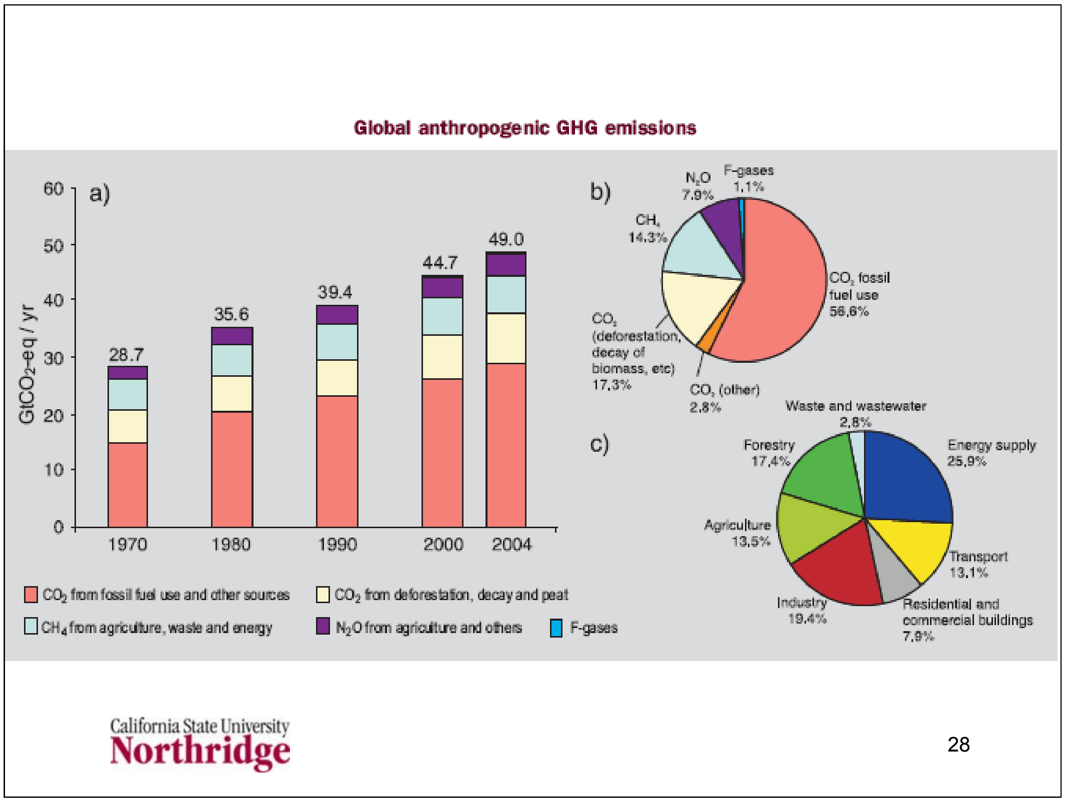
The CO_2 generation from electric power is the main souce of CO_2 for residential and commercial users. Transportation has almost no electricity use, but it is the highest producing sector for CO_2.



US Environmental Protection Agency, Inventory of US Greenhouse Gas Emissions and Sinks 1990-2006, April 15, 2008, Figure ES-16. http://epa.gov/climatechange/ emissions/downloads/08ES.pdf accessed February 9, 2009



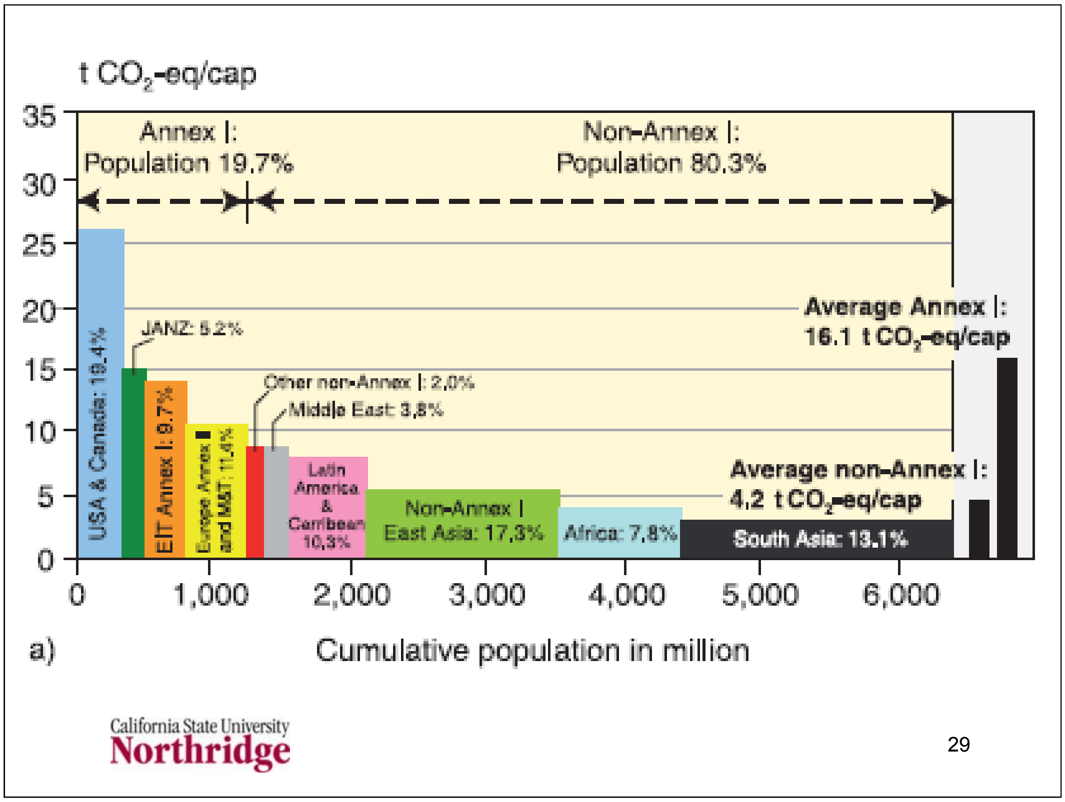
US Environmental Protection Agency, Inventory of US Greenhouse Gas Emissions and Sinks 1990-2006, April 15, 2008, Figure ES-15. http://epa.gov/climatechange/ emissions/downloads/08ES.pdf accessed February 9, 2009



IPCC, *Climate Change2007: Synthesis Report*, Intergovernmental Panel on Climate Change, 2007, Figure 2.1. Downloaded from http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf, March 3, 2007.

This figure from the 2007 report of the Intergovernmental Panel on Climate Change shows not only the emissions, but also the source of CO_2 from deforfestation and decay of biomass.

In this chart, “energy sypply” denotes the emissions associated with all aspects of providing energy to the ultimate consumer. This includes the



IPCC, *Climate Change2007: Synthesis Report*, Intergovernmental Panel on Climate Change, 2007, Figure 2.2. Downloaded from http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf, March 3, 2007

This figure is based on 2004 population data. Note that the area of each region gives the magnitude of the GHG emissions in tonnes of CO_2 . It is the product of the vertical axis, tonnes of CO_2 per capita, and population along the horizontal axis.

Annex I countries

The group of countries included in Annex I (as amended in 1998) to the *United Nations Framework Convention on Climate Change (UNFCCC)*, including all the OECD countries in the year 1990 and countries with economies in transition. Under Articles 4.2 (a) and 4.2 (b) of the Convention, Annex I countries committed themselves specifically to the aim of returning individually or jointly to their 1990 levels of *greenhouse gas* emissions by the year 2000. By default, the other countries are referred to as *Non-Annex I countries.* For a list of Annex I countries, see http://unfccc.int.

This

CO_2 Sequestration

- Reduction of CO_2 is a two-fold task
  - Removal of CO_2 from combustion gases
  - Disposal of CO_2 removed
- Current cost estimates are $100 to $300 per ton of ***carbon*** emissions avoided
- Research goal is $10/ton
- See list of sequestration processes at http://www.fossil.energy.gov/fred/feprograms.jsp?prog=Carbon+Sequestration

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Reference: http://www.fossil.energy.gov/programs/sequestration/index.html

The joint Office of Fossil Energy and Office of Science April 1999 draft report *Carbon Sequestration: State of the Science* subsequently has assessed "...key areas for research and development (R&D) that could lead to an understanding of the potential for future use of carbon sequestration as a major tool for managing carbon emissions."

To be successful, the techniques and practices to sequester carbon must meet the following requirements: (1) be effective and cost-competitive, (2) provide stable, long term storage, and (3) be environmentally benign.

Using present technology, estimates of sequestration costs are in the range of $100 to $300/ton of carbon emissions avoided. The goal of the program is to reduce the cost of carbon sequestration to $10 or less per net ton of carbon emissions avoided by 2015. Achieving this goal would save the U.S. trillions of dollars.

Further, achieving a mid-point stabilization scenario (e.g., 550 parts per million CO2) would not require wholesale introduction of zero emission systems in the near term. This would allow time to develop cost effective technology over the next 10-15 years that could be deployed for new capacity and capital stock replacement capacity.

The near term program will examine and identify a spectrum of science-based sequestration approaches that have the greatest potential to yield the cost-effective technologies that are required. For example, a competitive solicitation was issued in FY 1998 and resulted in the selection of 12 innovative novel concepts for the control of atmospheric emissions of CO_2, methane and nitrous oxide. In May 1999 six of the most promising concepts were selected for further study.

Modeling and assessments provide the capabilities to evaluate technology options in a total systems context, considering costs and impacts over the full product cycle. Further, the societal and environmental effects are analyzed to mental effects are analyzed to provide a basis for assessing trade-offs between local environmental impacts and global impacts.

CO_2 Removal Options

- Absorption (chemical and physical)
- Adsorption (physical and chemical)
- Low-temperature distillation
- Gas separation membranes
- Mineralization and biomineralization
- Current DOE research goal is 90% reduction with 99% capture for 100 years with energy cost increase < 10%

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Reference: http://www.fe.doe.gov/coal_power/sequestration/sequestration_capture.shtml (accessed March 2007)

Before CO_2 gas can be sequestered from power plants or industrial sources, it must be captured as a relatively pure gas.

CO_2 is routinely separated and captured as a by-product from industrial processes such as synthetic ammonia production, hydrogen production, and limestone calcination. However, existing capture technologies are not cost-effective when considered in the context of CO_2 sequestration.

Carbon dioxide capture is generally estimated to represent three-fourths of the total cost of a carbon capture, storage, transport, and sequestration system. The program area will pursue evolutionary improvements in existing CO_2 capture systems and also explore revolutionary new capture and sequestration concepts. The most likely options currently identifiable for CO_2 separation and capture include the following:

Absorption (chemical and physical)

Adsorption (physical and chemical)

Low-temperature distillation

Gas separation membranes

Mineralization and biomineralization

Opportunities for significant cost reductions exist since very little R&D has been devoted to CO_2 capture and separation technologies. Several innovative schemes have been proposed that could significantly reduce CO_2 capture costs, compared to conventional processes. "One box" concepts that combine CO_2 capture with deduction of criteria-pollutant emissions are concepts to be explored.

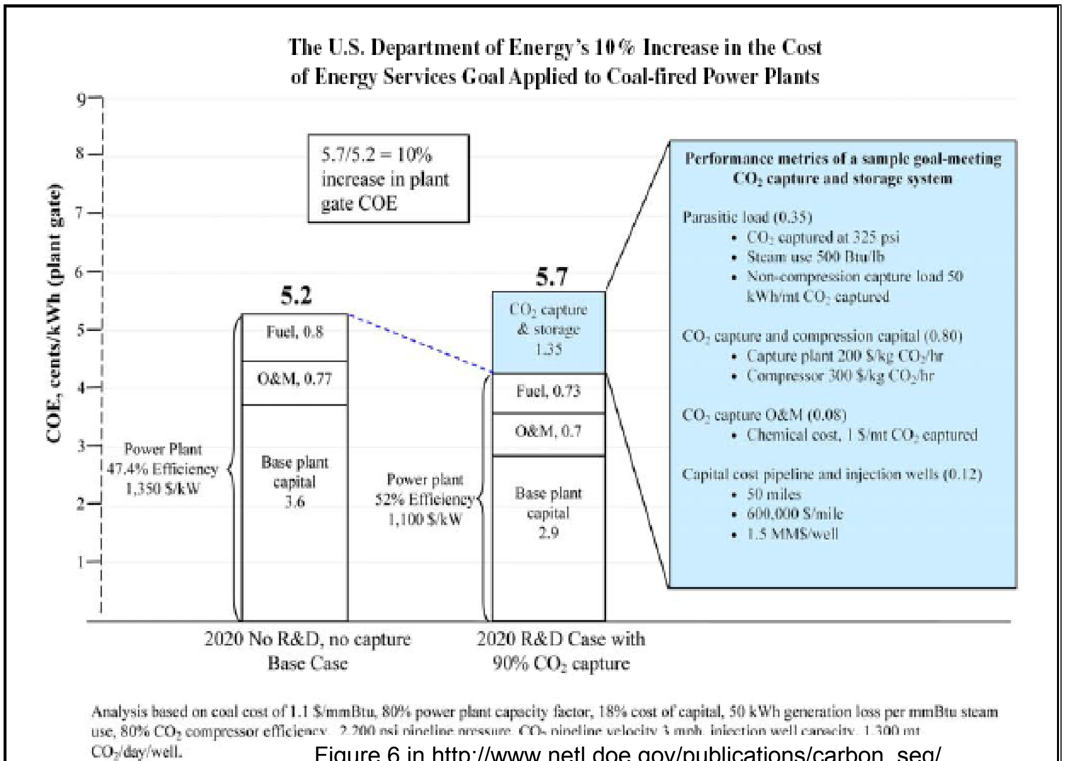

Figure 6 in http://www.netl.doe.gov/publications/carbon_seq/2006%20Sequestration%20Roadmap%20FINAL.pdf

California Activities

- 2002: AB 1493 approved – requires California Air Resources Board (ARB) to set GHG standards for new vehicles
- 2004: ARB adopts standards for new vehicles in 2009-2016 that reduce GHG emissions by 22% to 30%
- December 11, 2007: Auto industry lawsuit ruled in favor of regulation
- December 18, 2007: Waiver denied

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The adoption of regulations to control greenhouse gases from cars and trucks in California was controversial.

EPA delayed acting on California's waiver application for over two years. (The Federal Clean Air Act allows California to request a waiver from the stipulation in the Act that no state can set its own mobile source standards. However this waiver must be approved by EPA.)

The auto industry sued to have the regulations overturned on the basis that they were fuel economy regulations in disguise. This lawsuit by the automobile industry was decided in favor of ARB in December 2007. However only a week later EPA Administrator Stephen L. Johnson announced that EPA was denying California's waiver application.

California had planned to sue EPA over this decision stating that it was incorrect. With the election of President Obana, however, California has asked EPA to reconsider the waiver requrest. The basis for Johnson's decision was that the new fuel-economy regulations passed by Congress in December 2007 (and subsequently approved by the President) would provide more greenhouse gas reductions in California than the regulations proposed by the ARB. The ARB has contested this and has published a report and an addendum that show the California regulation would reduce greenhouse gases more. These reports were accessed on line on February 13, 2008 at the two following URLs.
http://www.arb.ca.gov/cc/ccms/ab1493_v_cafe_study.pdf
http://www.arb.ca.gov/cc/ccms/pavley-addendum.pdf

California Activities II

- 2006: AB 32 approved; requires ARB to
  - Set GHG emissions cap for 2020 by 1/1/08
  - Adopt emission reductions plan by 1/1/09
  - Adopt regulations by January 1, 2011 to achieve the maximum technologically feasible and cost-effective GHG reductions
    - including provisions for using both market mechanisms and alternative compliance mechanisms
  - Adopt list of measures by 7/1/07 that can be implemented before 1/1/10 and adopt such measures

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The regulatory process associated with climate change has become one of the biggest efforts of ARB. A variety of working groups are planning approaches to regulations. The Board recently adopted the 1990 baseline level, so now emission-reduction targets are known. The next step is the development of regulations. This will most likely be a combination of a cap-and-trade regulation and some “command-and-control” regulations.

California Activities III

- 2005 Governor's executive order to have state agencies plan GHG reductions
  - Reduce to 2000 levels by 2010
  - Reduce to 1990 levels by 2020
  - Reduce below 80% of 1990 levels by 2050
- Interagency climate action team report in 2006 outlines strategies for state agencies to follow for 2020 target
  - http://www.climatechange.ca.gov/climate_action_team/

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Is Global Warming Real?

- Problem: find a trend in a very noisy data set (with other trends), attribute that trend to a definite cause, and predict its future
- Issue: some indicators argue against the trend if most others substantiate it
- Issue: if trend is real, required action is expensive and requires international cooperation among different nations

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Is Global Warming Real? II

- Global warming has generally been accepted by the scientific community for several years leading to an international convention in 1990 and the Kyoto treaty in 1997
  - Most nations have lagged in their commitments to the Kyoto treaty because of costs
  - US has embarked on large-scale research effort but has not pursued reductions

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The US government has never had strong support for the Kyoto protocol. President Clinton, who was president when the treaty was signed, never sent it to the senate for approval. (He apparently felt that it would not pass and did not want to make a failing effort.)

While he was campaigning in 2000, President Bush supported regulations for reducing greenhouse gas emissions, but after he was inaugurated he changed his position. Since that time the US has not taken a lead role in addressing greenhouse gas emissions. There have been several R&D programs in the US, but no work at regulations.

During this time, the EPA contended that it did not have the legal authority to regulate CO_2 emissions. The state of Massachusetts sued the EPA saying that they had not only the authority, but also the obligation to do so. On April 2, 2007 the Supreme Court (in a 5-4 decision) ruled that EPA had both the authority to regulate and an obligation to consider the scientific evidence for and against regulation to make a decision. http://www.supremecourtus.gov/opinions/06pdf/05-1120.pdf (accessed February 12, 2008).

The warnings from the 2007 IPCC reports have made most US politicians feel that there is a problem to be addressed, but nobody is sure how to do it and President Obama campaigned on addressing climate change and included it in his inauguration speech.

Is Global Warming Real? III

- There are still some who believe that effects are due to sources other than human activities
- Some suggest that we can adapt to warming
- Some technical concerns remain in details of analyses
- See web sites below for more information

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A Google search for global warming turned up about 25,500,000 hits on February 13, 2008. Many are governmental sites; others are from environmental groups. There are also the skeptics who have the last web site on this list.

United Nations Intergovernmental Panel on Climate Change

http://www.ipcc.ch/

US Environmental Protection Agency

http://epa.gov/climatechange/index.html

State of California

http://www.climatechange.ca.gov/

US Department of Energy

http://www.energy.gov/sciencetech/climatechange.htm

National Oceanographic and Atmospheric Administration (NOAA)

http://www.ncdc.noaa.gov/oa/climate/globalwarming.html

Chicago Climate Exchange

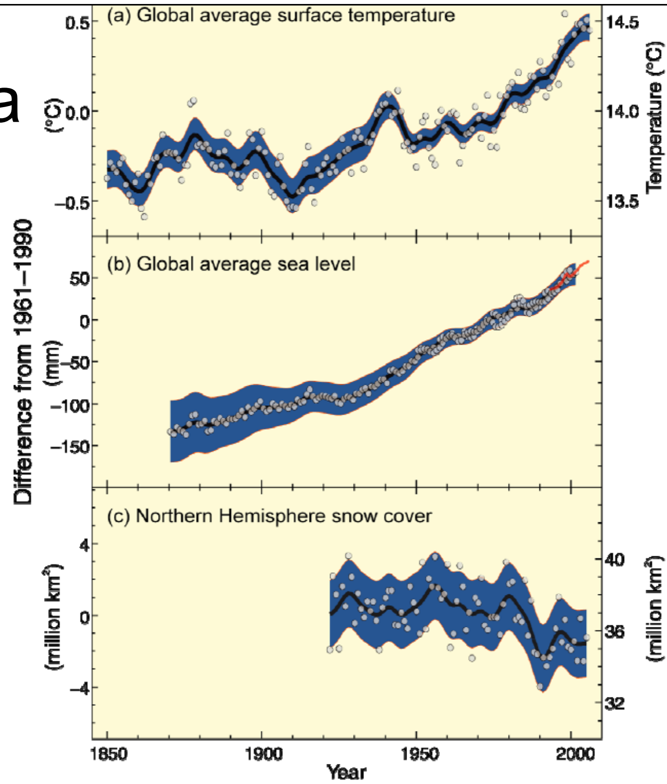
http://www.chicagoclimatex.com/

Cooler heads coalition

http://www.globalwarming.org/

IPCC Data

- Signifi-cant change from Fourth Assess-ment Report



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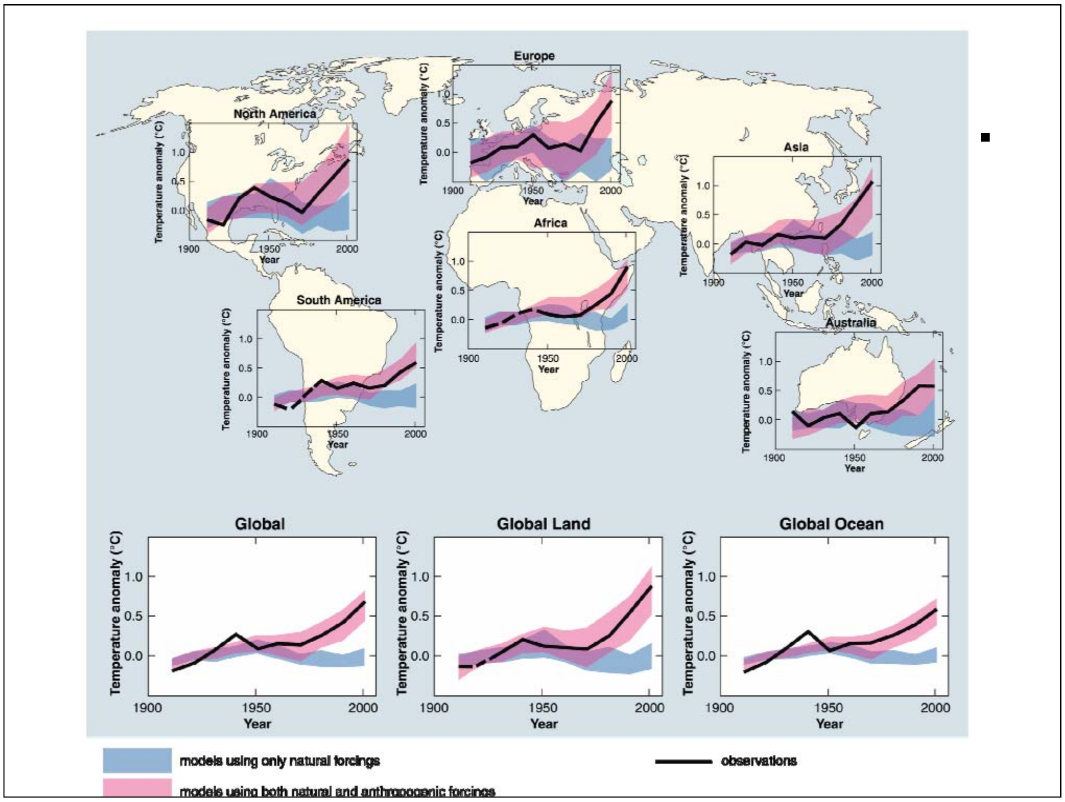
IPCC, *Climate Change2007: Synthesis Report*, Intergovernmental Panel on Climate Change, 2007, Figure 1.1. Downloaded from http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf, March 3, 2007.

Circles show yearly values, smoothed curves are ten-year running averages. The shaded blue areas represent uncertainty in the results. The later data on global average sea levels, shown in red, are taken from satellite data; previous data were taken from tidal gages. Snow cover is for March-April.



IPCC, *Climate Change2007: Synthesis Report*, Intergovernmental Panel on Climate Change, 2007, Figure 2.5. Downloaded from http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf, March 3, 2007.

This chart shows global observations of surface temperatures from 1900 to 2000. The data are plotted as the differnce between the yearly temperature and the average temperature for 1901-1950. The plotted lines show a ten-year average, plotted at the midpoint of the aveaging period. The shaded blue area shows the range for modeled temperatures, assuming that there is no anthropogenic forcing. The pink area shows the same range with the actual human effects present. This figure plays a large role in the conclusion that the effects of global warming are due to human activities.