

Environmental Aspects of Energy Production and Use

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The impacts that energy production and use have on the environment start with the extraction of the basic resource. The mining of coal and uranium and the drilling and extraction of oil and natural gas.

Some energy resources, such as coal or natural gas, have minimal refining. Crude oil undergoes extensive refining to produce a range of products that are used.

Both the initial fuel resource and refined products are transported by a variety of means. These include ships (for crude oil and petroleum products and some coal), rail (coal and some petroleum products), pipelines (crude oil, petroleum products, natural gas, and coal slurry), and trucks for local delivery of energy products to homes, commercial locations and retail gasoline distribution. Transportation has the possibility of accidental spills especially from tanker spills and pipeline ruptures.

Oil refinery processes also have a potential for accidents that can affect the environment, however the greatest potential for accidents comes from chemical plants that are preparing toxic compounds such as pesticides.

Electric power lines are another way of transporting energy from one point to another. This power transmission can remove the emissions associated with power production away from the point where the power is used. It can also remove the threat of accidents from nuclear power plants away from urban areas.

Much of these notes will examine air pollution which is the major environmental impact from energy production and use.

The issue of global warming or climate change is different from the local effects caused by individual sources. It is less easy to solve because it requires cooperation among all countries in the world to address the issue. It also requires action now to provide later benefits.

Main Ideas

- Multimedia impacts
 - Air pollution
 - Water pollution and ocean spills
 - Solid waste
- Impacts occur in extraction, refining, transportation, distribution and use
- Major impact is in air pollution
- Stratospheric ozone and climate change

Fossil fuels form the major link between energy resources and air pollution. Just as the majority of energy used in both the US and the world comes from fossil fuels, so too does the majority of air pollution.

The regulation of air pollution started in the 17th century when the King of England directed that certain smoky coals known as sea coals should not be burned in the City of London. Until the 1950s air pollution regulations were directed at the reduction of smoke and air pollution control was known as smoke prevention.

In the last century, there were two dramatic air pollution incidents in which air pollution led to increased mortality over a short time period. These occurred in the Muese Valley in Belgium in 1936 and in London in 1948. The main contaminants in these incidents were particulate matter and sulfur oxides. During the early 1940s air pollution started to appear in Southern California and experiments by Aarie Haagen-Smidt at Cal Tech during the 1950s showed that the main component of this pollution ozone which was formed in the atmosphere from reactions of hydrocarbons and oxides of nitrogen.

Although local and state efforts were made to control pollution and Federal Clean Air Act legislation was passed in 1955, 1963, and 1967, the first stringent Federal law as passed in the 1970 amendments to the clean air act. Amongst other provisions, these amendments directed the federal Environmental Protection Agency to issue criteria and standards for air pollutants that came from “numerous or diverse ... sources.” Such pollutants have become known as criteria pollutants.

Air pollution legislation and regulations deal separately with criteria pollutants and with toxic air contaminants.

Air Pollution

- Most air pollution comes from the combustion of fossil fuels for energy use
 - Air pollution control governed by Federal Clean Air Act that defines criteria pollutants
 - Come from “numerous or diverse mobile or stationary sources”
 - EPA administrator sets national ambient air quality standards (NAAQS)
 - Primary standards, “allowing an adequate margin of safety, are requisite to protect the public health”
 - Secondary standards to “protect the public welfare”

The EPA administrator sets two kinds of ambient standards: primary standards to protect public health and secondary standards to protect public welfare. The latter standards include such items as visibility, ecosystem damage, material damage, and agricultural crop losses.

States that exceed the NAAQS must prepare plans known as state implementation plans or SIPs to meet the standards. Primary standards must be met by a fixed deadline. There is no deadline for secondary standards.

Historically many areas of the country have been unable to meet the primary standards leading to revisions in the Clean Air Act in 1977 and 1990. Because of the problems in meeting primary standards there has been little emphasis on secondary standards.

One exception to this is the acid deposition program that was explicitly written into the Act with the 1990 amendments. This program is designed to reduce ecosystem damage caused by acidic gases that are deposited into lakes and other fragile ecosystems through rain or dry deposition. The main sources of acid deposition are from reactions in the atmosphere where of sulfur and nitrogen oxides form sulfuric and nitric acid.

List of Criteria Pollutants

- Ozone (formed in atmosphere)
- Sulfur dioxide (primary pollutant)
- Nitrogen dioxide (direct and secondary)
- Particulate matter (direct and secondary)
- Carbon monoxide (direct)
- Lead (direct)

Ambient pollutants are either emitted directly from sources (so called primary pollutants) or formed by reactions in the atmosphere (so called secondary pollutants). Ozone is the main example of a secondary pollutant. It is formed by photochemical reactions between oxides of nitrogen and hydrocarbons typically called volatile organic compounds or VOCs.

Combustion sources emit two main oxides of nitrogen, nitric oxide, NO, and nitrogen dioxide, NO₂. The sum of these two compounds is written as NO_x (and pronounced nocks.) The majority of the NO_x emissions from combustion sources are NO. About 10% of the total NO_x emissions are NO₂. However, NO can react to form NO₂ in the atmosphere. NO is not considered hazardous to health directly, but NO₂ is. Presently there are no areas in the US that exceed the NAAQS for NO₂.

Sulfur dioxide, SO₂, emissions come almost exclusively from the combustion of sulfur containing fuels. (Sulfur processing plants are an additional source of SO₂.)

The regulation of particulate matter is based on size of the particles. This is defined in terms of the mean aerometric diameter, the diameter of a sphere with equivalent drag characteristics. The NAAQS for particulate matter have changed from a standard for total suspended particulate matter (which has a mean aerometric diameter of 30 μm.) to the current standard for particulate matter with a mean aerometric diameter of 2.5 μm. (From about 1980 to 2000 the standard was for particulate matter with a mean aerometric diameter of 10 μm.) The finer particles are better able to penetrate deeper into the lung and have a greater impact on human health for this reason. In addition, finer particles tend to be those that have a greater chemical toxicity. Thus control of fine particles is thought to provide greater health protection. Particulate matter is directly emitted and is formed in the atmosphere from reactions of gaseous precursors. The latter is called secondary particulate matter,

CO and lead originate mainly from gasoline-powered automobiles. The elimination of lead from gasoline has eliminated lead as a pollution problem in almost all areas.

Criteria Pollutant Control

- States prepare State Implementation Plans (SIPs) to achieve National Ambient Air Quality Standards (NAAQS)
- SIP requirements in Clean Air Act
- Attainment areas do not need SIPs
- Variety of requirements: NSR, NSPS, RACT, RFG, I&M, etc.

Since the 1970 amendments to the Act there have been several rounds of SIP submittals. SIPs that are prepared by states must be approved by EPA. To be approved the SIP must contain all the elements that Congress has required in the Act. In particular, it must show a plan of proposed regulations that will allow an area to meet the primary NAAQS by the required attainment date.

Among the various requirements are a preconstruction review and permit program for major new sources or major modifications to existing sources. This program is known as **New Source Review** or NSR. Permit programs are required in both attainment and nonattainment areas. In nonattainment areas the review must show that the new source will not degrade air quality. The nonattainment program is called PSD for **P**revention of **S**ignificant **D**eterioration. In attainment areas, NSR requires the user to use equipment that achieves the **Lowest Achievable Emission Rate** (LAER) and obtain emission reductions for other sources that are greater than the emission increases caused by the new source. In attainment areas, sources are required to use **Best Available Control Technology** which is less stringent than LAER.

Since the 1970 amendments to the Act, EPA has been required to set **New Source Performance Standards**. These set minimum technology requirements for new sources.

In all SIPs states must include requirements that sources are retrofitted using **Reasonably Available Control Technology** (RACT) as defined by EPA. Certain, more polluted, areas are required to use reformulated gasoline (RFG).

States must implement vehicle **Inspection and Maintenance** (I&M) programs. There are two program levels, basic and enhanced. Enhanced programs, which are required in more polluted areas, test the vehicle under load. Basic programs use an idle test.

Stationary sources also have an operating permit program that is required under Title V of the 1990 amendments to the Act.

Toxic Pollutants

- 1970 amendments to the act called on EPA to control “hazardous air pollutants”
- Only seven were regulated by 1990
- In 1990 amendments to the Act, Congress specified 189 pollutants, one of which was subsequently removed from the list

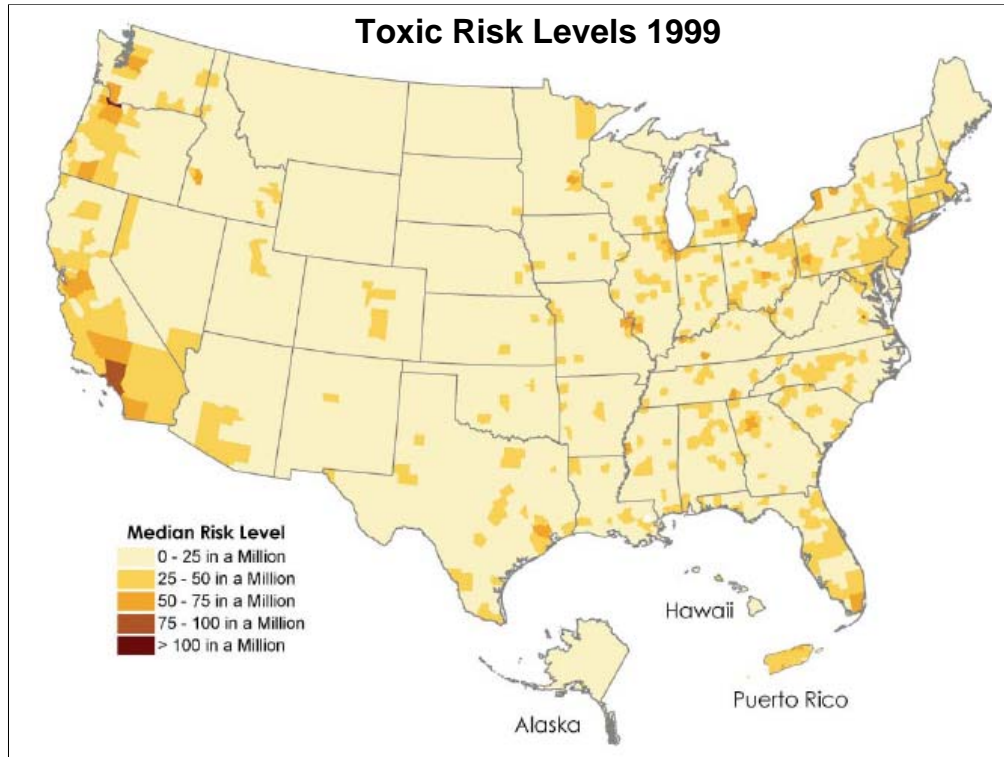
Reference: <http://www.epa.gov/ttn/atw/> (Accessed February 12, 2007)

In the 1970 amendments to the Act, hazardous or toxic pollutants were thought to be emissions that came from localized sources. This was in contrast to criteria pollutants that came from many and diverse sources. Thus hazardous pollutants were to be controlled under a separate regulatory scheme that did not make them part of SIPs or require NAAQS.

Another part of the reasoning for a separate control program was the idea that criteria pollutants have a threshold below which there are no health effects. Toxic pollutants, on the other hand, were considered to have no threshold. Thus toxic pollutants could not have a NAAQS that could be set with an adequate margin of safety. Recent research in standard setting has blurred the distinction between criteria pollutants and toxics in terms of health effects and the margin of safety.

The seven regulated toxic pollutants (under the program called NESHAPs for National Emission Standard for Hazardous Air Pollutants) were asbestos, benzene, beryllium, inorganic arsenic, mercury, radionuclides and vinyl chloride. The small number of regulated pollutants was due to the stringent requirements under the 1970 amendments for determining the risk of a hazardous pollutant prior to regulating it.

Noncancer risks are evaluated in terms of a reference concentration. This is an estimate (with uncertainty spanning perhaps an order of magnitude) of a continuous inhalation exposure to the human population (including sensitive subgroups which include children, asthmatics and the elderly) that is likely to be without an appreciable risk of deleterious effects during a lifetime. It can be derived from various types of human or animal data, with uncertainty



Reference: Figure 35 in USEPA Latest Findings on National Air Quality - Status and Trends through 2006 downloaded on February 5, 2010 from <http://www.epa.gov/air/airtrends/2007/>

This risk assessment to determine the cumulative risk from toxic air pollutants was done in 1999 and has not been repeated since. About 25% of the risk came from exposure to benzene.

(continued from previous notes page)

Standards may include operational improvements and implementation is done by individual states by permit requirements for the affected facilities.

Within eight years after a MACT standard is issued, EPA must assess the residual risk associated with the source category and issue additional standards adequate to provide an ample margin of safety to protect public health and, after considering costs and feasibility, the environment. EPA has begun residual risk assessments, but none have been completed.

EPA is also to set standards for area sources that require a lower level of controls. This level of control technology is known as GACT for generally available control technology.

Mobil sources have been found to be a major source of toxic emissions. These emissions include benzene, 1,3-butadiene, formaldehyde, acetaldehyde. EPA projects that future regulations to reduce VOCs from motor vehicles will reduce emissions of these toxic pollutants. Except for regulations to hold refineries to current levels of "overcompliance" with regulations for levels of toxic compounds in gasoline, EPA has proposed no further regulations on mobile source toxics.

Air Pollution Sources

- Stationary sources
 - Point – large individual sources like power plants with specific emission locations
 - Area – distributed sources like gasoline stations or dry cleaners
- Mobile sources
 - Onroad – cars, trucks, buses, motorcycles
 - Offroad – agriculture and construction equipment, lawn and garden equipment, locomotives, aircraft, forklift trucks, boats, recreational vehicles, offroad motorcycles.

The process of determining emissions from all sources is known as obtaining an emissions inventory. This process is based on the use of emission factors which are used to measure the typically recorded output or input of a facility.

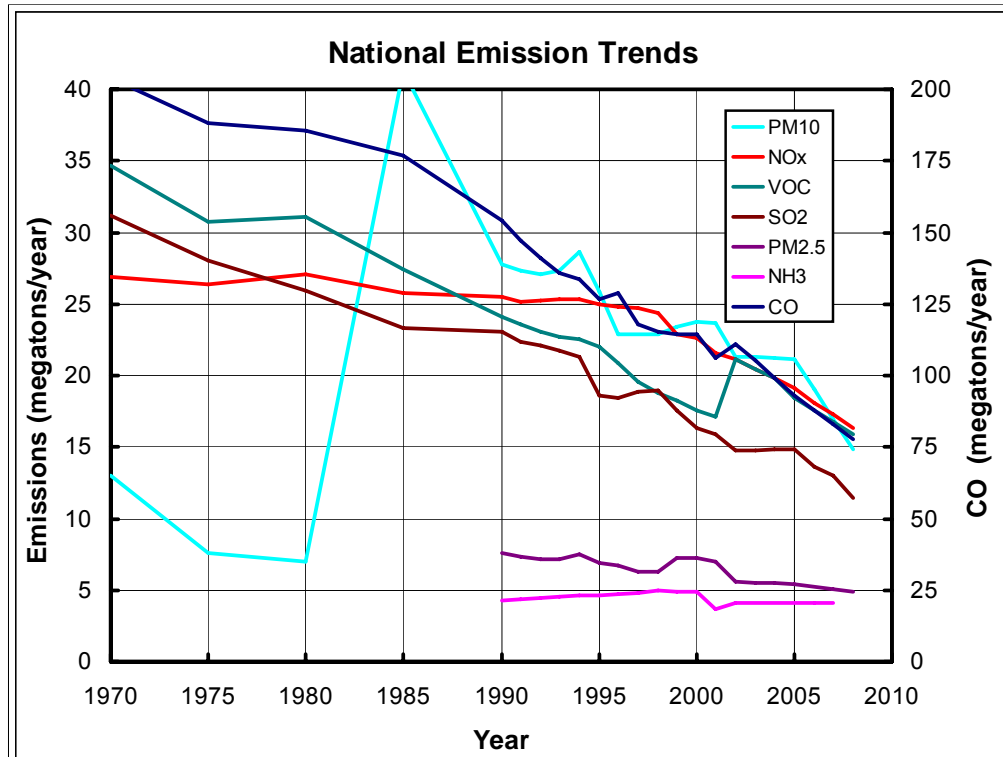
Regulations for stationary sources are usually set by state or local agencies. EPA has to approve regulations that are part of SIPs and may not approve regulations that are not stringent enough.

Mobile source regulations are done mainly by EPA. California is the only state that has the authority to set separate exhaust standards for mobile sources. States can regulate the fuel that is used by mobile sources and states are responsible for maintaining vehicle inspection and maintenance programs.

There are very few cases in which emissions are directly measured. Direct measurements are only required on large emission sources that use continuous emission monitors to obtain the mass emission rate of pollutants. In other cases emissions are estimated by emission factors that relate emissions to activity data that are more typically monitored.

In combustion processes, many emission factors are linked to the heat input rate for the process. Since fuel flow rates are usually measured and the heating value of the fuel is reasonably well known, this provides an estimate of the emissions.

Obtaining emissions for all sources in a region, particularly a large urban region, can be a data collection nightmare, with the need to obtain data from a large number of sources.



National statistics are misleading. In some urban areas, like Los Angeles, significant reductions in emissions have occurred. However, in other areas emissions have increased. Thus the national emission trends appear to show only a slight decrease, but the ambient air quality has improved in areas where it was particularly bad.

The graph above shows emissions for ammonia which is not regarded as a pollutant in its own right. However, ammonia can contribute to the formation of ammonium nitrate and ammonium sulfate what become particular matter. Although this role for ammonia has been known for several years, the potential need to control ammonia emissions has only been recently considered. Thus the inventory for this species starts in 1990.

Lead emissions are not shown here because lead emissions have been virtually eliminated as an air pollutant due to its removal from gasoline.

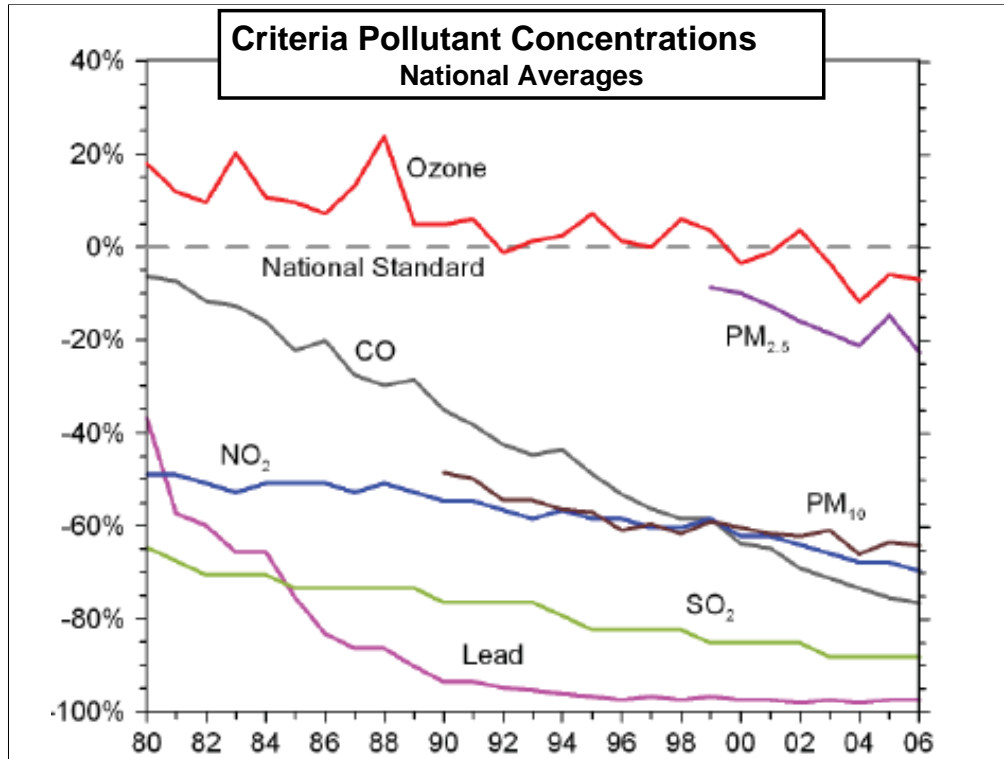
Reference: <http://www.epa.gov/ttn/chieftrends/index.html#tables> (Spreadsheet with data for plot downloaded February 5, 2010)

NOx is a pollutant that comes from mainly from combustion. Both mobile and stationary sources play a role in NOx emissions.

Control programs in place at the enactment of the 1970 amendments to the Clean Air Act and subsequent control programs have reduced NOx emissions from cars and trucks on highway. However, emission reductions in other source categories have come much later in time. Nonroad NOx emissions are a growing source. In 1970 they were regarded as a small source, but their control has been in effect since the late 1990s.

CO is overwhelmingly a pollutant that comes from mobile sources, particularly gasoline-powered engines. Catalytic converters have reduced this pollutant.

VOC is an acronym for volatile organic compounds. This refers to hydrocarbons that are active in the formation of ozone. Methane is not considered a VOC since it does not participate in ozone formation. The major source of VOC emissions, highway vehicles, has been under increasingly stringent controls since the 1960s as shown. Off-road vehicles have continued to grow however. Large combustion devices, like electrical utility boilers, have low VOC emissions because combustion can be more efficient.



Reference: Figure 1 in USEPA Latest Findings on National Air Quality - Status and Trends through 2006 downloaded on February 5, 2010 from <http://www.epa.gov/air/airtrends/2007/>

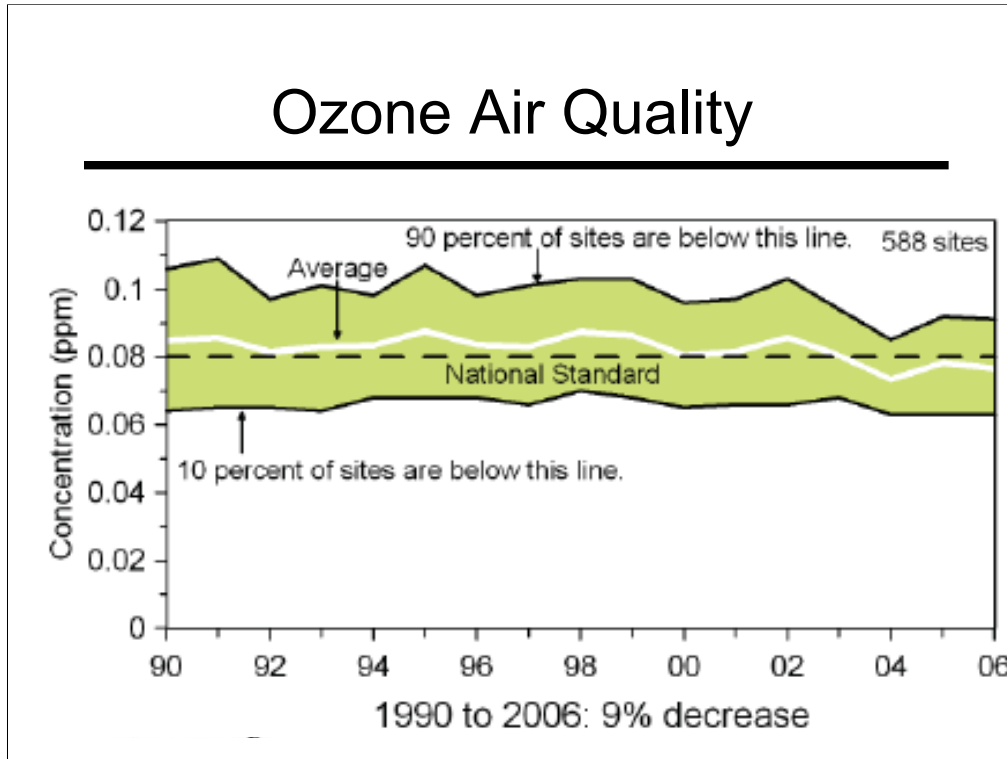
SO₂ is a pollutant that comes overwhelmingly from stationary sources. Combustion of sulfur containing fuels, coal in particular, accounts for most of the emissions of SO₂. Other sulfur oxides that are formed in the combustion process typically recombine with water formed during combustion and become part of particulate matter.

Reductions in SO₂ after 1990 are due to the acid rain provisions of the 1990 amendments to the Clean Air Act. The bump between 1995 and 1999 was due to the form of the acid rain provisions that rewarded early reductions in the Phase I period by allowing companies who had early emissions to defer compliance with the more stringent Phase II emission limits.

Transportation sources make a small contribution to SO₂ emissions because the sulfur content of vehicle fuels was initially limited by requirements for engine performance and refinery requirements for use of catalysts in oil refining. Subsequent regulations for motor vehicles fuels have limited sulfur even more, but there have been increased emissions due to greater use of diesel fuels. Currently enacted regulations that take effect between 2006 and 2012 will reduce this already small contribution to SO₂ emissions.

The size of particulate matter measured as a criteria pollutant has changed since the initial 1970's standard of total suspended particulates (TSP) that had a diameter less than 30 micrometers. Subsequent considerations of health effects led to a consideration of PM₁₀ and PM_{2.5}, with diameters less than 10 μm and 2.5 μm respectively.

PM₁₀ and PM_{2.5} come mainly from agriculture and forestry; this is mainly dust from agricultural operations. Industrial processes make the second largest contribution to PM₁₀, mostly from materials processing. Combustion processes make a relatively larger percent contribution to PM_{2.5} than they do to PM₁₀. This is because most combustion particulate is very small diameter. Particulate matter from combustion sources have a chemical nature that is more hazardous to human health than other particulate matter. Diesel particulate matter has been classified as a toxic air contaminant by the California Air Resources Board. The US EPA believes that the data on diesel particulate matter do not allow a full risk assessment and they track diesel particulate matter as a separate category when they consider toxic emission inventories.



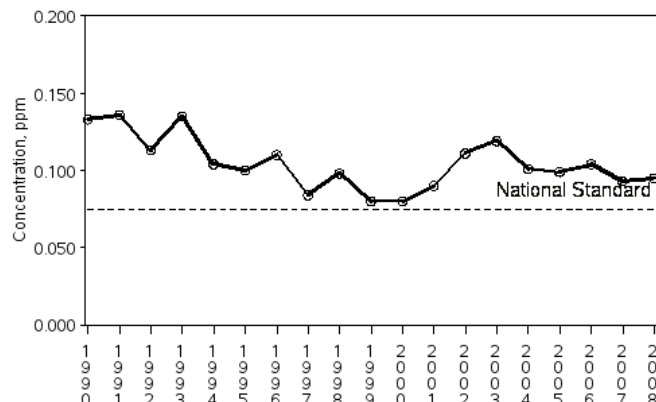
Reference: Figure 1 in USEPA Latest Findings on National Air Quality - Status and Trends through 2006 downloaded on February 5, 2010 from <http://www.epa.gov/air/airtrends/2007/>

The green band shows the distribution of ozone levels among the trend sites, displaying the middle 80 percent. The white line represent the average among all the trend sites. Ninety percent of sites have concentrations below the top line, while ten percent of sites have concentrations below the bottom line. The Ozone (8-hour) standard used for comparison here the concentration plotted is the annual 4th maximum 8-hour average. This shows the variability of air quality. Ozone has been one of the most difficult pollutants to reduce and the air quality standard has been lowered as new health data have shown effects below previous standard levels.

Figure 5 in the EPA trends report cited above shows that there has been a 49% reduction in emissions (averaged over all pollutants) since 1908. This has occurred despite the following changes over the same time period: an energy-consumption increase of 28%, a population increase of 30%, an increase of 101% in vehicle miles traveled and an increase of 121% in the gross domestic product.

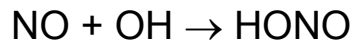
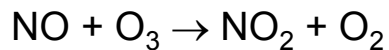
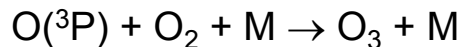
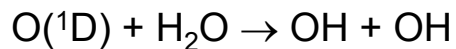
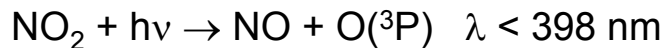
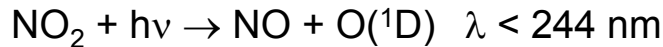
Ozone Air Quality, 1990 - 2008
 (Based on Annual 4th Maximum 8-Hour Average)
 Los Angeles-Long Beach, CA
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The ozone trend for the Reseda air monitoring station is shown in the graphic at the right. Although it was decreasing in the 1990s it had a significant rise from 2000 to 2003. Ozone concentrations are influenced by weather as well as by emission trends. This plot is from an interactive web page that starts at <http://www.epa.gov/airtrends/ozone.html>



Atmospheric Photochemistry

- Basic mechanism known since 1950s



Photochemical reactions (chemical reactions in the presence of sunlight) produce photochemical smog. The criteria pollutant associated with photochemical smog is ozone. Ozone is produced by a complex series of reactions a small number of which are shown on this and the next slide.

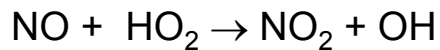
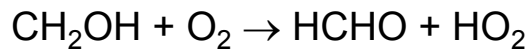
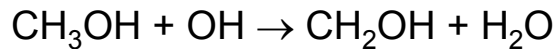
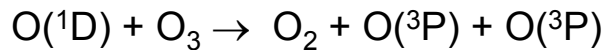
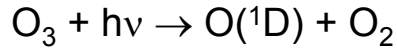
The reaction steps on the chart are the reactions that are regarded as the start of the mechanism for photochemical smog formation. In these reactions the symbol $h\nu$ represents the photochemical energy that splits a molecule. Such a reaction is known as photolysis. The (${}^1\text{D}$) and (${}^3\text{P}$) indicate the electronic energy states of the oxygen atoms that are formed in the reactions. Recall that the visible part of the spectrum lies between 300 and 700 nm and shorter wavelengths mean higher frequencies that correspond to greater energy in the photon participating in the reaction.

The symbol M represents a collision partner, sometimes called a third body. This means that another molecule must participate in the reaction to absorb energy. The presence of this third body affects the form of the equation used to model the rate of the reaction.

Compounds like O atoms, hydroxyl (OH), and HONO are called free radicals. These are highly reactive atoms or molecules that have an unbound electron. They are not ions because they have the same number of protons and electrons, but the bonding structure of the radicals makes them want to enter into reactions with other molecules.

Atmospheric Photochemistry 2

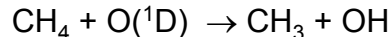
- Other reactions



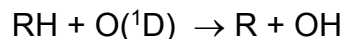
Additional reactions are shown in this slide. This reaction shows the participation of additional free radical reactions and additional photolysis reactions.

These reactions show how intermediate products such as formaldehyde (HCHO) and nitric acid (HNO₃) can be produced.

There is a general set of hydrocarbon reactions that have not been shown here. One such reaction is shown below.

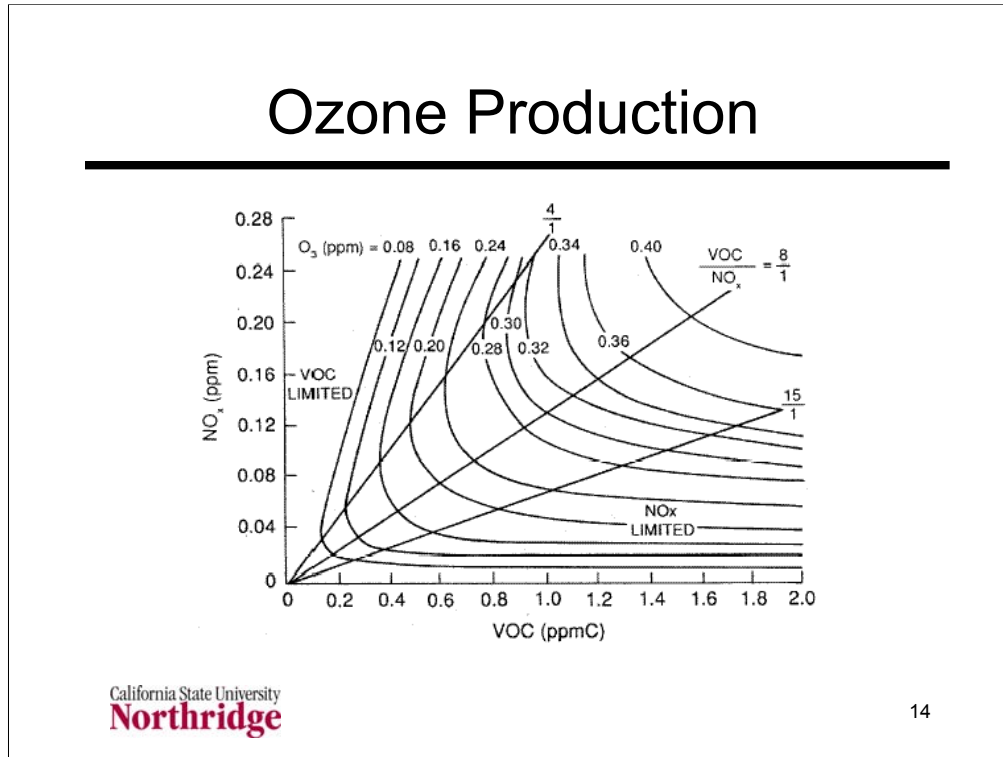


This is called a chain branching reaction because there is one free radical in the reactants and two free radicals in the products. Other hydrocarbons can participate in similar reactions. The general reaction equivalent to the one shown above for methane, may be written as follows.



In this general reaction, R represents some radical containing hydrogen and carbon atoms. For example, in the methane reaction R = CH₃.

The wide range of reactions that can take place lead to different amounts of ozone. Detailed chemical kinetic models are required to simulate the entire mechanism.



The diagram shown here, called an EKMA diagram, is taken from National Academy of Sciences, *Rethinking the Ozone Problem*, 1991, which says that the diagram was adapted from a 1977 reference to Dodge. (EKMA stands for **E**mpirical chemical **K**inetics **M**odeling **A**pproach.) This diagram formed the basis for air quality planning in the late 1970s and early 1980s. The basic point of this diagram – the need to choose controls over hydrocarbons or NO_x as a way to control ozone – remains true today even when more sophisticated models are used.

This diagram was based on experimental data which showed that the amount of ozone formed in photochemical smog depended on the initial concentration of reactants, volatile organic compounds (VOC) and oxides of nitrogen (NO_x). When the VOC/NO_x ratio is about 4/1 or less, the reaction is VOC limited. This region is on the left side of the diagram. Here ozone is reduced by controlling VOC. In this region, controls on NO_x will actually increase ozone.

When the ratio of VOC/NO_x is about 15/1 or more, as shown in the lower right side of the diagram, the control of NO_x is the best way to reduce ozone. Between these limits, reductions in either NO_x or VOC will reduce ozone.

The limitation of the EKMA model is that it gives a single value for an urban area. Recent models use the full integration of partial differential equations to examine photochemical reactions with variation of emissions and wind over space and time.

Cap-and-Trade Programs

- Emission requirements set for all sources in an area
- Sources have three options
 - Comply with emission limits
 - Produce excess emissions and buy credits from others who generate credits
 - Reduce emissions beyond requirements to generate credits for sale
- Used for acid rain controls
 - Proposed for CO₂ controls

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Placing a uniform requirement on all existing emission sources is not economically efficient. Some sources may be able to comply easily while others because of their age or other factors may have great difficulty in complying. Cap-and-trade programs are designed to address this imbalance in the ability that different companies have to comply and produce the same overall environmental benefits at lower total cost.

The emissions cap applies to an entire source group in an area. This cap can decrease over time to bring about overall emission reductions. For climate change controls the averaging area could be global.

Environmental concerns about cap-and-trade programs is that they can produce excess emissions in a local area in which a large number of sources choose to purchase credits. Cap-and-trade programs are generally less controversial when they are limited to large sources whose emissions are dispersed over a large area.

Cap-and-trade programs include the Acid Deposition program under the 1990 Clean Air Act Amendments, the RECLAIM program in the South Coast Air Quality Management District for NO_x and SO₂ from large stationary sources, the Northeastern US Ozone Transport region trading program, and the Clean Air Interstate Rule. The acid-deposition program is considered one of the biggest successes of cap-and-trade.

Cap-and-trade programs require continuous emission monitors (CEM) with real time reporting of emission results as assurance that each participant in the program is achieving its stated emissions levels.

Reference: National Research Council of the National Academies, *Air Quality Management in the United States*, National Academies Press, 2004, pp 196-209.

Permitting Programs

- Operating permits set limits for facility operating conditions and emissions
 - Emissions limits (e.g. pounds per million Btu)
 - Maximum operating rate and hours
- Title V of 1990 CAAA provides national program for operating permits
- Preconstruction review permits
 - New Source Review (NSR)
 - Prevention of Significant Deterioration (PSD)

There are two distinct kinds of permitting programs in air pollution control. The first is the permit to construct. This involves a preconstruction review which is quite elaborate and discussed in detail in the next chart.

The second is the permit to operate. This is a permit that is renewed annually and lists the specific emission limits that a source must achieve for each of its processes.

Prior to the 1990 Clean Air Act Amendments (1990 CAAA) operating permits depended on state law and permit programs had a wide range of stringency. Title V of the 1990 CAAA set up a stringent program for operating permits and gave EPA the responsibility for setting nationwide standards for operating permits.

Large stationary sources are required to have these permits. (Local rules may require permits for smaller sources.) There is a public review process for issuing the permits and once issued, permits are available for public review. Many Title V permits in California can be reviewed starting at the California Air Resources Board web site (accessed February 13, 2007) <http://www.arb.ca.gov/fcaa/tv/tvinfo/permits/permits.htm>

For example the Title V permit for the PG&E compressor station at Hinkley, CA, is <http://www.arb.ca.gov/fcaa/tv/tvinfo/permits/moj/hinkperm.pdf> (accessed February 13, 2007). This permit for a facility that has 44,735 HP of engines (mainly for compressors but also for generators) is 52 pages long.

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
- Montreal Protocol limits CFCs

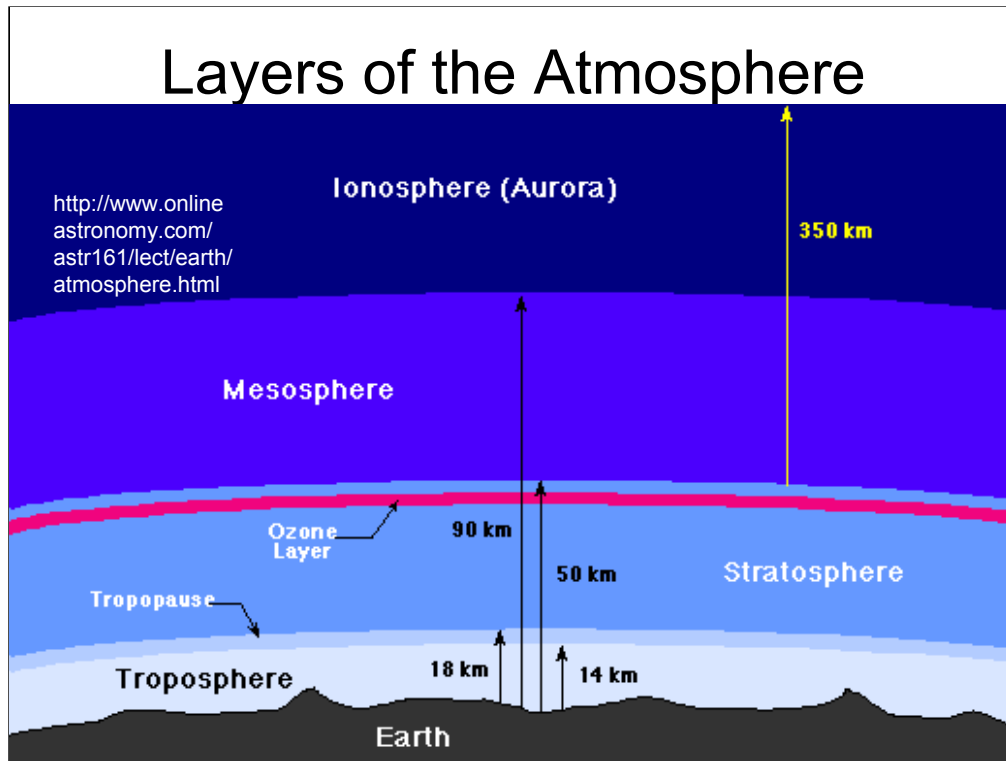
Although ground level ozone has deleterious effects on human health, ozone in the stratosphere acts to reduce incoming solar radiation. Without this ozone the planetary energy balance would be different and the amount of high energy ultraviolet radiation would add to the intensity of the current solar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

Ozone in the stratosphere – see the diagram of the atmosphere on the next page – 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 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 page after next.)

Nitric oxide can also interfere with ozone in the stratosphere. When the idea of supersonic passenger travel was considered there was a concern that NO_x 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.

The Montreal protocol is discussed on the notes page after the next one.



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 $T_0 = 15.0^\circ\text{C}$ ($= 59.0^\circ\text{F}$) and $p_0 = 101.325 \text{ kPa}$ (2116.22 psfa). The ideal gas equation the ideal gas law, $\rho = P/RT$ is used to find the density and $\rho_0 = 1.22500 \text{ kg/m}^3$ ($0.076474 \text{ lb}_m/\text{ft}^3$). 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: $dp/dz = -\rho g = Pg/RT$, where g is the acceleration of gravity.

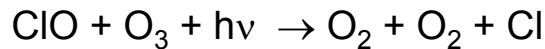
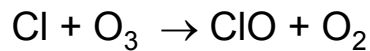
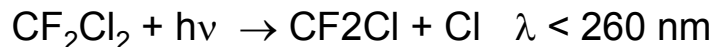
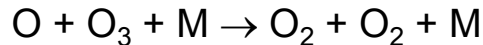
Combining the ideal gas equation, the lapse rate equation, and the equation for hydrostatic equilibrium gives the equation at the right for the pressure in a given layer that starts at $z = z_k$ where $p = p_k$ and $T = T_k$.

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

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)

Stratospheric Photochemistry



What is a Dobson Unit?

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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.

Chlorofluorocarbons (CFCs) that reach the stratosphere can be photolyzed (react with sunlight) releasing Cl atoms. These atoms can react with ozone creating a new equilibrium that reduces the normal ozone concentration by as much as 60% in arctic regions (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°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

- Atmospheric heat balance
- Radiation balance and radiative forcing
- Global warming potentials (GWP) and equivalent CO₂ emissions
- Intergovernmental Panel on Climate Change (IPCC)
 - Fourth assessment report in 2007
- 2004 US greenhouse gas inventory

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.

It is interesting to compare the conclusions from various reports.

"the balance of evidence suggests that there is a discernible human influence on global climate," (IPCC 1995)

"[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).

"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)

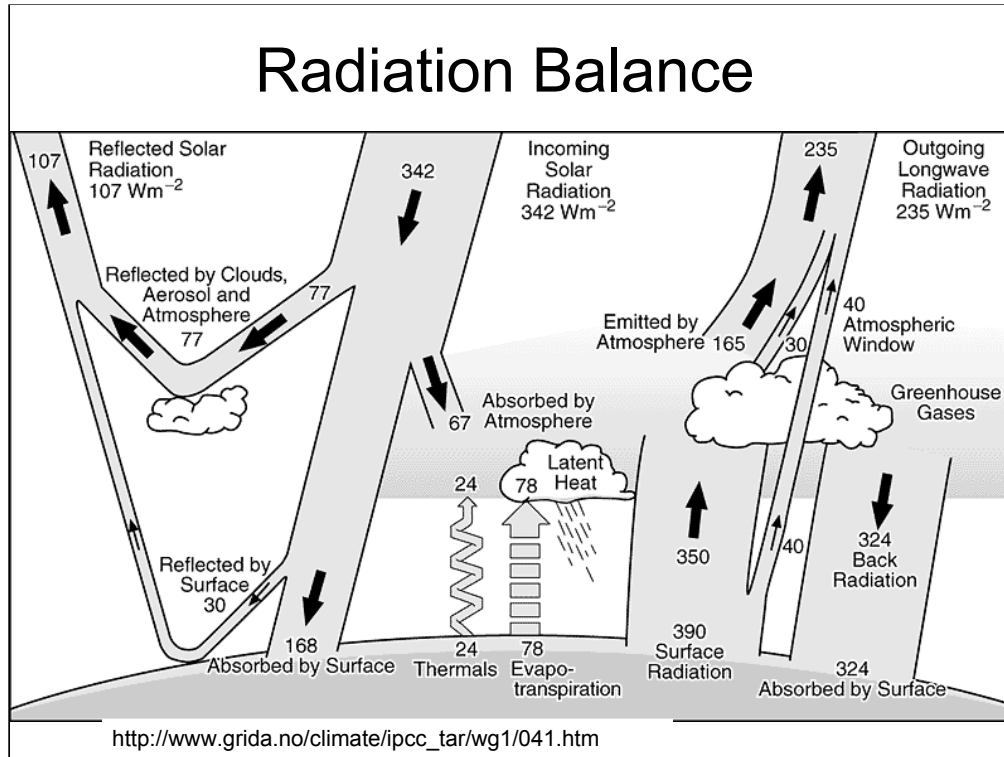
Greenhouse Gases

- Incoming solar radiation mainly in UV and visible
- Outgoing terrestrial radiation infrared
- Atmospheric gases absorb different amounts at different wavelengths
- Greenhouse gases: CO₂, CH₄, N₂O
- Equivalent tons of carbon measure

The impact of greenhouse gases has been hypothesized for many years. In particular, anthropogenic emissions of CO₂ have increased ambient CO₂ levels and continued CO₂ emissions are forecast in the future. Since CO₂ 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 many 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 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. However, this effect is separate from the effect of greenhouse gases.



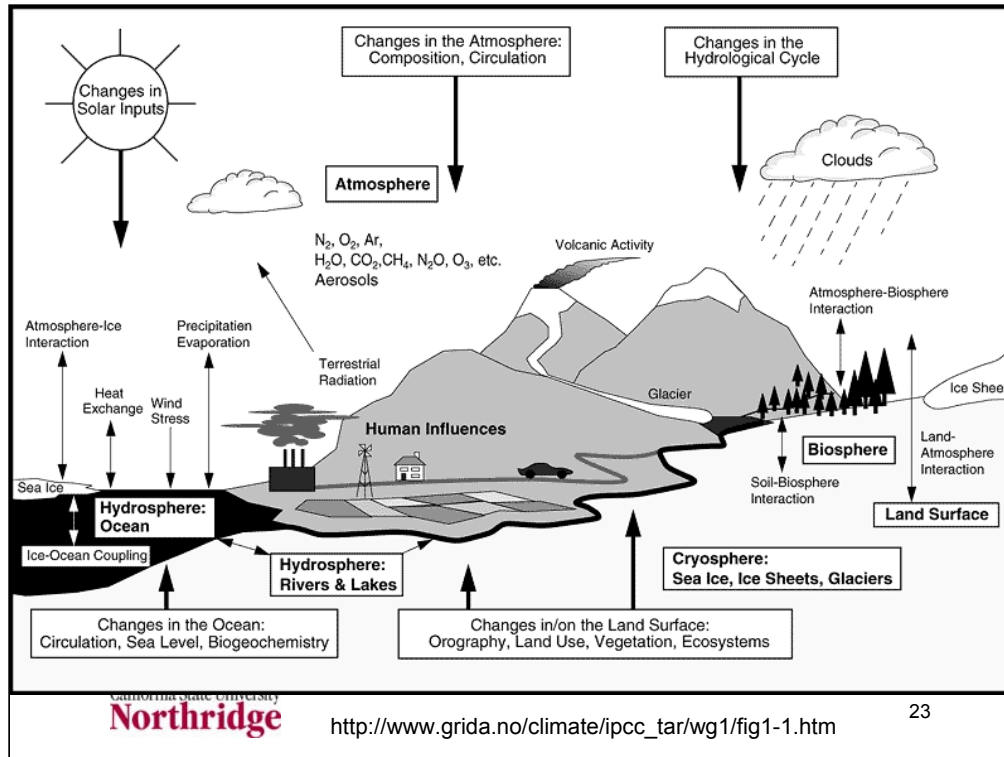
Reference: http://www.grida.no/climate/ipcc_tar/wg1/041.htm

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.



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 (CO₂), methane (CH₄), nitrous oxide (N₂O) and ozone (O₃), which do absorb and emit infrared radiation. Water vapor (H₂O), 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, CO₂ and O₃ 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.

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.

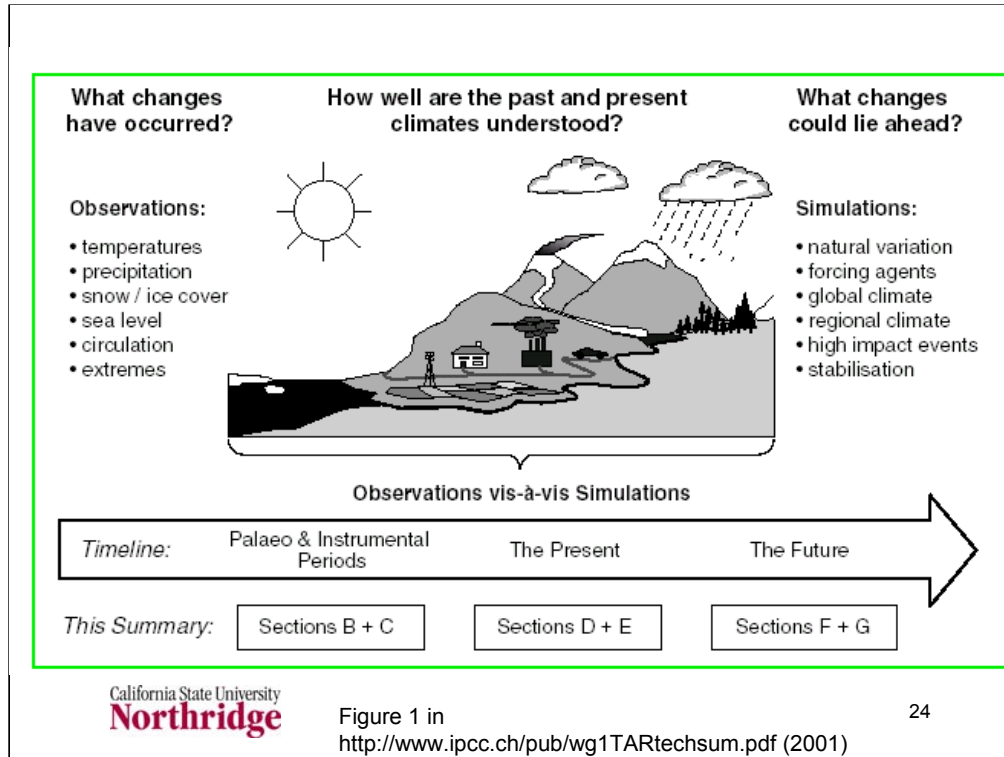


Figure: Intergovernmental Panel on Climate Change (IPCC), *Climate Change 2001: The Scientific Basis*, IPCC, 2001. Figure taken from technical summary available at <http://www.ipcc.ch/pub/wg1TARtechsum.pdf>.

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).”

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: Climate 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>.

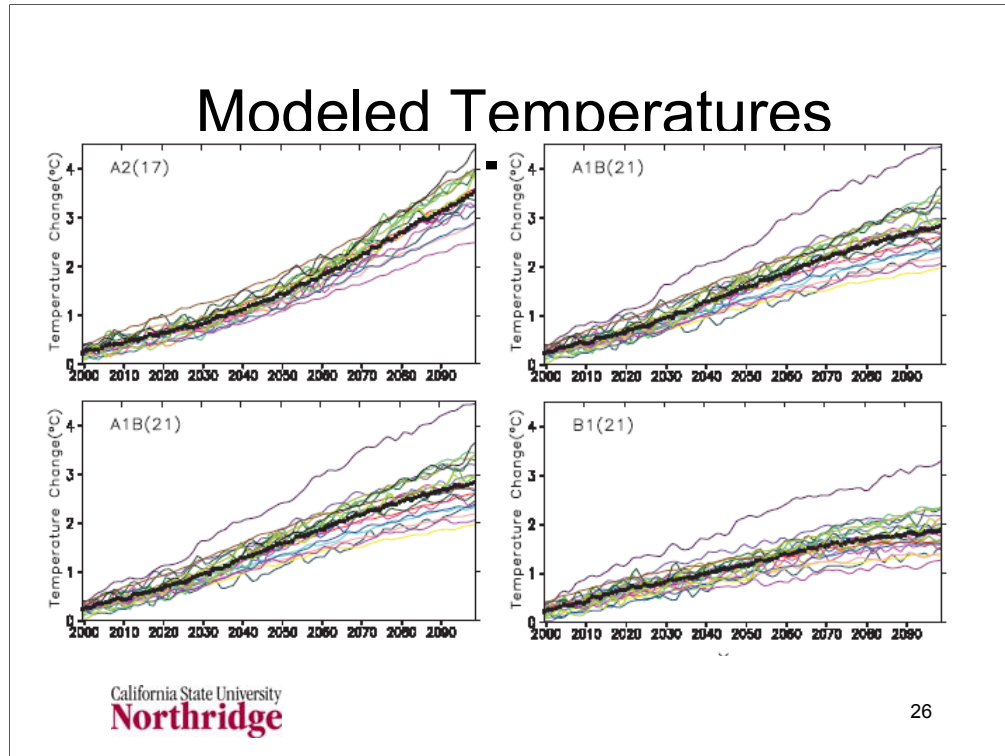
“Despite notable progress in improving sea ice formulations, AOGCMs have typically achieved only modest progress in simulations of observed sea ice since the TAR.” (p. 592).

Climate Measures

- 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) CO₂ concentration.
 - Model sensitivity results on notes page

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.



IPCC, *Climate Change 2007: 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 forecasts 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, predict the sea level rise. These also show the kind of variation shown in the temperature predictions.

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>

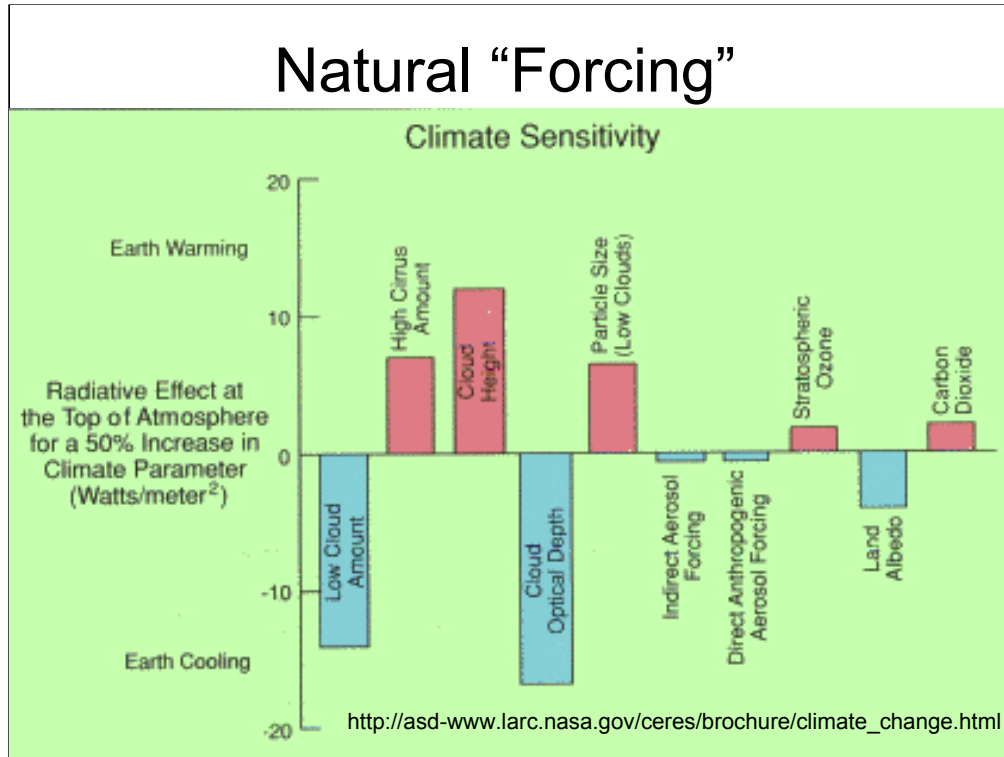
Radiative forcing (or RF) is the change in **net radiative flux** at the tropopause after the climate has been perturbed, **after allowing the stratosphere to come into equilibrium with the perturbation**. The perturbation can from a gas such as carbon dioxide, or particulate matter, such as aerosols.

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.



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 annual average) is 342 W/m².

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 Potential

• CO ₂	1	CH ₄	21
• N ₂ O	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 ₂ F ₆	9,200	C ₄ F ₁₀	7,000
• C ₆ F 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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The global warming potential of a gas compares the effect of global warming for a particular gas to that of CO₂. Many gases are much more effective at global warming than CO₂, but are not present in nearly the amounts that CO₂ is.

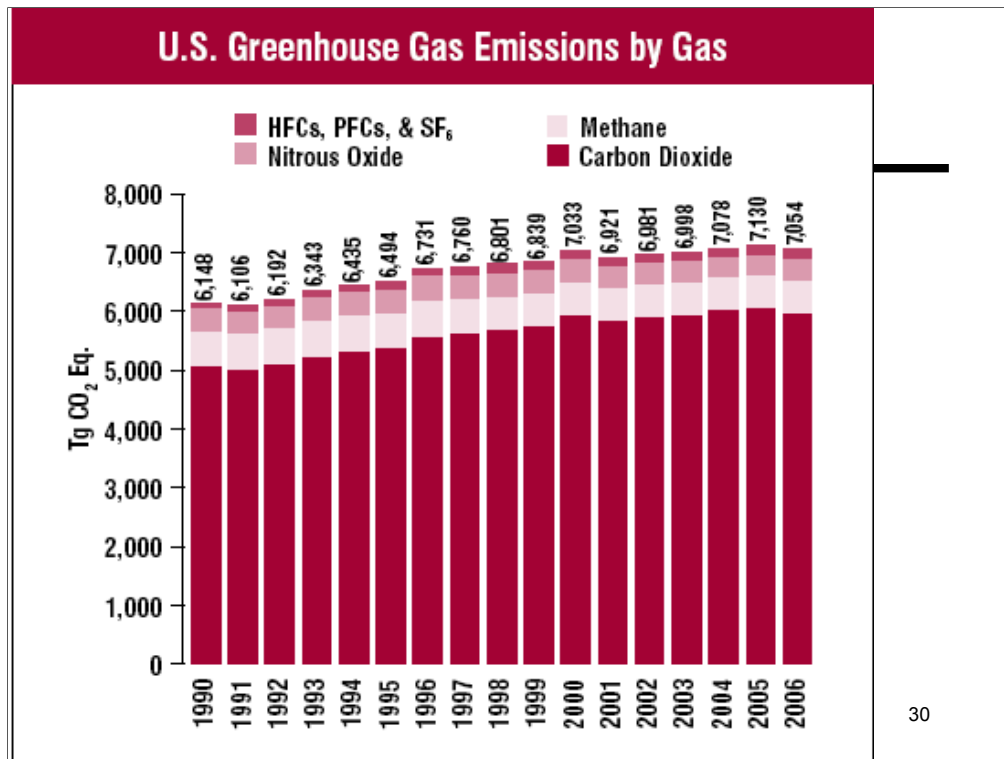
GWP defined as the ratio of the time-integrated radiative forcing from the instantaneous release of 1 kg of a trace substance relative to that of 1 kg of CO₂

GWP measures both direct (trace substance a greenhouse gas) or indirect effects (particles affect radiation response)

Total emissions of greenhouse gases are reported GWP-weighted emissions typically measured in teragrams of CO₂ equivalent. Because the lifetime of different different gases in the atmosphere varies, GWP data are generated for different periods of time. The data conventionally used for aggregating effects of GWP data are based on comparing the 100-year lifetime effects of the different gases.

As more data become available, new values for GWP are generated. However, to keep historical track of aggregate GHG emissions the values used have been kept constant.

For example, the emission of one kilogram of methane would have the same climate change effect as the emission of 21 kg of CO₂ according to this table.



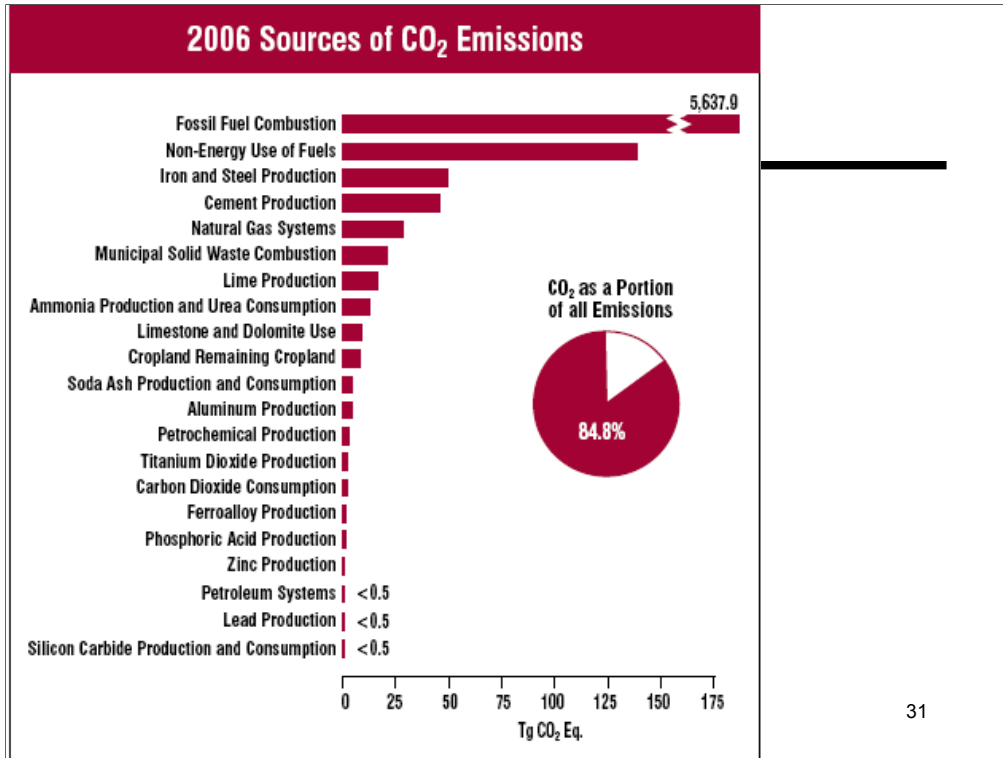
US Environmental Protection Agency, Inventory of US Greenhouse Gas Emissions and Sinks 1990-2006, April 15, 2008, Figure ES-1.

<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 CO₂ 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.

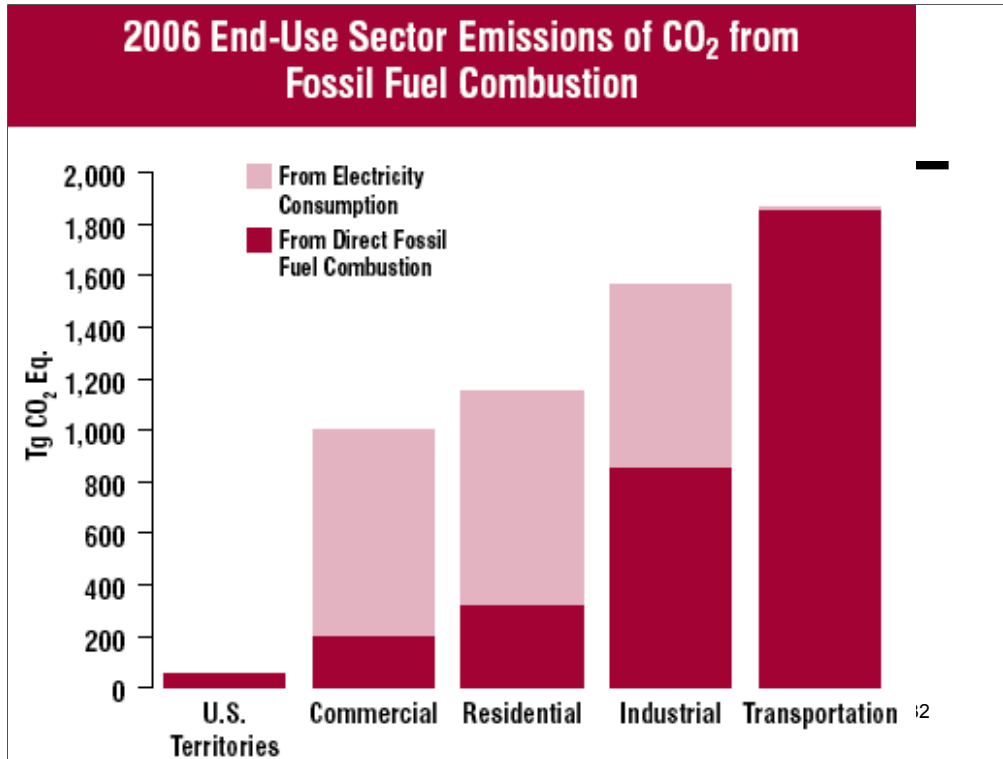
http://epa.gov/climatechange/emissions/downloads/08_ES.pdf
http://epa.gov/climatechange/emissions/downloads/08_ES.pdf



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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.

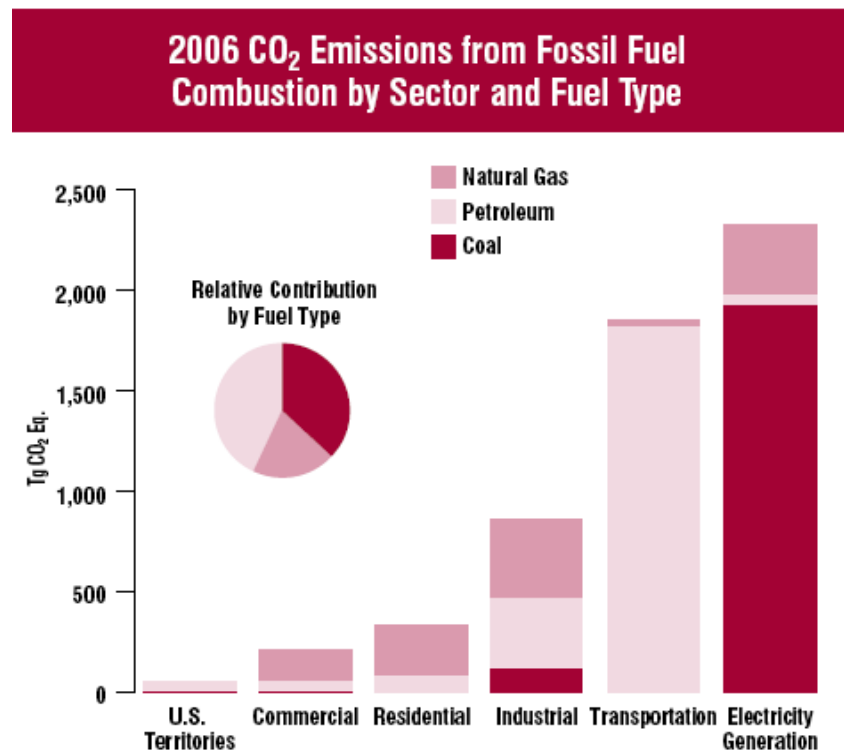
Note that the top bar – Fossil Fuel Combustion – is over 32 times longer than the total length of the horizontal axis. The components of this combustion bar are shown on a later slide.

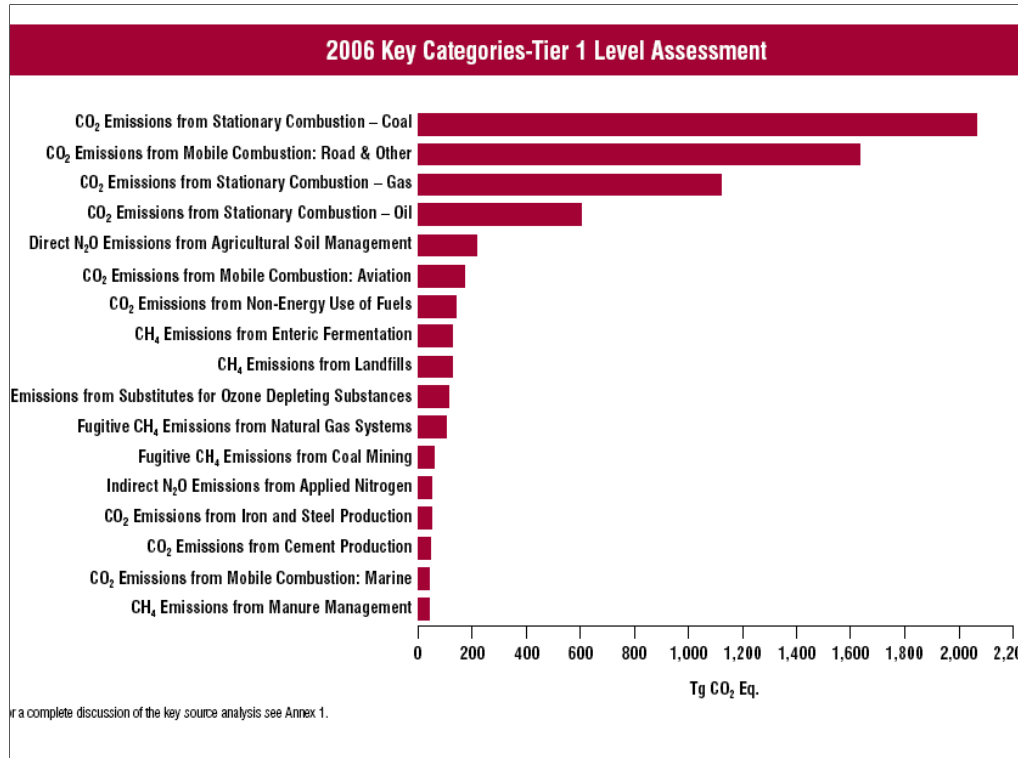


US Environmental Protection Agency, Inventory of US Greenhouse Gas Emissions and Sinks 1990-2006, April 15, 2008, Figure ES-6. <http://epa.gov/climatechange/emissions/downloads/08ES.pdf> accessed February 9, 2009.

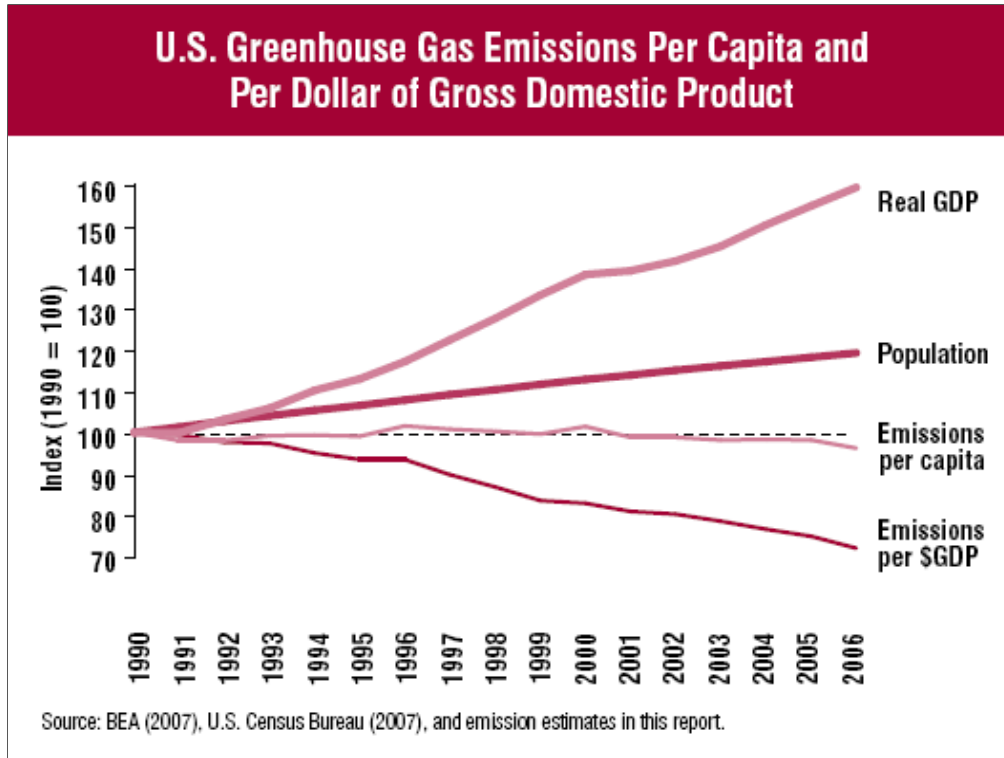
The CO₂ generation from electric power is the main source of CO₂ for residential and commercial users. Transportation has almost no electricity use, but it is the highest producing sector for CO₂.

The chart at the right shows the CO₂ generated by various fuels for different sectors, with electricity generation shown as an individual sector.

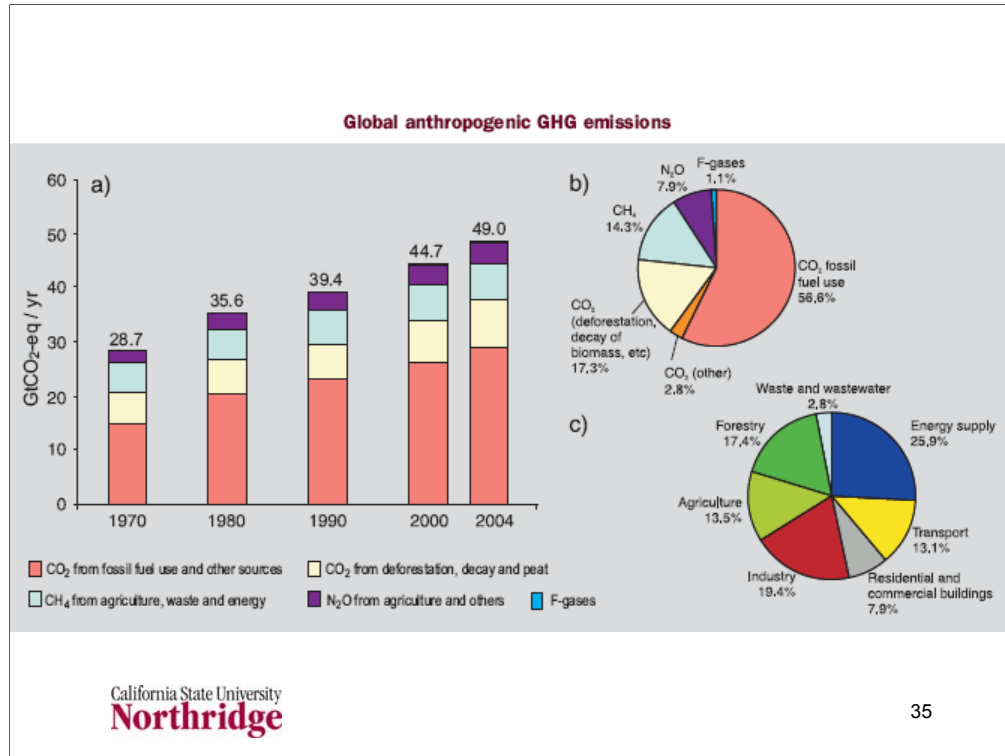




US Environmental Protection Agency, Inventory of US Greenhouse Gas Emissions and Sinks 1990-2006, April 15, 2008, Figure ES-16. <http://epa.gov/climatechange/emissions/downloads/08ES.pdf> accessed February 9, 2009



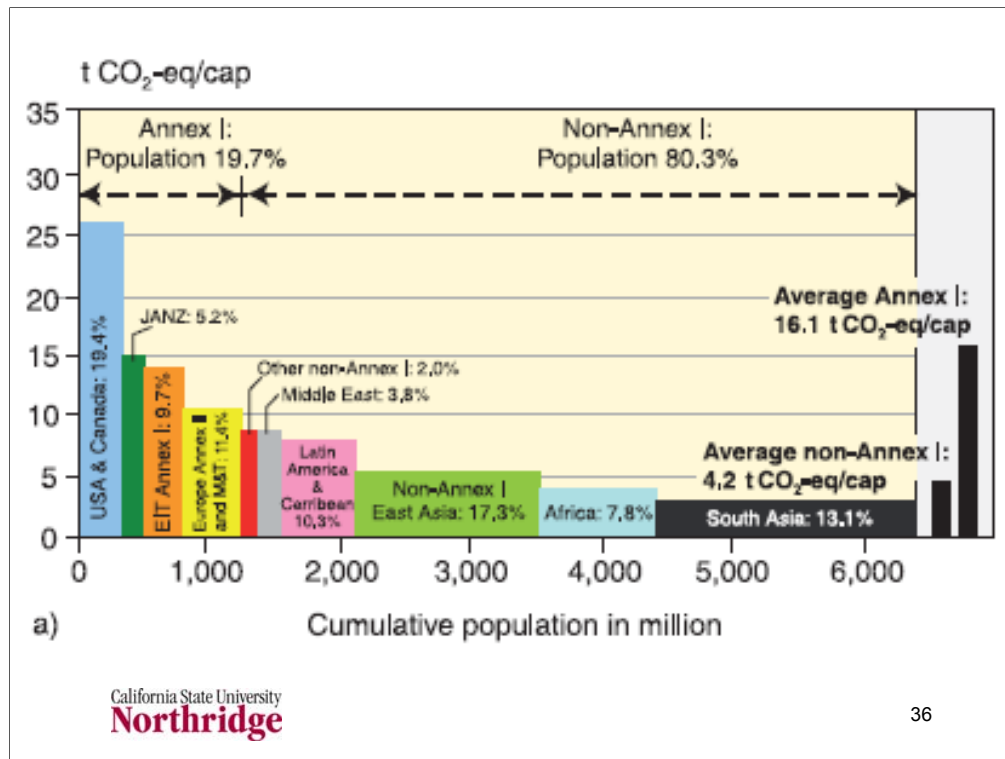
US Environmental Protection Agency, Inventory of US Greenhouse Gas Emissions and Sinks 1990-2006, April 15, 2008, Figure ES-15. <http://epa.gov/climatechange/emissions/downloads/08ES.pdf> accessed February 9, 2009



IPCC, *Climate Change 2007: 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 CO₂ from deforestation and decay of biomass.

The “energy supply” section in the pie chart on the lower right is not defined in the synthesis report nor in the working group three report where it originally appears. Presumably this denotes the emissions associated with all aspects of providing energy to the ultimate consumer. This includes not only the mining and refining of fossil fuels and uranium, but also the emissions from electricity generation.



IPCC, *Climate Change 2007: 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 CO₂. It is the product of the vertical axis, tonnes of CO₂ 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>.

CO₂ Sequestration

- Reduction of CO₂ is a two-fold task
 - Removal of CO₂ from combustion gases
 - Disposal of CO₂ 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 CO₂, 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.

CO₂ 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 CO₂ gas can be sequestered from power plants or industrial sources, it must be captured as a relatively pure gas.

CO₂ 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 CO₂ 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 CO₂ capture systems and also explore revolutionary new capture and sequestration concepts. The most likely options currently identifiable for CO₂ separation and capture include the following:

Absorption (chemical and physical)

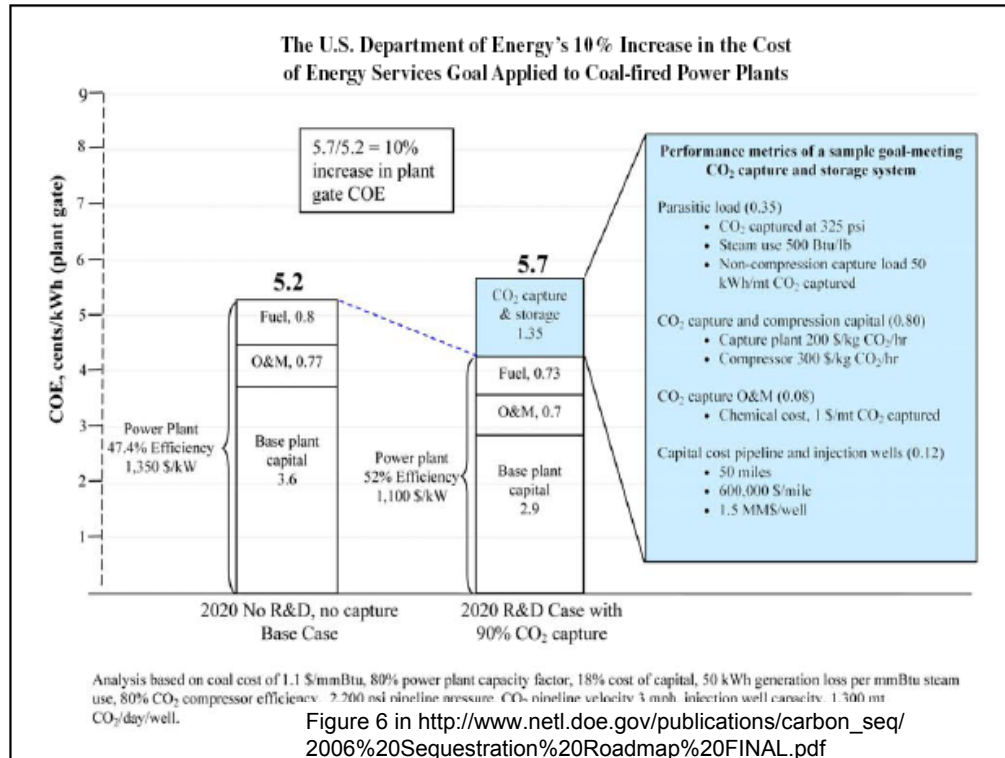
Adsorption (physical and chemical)

Low-temperature distillation

Gas separation membranes

Mineralization and biomineralization

Opportunities for significant cost reductions exist since very little R&D has been devoted to CO₂ capture and separation technologies. Several innovative schemes have been proposed that could significantly reduce CO₂ capture costs, compared to conventional processes. "One box" concepts that combine CO₂ capture with deduction of criteria-pollutant emissions are concepts to be explored.



References (accessed April 4, 2008): <http://www.futuregenalliance.org/>
<http://www.iht.com/articles/ap/2007/12/19/america/Coal-Plant-Optional.php>
<http://www.netl.doe.gov/technologies/coalpower/futuregen/index.html>

<http://www.netl.doe.gov/publications/press/2009/7637.html> (Accessed February 5, 2010)

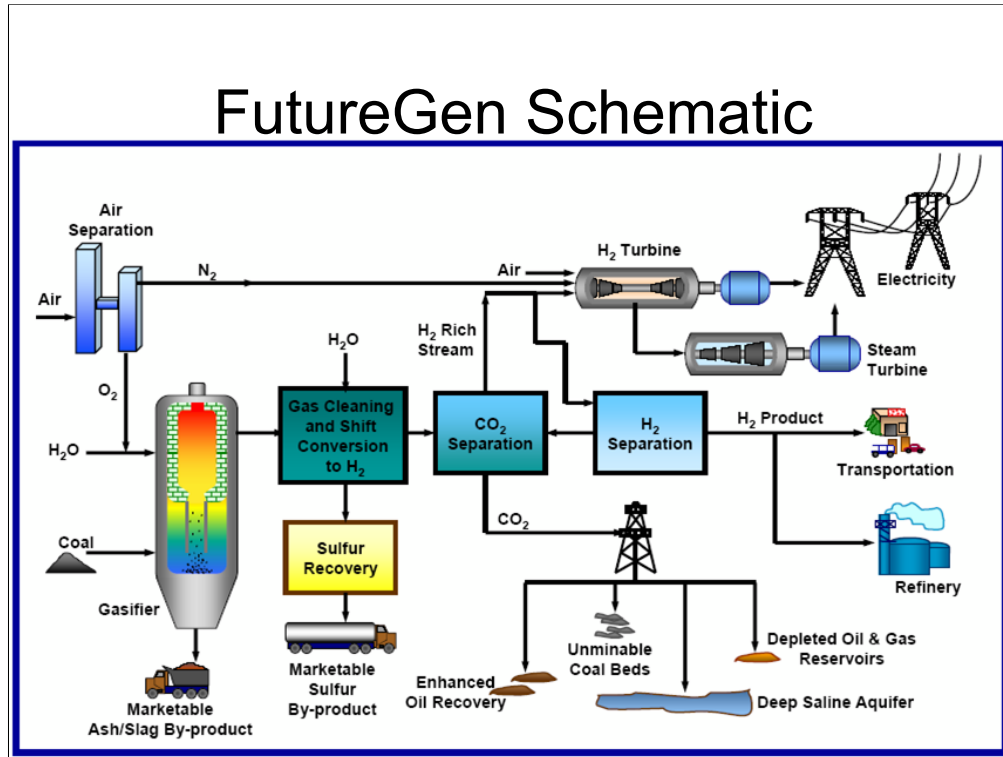
This chart is an early DOE forecast that is now being implemented in a proposed partnership between the US Department of Energy (DOE) and industrial participants known as the FutureGen Alliance. Some of the industrial participants include: American Electric Power, Anglo American, BHP Billiton, the China Huaneng Group, CONSOL Energy Inc., E.ON U.S., Foundation Coal, Luminant, PPL Corporation, Rio Tinto Energy America, Peabody Energy, Southern Company, and Xstrata Coal.

The project was cancelled by DOE in January 2008 because of increasing costs. The originally proposed cost in 2003 was \$1.5 billion. In December, 2008, the cost was given as \$1.8 billion. DOE continued seeking projects in carbon capture and sequestration (CCS), but did not want to build the ambitious FutureGen project.

On July 14, 2009, with additional funding for energy projects from the 2009 "stimulus" bill (HR-1) DOE decided to continue work on the FutureGen project. The Alliance plans to complete a preliminary design with a refined cost estimate and carry out other activities before early 2010..

Following these activities, which will be completed in early 2010, the Department and the Alliance will decide whether to continue the project through construction and operation. Both DOE and the FutureGen Alliance agree that a decision to move forward is the preferred outcome and anticipate reaching a new cooperative agreement for the full project. Funding will be phased and conditioned based on completion of necessary NEPA reviews.

The total cost of the project is estimated to be \$2.4 billion. DOE's anticipated financial contribution is \$1.073 billion, \$1 billion coming from "stimulus" funds for CCS research. The FutureGen Alliance's is expected to contribute \$400 million to \$600 million. Continuation of the project is predicated on obtaining other non-federal funds to fill the gap between the available funds and the \$2.4 million cost estimate



Reference: http://www.psenterprise.com/consulting/r_and_d/images/vpdm_futuregen.png
 accessed February 5, 2010

This chart shows a typical schematic diagram of the FutureGen process. It uses a process known as integrated gasification and combined cycle (IGCC) in which the goal is reacted with steam and oxygen to produce a gaseous fuel consists of H₂ and CO. There is also some CO₂ in this gas stream, but it does not provide any energy.

The gaseous fuel (which is only a small fraction of the total mass from the combustion process) is then cleaned and the clean gas, which is already at high pressures from the coal gasification process is used as the fuel in a gas turbine. The high-temperature gas turbine exhaust then enters a heat exchanger system known as a heat-recovery steam generator (HRSG). There the turbine exhaust provides the energy to produce steam in a Rankine cycle. Both the gas turbine and the steam turbine produce electricity.

There are two existing facilities in the US that IGCC; both of them were developed with funding from DOE. The gas-cleaning step in these existing facilities does not have the shift conversion step, shown in the diagram above, that drives the fuel gas composition towards CO₂ and H₂ by the so-called water-gas shift reaction: $\text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2$. The mixture of CO₂ and H₂ (along with some unreacted CO) is then separated to provide a gas turbine fuel that is only H₂ (with impurities from the lack of a perfect separation process). The separated CO₂ can then be sequestered in various methods as shown in the diagram.

There are many feedback loops that are not shown here for simplicity. The steam required for the steam-reforming process in the gasifier is produced by sending make up water through the same steam generator that is used to produce steam for the steam turbine. The air for the oxygen manufacture can be compressed in the gas turbine compressor. CO removed in the separation process can be recycled back into the gas clean-up stage.

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 CO₂ 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)

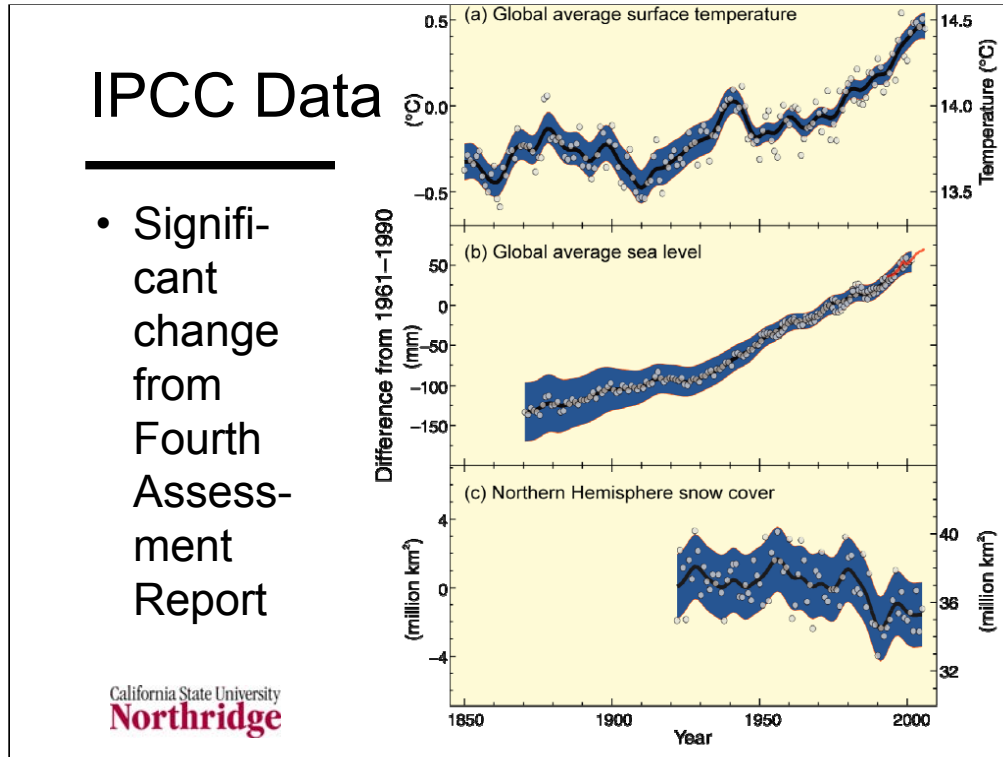
<http://www.ncdc.noaa.gov/oa/climate/globalwarming.html>

Chicago Climate Exchange

<http://www.chicagoclimatex.com/>

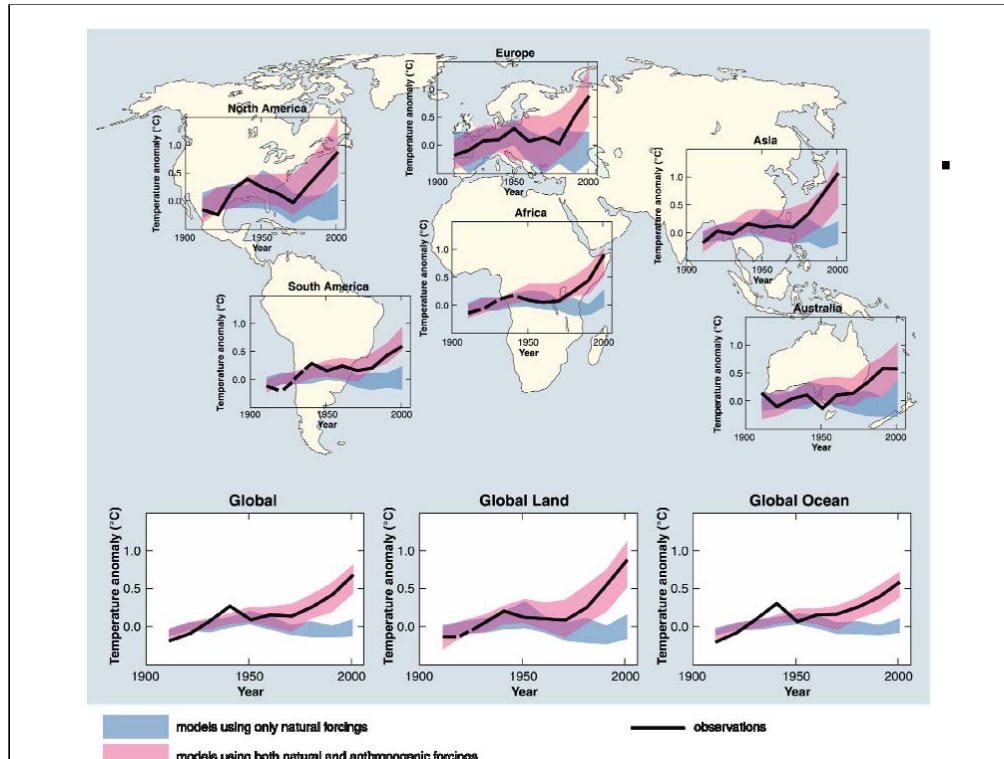
Cooler heads coalition

<http://www.globalwarming.org/>



IPCC, *Climate Change 2007: 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 Change 2007: 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 difference 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 averaging 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.