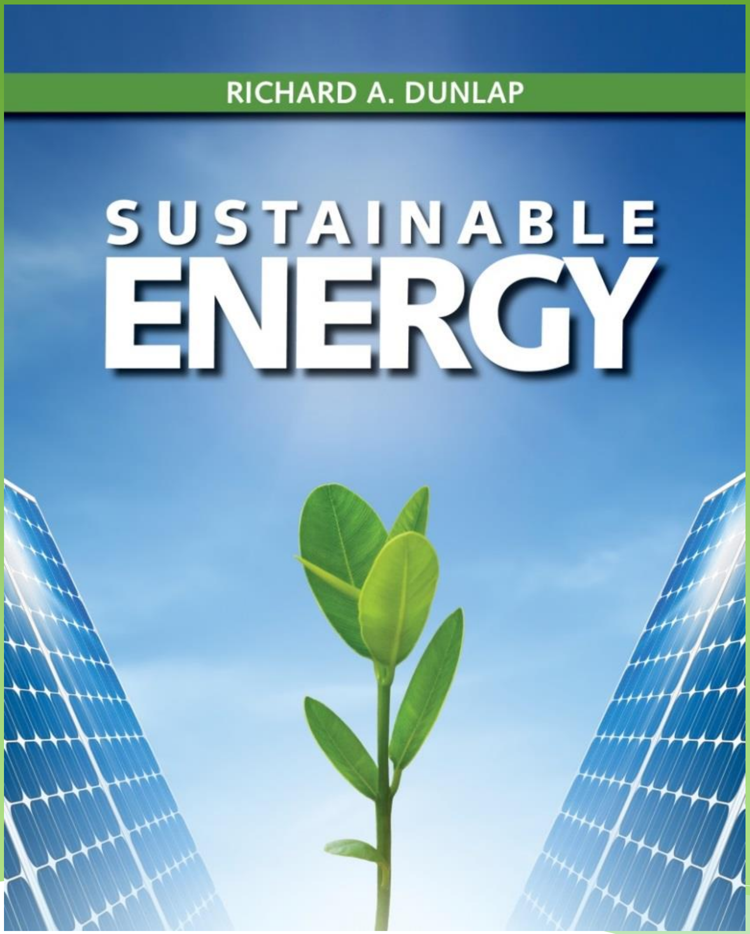
Sustainable Energy



Chapter 4

* Environmental Consequences of Fossil Fuel Use

CENGAGE Learning

Learning Objectives

- The causes and effects of thermal pollution.
- The causes and types of chemical pollution.
- Principles of the greenhouse effect.
- The reasons for global climate change.
- Methods of carbon sequestration.

Pollution

Utilization of fossil fuels as a source of energy almost always involves combustion.

Combustion of fossil fuels produces several types of pollution

- Thermal pollution
- Chemical pollution
- Particulates
- Greenhouse gasses

Thermal pollution

Conversion of thermal energy to mechanical energy is limited by the Carnot efficiency.

Typical Carnot efficiency for an automobile engine is ~17% and for a thermal generating station it is ~40%.

The remaining energy is given off to the environment as excess heat.

Cooling of thermal generating stations

Thermal generating stations that burn coal, oil or natural gas (as well as nuclear generating stations) need to release excess heat into the environment.

Either a body of water or the atmosphere can be used as a heat sink.

Once-through cooling

A heat exchanger can be used to transfer excess heat to a nearby body of water (i.e. lake, river, ocean).

Advantages of once-through cooling

- water has a high heat capacity and carries considerable heat
- water has a high thermal conductivity and heat transfer is efficient
- appropriate bodies of water are common (lakes, rivers, ocean)
- water temperature is relatively stable over the year
- cooling infrastructure is simple and economical

Disadvantages of once-through cooling

Changes in the ecology of a body of water can result from

- changes in oxygen content
- changes in temperature
- changes in thermal profile (temperature gradients)

Air cooling

Transfer of heat to the atmosphere through cooling towers is in common use at present.

This can cause local regions of increased fog and precipitation.

Cooling towers

Figure 1.10: Cooling towers typically used for thermal generating stations.

Chemical pollution

Types of chemical pollution associated with fossil fuel use

- Carbon monoxide
- Nitrogen-oxygen compounds
- Hydrocarbons
- Sulfur dioxide

Carbon monoxide

CO is produced by the incomplete combustion of carbon by the reaction

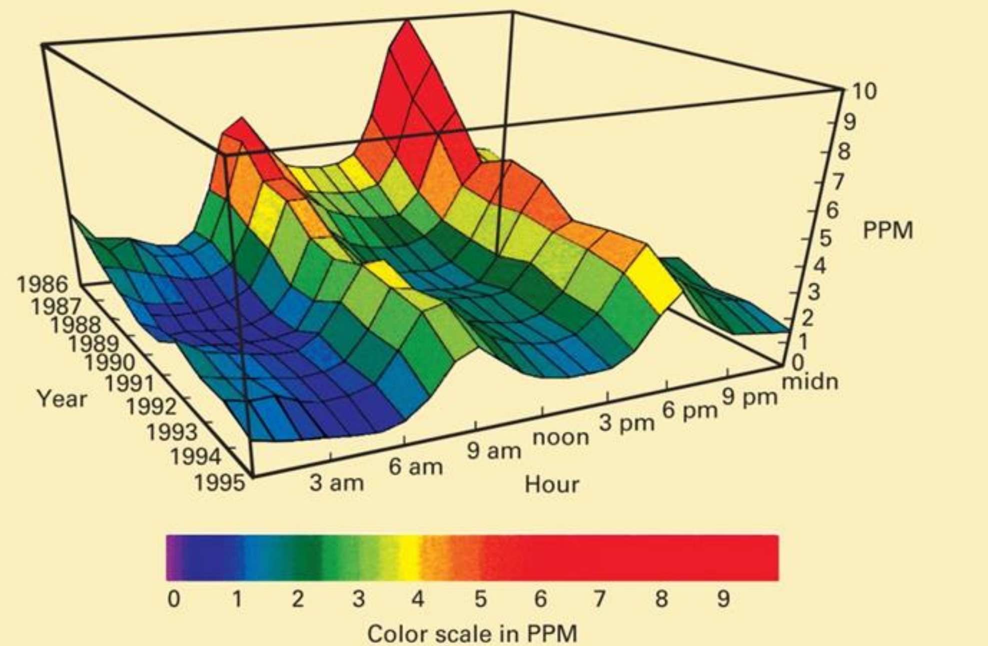
$$2C + O_2 \rightarrow 2CO \quad (4.1)$$

The primarily source of CO is internal combustion engines in vehicles.

Adverse health effects range from headaches to death, depending on concentration and exposure time.

Atmospheric concentration of CO

CO produced by vehicles and dissipates on a time scale of hours



U.S. EPA Fig 3-9 on page 3-25 from "Air Quality Criteria for Carbon Monoxide" EPA 600/P-99/001F (2000) At http://www.epa.gov/ncea/pdfs/coaqcd.pdf(2000) At http://www.epa.gov/ncea/pdfs/coaqcd.pdf

Figure 4.1: Average CO concentration in the air (in ppm per volume) as a function of the time of day in Denver, Colorado for years 1986 through 1995. Data are shown are average weekday values during the winter season (November to February).

Effects of emission controls

CO and other pollutants substantially decreased due to emission standards since 1960s

Table 4.2: U.S. emission standards for CO, NO_x and hydrocarbons in grams per mile (grams per km).

year	CO	NO_x	HC
1960 (precontrol estimate)	84.0 (52.2)	4.1 (2.5)	10.6 (6.58)
1970	34.0 (21.1)	5.0 (3.1)	4.1 (2.5)
1975	15.0 (9.3)	3.1 (1.9)	1.5 (0.93)
1980	7.0 (4.3)	2.0 (1.2)	0.41 (0.25)
1981	3.4 (2.1)	1.0 (0.62)	0.41 (0.25)
1983	3.4 (2.1)	1.0 (0.62)	0.41 (0.25)
1994	3.4 (2.1)	0.4 (0.25)	0.25 (0.16)
2001	3.4 (2.1)	0.2 (0.12)	0.125 (0.078)
2004	1.7 (1.1)	0.07 (0.04)	0.09 (0.056)

Nitrogen-oxygen compounds

Nitric oxide (NO) is formed by any combustion process in air by the reaction

$$N_2 + O_2 \rightarrow 2NO \qquad (4.2)$$

Nitrogen dioxide

NO reacts with ozone (O_3) in the atmosphere to yield Nitrogen dioxide (NO2)

$$NO + O_3 \rightarrow NO_2 + O_2 \qquad (4.3)$$

NO_2 is highly toxic.

Health effects range from respiratory irritation to heart damage, depending on concentration and exposure.

Atmospheric concentration of NO_2

Daily fluctuations of atmospheric NO_2 concentration due to human activities

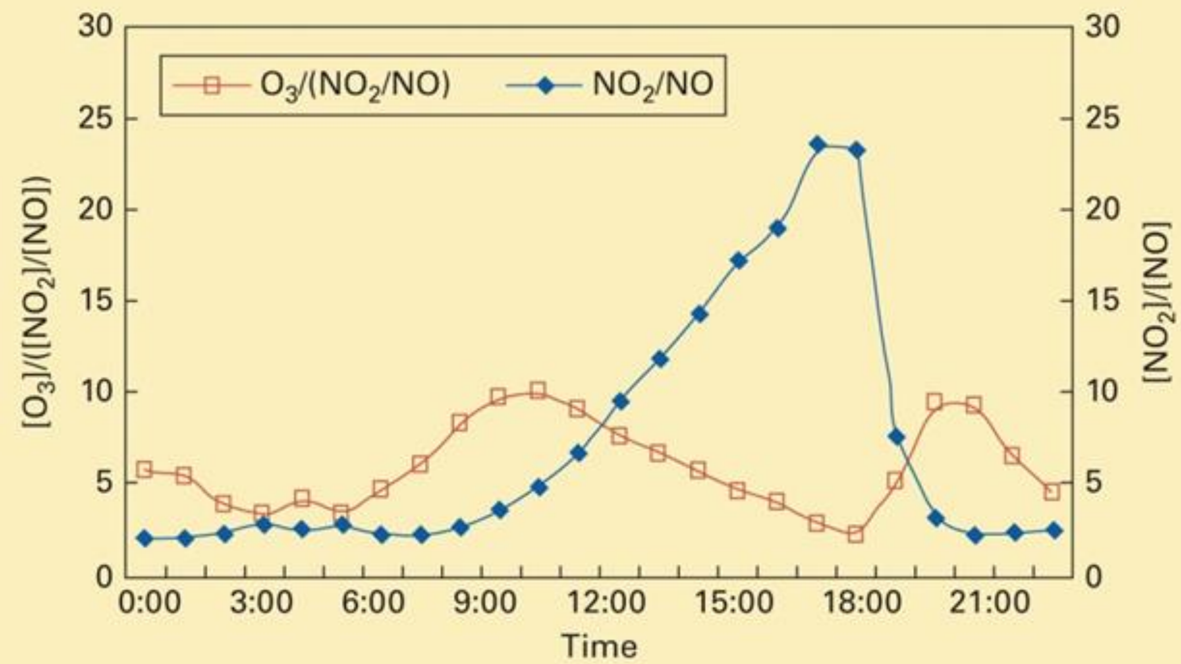


Figure 4.2: $O_3/(NO_2/NO)$ and NO_2/NO ratios as a function of time of day in Beijing.

Based on Wen-xing Wang, Fa-he Chai, Kai Zhang, Shu-lan Wang, Yi-zhen Chen, Xue-zhong Wang and Ya-qin Yang "Study on ambient air quality in Beijing for the summer 2008 Olympic Games" Air Qual Atmos Health 1 (2008) 31–36

Hydrocarbons

Hydrocarbons are produced during the incomplete combustion of fossil fuels.

Health effects range from eye irritation to lung disease.

Greatly reduced by emission control standards for vehicles.

Sulfur dioxide

Sulfur dioxide produced primarily from the oxidation of sulfur in sulfur-containing fossil fuels (mostly coal)

Table 4.5: Sources of SO_2 pollution.

source	% SO_2
coal	65
industrial	25
other	10

Acid rain

Sulfur dioxide reacts with oxygen in the atmosphere

$$2SO_2 + O_2 \rightarrow 2SO_3 \quad (4.4)$$

This is followed by the reaction with water to produce sulfuric acid

$$SO_3 + H_2O \rightarrow H_2SO_4 + O_2 \quad (4.5)$$

This acid rain has adverse effects on buildings, vehicles, etc.

Particulate pollution

Particulates are dust particles produced during the combustion of fossil fuels (primarily coal) or wood.

Primarily a problem for coal fired generating stations.

Removal of particulate pollution

Particulates may be removed from smoke of coal fired generating stations by filtering or electrostatic precipitation

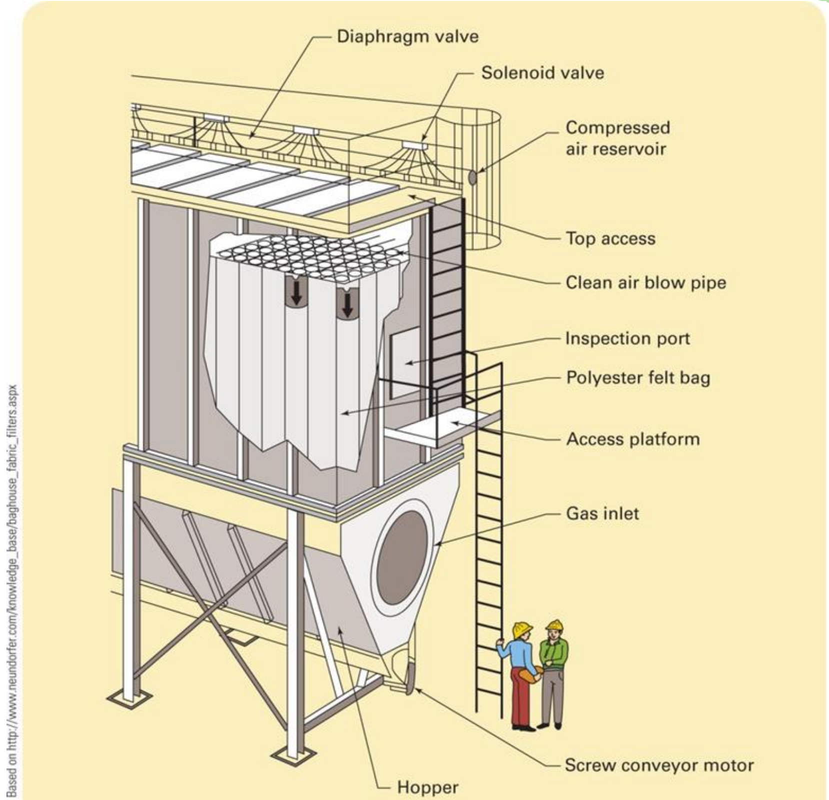


Figure 4.3: Baghouse with filters for particulate removal.

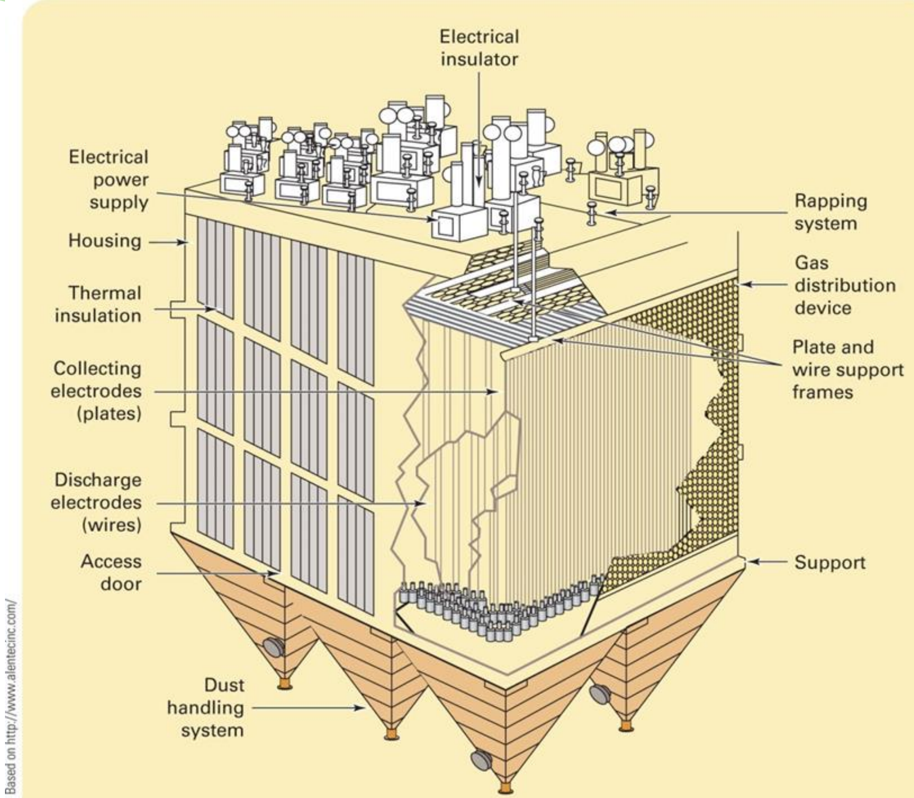


Figure 4.4: Electrostatic precipitator used to collect particulate matter from coal exhaust.

Dissipation of pollution in the atmosphere

Temperature profile for the atmosphere

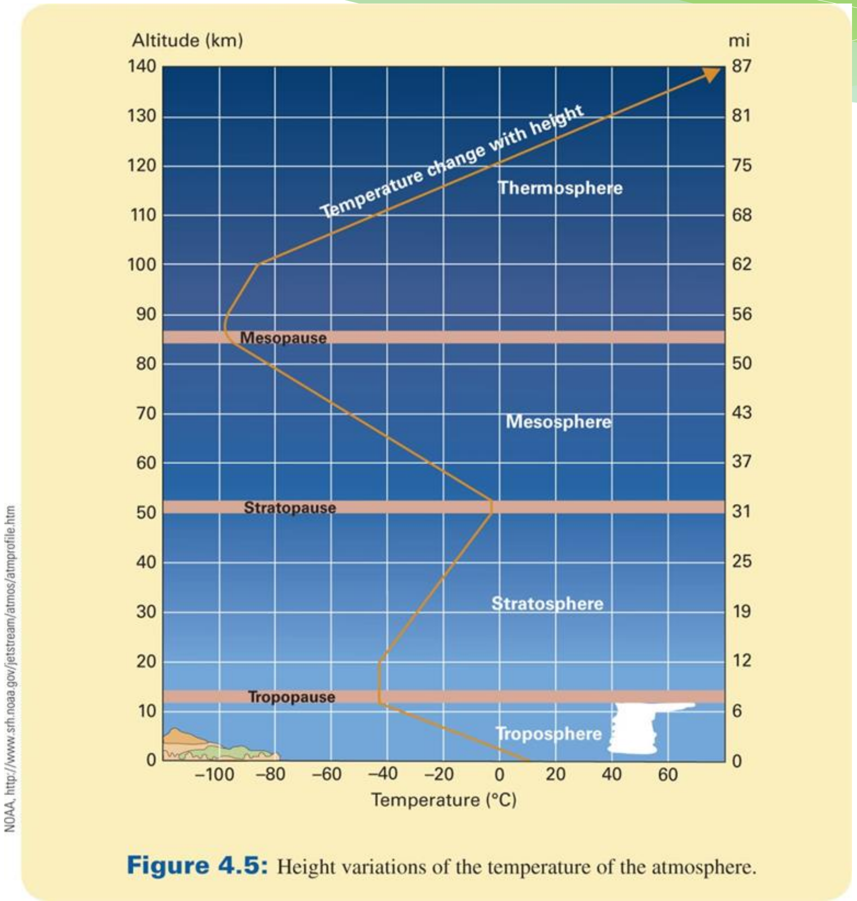


Figure 4.5: Height variations of the temperature of the atmosphere.

Adiabatic Lapse Rate (ALR)

The adiabatic lapse rate (ALR) is the normal rate at which the temperature near the surface of the earth decreases as a function of increasing altitude.

This is typically about 10 °C/km.

Stable and unstable atmospheric conditions

Unstable condition: If the actual temperature decreases faster than ALR warm (polluted) air near the surface readily mixes with air above it and the pollution is dispersed.

Stable condition: If the actual temperature decreases slower than ALR warm (polluted) air near the surface does not mix with air above it and the pollution is trapped near the surface.

Temperature inversion: Temperature increases with altitude near the surface and this severely inhibits mixing.

Examples of temperature profiles

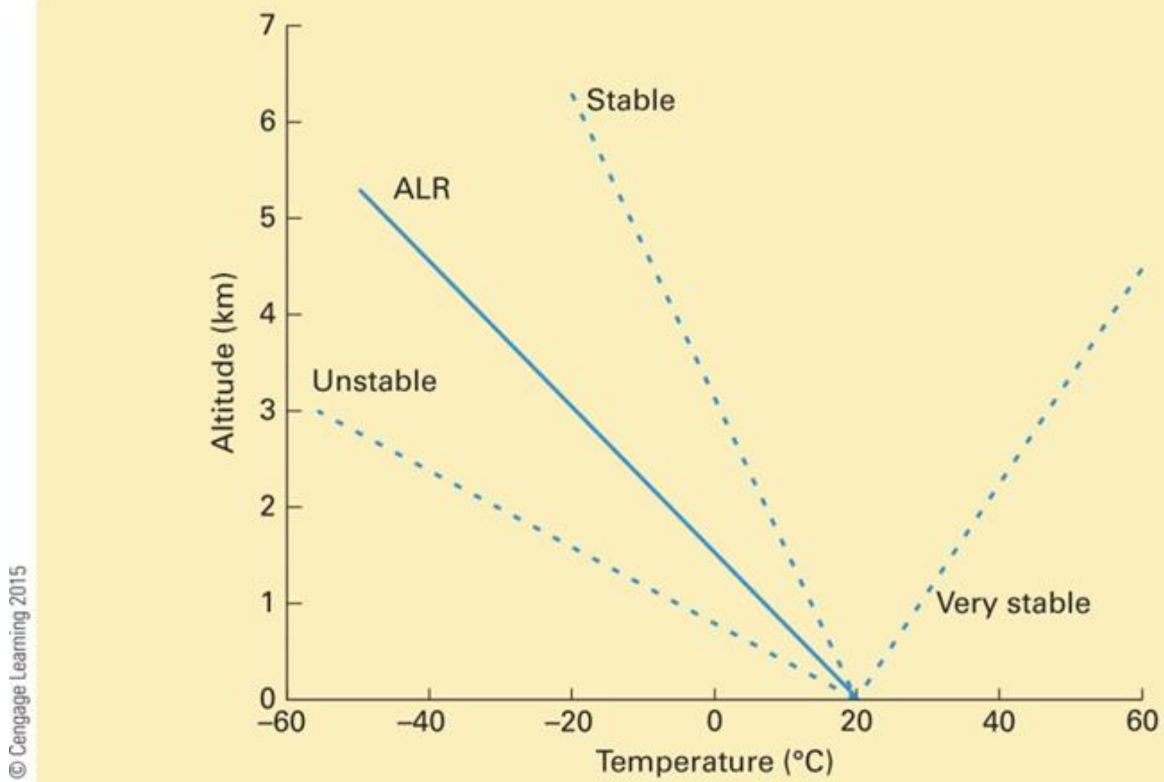
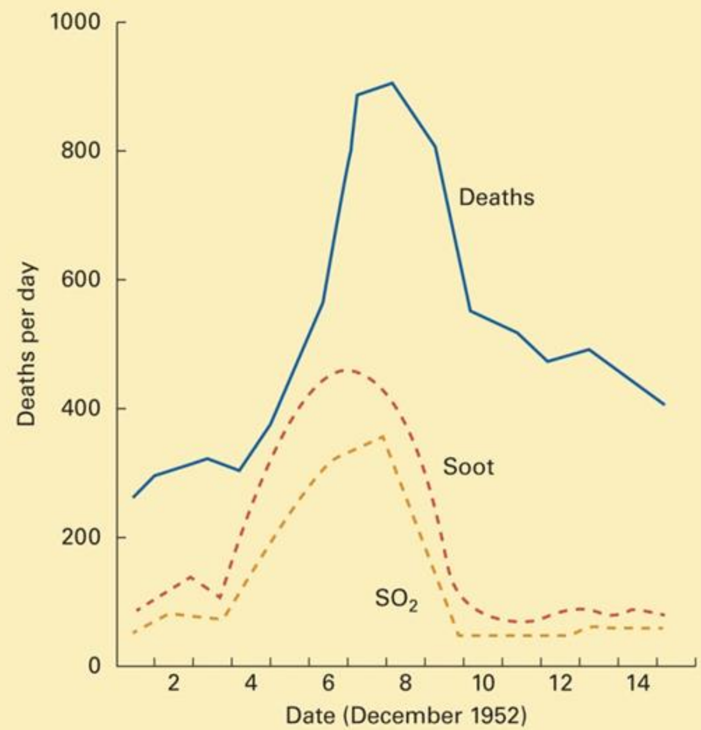


Figure 4.6: Examples of temperature variations in the atmosphere that are faster (unstable) or slower (stable) than the ALR.

Health effects of stable atmospheric conditions

Increased exposure to high levels of pollution

London 1952 - Estimated 12,000 deaths from excess exposure to pollution



Based on J. Fenger "Air pollution in the last 50 years–from local to global," Atmospheric Environment 43 (2009) pp. 13–22

Figure 4.7: Correlation between measured pollutants and death rate in London in 1952.

Equilibrium temperature of a planet

A planet without an atmosphere and an albedo, a, has incident solar radiation S (in W/m^2)

The total power absorbed by the planet is

$$P_{absorbed} = (1 - a)S\,\pi R^2 \qquad (4.6)$$

The total power radiated is given by the Stefan-Boltzmann law

$$P_{radiated} = 4\pi R^2 \sigma T^4 \qquad (4.7)$$

The equilibrium surface temperate is

$$T = \left[\frac{(1 - \alpha)S}{4\sigma}\right]^{1/4} \qquad (4.8)$$

The greenhouse effect

If an atmosphere is present then certain molecules in the atmosphere will transmit the short wavelength solar radiation but will block the re-irradiated long wavelength radiation from the planet, leading to an increase in equilibrium surface temperature.

If the earth had no atmosphere the equilibrium surface temperature would be about -19°C.

With the present atmosphere the equilibrium surface temperature is about +11°C.

Greenhouse gases in the atmosphere

Table 4.6: Greenhouse gases in the earth's atmosphere. The relative absorption is normalized to the absorption per molecule for CO_2. Radiative forcing is a measure of the overall effectiveness of a particular gas at altering the energy balance in the atmosphere, that is, its ability to contribute to global warming. Data are shown for the most abundant chlorofluorocarbon (CFC), CCl_2F_2.

molecular species	approximate current concentration in atmosphere	relative infrared absorption per molecule	radiative forcing (W/m^2)
carbon dioxide (CO_2)	390 ppm	1	1.85
methane (CH_4)	1.8 ppm	25	0.51
nitrous oxide (N_2O)	320 ppb	298	0.18
CFC (CCl_2F_2)	530 ppt	10,900	0.17

Climate change

CO_2 is produced by the combustion of fossil fuels.

This CO_2 adds to the greenhouse gases in the atmosphere and raises the equilibrium surface temperature of the earth.

Historical temperature and CO_2 concentration trends

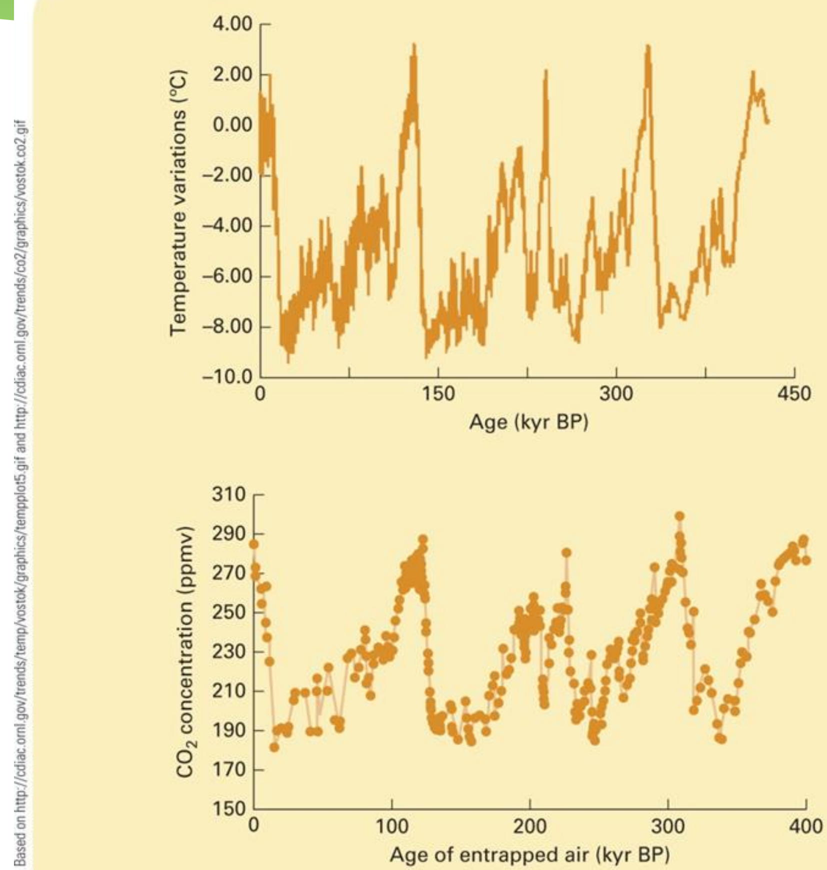


Figure 4.8: Measured temperature fluctuations and CO_2 concentrations as measured from ice core data at Vostok, Antarctica in 1000s of years before present (kyr BP).

Recent CO_2 concentration in the atmosphere

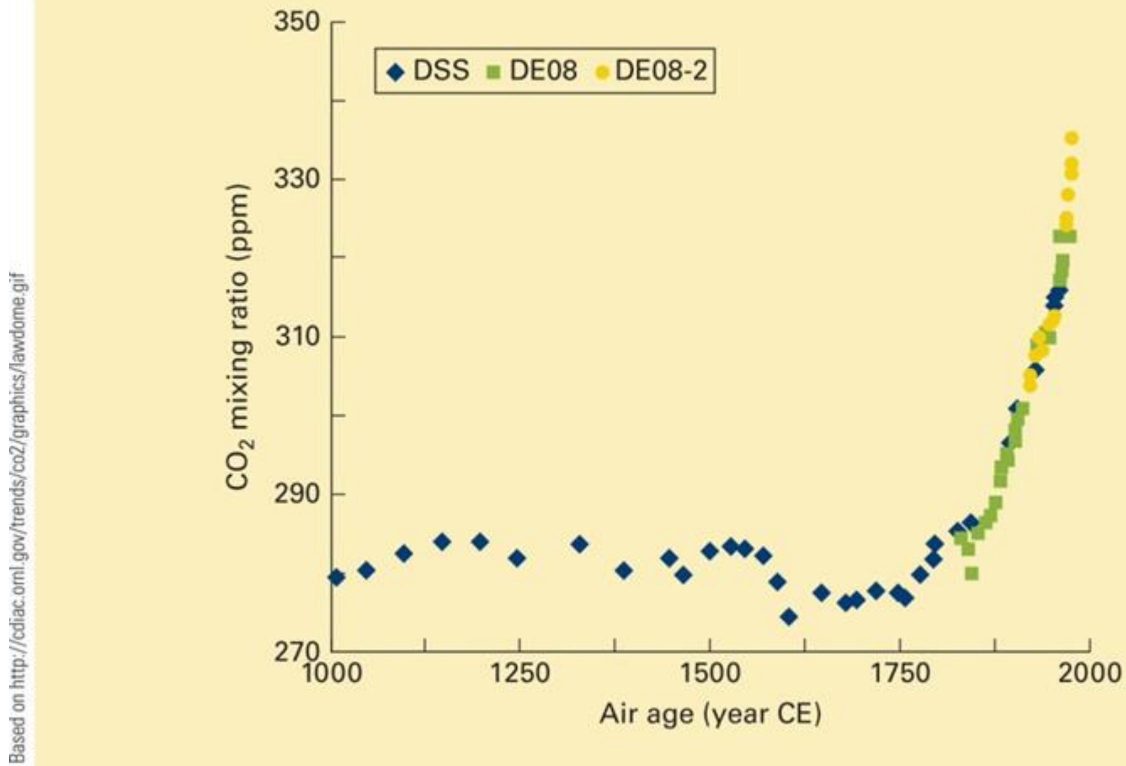


Figure 4.9: Atmospheric CO_2 concentration for the past 1000 years, taken at Law Dome, Antarctica.

Atmospheric CO_2 observed in Hawaii

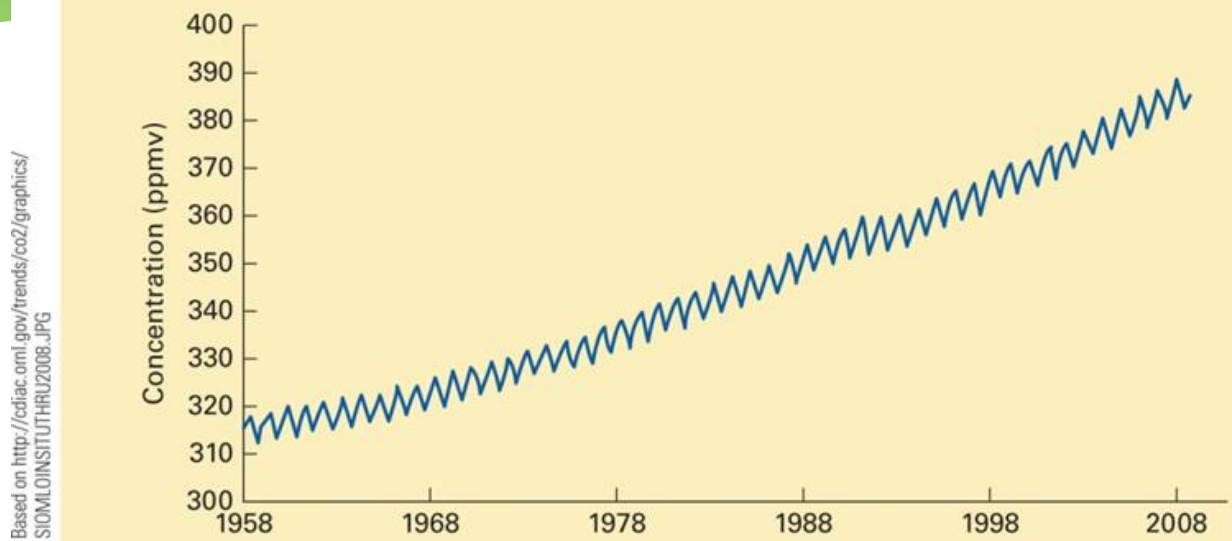


Figure 4.10: Measured atmospheric CO_2 concentration at Mauna Loa Observatory in Hawaii. The annual oscillations are due to fluctuations resulting from the seasonal growth of vegetation (which absorbs CO_2).

Oscillations are due to seasonal fluctuations resulting from vegetation growth

Evidence for global warming

Direct temperature measurements

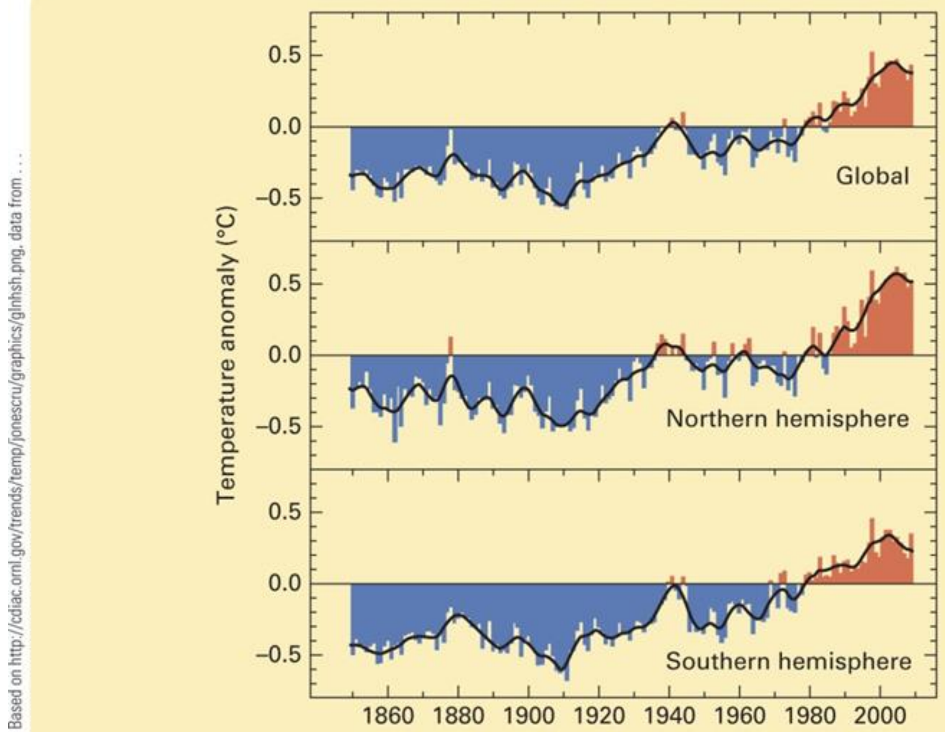


Figure 4.11: Mean global temperature measured relative to the average for the period 1850–2009.

Other evidence

- reduction in size of glaciers
- reduction in arctic sea ice
- increase in sea level
- biological changes
- increase range of some species
- thawing permafrost in arctic
- weather fluctuations

Glacial reduction

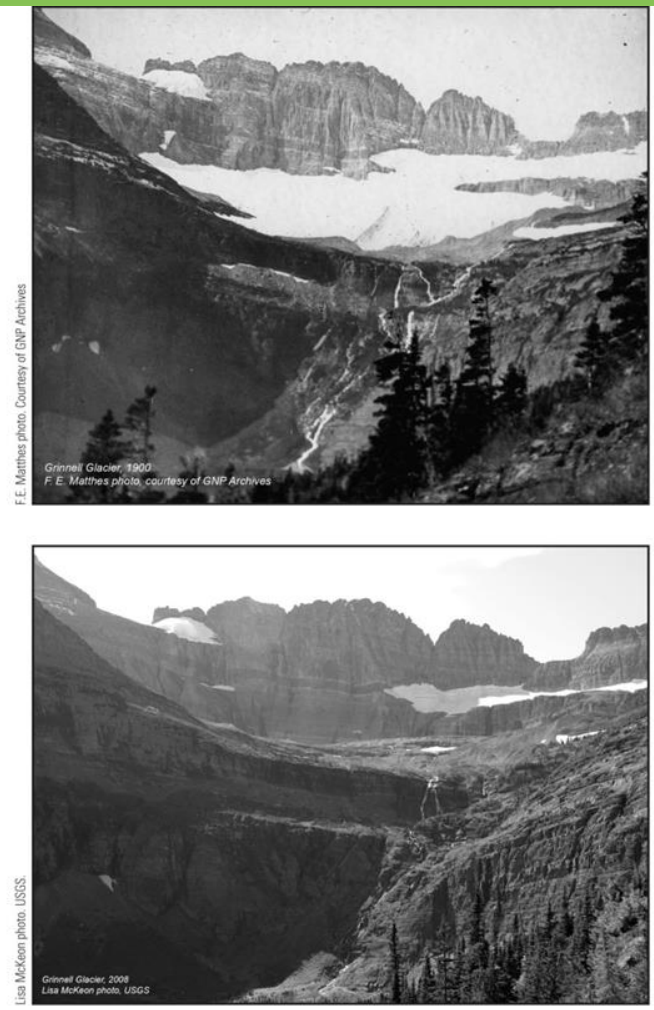


Figure 4.12: Reduction in the size of the Grinnell Glacier in Glacier National Park between 1900 (top) and 2008 (bottom).

Predicted temperature changes for the next century

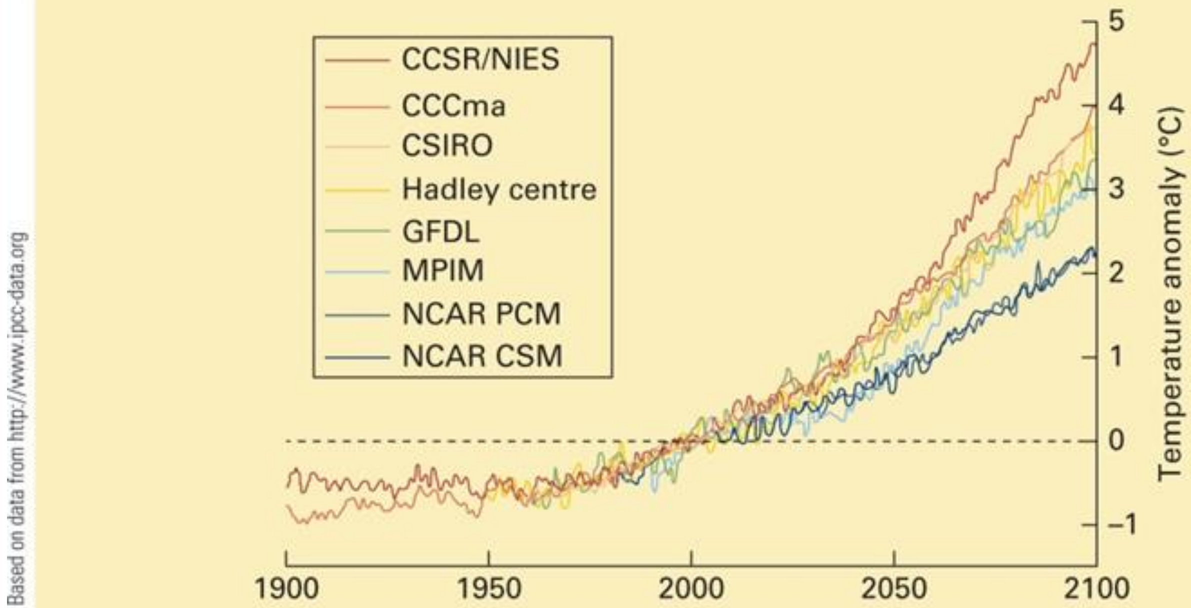


Figure 4.14: Predicted average world temperature increase as a result of CO_2 emissions based on various models.

Possibility of carbon sequestration

Underground - in depleted oil and natural gas wells

In oceans - trapped in cold regions deep in the oceans

Solid storage - stored in solids using reactions such as

$$CaO + CO_2 \rightarrow CaCO_3 \quad (4.10)$$

$$MgO + CO_2 \rightarrow MgCO_3 \quad (4.11)$$

Carbon emissions worldwide

Table 4.8: Carbon emissions for the top 20 CO_2-producing countries in 2007.

country	carbon/year (10^6 t/y)	population (10^6)	carbon/year per-capita (kg/y)	GDP (US$$10^9$)	carbon/year per $GDP (kg/(y·$))
China	1782	1321.8	1348	2527	0.71
United States	1592	301.1	5287	13,160	0.12
India	440	1129.9	389	805	0.55
Russia	419	141.4	2963	733	0.57
Japan	342	127.5	2682	4883	0.07
Germany	215	82.4	2609	2875	0.07
Canada	152	33.4	4551	1089	0.14
United Kingdom	147	60.8	2418	2346	0.06
South Korea	137	49	2796	897	0.15
Iran	135	65.4	2064	193	0.70
Mexico	128	108.7	1178	743	0.17
Italy	124	58.1	2134	1785	0.07
South Africa	118	44	2682	201	0.59
Saudi Arabia	110	27.6	3986	282	0.39
Indonesia	108	234.7	460	265	0.41
Australia	102	21.1	4834	645	0.16
France	101	61.1	1653	2151	0.05
Brazil	100	190	526	967	0.10
Spain	98	40.4	2426	1084	0.09
Ukraine	87	46.3	1879	82	1.06

Factors affecting carbon emissions

- climate
- sources of energy
- national energy policies

France better than Spain or Italy - extensive nuclear program may be a factor.

Brazil better than Mexico - extensive biofuels program may be a factor.

Canada better than Australia - extensive hydroelectric resources may be a factor.

Summary

- Combustion of fossil fuels produces pollution which can be
- categorized as
  - Thermal pollution
  - Chemical pollution
  - Particulates
  - Greenhouse gases
- Internal combustion vehicles and coal fired generating stations are the major contributors to the first three categories
- All fossil fuel combustion produces CO_2
- Greenhouse gases contribute to global warming
- Carbon sequestration may mitigate the effects of greenhouse gas emissions