

release of methane, a greenhouse gas, to the atmosphere. This would contribute to additional warming. Uncertainties and feedbacks affecting climate include the following factors.

1 Variations in solar activity

Some researchers suggest that climate is influenced more by variations in solar output than by greenhouse gases. For example, from 1645 to 1715, sunspot (solar flare) activity was minimal and the Earth experienced a "Little Ice Age." However, several studies show that although it may have some influence, global mean temperature changes, recently and in the future, are due less to solar variability and more to greenhouse gases (Hansen and Lacis 1990, Thomson 1995).

2 Changes in the hydrosphere and cryosphere

Several interactions of the climate system with water and ice produce important feedbacks. First, water vapor is a greenhouse gas. In response to ocean warming and increased evaporation, concentrations of atmospheric water vapor increase. This process is a classical positive feedback loop, that is, warming produces a gas that causes even more warming. The positive contribution of increasing atmospheric water vapor to global warming is significant (Manabe and Wetherald 1967).

Also, clouds are a very important factor in determining the amount of heat retained by the Earth and many of the differences in GCM predictions have to do with their treatment of clouds. As the ocean warms and evaporation increases, cloudiness increases. The role of clouds in greenhouse warming is the subject of intense research. Low cumulus clouds reflect solar energy and have a net cooling effect, whereas high stratus clouds trap solar

energy and contribute to additional warming (Figure 4.5). Model simulations suggest that overall clouds may amplify warming by a factor of 1.3 to 1.8 (Cess et al. 1989). Increased cloudiness should increase nighttime and wintertime minimum temperatures and lead to a decrease in both daily and seasonal temperature ranges. Data for the United States since 1900 confirm just such a trend (see Chapter 3).

Finally, snow cover and glaciers are white and highly reflective (have a high solar albedo). As they melt, the albedo decreases and a greater quantity of heat is absorbed by the darker earth or vegetation surface. Snow cover in the Northern Hemisphere has declined by about 10% over the past 20 years. As a result, spring warming has been significantly enhanced during the twentieth century (Groisman et al. 1994).

3 Chemical interactions and the oxidative state of the atmosphere

Greenhouse gas emissions may affect climate indirectly through chemical interactions taking place in the atmosphere (Box 4.2). These interactions are complex and some are not well understood. Nevertheless, studies suggest that they can have important consequences for climate change (Fuglestedt et al. 1996).

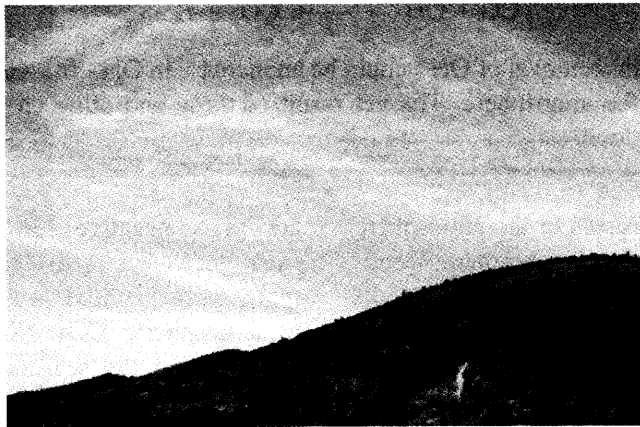
The stratospheric ozone layer protects the Earth from excessive ultraviolet radiation (UV). Stratospheric ozone depletion leads to increases in ground-level UV. Formation of tropospheric ozone (O₃) (an air pollutant and greenhouse gas, Box 10.1) is enhanced by UV.

4 Sulfate aerosols and dust

Several natural sources have a cooling effect on the planet. Volcanic activity and human-induced increases in deforestation and desertification lead to increased dust levels in the atmosphere. The resulting reduction in



(a)



(b)

Fig. 4.5 (a) Cumulus clouds reflect solar energy back to space and have a cooling effect; (b) cirrus clouds allow solar energy through, but trap heat and have a warming effect. However, how global warming will affect clouds and, in turn, the overall radiation balance of the Earth remains one of the largest uncertainties in global climate modeling.

sunlight reaching the Earth's surface has a cooling effect on climate.

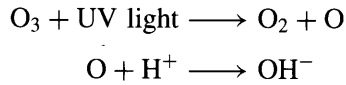
Sulfur comes from both natural and anthropogenic sources. Natural sulfur compounds are emitted by some plankton species in the ocean and serve as cloud condensation nuclei (Charlson et al. 1987). Combustion of fossil fuel, especially high-sulfur coal, releases sulfur to the atmosphere. Such emissions are

expected to increase atmospheric sulfur by 160 to 270% between 1994 and 2040. Inhalation of sulfur particles contributes to human respiratory illness and is a significant air pollutant causing acid rain and damage to ecosystems.

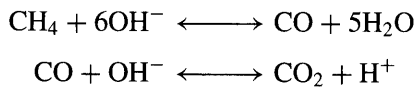
These detrimental effects of atmospheric sulfur are offset to some degree by sulfur's role in decreasing greenhouse warming. Small

Box 4.2 Feedbacks and uncertainties in atmospheric chemistry

Stratospheric ozone depletion increases the formation of hydroxyl radicals (OH^-) in the atmosphere.



Reaction with hydroxyl radicals in turn is a primary sink for many gases including CO , CH_4 , and CFCs, and nonmethane hydrocarbons (NMHC), all of which decrease the oxidation state of the atmosphere by neutralizing hydroxyl radicals. For example, methane is oxidized to CO_2 (which has only 1/20th of the per molecule warming potential as CH_4):



Counterbalancing this removal of OH^- could be an increase in OH^- from increasing amounts of water vapor in the atmosphere. The net result of these and other chemical interactions are not well understood.

sulfur particles or aerosols in the atmosphere reflect solar energy. In the Northern Hemisphere, the negative radiative forcing (cooling) due to sulfate aerosols is about equal to the positive radiative forcing (warming) due to anthropogenic greenhouse gases (Charlson et al. 1992, Charlson and Wigley 1994). Thus, the current negative forcing from anthropogenic sulfur emissions substantially offsets global greenhouse warming, especially in the Northern Hemisphere (Taylor and Penner 1994, Figure 4.6). Ironically, reductions in sulfur emission to improve public health and environmental quality will probably exacerbate global warming.

5 The CO_2 fertilization effect

Plants, through photosynthesis, take up CO_2 and convert it to organic carbon. Studies, primarily in greenhouses, indicate that increased atmospheric CO_2 increases plant growth. If true on a larger scale, this process could

act as a negative feedback on warming, since increased plant biomass would mean more carbon stored organically rather than as atmospheric CO_2 . Since the 1960s, the amplitude of the seasonal atmospheric CO_2 variation, that is, low in summer as plants take up CO_2 and high in winter as plants die, has been increasing. This suggests that plant biomass might indeed be increasing and having a greater effect on seasonal increases and decreases in atmospheric CO_2 .

6 Changes in forest carbon

Forest harvesting releases huge quantities of stored carbon into the atmosphere. Globally, forests and their soils contain about 2,000 billion tonnes (Gt) of carbon. The carbon storage of the Amazon forest alone is equal to about 30 years of current fossil-fuel combustion. Trees are converted to lumber and paper – products that store carbon for much shorter time periods than forests. The

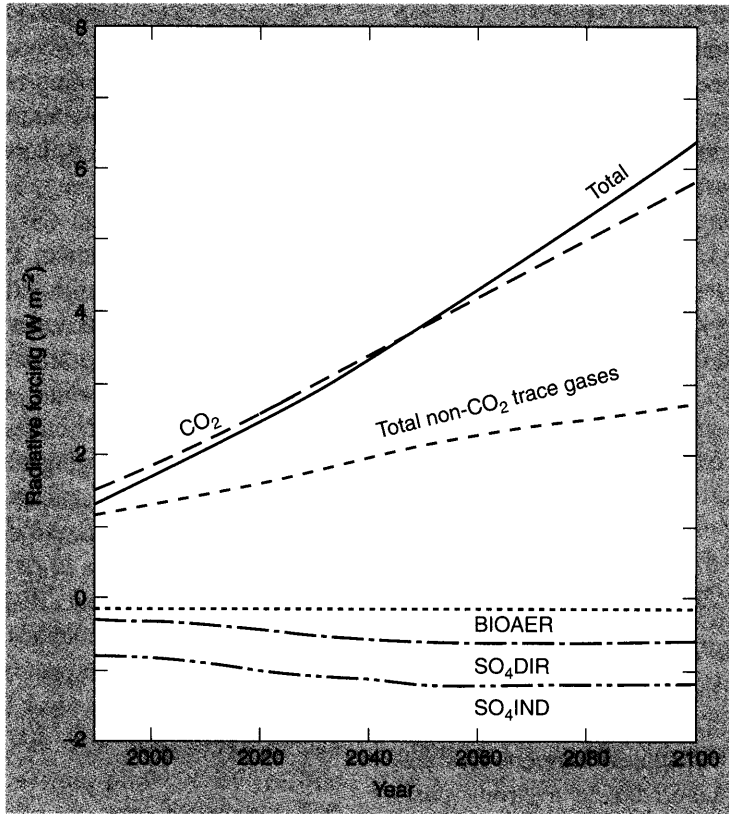


Fig. 4.6 Radiative forcing components. Total non-CO₂ includes methane, water vapor, N₂O, tropospheric ozone, and halocarbons. Negative forcing is from SO₄ aerosols and biomass burning (From Kattenberg A, Giorgi F, Grassl H, Meehl GA, Mitchell JFB, et al. 1996. Climate models – projections of future climate. In: Houghton JT, Filho LGM, Callender BA, Harris N, Kattenberg A, Maskell K, eds *Climate Change 1995: The Science of Climate Change*. Intergovernmental Panel on Climate Change, World Meteorological Organization and United Nations Environment Program. Cambridge: Cambridge University Press, p. 321. Reproduced by permission of Intergovernmental Panel on Climate Change).

destruction of forests, largely for agriculture, contributed an estimated one-third of the CO₂ emitted to the atmosphere during the last century. In 1990, deforestation in the low latitudes emitted 1.6 Gt of carbon per year, whereas forest expansion and growth in mid- and high-latitude forests sequestered 0.7 Gt of carbon, for a net flux to the atmosphere of 0.9 Gt of carbon per year (Dixon et al. 1994).

Global warming could cause latitudinal and elevational shifts in forest habitat (Chapter 6).

Forests may not be able to migrate fast enough. Any large-scale forest demise could release considerable CO₂ to the atmosphere – a positive feedback to warming. Also, warming could increase respiration rates in living plants and lead to increased release of CO₂. The correlation between CO₂ and temperature for the Little Ice Age suggests that a 2 °C warming might result in a total release of 80 Gt of carbon over decades, but the range of possibilities is large (Woodwell et al. 1998).

In contrast, some studies suggest a negative feedback on warming from changes in terrestrial carbon. For example, a doubled CO₂ climate could be an average 5.4 °C warmer and 17.5 mm day⁻¹ wetter. Such change would lead to an increase in plant growth, a 75% increase in the area of tropical rain forests (discounting harvesting), and a reduction in desert and semidesert areas by 60% and 20%, respectively. The overall effect would be a removal of 235 Gt from the atmosphere and its storage as organic carbon in the terrestrial biosphere (Prentice and Fung 1990). However, much, if not all, of the cooling accomplished by expanding forests biomass (and carbon storage) could be offset because forests reflect less solar energy than lighter cleared areas or grasslands (Betts 2000).

7 Changes in soil organic matter

Carbon released by soil respiration accounts for about 10% of the carbon in the atmospheric pool, and increased temperatures and respiration rates could create a strong positive feedback – releasing additional CO₂ to the atmosphere. Soils are the largest terrestrial reservoir of carbon, holding almost three times more carbon than vegetation (Chapter 1). About two-thirds of carbon in forest ecosystems is contained in the soil and in peat deposits. Greenhouse warming should increase the metabolic rate of microorganisms that oxidize organic matter in the soil. A greenhouse temperature increase of 0.03 °C year⁻¹ (a likely scenario) from 1990 to 2050 would release 61 Gt of carbon as CO₂ from soil organic matter – that is, about 19% of the total CO₂ released from the combustion of fossil fuel during the same period (Jenkinson et al. 1991). However, studies in the tall grass prairie of North America suggest that soil respiration acclimatizes somewhat to increased temperature, thus weakening the strength of the positive feedback (Luo et al. 2001).

As soils warm, farmlands, wetlands, tundra, and peat could all become sources of potential positive warming feedbacks. Higher temperature will promote the conversion of soil nitrogen to atmospheric nitrous oxide (N₂O) (a greenhouse gas). Soil warming will also increase CO₂ and CH₄ loss from wetlands, which contain about 15% of the global soil carbon. If the high-latitude permafrost melts, microbial breakdown of soil organic matter will release additional carbon to the atmosphere. In fact, some evidence suggests that the Arctic tundra, in response to warming, is already changing from a net CO₂ sink to a source (Oechel et al. 1993). Also, across northern latitudes an estimated 450 billion tonnes of carbon is tied up in peat – a carbon-rich soil deposit. Rising temperatures may already be responsible for triggering the release of carbon from peat bogs to the atmosphere, which in some areas increased 65% in 12 years (Freeman et al. 2001).

8 Ocean feedbacks

The ocean plays an important role in global climate (see Chapter 1). Some of the additional heat from greenhouse warming is absorbed by the surface layer of the ocean and transported by mixing to the deep ocean – a negative feedback that acts to substantially slow global warming. On the other hand, the water solubility of CO₂ and CH₄ decreases by approximately 1 to 2% per 1 °C increase in ocean temperature. Therefore, as the oceans warm, CO₂ will move from the large ocean reservoir into the atmosphere, a positive feedback that will further enhance the greenhouse effect.

Reservoirs of solid carbon hydrates represent a significant potential source of greenhouse gases. Given the proper temperature and pressure, carbon dioxide and methane form icelike crystalline solids called *clathrates*, or

gas hydrates. These forms of carbon occur in some shallow sea sediments and tundra. Warming could melt these clathrates, releasing large quantities of methane or carbon dioxide into the water column and from there into the atmosphere, increasing global warming (Wilde and Quinby-Hunt 1997).

Studies using a coupled ocean-atmosphere model suggest that increased rainfall from greenhouse warming will result in surface freshening (decreased density) and stratification of seawater over a large area of the Southern Ocean. The decrease in downward mixing and transport of heat and carbon to the deep ocean could substantially decrease the oceanic uptake of CO₂ over the next few decades (Sarmiento et al. 1998).

9 Overall climate carbon cycle feedbacks

At least one study linking a carbon cycle model to an AOGCM suggests that global warming will reduce both terrestrial and oceanic uptake of CO₂. Net ecosystem productivity (carbon storage) will be strongly reduced in the subtropics by increases in soil aridity. At the same time, three factors will reduce oceanic uptake of carbon, especially at high latitudes: (1) decreased solubility of CO₂ at higher temperatures, (2) increased density stratification with warm waters lying on the surface that reduce vertical mixing and transport of CO₂ to the deep ocean, and (3) changes in the biogeochemical cycle of CO₂. The gain in atmospheric CO₂ from these feedbacks is 10% with a doubled and 20% with a quadrupled CO₂ atmosphere. This translates into a 15% higher mean global temperature increase than would occur in the absence of these feedbacks (Friedlingstein et al. 2001).

10 The human dimension

Perhaps the greatest sources of uncertainty in predicting future climate change arise from

the human dimension (Chapters 9 to 12). Future greenhouse gas emissions depend on human population and economic growth, and per capita emissions. New technologies might directly reduce or sequester greenhouse gas emissions from fossil-fuel combustion. Continued increases in energy efficiency and use of alternative (nonfossil fuel) energy could reduce emission growth rates. Mitigation and adaptation could, in a variety of ways, offset the negative impacts of climate change. Continuing attempts at international agreements could fail or could succeed in greatly reducing greenhouse gas emissions.

Scenario-Based Climate Predictions

Despite the complexity of the Earth-climate system and the uncertainties involved in modeling, our ability to predict the climatic effects of greenhouse gas emissions continues to improve. New models consider the effects of sulfate aerosol cooling, of changes in the Earth's albedo due to melting ice, and the changes in atmospheric trace gas concentrations other than CO₂. The ability to "predict" changes that already occurred during the twentieth century or earlier has led to improved confidence in these models. Nevertheless, models often differ significantly in their predicted outputs. The Intergovernmental Panel on Climate Change (IPCC), to encompass the range of uncertainty in predicted changes, collected results from numerous models incorporating transient increases in greenhouse gases. Most studies assume a 1% per year increase in atmospheric greenhouse gas concentrations until CO₂ doubling, tripling, or quadrupling. In addition, the IPCC developed a series of emission scenarios (SRES) to encompass possible ranges of future human population and economic growth that influence fossil-fuel consumption (Box 4.3).

Box 4.3 Emission scenarios (SRES)

In earlier studies, the IPCC used a set of scenarios called IS92 for a range of future economic and population assumptions. For example, IS92a, often called the *business as usual scenario*, assumes continuation of current rates of population and economic growth. Following 1996, the IPCC developed a set of 40 new scenarios covering a wide range of possible future demographic, economic, and technological forces that influence future greenhouse gas and aerosol emissions. In the Special Report on Emission Scenarios (SRES), each scenario represents a specific quantification of four primary “storylines.” However, for illustrative purposes, six Illustrative Marker Scenarios are most often cited (A1B, A1T, A1FI, A2, B1, and B2). Detailed definitions and references to these scenarios can be found in IPCC (2001).

A1. The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in midcentury and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, infrastructure capacity building, and increased cultural and social interactions, with substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil-intensive (A1FI), nonfossil energy sources (A1T), or a balance across all sources (A1B) (where balance is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end-use technologies).

A2. The A2 storyline and scenario family describe a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing populations. Economic development is primarily region-oriented, and *per capita* economic growth and technological change are more fragmented and slower than in other storylines.

B1. The B1 storyline and scenario family describes a convergent world with the same global population that peaks in midcentury and declines thereafter, as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reduction in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.

B2. The B2 storyline and scenario family describe a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels.