

## 5.4 Risks Facing the Earth System as a Whole

Nearly all of the consequences of global change for human well-being discussed above deal with particular sectors of society. A sectoral approach to impacts and consequences lends itself to economic analysis and interpretation. Much of the debate surrounding the severity of such impacts then revolves around cost-benefit analyses of mitigation of global change compared to adapting to its consequences. Some argue that the costs of mitigation far outweigh the benefits, and therefore the appropriate societal response is to adapt to the coming changes. However, all such analyses implicitly assume that global change will consist of only moderate changes to the natural variability of the global environment within an overall envelope of well-buffered stability.

As shown in Chap. 2, the palaeo-record shows that abrupt changes and surprises are a common feature of the Earth System and that environmental extremes beyond those recorded during the period of instrumental record occur frequently. In fact, human societies have developed over a period of time in Earth System history (the Holocene) that is relatively short and relatively stable over many parts of the world when compared to the total range of variability characteristic of the last 400 000 years (Fig. 1.3).

The concept of thresholds and abrupt changes (Fig. 5.30) is crucial to understanding the nature of the risks to the Earth System as a whole (Box 4.1). This type of change arises when a well-buffered system is forced beyond a certain limit. Until the time that the threshold is approached, it appears that the system is unresponsive to the forcing function. However, when the threshold is passed, the response can be sudden and severe. In fact, the system can move to another state very quickly when the threshold is passed, a state which may prove to be difficult to reverse or may even be irreversible. Changes of this nature are especially dangerous in the context of global change. Societies can have little or no warning that a forcing factor is approaching such a threshold, and by the time that the change in Earth System functioning is observed, it will likely be too late to avert the major change. Many of the examples of catastrophic failures discussed below show features of threshold-abrupt change behaviour.

### 5.4.1 Catastrophic Failures

The stratospheric ozone episode demonstrates that catastrophic failures of the Earth System are not only possible, but that recently humankind narrowly escaped one. Other catastrophic failures are possible as the Earth System as a whole adjusts to an ever-increasing suite of interacting human forcings.

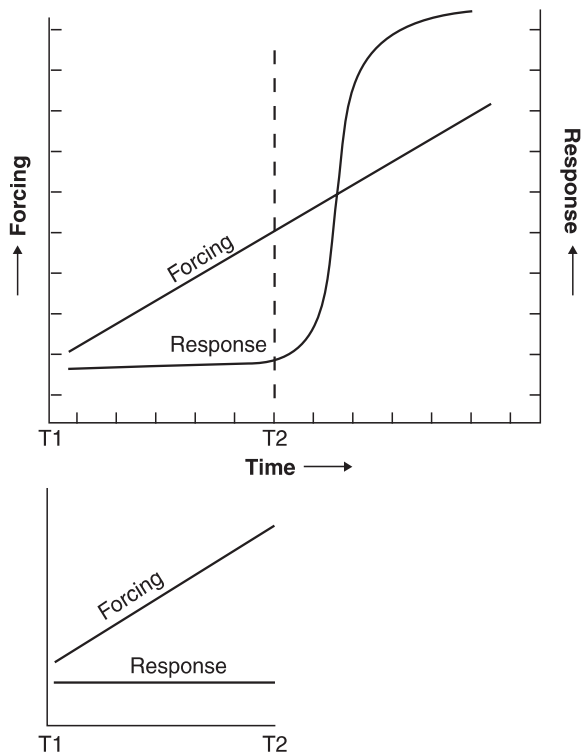


Fig. 5.30. Thresholds and abrupt changes. Many processes within the Earth System are well-buffered and appear to be unresponsive to a forcing factor (e.g., between  $T_1$  and  $T_2$  in lower figure) until a threshold is crossed and then a major change occurs abruptly (see also Box 4.1.)

### Ozone Hole

The development of the ozone hole was an unforeseen and unintended consequence of widespread use of chlorofluorocarbons (CFCs) as refrigerants (Box 5.5). Had bromofluorocarbons been used instead, the result could have been catastrophic. In terms of function as a refrigerant or insulator, bromofluorocarbons are as effective as chlorofluorocarbons. However, on an atom for atom basis, bromine is about 100 times more effective at destroying ozone than is chlorine. As the Nobel Laureate Paul Crutzen (1995) has written:

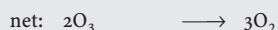
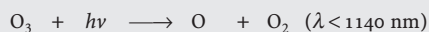
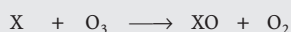
This brings up the nightmarish thought that if the chemical industry had developed organobromine compounds instead of the CFCs – or, alternatively, if chlorine chemistry would have run more like that of bromine – then without any preparedness, we would have been faced with a catastrophic ozone hole everywhere and at all seasons during the 1970s, probably before the atmospheric chemists had developed the necessary knowledge to identify the problem and the appropriate techniques for the necessary critical measurements. Noting that nobody had given any thought to the atmospheric consequences of the release of Cl or Br before 1974, I can only conclude that mankind has been extremely lucky.

Humankind was also lucky in a number of other ways. First, much of the stratospheric chemistry needed to respond to the ozone hole crisis had been developed in

## Box 5.5. The Ozone Hole

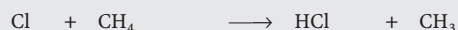
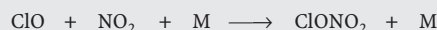
Paul Crutzen

Stratospheric ozone is formed through the photolysis of  $O_2$  and recombination of the two resulting O atoms with  $O_2$  ( $3O_2 \rightarrow 2O_3$ ). These reactions are clearly beyond human control. Reactions are also needed to reproduce  $O_2$ , otherwise within 10 000 years all oxygen would be converted to ozone. Besides the *Chapman reactions*  $O + O_3 \rightarrow 2O_2$ , these reactions also involve several reactive radicals. The ozone destroying reaction chains can be written as



where X stands for OH, NO, Cl or Br, and XO correspondingly for  $HO_2$ ,  $NO_2$ , ClO and BrO. These catalysts are influenced by human activities, especially by the production of industrial chlorine, which is transferred to the stratosphere in the form of  $CCl_4$ ,  $CH_2Cl_2$  and most importantly the chlorofluorocarbon ( $CFCl_3$  and  $CF_2Cl_2$ ) gases. The current content of chlorine in the stratosphere, about  $3 \text{ nmol mol}^{-1}$ , is about six times higher than what is naturally supplied by  $CH_3Cl$ .

For a long time it was believed that chemical loss of ozone by reactive chlorine would mostly take place in the 25–50 km height region and that at lower altitudes in the stratosphere, which contains most ozone, only relatively little loss would take place. The reason is that the  $NO_x$  and the  $ClO_x$  radicals react to form  $ClONO_2$  and HCl:

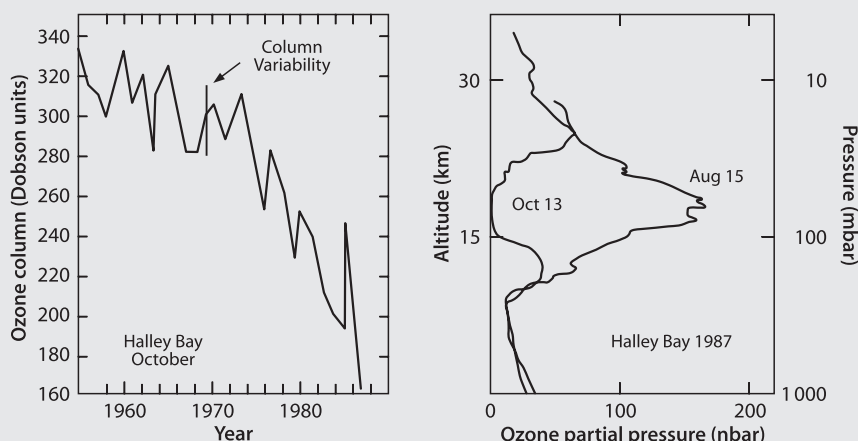


Most inorganic chlorine is normally present as HCl and  $ClONO_2$ , which do not react with each other and with ozone in the gas phase, thus protecting ozone from otherwise much larger destruction.

This favourite situation does not always exist. In 1985 scientists from the British Antarctic Survey presented their observations showing total ozone depletions over the Antarctic by more than 50% during the late winter/springtime months September to November, with ozone depletions taking place in the 14–22 km height region where normally maximum ozone concentrations are found (Fig. 5.31). Within a few weeks after polar sunrise almost all ozone is destroyed, creating the *ozone hole*.

Fig. 5.31.

*Left:* The rapid decrease in total ozone column over the Antarctic from 1956 to 1988 (100 Dobson units correspond to a layer of ozone 1 mm thick if it could be compressed to standard temperature and pressure at the Earth's surface); *right:* altitudinal dependence of ozone loss between August and October 1987 (the drastic ozone losses constitute the so-called ozone hole) (Farman et al. 1985; Hofmann et al. 1989)



earlier research undertaken to evaluate the impact of supersonic aircraft on the atmosphere. Second, scientists of the British Antarctic Survey had done careful, systematic measurements of ozone concentrations over Antarctica for many years so that a clear trend could be detected (Fig. 5.33). Third, the areas of the world most affected by stratospheric ozone are very lightly populated.

Stratospheric ozone depletion is an example of a powerful, non-linear feedback system, as well as a clear case of an anthropogenically driven chemical instability in the Earth System. The rapidity with which the ozone hole developed is characteristic of threshold-abrupt change behaviour. Luckily, in this case the damage is reversible, albeit over a considerable period of time.

## Cleansing Efficiency of the Atmosphere

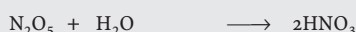
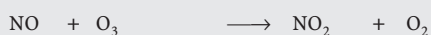
A wide range of substances, of both natural and anthropogenic origin, is released from the Earth's surface into the atmosphere. However, in the long term, these do not accumulate in the atmosphere but rather are converted into other forms, in the case of pollutants into less harmful substances, and rained out of the atmosphere. Thus, the atmosphere can be thought of as a giant washing machine that has the ability to clean itself of harmful substances that are introduced. This capability is sometimes referred to as the cleansing efficiency of the atmosphere.

In more technical terms, the atmosphere is an oxidising medium and its ability to oxidise a wide range of

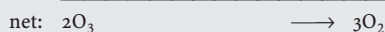
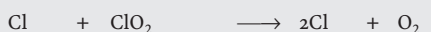
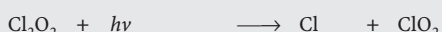
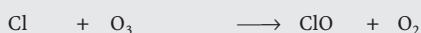
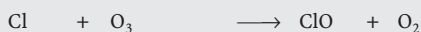
How was this possible? Nobody had expected this; in fact, it was believed that at high latitudes ozone in the lower stratosphere was largely chemically inert.

It only took some two years of research to identify the main processes that lead to these large ozone depletions and to show that the CFCs were the culprits. The explanation involves each of the following necessary conditions:

First, low temperatures, below about  $-80^{\circ}\text{C}$ , are needed to produce ice particles consisting of nitric acid and water vapour. In this process also the  $\text{NO}_x$  catalysts are removed from the stratosphere through the reactions



thereby producing  $\text{HNO}_3$ , which is incorporated in the particles. Secondly, on the surface of the ice particles  $\text{HCl}$  and  $\text{ClONO}_2$  react with each other to produce  $\text{Cl}_2$  and  $\text{HNO}_3$ ; the latter is immediately incorporated in the particles. Thirdly, after the return of daylight after the polar night,  $\text{Cl}_2$  is photolysed to produce 2  $\text{Cl}$  atoms. Fourthly, the chlorine atoms start a catalytic chain of reactions, leading to the destruction of ozone:



The breakdown of ozone is proportional to the square of the  $\text{ClO}$  concentrations. As these grew for a long time by more than 4% per year, ozone loss increased by 8% from one year to the next. Also, because there is now about six times more chlorine, about  $3 \text{ nmol mol}^{-1}$ , in the stratosphere compared to natural conditions when chlorine was solely provided by  $\text{CH}_3\text{Cl}$ , the ozone depletion is now 36 times greater than prior to the 1930s

when CFC production started. Earlier chlorine-catalysed ozone destruction was unimportant. Finally, enhanced  $\text{ClO}$  concentrations are advected to the lower stratosphere by downwind transport from the middle and upper stratosphere within a meteorologically stable vortex with the pole more or less at the centre. This is important because at the higher altitudes more organic chlorine is converted to much more reactive inorganic chlorine gases, including the ozone-destroying catalysts  $\text{Cl}$ ,  $\text{ClO}$ , and  $\text{Cl}_2\text{O}_2$ .

All five factors have to come together to cause the ozone hole (Fig. 5.32). It is not surprising that the ozone hole was not predicted. This experience shows the critical importance of measurements. What other surprises may lie ahead involving instabilities in other parts of the complex Earth System?

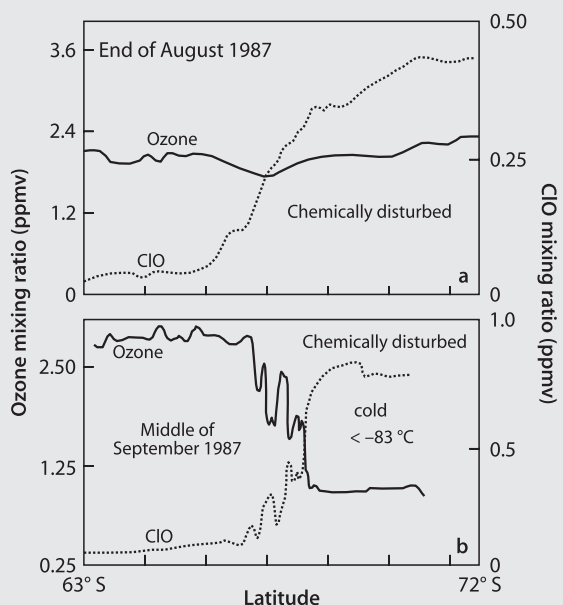


Fig. 5.32. High concentrations of  $\text{ClO}$  radicals and simultaneous rapid ozone destruction in winter with very low temperatures (Anderson et al. 1989)

chemical species and facilitate their removal from the atmosphere is also referred to as its oxidising efficiency. Removal of substances from the atmosphere is thus effected by the increased solubility of the oxidised products, which are then removed by precipitation. The oxidation reaction, and not the subsequent dissolution and removal via precipitation, is usually the rate-limiting step. The  $\text{OH}$  (hydroxyl) radical, a highly reactive chemical species, is the primary oxidising agent, and is often called the detergent of the atmosphere. As the  $\text{OH}$  radical is involved in a wide range of reactions, changes in the composition of reactive gases in the atmosphere, such as  $\text{NO}_x$ , could affect the concentration of  $\text{OH}$  and thus the atmosphere's cleansing efficiency, an important Earth System process.

In general, the concentration of the  $\text{OH}$  radical and hence the oxidising efficiency of the atmosphere is controlled by  $\text{O}_3$ , water vapour, UV radiation and levels of trace gases with which it reacts, such as  $\text{CH}_4$ ,  $\text{CO}$  and volatile organic compounds. The concentrations of  $\text{OH}$  at any one time are very low and highly variable due in part to its rapid cycling with other  $\text{HO}_x$  species, such as  $\text{HO}_2$  and  $\text{H}$ . Given that the concentration of  $\text{OH}$  depends on many other species that are influenced by human activities, it is important to determine if the  $\text{OH}$  concentration is changing in recent decades. Direct measurement of  $\text{OH}$  concentration is extremely difficult so most estimates of its concentration are based on measured concentrations of some species with which it reacts, atmospheric transport models and simulations of the reaction

chemistry. Such models are sensitive to the assumed changes in emissions of compounds such as  $\text{NO}_x$ ,  $\text{CO}$ ,  $\text{CH}_4$  and hydrocarbons, all affected by human activities.

Despite the difficulties, estimates of OH concentration have improved in recent years (Fig. 5.34). The con-

sensus of the several modelling studies that have been undertaken is that globally averaged OH concentration has remained relatively constant with a maximum estimated decrease of around 20% (Wang and Jacob 1998). Two observationally-based estimates of the concentration of methyl chloroform ( $\text{CH}_3\text{CCl}_3$ ) also show relatively small changes but in opposite directions. Estimates by Krol et al. (1998) show a small increase in OH concentration of about 0.46% per year for the period 1978–1993. An estimate by Prinn et al. (2001), on the other hand, suggests that the concentration of OH has decreased globally, but especially in the northern hemisphere, over the last 23 years. These latter estimates suggest that the OH radical concentration increased from 1978, when measurements began, peaked in the 1988–1990 period, and has decreased since then at an accelerating rate (Fig. 5.35). The significance of this recent observed decrease is difficult to determine at present. The trend is not long enough or pronounced enough to determine if it is part of natural variability or whether anthropogenic influences play a role. In addition, the methodology requires that emissions of  $\text{CH}_3\text{CCl}_3$  must be very well known, which is a matter for debate.

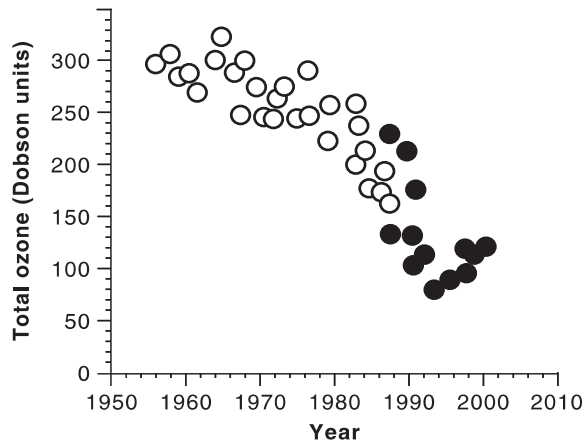


Fig. 5.33. Measurements of the ozone hole over Antarctica (based on data from J. D. Shanklin, British Antarctic Survey). Filled circles indicate measurements taken after the implementation of the Montreal Protocol

Fig. 5.34. Global concentration fields of OH ( $10^6 \text{ molecules cm}^{-3}$ ) in the atmospheric surface layers: top January, bottom July (Spivakovsky et al. 2000)

