

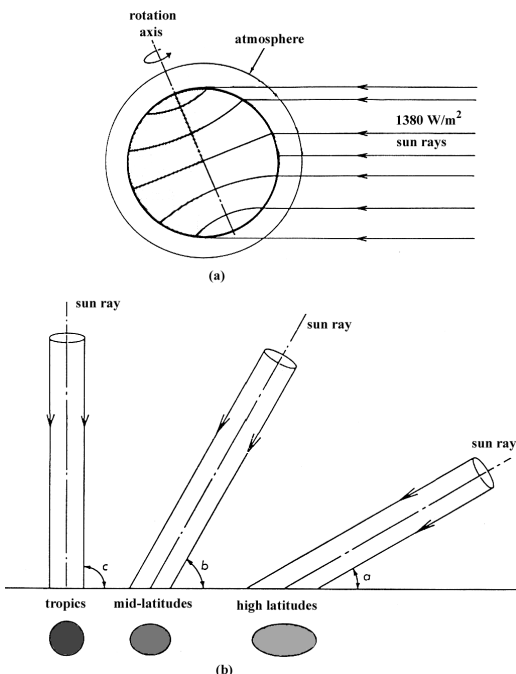
# Chapter 10

## GLOBAL ATMOSPHERIC PROBLEMS

### 10.1 Basic Remarks on Climate

The climate of the earth is the mean state of the atmosphere, after averaging over many weather fluctuations, and consists in a series of circulation patterns that are driven by the solar radiation. The angle of incidence of the solar radiation varies with latitude (Figure 10-1), with the tropics receiving more heat per square meter than the polar regions. The result is differential heating: The tropics collect more heat than the poles. But, since the earth is approximately in thermal equilibrium (it does not keep on heating), the heat received by the sun is matched by an equal heat loss to space. The major difference, however, is that this heat loss is largely nondirectional, with about as much heat being lost at the poles as in the tropics. This implies that the tropics receive more heat than they lose, while the poles lose more heat than they receive. The balance is accomplished by an overall heat flux in the atmosphere that conveys the excess tropical heat to the deficient poles. This sets the atmosphere in motion, operating as a thermal engine.

Warm air rises and cold air sinks. Thus, an efficient way for the atmosphere to convey heat is by having warm air rise from the surface at the tropics, move poleward, lose heat, sink as colder air, and return equatorward as cold air on the surface. But, because the atmosphere is very much thinner than it is wide, such global convection cannot occur as a single cell. Rather, such cell can extend only to a latitude of  $30^\circ$  (Figure 10-2). Warm air at the equator causes abundant evaporation, and as this air rises, its moisture condenses, causing the well known tropical rainfalls (and rainforests). At about 10 to 15 km above the earth's surface, this air, now significantly dryer, branches out with half going northward to about  $30^\circ\text{N}$  and the other half going southward to about  $30^\circ\text{S}$ . At those latitudes, called *horse latitudes*, the dry air cools, descends and begins

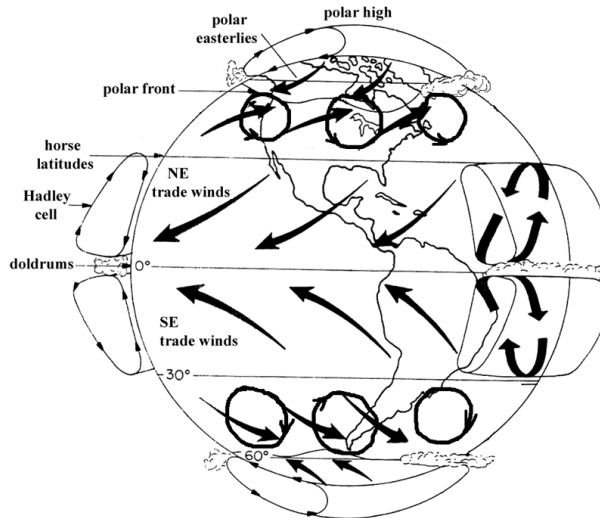


**Figure 10-1.** The decreasing angle of incidence with latitude causes solar radiation to heat the tropics more effectively than the polar regions.

its return toward the equator to close the loop. Consistently dry air at 30°N and 30°S explains the existence of deserts at those latitudes. This subtropical loop is called the *Hadley cell*.

The equatorbound winds on the earth surface are subject the so-called *Coriolis force* caused by the rotation of the earth and are greatly deflected, to the right in the northern hemisphere and to the left in the southern hemisphere. As a result, winds blow mostly from the east, with a slight northerly origin between 0° and 30°N and a slight southerly origin between 0° and 30°S (Figure 10-2). Because these winds were used extensively for transoceanic trade by sailing ships that relied on them for propulsion, they have been named the *trade winds*. The relatively quiet equator has been called the *doldrums*, and the relatively quiet latitudes around  $\pm 30^\circ$  were the sailor's nightmare. Being trapped in these wind-less latitudes usually meant losing many days at sea and getting low in freshwater and food. Horses onboard had often to be discarded for the survival of the people, hence the name of these latitude bands, the *horse latitudes*.

Another convective cell similar to the Hadley cell exists near each pole. Here, the cold air sinks at the pole, moves equatorward, turning gradually warmer, down to about 60° of latitude where it begins to rise and return toward the pole. The sinking of air at the surface at the pole causes a high pressure,



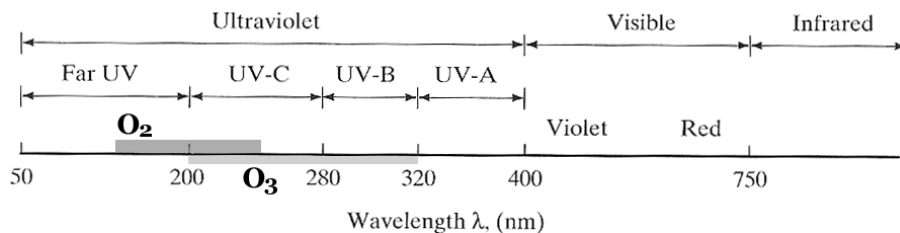
**Figure 10-2.** The general circulation in the atmosphere. Heat is transported poleward in each hemisphere in a series of three steps: a vertical cell from the equator on 30° (Hadley cell), weather systems conveying heat horizontally from 30° to 60°, and a second vertical cell from 60° to the pole. [Adapted from Lutgens and Tarbuck, 1989]

called the *polar high*. Deflection by the Coriolis force generates a system of easterly winds. At the upper level, the sinking causes a low pressure and its associated winds are westerly, forming the so-called *polar vortex*. The outer edge of this upper-level vortex reaches as far as 45–50° and is characterized by strong gradients forming the *polar front* and by a very strong wind called the *jet stream*.

The band between 30° and 60° of latitudes, in each hemisphere, is quite another story. Here, the atmosphere is most unstable and perpetually generates weather systems, most often low-pressure systems (*cyclones*). These transient systems are associated with meandering of the jet stream above and are the means by which air is redistributed across latitudes and the heat conveyed from the warmer subtropics to the colder polar regions.

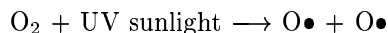
## 10.2 Stratospheric Ozone Holes

Above the troposphere where weather fluctuations take place lies the stratosphere, where the air is very calm, in a permanent state of inversion. This inversion is created because of the absorption of solar ultraviolet (UV) light by oxygen. It takes place at about 15 to 20 km above ground, because oxygen is too rarefied above this level to block UV rays effectively and, below that, there is no UV light that oxygen has not already absorbed. Due to its atomic nature,

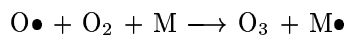


**Figure 10-3.** The ultraviolet (UV), visible and infrared portions of the solar radiation ranked according to wavelength. Oxygen effectively absorbs all UV radiation in the range shorter than 242 nm (darker gray band), whereas ozone is capable of absorbing radiation in the range of 200 to 320 nm (lighter gray band). Note that the spectrum is not drawn to scale. [Adapted from Masters, 1997]

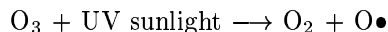
oxygen is most apt at absorbing UV radiation at wavelengths shorter than 242 nm (Figure 10-3). The reaction is



Once atomic oxygen is present, which is very reactive (as indicated by the bullet after its symbol), it quickly binds with an oxygen molecule to form ozone:



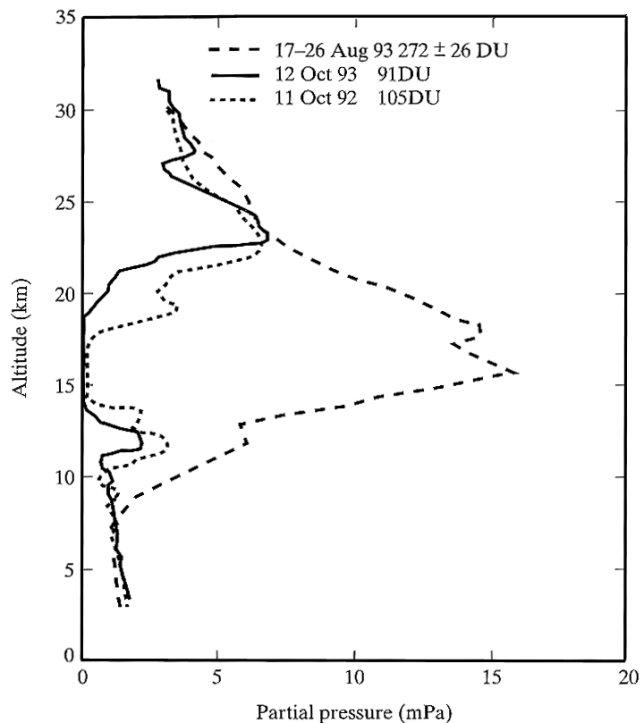
where M is any neighboring molecule (usually nitrogen) that absorbs the excess energy, without which ozone would self-destruct. In its turn, ozone ( $\text{O}_3$ ) absorbs UV light and can do so at longer, less energetic wavelengths because it is a more fragile molecule than oxygen:



which is effective in the range between 200 and 320 nm (Figure 10-3). Together oxygen and ozone in the stratosphere remove most of the UV solar radiation and protect our bodies from harm, such as skin cancer.

Thus, while ozone is a pollutant at ground level (see section on photochemical smog in Chapter 8), it is beneficial at higher altitudes, even vital. The problem is that ozone in the stratosphere has been depleted, especially near the poles during springtime (Figures 10-4 and 10-5). The culprits were identified in the late 1980s and are the chloro-fluoro-carbons (CFCs), artificial chemicals designed by chemical engineers to have particular physical properties, such as no solubility in water, condensation at temperatures making them useful in refrigeration, and good propellant characteristics. There are many types of CFCs, but their chemical formulas all contain some chlorine and fluorine. Examples are  $\text{CCl}_3\text{F}$ ,  $\text{CCl}_2\text{F}_2$  and  $\text{CHClF}_2$ .

Although these compounds were initially thought to be inert, because in the laboratory they had not been tested under the low pressures and temperatures

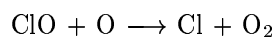
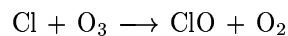


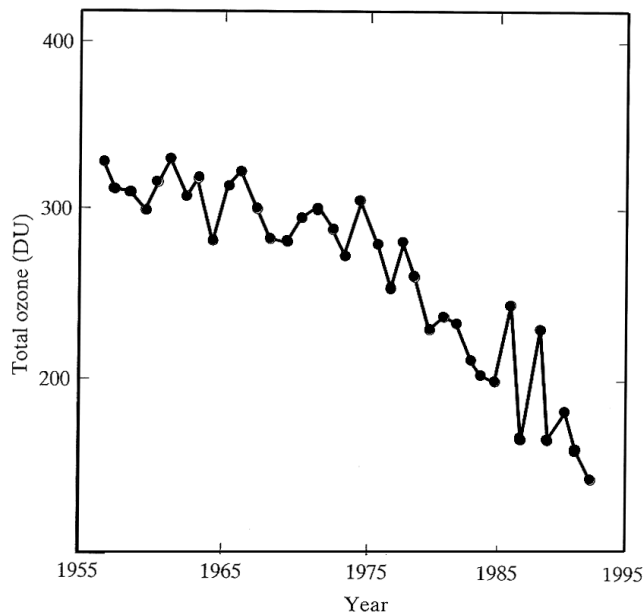
**Figure 10-4.** Vertical profiles of ozone concentrations at three different times over the South Pole. The August 1993 profile with the large maximum near 15 km of altitude is representative of normal conditions, which exist during the winter polar night, when chlorine is not active. The other two profiles, of October 1992 and 1993, are typical of spring conditions when sunlight has returned and chlorine removes most of the ozone. [From Masters, 1997]

characteristics of the polar stratosphere and subjected to UV light, they proved to be quite reactive under those conditions. Let us take the example of  $\text{CCl}_2\text{F}_2$ . Under UV radiation, it loses its two chlorine atoms:



The atomic chlorine (Cl) is the source of the problem. Indeed, it reacts with ozone to destroy it

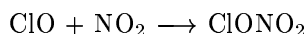
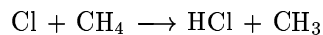




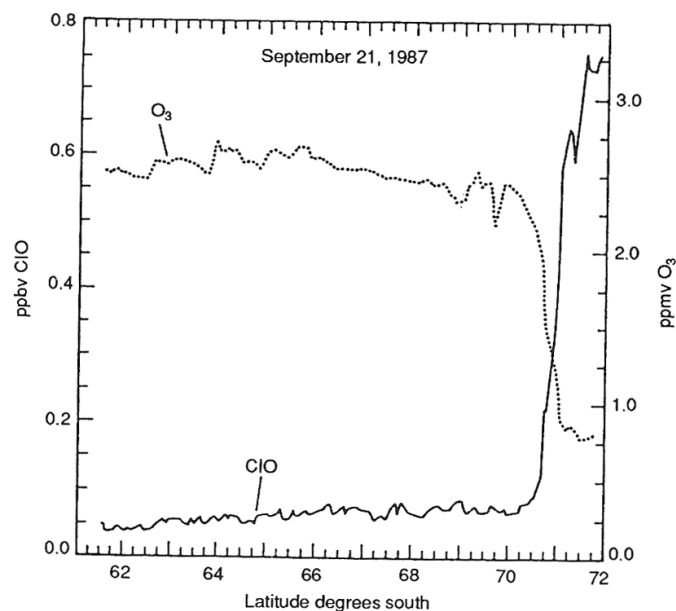
**Figure 10-5.** Ozone concentrations measured over Halley Bay, Antarctica ( $76^{\circ}\text{S}$ ) averaged over the month of October for every year from 1957 to 1993. October is the month of the year when ozone depletion reaches its peak. Concentrations are in Dobson Units (DU), with 1 DU corresponding to a thickness of 0.01 mm of pure ozone at a pressure of 1 atm and temperature of  $0^{\circ}\text{C}$ . [From UNEP, 1994]

Through these reactions, the chlorine atom not only takes one ozone molecule away but also an atomic oxygen, which would have generated a new ozone molecule had it not been caught in this reaction, and, moreover, comes out intact, ready for another round. In other words, Cl acts as a catalyst. It has been estimated that a single chlorine atom can repeat this catalytic reaction cycle tens of thousands of times. Figure 10-6 shows evidence that ozone depletion is related to the presence of chlorine.

Eventually, the chlorine atom and its companion ClO are removed from circulation by other reactions:



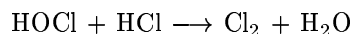
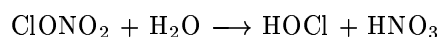
These require the presence of methane ( $\text{CH}_4$ ), a potent greenhouse gas, and nitrogen dioxide ( $\text{NO}_2$ ), a notorious pollutant, which is directly deposited in the stratosphere by airline jets but can also seep from the troposphere. It is quite ironic that those forms of contamination can actually be helpful in this context. Somehow, two forms of contamination can lessen the impact of each



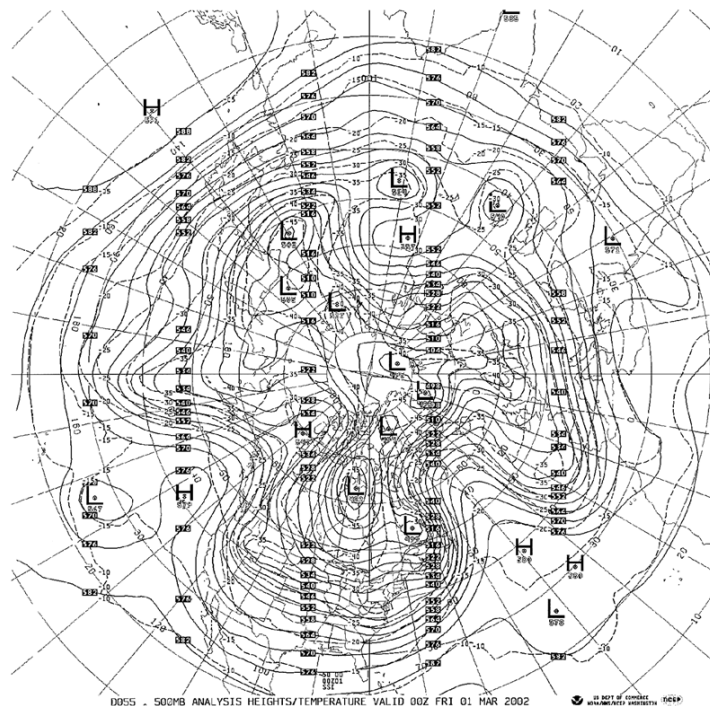
**Figure 10-6.** Concentrations of ozone and ClO at an altitude of 18 km (in the stratosphere) over a range of southern latitudes approaching the South Pole, measured on 27 September 1987. The sharp decrease in ozone concentration at 71°S is evidently concomitant with an equally sharp rise in ClO, pointing to the role that chlorine plays in destroying stratospheric ozone. [From Boubel et al., 1994]

other. In the products, HCl (chloric acid) is highly water soluble and some of it eventually precipitates into the troposphere, while chlorine nitrate ( $\text{ClONO}_2$ ) is inactive as far as ozone is concerned.

In the darkness of the polar winter, chlorine atoms are sequestered in the form of chlorine gas ( $\text{Cl}_2$ )

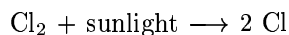


A physical phenomenon occurs simultaneously. The extremely low temperatures (which may drop below  $-90^\circ\text{C}$ ) contribute to a certain sinking of air, which under the action of the planetary rotation, forms a tight cyclonic circulation centered on the pole and called the *polar vortex* (Figure 10-7). This vortex lasts more or less as long as the polar night, and begins to meander and disintegrate in the spring. While it persists in winter, this vortex effectively traps the polar air and all its chemicals. Thus, the chlorine remains present, except in an inactive form.



**Figure 10-7.** The polar vortex over the North Pole on 1 March 2002, shortly before disintegration. Contours are those of height (in decameters) of the 500 mb pressure surface. Because of the earth's rotation, wind blows in a direction everywhere parallel to these contours. [From NOAA, 2002]

Once sunlight returns in the spring, the sequestered chlorine reappears in its atomic form:



and the destruction of ozone resumes. Yet, at the same time, the polar vortex is about to break apart, and one of two scenarios can occur.

The more fortunate scenario is that of early break-up of the polar vortex, preferably slightly ahead of the catalytic chlorine reactions. In such case, the precursor chemicals have a chance to disperse toward lower latitudes, thereby diluting their impact over a larger area. Such years can be noted on Figure 10-5, when the total ozone over Halley Bay was higher than in other years. The unfortunate situation occurs when the polar vortex is late at breaking up. Then, the catalytic chlorine reactions prey intensely on the polar ozone, creating a dramatic reduction (see Figure 10-4). Such intense destruction has become known as an *ozone hole*.

Ozone measurements have been made over Antarctica since 1957, as part of a larger scientific program to collect more geophysical data on Earth. Spring-



time ozone losses began to occur in the 1970s (Figure 10-5), but the anomalously low data were initially cast aside as probably caused by a faulty instrument. It took until 1985 for scientists to admit that the data were not faulty and that ozone was indeed being lost over the polar regions. They coined the expression *ozone hole*, which is evidently an exaggeration since the situation is actually a thinning rather than a disparition of ozone, but the expression caught the attention of the public and governments. Eventually, the connection was made with the CFCs, thanks to data correlations such as the one shown in Figure 10-6. Quickly, the scientific evidence became well established, and the issue received international attention. An agreement was signed in 1987 by most industrialized nations, which became known as the *Montreal Protocol on Substances that Deplete the Ozone Layer*. This treaty called for a 50% reduction in the use of CFCs by 1999, but it was realized shortly afterwards that this measure was insufficient, and a new treaty was signed in London in 1990 that set a timetable for the complete phase-out of CFCs by 2000. Exception was made for developing nations, for which the deadline was set at 2010. Chemical engineers quickly went to work and in short order had designed substitutes. This enable a phase-out ahead of schedule, and by 1996 all CFC production had ceased. This is an environmental success story. Scientists, however, warn that the persistence of older chlorine in the stratosphere will delay the return to normal conditions for several decades, possibly more than a century.

### 10.3 The Greenhouse Effect

The role of CO<sub>2</sub> in the global heat budget.

### 10.4 Climate Change?

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### 10.5 Feedback Mechanisms

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### 10.6 What the Experts Have to Say

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## Chapter 11

# NEXT CHAPTER

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