Stratospheric ozone depletion

Authors

Jozef Syktus and Stephen Jeffrey, Department of Natural Resources and Water

Reviewers

Paul Lawrence and Joe Scanlan, Department of Natural Resources and Water

Key findings

- Atmospheric concentrations of ozone depleting substances have decreased as a result of the effectiveness of the Montreal Protocol.
- The global (60°S–60°N) ozone concentration is projected to return to pre-1980 levels by around the middle of the 21st century.
- Antarctic ozone levels are projected to return to pre-1980 levels around 2060–75, which is 10–25 years later than previously estimated.
- The long time lag between emission of ozone depleting substances and the recovery of stratospheric ozone implies a continuing risk to human health and the environment from ongoing exposure to elevated levels of UV-B radiation.
- Queensland people will continue to experience increased rates of skin cancer arising from increased levels of UV radiation until about 2060, because of the long lag time between exposure and cancer formation.
- Ozone recovery is strongly coupled to climate change processes through the influence of increasing concentrations of greenhouse gases.

Indicators and summary of status

Indicator	Status of indicator
Stratospheric ozone concentrations and trends	Significant stratospheric ozone depletion still occurs over Antarctica during spring each year.
	Stratospheric ozone depletion has stabilised since a significant decrease in the concentration of ozone depleting substances in the 1980s and 1990s. Substantial recovery of the ozone layer is expected by 2050 in mid-latitudes and by 2075 in high latitudes (polar regions).
	The production and consumption of major ozone depleting substances, with the exception of hydrochlorofluorocarbons, have been phased out in Australia. Commonwealth Regulations have replaced state and territory legislation for managing ozone depleting substances.
	Information quality is very good; accurate and comprehensive measurements of stratospheric ozone are available from multiple sources.
Recovery and destruction of ozone depleting substances	The phasing-out of ozone depleting substances is progressing well in response to the Montreal Protocol and other associated national actions to phase out such substances and replace them with less harmful substitutes.
	There has been a downward trend in the concentration of ozone depleting substances since they reached peak levels in the late 1990s.
	The Australian Government is responsible for the regulation of the use, recovery and destruction of ozone depleting substances. Since regulation commenced, Australia has collected over 3000 tonnes of ozone depleting substances, which have been recycled, stored or destroyed.
	Data accuracy is very good due to statutory requirements.
Level of UV-B radiation at the Earth's surface	Elevated levels of solar UV-B radiation at ground level continue to pose a significant health risk in Queensland.
	The trend in UV radiation is unclear. Although stratospheric ozone depletion appears to have stabilised, observations show that ground-level UV-B radiation has not yet decreased.
	The Bureau of Meteorology issues a UV index forecast every day to provide information about the risk of overexposure to high levels of UV radiation.
	Accurate data are available from New Zealand and these data can be used as an indicator of conditions in Queensland. In the absence of specific Australian data, information quality is rated as moderate.

Importance

Ozone is a naturally occurring gas that is a minor component of the Earth's atmosphere; unlike carbon dioxide, it is not uniformly mixed throughout the atmospheric column. The highest concentration of ozone is in the stratosphere, which forms the upper part of the atmosphere and lies about 10–50 km above the Earth's surface. Approximately 90% of ozone is concentrated in a thin layer between 10 km and 17 km above the Earth's surface. Ozone also occurs as a pollutant in the troposphere. Ozone levels are expressed in Dobson Units (DU), and the average amount of ozone in the atmosphere is about 300 DU.

Stratospheric ozone is an important determinant of the thermal structure of the stratosphere through absorption of solar radiation. Ozone has the capacity to strongly absorb short wavelengths of incoming solar radiation and thus provides a protective blanket that shields the Earth's surface from the damaging effects of short-wave radiation from the sun. Exposure to excessive amounts of short-wave ultraviolet (UV) radiation, such as UV-B, is harmful to most forms of life, although humans (and most animals) require small amounts of UV-B for the production of vitamin D. Consequently, the ozone layer plays an important part in the ecological framework for life on the Earth's surface.

The ozone layer began forming some two billion years ago when marine organisms began producing oxygen via photosynthesis. Ozone is formed by UV-catalysed photochemical reactions between oxygen molecules in the stratosphere, particularly in the tropics, where intense UV light drives chemical decomposition to produce large amounts of ozone. Stratospheric ozone is being continually formed and destroyed as part of the natural cycle.

The natural balance of ozone production and depletion has been disturbed by the emission of synthetic chemical compounds, called ozone depleting substances (ODSs), such as chlorofluorocarbons (CFCs), halons, methyl bromide and hydrochlorofluorocarbons (HCFCs). These compounds were used in a variety of industrial and domestic applications such as refrigeration and as propellants in aerosol spray cans. Ozone depletion is effected by chemical reactions involving various compounds of chlorine and bromine. These compounds are produced in the stratosphere as a result of the catalytic breakdown of ODSs by ultraviolet light.

As a consequence of the damage to the ozone layer, incidental exposure to UV-B radiation has increased in Australia, resulting in potentially significant impacts on human health, the health of terrestrial and marine ecosystems, agricultural productivity and the durability of materials. Increased exposure to UV radiation increases the risk of skin cancers, especially aggressive forms such as melanomas. Skin cancers appear long after sustained UV exposure and current modelling estimates that skin cancer rates will continue to rise through to 2060, because of the rapid depletion of ozone that began in the 1980s.

The depletion of stratospheric ozone caused by the release of synthetic ozone depleting substances has resulted in changes in the global atmospheric circulation.

Antarctic ozone depletion and the interaction of increasing concentrations of greenhouse gases have strengthened the Antarctic polar vortex in recent decades, resulting in significant changes in the atmospheric circulation pattern of the Southern Hemisphere (Thompson and Solomon 2002). These changes have far-reaching implications for surface climate in the Australian region, both on land and in the marine environment (Syktus 2005; Cai 2006; Cai and Cowan 2007).

Changes in climate arising from the accumulation of greenhouse gases in the atmosphere have resulted in a cooling of the stratosphere. This, in turn, creates meteorological conditions conducive to further destruction of ozone in both the Arctic and Antarctic regions, thus influencing the timing and extent of ozone recovery in different regions. Model simulations suggest that increased concentrations of greenhouse gases may delay the return of global column ozone to pre-1980 values by up to 15 years.

Since the previous reporting period, a number of comprehensive reports documenting ozone depletion and related impacts have been released. The *Scientific Assessment of Ozone Depletion: 2006,* prepared during 2005–06 by the Scientific Assessment Panel of the UN Montreal Protocol on Substances that Deplete the Ozone Layer and released in early 2007, is the most comprehensive assessment of the current state of scientific understanding of the issue (WMO 2007). This report, a substantial update of the 2002 report (WMO 2003), includes two new chapters considering the impact of climate change on ozone depletion. In 2005 the Intergovernmental Panel on Climate Change (IPCC) and the Technology and Economic Assessment Panel (TEAP) released the *IPCC/TEAP Special Report on Safeguarding the Ozone Layer and the Global Climate System: Issues Related to Hydrofluorocarbons and Perfluorocarbons* (IPCC and TEAP 2005) to provide a balanced scientific, technical and policy-relevant report describing the impact of alternatives to ozone depleting substances on the global climate system.

The presence of long-lived atmospheric pollutants such as chlorofluorocarbons and halons means that stratospheric ozone depletion will, for several decades at least, continue to have a negative impact on human health and contribute to other environmental problems related to the existing high levels of ultraviolet radiation in Australia. In 2003, the Commonwealth Government extended its ozone-protection legislation and created a single national system for managing ozone depleting substances and their synthetic replacements that act as greenhouse gases. The Regulations under the *Ozone Protection and Synthetic Greenhouse Gas Management Act 1989* commenced in 2005 and 2006 and Australia is an active member of the international community working on the protection of the ozone layer.

The depletion of stratospheric ozone has important implications for our regional climate, and thereby for human health, agriculture and biodiversity. Continued monitoring and actions to protect the condition of the ozone layer remain important issues.

Pressure and condition

The current status, historical trends and future projections of the ozone layer, ozone depleting substances, UV radiation and their interactions with climate change are described below.

The ozone layer

Ozone gas is produced naturally in the stratosphere by chemical reactions involving oxygen molecules and UV radiation. Ozone production predominantly takes place in the tropics; however, stratospheric winds transport the ozone-rich tropical air toward the poles, resulting in increased concentrations in high latitudes. Ozone production is balanced by natural processes that destroy ozone, and the distribution is controlled by atmospheric air motion. The total amount of ozone in the stratosphere is controlled by different natural and human-induced processes such as solar variability, volcanic aerosols, changes in atmospheric dynamics, and increasing concentrations of chlorine and bromine. Ozone destruction is accelerated by the presence of free radicals, such as hydroxyl (OH), nitric oxide (NO), atomic chlorine (Cl) and atomic bromine (Br). In recent decades stratospheric ozone has been declining, mostly because of significant emissions and subsequent atmospheric accumulation of CFCs and similar chlorinated and brominated organic molecules, which have caused an increase in the concentration of ozone depleting catalysts above the natural background.

Since the late 1970s ozone levels have declined, especially over polar areas and in particular over the Antarctic continent. Data collected in the upper atmosphere have shown that there has been a general thinning of the ozone layer over most of the globe since the 1980s. In addition to this general thinning, more dramatic ozone depletion occurs over Antarctica each spring when the 'ozone hole' forms (Solomon et al. 2005). This damage is due not only to the abundance of ozone depleting substances in the stratosphere but also to the special meteorological conditions over Antarctica which facilitate the destruction of ozone.

More than two decades have passed since the first observation of the large seasonal depletion of stratospheric ozone over Antarctica (Farman et al. 1985). Since then, polar and mid-latitude ozone losses have been well documented, and the dominant role of halogen chemistry in causing the observed depletion has been demonstrated (Newman and Rex 2007). A worldwide network of ozone observation stations has documented continuing ozone reductions over many areas of the globe. In particular, the observation of extensive ozone depletion over the Southern Hemisphere polar area has been the focus of intense public and scientific attention during the past few decades (WMO 2003, 2007).

Analysis of global ozone data for the period 1964–2000 (Fioletov et al. 2002) has shown that globally averaged total ozone started to decrease around 1980. The strongest depletion of ozone occurred from 1980 to 1993, when ozone levels dropped to about 5% below the 1964–80 average value. Global ozone depletion has since stabilised, and the global mean total column ozone values for the period 2002–05 were 3.5% below the 1964–80 average values. These values are similar to 1998–2001 values, thereby indicating that global ozone is no longer decreasing. The mid-latitude atmospheric total column ozone values for the period 2002–05 were approximately 3% and 6% below pre-1980 values in the Northern and Southern Hemispheres, respectively. In contrast, total column ozone over the tropics (25°S–25°N) during the same period did not change significantly (Chipperfield and Fioletov 2007). The behaviour of column ozone in the two hemispheres during the 1990s was different. The Northern Hemisphere ozone level reached a minimum in 1993, then increased. The Southern Hemisphere experienced a continuing decrease through the late 1990s, followed by recent stabilisation. In summary, observations combined with modelling studies indicate that the depletion of ozone in extra-polar (60°S–60°N) regions has stabilised and there has been no further decline in recent years (Newman and Rex 2007). The stabilisation of ozone levels is related to the near-constant level of ozone depleting substances during this period.

The ozone concentration in the mid-latitudes is strongly affected by mixing between mid-latitude air masses and ozone-depleted polar air masses. The contribution of polar ozone depletion to mid-latitude ozone depletion has been significant: the contribution is estimated to be one-half in the Southern Hemisphere and about one-third in the Northern Hemisphere (Newman and Rex 2007).

Ozone data collected from various sites in the Australian region are generally consistent with the global data: (i) ozone depletion increases toward higher latitudes; and (ii) depletion was significant throughout the 1980s and 1990s, but ozone levels have recently stabilised. Data collected by the Bureau of Meteorology (Table 3.2) indicate that there has been 3–7% depletion over the Australian continent; however, levels have now stabilised and there has been a slight increase in ozone in lower latitudes.

Severe ozone depletion was first observed over Antarctica in the early 1980s. Each year much of the stratospheric ozone above Antarctica is destroyed during the period August to October, creating the ozone hole. The extensive depletion of the ozone layer in the upper troposphere and lower stratosphere in this region reached record levels in recent decades. Ozone depletion over the Antarctic continent is very severe and is caused by chlorine and bromine gases in the stratosphere, in a seasonally recurring process that takes place in the unique meteorological conditions associated with the very cold polar vortex. The springtime ozone depletion caused by halogens above Antarctica has been significant throughout the past decade, ozone levels being reduced to between 40% and 55% below pre-1980 levels, with short periods in which 70% of ozone was destroyed (Figure 3.10). At some altitudes ozone destruction is almost total (Solomon et al. 2005, 2007).

In 2006 the size of the hole in the Antarctic ozone layer was the largest on record, reaching an average area of 27.4 million km² (more than three times the size of the Australian continent). The ozone mass deficit averaged

over the entire ozone hole period (from 19 July to 1 December 2006) was the most severe since 1979. During the period 2002–06, however, the average ozone mass deficit was significantly lower than in the 1990s. The extensive depletion that occurred in 2006 was caused by the continuing abundance of ozone destroying substances in the polar atmosphere combined with a very cold stratospheric winter. In contrast, the 2002 ozone mass deficit was one of the lowest since the 1980s, because of polar stratospheric warming. This clearly demonstrates that observed ozone changes are caused by both chemical and dynamic factors.

Arctic ozone loss in any given year depends strongly on the prevailing meteorological conditions. Arctic ozone has been depleted by up to 30% in recent years because of cold atmospheric conditions. However, the losses observed in warm years have been very limited.

During the past few years, variations in the concentration of stratospheric ozone over much of the polar and extra-polar (60°S–60°N) regions have largely been due to variations in meteorological conditions, given that the abundance of ozone depleting gases has been near-constant over this period. In polar regions, springtime

ozone depletion continues to be severe, particularly during cold stratospheric winters over the Antarctic. Ozone abundance in the extra-polar regions has not declined further in recent years.

The 2006 Scientific Assessment of Ozone Depletion (WMO 2007) reported that during the period 1992–2005 chemical ozone loss in the Arctic and Antarctic was controlled by the extent of chlorine activation, which is influenced by polar stratospheric clouds and thus very low temperatures. Column ozone loss over Antarctica was almost complete, whereas loss over the Arctic was much less extensive because stratospheric temperatures over Antarctica are lower than those over the Arctic. Chemical ozone depletion over the Arctic is currently not total, whereas ozone loss over Antarctica at times can be almost complete. Global ozone recovery is expected to follow decreases in the loading of ozone depleting substances in the stratosphere. However, other factors such as the emission of greenhouse gases (carbon dioxide, methane and nitrous oxide) are contributing to the ongoing depletion of ozone (Bodeker and Waugh 2007).

Current projections are that global (60°S–60°N) ozone will return to pre-1980 levels by the middle of the 21st century (Chipperfield and Fioletov 2007). The expected delay in the recovery is primarily the result of revised estimates of the amount of CFCs contained in equipment such as refrigerators, and also the result of higher estimates of the future production of the CFC substitute, HCFC, which, although more ozone-friendly, still destroys ozone and is also a powerful greenhouse gas. The increasing concentration of greenhouse gases in the atmosphere is causing increased absorption of outgoing long-wave radiation in the troposphere, resulting in a warming of the Earth's surface and troposphere, and cooling of the stratosphere. Model simulations suggest that the cooling of the stratosphere could delay ozone recovery (Newman and Rex 2007).

TABLE 3.2 *Total column ozone for the summer period (December to February, in Dobson Units). The relative change in ozone levels is the 1990–99 average relative to the 1964–80 average.*

Location	Ozone amount		
	1964–80	1990–99	2000–04
Darwin (12°S)		251	253
Brisbane (28°S)	282	274	−2.8%	273
Melbourne (38°S)	299	279	−6.7%	279
Macquarie Island (55°S)	314	303	−3.5%	299

Source: Australia State of the Environment 2006 website
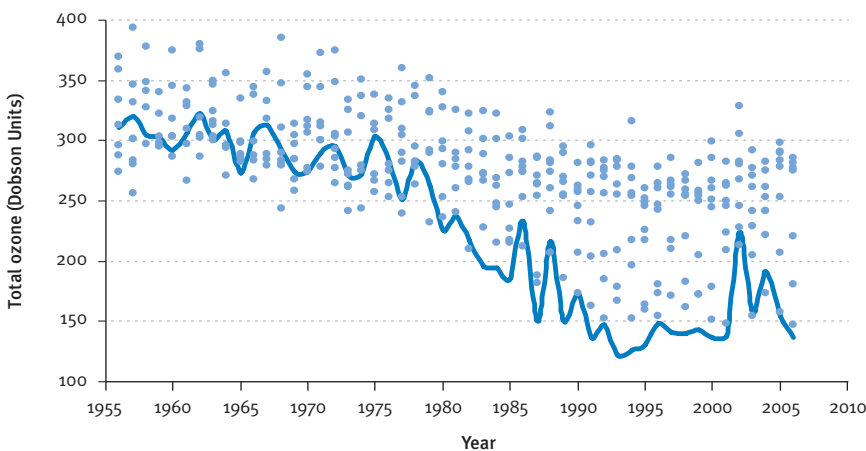
FIGURE 3.10 *Average October ozone levels at the Halley station (in Antarctica) between 1955 and 2006. The thick line represents October values; dots represent the seasonal variation of ozone concentration for the months from August to April*
Source: BAS 2007

Atmosphere

The annual occurrence of the Antarctic ozone hole is projected to continue for decades. Ozone recovery in this region is projected to reach pre-1980 levels around 2060–75 (Newman and Rex 2007), which is some 10–25 years later than previously estimated (WMO 2003). The revised estimate is the result of improved understanding of polar atmospheric motion and how this influences the time evolution of ozone depleting substances in these regions. In addition, the strengthening of the Antarctic vortex in recent years has created meteorological conditions conducive to the formation of very cold air, which is known to accelerate catalytic reactions leading to chemical ozone loss. Although it is estimated that ozone depleting substances have reached peak levels in the Antarctic stratosphere, these substances nonetheless have long lifetimes.

The recent WMO (2007) assessment estimated that polar ozone depletion will remain high, although variable, in the coming decades. Furthermore, the Antarctic ozone hole is not projected to decrease significantly for the next two decades. High ozone loss is also projected to continue in cold Arctic winters over the next 15 years (Newman and Rex 2007).

Monitoring studies have confirmed that the phasing-out of ozone depleting substances has led to a decline in the atmospheric concentration of these chemicals from the peak values reached in 1992–94, first in the troposphere, and now in the stratosphere (Clerbaux and Cunnold 2007). Therefore it is unlikely that total ozone concentration averaged over the region 60°S–60°N will decrease further. The observed decline in the abundance of ozone depleting substances clearly reflects the success of the Montreal Protocol and its Amendments and Adjustments. The history, trends and expected recovery times for stratospheric ozone are summarised in Table 3.3.

Ozone depleting substances

In recent decades, stratospheric ozone concentrations have been depleted by gases containing the halogens chlorine and bromine. Although halogen gases occur naturally, their concentration has increased substantially because of emissions from anthropogenic activities throughout the latter half of the 20th century. Emissions have arisen from equipment containing halogen source gases (throughout the entire life cycle of development, production, use, maintenance, repair and end-of-life disposal), evaporation and leakage from banks, and intentional releases. Halogen source gases are widely used in industrial, agricultural and domestic applications. More than 100 compounds are now classified as 'ozone depleting'; the most common are chlorofluorocarbons, hydrochlorofluorocarbons, halons, methyl bromide and chlorinated solvents (such as methyl chloroform and carbon tetrachloride).

Source gases that contain carbon, chlorine and fluorine are called chlorofluorocarbons (CFCs). CFCs, carbon tetrachloride and methyl chloroform have historically been the most widely used chlorine-containing gases that contribute to ozone depletion. These substances have very long atmospheric lifetimes (50–200 years) and have been widely used in applications such as refrigeration, air conditioning, foam blowing, aerosol propellants and cleaning solvents. (For more details, see IPCC and TEAP 2005; Clerbaux and Cunnold 2007.)

Halons are another category of halogen source gases that contribute to ozone depletion. Halons are halogenated hydrocarbon gases that are used in fire extinguishers, military hardware, and aircraft engines. Methyl bromide

TABLE 3.3 *Summary of stratospheric ozone condition and trends*

Domain	History	Current state and trends	Recovery	Relevant processes
Global	*Circa* 1980 —depletion commenced 1980–93 —period of maximum depletion —total ozone about 5% lower than 1964–80 average	1998–2001 —levels similar to 2002–05 levels 2002–05 —3.5% lower than 1964–80 average Ozone depletion has stabilised, total ozone levels are not expected to decline further	Middle of the 21st century	Full recovery may be complicated by stratospheric cooling caused by increased levels of atmospheric CO_2
Polar Antarctica	1975–95 —rapid decline	Over the past decade: —40–55% lower than pre-1980 levels —short periods of depletion reaching 70% —total depletion at some altitudes —ozone depletion has stabilised	2060–75 No decrease in the areal extent of the ozone hole in the next two decades	Significant depletion occurs during very cold stratospheric winters
Arctic		Over the past decade: —up to 30% depletion during cold winters —limited depletion during warm winters	Episodes of significant loss are expected to occur during cold winters for the next 15 years	
Mid-latitudes	1980s to 1990s —steady decline	2002–05 —3% lower than 1964–80 average (Northern Hemisphere) —6% lower than 1964–80 average (Southern Hemisphere) Ozone depletion has stabilised		Depletion is caused substantially by atmospheric mixing of ozone-depleted air from polar regions
Tropics	1980–2004 —no significant change	Little or no depletion of ozone		Atmospheric motion reduces residence time so source gases undergo little conversion to ozone depleting reactive gases

is a halon that is widely used for agricultural fumigation, quarantine and pre-shipment applications.

CFCs are being phased out under Montreal Protocol regulations and replaced by more 'ozone-friendly' hydrochlorofluorocarbons (HCFCs). HCFCs deplete ozone but have less impact than CFCs because they have shorter atmospheric lifetimes. The production and use of HCFCs have been growing strongly during the past decade. As yet there is not a more ozone-friendly substitute for halons.

In addition to the halogen source gases, stratospheric ozone is influenced by a number of other gases. For example, methane and nitrous oxide react with stratospheric ozone to form water vapour and reactive hydrogen and nitrogen oxides, respectively. Their abundance has increased as a result of human activities, but their overall impact in the stratosphere is much lower than that of halogen gases.

After emission, halogen source gases accumulate in the atmosphere and either are naturally removed from the air or can participate in chemical conversions. The time required to remove or convert source gases varies from one year to hundreds of years for most chlorine and bromine compounds. Gases with short lifetimes such as HCFCs and methyl bromide are, to a large extent, destroyed in the troposphere and therefore only a fraction of emissions contribute to ozone depletion in the stratosphere. The total pool of halogen source gases present in the atmosphere depends on the lifetime of the gas and the amount emitted into the atmosphere. The total emission of source gases over time is a function of annual production and is usually influenced by the amount of accumulated substances stored in 'banks'. Banks represent the quantity of ozone depleting substances contained in existing equipment or stockpiles, which has not yet been released to the atmosphere. A significant contribution of CFC and HCFC emissions has come from banks in recent decades.

The potential for ozone depleting substances to destroy stratospheric ozone is quantified using the Ozone Depletion Potential (ODP) concept, which calculates a substance's potential to destroy ozone over its lifetime on a 'per mass' basis relative to CFC-11, which is defined as having an ODP of one. The combined potential of all ODSs to destroy ozone (Clerbaux and Cunnold 2007) is expressed as 'equivalent effective stratospheric chlorine'.

The understanding of the chemical processes involved in ozone destruction has expanded greatly since the link to CFCs was first proposed in 1974 (Molina and Rowland 1974). In 1973 chemists Rowland and Molina began studying the impacts of CFCs in the Earth's atmosphere. They discovered that CFC molecules were sufficiently stable to remain in the atmosphere until they reached the middle of the stratosphere, where they would (after an average of 50–100 years) be broken down by UV radiation, releasing chlorine atoms. Rowland and Molina proposed that the free chlorine atoms could be expected to cause the destruction of large amounts of ozone. They based their argument on an analogy with the contemporary work of Crutzen, who had shown that nitric oxide (NO) could catalyse the destruction of ozone. In 1995 Crutzen, Molina and Rowland were awarded the Nobel prize for chemistry

for their pioneering work on this problem. After publishing their paper in 1974, Rowland and Molina testified at a hearing before the US House of Representatives, informing the House of the possible impacts of ozone depletion on human health, marine and terrestrial biota and climate (Rowland, pers. comm. 2003). As a result of the hearing, significant funding was made available to study various aspects of the problem and to confirm the initial findings. In 1976 the US National Academy of Sciences released a report that confirmed the scientific credibility of the ozone depletion hypothesis. Since 1981 the United Nations Environment Programme has sponsored a series of scientific assessments of ozone depletion.
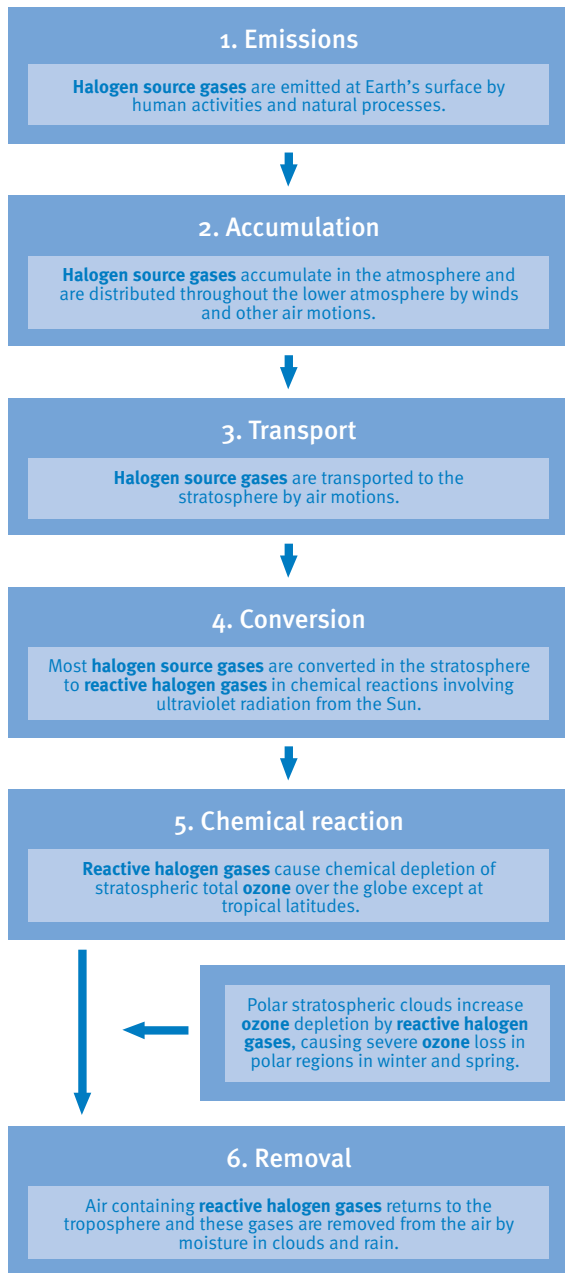
The source gases do not directly deplete ozone. They are generally very stable in the troposphere, where they have long residence times and form reservoirs for chlorine and bromine. The un-reactive source gases enter the stratosphere via atmospheric motion and then undergo conversion to release highly reactive chlorine and bromine atoms, which then participate in further reactions that destroy ozone. The key step is the conversion of halogen source gases in the stratosphere to reactive halogen gases in chemical reactions involving UV radiation. The conversion occurs principally in the stratosphere because of the increased UV intensity. The chemical destruction of ozone may be further accelerated by the presence of polar stratospheric clouds, which (i) provide a surface to assist the chemical breakdown, and (ii) remove nitric acid from the atmosphere, which enables the catalytic cycle of ozone destruction to continue. (Nitric acid can remove the reactive gases which destroy ozone.)

The principal steps in the depletion of stratospheric ozone are illustrated schematically in Figure 3.11.

Motorway at Vulture Street, Brisbane
Photo: Laurence Knight

Atmosphere

Principal steps in the depletion of stratospheric ozone

1. Emissions

Halogen source gases are emitted at Earth's surface by human activities and natural processes.

↓

2. Accumulation

Halogen source gases accumulate in the atmosphere and are distributed throughout the lower atmosphere by winds and other air motions.

↓

3. Transport

Halogen source gases are transported to the stratosphere by air motions.

↓

4. Conversion

Most **halogen source gases** are converted in the stratosphere to **reactive halogen gases** in chemical reactions involving ultraviolet radiation from the Sun.

↓

5. Chemical reaction

Reactive halogen gases cause chemical depletion of stratospheric total **ozone** over the globe except at tropical latitudes.

← Polar stratospheric clouds increase **ozone** depletion by **reactive halogen gases,** causing severe **ozone** loss in polar regions in winter and spring.

6. Removal

Air containing **reactive halogen gases** returns to the troposphere and these gases are removed from the air by moisture in clouds and rain.

FIGURE 3.11 *Principal steps in the depletion of stratospheric ozone. Depletion begins with the emission of halogen source gases from anthropogenic uses and ends when the reactive halogen gases are removed from the atmosphere by rain and snow.*
Source: WMO 2007

As a result of anthropogenic emissions and the subsequent accumulation of ozone depleting substances in the atmosphere, stratospheric ozone levels have been depleted globally, but the most pronounced impact of ozone depleting substances is at high latitudes. The presence of the ozone hole over Antarctica is caused by the atmospheric conditions in that region. First, stratospheric polar air has a relatively long residence time (between four

and seven years), enabling effective conversion of halogen source gases to reactive halogen gases which destroy ozone. Second, the conversion is aided by the presence of polar stratospheric cloud particles made of water, ice, or nitric acid. (The formation of polar stratospheric cloud is facilitated by the presence of very cold air in the winter polar vortex.) Third, when sunlight returns to the polar region in spring, the UV radiation rapidly breaks down the chlorine gas (Cl_2) into two chlorine atoms, releasing the free chlorine into the surrounding environment. The free chlorine can then participate in catalytic reactions that destroy ozone molecules.

The production and depletion of ozone is a complicated chemical process with more than 100 distinct chemical species involved. Each chlorine atom can destroy up to 100 000 ozone molecules before it is removed from the atmosphere. Bromine is involved in a second set of catalytic reactions with chlorine, leading to severe ozone loss. A bromine atom can destroy approximately 60 times more ozone molecules per atom than chlorine. However, the concentration of bromine in the stratosphere is about 160 times lower than that of chlorine. The most reactive gases that cause ozone depletion are the monoxides of both chlorine and bromine. Other reactive gases include hydrogen bromide, bromine nitrate, hydrogen chloride and chloride nitrate. The aforementioned chlorine and bromine compounds act as catalysts in the ozone depletion processes, so they can be recycled and initiate the destruction process many times before they undergo a reaction that breaks the catalytic chain.

The annual cycle of conversion of ozone depleting substances into reactive halogen gases during winter and the strong depletion of ozone via catalytic reactions during spring is terminated by the increasing temperature during late spring and summer. Increasing temperature and subsequent weakening of the polar vortex ends the solar insolation of air masses, allowing mixing of polar air with air from adjacent latitudes. The mixing process dilutes the ozone-destroying forms of chlorine, allowing the ozone layer to recover, at least until the following spring.

The reactive halogen gases do not remain in the stratosphere indefinitely but react with gases such as methane to form hydrogen chloride, which is then circulated into the troposphere and may eventually be washed away by rain. Therefore, if the release of ozone depleting substances into the stratosphere is limited, the ozone layer can be repaired.

The future evolution of the ozone layer depends strongly on the production, use and emissions of ozone depleting substances. The production and use of ozone depleting substances is subject to regulations under the Montreal Protocol, which was first signed in 1987. Since regulation commenced there has been a decrease in the observed combined abundance of synthetic ozone depleting substances in the troposphere from the peak values reached during the period 1992–94. The 2007 WMO Ozone Assessment (Clerbaux and Cunnold 2007) reported that by 2005 the total combined abundance of ozone depleting gases in the troposphere had decreased by 9% from the former peak values. In particular, the contribution from short-lived gases such as methyl bromide, methyl

chloroform and HCFCs has been substantial. Since the 1990s the quantity of CFCs consumed has decreased strongly as a result of regulation and the application of HCFCs as a substitute. However, CFCs, which have very long lifetimes in the atmosphere, still accounted for about 62% of total tropospheric chlorine in 2004. The current global emissions of CFCs are approximately 25% of those during the period of maximum emissions around 1986 and are largely determined by the pattern of historical use. The quantity of HCFCs has, however, increased strongly since the mid-1990s and accounted for 6% of total tropospheric chlorine in 2004, versus 5% of total chlorine in 2000. The decline in total chlorine during the period 2000–04 was slightly faster than projected in the 2002 WMO Ozone Assessment (WMO 2003), which used baseline emission scenarios following the 1999 Beijing Amendments. Total tropospheric bromine from halons and methyl bromide peaked in 1998 and has declined since then, because of decreased use of methyl bromide. Bromide from halons is still continuing to increase, but at a slower rate.

The observed total combined abundance of ozone depleting substances in the stratosphere is also decreasing from the peak values of the late 1990s. The decline is largely consistent with surface observations of ODS emissions and the time lag required for transport from the Earth's surface to the stratosphere. Recent observations show that the total chlorine abundance in the stratosphere has declined from the 1990s peak, while bromine abundance is still increasing and its budget in the stratosphere is less well constrained (Clerbaux and Cunnold 2007; Dorf et al. 2006). The past and expected future abundance of atmospheric halogen gases are illustrated in Figure 3.12.
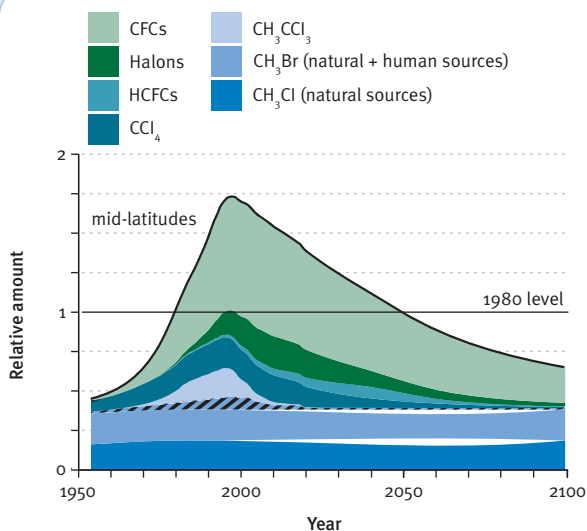
FIGURE 3.12 *Historical and future estimates of the abundance of atmospheric halogen source gases. The strong rise in effective stratospheric chlorine values in the 20th century has reversed in the past decade and is projected to return to pre-1980 values around 2050 in mid-latitudes. The return to pre-1980 values in polar regions is projected to occur around 2065.*
Key: CCl_4 = carbon tetrachloride; CH_3CCl_3 = methyl chloroform; CH_3Br = methyl bromide; CH_3Cl = methyl chloride.
Source: Modified from WMO 2007

In summary, the decrease in ozone depleting substances is the dominant factor in the expected recovery of the ozone layer to pre-1980 levels. The recovery is projected to span much of the 21st century and is expected to take place later than projected by the 2002 WMO assessment. The current best estimate is that, at mid-latitudes, total effective chlorine will return to pre-1980 levels by 2050 and, for the Antarctic, by around 2065. The estimates show that the Montreal Protocol is working well, although failure to comply with its regulations would delay or could even prevent the recovery of the ozone layer.

UV radiation and its impact on human health and the environment

The most serious and practical consequence of the depletion of the ozone layer has been the increased intensity of ultraviolet (UV) radiation reaching the Earth's surface. UV radiation is the portion of the Sun's electromagnetic spectrum having wavelengths longer than X-rays and shorter than visible light. Increased exposure to UV radiation, particularly the UV-B component, has negative impacts on materials, living organisms, and plants in both terrestrial and marine ecosystems. Changes in UV-B radiation at the Earth's surface have been measured directly and have also been estimated from changes in ozone levels. Calculations of UV-B radiation changes using a relationship between total atmospheric column ozone and total irradiation reaching the Earth's surface show a UV radiation increase of 6–14% since the 1980s at various locations distributed over the mid-latitudes to high latitudes of both hemispheres (Bais and Lubin 2007). These results are supported by satellite measurements of UV irradiance, which show significant increases in surface UV-B at latitudes greater than 40° in both hemispheres.

Studies have shown that the average erythemal UV radiation (that which causes the sunburning response in humans) has increased by up to a few per cent per decade between 1979 and 1998. The increased irradiance is due to ozone depletion and is observed over a wide range of latitudes (WMO 2007). More recently, measurements of UV radiation levels (WMO 2007) at several unpolluted locations around the globe show a decrease in UV levels since the late 1990s. The decrease is in accordance with the stabilisation of ozone depletion in mid-latitudes in recent decades. It is difficult, however, to attribute the changes in UV radiation directly to ozone changes, because other factors such as changes in clouds and aerosols play a part. Even if ozone changes were linear, at least 10 to 15 years of measured UV radiation data would be required to detect a trend. Surface ultraviolet radiation measurements did not begin at some locations until the 1990s.

Atmosphere

In Australia UV radiation is monitored at sites in Melbourne, Sydney and Adelaide, but data have been available only since the mid-1990s. Long-term measurements of erythemal UV index are available from Lauder in New Zealand and there is good correlation between available data from Australian stations and longer time-series data from New Zealand. At Lauder the UV index values show an increase of 5% per decade during the period 1978–98 and estimates for the southern part of Australia show a 10–15% increase during the same period. During the period 1998–2004 the UV index decreased by 1% per year in Australia and New Zealand (DEWR 2006), but the decline is larger than expected from calculations based on ozone increases. However, as mentioned earlier, radiation is influenced by a number of other factors, such as large-scale biomass burning which occurred during the 1998 fires in Indonesia.

Modelling experiments have been performed using projected ozone levels for the next few decades (WMO 2007). The results indicate that UV irradiation is currently close to the estimated maximum and is projected to return to pre-1980 levels at mid-latitudes between 2040 and 2070. The return to pre-1980 levels is expected to take longer in the southern high latitudes. Climate change is influencing surface UV radiation through changes in cloud cover, aerosol and air pollution in the atmosphere, and also surface reflectivity. The continuing drought and low levels of cloud cover in eastern Australia are likely to be factors contributing to the relatively high levels of UV radiation currently being experienced.

Considerable progress has been made in recent years in understanding the impact that ozone depletion and increased UV radiation have on various biological, geochemical and physical processes. The observed increase in UV-B radiation has been linked to adverse changes in human health, terrestrial ecosystems, aquatic ecosystems, biogeochemical cycling, air quality and the durability of materials. The recent UNEP report on the environmental effects of ozone depletion (UNEP 2007) has documented many aspects of those impacts.

The adverse impact of increased UV radiation on human health has been the subject of considerable research. However, UV radiation is also known to have had negative impacts on animals and broader ecosystems. For example, aquatic organisms such as frogs, fish and phytoplankton are strongly affected by UV-B radiation, particularly in polar areas. Recent studies have shown that the growth, photosynthesis, protein and pigment content, and reproduction of phytoplankton are adversely affected by increased doses of UV radiation (UNEP 2007). These effects could have wider implications for the global climate through changes in the carbon cycle in the oceans and the oceans' capacity to absorb carbon dioxide. Similarly, the number of frogs, toads and other amphibians has decreased strongly across the world during the past decade. The cause of this decrease appears to be a complex combination of factors. The recent review of literature by Häder et al. (2007) implicates UV radiation as one of the contributing factors.

Agricultural systems have also been adversely affected by increased UV radiation. Increased UV irradiance is known to decrease both crop yield and quality. In a broader terrestrial ecosystem, the effects on plants and aquatic organisms can lead to changes in the competitive balance between species and, consequently, changes in the species composition of the ecosystem (UNEP 2007). Furthermore, the combination of changes in UV-B radiation and changes in carbon dioxide and water availability arising from climate change can result in complex plant responses. For example, in terrestrial ecosystems, cycling of carbon and nutrients can be altered, and in aquatic ecosystems the biological availability and toxicity of metals can be altered, leading to bioaccumulation in the food chain. The changes in community structure and changes in biogeochemical cycling are more important than changes in overall biomass and productivity.

Increased exposure to UV-B radiation is also known to adversely affect materials and structures, causing accelerated degradation of paints, plastic and wood.

Increased exposure to UV radiation, particularly the UV-B component, is known to suppress some functions of the human immune system, which is a contributing factor to the increased incidence of skin cancer, the reduced effectiveness of vaccines and viral reactivation. Skin effects include sunburn (erythema), ageing of the skin and skin cancers such as squamous and basal cell carcinomas and melanoma. Damage to eyes can include cataracts, photokeratitis (sunburn of the eye) and pterygia (corneal lesions) (UNEP 2007). Exposure to increased levels of UV-B radiation can also cause changes in the molecular structure of the DNA in living cells.

Estimates of the future incidence rates of skin cancer have been calculated, based on projected future levels of ozone and UV radiation. The results show that, with the current elevated levels of UV radiation and allowing that skin cancer occurs long after exposure, increased skin cancer rates will continue until the end of the 21st century (WMO 2007). Current modelling predicts that skin cancer rates will continue to rise through to 2060 as a consequence of the ozone depletion that began in the 1980s (Figure 3.13).

Increased levels of UV radiation have a number of significant implications for Australia, because of its geographical location at mid- to low latitudes and the high proportion of days with clear skies and low levels of pollution. Australia, and Queensland in particular, have the highest incidence rate of skin cancer in the world. Factors contributing to Australia's skin cancer rates include the generally light-skinned population, an active outdoor lifestyle, relatively clear skies and increased levels of UV radiation. Each year more than 380 000 people in Australia are diagnosed with non-melanoma types of skin cancer, which are the most common forms of skin cancer and are strongly related to exposure to UV radiation. However, non-melanoma forms of skin cancer are less life-threatening than melanoma types, which are the most aggressive form of skin cancer.

Australia has a higher incidence rate of melanomas than any other country, primarily a result of people with fair skin being exposed to very high levels of UV radiation. The melanoma incidence rates are four times higher in Australia than in Northern Hemisphere countries such as Canada, the UK and the USA. In 1997 the incidence rate was 50.5 cases per 100 000 in men and 39.9 cases per
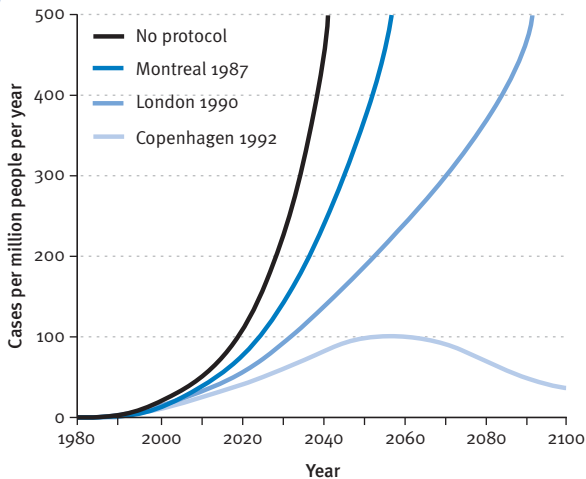
FIGURE 3.13 *Estimate of skin cancer incidence rates due to the effect of ozone depleting substances. The figure illustrates the effect the Montreal Protocol and subsequent Amendments may have in restoring incidence rates to pre-1980 rates (see Figure 3.14 for comparison with effective chlorine abundance in the stratosphere).*
Source: Modified from WMO 2007

100 000 in women. Queensland, the state with the highest incidence rate of melanoma in Australia, had rates almost 30% higher. Melanoma mortality rates for Australia in 1997 were 6.3 per 100 000 for men and 3.5 per 100 000 for women. In 2001, 8885 people were diagnosed with melanoma and 1074 people died.

The projections of new melanoma cases show an increase of 23–28% between 2002 and 2011 (AIHW 2005). The lifetime risk of developing a melanoma before the age of 75 in the Australian population is 1 in 34 for females and 1 in 25 for males (AIHW 2004). Recent analysis has shown that during the period 1982–2002 the incidence of melanoma increased by 10.4% per year among males and 8.4% per year among females (Coory et al. 2006). The study indicated that the overall incidence rates of melanoma are unlikely to decrease for at least another 20 years. However, the study also noted that primary prevention programs have led to a decline in skin cancer rates among young people and melanoma mortality has stabilised. This shows that younger Australians are now protecting themselves better from UV radiation than in the past, while in the older population the detection and treatment of melanomas are taking place earlier than they did in the past.

The 'UV index' is a measure of daily surface UV levels that is used widely in Australia to provide public information about the risk of health damage from increased exposure to UV radiation. The Bureau of Meteorology, Cancer Council Australia and the Australian Radiation Protection and Nuclear Safety Agency have adopted the UV Alert system, which is based on the World Health Organization's Global Solar UV Index. Since 1997 the Bureau of Meteorology has issued a daily UV index forecast on its website (BoM 2007) to help people avoid overexposure to high levels of UV radiation. Educational campaigns designed to raise public awareness of the dangers of overexposure to UV radiation have been mounted throughout Australia for over 20 years.

Interaction between climate change and ozone depletion

The interconnection between stratospheric ozone depletion and climate change has emerged during the past decade as an important new development. It has been established that climate change has affected the evolution and recovery of the ozone layer through changes in atmospheric motion, chemical composition and temperature. The changes to the ozone layer are known to have affected the climate through radiative processes, which in turn affect atmospheric dynamics. It is clear, therefore, that climate change and ozone depletion are not independent scientific and societal issues, but in fact are strongly coupled. There is a further connection between ozone depletion and global climate change: many of the synthetic ozone depleting substances are also very potent greenhouse gases contributing to global warming.

Stratospheric ozone is influenced by changes in temperature and winds in the stratosphere. Satellite and radiosonde monitoring show that the global mean lower stratospheric temperature has cooled by approximately 0.5°C per decade over the period 1979–2004; however, the cooling observed over the past two decades has slowed in recent years (Baldwin and Dameris 2007). Model calculations show that ozone depletion was the main cause of the cooling over this period. Lower stratospheric cooling is evident at all latitudes: the strongest changes are observed in both the Arctic and Antarctic during winter and spring, but those regions experience considerable inter-annual variability. Satellite

observations show a larger cooling trend in the upper stratosphere, with cooling values of 1–2°C per decade. There has been little further decline in upper stratospheric temperatures since the mid-1990s (Baldwin and Dameris 2007). Model calculations show that both ozone depletion and the increase in well-mixed greenhouse gases have contributed to the observed changes. There has been large variability in Antarctic temperatures in recent years, but the long-term cooling rate of the Antarctic stratosphere has reduced. The cooling of the stratosphere has resulted in meteorological conditions that are conducive to the formation of polar stratospheric clouds, which assist in the destruction of ozone in both the Arctic and Antarctic regions, thus influencing the timing and extent of ozone recovery in different regions. Model simulations suggest that increased concentrations of greenhouse gases may complicate the return of global column ozone to pre-1980 values, because the enhanced greenhouse effect results in a cooling of the stratosphere. Cooling in the upper stratosphere slows the photochemical reactions which destroy ozone. Cooling in the lower stratosphere leads to increased ozone destruction due to enhanced chlorine activation on polar stratospheric clouds.

The depletion of stratospheric ozone caused by the release of synthetic ozone depleting substances has resulted in changes in the global atmospheric circulation. Antarctic ozone depletion and the interaction of increasing concentrations of greenhouse gases have strengthened the Antarctic polar vortex in recent decades, resulting in significant changes in the atmospheric circulation pattern of the Southern Hemisphere (Thompson and Solomon 2002). These changes have far-reaching implications for surface climate in the Australian region, both on land and in the marine environment. Antarctic ozone depletion has caused an intensification of the Southern Ocean super-gyre circulation. These changes resulted from strengthening of the circumpolar westerly wind and a weakening of the mid-latitude westerly extending from the stratosphere to the Earth's surface.

The intensification of the gyre circulation in the Southern Ocean resulted in increased advection of warm water southward, including strengthening of the East Australian Current (Cai 2006). The southward shift may have resulted in the large observed warming in the Southern Hemisphere mid-latitude ocean water and has caused a southward shift in many marine species in the South West Pacific region. A recent study (Le Quéré et al. 2007) has shown that the ability of the Southern Ocean to absorb carbon dioxide from the atmosphere has decreased in recent decades. This change has been caused by the observed increase in Southern Ocean winds resulting from the depletion of stratospheric ozone, and also the changes in sea surface temperature gradients resulting from global warming (Cai and Cowan 2007). The climate changes caused by stratospheric ozone depletion are known to have contributed to large-scale changes in Southern Hemisphere circulation patterns which have contributed to the persistence of dry conditions in eastern Australia during the past decade (Syktus 2005).

Response
International response

The Montreal Protocol on Substances that Deplete the Ozone Layer is an international agreement that aims to regulate the production and consumption of halogen source gases that destroy the ozone layer. The Protocol was signed in 1987 and became legally binding in 1989. Since then it has been subject to a number of Amendments and Adjustments: London (1990), Copenhagen (1992), Vienna (1995), Montreal (1997) and Beijing (1999). The successive revisions expanded the list of regulated substances, accelerated control measures and set timelines for phasing out the use and production of some of the regulated substances. Currently 191 countries are signatories to the Protocol. The schedule for phasing out controlled substances is summarised in Table 3.4. For a detailed description of Protocol obligations, including exemptions, see UNEP 2006.

Chlorofluorocarbons (CFCs) have largely been replaced by hydrochlorofluorocarbons (HCFCs). While HCFCs are ozone depleting substances, their impact is much lower than that of CFCs and they were introduced as a transitional substance. HCFCs are scheduled to be phased out by 2020 and will be replaced by the second generation of CFC substitutes: hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs). HFCs and PFCs are not ozone depleting substances, but most are powerful greenhouse gases and are controlled substances under the 1997 Kyoto Protocol.

TABLE 3.4 *Summary of measures aimed at reducing the atmospheric abundance of ozone depleting substances under the Montreal Protocol*

| Substance	Developed countries	Developing countries
Chlorofluorocarbons	Phased out end of 1995	Phased out 2010
Halons	Phased out end of 1993	Phased out 2010
Carbon tetrachloride	Phased out end of 1995	Phased out 2010
Methyl chloroform	Phased out end of 1995	Phased out 2015
Hydrochlorofluorocarbons	Frozen in 1996 Phased out 2020	Frozen in 2016 Phased out 2040
Methyl bromide	Frozen in 1995 Phased out 2005	Frozen in 2002 Phased out 2015
Bromochloromethane	Phased out 2002	Phased out 2002

Source: DEWR 2007

The Montreal Protocol has successfully halted the increasing abundance of most ozone depleting substances in the atmosphere:

- at the end of 2005 there had been a 95% aggregate reduction in the production and consumption of all controlled substances;
- developing countries had reduced production of ozone depleting substances by 70% at the end of 2005;
- by 2005, the total combined abundance of anthropogenic ozone depleting gases in the troposphere had decreased by 9% from the peak value observed in the period 1992–94;
- both developed and developing countries have met phase-out targets ahead of schedule;
- the reduction in the abundance of ozone depleting substances in the atmosphere has assisted in combating global warming. Most ozone depleting substances are potent greenhouse gases, and the reductions achieved between 1990 and 2000 are equivalent to the removal of 25 billion tonnes of CO_2; and
- controls implemented under the Protocol have enabled the global community to avoid millions of cases of fatal skin cancer and tens of millions of cases of non-fatal skin cancer and cataracts.

Figure 3.14 shows the effect that the Protocol and its various Amendments have had and are expected to have in reducing effective stratospheric chlorine throughout the coming decades.
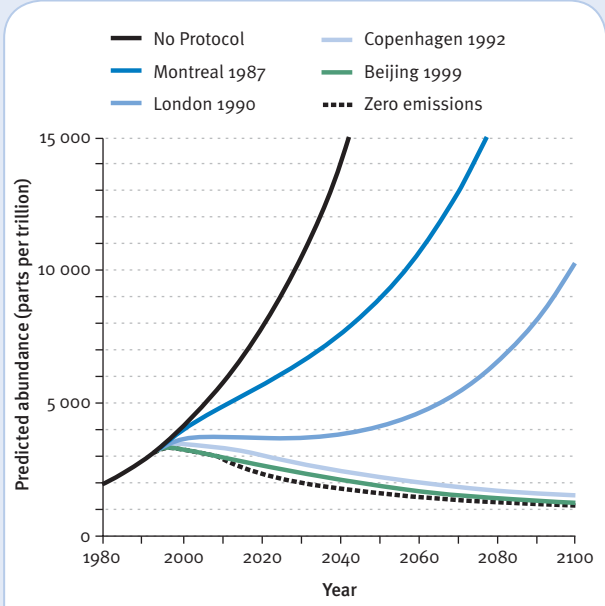
FIGURE 3.14 *Effect of the Montreal Protocol on the abundance of effective stratospheric chlorine (combined effects of chlorine and bromine). The reduction is a result of restrictions on the production and consumption of synthetic ozone depleting substances. The projections of the future abundance of effective stratospheric chlorine are shown for the following scenarios: no Protocol regulations; regulations under the original 1987 Montreal Protocol; and additional regulations from ongoing Amendments and Adjustments. The 'zero emissions' line shows stratospheric abundance for the case where all emissions are reduced to zero in 2003. Source: Modified from WMO 2007*

National response

Australia is a signatory to the Montreal Protocol and all of its subsequent Amendments. Australia is actively engaged in supporting international efforts to support and promote the aims of the Protocol through a number of activities:

- membership of various panels, including the Implementation Committee and Scientific Assessment Panel;
- contributions to the Multilateral Fund for the Implementation of the Montreal Protocol, to assist developing nations in meeting their obligations under the Protocol; and
- participation in bilateral projects to transfer skills and technology to developing nations.

In Australia the *Ozone Protection and Synthetic Greenhouse Gas Management Act 1989* (Cwlth) controls the manufacturing, importation and export of all ozone depleting substances and their synthetic greenhouse gas replacements. Regulations developed under the Act (as amended in 2003) are replacing state and territory ozone protection legislation.

Australia has implemented a range of actions to fulfil its obligations under the Montreal Protocol. It has:

- enacted legislation to control the production and use of controlled substances and their substitutes;
- established the National Halon Bank to store waste halon;
- developed a national licensing system to strictly control the import, export and manufacture of controlled substances; and
- met or exceeded all obligations for the phasing-out of controlled substances.

As a result of global and national commitments to the Montreal Protocol, the abundance of ozone depleting substances has decreased, and Australia has assisted significantly in this effort. While Australia accounts for only about 1% of global emissions, the national contribution to the protection of the ozone layer has been substantial through its international efforts in promoting Protocol activities and supporting developing nations.

Despite the progress made since inception of the Protocol, the ozone layer remains fragile and is still under threat.

References

AIHW 2004, *Cancer in Australia 2001*, Cancer series no. 28, AIHW cat. no. CAN 23, Australian Institute of Health and Welfare, Canberra.

AIHW 2005, *Health system expenditures on cancer and other neoplasms in Austral 2000–01*, Health and welfare expenditure series no. 22, AIHW cat. no. HWE 29, Australian Institute of Health and Welfare, Canberra.

Bais, A.F. and Lubin, D. 2007, *Surface ultraviolet radiation: past, present and future*, Chapter 7 in *Scientific Assessment of Ozone Depletion: 2006,* Global Ozone Research and Monitoring Project—Report No. 50, Geneva.

Baldwin, M. and Dameris, M. 2007, *Climate ozone connections*, Chapter 5 in *Scientific Assessment of Ozone Depletion: 2006,* Global Ozone Research and Monitoring Project—Report No. 50, Geneva.

BAS 2007, *British Antarctic Survey*, Natural Environment Research Council, viewed 30 May 2007, ‹www.antarctica.ac.uk›.

Bodeker, G.E. and Waugh, D.W. 2007, *The ozone layer in the 21st century*, Chapter 6 in *Scientific Assessment of Ozone Depletion: 2006,* Global Ozone Research and Monitoring Project—Report No. 50, Geneva.

BoM 2007, *About forecasts for sun safety*, Bureau of Meteorology, Commonwealth of Australia, viewed 4 June 2007, ‹www.bom.gov.au/info/about_uv.shtml›.

Cai, W. 2006, 'Antarctic ozone depletion causes an intensification of the Southern Ocean super-gyre circulation', *Geophysical Research Letters* 33(3), Article No. L03712.

Cai, W. and Cowan, T. 2007, 'Trends in Southern Hemisphere circulation in IPCC AR4 models over 1950–99: Ozone depletion versus greenhouse forcing', *Journal of Climate* 20(4): 681–693.

Chipperfield, M.P. and Fioletov, V.E. 2007, *Global ozone: past and present*, Chapter 3 in *Scientific Assessment of Ozone Depletion: 2006,* Global Ozone Research and Monitoring Project—Report No. 50, Geneva.

Clerbaux, C. and Cunnold, D.M. 2007, *Long-lived compounds*, Chapter 1 in Scientific Assessment of Ozone Depletion: 2006, Global Ozone Research and Monitoring Project—Report No. 50, Geneva.

Coory, M., Baade, P., Aitken, J., Smithers, M., Roderick, G., McLeod, C. and Ring, I. 2006, 'Trends for in situ and invasive melanoma in Queensland, Australia, 1982–2002', *Cancer Causes and Control* 17(1): 21–27.

DEWR 2006, *State of the Environment 2006: Dobson Ozone Summer Mean Data — Brisbane*, Department of the Environment and Water Resources, Canberra, viewed 30 May 2007, ‹www.environment.gov.au/soe/2006/publications/drs/pubs/278/atm/a_11_ozone_summer_mean_dl.xls›.

DEWR 2007, *Montreal Protocol on substances that deplete the ozone layer*, Department of the Environment and Water Resources, Canberra, viewed 1 June 2007, ‹www.environment.gov.au/atmosphere/ozone/legislation/montp.html›.

Dorf, M., Butler, J.H., Butz, A., Camy-Peyret, C., Chipperfield, M.P., Kritten, L., Montzka, S.A., Simmes, B., Weidner, F. and Pfeilsticker, K. 2006, 'Long-term observations of stratospheric bromine reveal slow down in growth', *Geophysical Research Letters* 33(10), Article No. L10812.

Farman, J.C., Gardiner, B.G. and Shanklin, J.D. 1985, 'Large losses of total ozone in Antarctica reveal seasonal ClO_x/NO_x interaction', *Nature* 315(6016): 207–210.

Fioletov, V.E., Bodeker, G.E., Miller, A.J., McPeters, R.D. and Stolarski, R. 2002, 'Global and zonal total ozone variations estimated from ground-based and satellite measurements: 1964–2000', *Journal of Geophysical Research D: Atmospheres* 107(22), Article No. 4647.

Häder, D.P., Kumar, H.D., Smith, R.C. and Worrest, R.C. 2007, 'Effects of solar UV radiation on aquatic ecosystems and interactions with climate change', *Photochemical and Photobiological Sciences* 6: 267–285.

IPCC and TEAP 2005, *IPCC/TEAP Special Report on Safeguarding the Ozone Layer and the Global Climate System: Issues Related to Hydrofluorocarbons and Perfluorocarbons*, B. Metz, L. Kuijpers, S. Solomon, S.O. Andersen, O. Davidson, J. Pons, D. de Jager, T. Kestin, M. Manning, and L. Meyer (eds), Intergovernmental Panel on Climate Change and Technology and Economic Assessment Panel, Cambridge University Press, New York.

Le Quéré, C., Rödenbeck, C., Buitenhuis, E.T., Conway, T.J., Langenfelds, R., Gomez, A., Labuschagne, C., Ramonet, M., Nakazawa, T., Metzl, N., Gillett, N. and Heimann, M. 2007, 'Saturation of the southern ocean CO_2 sink due to recent climate change', *Science,* May 2007.

Molina, M.J. and Rowland, F.S. 1974, 'Stratospheric sink for chlorofluoromethanes: Chlorine atom-catalysed destruction of ozone', *Nature* 249: 810–812.

Newman, P.A. and Rex, M. 2007, *Polar ozone: past and present*, Chapter 4 in Scientific Assessment of Ozone Depletion: 2006, Global Ozone Research and Monitoring Project—Report No. 50, Geneva.

Solomon, S., Portmann, R.W. and Thompson, D.W.J. 2007, 'Contrasts between Antarctic and Arctic ozone depletion', *Proceedings of the National Academy of Sciences of the United States of America* 104(2): 445–449.

Solomon, S., Portmann, R.W., Sasaki, S., Hofmann, D.J. and Thompson, D.W.J. 2005, 'Four decades of ozonesonde measurements over Antarctica', *Journal of Geophysical Research D* 110(21): D21311.

Syktus, J. 2005, 'Reasons for decline in eastern Australia's rainfall', *Bulletin of the American Meteorological Society* 86(5): 624.

Thompson, D.W.J. and Solomon, S. 2002, 'Interpretation of recent Southern Hemisphere climate change', *Science* 296(5569): 895–899.

UNEP 2006, *Handbook for the Montreal Protocol on Substances that Deplete the Ozone Layer, 7th edition*, Secretariat of The Vienna Convention for the Protection of the Ozone Layer and The Montreal Protocol on Substances that Deplete the Ozone Layer, United Nations Environment Programme, Nairobi.

UNEP 2007, 'Environmental effects of ozone depletion and its interactions with climate change: 2006 assessment', United Nations Environment Programme, *Photochemical and Photobiological Sciences* 6(3): 201–332.

WMO 2003, *Scientific Assessment of Ozone Depletion: 2002,* Global Ozone Research and Monitoring Project—Report No. 47, World Meteorological Organization, Geneva.

WMO 2007, *Scientific Assessment of Ozone Depletion: 2006,* Global Ozone Research and Monitoring Project—Report No. 50, World Meteorological Organization, Geneva.

Atmosphere

Stratospheric ozone depletion