EXECUTIVE SUMMARY

WMO/UNEP
"Scientific Assessment of Ozone Depletion: 2010"

PREPARED BY THE
SCIENTIFIC ASSESSMENT PANEL
OF THE
MONTREAL PROTOCOL ON SUBSTANCES
THAT DEPLETE THE OZONE LAYER

****

Contents

****

Executive Summary
Scientific Assessment of Ozone Depletion: 2010

OVERVIEW

It has been recognized since the 1970s that a number of compounds emitted by human activities deplete stratospheric ozone. The Montreal Protocol on Substances that Deplete the Ozone Layer was adopted in 1987 to protect global ozone and, consequently, protect life from increased ultraviolet (UV) radiation at Earth's surface. Chlorine- and bromine-containing substances that are controlled by the Montreal Protocol are known as ozone-depleting substances (ODSs). ODSs are responsible for the depletion of stratospheric ozone observed in polar regions (for example, the "ozone hole" above Antarctica) and in middle latitudes. The severe depletion of stratospheric ozone observed in the Antarctic has increased UV at the surface and affected climate at southern high latitudes.

The Montreal Protocol and its Amendments and Adjustments have successfully controlled the global production and consumption of ODSs over the last two decades, and the atmospheric abundances of nearly all major ODSs that were initially controlled are declining. Nevertheless, ozone depletion will continue for many more decades because several key ODSs last a long time in the atmosphere after emissions end.

In contrast to the diminishing role of ODSs, changes in climate are expected to have an increasing influence on stratospheric ozone abundances in the coming decades. These changes derive principally from the emissions of long-lived greenhouse gases, mainly carbon dioxide (CO_2), associated with human activities. An important remaining scientific challenge is to project future ozone abundances based on an understanding of the complex linkages between ozone and climate change.

Most ODSs are potent greenhouse gases. The buildup of ODS abundances over the last decades contributes to global warming. The actions taken under the Montreal Protocol have reduced the substantial contributions these gases would have made to global warming.

There is now new and stronger evidence of the effect of stratospheric ozone changes on Earth's surface climate, and of the effects of climate change on stratospheric ozone. These results are an important part of the new assessment of the depletion of the ozone layer presented here.

CHANGES IN GASES THAT AFFECT STRATOSPHERIC OZONE AND CLIMATE

Changes in the global atmospheric abundance of a substance are determined by the balance between its emissions and removals from the atmosphere. Declines observed for ozone-depleting substances controlled under the Montreal Protocol are due to global emission reductions that have made emissions smaller than removals. Most ODSs are potent greenhouse gases. As the majority of ODSs have been phased out, demand for hydrochlorofluorocarbon

(HCFC) and hydrofluorocarbon (HFC) substitutes for the substances controlled under the Montreal Protocol has increased; these are also greenhouse gases. HCFCs deplete much less ozone per kilogram emitted than chlorofluorocarbons (CFCs), while HFCs are essentially non-ozone depleting gases.

Ozone-Depleting Substances and Substitutes: Tropospheric Abundances and Emissions

- **The amended and adjusted Montreal Protocol continues to be successful at reducing emissions (Figure ES-1) and thereby abundances of most controlled ozone-depleting substances in the lower atmosphere (troposphere), as well as abundances of total chlorine and total bromine from these ozone-depleting substances.** By 2008, the total tropospheric abundance of chlorine from ODSs and methyl chloride had declined to 3.4 parts per billion (ppb) from its peak of 3.7 ppb. However, the rate of decline in total tropospheric chlorine by 2008 was only two-thirds as fast as was expected. This is because HCFC abundances increased more rapidly than expected, while CFCs decreased more slowly than expected. The discrepancy in CFC decreases is most likely because of emissions from "banks" in existing applications such as refrigerators, air conditioners, and foams. The rapid HCFC increases are coincident with increased production in developing countries, particularly in East Asia. The rate of decline of total tropospheric bromine from controlled ODSs was close to that expected and was driven by changes in methyl bromide.

- **Declines in CFCs made the largest contribution to the observed decrease in total tropospheric chlorine during the past few years and are expected to continue to do so through the rest of this century.** Observations show that CFC-12 tropospheric abundances have decreased for the first time. The decline of methyl chloroform (CH_3CCl_3) abundances made a smaller contribution to the decrease in total chlorine than described in past Assessments, because this short-lived substance has already been largely removed from the atmosphere.

- **Carbon tetrachloride (CCl_4) tropospheric abundances have declined less rapidly than expected.** Emissions derived from data reported to the United Nations Environment Programme (UNEP) are highly variable and on average appear smaller than those inferred from observed abundance trends. Although the size of this discrepancy is sensitive to uncertainties in our knowledge of how long CCl_4 persists in the atmosphere (its "lifetime"), the variability cannot be explained by lifetime uncertainties. Errors in reporting, errors in the analysis of reported data, and/or unknown sources are likely responsible for the year-to-year discrepancies.

- **Observations near the tropical tropopause suggest that several very short-lived industrial chlorinated chemicals, not presently controlled under the Montreal Protocol (e.g., methylene chloride, CH_2Cl_2; chloroform, $CHCl_3$; 1,2 dichloroethane, CH_2ClCH_2Cl; perchloroethylene, C_2Cl_4), reach the stratosphere.** However, their contribution to stratospheric chlorine loading is not well quantified.

- **Bromine from halons stopped increasing in the troposphere during 2005–2008.** As expected, abundances of halon-1211 decreased for the first time during 2005–2008, while halon-1301 continued to increase but at a slower rate than in the previous Assessment.

- **Tropospheric methyl bromide abundances continued to decline during 2005–2008, as expected due to reductions in industrial production, consumption, and emission.** About half of the remaining methyl bromide consumption was for uses not controlled by the Montreal Protocol (quarantine and pre-shipment applications).

- **Tropospheric abundances and emissions of some HCFCs are increasing faster now than four years ago.** Abundances of HCFC-22, the most abundant HCFC, increased more than 50% faster in 2007–2008 than in 2003–2004, while HCFC-142b abundances increased about twice as fast as in 2003–2004. HCFC-141b abundances increased at a similar rate to that observed in 2003–2004. Total emissions of HCFCs are projected to begin to decline during the coming decade due to measures already agreed to under the Montreal Protocol (Figure ES-1).

- **Tropospheric abundances and emissions of HFCs, used mainly as substitutes for CFCs and HCFCs, continue to increase.** For example, abundances of HFC-134a, the most abundant HFC, have been increasing by about 10% per year in recent years. Abundances of other HFCs, including HFC-125, -143a, -32, and -152a, have also been increasing. Regional studies suggest significant HFC emissions from Europe, Asia, and North America.

CFCs, HCFCs, HFCs, and Climate Change

- **The Montreal Protocol and its Amendments and Adjustments have made large contributions toward reducing global greenhouse gas emissions (Figure ES-1).** In 2010, the decrease of annual ODS emissions under the Montreal Protocol is estimated to be about 10 Gigatonnes of avoided CO_2-equivalent[1] emissions per year, which is about five times larger than the annual emissions reduction target for the first commitment period (2008–2012) of the Kyoto Protocol.

- **The sum of the HFCs currently used as ODS replacements contributes about 0.4 Gigatonnes of CO_2-equivalent per year to total global CO_2-equivalent emissions, while the HCFCs contribute about 0.7 Gigatonnes.** CO_2-equivalent emissions of HFCs are increasing by about 8% per year and this rate is expected to continue to grow, while the contribution from HCFCs is expected to start decreasing in the next decade.

- **Emissions of HFC-23, a byproduct of HCFC-22 production, contributed about 0.2 Gigatonnes of CO_2-equivalent per year in 2006–2008.** HFC-23 is a particularly potent greenhouse gas with a lifetime of about 220 years. Its emissions have increased in the past decade despite global emissions reduction measures, including those covered by the Kyoto Protocol's Clean Development Mechanism projects.

Total Chlorine and Bromine and Implications for Ozone Depletion

- **Total chlorine has continued to decline from its 1990s peak values in both the troposphere and the stratosphere. Total tropospheric bromine is decreasing from**

---

[1] GWP-weighted emissions, also known as CO_2-equivalent emissions, are defined as the amount of gas emitted multiplied by its 100-year Global Warming Potential (GWP).

its peak values, which occurred comparatively recently, while stratospheric bromine is no longer increasing.

- **Relative declines in the sum of stratospheric chlorine and bromine from peak values are largest in midlatitudes and smallest in Antarctica** (refer to Figure ESA-1 in the Appendix of this Executive Summary). These declines are not as pronounced as observed in their tropospheric abundances. Differences between declines in the troposphere and different regions of the stratosphere are primarily associated with the time required for air to move from the troposphere to those regions. The relative declines are smallest in Antarctica primarily because the transport times to polar regions are the largest.
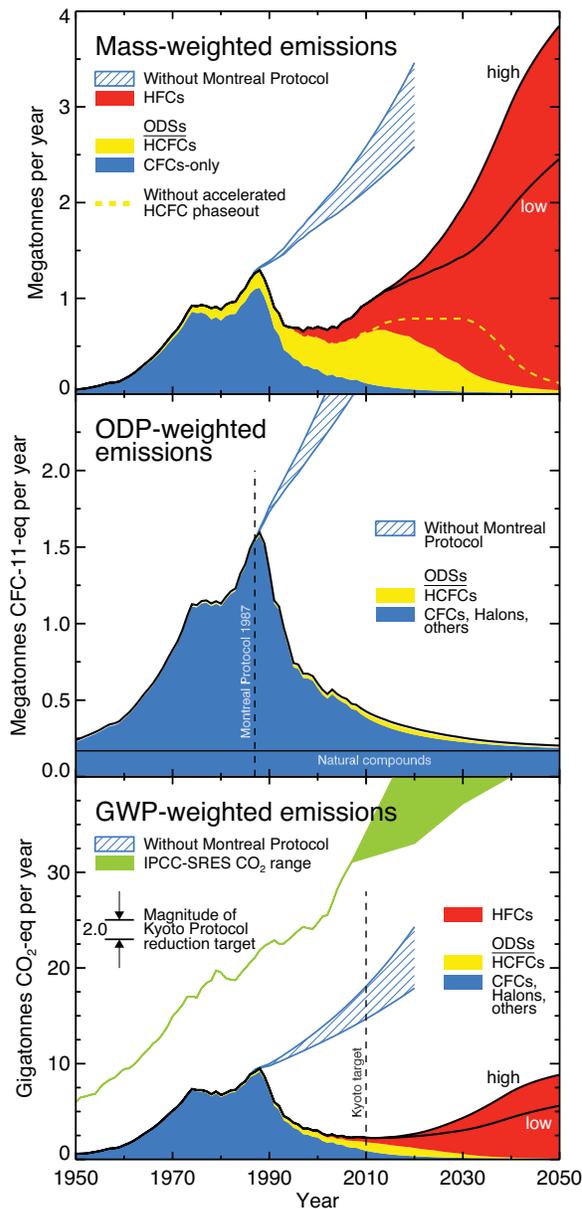
Mass-weighted emissions

Without Montreal Protocol
HFCs
ODSs
HCFCs
CFCs-only
Without accelerated HCFC phaseout

high
low

Megatonnes per year

ODP-weighted emissions

Without Montreal Protocol
ODSs
HCFCs
CFCs, Halons, others

Montreal Protocol 1987

Natural compounds

Megatonnes CFC-11-eq per year

GWP-weighted emissions

Without Montreal Protocol
IPCC-SRES CO_2 range

Magnitude of Kyoto Protocol reduction target
2.0

HFCs
ODSs
HCFCs
CFCs, Halons, others

Kyoto target

high
low

Gigatonnes CO_2-eq per year

1950   1970   1990   2010   2030   2050
Year

Figure ES-1. Emissions of ODSs and their substitutes. Global emissions of ODSs (CFCs, halons, HCFCs, and others) and their non-ozone depleting substitutes (HFCs) from 1950 to 2050. Emissions are the total from developing and developed countries. The legends identify the specific groups of substances included in each panel. The high and low HFC labels identify the upper and lower limits, respectively, in global baseline scenarios. The blue hatched regions indicate the emissions that would have occurred, in the absence of the Montreal Protocol, with 2–3% annual production increases in all ODSs.

Top panel: Global mass-weighted emissions expressed as Megatonnes per year. The yellow dashed line shows HCFC emissions calculated without the provisions of the 2007 accelerated HCFC phaseout under the Montreal Protocol.

Middle panel: Global Ozone Depletion Potential–weighted emissions expressed as Megatonnes of CFC-11-equivalent per year. The emissions of individual gases are multiplied by their respective ODPs (CFC-11 = 1) to obtain aggregate, equivalent CFC-11 emissions. The dashed line marks 1987, the year of the Montreal Protocol signing.
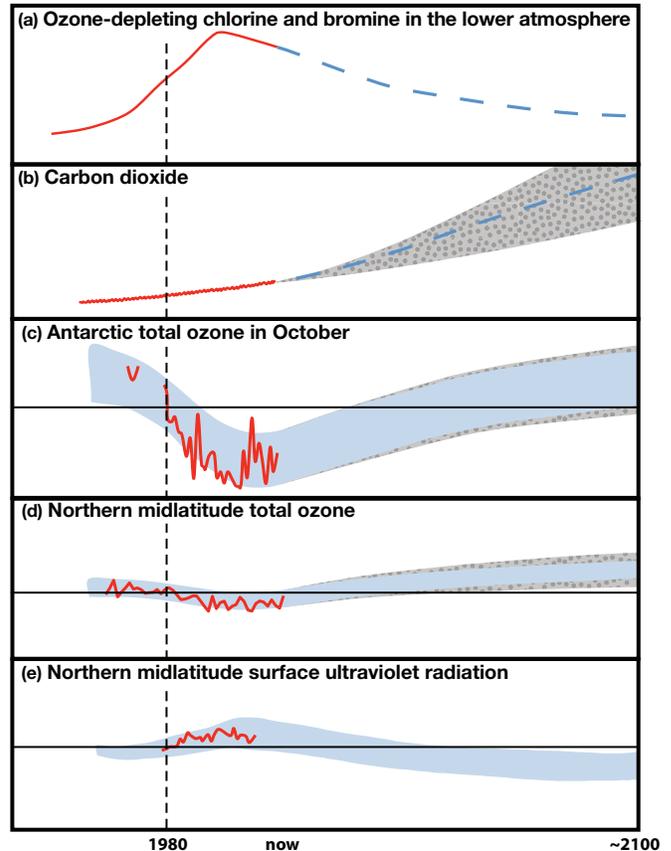
Bottom panel: Global GWP-weighted emissions expressed as Gigatonnes of CO_2-equivalent per year. The emissions of individual gases are multiplied by their respective GWPs (direct, 100-year time horizon; CO_2 = 1) to obtain aggregate, equivalent CO_2 emissions. Shown for reference are emissions for the range of CO_2 scenarios from the Intergovernmental Panel on Climate Change (IPCC) *Special Report on Emission Scenarios* (SRES). The CO_2 emissions for 1950–2007 are from global fossil fuel use and cement production. Beyond 2007, the shaded region for CO_2 reflects the maximum (A1B) and minimum (B2) SRES scenarios. The dashed line marks 2010, the middle year of the first commitment period of the Kyoto Protocol. Also shown is the magnitude of the reduction target of the first commitment period of the Kyoto Protocol, which is based on a 1990–2010 projection of global greenhouse gas emission increases and the reduction target for participating countries.

4

OZONE AND CLIMATE: ANTARCTIC

The Antarctic ozone hole is the clearest manifestation of the effect of ODSs on the ozone layer. The depletion far exceeds natural variability and has occurred without exception since 1980. The ozone hole also provides the most visible example of how ozone depletion affects surface climate.

- **Springtime Antarctic total column ozone losses (the ozone hole), first recognizable around 1980, continue to occur every year (Figure ES-2c).** Although the ozone losses exhibit year-to-year variations that are primarily driven by year-to-year changes in meteorology, October mean column ozone within the vortex has been about 40% below 1980 values for the past fifteen years. The average erythemal ("sunburning") UV measured at the South Pole between 1991 and 2006 was 55–85% larger than the estimated values for the years 1963–1980.

- **Doubts raised since the previous Assessment regarding our understanding of the cause of the Antarctic ozone hole have been dispelled.** New laboratory measurements on the key chemistry involved in polar ozone depletion have reaffirmed that past changes in ODSs are indeed the cause of the ozone hole. This is also supported by quantification of the chemicals responsible for the ozone hole via field observations.

- **There is increased evidence that the Antarctic ozone hole has affected the surface climate in the Southern Hemisphere.** Climate models demonstrate that the ozone hole is the dominant driver of the observed changes in surface winds over the Southern Hemisphere mid and high latitudes during austral summer. These changes have contributed to the observed warming over the Antarctic Peninsula and cooling over the high plateau. The changes in the winds have also been linked to regional changes in precipitation, increases in sea ice around Antarctica, warming of the Southern Ocean, and a local decrease in the ocean sink of CO_2.

- **The trends in the summertime winds in the Southern Hemisphere are not expected to persist over the next few decades.** This is because of the expected offsetting influences on the surface winds of increasing greenhouse gases and the recovering ozone hole.

- **Observed Antarctic springtime column ozone does not yet show a statistically significant increasing trend (Figure ES-2c).** Year-to-year variability, due to meteorology, is much larger than the expected response to the small ODS decreases in the Antarctic vortex to date. This is consistent with simulations using chemistry-climate models (CCMs).

- **The evolution of Antarctic springtime column ozone over the rest of the century is expected to be dominated by the decline in ODS abundance (Figure ES-2c).** CCM simulations show that greenhouse gas changes have had, and will continue to have, a small impact on the ozone hole compared to the effects of the ODS changes. There are some indications that small episodic Antarctic ozone holes may occur even through the end of the century. In spring and early summer, Antarctica will continue to experience excess surface UV.

Figure ES-2. Schematic of the influence of ozone-depleting substances (ODSs) and climate change on the stratospheric ozone layer, and the influence of ozone changes on surface ultraviolet radiation. The red lines are based on observations to date. The blue dashed lines represent one commonly accepted scenario for the future. Shaded areas represent year-to-year variability and uncertainties in simulations of the past and future. The dashed vertical line at 1980, a year used as a benchmark for ozone and UV recovery, demarcates the situation before and after significant changes to the ozone layer. The curve for carbon dioxide (CO_2), a greenhouse gas important to Earth's climate, is shown because its changes can affect stratospheric temperatures as well as wind patterns, both of which affect stratospheric ozone.

(a) Ozone-depleting chlorine and bromine in the lower atmosphere
(b) Carbon dioxide
(c) Antarctic total ozone in October
(d) Northern midlatitude total ozone
(e) Northern midlatitude surface ultraviolet radiation

1980   now   ~2100

(a) Combined effective abundance of ozone-depleting chlorine and bromine in the lower atmosphere (troposphere). The red line is a representation of the measured atmospheric abundances. The blue dashed line is the expected combined effective abundance of chlorine and bromine based on the most likely ODS scenario used in this report and current understanding of the workings of the atmosphere. Because of the Montreal Protocol, a continued decline is expected through the end of this century, with a return to the 1980 benchmark value occurring around the middle of this century. A similar curve for the stratosphere would be shifted to the right (later dates) by a few years because of the time lag in the transport of substances from the surface to the stratosphere.

(b) The atmospheric abundance of carbon dioxide, the major anthropogenic greenhouse gas that changes Earth's climate, including in the stratosphere; CO_2 abundance is a proxy for climate change. The gray dotted/shaded area represents expectations of increasing future CO_2 abundance based on different scenarios used in this Assessment.

(c) The extent of the Antarctic ozone hole, as measured by the amount of ozone in the total overhead column averaged for the month of October. The ozone hole is the clearest indicator of ozone layer depletion by ODSs, and the ODSs in the atmosphere have been and are expected to continue to be the primary control on the extent and duration of the ozone hole. Antarctic ozone is expected to return to pre-1980 benchmark values in the late 21st century. The blue shaded area shows the estimated year-to-year variability of ozone for one scenario that includes changes in ODSs (panel a), CO_2 (panel b, blue dashed line), and changes in nitrous oxide and methane (not shown), but does not capture all uncertainties. The gray dotted/shaded area shows the uncertainty due to different climate scenarios, but again does not capture all uncertainties.

(d) The extent of northern midlatitude ozone depletion, as measured by the amount of ozone in the total overhead column between 30°N and 60°N averaged over each year; blue and gray shaded areas as in panel c. Panels c and d show the approximate relative magnitudes of the northern midlatitude ozone depletion and the Antarctic ozone hole. Influences of the quasi-biennial oscillation (QBO), volcanoes, and solar cycle have been removed from the observational data. The future projections do not include the influence of any volcanic eruptions or solar cycle variations. Natural variability makes it difficult to identify the projected return of northern midlatitude ozone levels to pre-1980 levels, but the expectation is that climate change will hasten this return by several decades, such that it will occur before the middle of the 21st century (before the return of stratospheric chlorine and bromine to the 1980 benchmark value, and before the return of Antarctic ozone, panel c).

(e) Changes in clear-sky surface UV radiation at northern midlatitudes that accompany the ozone changes of the ODS scenario above. Because the ozone depletion in the northern midlatitudes has been small, the UV changes also have been small. The blue shaded area shows the year-to-year variability of surface UV for the ozone changes of panel d. Clouds, aerosols, and air pollution significantly affect surface UV, but it is difficult to project their future changes. The uncertainties in these changes, which are larger than the uncertainties due to ozone changes, are not represented in the figure. The expectation is that climate change will result in northern midlatitude clear-sky surface UV radiation levels well below 1980 values by the second half of this century.

6

As a result of the controls introduced by the Montreal Protocol and its Amendments and Adjustments, it is expected that the decline in ODSs will lead to an increase in stratospheric ozone abundances. However, it will be challenging to attribute ozone increases to the decreases in ODSs during the next few years because of natural variability, observational uncertainty, and confounding factors, such as changes in stratospheric temperature or water vapor. A feature of this Assessment is the coordinated use by the community of chemistry-climate models (CCMs) with integrations covering the period from 1960–2100, which has allowed more detailed study of the long-term changes in the stratosphere and of the relative contributions of ODSs and greenhouse gases (GHGs).

- **Average total ozone values in 2006–2009 remain at the same level as the previous Assessment, at roughly 3.5% and 2.5% below the 1964–1980 averages respectively for 90°S–90°N and 60°S–60°N.** Midlatitude (35°–60°) annual mean total column ozone amounts in the Southern Hemisphere [Northern Hemisphere] over the period 2006–2009 have remained at the same level as observed during 1996–2005, at ~6% [~3.5%] below the 1964–1980 average.

- **The ozone loss in Arctic winter and spring between 2007 and 2010 has been variable, but has remained in a range comparable to the values prevailing since the early 1990s.** Substantial chemical loss continues to occur during cold Arctic winters.

- **Robust linkages between Arctic stratospheric ozone depletion and tropospheric and surface climate trends have not been established, as expected from the smaller ozone depletion compared with the Antarctic.**

- **Chemistry-climate models reproduce both the latitudinal and vertical structure of the observed ozone trends in both northern and southern midlatitudes during the past periods of increase of the ODSs, confirming our basic understanding of ozone change.** Simulations agree with observations that the last decade has shown flattening of the time series of global total ozone.

- **Analyses based on surface and satellite measurements show that erythemal UV irradiance over midlatitudes has increased since the late 1970s (Figure ES-2e).** This is in qualitative agreement with the observed decrease in column ozone, although other factors (mainly clouds and aerosols) have influenced long-term changes in erythemal irradiance. Clear-sky UV observations from unpolluted sites in midlatitudes show that since the late 1990s, UV irradiance levels have been approximately constant, consistent with ozone column observations over this period.

- **New analyses of both satellite and radiosonde data give increased confidence in changes in stratospheric temperatures between 1980 and 2009.** The global-mean lower stratosphere cooled by 1–2 K and the upper stratosphere cooled by 4–6 K between 1980 and 1995. There have been no significant long-term trends in global-mean lower stratospheric temperatures since about 1995. The global-mean lower-stratospheric cooling did not occur linearly but was manifested as downward steps in temperature in the early 1980s and the early 1990s. The cooling of the lower stratosphere includes the tropics and is not limited to extratropical regions as previously thought.

- **The evolution of lower stratospheric temperature is influenced by a combination of natural and human factors that has varied over time.** Ozone decreases dominate the lower stratospheric cooling since 1980. Major volcanic eruptions and solar activity have clear shorter-term effects. Models that consider all of these factors are able to reproduce this temperature time history.

- **Changes in stratospheric ozone, water vapor, and aerosols all radiatively affect surface temperature.** The radiative forcing[2] of climate in 2008 due to stratospheric ozone depletion (-0.05 ± 0.1 Watts per square meter, W/m^2) is much smaller than the positive radiative forcing due to the CFCs and HCFCs largely responsible for that depletion (about $+0.3$ W/m^2). For context, the current forcing by CO_2 is approximately $+1.7$ W/m^2. Radiative calculations and climate modeling studies suggest that the radiative effects of variability in stratospheric water vapor ($\pm \sim 0.1$ W/m^2 per decade) can contribute to decadal variability in globally averaged surface temperature. Climate models and observations show that major volcanic eruptions (e.g., Mt. Pinatubo in 1991, roughly -3 W/m^2) can cool the surface for several years.

- **The global middle and upper stratosphere are expected to cool in the coming century, mainly due to CO_2 increases.** Stratospheric ozone recovery will slightly offset the cooling. HFCs could warm the tropical lower stratosphere and tropopause region by about 0.3°C if stratospheric abundances reach the 1 ppb level.

- **Emerging evidence from model simulations suggests that increasing greenhouse gases lead to an acceleration of the stratospheric circulation usually referred to as the Brewer-Dobson circulation.** Such an acceleration could have important consequences, particularly decreases in column ozone in the tropics and increases in column ozone elsewhere. However, responsible mechanisms remain unclear and observational evidence for the circulation increase is lacking.

- **Global ozone is projected to increase approximately in line with the ODS decline, and the increase is accelerated by cooling of the upper stratosphere.** Global ozone is not very sensitive to circulation changes, so high confidence can be placed in this projection.

- **The evolution of ozone in the Arctic is projected to be more sensitive to climate change than in the Antarctic.** The projected strengthening of the stratospheric Brewer-Dobson circulation is expected to significantly increase lower stratospheric ozone in the Arctic, augmenting the GHG-induced ozone increase from upper stratospheric cooling and hastening the return to 1980 levels.

- **GHG-induced temperature and circulation changes are projected to hasten the return of midlatitude total column ozone to 1980 levels by several decades, rising well above 1980 levels by the end of the century.** The effect is most pronounced in northern midlatitudes (Figure ES-2d), where it would result in clear-sky surface UV radiation levels well below 1980 values by the second half of the century (Figure ES-2e). In southern midlatitudes, the effect of circulation changes is projected to be weaker and ozone is also influenced by depletion in the Antarctic, where the return to 1980 levels occurs much later.

---

[2] Positive radiative forcings generally warm the surface; negative radiative forcings generally cool the surface.

Cases related to the elimination of future emissions, production, and banks for various ozone-depleting substances (ODSs) can be formulated starting from a baseline future emission scenario. The baseline scenario here has been developed to account for past and present levels of ODSs along with emission projections. This scenario projects that stratospheric chlorine and bromine levels are likely to return to 1980 levels in midcentury for the midlatitudes and about 25 years later in the Antarctic vortex. These additional cases are used to evaluate the impact of various hypothetical policy options.

Information for Policymakers

- **The Montreal Protocol has both protected the ozone layer and provided substantial co-benefits by reducing climate change** (see Figure ES-1, bottom two panels). It has protected the stratospheric ozone layer by phasing out production and consumption of ozone-depleting substances. Simulations show that unchecked growth in the emissions of ODSs would have led to global ozone depletion in the coming decades very much larger than current levels. Solar UV radiation at the surface would also have increased substantially.

- **Projections of hydrofluorocarbon (HFC) growth in scenarios that assume no controls suggest that by 2050, Global Warming Potential–weighted emissions from these substances could be comparable to the GWP-weighted emissions of chlorofluorocarbons (CFCs) at their peak in 1988** (see Figure ES-1, bottom panel). The highest projection assumes that developing countries use HFCs with GWPs comparable to those currently in use.

- **The accelerated hydrochlorofluorocarbon (HCFC) phase-out agreed to by the Parties to the Montreal Protocol in 2007 is projected to reduce ozone depletion and to help reduce climate forcing** (see Figure ES-1). This acceleration is expected to reduce cumulative HCFC emissions by about 0.7 million Ozone Depletion Potential–tonnes between 2011 and 2050 and would bring forward the year equivalent effective stratospheric chlorine (EESC) returns to 1980 levels by 4–5 years. The accelerated HCFC phasedown is projected to reduce greenhouse gas emissions by about 0.5 Gigatonnes of carbon dioxide (CO_2)-equivalent per year averaged over 2011 through 2050. The projected benefit would be determined by the climate impact of the replacements. In comparison, global anthropogenic emissions of CO_2 were greater than 30 Gigatonnes per year in 2008.

- **Since the previous Assessment, new fluorocarbons have been suggested as possible replacements for potent HCFC and HFC greenhouse gases.** For example, HFC-1234yf (Ozone Depletion Potential (ODP) = 0; 100-year GWP = 4) is proposed to replace HFC-134a (ODP = 0; 100-year GWP = 1370) in mobile air conditioning. To fully assess the environmental impacts, each proposed substance would need to be evaluated for its ODP, GWP, atmospheric fate, safety, and toxicity. Preliminary analyses indicate that global replacement of HFC-134a with HFC-1234yf at today's level of use is not expected to contribute significantly to tropospheric ozone formation or produce harmful levels of the degradation product TFA (trifluoroacetic acid). It is well established that TFA is a

9

ubiquitous component of the environment, but uncertainties remain regarding its natural and anthropogenic sources, long-term fate, and abundances.

Due to the success of the Montreal Protocol and its Amendments and Adjustments in reducing the production, emissions, and abundances of controlled ODSs, emissions from other compounds and activities not controlled by the Montreal Protocol have become relatively more important to stratospheric ozone.

- **Increasing abundances of radiatively important gases, especially carbon dioxide (CO_2) and methane (CH_4), are expected to significantly affect future stratospheric ozone through effects on temperature, winds, and chemistry.** CO_2 increased in the atmosphere at 2.1 parts per million per year from 2005–2008, while CH_4 increased by about 6.7 parts per billion per year from 2006–2008.

- **Nitrous oxide (N_2O) is known to both deplete global ozone and warm the climate. The current ODP-weighted anthropogenic emission is larger than that of any ODS.**

- **Deliberate large injections of sulfur-containing compounds into the stratosphere, which have been suggested as a climate intervention approach (geoengineering), would alter the radiative, dynamical, and chemical state of the stratosphere and could be expected to have substantial unintended effects on stratospheric ozone levels.**

Options for Policy Formulation

Additional cases have been developed to show the impact of further control measures on various substances. Table ES-1 below shows the percentage reductions in integrated chlorine and bromine levels and integrated GWP-weighted emissions, relative to the baseline scenario, that can be achieved in these hypothetical cases.

- **Halons and CFCs: Leakage from banks is the largest source of current ODP-weighted emissions of ODSs.** A delay in the capture and destruction of estimated CFC banks from 2011 to 2015 is currently thought to reduce the possible ozone and climate benefits that could be achieved by about 30%.

- **Carbon tetrachloride (CCl_4):** Elimination of future CCl_4 emissions after 2010 would have an EESC impact comparable to the capture and destruction of CFC and halon banks. This is a much larger effect than was estimated in the previous Assessment because of a revision in the estimated emissions.

- **HCFCs:** The recent growth in reported HCFC production in developing countries was larger than projected in the previous Assessment. This alone would have resulted in a larger projected HCFC production in the new baseline scenario compared to the previous Assessment, but is expected to be more than compensated for by the accelerated HCFC phasedown agreed to by the Parties to the Montreal Protocol in 2007.

- **Elimination of all emissions of chlorine- and bromine-containing ODSs after 2010:** This would bring forward the return of EESC to 1980 levels by about 13 years. The elimination of these ODS emissions would have a climate impact equivalent to about a

10

0.7 Gigatonnes of CO_2-equivalent per year reduction from 2011 through 2050, on average. The sum of current banks of CFCs plus HCFCs contributes about the same amount to these CO_2-equivalent emissions as future HCFC production.

- **Methyl bromide:** Two methyl bromide cases were examined. Case 1: A phaseout of quarantine and pre-shipment emissions beginning in 2011 would accelerate the return of EESC to 1980 levels by 1.5 years, relative to a case of maintaining emissions at 2004–2008 average levels. Case 2: Continuing critical use exemptions at the approved 2011 level indefinitely would delay the return of EESC to 1980 levels by 0.2 year.

Table ES-1. Hypothetical cases. Reductions in integrated chlorine and bromine levels (as measured by equivalent effective stratospheric chlorine, EESC) and integrated GWP-weighted emissions, relative to the baseline scenario, that can be achieved in hypothetical cases developed to show the impact of further control measures on various substances.

Substance or Group of Substances	Reductions (%) in Integrated EESC (equivalent effective stratospheric chlorine)		Reduction in Cumulative GWP-Weighted Emissions from 2011 to 2050 (Gigatonnes of CO_2-equivalent)	
Bank capture and destruction in 2011 and 2015:	*2011*	*2015*	*2011*	*2015*
CFCs	11	7.0	7.9	5.5
Halons	14	9.1	0.4	0.3
HCFCs	4.8	5.3 [1]	4.9	5.5 [1]
Production elimination after 2010:				
HCFCs		8.8		13.2
CH_3Br for quarantine and pre-shipment		6.7		0.002
Total emissions elimination after 2010:				
CCl_4 [2]		7.6		0.9
CH_3CCl_3		0.1		0.004
HFCs		0.0		Up to 170 [3]

[1] The impact of a 2015 HCFC bank recovery is larger than a 2011 bank recovery because this calculation assumes destruction of the bank in only a single year, and because the bank in 2015 is larger than the bank in 2011 owing to continued annual production that is larger than the annual bank release.

[2] Banks are assumed to be zero. Emissions include uncertain sources such as possible fugitive emissions and unintended byproduct emissions.

[3] Strongly dependent on future projections and does not include HFC-23 emissions. Currently HFCs are not controlled under the Montreal Protocol, but are included in the basket of gases of the Kyoto Protocol.

APPENDIX:
SCIENTIFIC SUMMARIES OF THE CHAPTERS

CHAPTER 1: OZONE-DEPLETING SUBSTANCES AND RELATED CHEMICALS

- **The amended and adjusted Montreal Protocol continues to be successful at reducing emissions and atmospheric abundances of most controlled ozone-depleting substances (ODSs).**

Tropospheric Chlorine

- **Total tropospheric chlorine from long-lived chemicals (~3.4 parts per billion (ppb) in 2008) continued to decrease between 2005 and 2008.** Recent decreases in tropospheric chlorine (Cl) have been at a slower rate than in earlier years (decreasing at 14 parts per trillion per year (ppt/yr) during 2007–2008 compared to a decline of 21 ppt/yr during 2003–2004) and were slower than the decline of 23 ppt/yr projected in the A1 (most likely, or baseline) scenario of the 2006 Assessment. The tropospheric Cl decline has recently been slower than projected in the A1 scenario because chlorofluorocarbon-11 (CFC-11) and CFC-12 did not decline as rapidly as projected and because increases in hydrochlorofluorocarbons (HCFCs) were larger than projected.

- **The contributions of specific substances or groups of substances to the decline in tropospheric Cl have changed since the previous Assessment.** Compared to 2004, by 2008 observed declines in Cl from methyl chloroform (CH_3CCl_3) had become smaller, declines in Cl from CFCs had become larger (particularly CFC-12), and increases in Cl from HCFCs had accelerated. Thus, the observed change in total tropospheric Cl of -14 ppt/yr during 2007–2008 arose from:
  - -13.2 ppt Cl/yr from changes observed for CFCs
  - -6.2 ppt Cl/yr from changes observed for methyl chloroform
  - -5.1 ppt Cl/yr from changes observed for carbon tetrachloride
  - -0.1 ppt Cl/yr from changes observed for halon-1211
  - $+10.6$ ppt Cl/yr from changes observed for HCFCs

- **Chlorofluorocarbons (CFCs), consisting primarily of CFC-11, -12, and -113, accounted for 2.08 ppb (about 62%) of total tropospheric Cl in 2008.** The global atmospheric mixing ratio of CFC-12, which accounts for about one-third of the current atmospheric chlorine loading, decreased for the first time during 2005–2008 and by mid-2008 had declined by 1.3% (7.1 ± 0.2 parts per trillion, ppt) from peak levels observed during 2000–2004.

- **Hydrochlorofluorocarbons (HCFCs), which are substitutes for long-lived ozone-depleting substances, accounted for 251 ppt (7.5%) of total tropospheric Cl in 2008.**

HCFC-22, the most abundant of the HCFCs, increased at a rate of about 8 ppt/yr (4.3%/yr) during 2007–2008, more than 50% faster than observed in 2003–2004 but comparable to the 7 ppt/yr projected in the A1 scenario of the 2006 Assessment for 2007–2008. HCFC-142b mixing ratios increased by 1.1 ppt/yr (6%/yr) during 2007–2008, about twice as fast as was observed during 2003–2004 and substantially faster than the 0.2 ppt/yr projected in the 2006 Assessment A1 scenario for 2007–2008. HCFC-141b mixing ratios increased by 0.6 ppt/yr (3%/yr) during 2007–2008, which is a similar rate observed in 2003–2004 and projected in the 2006 Assessment A1 scenario.

- **Methyl chloroform (CH_3CCl_3) accounted for only 32 ppt (1%) of total tropospheric Cl in 2008, down from a mean contribution of about 10% during the 1980s.**

- **Carbon tetrachloride (CCl_4) accounted for 359 ppt (about 11%) of total tropospheric Cl in 2008.** Mixing ratios of CCl_4 declined slightly less than projected in the A1 scenario of the 2006 Assessment during 2005–2008.

Stratospheric Chlorine and Fluorine

- **The stratospheric chlorine burden derived by ground-based total column and space-based measurements of inorganic chlorine continued to decline during 2005–2008.** This burden agrees within ±0.3 ppb (±8%) with the amounts expected from surface data when the delay due to transport is considered. The uncertainty in this burden is large relative to the expected chlorine contributions from shorter-lived source gases and product gases of 80 (40–130) ppt. Declines since 1996 in total column and stratospheric abundances of inorganic chlorine compounds are reasonably consistent with the observed trends in long-lived source gases over this period.

- **Measured column abundances of hydrogen fluoride increased during 2005–2008 at a smaller rate than in earlier years.** This is qualitatively consistent with observed changes in tropospheric fluorine (F) from CFCs, HCFCs, hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs) that increased at a mean annual rate of 40 ± 4 ppt/yr (1.6 ± 0.1%/yr) since late 1996, which is reduced from 60–100 ppt/yr observed during the 1980s and early 1990s.

Tropospheric Bromine

- **Total organic bromine from controlled ODSs continued to decrease in the troposphere and by mid-2008 was 15.7 ± 0.2 ppt, approximately 1 ppt below peak levels observed in 1998.** This decrease was close to that expected in the A1 scenario of the 2006 Assessment and was driven by declines observed for methyl bromide (CH_3Br) that more than offset increased bromine (Br) from halons.

- **Bromine from halons stopped increasing during 2005–2008.** Mixing ratios of halon-1211 decreased for the first time during 2005–2008 and by mid-2008 were 0.1 ppt below levels observed in 2004. Halon-1301 continued to increase in the atmosphere during 2005–2008 but at a slower rate than observed during 2003–2004. The mean rate of increase was 0.03–0.04 ppt/yr during 2007–2008. A decrease of 0.01 ppt/yr was observed for halon-2402 in the global troposphere during 2007–2008.

- **Tropospheric methyl bromide (CH$_3$Br) mixing ratios continued to decline during 2005–2008, and by 2008 had declined by 1.9 ppt (about 20%) from peak levels measured during 1996–1998.** Evidence continues to suggest that this decline is the result of reduced industrial production, consumption, and emission. This industry-derived emission is estimated to have accounted for 25–35% of total global CH$_3$Br emissions during 1996–1998, before industrial production and consumption were reduced. Uncertainties in the variability of natural emissions and in the magnitude of methyl bromide stockpiles in recent years limit our understanding of this anthropogenic emissions fraction, which is derived by comparing the observed atmospheric changes to emission changes derived from reported production and consumption.

- **By 2008, nearly 50% of total methyl bromide consumption was for uses not controlled by the Montreal Protocol (quarantine and pre-shipment applications).** From peak levels in 1996–1998, industrial consumption in 2008 for controlled and non-controlled uses of CH$_3$Br had declined by about 70%. Sulfuryl fluoride (SO$_2$F$_2$) is used increasingly as a fumigant to replace methyl bromide for controlled uses because it does not directly cause ozone depletion, but it has a calculated direct, 100-year Global Warming Potential (GWP$_{100}$) of 4740. The SO$_2$F$_2$ global background mixing ratio increased during recent decades and had reached about 1.5 ppt by 2008.

Stratospheric Bromine

- **Total bromine in the stratosphere was 22.5 (19.5–24.5) ppt in 2008. It is no longer increasing and by some measures has decreased slightly during recent years.** Multiple measures of stratospheric bromine monoxide (BrO) show changes consistent with tropospheric Br trends derived from observed atmospheric changes in CH$_3$Br and the halons. Slightly less than half of the stratospheric bromine derived from these BrO observations is from controlled uses of halons and methyl bromide. The remainder comes from natural sources of methyl bromide and other bromocarbons, and from quarantine and pre-shipment uses of methyl bromide not controlled by the Montreal Protocol.

Very Short-Lived Halogenated Substances (VSLS)

VSLS are defined as trace gases whose local lifetimes are comparable to, or shorter than, tropospheric transport time scales and that have non-uniform tropospheric abundances. In practice, VSLS are considered to be those compounds having atmospheric lifetimes of less than 6 months.

- **The amount of halogen from a very short-lived source substance that reaches the stratosphere depends on the location of the VSLS emissions, as well as atmospheric removal and transport processes.** Substantial uncertainties remain in quantifying the full impact of chlorine- and bromine-containing VSLS on stratospheric ozone. Updated results continue to suggest that brominated VSLS contribute to stratospheric ozone depletion, particularly under enhanced aerosol loading. It is unlikely that iodinated gases are important for stratospheric ozone loss in the present-day atmosphere.

- **Based on a limited number of observations, very short-lived source gases account for 55 (38–80) ppt chlorine in the middle of the tropical tropopause layer (TTL).** From observations of hydrogen chloride (HCl) and carbonyl chloride ($COCl_2$) in this region, an additional ~25 (0–50) ppt chlorine is estimated to arise from VSLS degradation. The sum of contributions from source gases and these product gases amounts to ~80 (40–130) ppt chlorine from VSLS that potentially reaches the stratosphere. About 40 ppt of the 55 ppt of chlorine in the TTL from source gases is from anthropogenic VSLS emissions (e.g., methylene chloride, CH_2Cl_2; chloroform, $CHCl_3$; 1,2 dichloroethane, CH_2ClCH_2Cl; perchloroethylene, C_2Cl_4), but their contribution to stratospheric chlorine loading is not well quantified.

- **Two independent approaches suggest that VSLS contribute significantly to stratospheric bromine.** Stratospheric bromine derived from observations of BrO implies a contribution of 6 (3–8) ppt of bromine from VSLS. Observed, very short-lived source gases account for 2.7 (1.4–4.6) ppt Br in the middle of the tropical tropopause layer. By including modeled estimates of product gas injection into the stratosphere, the total contribution of VSLS to stratospheric bromine is estimated to be 1–8 ppt.

- **Future climate changes could affect the contribution of VSLS to stratospheric halogen and its influence on stratospheric ozone.** Future potential use of anthropogenic halogenated VSLS may contribute to stratospheric halogen in a similar way as do present-day natural VSLS. Future environmental changes could influence both anthropogenic and natural VSLS contributions to stratospheric halogens.

Equivalent Effective Stratospheric Chlorine (EESC)

EESC is a sum of chlorine and bromine derived from ODS tropospheric abundances weighted to reflect their potential influence on ozone in different parts of the stratosphere. The growth and decline in EESC varies in different regions of the atmosphere because a given tropospheric abundance propagates to the stratosphere with varying time lags associated with transport. Thus the EESC abundance, when it peaks, and how much it has declined from its peak vary in different regions of the atmosphere.
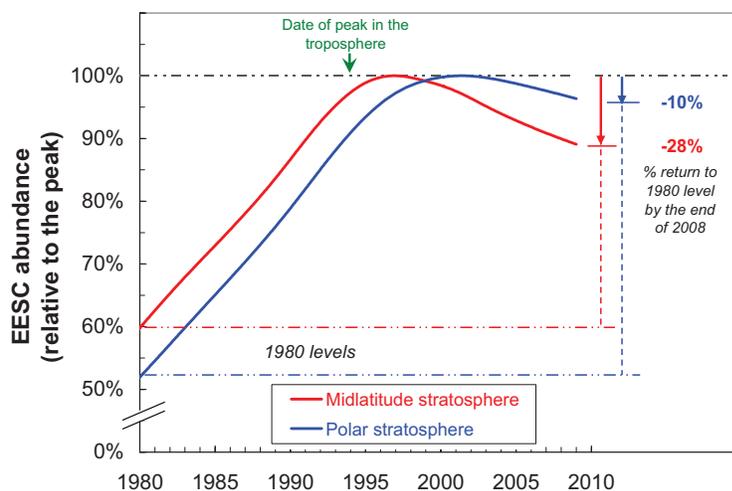

Figure ESA-1. Stratospheric EESC derived for the midlatitude and polar stratospheric regions relative to peak abundances, plotted as a function of time. Peak abundances are ~1950 ppt for the midlatitude stratosphere and ~4200 ppt for the polar stratosphere. Percentages shown to the right indicate the observed change in EESC by the end of 2008 relative to the change needed for EESC to return to its 1980 abundance. A significant portion of the 1980 EESC level is from natural emissions.

15

- **EESC has decreased throughout the stratosphere.**
  - By the end of 2008, midlatitude EESC had decreased by about 11% from its peak value in 1997. This drop is 28% of the decrease required for EESC in midlatitudes (red curve in figure) to return to the 1980 benchmark level.

  - By the end of 2008, polar EESC had decreased by about 5% from its peak value in 2002. This drop is 10% of the decrease required for EESC in polar regions (blue curve in figure) to return to the 1980 benchmark level.

- **During the past four years, no specific substance or group of substances dominated the decline in the total combined abundance of ozone-depleting halogen in the troposphere.** In contrast to earlier years, the long-lived CFCs now contribute similarly to the decline as do the short-lived CH_3CCl_3 and CH_3Br. Other substances contributed less to this decline, and HCFCs added to this halogen burden over this period.

Emission Estimates and Lifetimes

- **While global emissions of CFC-12 derived from atmospheric observations decreased during 2005–2008, those for CFC-11 did not change significantly over this period.** Emissions from banks account for a substantial fraction of current emissions of the CFCs, halons, and HCFCs. Emissions inferred for CFCs from global observed changes did not decline during 2005–2008 as rapidly as projected in the A1 scenario of the 2006 Assessment, most likely because of underestimates of bank emissions.

- **Global emissions of CCl_4 have declined only slowly over the past decade.**
  - These emissions, when inferred from observed global trends, were between 40 and 80 Gigagrams per year (Gg/yr) during 2005–2008 given a range for the global CCl_4 lifetime of 33–23 years. By contrast, CCl_4 emissions derived with a number of assumptions from data reported to the United Nations Environment Programme (UNEP) ranged from 0–30 Gg/yr over this same period.

  - In addition, there is a large variability in CCl_4 emissions derived from data reported to UNEP that is not reflected in emissions derived from measured global mixing ratio changes. This additional discrepancy cannot be explained by scaling the lifetime or by uncertainties in the atmospheric trends. If the analysis of data reported to UNEP is correct, unknown anthropogenic sources may be partly responsible for these observed discrepancies.

- **Global emissions of HCFC-22 and HCFC-142b derived from observed atmospheric trends increased during 2005–2008.** HCFC-142b global emissions increased appreciably over this period, compared to a projected emissions decline of 23% from 2004 to 2008. By 2008, emissions for HCFC-142b were two times larger than had been projected in the A1 scenario of the 2006 Assessment. These emission increases were coincident with increasing production of HCFCs in developing countries in general and in East Asia particularly. It is too soon to discern any influence of the 2007 Adjustments to the Montreal Protocol on the abundance and emissions of HCFCs.

- **The sum of CFC emissions (weighted by direct, 100-year GWPs) has decreased on average by 8 ± 1%/yr from 2004 to 2008, and by 2008 amounted to 1.1 ± 0.3**

Gigatonnes of carbon dioxide–equivalent per year ($GtCO_2$-eq/yr). The sum of GWP-weighted emissions of HCFCs increased by $5 \pm 2\%$/yr from 2004 to 2008, and by 2008 amounted to 0.74 ± 0.05 $GtCO_2$-eq/yr.

- **Evidence is emerging that lifetimes for some important ODSs (e.g., CFC-11) may be somewhat longer than reported in past assessments**. In the absence of corroborative studies, however, the CFC-11 lifetime reported in this Assessment remains unchanged at 45 years. Revisions in the CFC-11 lifetime would affect estimates of its global emission derived from atmospheric changes and calculated values for Ozone Depletion Potentials (ODPs) and best-estimate lifetimes for some other halocarbons.

Other Trace Gases That Directly Affect Ozone and Climate

- **The methane (CH_4) global growth rate was small, averaging 0.9 ± 3.3 ppb/yr between 1998–2006, but increased to 6.7 ± 0.6 ppb/yr from 2006–2008.** Analysis of atmospheric data suggests that this increase is due to wetland sources in both the high northern latitudes and the tropics. The growth rate variability observed during 2006–2008 is similar in magnitude to that observed over the last two decades.

- **In 2005–2008 the average growth rate of nitrous oxide (N_2O) was 0.8 ppb/yr, with a global average tropospheric mixing ratio of 322 ppb in 2008.** A recent study has suggested that at the present time, Ozone Depletion Potential–weighted anthropogenic emissions of N_2O are the most significant emissions of a substance that depletes ozone.

- **Long-term changes in carbonyl sulfide (COS) measured as total columns above the Jungfraujoch (46.5°N) and from surface flasks sampled in the Northern Hemisphere show that atmospheric mixing ratios have increased slightly during recent years concurrently with increases in "bottom-up" inventory-based emissions of global sulfur.** Results from surface measurements show a mean global surface mixing ratio of 493 ppt in 2008 and a mean rate of increase of 1.8 ppt/yr during 2000–2008. New laboratory, observational, and modeling studies indicate that vegetative uptake of COS is significantly larger than considered in the past.

Other Trace Gases with an Indirect Influence on Ozone

- **The carbon dioxide (CO_2) global average mixing ratio was 385 parts per million (ppm) in 2008 and had increased during 2005–2008 at an average rate of 2.1 ppm/yr.** This rate is higher than the average growth rate during the 1990s of 1.5 ppm/yr and corresponds with increased rates of fossil fuel combustion.

- **Hydrofluorocarbons (HFCs) used as ODS substitutes continued to increase in the global atmosphere.** HFC-134a is the most abundant HFC; its global mixing ratio reached about 48 ppt in 2008 and was increasing at 4.7 ppt/yr. Other HFCs have been identified in the global atmosphere at <10 ppt (e.g., HFC-125, -143a, -32, and -152a) and were increasing at ≤1 ppt/yr in 2008.

- **Emissions of HFC-23, a byproduct of HCFC-22 production, have increased over the past decade even as efforts at minimizing these emissions were implemented in both developed and developing countries.** These emission increases are concurrent with

rapidly increasing HCFC-22 production in developing countries and are likely due to increasing production of HCFC-22 in facilities not covered by the Kyoto Protocol's Clean Development Mechanism projects. Globally averaged HFC-23 mixing ratios reached 21.8 ppt in 2008, with a yearly increase of 0.8 ppt/yr (3.9%/yr).

- **The sum of emissions (weighted by direct, 100-year GWPs) of HFCs used as ODS replacements has increased by 8–9%/yr from 2004 to 2008, and by 2008 amounted to 0.39 ± 0.03 GtCO$_2$-eq/yr.** Regional studies suggest significant contributions of HFC-134a and -152a emissions during 2005–2006 from Europe, North America, and Asia. Emissions of HFC-23, most of which do not arise from use of this substance as an ODS replacement, added an additional 0.2 Gt CO$_2$-eq/year, on average, during 2006–2008.

- **Sulfur hexafluoride (SF$_6$) and nitrogen trifluoride (NF$_3$):** Global averaged mixing ratios of SF$_6$ reached 6.4 ppt in 2008, with a yearly increase of 0.2 ppt/yr. NF$_3$ was detected in the atmosphere for the first time, with a global mean mixing ratio in 2008 of 0.45 ppt and a growth rate of 0.05 ppt/yr, or 11%/yr.

Direct Radiative Forcing

The abundances of ODSs as well as many of their replacements contribute to radiative forcing of the atmosphere. These climate-related forcings have been updated using the current observations of atmospheric abundances and are summarized in Table ESA-1. This table also contains the primary Kyoto Protocol gases as reference.

- **Over these 5 years, radiative forcing from the sum of ODSs and HFCs has increased but, by 2008, remained small relative to the forcing changes from CO$_2$ (see Table ESA-1).**

Table ESA-1. Direct radiative forcings of ODSs and other gases, and their recent changes.

Specific Substance or Group of Substances	Direct Radiative Forcing (2008), milliWatts per square meter (mW/m^2)	Change in Direct Radiative Forcing (2004–2008), mW/m^2
CFCs [*]	268	−7
HCFCs [*]	45	7
HFCs [#, a]	15	5
HFC-23 [#]	4	0.7
CO$_2$ [#]	1740	139
CH$_4$ [#]	500	4
N$_2$O [#]	170	12
PFCs [#]	5.4	0.5
SF$_6$ [#]	3.4	0.5
Sum of Montreal Protocol gases	313	0
Sum of Kyoto Protocol gases	2434	161

[*] Montreal Protocol Gases (CFCs and HCFCs).
[#] Kyoto Protocol Gases (CO$_2$, CH$_4$, N$_2$O, HFCs, PFCs, and SF$_6$).
[a] Only those HFCs for which emissions arise primarily through use as ODS replacements (i.e., not HFC-23).

CHAPTER 2: STRATOSPHERIC OZONE AND SURFACE ULTRAVIOLET RADIATION

Global Ozone Observations and Interpretation

As a result of the Montreal Protocol, ozone is expected to recover from the effect of ozone-depleting substances (ODSs) as their abundances decline in the coming decades. The 2006 Assessment showed that globally averaged column ozone ceased to decline around 1996, meeting the criterion for the first stage of recovery. Ozone is expected to increase as a result of continued decrease in ODSs (second stage of recovery). This chapter discusses recent observations of ozone and ultraviolet radiation in the context of their historical records. Natural variability, observational uncertainty, and stratospheric cooling necessitate a long record in order to attribute an ozone increase to decreases in ODSs. Table ESA-2 summarizes ozone changes since 1980.

The primary tools used in this Assessment for prediction of ozone are chemistry-climate models (CCMs). These CCMs are designed to represent the processes determining the amount of stratospheric ozone and its response to changes in ODSs and greenhouse gases. Eighteen CCMs have been recently evaluated using a variety of process-based comparisons to measurements. The CCMs are further evaluated here by comparison of trends calculated from measurements with trends calculated from simulations designed to reproduce ozone behavior during an observing period.

Total Column Ozone

- **Average total ozone values in 2006–2009 have remained at the same level for the past decade, about 3.5% and 2.5% below the 1964–1980 averages respectively for 90°S–90°N and 60°S–60°N.** Average total ozone from CCM simulations behaves in a manner similar to observations between 1980 and 2009. The average column ozone for 1964–1980 is chosen as a reference for observed changes for two reasons: 1) reliable ground-based observations sufficient to produce a global average are available in this period; 2) a significant trend is not discernible in the observations during this period.

- **Southern Hemisphere midlatitude (35°S–60°S) annual mean total column ozone amounts over the period 2006–2009 have remained at the same level as observed during 1996–2005, approximately 6% below the 1964–1980 average.** Simulations by CCMs also show declines of the same magnitude between 1980 and 1996, and minimal change after 1996, thus both observations and simulations are consistent with the expectations of the impact of ODSs on southern midlatitude ozone.

- **Northern Hemisphere midlatitude (35°N–60°N) annual mean total column ozone amounts over the period 2006–2009 have remained at the same level as observed during 1998–2005, approximately 3.5% below the 1964–1980 average.** A minimum about 5.5% below the 1964–1980 average was reached in the mid-1990s. Simulations by CCMs agree with these measurements, again showing the consistency of data with the expected impact of ODSs. The simulations also indicate that the minimum in the mid-1990s was primarily caused by the ozone response to effects of volcanic aerosols from

the 1991 eruption of Mt. Pinatubo.

- **The latitude dependence of simulated total column ozone trends generally agrees with that derived from measurements, showing large negative trends at Southern Hemisphere mid and high latitudes and Northern Hemisphere midlatitudes for the period of ODS increase.** However, in the tropics the statistically significant range of trends produced by CCMs (−1.5 to −4 Dobson units per decade (DU/decade)) does not agree with the trend obtained from measurements (+0.3 ± 1 DU/decade).

Ozone Profiles

- **Northern Hemisphere midlatitude (35°N–60°N) ozone between 12 and 15 km decreased between 1979 and 1995, and increased between 1996 and 2009.** The increase since the mid-1990s is larger than the changes expected from the decline in ODS abundances.

- **Northern Hemisphere midlatitude (35°N–60°N) ozone between 20 and 25 km declined during 1979–1995 and has since ceased to decline.** Observed increases between 1996 and 2008 are statistically significant at some locations but not globally.

- **Northern Hemisphere midlatitude (35°N–60°N) ozone between 35 and 45 km measured using a broad range of ground-based and satellite instruments ceased to decline after the mid-1990s, consistent with the leveling off of ODS abundances.** All datasets show a small ozone increase since that time, with varying degrees of statistical significance but this increase cannot presently be attributed to ODS decrease because of observational uncertainty, natural ozone variability, and stratospheric cooling. CCMs simulate the ozone response to changes in ODSs and increases in greenhouse gases; analysis of CCM results suggests that longer observational records are required to separate these effects from each other and from natural variability.

- **In the midlatitude upper stratosphere (35–45 km) of both hemispheres, the profile ozone trends derived from most CCMs from 1980 to 1996 agree well with trends deduced from measurements.** The agreement in both magnitude and shape of the ozone trends provides evidence that increases in ODSs between 1980 and 1996 are primarily responsible for the observed behavior.

- **In the tropical lower stratosphere, all simulations show a negative ozone trend just above the tropopause, centered at about 18–19 km (70–80 hectoPascals, hPa), due to an increase in upwelling.** The simulated trends in the lower tropical stratosphere are consistent with trends deduced for 1985–2005 from Stratospheric Aerosol and Gas Experiment (SAGE II) satellite data, although uncertainties in the SAGE II trends are large. The near-zero trend in tropical total ozone measurements is inconsistent with the negative trend found in the integrated SAGE I + SAGE II stratospheric profiles. The tropospheric ozone column does not increase enough to resolve this discrepancy.

Table ESA-2. Summary of ozone changes estimated from observations.

	Column ozone	12–15 km	20–25 km	35–45 km	Comment
Data sources	Ground-based, satellite	Ozonesondes	Ozonesondes, satellites, FTIR	Satellites, Umkehrs, FTIR	
Northern midlatitudes 1980–1996	Declined by about 6%	Declined by about 9%	Declined by about 7%	Declined by about 10%	1992–1996 column and lower stratosphere data affected by Mt. Pinatubo
Northern midlatitudes 1996–2009	Increased from the minimum values by about 2% by 1998 and remained at the same level thereafter	Increased by about 6%	Increased by about 2.5%	Increased by 1 to 2%, but uncertainties are large	
Southern midlatitudes 1980–1996	Declined by 6%	No information	Declined by about 7%	Declined by about 10%	
Southern midlatitudes 1996–2009	Remained at approximately the same level	No statistically significant changes	No statistically significant changes	Increased by 1 to 3%, but uncertainties are large	

Polar Ozone Observations and Interpretation

- **The Antarctic ozone hole continued to appear each spring from 2006 to 2009.** This is expected because decreases in stratospheric chlorine and bromine have been moderate over the last few years. Analysis shows that since 1979 the abundance of total column ozone in the Antarctic ozone hole has evolved in a manner consistent with the time evolution of ODSs. Since about 1997 the ODS amounts have been nearly constant and the depth and magnitude of the ozone hole have been controlled by variations in temperature and dynamics. The October mean column ozone within the vortex has been about 40% below 1980 values for the past fifteen years.

- **Arctic winter and spring ozone loss has varied between 2007 and 2010, but remained in a range comparable to the values that have prevailed since the early 1990s.** Chemical loss of about 80% of the losses observed in the record cold winters of 1999/2000 and 2004/2005 has occurred in recent cold winters.

- **Recent laboratory measurements of the chlorine monoxide dimer (ClOOCl) dissociation cross section and analyses of observations from aircraft and satellites have reaffirmed the fundamental understanding that polar springtime ozone depletion is caused primarily by the ClO + ClO catalytic ozone destruction cycle, with significant contributions from the BrO + ClO cycle.**

- **Polar stratospheric clouds (PSCs) over Antarctica occur more frequently in early June and less frequently in September than expected based on the previous satellite**

PSC climatology. This result is obtained from measurements by a new class of satellite instruments that provide daily vortex-wide information concerning PSC composition and occurrence in both hemispheres. The previous satellite PSC climatology was developed from solar occultation instruments that have limited daily coverage.

- **Calculations constrained to match observed temperatures and halogen levels produce Antarctic ozone losses that are close to those derived from data.** Without constraints, CCMs simulate many aspects of the Antarctic ozone hole, however they do not simultaneously produce the cold temperatures, isolation from middle latitudes, deep descent, and high amounts of halogens in the polar vortex. Furthermore, most CCMs underestimate the Arctic ozone loss that is derived from observations, primarily because the simulated northern winter vortices are too warm.

Ultraviolet Radiation

Ground-based measurements of solar ultraviolet (UV) radiation (wavelength 280–400 nanometers) remain limited both spatially and in duration. However, there have been advances both in reconstructing longer-term UV records from other types of ground-based measurements and in satellite UV retrievals. Where these UV datasets coincide, long-term changes agree, even though there may be differences in instantaneous, absolute levels of UV.

- **Ground-based UV reconstructions and satellite UV retrievals, supported in the later years by direct ground-based UV measurements, show that erythemal ("sunburning") irradiance over midlatitudes has increased since the late 1970s, in qualitative agreement with the observed decrease in column ozone.** The increase in satellite-derived erythemal irradiance over midlatitudes during 1979–2008 is statistically significant, while there are no significant changes in the tropics. Satellite estimates of UV are difficult to interpret over the polar regions.

- **In the Antarctic, large ozone losses produce a clear increase in surface UV radiation.** Ground-based measurements show that the average spring erythemal irradiance for 1990–2006 is up to 85% greater than the modeled irradiance for 1963–1980, depending on site. The Antarctic spring erythemal irradiance is approximately twice that measured in the Arctic for the same season.

- **Clear-sky UV observations from unpolluted sites in midlatitudes show that since the late 1990s, UV irradiance levels have been approximately constant, consistent with ozone column observations over this period.**

- **Surface UV levels and trends have also been significantly influenced by clouds and aerosols, in addition to stratospheric ozone.** Daily measurements under all atmospheric conditions at sites in Europe and Japan show that erythemal irradiance has continued to increase in recent years due to net reductions in the effects of clouds and aerosols. In contrast, in southern midlatitudes, zonal and annual average erythemal irradiance increases due to ozone decreases since 1979 have been offset by almost a half due to net increases in the effects of clouds and aerosols.

Globally averaged total column ozone has declined over recent decades due to the release of ozone-depleting substances (ODSs) into the atmosphere. Now, as a result of the Montreal Protocol, ozone is expected to recover from the effects of ODSs as ODS abundances decline in the coming decades. However, a number of factors in addition to ODSs have led to and will continue to lead to changes in ozone. Discriminating between the causes of past and projected ozone changes is necessary, not only to identify the progress in ozone recovery from ODSs, but also to evaluate the effectiveness of climate and ozone protection policy options.

Factors Affecting Future Ozone and Surface Ultraviolet Radiation

- **At least for the next few decades, the decline of ODSs is expected to be the major factor affecting the anticipated increase in global total column ozone. However, several factors other than ODS will affect the future evolution of ozone in the stratosphere.** These include changes in (i) stratospheric circulation and temperature due to changes in long-lived greenhouse gas (GHG) abundances, (ii) stratospheric aerosol loading, and (iii) source gases of highly reactive stratospheric hydrogen and nitrogen compounds. Factors that amplify the effects of ODSs on ozone (e.g., stratospheric aerosols) will likely decline in importance as ODSs are gradually eliminated from the atmosphere.

- **Increases in GHG emissions can both positively and negatively affect ozone.** Carbon dioxide (CO_2)-induced stratospheric cooling elevates middle and upper stratospheric ozone and decreases the time taken for ozone to return to 1980 levels, while projected GHG-induced increases in tropical upwelling decrease ozone in the tropical lower stratosphere and increase ozone in the extratropics. Increases in nitrous oxide (N_2O) and methane (CH_4) concentrations also directly impact ozone chemistry but the effects are different in different regions.

- **The Brewer-Dobson circulation (BDC) is projected to strengthen over the 21st century and thereby affect ozone amounts.** Climate models consistently predict an acceleration of the BDC or, more specifically, of the upwelling mass flux in the tropical lower stratosphere of around 2% per decade as a consequence of GHG abundance increases. A stronger BDC would decrease the abundance of tropical lower stratospheric ozone, increase poleward transport of ozone, and could reduce the atmospheric lifetimes of long-lived ODSs and other trace gases. While simulations showing faster ascent in the tropical lower stratosphere to date are a robust feature of chemistry-climate models (CCMs), this has not been confirmed by observations and the responsible mechanisms remain unclear.

- **Substantial ozone losses could occur if stratospheric aerosol loading were to increase in the next few decades, while halogen levels are high.** Stratospheric aerosol increases may be caused by sulfur contained in volcanic plumes entering the stratosphere or from human activities. The latter might include attempts to geoengineer the climate system by enhancing the stratospheric aerosol layer. The ozone losses mostly result from enhanced heterogeneous chemistry on stratospheric aerosols. Enhanced aerosol heating within the stratosphere also leads to changes in temperature and circulation that affect ozone.

- **Surface ultraviolet (UV) levels will not be affected solely by ozone changes but also by the effects of climate change and by air quality change in the troposphere.** These tropospheric effects include changes in clouds, tropospheric aerosols, surface reflectivity, and tropospheric sulfur dioxide (SO_2) and nitrogen dioxide (NO_2). The uncertainties in projections of these factors are large. Projected increases in tropospheric ozone are more certain and may lead to reductions in surface erythemal ("sunburning") irradiance of up to 10% by 2100. Changes in clouds may lead to decreases or increases in surface erythemal irradiance of up to 15% depending on latitude.

Expected Future Changes in Ozone

Full ozone recovery from the effects of ODSs and return of ozone to historical levels are not synonymous. In this chapter a key target date is chosen to be 1980, in part to retain the connection to previous Ozone Assessments. Noting, however, that decreases in ozone may have occurred in some regions of the atmosphere prior to 1980, 1960 return dates are also reported.

The projections reported on in this chapter are taken from a recent compilation of CCM simulations. The ozone projections, which also form the basis for the UV projections, are limited in their representativeness of possible futures since they mostly come from CCM simulations based on a single GHG emissions scenario (scenario A1B of *Emissions Scenarios. A Special Report of Working Group III of the Intergovernmental Panel on Climate Change*, Cambridge University Press, 2000) and a single ODS emissions scenario (adjusted A1 of the previous (2006) Ozone Assessment).

Throughout this century, the vertical, latitudinal, and seasonal structure of the ozone distribution will be different from what it was in 1980. For this reason, ozone changes in different regions of the atmosphere are considered separately.

- **The projections of changes in ozone and surface clear-sky UV are broadly consistent with those reported on in the 2006 Assessment.**

- **The capability of making projections and attribution of future ozone changes has been improved since the 2006 Assessment.** Use of CCM simulations from an increased number of models extending through the entire period of ozone depletion and recovery from ODSs (1960–2100) as well as sensitivity simulations have allowed more robust projections of long-term changes in the stratosphere and of the relative contributions of ODSs and GHGs to those changes.

- **Global annually averaged total column ozone is projected to return to 1980 levels before the middle of the century and earlier than when stratospheric halogen loading returns to 1980 levels.** CCM projections suggest that this early return is primarily a result of GHG-induced cooling of the upper stratosphere because the effects of circulation changes on tropical and extratropical ozone largely cancel. Global (90°S–90°N) annually averaged total column ozone will likely return to 1980 levels between 2025 and 2040, well before the return of stratospheric halogens to 1980 levels between 2045 and 2060.

- **Simulated changes in tropical total column ozone from 1960 to 2100 are generally small.** The evolution of tropical total column ozone in models depends on the balance between upper stratospheric increases and lower stratospheric decreases. The upper

stratospheric increases result from declining ODSs and a slowing of ozone destruction resulting from GHG-induced cooling. Ozone decreases in the lower stratosphere mainly result from an increase in tropical upwelling. From 1960 until around 2000, a general decline is simulated, followed by a gradual increase to values typical of 1980 by midcentury. Thereafter, although total column ozone amounts decline slightly again toward the end of the century, by 2080 they are no longer expected to be affected by ODSs. Confidence in tropical ozone projections is compromised by the fact that simulated decreases in column ozone to date are not supported by observations, suggesting that significant uncertainties remain.

- **Midlatitude total column ozone is simulated to evolve differently in the two hemispheres**. Over northern midlatitudes, annually averaged total column ozone is projected to return to 1980 values between 2015 and 2030, while for southern midlatitudes the return to 1980 values is projected to occur between 2030 and 2040. The more rapid return to 1980 values in northern midlatitudes is linked to a more pronounced strengthening of the poleward transport of ozone due to the effects of increased GHG levels, and effects of Antarctic ozone depletion on southern midlatitudes. By 2100, midlatitude total column ozone is projected to be above 1980 values in both hemispheres.

- **October-mean Antarctic total column ozone is projected to return to 1980 levels after midcentury, later than in any other region, and yet earlier than when stratospheric halogen loading is projected to return to 1980 levels.** The slightly earlier return of ozone to 1980 levels (2045–2060) results primarily from upper stratospheric cooling and resultant increases in ozone. The return of polar halogen loading to 1980 levels (2050–2070) in CCMs is earlier than in empirical models that exclude the effects of GHG-induced changes in circulation. Our confidence in the drivers of changes in Antarctic ozone is higher than for other regions because (i) ODSs exert a strong influence on Antarctic ozone, (ii) the effects of changes in GHG abundances are comparatively small, and (iii) projections of ODS emissions are more certain than those for GHGs. Small Antarctic ozone holes (areas of ozone <220 Dobson units, DU) could persist to the end of the 21st century.

- **March-mean Arctic total column ozone is projected to return to 1980 levels two to three decades before polar halogen loading returns to 1980 levels, and to exceed 1980 levels thereafter.** While CCM simulations project a return to 1980 levels between 2020 and 2035, most models tend not to capture observed low temperatures and thus underestimate present-day Arctic ozone loss such that it is possible that this return date is biased early. Since the strengthening of the Brewer-Dobson circulation through the 21st century leads to increases in springtime Arctic column ozone, by 2100 Arctic ozone is projected to lie well above 1960 levels.

Uncertainties in Projections

- **Conclusions dependent on future GHG levels are less certain than those dependent on future ODS levels since ODS emissions are controlled by the Montreal Protocol.** For the six GHG scenarios considered by a few CCMs, the simulated differences in stratospheric column ozone over the second half of the 21st century are largest in the

northern midlatitudes and the Arctic, with maximum differences of 20–40 DU between the six scenarios in 2100.

- **There remain sources of uncertainty in the CCM simulations.** These include the use of prescribed ODS mixing ratios instead of emission fluxes as lower boundary conditions, the range of sea surface temperatures and sea ice concentrations, missing tropospheric chemistry, model parameterizations, and model climate sensitivity.

- **Geoengineering schemes for mitigating climate change by continuous injections of sulfur-containing compounds into the stratosphere, if implemented, would substantially affect stratospheric ozone, particularly in polar regions.** Ozone losses observed following large volcanic eruptions support this prediction. However, sporadic volcanic eruptions provide limited analogs to the effects of continuous sulfur emissions. Preliminary model simulations reveal large uncertainties in assessing the effects of continuous sulfur injections.

Expected Future Changes in Surface UV

While a number of factors, in addition to ozone, affect surface UV irradiance, the focus in this chapter is on the effects of changes in stratospheric ozone on surface UV. For this reason, clear-sky surface UV irradiance is calculated from ozone projections from CCMs.

- **Projected increases in midlatitude ozone abundances during the 21st century, in the absence of changes in other factors, in particular clouds, tropospheric aerosols, and air pollutants, will result in decreases in surface UV irradiance.** Clear-sky erythemal irradiance is projected to return to 1980 levels on average in 2025 for the northern midlatitudes, and in 2035 for the southern midlatitudes, and to fall well below 1980 values by the second half of the century. However, actual changes in surface UV will be affected by a number of factors other than ozone.

- **In the absence of changes in other factors, changes in tropical surface UV will be small because changes in tropical total column ozone are projected to be small.** By the middle of the 21st century, the model projections suggest surface UV to be slightly higher than in the 1960s, very close to values in 1980, and slightly lower than in 2000. The projected decrease in tropical total column ozone through the latter half of the century will likely result in clear-sky surface UV remaining above 1960 levels. Average UV irradiance is already high in the tropics due to naturally occurring low total ozone columns and high solar elevations.

- **The magnitude of UV changes in the polar regions is larger than elsewhere because ozone changes in polar regions are larger.** For the next decades, surface clear-sky UV irradiance, particularly in the Antarctic, will continue to be higher than in 1980. Future increases in ozone and decreases in clear-sky UV will occur at slower rates than those associated with the ozone decreases and UV increases that occurred before 2000. In Antarctica, surface clear-sky UV is projected to return to 1980 levels between 2040 and 2060, while in the Arctic this is projected to occur between 2020 and 2030. By 2100, October surface clear-sky erythemal irradiance in Antarctica is likely to be between 5% below to 25% above 1960 levels, with considerable uncertainty. This is consistent with multi-model-mean October Antarctic total column ozone not returning to 1960 levels by

2100. In contrast, by 2100, surface clear-sky UV in the Arctic is projected to be 0–10% below 1960 levels.

CHAPTER 4: STRATOSPHERIC CHANGES AND CLIMATE

- **Stratospheric climate trends since 1980 are better understood and characterized than in previous Assessments and continue to show the clear influence of both human and natural factors.**
  - **New analyses of both satellite and radiosonde data give increased confidence relative to previous Assessments of the complex time/space evolution of stratospheric temperatures between 1980 and 2009.** The global-mean lower stratosphere cooled by 1–2 K and the upper stratosphere cooled by 4–6 K from 1980 to about 1995. There have been no significant long-term trends in global-mean lower stratospheric temperatures since about 1995. The global-mean lower-stratospheric cooling did not occur linearly but was manifested as downward steps in temperature in the early 1980s and the early 1990s. The cooling of the lower stratosphere included the tropics and was not limited to extratropical regions as previously thought.
  - **The complex evolution of lower stratospheric temperature is influenced by a combination of natural and human factors that has varied over time.** Ozone decreases dominate the lower stratospheric cooling over the long term (since 1980). Major volcanic eruptions and solar activity have clear shorter-term effects. Since the mid-1990s, slowing ozone loss has contributed to the lack of temperature trend. Models that consider all of these factors are able to reproduce this complex temperature time history.
  - **The largest lower stratospheric cooling continues to be found in the Antarctic ozone hole region during austral spring and early summer.** The cooling due to the ozone hole strengthened the Southern Hemisphere polar stratospheric vortex compared with the pre-ozone hole period during these seasons.
  - **Tropical lower stratospheric water vapor amounts decreased by roughly 0.5 parts per million (ppm) around 2000 and remained low through 2009.** This followed an apparent but uncertain increase in stratospheric water vapor amounts from 1980–2000. The mechanisms driving long-term changes in stratospheric water vapor are not well understood.
  - **Stratospheric aerosol concentrations increased by between 4 to 7% per year, depending on location, from the late 1990s to 2009.** The reasons for the increases in aerosol are not yet clear, but small volcanic eruptions and increased coal burning are possible contributing factors.

- **There is new and stronger evidence for radiative and dynamical linkages between stratospheric change and specific changes in surface climate.**
  - **Changes in stratospheric ozone, water vapor, and aerosols all radiatively affect surface temperature.** The radiative forcing of climate in 2008 due to stratospheric ozone depletion (-0.05 ± 0.1 Watts per square meter, W/m^2) is much smaller than the

positive radiative forcing due to the chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) largely responsible for that depletion (+0.31 ± 0.03 W/m^2). Radiative calculations and climate modeling studies suggest that the radiative effects of variability in stratospheric water vapor (roughly ±0.1 W/m^2 per decade) can contribute to decadal variability in globally averaged surface temperature. Climate models and observations show that the negative radiative forcing from a major volcanic eruption such as Mt. Pinatubo in 1991 (roughly −3 W/m^2) can lead to a surface cooling that persists for about two years.

- **Observations and model simulations show that the Antarctic ozone hole caused much of the observed southward shift of the Southern Hemisphere middle latitude jet in the troposphere during summer since 1980.** The horizontal structure, seasonality, and amplitude of the observed trends in the Southern Hemisphere tropospheric jet are only reproducible in climate models forced with Antarctic ozone depletion. The southward shift in the tropospheric jet extends to the surface of the Earth and is linked dynamically to the ozone hole-induced strengthening of the Southern Hemisphere stratospheric polar vortex.

- **The southward shift of the Southern Hemisphere tropospheric jet due to the ozone hole has been linked to a range of observed climate trends over Southern Hemisphere mid and high latitudes during summer.** Because of this shift, the ozone hole has contributed to robust summertime trends in surface winds, warming over the Antarctic Peninsula, and cooling over the high plateau. Other impacts of the ozone hole on surface climate have been investigated but have yet to be fully quantified. These include: observed increases in sea-ice area averaged around Antarctica; a southward shift of the Southern Hemisphere stormtrack and associated precipitation; warming of the subsurface Southern Ocean at depths up to several hundred meters; and decreases of carbon uptake over the Southern Ocean.

- **In the Northern Hemisphere, robust linkages between Arctic stratospheric ozone depletion and the tropospheric and surface circulation have not been established, consistent with the comparatively small ozone losses there.**

- **The influence of stratospheric changes on climate will continue during and after stratospheric ozone recovery.**
  - **The global middle and upper stratosphere are expected to cool in the coming century, mainly due to carbon dioxide (CO_2) increases**. The cooling due to CO_2 will cause ozone levels to increase in the middle and upper stratosphere, which will slightly reduce the cooling. Stratospheric ozone recovery will also reduce the cooling. These ozone changes will contribute a positive radiative forcing of climate (roughly +0.1 W/m^2) compared to 2009 levels, adding slightly to the positive forcing from continued increases in atmospheric CO_2 abundances. Future hydrofluorocarbon (HFC) abundances in the atmosphere are expected to warm the tropical lower stratosphere and tropopause region by roughly 0.3 K per part per billion (ppb) and provide a positive radiative forcing of climate.

  - **Chemistry-climate models predict increases of stratospheric water vapor, but confidence in these predictions is low.** Confidence is low since these same models: 1) have a poor representation of the seasonal cycle in tropical tropopause temperatures

28

(which control global stratospheric water vapor abundances) and 2) cannot reproduce past changes in stratospheric water vapor abundances.

- **Future recovery of the Antarctic ozone hole and increases in greenhouse gases are expected to have opposite effects on the Southern Hemisphere tropospheric middle latitude jet.** Over the next 50 years, the recovery of the ozone hole is expected to reverse the recent southward shift of the Southern Hemisphere tropospheric jet during summer. However, future increases in greenhouse gases are expected to drive a southward shift in the Southern Hemisphere tropospheric jet during all seasons. The net effect of these two forcings on the jet during summer is uncertain.

- **Climate simulations forced with increasing greenhouse gases suggest a future acceleration of the stratospheric Brewer-Dobson circulation.** Such an acceleration would lead to decreases in column ozone in the tropics and increases in column ozone elsewhere by redistributing ozone within the stratosphere. The causal linkages between increasing greenhouse gases and the acceleration of the Brewer-Dobson circulation remain unclear.

- **Future stratospheric climate change will affect tropospheric ozone abundances.** In chemistry-climate models, the projected acceleration of the Brewer-Dobson circulation and ozone recovery act together to increase the transport of stratospheric ozone into the troposphere. Stratospheric ozone redistribution will also affect tropospheric ozone by changing the penetration of ultraviolet radiation into the troposphere, thus affecting photolysis rates.

CHAPTER 5: A FOCUS ON INFORMATION AND OPTIONS FOR POLICYMAKERS

Ozone Depletion Potentials (ODPs) and Global Warming Potentials (GWPs) are metrics frequently used to quantify the relative impacts of substances on ozone depletion and climate forcing. In Chapter 5, both ODPs and GWPs have been updated. The direct GWPs for some compounds presented here have not appeared previously in WMO/UNEP or Intergovernmental Panel on Climate Change (IPCC) assessments. Indirect GWPs have also been reevaluated.

INFORMATION FOR POLICYMAKERS

- **The Montreal Protocol is working. It has protected the stratospheric ozone layer from much higher levels of depletion by phasing out production and consumption of ozone-depleting substances (ODSs).** Simulations show that unchecked growth in the emissions of ODSs would have led to ozone depletion globally in the coming decades much larger than has been observed. Solar UV-B radiation at the surface would also have increased substantially.

- **The Montreal Protocol and its Amendments and Adjustments have made large contributions toward reducing global greenhouse gas emissions.** Because many ODSs are potent greenhouse gases, the Montreal Protocol has successfully avoided larger climate forcing. In 2010, the decrease of annual ODS emissions under the Montreal Protocol is estimated to be about 10 Gigatonnes (Gt) of carbon dioxide–equivalent

($GtCO_2$-eq) per year, which is about five times larger than the annual emissions reduction target for the first commitment period (2008–2012) of the Kyoto Protocol.

- **The accelerated hydrochlorofluorocarbon (HCFC) phaseout agreed to by the Parties to the Montreal Protocol in 2007 is projected to reduce cumulative HCFC emissions by 0.6–0.8 million ODP-tonnes between 2011 and 2050 and bring forward the year equivalent effective stratospheric chlorine (EESC) returns to 1980 levels by 4–5 years. In terms relevant to climate, the accelerated HCFC phaseout is projected to reduce emissions by 0.4–0.6 $GtCO_2$-eq per year averaged over 2011 through 2050.** The actual climate benefit will be determined, in part, by the climate impact of the compounds used to replace the HCFCs. In comparison, global anthropogenic emissions of CO_2 were greater than 30 Gt per year in 2008.

- **EESC at midlatitudes is projected to return to 1980 levels in 2046 for the baseline (A1) scenario, 2–3 years earlier than projected in the previous Assessment.** This revision is primarily due to an improved understanding of lower stratospheric chlorine and bromine release from ODSs, along with contributions from smaller projected HCFC emissions, and despite larger projected emissions of carbon tetrachloride (CCl_4) and a smaller 1980 mixing ratio of methyl bromide (CH_3Br).

- **EESC in the Antarctic vortex is projected to return to 1980 levels around 2073 for the baseline (A1) scenario, 7–8 years later than projected in the previous Assessment.** This is primarily due to an improved understanding of lower stratospheric chlorine and bromine release from ODSs, with smaller contributions from changes in the emissions of CCl_4 and HCFCs and a smaller 1980 mixing ratio of CH_3Br. The return to 1980 levels in the Antarctic vortex is about 26 years later than the return of midlatitude EESC to 1980 levels.

- **Due to the ongoing success of the Montreal Protocol and its Amendments and Adjustments in reducing the production, emissions, and abundances of controlled ODSs, other compounds and activities not controlled by the Montreal Protocol are becoming relatively more important to stratospheric ozone levels.**

- **Increasing abundances of radiatively important gases that are not controlled by the Montreal Protocol, especially CO_2, methane (CH_4), and nitrous oxide (N_2O), are expected to significantly affect future stratospheric ozone levels** (see also Chapter 3). Under many IPCC future scenarios, it is projected that these gases will cause globally averaged ozone changes larger than those resulting from any of the ODS reduction cases explored in this chapter.

- **A nitrous oxide (N_2O) ODP of 0.017 has been calculated. The anthropogenic ODP-weighted emission of N_2O is larger than that of any current halogenated ODS emission**. The ODP of N_2O is more uncertain than it is for halogenated substances, but it has been known since 1970 that N_2O depletes stratospheric ozone. Reductions in N_2O emissions would also reduce climate forcing.

- **Since the previous Assessment, new fluorocarbons have been suggested as possible replacements for potent HCFC and hydrofluorocarbon (HFC) greenhouse gases.** For example, HFC-1234yf ($CF_3CF=CH_2$) (ODP = 0; 100-year GWP = 4) is proposed to replace HFC-134a (CH_2FCF_3) (ODP = 0; 100-year GWP = 1370) in motor vehicle

30

(mobile) air conditioning. Each new fluorocarbon proposed as a replacement will require an evaluation for ODP, GWP, atmospheric fate, safety, and toxicity for a thorough understanding of its potential environmental impact. Preliminary analyses of the atmospheric fate of HFC-1234yf indicate that global replacement of HFC-134a with HFC-1234yf at today's level of use is not expected to contribute significantly to tropospheric ozone formation or harmful levels of the degradation product TFA (trifluoroacetic acid). It is well established that TFA is a ubiquitous natural component of the hydrosphere, but uncertainties remain regarding its natural and anthropogenic sources, long-term fate, and abundances.

OPTIONS FOR POLICYMAKERS

A new baseline scenario for ODSs is presented in Chapter 5 that reflects our current understanding of atmospheric mixing ratios, production levels, and bank sizes. Elimination of future emissions, production, and banks of various ODSs are applied to this scenario to evaluate the maximum impacts of various hypothetical phaseouts (see Table ESA-3). The year EESC returns to 1980 levels, and integrated EESC changes, are two metrics used in the evaluation. The calculations of the years when EESC returns to the 1980 level in these hypothetical cases do not consider other effects such as changing atmospheric transport and lifetimes. An elimination of anthropogenic N_2O emissions is also considered and compared to some ODS cases using globally averaged total ozone. In addition to the hypothetical cases discussed below, the impacts on stratospheric ozone of other activities, such as the use of automotive biofuels, commercial subsonic aircraft, and rocket launches, are considered in Chapter 5. These other activities are not expected to substantially affect stratospheric ozone now or in the near future.

- **Projections suggest that unmitigated HFC growth could result in GWP-weighted emissions up to 8.8 GtCO$_2$-eq per year by 2050, comparable to the GWP-weighted emissions of chlorofluorocarbons (CFCs) at their peak in 1988.** The highest of these projections assumes that developing countries use HFCs with GWPs comparable to those currently used in the same applications in developed countries. The projected radiative forcing in 2050 from these compounds (up to 0.4 W/m^2) can be reduced by using compounds with lower GWPs.

- **Options available for limiting future halocarbon emissions will have less impact on future ozone levels than what has already been accomplished by the Montreal Protocol.**

- **Leakage of CFCs and leakage of halons from the banks are the largest sources of current ODP-weighted emissions of ODSs.** A delay of four years, from 2011 to 2015, in the capture and destruction of the estimated CFC banks is currently thought to reduce the potential ozone and climate benefits from these actions by about 30%. The percentage impact of a four-year delay in the capture and destruction of the halon banks is similar.

- **Elimination of future CCl$_4$ emissions is now projected to have a larger impact on integrated EESC than was projected in the previous Assessment.** Recent observed CCl$_4$ mixing ratios have declined more slowly than previously projected. Extrapolation

Table ESA-3. Summary of hypothetical cases for accelerating the recovery of the ozone layer and reducing carbon-equivalent emissions. The table below shows the reductions in integrated EESC and integrated CO_2-eq emissions relative to the baseline (A1) scenario that can be achieved in several hypothetical cases. The EESC excess above 1980 levels is integrated from 2011 until the time EESC returns to the 1980 level (before 2050). Any potential contribution from very short-lived substances is neglected.

Substance or Group of Substances	Reductions (%) in Integrated EESC (equivalent effective stratospheric chlorine)		Reduction in Cumulative GWP-Weighted Emissions from 2011 to 2050 (Gt of CO_2-equivalent)	
	2011	*2015*	*2011*	*2015*
Bank capture and destruction in 2011 and 2015:				
CFCs	11	7.0	7.9	5.5
Halons	14	9.1	0.4	0.3
HCFCs	4.8	5.3 [1]	4.9	5.5 [1]
Production elimination after 2010:				
HCFCs		8.8		13.2
CH₃Br for quarantine and pre-shipment		6.7		0.002
Total emissions elimination after 2010:				
CCl₄ [2]		7.6		0.9
CH₃CCl₃				
		0.1		0.004
HFCs		0.0		Up to 170 [3]

[1] The impact of a 2015 HCFC bank recovery is larger than a 2011 bank recovery because this calculation assumes destruction of the bank in only a single year, and because the bank in 2015 is larger than the bank in 2011 owing to continued annual production that is larger than the annual bank release.

[2] Banks are assumed to be zero. Emissions include uncertain sources such as possible fugitive emissions and unintended byproduct emissions.

[3] Strongly dependent on future projections and does not consider HFC-23 emissions. HFCs are not controlled by the Montreal Protocol, but are included in the basket of gases of the Kyoto Protocol.

of this trend leads to larger future projected emissions in the baseline scenario and thus to the increased projected impact of the elimination of emissions.

- **The estimated impact on integrated EESC resulting from elimination of future HCFC production is slightly smaller than in the previous Assessment.** The recent growth in reported HCFC production in developing countries was larger than projected in the previous Assessment. This alone would have resulted in a larger projected HCFC production in the new baseline scenario compared to the previous Assessment, but is projected to be more than compensated for by the accelerated HCFC phaseout agreed to by the Parties to the Montreal Protocol in 2007. Projections suggest that total emissions

of HCFCs will begin to decline in the coming decade due to measures already agreed to under the Montreal Protocol.

- **The elimination of all emissions of chlorine- and bromine-containing ODSs after 2010 would shift the year EESC reaches the 1980 level by about 13 years, from 2046 to 2033.** In terms relevant to climate, this would reduce emissions of these substances by about 0.7 GtCO$_2$-eq per year averaged over 2011 through 2050. Future production of HCFCs and the sum of the current banks of CFCs plus HCFCs contribute about equally to this number. In comparison, global anthropogenic emissions of CO$_2$ were greater than 30 Gt per year in 2008.

- **A phaseout of methyl bromide emissions from quarantine and pre-shipment (QPS) applications beginning in 2011 would shift the year EESC reaches the 1980 level earlier by 1.5 years compared to continued use at current levels.** Continuing Critical Use Exemptions (CUEs) indefinitely at the approved 2011 level would delay the return of EESC to 1980 levels by 0.2 years.

- **Elimination of anthropogenic emissions of very short-lived substances (VSLS) could shift the year EESC reaches the 1980 level earlier by almost 3 years**, if anthropogenic VSLSs contribute 40 parts per trillion of EESC to the stratosphere. It remains unclear, however, how VSLS emissions reductions at different surface locations would affect their contribution to stratospheric chlorine. VSLSs are not controlled by the Montreal Protocol.