EXECUTIVE SUMMARY

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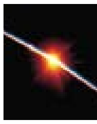
Synopsis

Depletion of the stratospheric ozone layer by human-produced ozone-depleting substances has been recognized as a global environmental issue for more than three decades, and the international effort to address the issue via the United Nations Montreal Protocol marked its 20-year anniversary in 2007. Scientific understanding underpinned the Protocol at its inception and ever since. As scientific knowledge advanced and evolved, the Protocol evolved through amendment and adjustment. Policy-relevant science has documented the rise, and now the beginning decline, of the atmospheric abundances of many ozone-depleting substances in response to actions taken by the nations of the world. Projections are for a return of ozone-depleting chemicals (compounds containing chlorine and bromine) to their "pre-ozone-depletion" (pre-1980) levels by the middle of this century for the midlatitudes; the polar regions are expected to follow suit within 20 years after that. Since the 1980s, global ozone sustained a depletion of about 5 percent in the midlatitudes of both the Northern Hemisphere and Southern Hemisphere, where most of the Earth's population resides; it is now showing signs of turning the corner towards increasing ozone. The large seasonal depletions in the polar regions are likely to continue over the next decade but are expected to subside over the next few decades. Ozone-depleting substances should have a negligible effect on ozone in all regions beyond 2070, assuming continued compliance with the Montreal Protocol.



Large increases in surface ultraviolet (UVB; 280-315 nm) radiation and the associated impacts on human health and ecosystems would likely have occurred if atmospheric abundances of ozone-depleting substances had continued to grow. Scientific findings regarding the role of ozone-depleting chemicals, projected ozone losses, and the potential UV impacts galvanized international decision making in the 1980s. As a result of the worldwide adherence to the 1987 Montreal Protocol and its Amendments and Adjustments, the large impacts were avoided, and future trends in UVB and UVA (315-400 nm) at the surface are expected to be more influenced by factors other than stratospheric ozone depletion (such as changes in clouds, atmospheric fine particles, and air quality in the lower atmosphere).

Emissions of ozone-depleting substances by the United States have been significant throughout the history of the ozone depletion issue. At the same time, the United States has played a leading role in advancing the scientific understanding, leading the international decision making, and leading industry's actions to reduce usage of ozone-depleting substances. Continued future declines in emissions of ozone-depleting substances from the United States, along with those from other nations, will play a key role in ensuring the ozone layer's recovery.

Projections of a changing climate have added a new dimension to the issue of the stratospheric ozone layer and its recovery, and scientific knowledge is emerging on the interconnections between these two global issues. Climate change is expected to alter the timing of the recovery of the ozone layer. Ozone-depleting chemicals and ozone depletion are known to influence climate change. The curtailment of the ozone-depleting substances not only helped the ozone layer but also very likely lessened the forcing of climate (*i.e.*, how it alters climate).

Climate change and ozone layer depletion are coupled; this has led to new scientific and decision-making challenges. The recovery of the ozone layer will occur in an atmosphere that is different from where we started roughly three decades back. Our scientific understanding of the connections between climate change and ozone layer depletion is at an early but rapidly advancing stage. That topic will remain a focus for the scientific community's efforts over the next few decades.

ES.1 WHAT IS OZONE LAYER DEPLETION AND WHY IS IT A CONCERN?

The stratospheric ozone layer lies in a region of the atmosphere approximately 15 to 45 kilometers (roughly 9 to 28 miles) above Earth's surface. The ozone layer acts as a protective shield, preventing most of the Sun's harmful ultraviolet (UV) radiation from reaching the surface. The depletion of the ozone layer can therefore lead to enhancements of the UV radiation that reaches Earth's surface, with consequences for human health, the Earth's ecosystems, and physical materials. The ozone layer and its changes can also alter the atmosphere's temperature structure and weather/climate-related circulation patterns.

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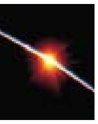

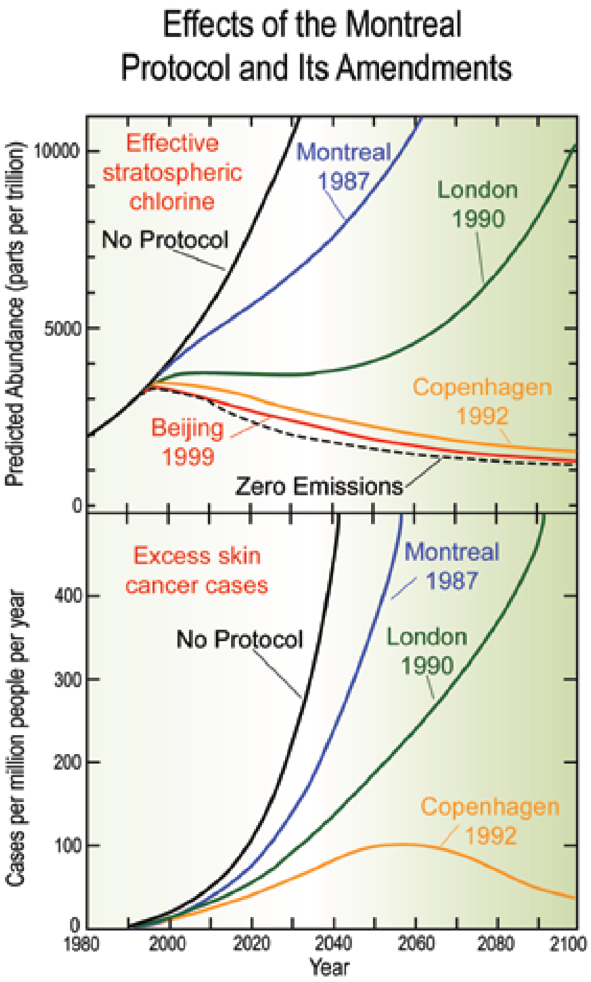

Figure ES.1 Effect of the Montreal Protocol. The top panel gives a measure of the projected future abundance of ozone-depleting substances in the stratosphere, without and with the Protocol and its various Amendments. The bottom panel shows similar projections for how excess skin cancer cases might have increased (adapted from Appendix A of this Report).

Research in the 1970s and early 1980s showed that the ozone-depleting substances (ODSs), mainly chlorofluorocarbons (CFCs) and certain compounds containing bromine, would deplete stratospheric ozone. The discovery of the springtime Antarctic ozone hole in 1985 showed that ozone depletion was real and occurring at that time, and was not just a prediction for the future.

Faced with the scientific consensus that ozone depletion was real and due to human-produced ozone-depleting substances, nations throughout the world agreed to the Montreal Protocol and its subsequent Amendments and Adjustments. The United States is a signatory to this protocol. The Protocol and its Amendments were successfully implemented starting in the late 1980s. Thus, this Protocol was one of the first international agreements to address a global environmental problem. The Montreal Protocol has had clear benefits in reducing ozone-depleting substances, placing the ozone layer on a path to recovery, and protecting human health (Figure ES.1).

Ozone layer depletion, like climate change, is a global issue with regional impacts. The depletion of the ozone layer is caused by the collective emissions of human-produced ozone-depleting substances at Earth's surface from various regions and countries. These ozone-depleting substances persist long enough in the atmosphere to be quite well mixed in the lower atmosphere and then be transported to the stratosphere, where their interaction with the harsh UV radiation releases chlorine and bromine. Thus, they pose a global threat, regardless of where on Earth's surface they are emitted. Emissions of ozone-depleting substances arise from their use as coolants, fire-extinguishing chemicals, electronics cleaning agents, and in foam blowing and other applications. The contributions to the global atmospheric burden of these ozone-depleting substances vary by regions and countries. There are large variations in the extent and timing of ozone depletion in various regions, and the impacts are also different. Consequently, the impacts of ozone layer depletion can be different in different regions of the world.

The findings from this Synthesis and Assessment Product are summarized in three parts. Section ES.2 of this Executive Summary lists the findings to inform the public in general nontechnical terms, and Section ES.3 summarizes findings for those involved in potential policy formulation. The Executive Summary findings are backed up by a more technical set of findings, primarily for scientists and secondarily for those who want to delve more into the details. These technical findings are listed near the beginning of Chapters 2 through 5, and in Chapter 6 on Policy Implications for the United States. Appendix A of this Synthesis and Assessment Product provides extensive background material on the science regarding the ozone layer, ozone-depleting substances, surface ultraviolet radiation, and connections to climate change.

ES.2 KEY FINDINGS ABOUT THE OZONE LAYER, SURFACE UV, OZONE-DEPLETING SUBSTANCES, AND CONNECTIONS TO CLIMATE CHANGE

ES.2.1 The Ozone Layer, Ozone-Depleting Substances, and Climate Change: What Are the Connections?

Ozone layer changes caused by ozone-depleting substances are intertwined with the issue of climate change, even though the two issues have been distinct in most policy formulations.

Over the course of the past 20 years, the close connections between stratospheric ozone depletion and climate change issues have become clearer (Figure ES.2).

- Ozone-depleting substances and many of the chemicals being used to replace them are potent greenhouse gases that influence the Earth's climate by trapping terrestrial infrared (heat) radiation that would otherwise escape to space.
- Ozone is itself a greenhouse gas. The stratospheric ozone layer heats the stratosphere and, indirectly, the lower atmosphere (troposphere). Thus, stratospheric ozone is a key component that affects climate. Depletion of the ozone layer has a cooling effect on climate, though large uncertainties exist regarding this effect, which is a combination of multiple contributing factors.
- The recovery of the ozone layer is influenced not only by the decreases in ozone-depleting substances required by the Montreal Protocol, but also by changes to climate and Earth's atmospheric composition.

Ozone-depleting substances are continuing to make a significant contribution to global climate change, but in the future ODSs are expected to make a smaller and smaller contribution. The direct ODS contribution to global climate change between 1750 (pre-industrial times) and 2005, as measured by a quantity called radiative forcing that is a metric for the ability to force climate change, is approximately 20% of that from carbon dioxide (CO_2), the largest human-caused contributor to global radiative forcing (Figure ES.3). The combined radiative forcing from ODSs and substitutes including hydrofluorocarbons (HFCs) is still increasing, but at a much slower rate than in the 1980s. The total contribution of human-produced ODSs and substitutes in 2005 was about 15% of the contribution from the major greenhouse gases (CO_2, methane [CH_4], nitrous oxide [N_2O]). The ODS contribution is expected to decline in coming decades as ODS emissions decline and CO_2 emissions continue to rise.

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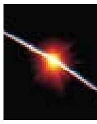


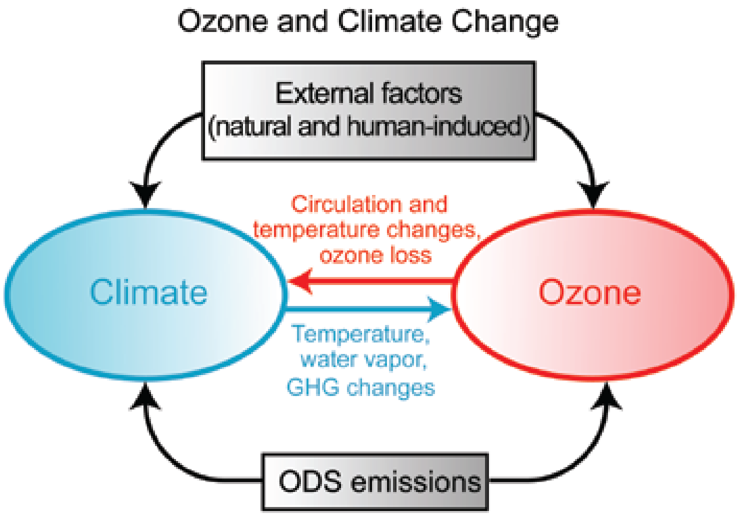


Figure ES.2 Simplified schematic of some of the processes that interconnect the issues of ozone layer depletion and climate change (adapted from Chapter 4 of this Report).

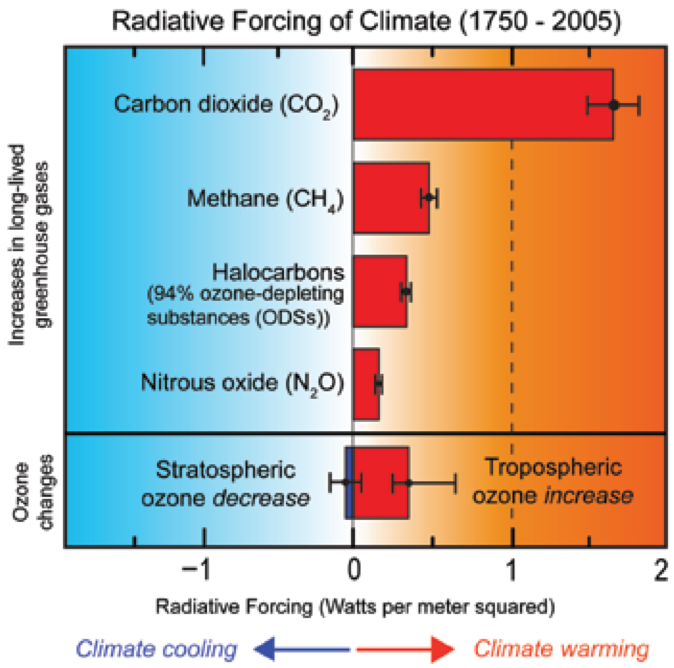
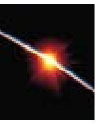


Figure ES.3 Radiative forcing values for the principal contributions to climate change from atmospheric gas changes since preindustrial times, including halogen-containing gases such as ODSs, and the cooling caused by depletion of stratospheric ozone. These climate influences are expressed as radiative forcings, a metric for the ability to force climate change (adapted from IPCC, 2007).



Total global production and consumption of ozone-depleting substances (ODSs) have declined substantially since the late 1980s in response to the Montreal Protocol. Hence, the total amount of ODSs in the atmosphere is now decreasing both in the troposphere and stratosphere.

Depletion of stratospheric ozone since about 1980 is estimated to have caused a slight *negative* (cooling) radiative forcing of climate (approximately –0.05 Watts per meter squared [W per m^2] with a range of −0.15 to +0.05 W per m^2) (Figure ES.3). While this forcing is likely to be a cooling term (*i.e.*, in the opposite direction to climate forcing by the ODSs that caused the depletion) it has large uncertainties. Globally averaged, it may even represent a warming within the error bars, or it could offset a large portion (up to 44%) of the ODS warming, while the current best estimate is an offset of approximately 15%. This estimate is based on observed ozone changes and assumes that they are due entirely to ODSs. Recent research has shown that ozone cooling and ODS warming often occur in different places and times, making it less appropriate to consider the two terms as offsetting one another than previously thought.

Climate change will lead to either increases or decreases in ozone abundances depending on the location in the atmosphere and the magnitude of climate change. While the surface temperature has increased, observed stratospheric temperature decreased starting in the 1960s and it is expected to continue to decrease. The global average trend is attributed mainly to ozone depletion, increased CO_2, and changes in water vapor. Dynamical changes are also likely to be important for local temperature changes, but are not significant for global mean stratospheric temperature trends. Stratospheric temperatures influence ozone amounts through chemical and transport processes. Stratospheric water vapor influences stratospheric ozone through chemistry, formation of polar stratospheric clouds, and changes in temperature.

ES.2.2 Ozone-Depleting Substances: Past, Present, and Future

The Montreal Protocol has been effective in reducing the use of ozone-depleting substances. Assuming continued compliance with the Protocol, the atmospheric abundance of ODSs is expected to decline back to its pre-1980 level by the middle of this century.

Total global production and consumption of ODSs have declined substantially since the late 1980s in response to the Montreal Protocol. By 2005, the annual aggregated production and consumption magnitudes of the ODSs, after accounting for their differences in ozone depletion capabilities, had declined 95 percent from peak amounts produced and consumed in the late 1980s.

In response to these global production and consumption changes, global ODS emissions have declined. Hence, the total amount of ODSs in the atmosphere, as measured by their combined ability to deplete the ozone layer, is now decreasing both in the troposphere and stratosphere.

In this Report, future halocarbon emissions are derived using a new bottom-up approach for estimating emissions from the sizes of the banks (ODSs produced but not yet released). The new method gives future CFC emissions that are higher than previously estimated in WMO (2003). There are still some uncertainties in the future abundances of ODSs.

The effective sum of chlorine and bromine in the stratosphere, with bromine weighted by its larger per-atom efficiency in depleting ozone, is estimated to recover to the 1980 value between 2040 and 2050 in the midlatitudes (Figure ES.4) and between 2060 and 2070 in the polar regions.

ES.2.3 Ozone in the Stratosphere: Past, Present, and Future

Total global ozone, as well as seasonal springtime ozone in both southern and northern polar regions, exhibited declines since the early 1980s, but recent observations show that ozone depletion is not worsening and in some atmospheric regions is showing signs that recovery has started. Ozone in the future is projected to recover as the atmospheric amounts of ODSs decline over the next few decades (with recovery above midlatitudes and the Arctic preceding Antarctic recovery). With continued adherence to the Montreal Protocol, ozone-depleting substances identified in the Protocol should have a negligible effect on ozone in all regions beyond 2070.

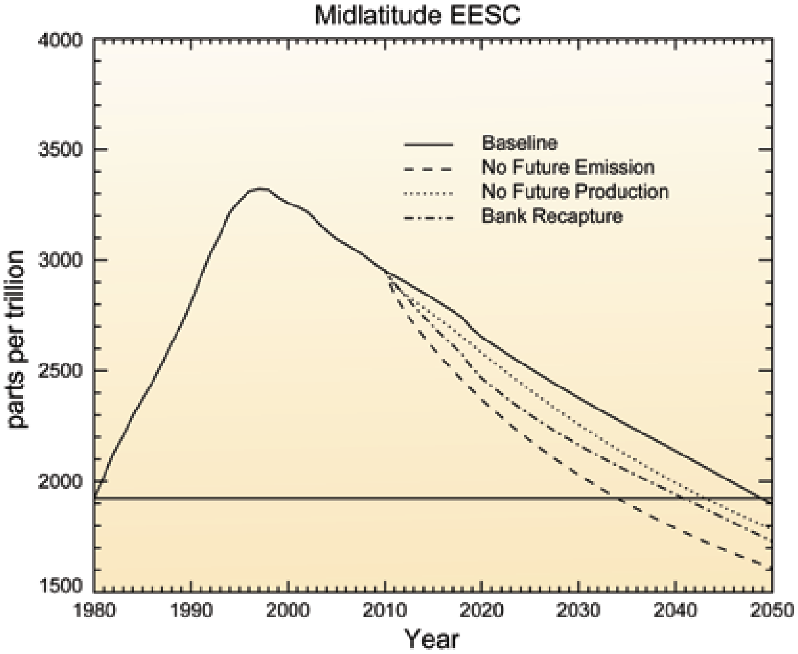
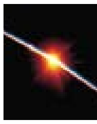


Figure ES.4 Estimates (presented in parts per trillion, [ppt]) of the effective sum of ozone-depleting chlorine and bromine in the stratosphere (called Equivalent Effective Stratospheric Chlorine, [EESC]), a metric that accounts for the differences in ozone depletion capabilities of chlorine and bromine. Estimates in the past are based upon observations, and estimates in the future are based upon a baseline scenario and three comparative test cases. The horizontal line represents the 1980 ("pre-ozone-depletion") level of EESC (adapted from WMO, 2007).



Total global ozone declined by roughly 5 percent since the early 1980s but has remained relatively constant over the last four years (2002 to 2006). Northern midlatitude ozone reached a minimum in 1993, and has increased somewhat since then. The 1993 minimum largely resulted from the increase of particles in the stratosphere caused by the eruption of Mt. Pinatubo. Southern midlatitude ozone decreased until the late 1990s, and has been constant since. There are no significant total ozone trends over the tropics.

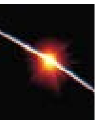
Ozone depletion in the upper stratosphere, where the influence of chlorine is easiest to detect, has slowed and has closely followed the trends in the sum of total chlorine. Although bromine plays a lesser role than chlorine in controlling ozone in the upper stratosphere, it too shows signs of leveling off in the stratosphere (see Section 2.4.2).

Antarctic ozone depletion can be measured in different ways, such as the total amount of ozone lost (called mass deficit), the minimum values of ozone observed, and the geographical area of the ozone hole. Over the last decade (1995 to 2006), the Antarctic ozone depletion by all these measures has not worsened. The ozone hole area and ozone mass deficit were observed to be below average in some recent winter years while higher minimum column amounts have also been recorded. This variability results from the strong influence of meteorological variability on ozone amounts, and not from any changes in the amounts of chlorine and bromine available for ozone depletion. Declines in the amounts of chlorine and bromine available for ozone depletion are likely quite small in this region.

Recent observations show that ozone depletion is not worsening and in some atmospheric regions is showing signs that recovery has started.

Arctic spring total ozone values over the last decade were lower than values observed in the 1980s. In addition, spring Arctic ozone is highly variable depending on meteorological conditions. For current halogen levels, human-caused chemical loss and variability in ozone transport are about equally important for year-to-year Arctic ozone variability. Colder-than-average vortex conditions result in larger halogen-driven chemical ozone losses.

If volcanic eruptions that inject material into the stratosphere were to occur in the coming



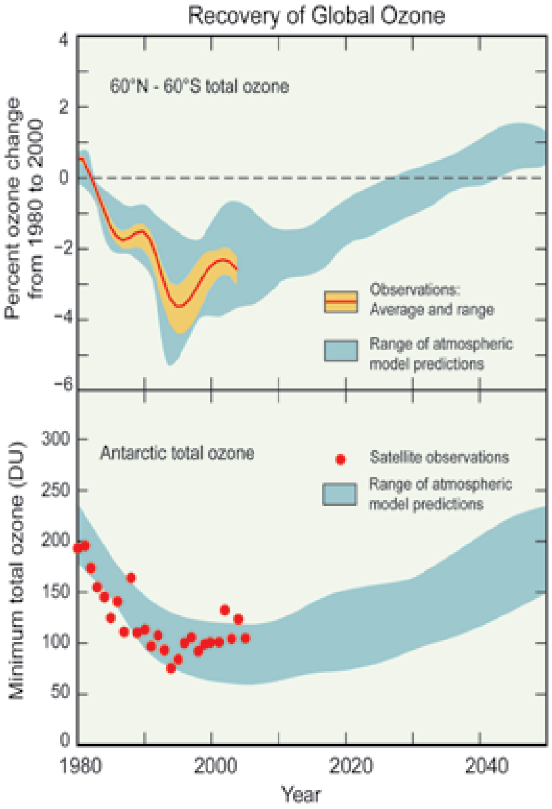


Figure ES.5 Global ozone recovery predictions (derived from Fahey, 2007).

decades, they are expected to cause major temperature and circulation changes in the stratosphere as have occurred after past eruptions. The changes are caused by the large increases in fine particles formed from sulfur dioxide injected into the stratosphere following such eruptions. The increases result in a transient shift in stratospheric ozone levels and climate because natural processes gradually remove the additional sulfate particles after the eruption.

The Montreal Protocol and its Amendments have prevented large increases in global surface ultraviolet radiation.

Assuming an absence of volcanic injections into the stratosphere, and based on the projected changes in ozone-depleting substances and changes in the major climate-relevant trace gases, modeling calculations predict the following for the future of the ozone layer (Figure ES.5).

- The ozone content between 60°N and 60°S, between now and 2020, will increase in response to decreases in halogen loading.
- Global ozone is expected to return to its 1980 value up to 15 years earlier than the halogen recovery date because of stratospheric cooling and changes in circulation associated with greenhouse gas emissions.
- Global ozone abundances (from 60°N to 60°S) are expected to be 2 percent above the 1980 values by 2100 for the assumed scenario for greenhouse gases noted in this report. Values at midlatitudes could be as much as 5 percent higher.

The minimum ozone value for Antarctic ozone is projected to start increasing after 2010 in several model calculations, while another measure of ozone depletion (the ozone mass deficit, the total amount lost in a season) begins decreasing around 2005 in most models.

- Model simulations show that the ozone amount in the Antarctic will reach the 1980 values 10 to 20 years earlier than the 2060 to 2070 time frame of when the ODSs reach their 1980 levels in polar regions.
- Ozone in the Arctic region is expected to increase as ODSs decline in the atmosphere. Because of large interannual variability, the simulated results do not show a smooth monotonic recovery of Arctic ozone. The dates of the minimum ozone from different models occur between 1997 and 2015.
- Most climate chemistry models show Arctic ozone values by 2050 larger than the 1980 values, with the recovery date between 2020 and 2040.

The above projections are based on currently available models. As our scientific understanding and modeling capabilities continue to evolve, our best predictions of the timing and extent of ozone layer recovery will also evolve.

ES.2.4 Surface Ultraviolet Radiation: Past, Present, and Future

The Montreal Protocol and its Amendments have prevented large increases in global surface UVB radiation. As the stratospheric ozone layer recovers over the next few decades, factors such as changes in clouds, atmospheric fine particles, and air quality in the lower atmosphere will be the dominant factors influencing future UV changes.

Surface UVB changes resulting from ozone depletion over Antarctica in early austral spring have been very large. Changes in the surface

UVB due to ozone depletion in most other locations of the world have not been clearly discernable, because the effects have been much smaller compared with changes due to other factors. For example, trends in UV exposure changes at ground level in the midlatitude United States attributable to ozone changes are difficult to discern from ground-based observations, since the observations are also dependent on changes in clouds and pollution from suspended fine particles in the air. What is clear is that in the absence of the Montreal Protocol, ozone depletion would have caused increases in surface UV by 2010 over most of the world, to such an extent that other factors (*e.g.*, clouds, atmospheric fine particles, air quality) would have been of relatively minor importance.

Possible future UV trends at the surface are likely to be influenced more by changes in clouds, atmospheric fine particles, and lower atmosphere air quality than by ozone layer depletion.

ES.3 IMPLICATIONS FOR THE UNITED STATES: IMPACTS, ACCOUNTABILITY, AND POTENTIAL MANAGEMENT OPTIONS

It is not possible to make a simple connection between emissions of ozone-depleting substances from the United States and the depletion of ozone above the country. This is because ODSs persist long enough in the atmosphere to be quite well mixed in the global lower atmosphere, before transport to the stratosphere occurs. Thus, ODSs pose a global threat, regardless of where on Earth's surface they are emitted. However, the depletion of stratospheric ozone over the various regions of the United States, and the contribution of emissions from the United States to the global burden of ozone-depleting substances, can be quantified.

Impacts: Changes in Ozone and Surface Ultraviolet Radiation over the United States

Ozone depletion above the continental United States (*i.e.*, the midlatitudes) has essentially followed the depletion occurring over the northern midlatitude regions: a decrease to a minimum around the mid-1990s and a slight increase since that time. The minimum total column ozone amounts over the continental United States, reached in 1993, were about 5 to 8 percent below the amounts present prior to 1980. The ozone increase since 1993 has diminished the ozone deficit to about 2 to 5 percent below the pre-1980 amounts. These midlatitude ozone changes are estimated to contain a significant contribution from the ozone depletion that occurs in the Arctic during springtime.

Ozone over Northern high latitudes, such as over northern Alaska, is most influenced by Arctic springtime total ozone values, which in recent years have been lower than those observed in the 1980s. The springtime ozone depletions are highly variable from year to year.

Calculations based on satellite observations of column ozone and surface reflectivity suggest that the averaged erythemal irradiance (which is a weighted combination of UVA and UVB based on skin sensitivity) over the United States had increased roughly by about 7 percent at the time when the ozone minimum was reached in 1993 and is now about 4 percent higher than in 1979. Direct surface-based observations do not show significant trends in UV levels over the United States over the past three decades because effects of clouds and atmospheric fine particles have likely masked the increase in UV due to ozone depletion over this region.

Accountability: United States Contributions to Ozone-Depleting Substances

The contributions of the United States to the emission of ODSs to date have been significant. For example, in terms of dispersive uses of ODSs regulated and restricted by the Montreal Protocol, emissions from the United States accounted for between 15 and 39 percent of the overall atmospheric abundance of ODSs measured between 1994 and 2004. The United States has also contributed significantly to emission reductions of ODSs, thereby helping efforts to achieve the expected recovery of the ozone layer and prevent large surface UV changes.

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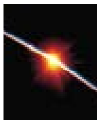

Future Options

United States emissions of ODSs in the future, like those from other developed nations, will be determined largely by the size of ODS "banks," *i.e.*, those ODSs that are already produced but not yet released to the atmosphere. While global ODS banks are estimated to have been 2960 ODP-kilotons (Kt) in 2005, ODS banks in the United States then were 830 ODP-Kt. Of this U.S. bank, approximately 210 ODP-Kt has been classified as accessible by the U.S. Environmental Protection Agency. The expected future declining emissions of ODSs from the United States and throughout the globe will also aid in reducing the climate forcing from these substances. While global banks amounted to between 5 and 24 Gt CO_2-equivalents, the accessible bank of hydrochlorofluorocarbons (HCFCs) in the United States, for example, amounted to between 0.9 and 1.1 Gt CO_2-equivalents.

Without the Montreal Protocol regulations, the levels of ODSs around 2010 likely would have been more than 50% larger than currently predicted. The increases in ODSs would have caused a corresponding substantially greater global ozone depletion.

While the Montreal Protocol has had a large beneficial effect on current and projected ozone depletion, options remain for the United States, and other countries as well, to reduce ozone depletion arising from ozone-depleting substances over the coming decades. The greatest reduction possible would be obtained from the hypothetical cessation of all future emissions of ozone-depleting substances (including emissions from banks and future production). If such a cessation had been implemented globally in 2007, the anticipated return of the ozone-depleting substances to their 1980 level would be advanced by about 15 years.

Methyl bromide is a potent ODS that has significant quarantine and pre-shipment (QPS) uses that are not restricted by the Montreal Protocol, and Critical Use Exemptions (CUEs) that are currently large compared to restricted uses. The importance of human-emitted methyl bromide to future ozone depletion will depend on the future magnitude of emissions from these unrestricted uses and from CUEs. Reducing these emissions would benefit the ozone layer.

The World Avoided

Without the Montreal Protocol regulations, the levels of ODSs around 2010 likely would have been more than 50 percent larger than currently predicted (Figure ES.1). The abundances in the remaining twenty-first century would have depended on the specific actions taken by humankind. The increases in ODSs would have caused a corresponding substantially greater global ozone depletion. The Antarctic ozone hole would have persisted longer and may have been even larger than what has been observed to date.