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 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. Global ozone sustained a depletion of about 5% since the 1980s in the midlatitudes of both the Northern Hemisphere and Southern Hemisphere, where most of the Earth's population resides; it is showing signs of turning the corner toward the return to 1980 levels. 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 (UV) radiation and the associated impacts on human health and ecosystems would 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 UV trends 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 depletion. 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 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. 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 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.

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

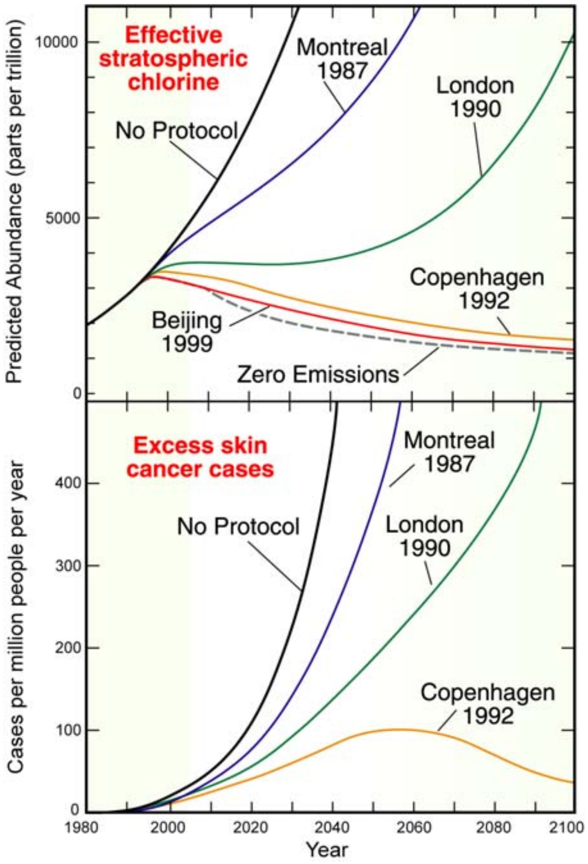

Figure ES.1 Effect of the Montreal Protocol. The top panel gives a measure of the projected future abundance of ozone-depleting substances in the stratosphere, without and with the Protocol and its various Amendments. The bottom panel shows similar projections for how excess skin cancer cases might have increased. (From Fahey, 2007)

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. This 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. Thus, they pose a global threat, irrespective 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. Below, 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, and the stratospheric ozone layer heats the stratosphere and lower atmosphere (troposphere) and is a key component that affects climate. Depletion of the ozone layer thereby influences climate.
- 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.

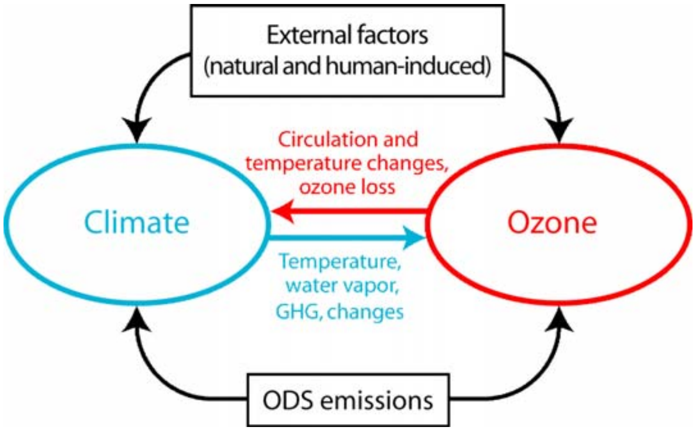

Figure ES.2 Simplified schematic of some of the processes that interconnect the issues of ozone layer depletion and climate change. (Adapted from Chapter 4 of this report)

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 ODS contribution to global climate change between 1750 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, the largest anthropogenic contributor to global radiative forcing (Figure ES.3). The combined radiative forcing from ODSs and substitutes including 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 (carbon dioxide, methane, and nitrous oxide). The ODS contribution is expected to decline in coming decades as ODS emissions decline and CO_2 emissions continue to rise.

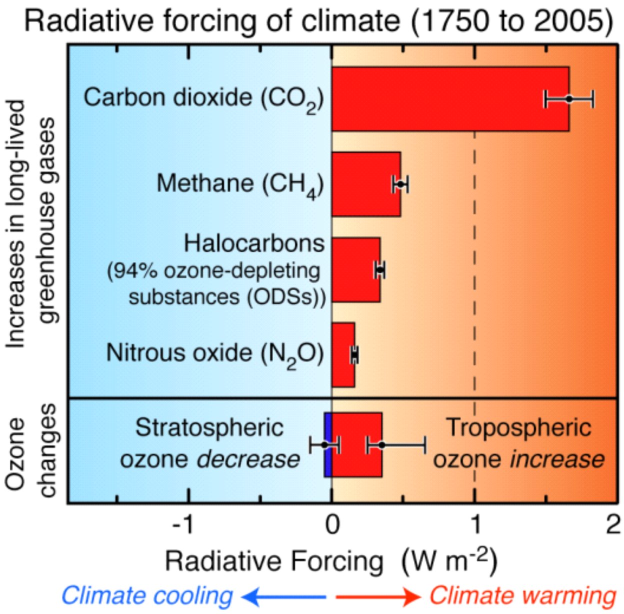

Figure ES.3 Radiative forcing values for the principal contributions to climate change from atmospheric gas changes since preindustrial times, including halogen-containing gases such as ODSs, and the cooling caused by depletion of stratospheric ozone. These climate influences are expressed as radiative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

Depletion of stratospheric ozone since about 1980 has caused a slight *negative* (cooling) radiative forcing of climate (approximately –0.05 W per m^2). This forcing is small; it is roughly 15% of, and in the opposite direction to, climate forcing by the ODSs that caused the depletion. Thus, ozone layer depletion currently does not appear to significantly offset the positive (warming) climate forcing by ODSs that caused the depletion (Figure ES.3).

Climate change will lead to either increases or decreases in ozone abundances depending on the location in the atmoshpere and the magnitude of climate change. Observed stratospheric temperature decreases began in the 1960s and are expected to continue. This trend is attributed to ozone depletion, increased carbon dioxide (CO_2), and changes in water vapor. 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% 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 ozone-depleting substances 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.

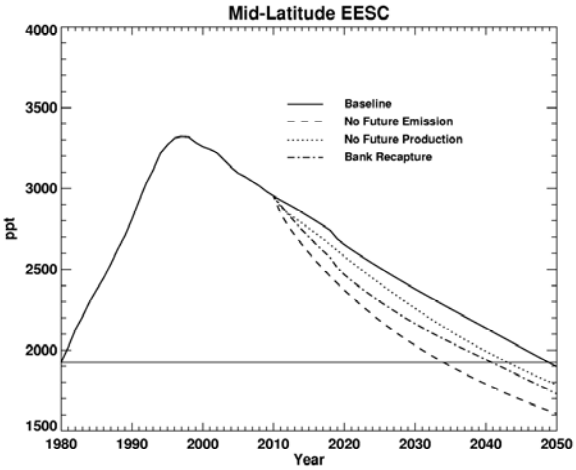

Figure ES.4 Estimates of the effective sum of ozone-depleting chlorine and bromine in the stratosphere (called Equivalent Effective Stratospheric Chlorine, EESC), a metric that accounts for the differences in ozone depletion capabilities of chlorine and bromine. Estimates in the past are based upon observations, and ones 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; see also chapter 5)

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 of beginning recovery. 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.

Total global ozone declined by roughly 5% 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 present due to the eruption of Mt. Pinatubo. Southern midlatitude ozone decreased until the late 1990s, and has been constant since. There are no significant 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 chlorine plus bromine. The slowdown of the negative (or decreasing) trend may be attributed to the fact that ozone-depleting chlorine and bromine are leveling off in this region of the stratosphere.

Antarctic ozone depletion can be measured in different ways, *e.g.*, total amount of ozone lost (called mass deficit), minimum values of ozone observed, geographical area of the ozone hole, *etc*. Over the last decade (1995 to 2006), the Antarctic ozone depletion by 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.

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 explosive volcanic eruptions were to occur in the coming 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 only a short-term shift in stratospheric ozone levels and climate because natural processes gradually remove the additional sulfate particles within a few years after the eruption.

Based on the projected changes in ozone-depleting substances and changes in the major climate-relevant trace gases, assuming no changes in activities such as a volcanic eruption, and using modeling calculations, the following are predicted for the future of the ozone layer (Figure ES.5):

- The ozone content between 60°N – 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 are expected to be 2 to 5% above the 1980 values by 2100 for the assumed scenario for greenhouse gases noted in this report.
- 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.

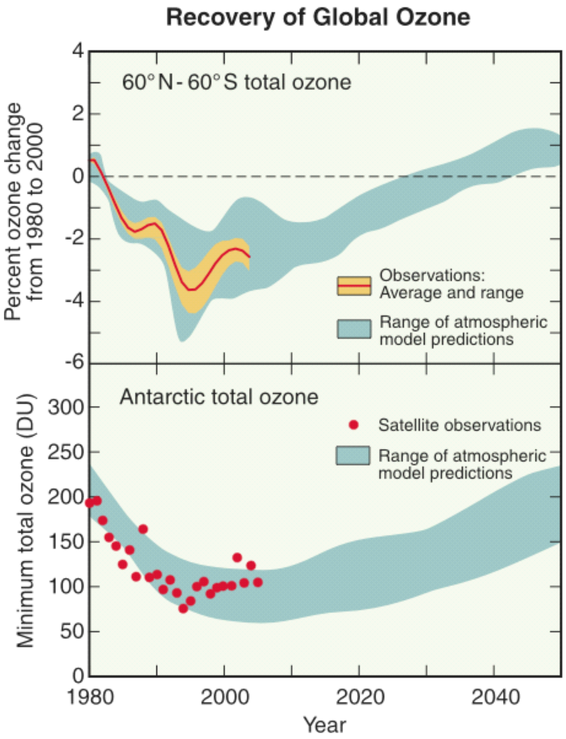

Figure ES.5 Global ozone recovery predictions. (From Fahey, 2007)

- 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 ozone-depleting substances 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 UV 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 UV changes resulting from ozone depletion over Antarctica in early Austral Spring have been very large. Changes in the surface UV 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 are difficult to discern and are dependent on changes in clouds and pollution from suspended fine particles in the air in addition to ozone changes. 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.

The future UV trend at the surface is likely to be influenced more by changes in cloud, aerosols, 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 with 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, irrespective of where on Earth's surface they are emitted. However, the depletion of stratospheric ozone over the various United States regions, 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 5-8% below the amounts present prior to 1980. The ozone increase since 1993 has diminished the ozone deficit to about 2-5% below the pre-1980 amounts. These midlatitude ozone changes are estimated to have 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 reflectivity of the surface 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% at the time when the ozone minimum was reached in 1993 and is now about 4% 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 aerosol have likely masked the increase in UV due to ozone depletion over this region.

Accountability: U.S. 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 the regulated uses of ODSs, emissions from the United States accounted for between 15 and 39% of the overall atmospheric abundance of ODSs measured during 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.

Future Options

United States emissions of ODS in the future, like those from other developed nations, will be determined to a large extent by the size of "banks of ODSs," *i.e.*, those ODSs that are already produced but not yet released to the atmosphere. The expected future declining emissions of ODSs from the United States will also aid in reducing the climate forcing from these substances.

While the Montreal Protocol has had a large beneficial effect on current and projected ozone depletion, there remain options 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 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 unregulated quarantine and pre-shipment uses, and critical use exemptions that are large compared to current regulated uses. The importance of human-emitted methyl bromide to future ozone depletion will depend on the magnitude of these future unregulated uses and of the critical use exemptions. Reducing such unregulated 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% larger than currently predicted (Figure ES.1). The abundances in the remaining 21st 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.

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