CHAPTER 6

Implications for the United States

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6.1 INTRODUCTION

The depletion of the stratospheric ozone layer due to human-produced ozone-depleting substances (ODSs) is a global phenomenon. Emissions of ODSs from around the globe contribute to depletion of the ozone layer throughout much of the stratosphere. ODSs emitted from different locations are well mixed within most of the lower atmosphere before they reach the stratosphere, where they contribute to chemical ozone depletion. Consequently, ozone depletion above a specific location is caused collectively by ODS emissions from different locations around the globe.

The observed pattern of the ozone depletion is not uniform around the globe; depletion above one region may differ from that above another region. However, this is not because of variations in emissions among regions, but because chemical and dynamical processes in the stratosphere cause regional variations in ozone and ozone loss rates. The extent of ozone depletion over a given region also varies with season and its overall magnitude changes with time. Consequently, the increase in ultraviolet (UV) light at the Earth's surface due to the depletion of the stratospheric ozone layer also varies with region and time.

Ozone depletion above a specific location is caused by the emissions of ozone-depleting substances from around the globe.

Because of these factors, a simple connection cannot be drawn between emissions of ODSs from a country or a region and the depletion of stratospheric ozone above that country or region. For example, there is substantial ozone depletion each austral spring over Antarctica, a continent with essentially no emissions of ozone-depleting substances. In contrast, the decrease in stratospheric ozone at northern midlatitudes, where the dominant emissions of ODSs occur, is significantly less.

The decades of release of ODSs, the associated decreases in stratospheric ozone and increases in surface UV radiation, along with the influence of ozone depletion and of ODSs on climate, have important implications for the United States. These implications can be viewed by examining three areas: impacts, accountability, and potential management options. Each area will be summarized in the following sections. The discussion of impacts will highlight past, present, and future changes in stratospheric ozone, surface UV radiation, and globally averaged radiative forcing. The section on accountability will address the United States' contributions to the emissions of ODSs and the associated contributions to Equivalent Effective Stratospheric Chlorine (EESC) and radiative forcing of the Earth's climate. In the section on potential management options, we will attempt to provide a scientific perspective of ODS issues that can be used for supporting future management decisions. These issues will be discussed generically without addressing any specific option.

6.2 IMPACTS

The changes in stratospheric ozone and surface UV radiation vary considerably among regions of the United States, which stretches over a wide range of latitudes in the Northern Hemisphere. Arctic ozone losses impact Alaska most prominently, while subtropical ozone changes affect Hawaii as well as Guam, Puerto Rico, and other United States territories.

Ozone above the continental United States and other northern latitudes decreased to a minimum in 1993 and has increased since that time.

6.2.1 Changes in Ozone over the United States

The changes in total column ozone amounts for various regions around the globe have been derived from observations made by both satellite and ground-based instruments. The ozone trends reported here are derived primarily from the satellite data.

- Ozone decreases above the continental United States have essentially followed those occurring over the northern midlatitudes: a decrease to a minimum in about 1993, followed by an 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 those present prior to 1980. The decreases roughly followed the increases in atmospheric abundance of ozone-depleting substances, which reached its maximum in roughly 1995. The ozone minimum occurred earlier than the maximum in ozone-depleting substances in large part due to the atmospheric changes brought about by the eruption of Mt. Pinatubo in 1991 (as discussed in Chapter 3). Column ozone increases since 1993 have brought the ozone deficit back to about 2 to 5 percent below the pre-1980 amounts. Model calculations suggest that these midlatitude ozone changes may have a significant contribution from the mixing of lower stratospheric ozone-depleted air from the northern polar latitudes during the spring period.
- Ozone depletion over northern high latitudes, such as over northern Alaska, is strongly influenced by Arctic springtime total ozone values, which have been significantly lower than those observed in the 1980s. However, these Arctic springtime ozone depletions are highly variable from year to year.
- There has been no significant ozone depletion at the lower latitudes of the tropics and subtropics around the globe. Hence, column ozone over the parts of the United States in these regions has been essentially unchanged from their 1980 values.

6.2.2 Changes in UV over the United States

Changes in UV levels over the United States have been obtained from ground-based and satellite-based measurements. Surface UV levels are strongly affected by clouds, atmospheric fine particles, and air pollution, in addition to stratospheric ozone depletion, making it difficult to attribute changes in UV to long-term changes in stratospheric ozone alone. This difficulty is particularly acute since stratospheric ozone depletion during the past three decades has been rather small (less than 10 percent), with the exception of the high latitudes. In a world without the Montreal Protocol, stratospheric ozone changes would have been much larger than have actually occurred, and the associated UV increases would have been so large as to stand out from other variability and be easily measured over a wide range of latitudes. In addition, ground-based records are of limited use in relating UV increases to ozone decreases that occurred during the 1980s and 1990s since many stations did not initiate measurements until the late 1990s, when ozone had already reached its minimum. A reliable way to derive the current changes in UV associated with ozone depletion is to use satellite measurements of atmospheric backscattered UV and the small amount reflected from the surface.

- Direct surface-based observations do not show significant UV trends for 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.
- Estimates of UV based on satellite measurements of column ozone and reflectivity of the surface suggest that the clear-sky erythemal irradiance (a weighted combination of UVA and UVB wavelength ranges based on skin sensitivity) over the

continental United States increased from 1979 to the mid-1990s by about 7 percent. Currently, this irradiance is about 4 percent higher than it was at the start of the record in 1979. Year-to-year seasonal variations ranged from only a few percent to about 20 percent.

- Barrow, Alaska, has experienced UVB increases in March and April related to springtime ozone depletion. While these increases are larger than those observed at midlatitudes in the mid-1990s, they are roughly ten times smaller than those observed at the southern high latitudes due to the Antarctic ozone hole.

6.2.3 Changes in Radiative Forcing

Globally averaged radiative forcing is a good metric for the relative contributions to climate change. Positive (negative) values for radiative forcing lead to warming (cooling). It is a reasonably good assumption that the global-average impacts from long-lived greenhouse gases scale with the magnitude of the globally averaged forcing. Many ODSs are themselves greenhouse gases, and hence ODSs contribute to radiative forcing.

The combined direct radiative forcing from ODSs and substitutes, including hydrofluorocarbons (HFCs), is still increasing, but at a slower rate than in the 1980s because the use of many ODSs (particularly chlorofluorocarbons [CFCs]) has been curtailed by the Montreal Protocol. This continued increasing trend in radiative forcing arises from continued increases in the atmospheric mixing ratios of hydrochlorofluorocarbons (HCFCs) and HFCs, which are being used as substitutes for CFCs in various applications.

- The total contribution of human-produced ODSs and substitutes to direct radiative forcing is approximately 0.34 W per m^2 (representing the change between pre-industrial times, *ca*. 1750, and the present), which is about 15 percent as large as the contribution from other greenhouse gases (1.66 W per m^2 from carbon dioxide [CO_2] plus 0.6 W per m^2 from methane [CH_4] and nitrous oxide [N_2O] together). The bulk of the direct forcing from halocarbons in 2005 was from CFCs (about 80 percent); other contributors include 10 percent from HCFCs, 7 percent from other ODSs, and 3 percent from HFCs. Projections of these contributions to 2100 under the SRES A1B emission scenario can be found in Chapter 5.

Changes in atmospheric ozone abundances contribute to climate change by modifying atmospheric radiative properties and atmospheric temperatures. Changes in stratospheric ozone are often considered to be indirect climate forcings of ODSs, though other processes have also influenced changes in stratospheric ozone over time.

- Depletion of stratospheric ozone since about 1980 is estimated to have caused a *negative* radiative forcing (cooling) on climate (of approximately −0.05 W per m^2), corresponding in absolute magnitude to about 15 percent of the total direct positive forcing by ODSs alone. However, the uncertainties on this forcing are large enough (±0.1 W per m^2, *i.e.*, a range of −0.15 to +0.05 W per m^2) to suggest that it could even be a *positive* radiative forcing (warming). Twentieth century increases in tropospheric ozone from pollution chemistry have caused a *positive* radiative forcing (of approximately +0.35 W per m^2). ODS emissions and abundances have very little influence over ozone abundances in the lower atmosphere.

The total contribution of human-produced ozone-depleting substances and substitutes to direct radiative forcing is about 15% as large as the contribution from other greenhouse gases.

6.2.4 Future Ozone and UV Changes over the United States

As stated earlier, changes in ozone over the United States should be similar to the changes occurring over similar latitudes around the globe. Ozone-depleting substances addressed by the Montreal Protocol and its amendments should have a declining effect on stratospheric ozone between now and 2050, and a small effect on stratospheric ozone beyond 2050, assuming compliance with the Montreal Protocol and if all other factors remain roughly the same. In order to predict the future trend of ozone in that time frame, one must consider projections for climate changes and changes in trace gases such as other halogens, CH_4, and N_2O (in addition to any changes in solar UV irradiance).

- Based on the prescribed surface concentrations of halocarbons used in the WMO (2007) baseline scenario (the scenario that was consistent with the Montreal Protocol provisions as of 2006), atmospheric halogen loading is estimated to recover to its 1980 value between 2040 and 2050 for midlatitudes, and between 2060 and 2070 for the polar regions.
- Between now and 2020, the simulated total ozone content between 60°N and 60°S will increase in response to this decrease in halogen loading.
- Three-dimensional climate chemistry models (3-D CCMs) predict that stratospheric cooling and changes in circulation associated with greenhouse gas emissions may enable global ozone to return to its 1980 value up to 15 years earlier than the expected halogen recovery date. Based on the assumed scenario for the greenhouse gases (which include CH_4 and N_2O), the ozone content is expected to be 2 to 5 percent above the 1980 values by 2100.
- Because of large interannual variability, the dates of the minimum in Arctic ozone from different models occur between 1997 and 2015. Most CCMs show Arctic ozone values at 2050 larger than the 1980 values, with recovery between 2020 and 2040. Results from the majority of the models indicate that future Arctic ozone depletion will not be significantly worse than what has already occurred.

By the end of this century, direct forcing from CFCs is expected to decrease to roughly 40% of its current value.

The future trend in surface UV is likely to be controlled more by changes in cloud cover, atmospheric fine particles, and tropospheric air quality than by changes in stratospheric ozone. Nevertheless, Equivalent Effective Stratospheric Chlorine (EESC) will still be a useful predictor for the relative effects of ODSs on future UV in terms of evaluating different scenarios.

6.2.5 Future Changes in Radiative Forcing

The radiative forcing from CO_2 increases to +5 W per m^2 by 2100 for the IPCC Special Report on Emission Scenarios (SRES) A1B scenario (Nakićenović**,** 2000), a scenario involving rapid economic growth and balanced energy sources. Forcing from halocarbons and their substitutes will decline in the future, assuming continued compliance with the Montreal Protocol, and is summarized below.

- Direct forcing from CFCs, which constitute a significant fraction of total ODS forcing in today's atmosphere, is expected to decrease from the current value of about +0.26 W per m^2 to about +0.1 W per m^2 by 2100. Direct forcing from HCFCs and other ODSs is expected to be negligible by 2100.
- The indirect forcing of ozone depletion is expected to approach zero when EESC returns to its 1980 levels, while the direct forcing due mainly to CFCs remaining in the atmosphere and the CFC substitutes that do not contain either chlorine or bromine (*e.g.*, HFCs) will continue.
- In the SRES A1B scenario, forcing from HFCs, which do not deplete stratospheric ozone, is predicted to increase to +0.15 W per m^2 and +0.24 W per m^2 by 2050 and 2100, respectively, while other scenarios result in smaller forcings from these chemicals. However, current observations suggest that the present atmospheric radiative forcing of the HFCs has been larger than computed for the SRES scenarios, primarily due to higher HFC-23 concentrations. Therefore, additional uncertainty perhaps should be attached to the SRES HFC projections.
- Changes in ozone due to changes in other trace gases (CH_4 and N_2O) and to changes in climate will also contribute to future forcing. For example, increases in atmospheric circulation due to climate change could increase the flux of ozone from the stratosphere to the troposphere, resulting in an additional positive radiative forcing.

6.3 ACCOUNTABILITY

As stated earlier, the amount of stratospheric ozone depletion at any location is, in large part, a result of long-lived ODSs emitted from all over the globe. In addition, ozone depletion in a given location is not simply and linearly related to ODS amounts in the atmosphere. Accordingly, there is no simple relationship between a country's contribution to global ODS emissions with the local ozone depletion occurring in

that region. To extend this association to local changes in UV radiation at the ground is further complicated by the dependence of UV on many local factors. Acknowledging this complexity, we can estimate the United States' contribution to the global emissions of ODSs to derive the United States' contribution to the atmospheric abundances of ODSs. We can then obtain a first approximation of the United States' contribution to ozone depletion at any location, and thereby estimate the United States' contribution to that portion of UV increase at that same location. In a similar manner, we can estimate the United States' contribution to changes in radiative forcing due to the emissions of ODSs.

This chapter uses several metrics to estimate the United States' ODS contributions. Ozone Depletion Potential (ODP) and Global Warming Potential (GWP) weighting is used to sum annual emissions to represent the United States' contribution in that particular year to future ozone depletion and radiative forcing. The same could be used for ODS "banks" since they represent potential future emissions. The atmospheric burden of a specific halocarbon calculated from historical United States emissions, when compared with the observed total burden, provides a measure of the United States' contribution to that halocarbon. The individual abundances can be combined using the formalism of Equivalent Effective Chlorine (EECl) and EESC to be used as a measure of ozone depletion contribution. Finally, radiative forcing calculated from the individual halocarbon abundances provides a measure of the United States' contribution to climate forcing.

6.3.1 Contribution of the United States to the Global Abundance of ODSs

It is difficult to accurately quantify the United States' contribution to the current atmospheric loading of ozone-depleting substances because of uncertainties associated with United States emission data prior to 1985. However, estimates of the United States' contributions to global consumption and emissions of ODSs for recent periods can be derived, respectively, from information compiled by the United Nations Environment Programme (UNEP) or from estimates made by the U.S. Environmental Protection Agency (EPA). It should be noted that consumption of ODSs can have different emission patterns (in location and time) depending on the particular end use of the ODS. The U.S. EPA vintaging model calculates ODS emissions based on a variety of factors associated with the use or product application of the ODS.

Production / Consumption

- Global production and consumption of ODSs have declined substantially since the late 1980s in response to the Montreal Protocol, its amendments and adjustments, and United States policy decisions. By 2005, annual global ODP-weighted production and consumption had declined 95 percent from the peak values of the late 1980s. By 2005, annual ODP-weighted production and consumption in the United States had declined by 97 to 98 percent based on UNEP data.
- During 1986 to 1994 the United States accounted for 25(±2) percent of the total annual global production and consumption of ODSs reported by UNEP when weighted by ODPs. From 2001 to 2005, this fraction has been 10(±2) percent. This decline has been maintained despite a slower decline in U.S. CH_3Br consumption reported to UNEP than in other nations owing to increased U.S. Critical Use Exemptions, CUEs (critical uses that are exempted from the Montreal Protocol). Increased CUEs caused the annual U.S. contribution to global CH_3Br consumption to increase from 23(±4) percent between 2000 to 2003, to 36(±1) percent during 2004 to 2005.

From 1986 to 1994, the United States accounted for about 25% of total production and consumption of ozone-depleting substances. From 2001 to 2005, this fraction had declined to 10%.

Burdens and EECl

- Taking into account the uncertainties in United States emissions estimates for past years, atmospheric chlorine from United States emissions accounted for 17 to 42 percent of global chlorine from regulated ODSs and substitute chemicals in 2005. Atmospheric chlorine from United States and global emissions has declined since the mid-1990s.
- The U.S. EPA vintaging model suggests that in 2005 the United States accounted for approximately 17 to 35 percent of the global atmospheric bromine burden arising from industrially produced CH_3Br and ha-

lons, similar to that calculated for the peak year, 1998. Changes in total tropospheric bromine from the United States emissions of ODSs regulated by the Montreal Protocol mimicked global trends until 2002. Further, the vintaging model suggests that bromine emissions from the United States began increasing in 2002, due primarily to increased emissions of CH_3Br.

- The decrease in tropospheric EECl since 1994 has been about 20 percent of what is needed to return EECl to 1980 values (*i.e.*, before substantial ozone depletion was observed). Atmospheric EECl calculated from United States emissions declined between 1994 and 2004; however, it declined much more slowly from 2004 to 2005. The United States accounted for 15 to 36 percent of EECl from industrially produced chemicals measured in the troposphere in 2005.

United States banks account for approximately 28 percent of total global banks of ozone-depleting substances.

Banks and Future Emissions

United States emissions of some ODSs in the future, like those from other developed nations, will be determined to a large extent by the size of the U.S. ODS "banks," *i.e.*, those ODSs that are already produced but not yet released to the atmosphere due to old devices, structures, and stockpiles that exist in the United States. The magnitude of halocarbon banks has been derived using a new bottom-up approach. This new method leads to larger CFC banks and yields potential future CFC emissions that are higher than previously estimated (WMO, 2003). The U.S. EPA has divided total banks into "accessible" and "non-accessible" categories, with accessible banks consisting of ODSs in refrigeration and air conditioning equipment and fire fighting equipment.

- If released in a single year, the ODS banks in the United States in 2005 would have been equivalent (in terms of their contribution to stratospheric ozone depletion) to 7 to 16 times the actual United States emissions of ODSs during that year.
- The U.S. EPA estimates that United States banks account for approximately 28 percent of global banks, whether they are accessible or not, of all ODSs (ODP-weighted). CFCs accounted for the largest fraction of the 2005 banks in the United States as well as throughout the globe.
- Approximately one-quarter of United States banks in 2005 were classified as being accessible (consisting of 210 ODP-kilotons, Kt) and these accessible banks were comprised predominantly of halons (roughly 140 ODP-Kt), CFCs (~38 ODP-Kt), and HCFCs (~31 ODP-Kt). CFCs accounted for 18 percent of the accessible banks of ODSs as defined currently by the U.S. EPA.
- Banks play an important role in current HCFC emission rates. Future emissions of HCFCs will also be determined by the magnitude of any additional HCFC production.

6.3.2 Contribution of the United States to Climate Change via Emission of Ozone-Depleting Substances and the Resulting Ozone Changes

The increased abundances of ODSs, as well as the associated depletion of stratospheric ozone, contribute to the radiative forcing of climate. Since activities in the United States have caused significant emissions of ozone-depleting substances and other greenhouse gases, the changes in climate attributable to human activities are, in part, attributable to the United States.

- Globally, the direct radiative forcing from ODSs and substitutes was approximately +0.34 W per m^2, roughly 20 percent of that from CO_2 in 2005. When indirect forcing associated with stratospheric ozone depletion is included, the *net* forcing from ODSs and substitutes is between +0.18 and +0.38 W per m^2. These values were estimated using the 100-year direct GWPs.
- The United States' contribution to this direct forcing amounted to between +0.068 and +0.16 W per m^2, or between roughly 20 and 50 percent of the global direct radiative forcing from these chemicals. This contribution has been fairly constant over the past decade. When net GWPs (*i.e.*, that includes direct and indirect forcings) are considered, the range for the U.S. contribution is +0.04 to +0.18 W per m^2.
- Considering ODSs acting as climate forcing agents and using a 100-year direct GWP weighting, the U.S. EPA estimates

that United States banks in 2005 account for about 32 percent of global banks. The range for net GWP weighting is (31-60) percent. These banks, if released to the atmosphere, would represent the equivalent of 6.2 gigatons (Gt) CO_2 emissions. Approximately one-quarter of United States banks in 2005 were classified as being accessible and they were comprised of HCFCs (0.9 to 1.1 Gt CO_2-equivalents), HFCs (0.4 Gt CO_2-equivalents), and CFCs (0.2-0.4 Gt CO_2-equivalents).

6.4 POTENTIAL MANAGEMENT OPTIONS

To provide quantitative information for assessing the societal benefit of potential future regulatory action, the future levels of ozone-depleting substances can be estimated for a variety of scenarios based on the findings noted above. These include scenarios to assess the influence of currently unrestricted uses, such as methyl bromide in quarantine and pre-shipment (QPS) applications, and unrestricted emissions from most banks and stockpiles. Equivalent Effective Stratospheric Chlorine (EESC) is a useful index for comparing the merits of different emissions scenarios. While changes in EESC do not relate in a simple way to stratospheric ozone levels that vary with location and time (due to the non-linearities that were mentioned earlier), it is clear that EESC changes are representative of the relative ozone depletion impacts. Based on projected EESC values and our understanding of atmospheric chemical and dynamical processes, we conclude the following:

- Amounts of atmospheric ozone-depleting substances, measured in terms of EESC, will be comparable to pre-1980 levels around 2050 if future emissions evolve in a manner consistent with current Montreal Protocol regulations. It is anticipated that, given the proven connection between ozone-depleting substances and stratospheric ozone loss, global ozone will also return to the pre-1980 levels roughly around the same time, assuming no other climate or atmospheric composition changes. However, as stated earlier, factors such as climate change and changes in other trace gases are predicted to accelerate global ozone recovery to pre-1980 values.
- The ozone-depleting substances (ODSs), measured in terms of EESC, in the Antarctic ozone-hole region will return to pre-1980 levels around 2060 to 2070. Thus, the Antarctic ozone hole will essentially disappear around this date assuming full compliance with the Montreal Protocol and its amendments and barring major influences by climate change and other factors.

The date at which the atmospheric abundances of ODSs return to their 1980 levels is 2049 for a baseline scenario (a scenario that is consistent with Montreal Protocol provisions as of 2006). This return can be accelerated under several scenarios.

- The hypothetical cessation of all future emissions of ozone-depleting substances (such as hydrochlorofluorocarbons (HCFCs), and chlorofluorocarbons (CFCs) from banks) starting in 2007 would hasten the decline of ozone-depleting substances to their 1980 level by roughly 15 years (to 2034).
- Under the scenario where no future production is assumed but emissions still arise from ODS banks, the EESC recovery date (*i.e.*, to the 1980 level) is moved up by roughly six years (to 2043).
- Under the scenario where all ODS banks were recovered and destroyed in 2007, but future production is allowed to continue as in the baseline case, the EESC recovery date is moved up by eight years (to 2041).
- The significance of various United States ODS banks has been evaluated in terms of their effect on integrated EESC and compared with the significance of the global banks. Of accessible ODS banks in the U.S., halon-1301 and HCFC-22 represent the greatest potential contribution to integrated EESC above 1980 levels. If total United States banks are considered, not just accessible ones, CFC-11 banks are the most significant potential contributors to integrated EESC. Banks deemed inaccessible may still be recovered with appropriate policy measures, market-based incentives and/or certain technological advances.

Global ozone will return to its pre-1980 levels around 2050. The Antarctic ozone hole is expected to disappear around 2060 to 2070.

There are some uses of methyl bromide for which production and consumption are not limited or restricted under the currently amended Montreal Protocol.

- Global consumption of methyl bromide (CH_3Br) for all fumigation-related uses declined by a factor of two from 1997 to 2005 despite substantial consumption in applications not regulated by the Montreal Protocol. Nearly half (43 percent) of the global, industrially derived emissions of CH_3Br during 2005 arose from QPS consumption not regulated by the Montreal Protocol.
- United States consumption of CH_3Br for all fumigation uses declined 40 percent from 1997 to 2005 despite enhanced Critical Use Exemptions (CUEs) and QPS consumption since 2001. Enhanced CUEs caused the annual United States contribution to global CH_3Br consumption for regulated uses to increase from 23(±4) percent during 2000 to 2003 to 36(±1) percent during 2004 to 2005. In the United States during 2001 to 2006, consumption of CH_3Br for fumigation not regulated by the protocol (QPS use) was, on average, 57(±20) percent of the amounts used and reported to UNEP in restricted applications and had increased by 13 percent per year, on average, from 2001 to 2005.

The coming decades will be a period of changing atmospheric levels of ozone-depleting substances superimposed on changing climate, climate variability, and other factors.

The expected increase in stratospheric ozone over the coming decades will decrease surface UV. However, the future UV trend at the surface is likely to be more dominated by changes in cloud cover, atmospheric fine particle abundances, and tropospheric air quality than by changes in ODS abundances projected in accordance with the provisions of the Montreal Protocol.

Little further reduction in radiative forcing from ODSs can be achieved by 2100 beyond that predicted under the current provisions of the Montreal Protocol. Emissions reductions, however, could lower radiative forcing in the coming decades. Reductions in HFC emissions could also have a modest effect in this area.

- Action could be taken to limit the release of CFCs and HCFCs from banks and thus reduce their future emissions beyond what the current Montreal Protocol is expected to accomplish. If the entire estimated global CFC and HCFC banks had been recovered and destroyed in 2007, the direct radiative forcing is expected to be reduced by about 0.015 W per m^2 and 0.07 W per m^2, respectively, in 2040, compared with the radiative forcing calculated assuming future emissions consistent with the Montreal Protocol regulations. However, a complete assessment of any benefits of such action would also need to include consideration of indirect influences associated with ozone depletion changes.

6.4.1 The World Avoided

The dramatic decrease in emissions of ODSs since the late 1980s, called for by the Montreal Protocol, has been achieved in the United States through a combination of regulations restricting the use, handling, and labeling of specific compounds, a robust program to evaluate alternative compounds, voluntary industry initiatives, and outreach and education programs that have raised awareness of the threats caused by ODSs and the need to control them. Various emissions scenarios have been used to compare the ozone and UV levels of today with what might have occurred in the absence of the Montreal Protocol and the associated actions, as a way to assess the effectiveness and value of the Protocol to the United States and the world.

- Without the implementation of the Montreal Protocol, EESC levels around 2010 likely would have been more than 50 percent larger than currently expected. The abundances during the remainder of the twenty-first century would have depended on any subsequent policy actions taken. These 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 that currently observed.

- The contributions of the United States to the ozone depletion via emission of ODSs to date have been significant. However, the United States has also contributed significantly to achieving the expected recovery of the ozone layer and associated surface UV changes, and reductions in direct climate forcing caused by ODSs by the phase-out of CFCs.
- The decline since the late 1980s of the United States' emissions of ODSs, considered on a CO_2-equivalent basis, corresponds to a climate benefit whose magnitude is large compared with the Kyoto Protocol's targets during its first commitment period. This benefit includes an offset of the −0.05 W per m^2 estimated in the Fourth Assessment Report of Working Group I of the Intergovernmental Panel on Climate Change (IPCC, 2007) due to the destruction of stratospheric ozone by ODSs (as discussed in Chapter 4).

The coming decades will be a period of changing atmospheric ODS levels superimposed on changing climate, climate variability, and other factors. Box 6.1 outlines the key gaps in scientific understanding that can be identified at this time and that could help inform future decisions regarding the continued recovery of the ozone layer back to a state that is not affected by ozone-depleting substances.

BOX 6.1: Gaps in Our Understanding and Continued Information Needs

In this document we have synthesized and assessed what is known about the depletion of the stratospheric ozone layer by ozone-depleting substances, the associated changes in surface UV radiation, and our expectations for the recovery of the ozone layer to pre-1980 values. We have described aspects of the interrelationship between stratospheric ozone depletion and climate change, such as the contribution of ozone-depleting substances to climate forcing, the impact of climate change on stratospheric ozone, and the effects of ozone depletion on climate. We have also outlined the importance of understanding the ozone-climate interrelationship, including variability of climate, in making accurate projections of future ozone as it recovers to pre-1980 values.

Evolving societal and decision-making imperatives arising from the continued global commitment to shepherd the ozone layer back to "good health" will drive future research on the stratospheric ozone issue. For example, the Parties to the Montreal Protocol recently made adjustments to the phase-out schedule to phase-out hydrochloro-fluorocarbons (HCFCs) earlier than scheduled; this adjustment agreement takes effect in mid-2008 and will be implemented over the coming few years as scheduled in the agreement. Questions still remain about topics such as the control of chlorofluorocarbon (CFC) bank emissions and the use of methyl bromide for exempted and unregulated purposes. Accurate predictions of the consequences of near-term decision options will require the United States and international scientific communities to acquire new observational data, to develop an improved understanding of the physical and chemical processes involved in ozone depletion and ozone-climate interactions, and to incorporate this understanding in global models used to project the future state of the ozone layer. Further, it will also require some reporting and documentation on production and use of ODSs and their substitutes.

At present, the scientific and regulatory communities are in the "*accountability*" phase of the ozone layer issue, because science-based regulation to protect ozone has been in place for nearly two decades. Decision makers are increasingly interested in having answers to the bottom-line questions: *Are our actions having the desired and expected effect? Is the ozone layer recovering? Are there other actions that would hasten ozone layer recovery?* As outlined in this document, scientists have addressed and/or partially answered many of these questions. However, gaps remain in our knowledge and information base and in our ability to answer these questions with sufficient clarity and accuracy for policy decisions.

BOX 6.1: Gaps in Our Understanding and Continued Information Needs *cont'd*

It has now become clear that it is critical to understand the linkages between stratospheric ozone depletion and climate change, because climate variations and change will alter the ozone recovery path and even the ozone abundance and distribution after ozone-depleting substances have returned to natural levels. This is owing to the fact that as the atmosphere moves toward a pre-1980 ODS abundance, other atmospheric conditions will not revert similarly toward their pre-1980 state. Understanding the implications of these different evolutions will be a key focus area of atmospheric ozone research.

The climate protection afforded by the Montreal Protocol regulation of ODSs has been significant over the last two decades. This protection derives from the fact that the principal ODSs are effective greenhouse gases. The findings of the IPCC Fourth Assessment Report, released in 2007, enhanced the global focus on climate protection and also increased interest in questions that lie at the nexus of these two global environmental issues. Decision support information demands an evaluation of the implications for ozone and climate protection for scenarios of future regulation under the Montreal Protocol. Decision makers need to know in detail how the ozone layer and the climate system are connected and what aspects of this linkage are likely to be most important in this evolving Earth system.

Based on our synthesis and assessment of the current state of knowledge and the above set of broad research imperatives, we have identified some key knowledge gaps. For simplicity they are listed in four different categories and are equally important. We believe that this description of the knowledge gaps will aid United States and international agencies in establishing research priorities and directions and in establishing reporting requirements.

Atmospheric Observations

Ozone observations: Precise and accurate ozone observations in the troposphere and stratosphere anchor our understanding of the present and future ozone layer. Furthermore, ozone observations must be geographically comprehensive and have extended duration. The recovery of the ozone layer is likely to manifest itself differently at different altitudes and regions in the stratosphere. Changes in the ozone abundance profiles in turn impact climate change. Therefore, more precise continued, uninterrupted, observations of temporal changes in distributions of column ozone as well as local ozone abundances over altitude and latitude are essential to identifying the path to recovery and to better predicting the future state of the ozone layer.

Observations and derivation of surface UV and associated factors: Predicting the surface UV changes, especially those due to stratospheric ozone changes, requires not only the measurements of the UV radiation but also of many associated factors. These include ozone (noted above), atmospheric fine particle abundances and properties, surface albedo, and transmission and reflection of radiation by clouds. Continuity in time, accuracy in value, and global coverage are necessary. Currently, most of the conclusions about the surface UV trends come from calculations that use observed ozone distributions. Facilitation and enhancement of this ability will better fill the need on recording and predicting UV changes.

ODS observations and EESC: The accuracy of our current predictions for the recovery of the ozone layer depends directly on the accuracy of our predictions of the return of ozone-depleting substances and EESC to their pre-ozone-depletion values. We lack adequate knowledge for many of the factors that influence how these quantities return to pre-1980 values. For example, we may not have sufficiently accurate values for the atmospheric lifetimes of many ODSs, especially in a changing climate. Another concern includes the accurate quantification and the eventual release of ODS from banks and stockpiles, an emission that is likely large enough to delay the ozone recovery by many years. Also, uncertainties in bank emissions can hinder the identification of potential ODS emissions in violation of Montreal Protocol regulations. Verification of these bank emissions and emissions from other unregulated activities, such as methyl bromide from QPS use, will require more extensive atmospheric monitoring on global and regional scales.

BOX 6.1: Gaps in Our Understanding and Continued Information Needs *cont'd*

In addition, we cannot precisely quantify how much and in what chemical form the short-lived chemicals (especially those containing halogens and many of natural origin) are transported to the stratosphere, transformed to reactive compounds, and contribute to EESC and ozone depletion. Detailed knowledge of these factors will become more critical as overall ODS emissions and abundances decrease in the future, thereby increasing the relative contributions of the short-lived substances and bank and fugitive emissions to ozone depletion. Accuracy of emission information needs to be established via verification of emissions on global and regional scales.

Process Understanding

There are many specific inputs required to account for the past and predict the future ozone levels as well as climate change. They include accurate rates of chemical and photochemical processes, timescales and rates of dynamical processes including variations, and identification and quantification of many microphysical processes involved in formation, persistence, and characteristics of polar stratospheric clouds and stratospheric sulfate aerosols. The rates of many of these known processes are not sufficiently accurate and there may be some unrecognized processes that are not quantified. Examples include the recently highlighted uncertainties in the photolysis rate of dichlorine peroxide (Cl_2O_2), a molecule that plays a critical role in polar ozone depletion, and uncertainties in the destruction rates and pathways of existing ODSs (especially HCFCs) and of not yet released, but planned, substitutes for ODSs. Therefore, a continuing effort to understand and determine rates and mechanisms of such processes is essential.

Global Models

We are in the early stages of developing climate models and Earth System models that include the known interconnecting processes that link climate and ozone. Projections from three-dimensional chemistry climate models (that did not include explicit land surface and ocean interactions) were used extensively for the first time only during the WMO/UNEP ozone assessment of 2007. Such models will be essential for future evaluations. These models are highly complex because they include all known important chemical, physical, and dynamical processes that influence ozone and other atmospheric constituents. The identification and parameterization of contributing processes and the completion and validation of these maturing climate models together represent important improvements in our ability to project future ozone abundances. The models have demonstrated skill in predicting observed ozone changes and attributing the cause of global ozone decreases to ODS emissions. However, additional improvements are needed due to the demand for more precise and accurate projections of future ozone abundances that include the relevant climate feedbacks. For example, climate benefits related to reductions in ODS emissions are influenced by our understanding of the climate forcing associated with changes in stratospheric ozone, but this influence currently has large uncertainties. The ozone-climate models need to be sufficiently accurate to identify regulatory options that would optimize the dual ozone-climate benefit.

Reporting and Documentation

The accumulation of global emissions of ODSs and other greenhouse gases has led to ozone depletion and climate change. The United States' contributions in both emission categories have been significant. The ability to quantify the United States' contributions is limited by gaps in our knowledge of country-specific emissions. Detail is lacking for historical emissions for ODSs as well as for other greenhouse gases. Efforts to fill these historical gaps will improve the statements of attribution and benefit concerning potential future United States actions. Efforts to avoid similar gaps in the future will add credibility to and confidence in documenting United States accountability for ozone depletion and climate change and in providing guidance for United States national regulations or United States participation in new international policy discussions.