Introduction

Ozone is present only in small amounts in the atmosphere. Nevertheless, it is vital to human well-being as well as agricultural and ecosystem sustainability. Most of Earth's ozone resides in the stratosphere, the layer of the atmosphere that is more than 10 kilometers (6 miles) above the surface. About 90% of atmospheric ozone is contained in the stratospheric "ozone layer", which shields Earth's surface from harmful ultraviolet radiation emitted by the Sun.

In the mid-1970s scientists discovered that some human-produced chemicals could lead to depletion of the stratospheric ozone layer. The resulting increase in ultraviolet radiation at Earth's surface would increase the incidents of skin cancer and eye cataracts, and also adversely affect plants, crops, and ocean plankton.

Following the discovery of this environmental issue, researchers sought a better understanding of this threat to the ozone layer. Monitoring stations showed that the abundances of ozone-depleting substances (ODSs) were steadily increasing in the atmosphere. These trends were linked to growing production and use of chemicals like chlorofluorocarbons (CFCs) for spray can propellants, refrigeration and air conditioning, foam blowing, and industrial cleaning. Measurements in the laboratory and in the atmosphere characterized the chemical reactions that were involved in ozone destruction. Computer models of the atmosphere employing this information were used to simulate how much ozone depletion was already occurring and to predict how much more might occur in the future.

Observations of the ozone layer showed that depletion was indeed occurring. The most severe and most surprising ozone loss was discovered to be recurring in springtime over Antarctica. The loss in this region is commonly called the "ozone hole" because the ozone depletion is so large and localized. A thinning of the ozone layer also has been observed over other regions of the globe, such as the Arctic and northern and southern midlatitudes.

The work of many scientists throughout the world has built a broad and solid scientific understanding of the ozone depletion process. With this understanding, we know that ozone depletion is occurring and why. Most importantly, we know that if the most potent ODSs were to continue to be emitted and increase in the atmosphere, the result would be more depletion of the ozone layer.

In 1985 the world's governments adopted the Vienna Convention for the Protection of the Ozone Layer, in response to the prospect of increasing ozone depletion. The Vienna Convention provided a framework to protect the ozone layer. In 1987, this framework led to the Montreal Protocol on Substances that Deplete the Ozone Layer (the Montreal Protocol), an international treaty designed to control the production and consumption of CFCs and other ODSs. As a result of the broad compliance with the Montreal Protocol and its Amendments and Adjustments as well as industry's development of "ozone-friendly" substitutes to replace CFCs, the total global accumulation of ODSs in the atmosphere has slowed and begun to decrease. The replacement of CFCs has occurred in two phases: first via the use of hydrochlorofluorocarbons (HCFCs) that cause considerably less damage to the ozone layer compared to CFCs, and second by the introduction of hydrofluorocarbons (HFCs) that pose no harm to ozone. In response, global ozone depletion has stabilized, and initial signs of recovery of the ozone layer have been identified. With continued compliance, substantial recovery of the ozone layer is expected by the middle of the 21st century. The day the Montreal Protocol was agreed upon, 16 September, is now celebrated as the International Day for the Preservation of the Ozone Layer.

The Amendment and Adjustment process is a vitally important aspect of the Montreal Protocol. At the Meeting of the Parties of the Montreal Protocol held in Kigali, Rwanda during October 2016, the Amendment process achieved an important new milestone, the Kigali Amendment. The Amendment phases down future global production and consumption of certain HFCs. While HFCs pose no threat to the ozone layer because they lack chlorine and bromine, they are greenhouse gases (GHGs), which lead to warming of surface climate. The amendment process was motivated by projections of substantial increases in the global use of HFCs in the coming decades. The control of HFCs under the Kigali Amendment marks the first time the Montreal Protocol has adopted regulations solely for the protection of climate.

The protection of the ozone layer and climate under the Montreal Protocol is a story of notable achievements: discovery, understanding, decisions, actions, and verification. It is a success story written by many: scientists, technologists, economists, legal experts, and policymakers, in which continuous dialogue has been a key ingredient. A timeline of milestones related to the science of stratospheric ozone depletion, international scientific assessments, and the Montreal Protocol is illustrated in **Figure Q0-1.**

To help communicate the broad understanding of the Montreal Protocol, ODSs, and ozone depletion, as well as the relationship of these topics to GHGs and climate change, this component of the *Scientific Assessment of Ozone Depletion: 2018* describes the state of this science with 20 illustrated questions and answers. Most of the material is an update to that presented in previous Ozone Assessments. A new question has been added describing the expansion of climate protection under the Montreal Protocol (Q19).

The questions address the nature of atmospheric ozone, the chemicals that cause ozone depletion, how global and polar ozone depletion occur, the extent of ozone depletion, the success of the Montreal Protocol, the possible future of the ozone layer, and the protection against climate change that is now provided by the Kigali Amendment. Computer model projections show that GHGs and changes in climate will have a growing influence on global ozone in the coming decades, and in some cases will exceed the influence of ODSs in most atmospheric regions by the end of this century. Ozone and climate are indirectly linked because both ODSs and their substitutes as well as ozone itself are GHGs that contribute to climate change.

A brief answer to each question is first given in dark red; an expanded answer then follows. The answers are based on the information presented in the 2018 and earlier Assessment reports as well as other international scientific assessments. These reports and the answers provided here were prepared and reviewed by a large number of international scientists who are experts in different research fields related to the science of stratospheric ozone and climate[1].

[1] See Appendix for Acknowledgments.

Figure Q0-1. Stratospheric ozone depletion milestones. This timeline highlights milestones related to the history of ozone depletion. Events represent the occurrence of important scientific findings, the completion of international scientific assessments, and milestones of the Montreal Protocol. The graph shows the history and near future of annual total emissions of ozone-depleting substances (ODSs) combined with natural emissions of halogen source gases. ODSs are halogen source gases controlled under the Montreal Protocol. The emissions, when weighted by their potential to destroy ozone, peaked in the late 1980s after several decades of steady increases as shown in the bottom panel. Between the late 1980s and the present, emissions have decreased substantially as a result of the Montreal Protocol and its subsequent Amendments and Adjustments coming into force (see Q14). The Protocol began with the Vienna Convention for the Protection of the Ozone Layer in 1985. The provisions of the Protocol and its Amendments and Adjustments decisions have depended on information embodied in international scientific assessments of ozone depletion that have been produced periodically since 1989 under the auspices of UNEP and WMO. A worldwide network of ground-based ozone measurement stations was initiated in 1957, as part of the International Geophysical Year. The number of atmospheric observations of ozone, CFCs, and other ODSs have increased substantially since the early 1970s. For example, BUV, SAGE, TOMS, and numerous other satellite instruments have provided essential global views of stratospheric ozone for the past five decades. The Nobel Prize in Chemistry in 1995 was awarded for research that identified the threat to ozone posed by CFCs and that described key reactive processes in the stratosphere. The abundance of stratospheric halogens peaked in the late 1990s and has subsequently exhibited a slow, steady decline (see Q15). Under the Protocol, January 2010 marked the end of allowable global production of CFCs and halons (with a few very small exemptions) and January 2013 the time of a production and consumption freeze on HCFCs by all parties. By the mid-2010s, ozone recovery in the upper stratosphere due to the controls on CFC and halogen production was documented. In October 2016 the Kigali Amendment brought the future production of HFCs under the auspices of the Montreal Protocol (see Q19). By 2018 the abundance of stratospheric halogens was 18% lower than the peak value (see Figure Q15-1).

(A megatonne = 1 million (10^6) metric tons = 1 billion (10^9) kilograms.)

EESC: Equivalent effective stratospheric chlorine | IPCC: Intergovernmental Panel on Climate Change | ODS: Ozone-depleting substance | TEAP: Technology and Economic Assessment Panel of the Montreal Protocol | UNEP: United Nations Environment Programme | WMO: World Meteorological Organization

Milestones in the History of Stratospheric Ozone Depletion