INTRODUCTION

Ozone is present only in small amounts in the atmosphere. Nevertheless, ozone 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 incidents of skin cancer and eye cataracts, suppress the immune systems of humans, and also adversely affect agriculture as well as terrestrial and oceanic ecosystems.

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 gases that are ozone-depleting substances (ODSs)[1], such as chlorofluorocarbons (CFCs), were steadily increasing in the atmosphere. These trends were linked to growing production and use of CFCs and other ODSs for spray can propellants, refrigeration and air conditioning, foam blowing, industrial cleaning, and other applications. 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.

By the mid-1980s observations of the ozone layer showed that depletion was indeed occurring. The most severe ozone loss, unexpected at the time of discovery, was found to be recurring each 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 foundation, we know that ozone depletion has been occurring and we understand 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 ever greater 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 through which nations agreed to take appropriate measures to protect human health and the environment from activities that harm the ozone layer, including cooperation on systematic observations, research and exchange of information. 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 subsequent amendments and adjustments as well as industry's development and deployment of "ozone-friendly" substitutes to replace CFCs, the total global accumulation of ODSs in the atmosphere has 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 do not deplete ozone. In response, global ozone depletion has stabilized, and initial signs of recovery of the ozone layer are being observed. 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 Montreal Protocol has also decreased the human drivers of global warming, because many CFCs and HFCs are potent greenhouse gases (GHGs).

The amendment and adjustment process is a vitally important aspect of the Montreal Protocol, allowing the protocol to evolve and address emerging issues as our scientific understanding matures. The Protocol was amended or adjusted between 1990 and 2007 at meetings held in London, Copenhagen, Vienna, Beijing, and Montreal (see Q14). The most recent amendment was formulated at the Meeting of the Parties of the Montreal Protocol held in Kigali, Rwanda during October 2016. The Kigali Amendment phases down future global production and consumption of some HFCs to protect future climate, an important new milestone for the Montreal Protocol (see Q19). The Kigali Amendment was motivated by projections of substantial increases in the global use of HFCs in the coming decades. The control of HFCs under this amendment marks the first time the Montreal Protocol has adopted controls solely for the protection of climate.

[1] Here and throughout, the term ozone-depleting substances (ODSs) refers to gases containing either chlorine or bromine that are released to the atmosphere as a result of human activity and are controlled under Annexes A, B, C, or E of the Montreal Protocol.

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 global warming, this component of the *Scientific Assessment of Ozone Depletion: 2022* report describes the state of this science with 20 illustrated questions and answers. The questions and answers 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 now provided by the Kigali Amendment. Computer model projections show that GHGs such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) will have a growing influence on global ozone in the coming decades, and in some cases may exceed the influence of ODSs on ozone by the middle of this century, given the expected future decline in the atmospheric abundance of ODSs.

For each question, a brief answer is first given in highlighted text; an expanded answer then follows. The answers are based on the information presented in the 2022 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[2].

[2] See Authors and Contributors at the end of this book.

Figure Q0-1. Stratospheric ozone depletion and policy 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.

Scientific Milestones. 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. The discovery of the Antarctic ozone hole in 1985 led to a major community effort that established, within a few years, that this phenomenon was caused by the human release of various chlorine and bromine compounds. The total global emission of these compounds peaked in 1987, the year the Montreal Protocol was signed. The Nobel Prize in Chemistry in 1995 was awarded for research that identified, in 1974, the threat posed by CFCs to the global ozone layer. The graph at the bottom shows the history and near future of annual total emissions of ozone-depleting substances (ODSs) combined with natural emissions of halogen source gases. The emissions, when weighted by their potential to destroy ozone, peaked in the late 1980s after several decades of steady increases. 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 total stratospheric halogen content peaked in the late 1990s, followed by a slow, steady decline (see Q15). In the mid-2010s scientists documented clear evidence that the rise in the abundance of upper stratospheric ozone, which had begun in the late 1990s, was caused by the decline in the stratospheric chlorine loading driven by the Montreal Protocol. At the end of 2022, the stratospheric halogen content was 18% less than the peak value (see Q15).

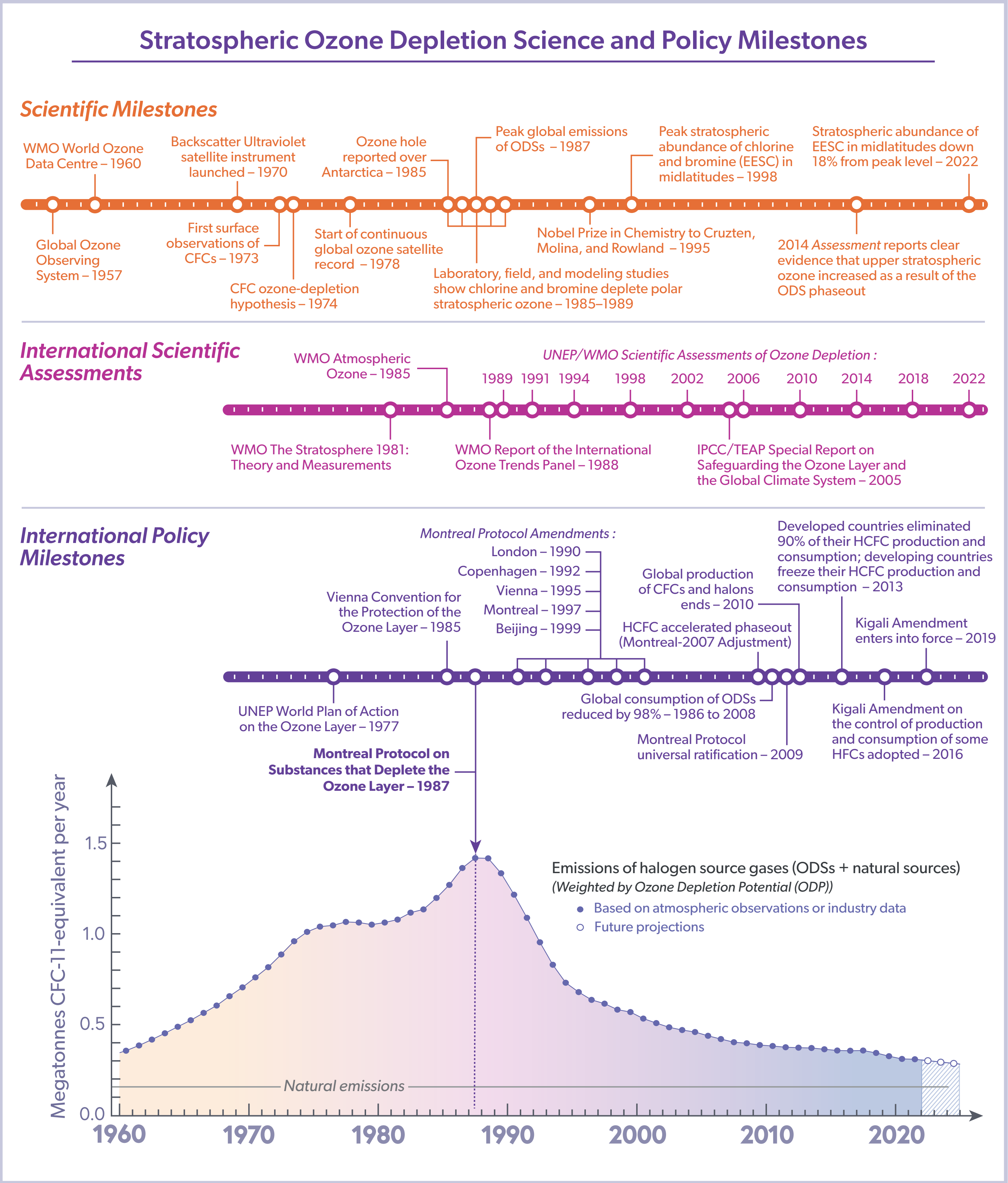
International Scientific Assessments. The provisions of the Montreal Protocol and its amendments and adjustments have depended on information embodied in international scientific assessments of ozone depletion that have been produced periodically since 1989 under the auspices of UNEP and WMO. These assessments incorporate new knowledge from ongoing observations, modeling studies, and analyses into a report designed to reflect the latest scientific understanding of how human activity affects the ozone layer.

International Policy Milestones. The Montreal Protocol, which is built on the framework established by the Vienna Convention, was signed on 16 September 1987. Under the Protocol, January 2010 marked the end of allowable production of CFCs and halons, with a few very small exemptions. In January 2013, a production and consumption freeze on HCFCs went into effect for all nations. In October 2016 the Kigali Amendment brought the future production of HFCs under the auspices of the Montreal Protocol (see Q19).

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

(Formally the term halogen refers to the elements fluorine, chlorine, bromine, iodine, and astatine that are in group 7A of the periodic table. Here and throughout, unless otherwise specified, halogen refers to chlorine and bromine, since source gases containing either of these two halogens constitute the ODSs controlled by the Montreal Protocol.)

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


Stratospheric Ozone Depletion Science and Policy Milestones
Scientific Milestones
WMO World Ozone Data Centre – 1960
Backscatter Ultraviolet satellite instrument launched – 1970
Ozone hole reported over Antarctica – 1985
Peak global emissions of ODSs – 1987
Peak stratospheric abundance of chlorine and bromine (EESC) in midlatitudes – 1998
Stratospheric abundance of EESC in midlatitudes down 18% from peak level – 2022
Global Ozone Observing System – 1957
First surface observations of CFCs – 1973
Start of continuous global ozone satellite record – 1978
Nobel Prize in Chemistry to Cruzten, Molina, and Rowland – 1995
2014 Assessment reports clear evidence that upper stratospheric ozone increased as a result of the ODS phaseout
CFC ozone-depletion hypothesis – 1974
Laboratory, field, and modeling studies show chlorine and bromine deplete polar stratospheric ozone – 1985–1989
International Scientific Assessments
WMO Atmospheric Ozone – 1985
UNEP/WMO Scientific Assessments of Ozone Depletion :
1989 1991 1994 1998 2002 2006 2010 2014 2018 2022
WMO The Stratosphere 1981: Theory and Measurements
WMO Report of the International Ozone Trends Panel – 1988
IPCC/TEAP Special Report on Safeguarding the Ozone Layer and the Global Climate System – 2005
International Policy Milestones
Montreal Protocol Amendments :
London – 1990
Copenhagen – 1992
Vienna – 1995
Montreal – 1997
Beijing – 1999
Vienna Convention for the Protection of the Ozone Layer – 1985
Global production of CFCs and halons ends – 2010
Developed countries eliminated 90% of their HCFC production and consumption; developing countries freeze their HCFC production and consumption – 2013
HCFC accelerated phaseout (Montreal-2007 Adjustment)
Kigali Amendment enters into force – 2019
UNEP World Plan of Action on the Ozone Layer – 1977
Global consumption of ODSs reduced by 98% – 1986 to 2008
Montreal Protocol universal ratification – 2009
Kigali Amendment on the control of production and consumption of some HFCs adopted – 2016
Montreal Protocol on Substances that Deplete the Ozone Layer – 1987
Megatonnes CFC-11-equivalent per year
0.0
0.5
1.0
1.5
1960
1970
1980
1990
2000
2010
2020
Natural emissions
Emissions of halogen source gases (ODSs + natural sources)
(Weighted by Ozone Depletion Potential (ODP))
Based on atmospheric observations or industry data
Future projections