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Synthesis of the 2014 Reports of the Scientific, Environmental Effects, and Technology & Economic Assessment Panels of the Montreal Protocol

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Synthesis of the 2014 Reports of the Scientific, Environmental Effects, and Technology & Economic Assessment Panels of the Montreal Protocol

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Based on the three assessment panel reports

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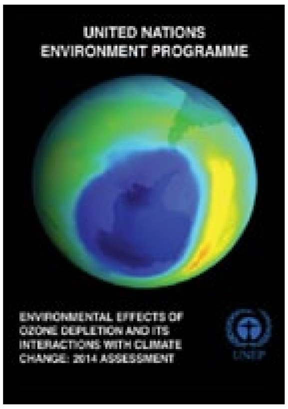
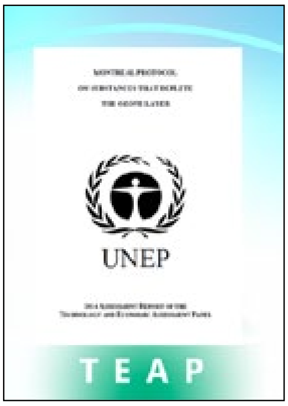
1. Introduction

The depletion of the ozone layer and the consequent increase in UV radiation at the surface of Earth has been an issue for over forty years. Over that period, there has been enormous progress in our understanding of the science behind ozone layer depletion and its recovery, the effects of ozone layer changes on surface UV radiation, and the consequences of changes in UV radiation on humans and the environment. Under the auspices of the Montreal Protocol, policy makers, industry, scientists and technologists have developed a collaborative process that has enabled a better understanding of the science, the environmental impacts, and the changes in technology that are necessary to safeguard society. This enables the Parties to the Protocol to balance the costs of action versus inaction, and assess the feasibility of coordinated societal, national and international action. Central to this process, the Montreal Protocol mandates regular independent updates on all these topics. Accordingly, the Scientific Assessment Panel (SAP), the Environmental Effects Assessment Panel (EEAP), and the Technology and Economic Assessment Panel (TEAP) have carried out major assessments at least every four years during the past three decades. Pages 5, 7 and 8 summarize major aspects of the ozone depletion issue and the Montreal Protocol.

The covers for the most recent 2014 assessment reports from the SAP, EEAP and TEAP are shown below. This report is a synthesis of the information contained in these three reports.[1]





This Synthesis Report presents the most recent, updated information and is particularly timely because:

1) **Just over 40 years ago, Molina and Rowland's landmark paper was published, which linked man-made chlorofluorocarbons with ozone layer depletion;**

2) **30 years ago, the Antarctic ozone hole was discovered – it is the 20th century's most dramatic manifestation of global environmental change;**

3) **30 years ago, the Vienna Convention was adopted in 1985, and 2015 celebrates the thirtieth anniversary of this convention. This convention was followed soon after by the Montreal Protocol in 1987, providing the highly successful international framework to address the issue of ozone layer depletion.**

Given these momentous landmarks, it is appropriate not just to synthesize the most recent information but also to take into account the wider perspective of looking ahead and looking back over the last four decades, including developments in the science and technology and in the regulatory actions during that period.

1 For these reports, see http://ozone.unep.org/en/assessment_panels.php

Photograph source: NASA

1.1 A look back: Four decades of science informing policy and global actions to restore the ozone layer

It had been known for many decades before the discovery of ozone depletion that latitude, season, time of day, clouds and air pollution all influence UV radiation. It was recognized that the unprecedented and substantial increases in UV radiation, which would result from uncontrolled depletion of the ozone layer, would lead to major environmental effects including:

- Increased skin cancers and cataracts
- Reduced growth and yield of crops
- Threats to the productivity and biodiversity of natural ecosystems and damage to the productivity of fisheries
- Degradation of materials used in clothing and construction

Following the landmark paper by Molina and Rowland (1974), by the mid-1980s it was clear that chlorofluorocarbons (CFCs) and, subsequently, other chemicals (e.g., halons, methyl bromide, and other industrially produced halogenated chemicals) could deplete the ozone layer and thus increase surface UV radiation.

In 1985, the dramatic loss of stratospheric ozone over Antarctica in the springtime (the 'ozone hole') was reported for the first time and within a few years atmospheric research had established unequivocally that this depletion was due to chlorine and bromine released from ozone depleting substances (ODS) in the stratosphere.

Several decades ago it also became clear that there are interactions between stratospheric ozone and climate. Many ODS are potent greenhouse gases, because they strongly absorb infrared radiation and are long lived in the atmosphere. Ozone itself is also a greenhouse gas, and its depletion partially offsets the impact of ODS, although the net effect of ODS is to increase the pace of climate change. On the other hand, increases in temperature and the circulation of the stratosphere, caused by greenhouse gases (mainly CO_2), affect stratospheric ozone layer and its recovery.

It was against this background that the Vienna Convention took action that culminated in the Montreal Protocol in 1987 (see pages 7 and 8). The abundances of these ODS, listed in the Annexes to the Montreal Protocol, had increased steadily during the 1970s and the early 1980s. Understanding of the science, recognition of the impacts, and awareness of the technological and economic challenges informed policy. The first line of the Vienna Convention notes "...the potentially harmful impact on human health and the environment through modification of the ozone layer..." The need to protect human health and the environment as well as human-support infrastructure has remained the fundamental stimulus for protecting the ozone layer.

Montreal Protocol: Actions that started the ozone layer on a path to recovery

- In the 1970s the potential threat to the ozone layer from the rapid growth in the atmospheric chlorofluorocarbons (CFCs) was first identified. In 1985, massive depletion of stratospheric ozone over the Antarctic in the springtime (the 'ozone hole') was reported and by the late 1980s global ozone depletion was clearly identified.
- By 1987, the world took action through the Vienna Convention and Montreal Protocol, where the science and technology communities have been working together to provide the information needed to solve the problem.
- Today, within 40 years of the risk being recognized, the ozone layer is showing signs that it is recovering, due to the combined actions of all the countries of the world. Leadership, investment and technological innovations have allowed a smooth transition out of ozone depleting substances, so much so that the threat to the ozone layer, as well as the international response, have remained virtually unnoticed by a large part of the world's population.
- Today, because the Montreal Protocol has protected the ozone layer, large increases in UV radiation have been prevented except near the poles. By preventing large increases in UV radiation the Protocol has protected human health, food production and natural ecosystems.
- Within a century of its recognition, ozone layer depletion will be reversed. The international response will have prevented several hundred million cases of skin cancer and tens of millions of cataracts.
- Many ozone depleting substances (ODS) are also potent greenhouse gases. By controlling ODS the Montreal Protocol has decreased emissions of this important class of greenhouse gases, in contrast to all other major greenhouse gases, which continue to increase.
- Some replacements for ODS are also potent greenhouse gases, and so have potentially harmful effects on climate. However, scientific and technological advances offer solutions, which if implemented could prevent this problem from becoming significant.

Essential principles of the Montreal Protocol

COMMITMENT:
Hailed as the single most successful international environmental agreement to date, the Montreal Protocol along with the Vienna Convention have been ratified by 197 Parties, making them the first universally ratified treaties in United Nations history.

CONSENSUS:
Decisions by Parties on policy, adjustments and amendments have all been made through consensus of the Parties to the Protocol.

ASSISTANCE:
Countries in the developed world[2] ("non-Article 5") assist developing countries ("Article 5") to meet their commitment to phase out ODS, through a unique funding mechanism, the Multilateral Fund whose operation is overseen by Parties through an Executive Committee. To date, the Executive Committee has approved the expenditure of approximately USD $3.2 billion for projects including industrial conversion, technical assistance, training and capacity building that will result in the phase-out of over 450,000 ODP tonnes of controlled substances once all the projects have been implemented.

INDEPENDENT ASSESSMENTS:
Assessments are provided through three interlocking assessment panels: the Scientific Assessment Panel (SAP); the Environmental Effects Assessment Panel (EEAP); and the Technology and Economic Assessment Panel (TEAP). The Panels operate independently, according to the terms of reference determined by the Parties, to provide policy-relevant information for Parties' decisions.

PERIODIC UPDATES:
The Panels provide annual and quadrennial updates that assess the atmospheric science, the impact on human health and the environment, and the technical and economic evaluation of the transition to alternatives in the various sectors. TEAP also organizes Task Forces to analyze and present timely technical information and recommendations when specifically requested by the Parties.

OPERATING INFRASTRUCTURE:
The Protocol benefits from the support of its implementing agencies (UNEP, UNIDO, UNDP and the World Bank) and bi-lateral donors working in partnership with developing countries to carry out national phase-out plans. It has established local "Ozone Units" in every Article 5 Party, bringing together key stakeholders and raising overall awareness.

MONITORING AND COMPLIANCE:
The Parties to the Montreal Protocol comply with the terms of the Protocol by reporting the production and consumption of the ODS, using only the allowed amounts for exempted uses, bringing to the attention of the Parties any potential new chemicals that could be used in their countries.

2 Parties to the Montreal Protocol are classified as Article 5 or Non-Article 5 in relation to their consumption of ODS. In general, A5 Parties are developing countries whilst non-A5s are industrialized.

1.2 Three decades of success: Translating the science into the policies and technologies that have saved the ozone layer

The Synthesis Report brings together the major findings of the 2014 reports of the Scientific Assessment Panel, the Environmental Effects Assessment Panel, and the Technology and Economic Assessment Panel. Findings are organized around major questions of interest to the Parties to the Protocol:

- The Montreal Protocol: Where Are We Today?
- What Are the Connections Between Ozone Layer Depletion, Ozone Depleting Substances, and Climate Change?
- What Did We Gain by Implementing the Montreal Protocol?
- The World Avoided: What Would the World Be Like in the Absence of the Montreal Protocol?
- Looking Ahead: What Are the Challenges?

Major findings of the 2014 reports are given in blue boxes below each question.
Highlights within those major findings are shown in green boxes.

A high-level summary of the 2014 findings is given on page 10.

Key messages of the 2014 reports of the Montreal Protocol assessment panels

1. The actions agreed by the Parties to the Montreal Protocol and its amendments have stimulated the replacement of ODS by innovative technologies and chemicals that do not damage the ozone layer (Section 2.1).
2. As a result, ODS levels in the atmosphere reached peak values in the late 1990s and are now slowly decreasing (Section 2.2).
3. In response to the initial stabilization and then the slow decline in ODS levels, ozone depletion has stopped getting worse. The springtime Antarctic ozone hole has not deepened further, and the global stratospheric ozone layer shows indications of recovery (Section 2.3).
4. The technological and policy advances supported by the Montreal Protocol have phased out the production and use of many chemicals whose emissions are damaging to the ozone layer, and these advances have prevented further increases in UV radiation and the resulting damage to human health and the environment (Section 2.4).
5. The phase-out of ODS, which are also greenhouse gases, will also have a positive effect on climate by avoiding their continued emissions into the atmosphere (Section 4.3).
6. The scale of the benefits is clear from models that give insights into what the world would have been like without a successful Montreal Protocol (Sections 3, 4 and 5). A recent model estimates that, in the USA alone, the Montreal Protocol and its amendments will prevent a total of 275-330 million cases of skin cancer and more than 20 million additional cataract cases by the early 2100s.
7. There are some remaining issues that merit vigilance from the Parties to the Montreal Protocol as they look to the future (Section 6):
   - Some ODS (e.g., carbon tetrachloride) are not decreasing in the atmosphere as expected from current models (Section 2.2).
   - Some ODS continue to be used without a clear timeframe for transition to alternatives, or are stored and could be released at a later date (Section 2.1).
   - Some chemicals that deplete stratospheric ozone are either exempted from controls (e.g., use of methyl bromide for quarantine and pre-shipment (QPS)), or are not regulated under the Protocol (i.e., nitrous oxide, N_2O).
   - Illegal manufacture and trade in ODS is a potential challenge as consumption and production are phased out.
   - Emissions from the current banks are projected to contribute more to future ozone layer depletion than those caused by future ODS production, assuming compliance with the Montreal Protocol. Destruction of unwanted banks would require stronger incentives such as achievement of reduction goals, meeting regulatory requirements, or economic gains.
8. Increasing use and emissions of high global warming potential (GWP) Hydrofluorocarbons (HFCs), which are replacements for ODS, could jeopardize the very substantial climate benefits achieved by the phase-out of ODS through the Montreal Protocol (Section 3.1).

2. The Montreal Protocol: Where are we today?

The Montreal Protocol adopted a strategy of moving away from production of ODS as soon as judged technologically and economically feasible. Consequently, the Parties in concert with industry conceived a strategy for substitution of ODS with more benign gases, as shown in the case of CFCs in Figure 1 below.

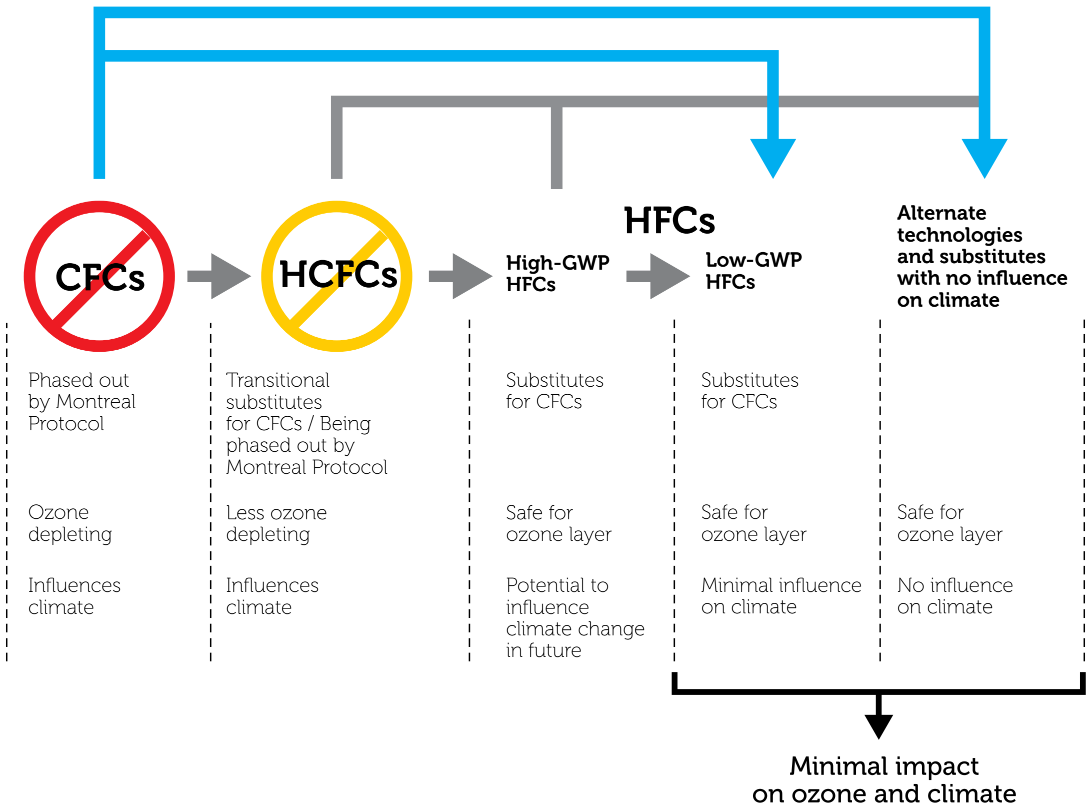


Figure 1. The general strategy following the adoption of the Montreal Protocol to move away from using ozone depleting substances. (Source: UNEP Synthesis Report, HFCs: A Critical Link in Protecting Climate and the Ozone Layer; November 2011).

Major Finding 2.1

Progress in technology reduced ODS use and had beneficial side effects.

Prior to the 1987 Montreal Protocol, CFCs, halons, and other ODS were widely used in many industrial and commercial sectors. They included refrigeration and air conditioning, foams, fumigants in the food and agriculture sectors, electronics cleaning, propellants in aerosols including important medical devices, and fire extinguishing systems. The controls implemented because of the Montreal Protocol have created incentives for non ozone-depleting technologies, processes, and chemicals in almost all sectors. This has stimulated development and implementation of new technologies (including many non-chemical options). The transition involved the use of less ozone-harmful substitutes such as hydrochlorofluorocarbons (HCFCs), which are less harmful than CFCs, as well as completely non ozone-depleting chemicals. These transitions have been supported in every sector by the Multilateral Fund (MLF), which has financed the costs associated with the transition in Article 5 Parties. These transitions reduced the emission of ozone depleting chemicals into the atmosphere and frequently led to technological improvements that had added benefits in many areas. With these mechanisms, the transition to alternatives continues in every sector. By this process, ODS amounts in the atmosphere have already been reduced; further reduction will continue into the future.

Highlight 2.1.1

Use of ODS in refrigeration and air conditioning is decreasing.

Refrigeration and Air Conditioning (RAC) demand accounted for a substantial part of ODS production. The transition from CFCs to mainly HCFCs in Article 5 countries and HFCs in non-Article 5 countries in RAC is one of the major reasons for decreases in concentrations of ODS in the atmosphere.

RAC and foams are two major sectors reliant on HCFCs and HFCs, perhaps less so in foams, but the future trends are markedly different (Figure 2) and their potential climate impacts are different. Consumption of HFC refrigerants in RAC applications dwarfs the consumption of HFC blowing agents used in foams. The projected exponential increase in Article 5 Parties of AC equipment containing high-GWP HFCs will, if left unchecked, have substantial climate impact as of the next decade and beyond. Early intervention in Article 5 Parties could avoid their use of high-GWP refrigerants and reduce their long-term demand for servicing.

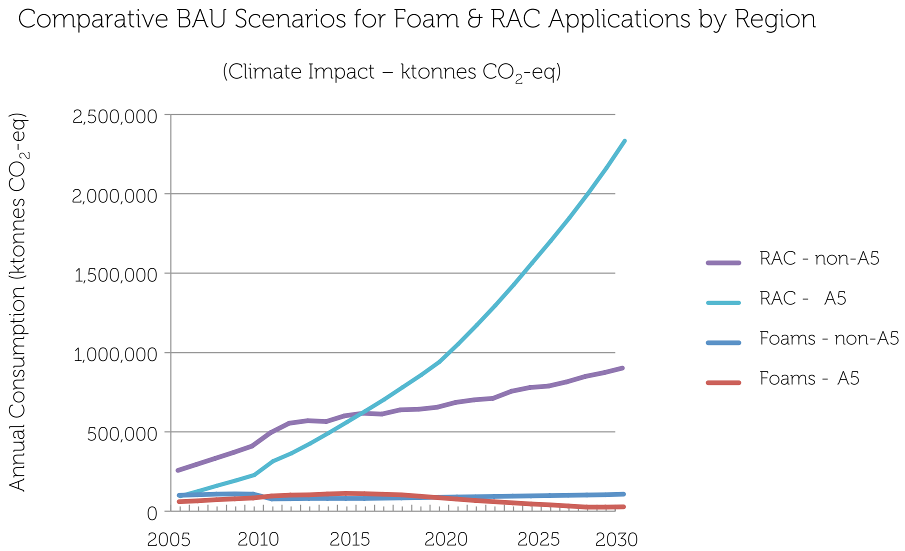


Figure 2. Projection of Business-as-Usual high-GWP HFC demand to 2030 for RAC and foams from non-Article 5 and Article 5 Parties. Source: TEAP XXV/5 Task Force Report, October 2014).

Highlight 2.1.2

CFCs used as blowing agents to make foams have been phased out.

Foams are used in modern society, especially in insulation, furnishings and automotive applications. CFCs, widely used as blowing agents to make foams, have now been phased out, but some CFCs in already installed foams contribute to the CFC "bank". The phaseout of CFCs in foam manufacture has contributed to the decrease in the concentration of ODS in the stratosphere.

Hydrocarbons now account for over 50% of blowing agents used globally, and provide a cost-effective, low-GWP solution for the majority of the industry. However, flammability can make foam production potentially unsafe unless proper measures and infrastructure to address safety and training are provided, especially for small and medium enterprises. Many Article 5 countries have been using HCFCs that may eventually be substituted by non-flammable blowing agents such as hydrofluoroolefins/hydrochlorofluoroolefins (HFOs/HCFOs) or CO_2-blown formulations. Figure 3 shows the historical transition away from ODS and illustrates how future blowing agent demand may be met.

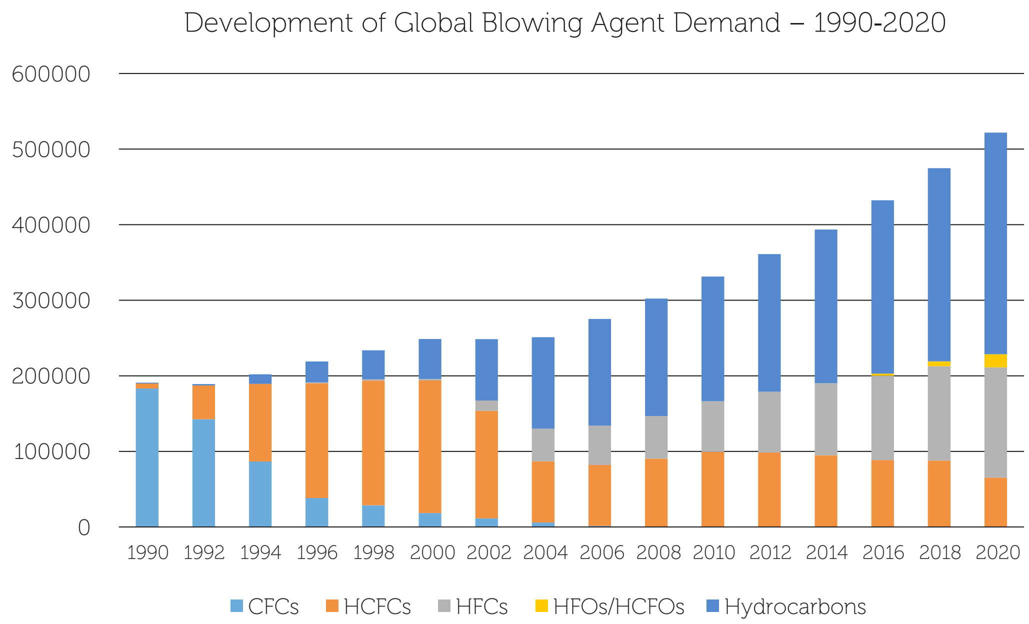


Figure 3. Demand for global blowing agents: 1990-2020 (Source: 2014 Assessment Report of the UNEP Flexible and Rigid Foams Technical Options Committee.)

Highlight 2.1.3

CFCs in inhalers for asthma and chronic obstructive pulmonary disease (COPD) have been successfully phased out.

When CFC-based aerosols were phased out in developed countries, CFC-free replacement inhalers were not available for the hundreds of millions of patients with asthma/COPD worldwide who relied on them, and so a temporary exemption was allowed. The safe phase-out of CFC metered dose inhalers (MDIs) has required two decades of coordinated activity involving the pharmaceutical industry, healthcare regulators and providers, and strong patient involvement. The extensive educational campaign associated with this transition has had a positive impact on the health of patients by increasing the awareness of the benefits of inhaled therapy, which has doubled in the last 20 years. Affordable CFC-free alternatives for all inhaled treatments have been developed, and are now available worldwide. Over 98% of the CFCs used in metered dose inhalers have now been phased out, and will likely disappear completely by 2016 (Figure 4).

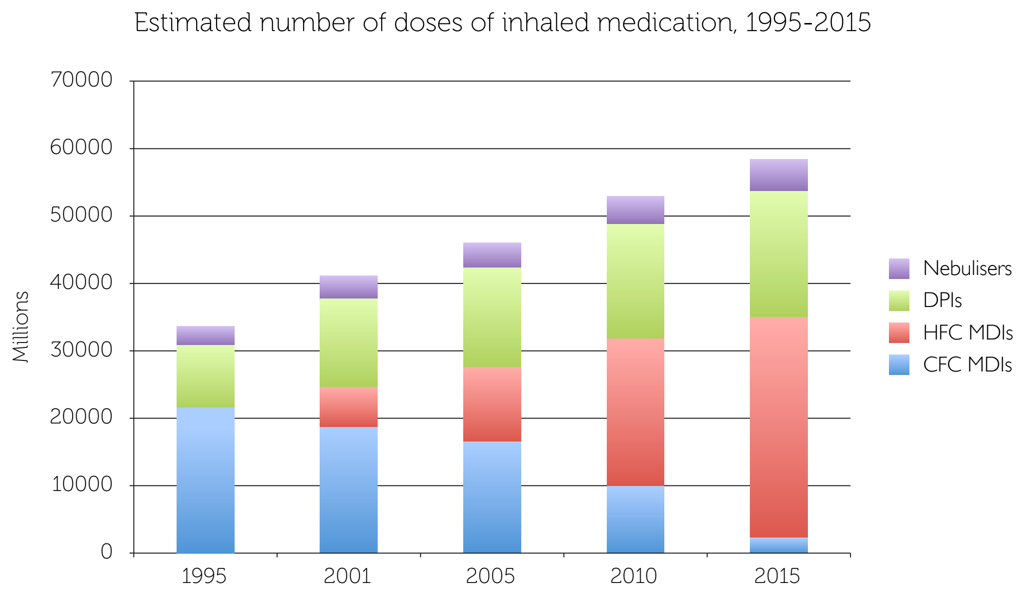


Figure 4. Estimated use of inhaled medications. Both HFC MDIs and dry powder inhalers (DPIs) have increased to replace CFC MDIs.

Highlight 2.1.4

Controlled uses of methyl bromide have been drastically reduced with immediate benefit to the ozone layer; but continued QPS uses prevent further benefits being realized.

The phase-out of methyl bromide (MB) has been a major success story for the Montreal Protocol. In the 1990s, agricultural industries faced the challenges of crop production in the face of the looming phase out of 70,000 tonnes of MB, which was being used as a fumigant at the time to control a wide variety of soil-borne and postharvest pests and diseases. Through a stepwise reduction strategy, including a process which allowed for exemptions for critical uses, the Montreal Protocol provided Parties with time to find alternatives that have replaced 90% of uses by 2015 and decreased MB in the atmosphere (Figure 5). The decrease in MB, with a short atmospheric lifetime of about 0.8 years, has contributed approximately 35% to the present decrease in concentrations of ODS in the stratosphere and has consequently contributed to the betterment of the ozone layer.

Currently however, 11,000 tonnes of MB are used annually for quarantine and pre-shipment (QPS) treatment, aimed at preventing the introduction of foreign pests or diseases into a country or territory, which could have devastating effects. Since no alternatives were considered to be available in 1992, it was excluded from controls under the Montreal Protocol. However, alternatives have become available for an estimated 40% of QPS uses of MB.

The side benefit of this MB phase-out process was the generation of a wealth of information on agricultural production systems, including pest and disease control, fertilization and watering practices, cultural practices, and storage technologies, which increased the competitiveness and sustainability of many production sectors, as well as improved food security.

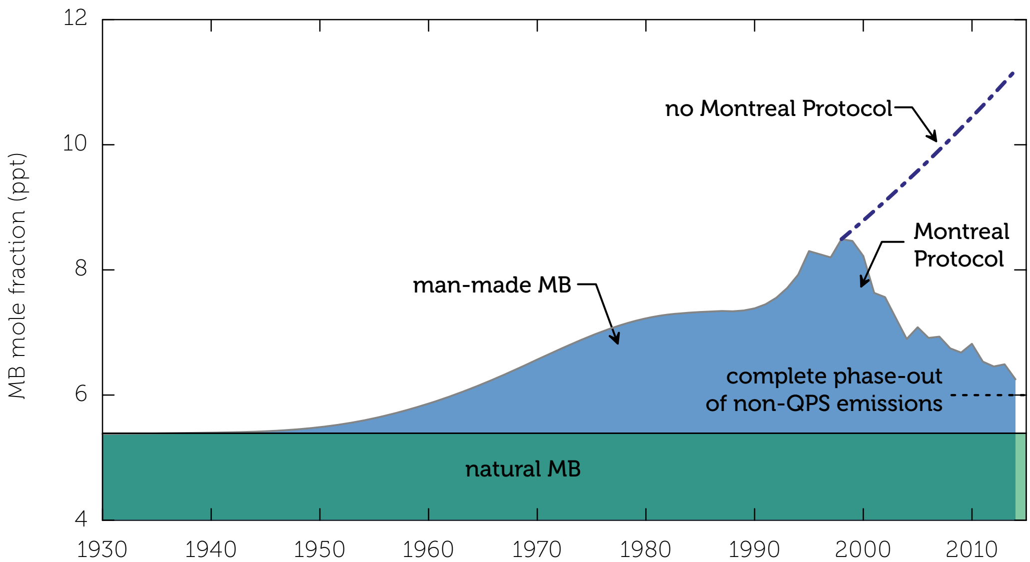


Figure 5. The impact of the MB restrictions in non-Quarantine and Preshipment (QPS) use on reduction in bromine concentrations in the troposphere since the late 1990s. (Source: Porter I., Derek N. and Fraser P., Latrobe University and CSIRO, Australia)

Highlight 2.1.5

Halon production has been phased out since 2010; fire protection in civil aviation remains an unresolved challenge.

Halons used in fire protection are the most potent ODS controlled under the Protocol. Early collaborative action of key sectors (military, industry and governments) led to phasing-out of their production and consumption in non-Article 5 Parties in 1994, followed by Article 5 Parties in 2010. However, halon use continues in existing equipment and legacy systems and continued use of halon 1301 is leading to its ongoing increase in the atmosphere, unlike all other Annex A ODS controlled under the Montreal Protocol.

Halon fire protection systems are still being installed in new civil aircraft, and will require halon for the life of the aircraft (estimated 30-40 years). The halon requirements of civil aviation appear modest in comparison to current stocks, but the aviation industry neither owns nor controls the halons needed to support existing and future aircraft. As a result of the lack of progress in implementing alternatives, it is nearly indisputable that civil aviation will need production of new halon 1301 in the future.

All of the halons currently used are obtained from stockpiles of recycled material – the halon banks. There are some uncertainties in the estimated sizes of the banks, so it will be important to monitor and update bank estimates, particularly for halon 1301.

Highlight 2.1.6

Technological advances enabled movement away from ozone depleting solvents and other industrial process chemicals.

One of the earliest and most rapid phase-outs was that of the use of methyl chloroform (MCF), a chemical with an atmospheric lifetime of only about five years that is now almost completely gone from the atmosphere. This phase-out led quickly to a small, but significant, drop in the overall ODS amounts in the atmosphere, contributing roughly one third of the decrease in ODS seen to date.

In non-Article 5 Parties, the use of ODS solvents as high performance cleaning agents has been replaced by cleaning processes that do not use solvents, as well as chemical alternatives such as HFCs and hydrofluoroethers (HFEs). Recently low GWP HFOs are emerging in the market to replace medium to high GWP HFCs and HFEs. In Article 5 Parties, MCF uses were completely phased out in 2012, and the phase-down of HCFC use in solvent application is underway.

Major Finding 2.2

In response to the technological changes that enabled reductions in ODS usage, the sum of ODS amounts in the atmosphere is now decreasing from its maximum in the late 1990s. The ODS amounts are expected to continue decreasing with adherence to the Montreal Protocol.

Highlight 2.2.1

ODS levels are projected to decline by about 0.6% each year until the end of this century, when they are expected to return to pre-1960 values, which represent atmospheric amounts before ODS were used substantially.

This slow rate of ODS decline is not due to any failure in the controls, but reflects the slow loss processes in the Earth system. These very stable, long-lived CFCs will be with us for a long time, well into the 21st century and well after the shorter-lived ODS will have been removed from the atmosphere.

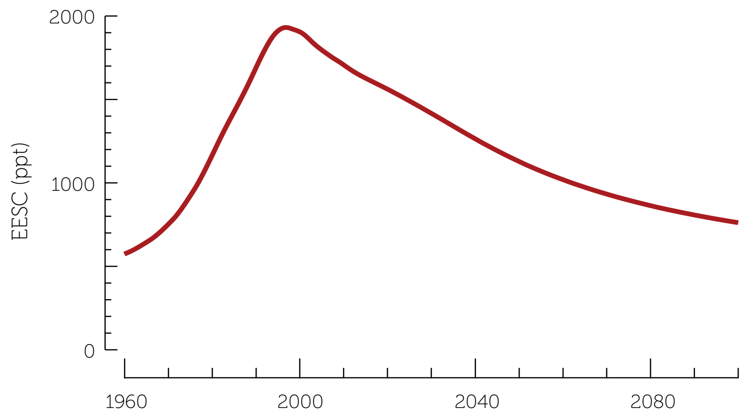


Figure 6. The levels of ODS in the atmosphere (as measured using a quantity called Effective Equivalent Stratospheric Chlorine (EESC) that takes into account the differences between chlorine and bromine in destroying the ozone layer) in the past and the future.

Highlight 2.2.2

A note of caution: Some chemicals are not changing in the atmosphere as expected with compliance with the Montreal Protocol.

In particular, it appears that carbon tetrachloride (CCl_4) is not decreasing as rapidly as expected. The reasons for this discrepancy, between atmospheric observations and expectations based on reported production, are still unresolved. Also, it is becoming clear that the recoverable banks of halons and HCFCs together with quarantine and pre-shipment (QPS) uses of methyl bromide are major potential sources of ODS emissions if not appropriately managed.

Major Finding 2.3

The reduction in atmospheric ODS concentrations has prevented further depletions in the stratospheric ozone layer, and there are some small signs of recovery.

Highlight 2.3.1

The global ozone layer has stabilized and is not getting worse, although it is still too early to unequivocally state that it is improving.

Both the observed and modeled global ozone layer levels are approximately 3 to 4% lower than in 1980. Modeling studies suggest that climate change will significantly influence when the ozone layer will return to its benchmark pre-1980 levels.

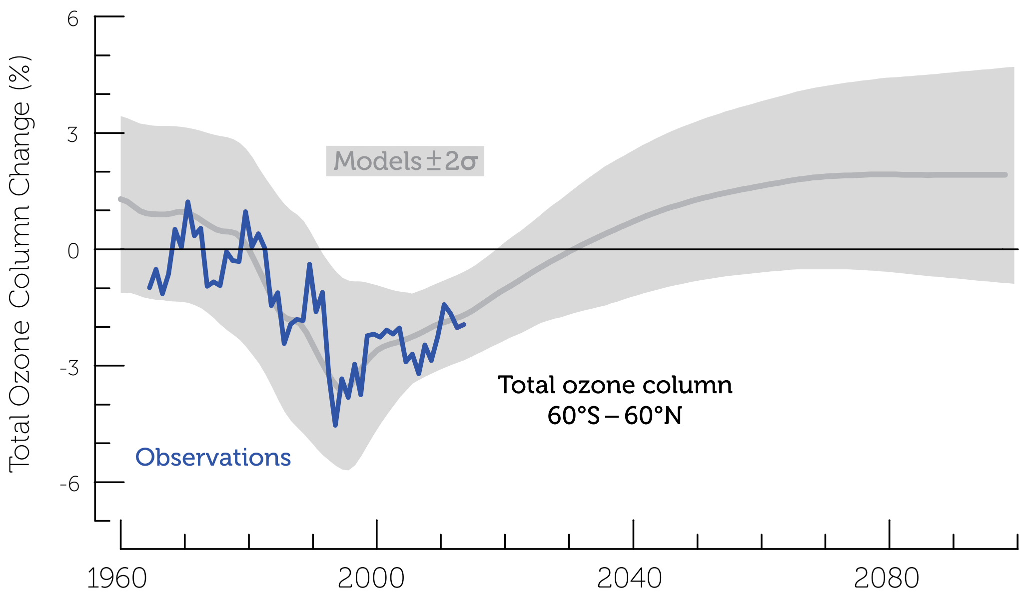


Figure 7. Total ozone columns of ozone between 60°S and 60°N (sometimes referred to as global ozone) observed (blue line) and calculated (gray line) based on our current knowledge. The gray area is the uncertainty in our calculated ozone changes.

Highlight 2.3.2

The Antarctic ozone hole has not worsened, but it continues to occur every year, with its magnitude essentially unchanged over the past decade within the expected year-to-year variability.

Our understanding indicates that it is too early to see clear signs of recovery of the Antarctic ozone hole. Climate change will have a lesser influence on the recovery of the ozone hole than on the global ozone.

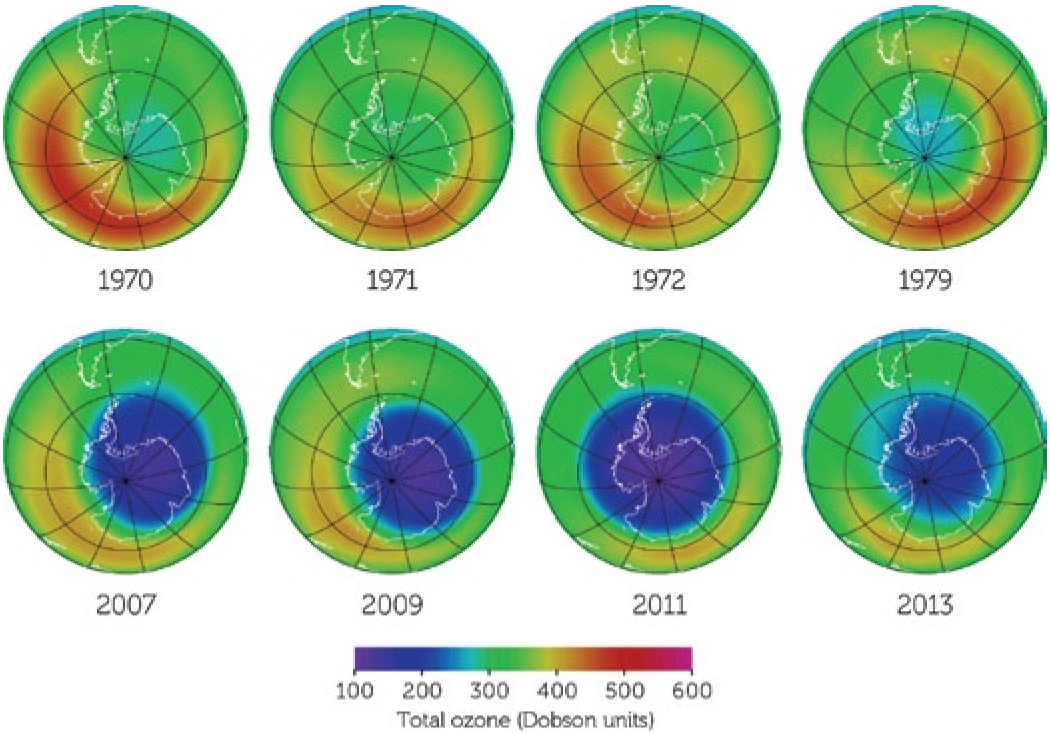


Figure 8. October monthly mean average of ozone over Antarctica between 1970 (prior to the ozone hole) and 2013. The ozone hole began developing in the 1970s, and in recent years, the ozone hole has stabilized.

Highlight 2.3.3

Upper stratospheric ozone declined during the 1980s and early 1990s mainly caused by ODS increases. It has increased by about 5% since 2000.

From 2000 to 2013 the decline in ODS abundances and a cooling of the stratosphere by increased carbon dioxide are both estimated to have made comparable contributions to the observed upper stratospheric ozone increases. This is yet another indicator of the strong linkage between ozone layer depletion and climate change.

Major Finding 2.4

The control of ozone depletion has prevented large changes in UV radiation in most parts of the globe, and minimised the damaging effects of ozone loss on human health and the environment.

Highlight 2.4.1

In the Antarctic, the large decreases in stratospheric ozone have led to very large transient UV increases. In the Arctic, episodic decreases of stratospheric ozone have caused large, short-term increases in UV-B radiation.

In particular, Arctic ozone depletion in 2011 led to substantial (40–50%) increases in sun-burning UV radiation that was measured in Alaska, Canada, Greenland and Scandinavia.

Highlight 2.4.2

However, in most parts of the world, increases in UV-B radiation measured since the mid-1990s are relatively small (5-10%).

These small changes are due largely to factors other than ozone depletion, including changes in cloudiness, atmospheric aerosols and, at high latitudes, snow- or ice-cover.

Highlight 2.4.3

Changes in lifestyle have increased UV exposure, and consequently the background prevalence of skin cancers. Nevertheless, the Montreal Protocol has limited the increases in solar UV-B radiation in populous areas in the world, and thus protected human health from the worst effects of ozone depletion.

Highlight 2.4.4

The Montreal Protocol has also limited the impact of increased UV radiation on ecosystems. However, the effects of the Antarctic ozone hole on both UV radiation and regional climates have led to discernible changes in a number of aquatic and terrestrial ecosystems in the Southern Hemisphere.

These include reduced marine phytoplankton along the west side of the Antarctic Peninsula, reductions in tree growth in Patagonia and moss bed growth in East Antarctica, but also an increased tree growth in eastern New Zealand, and the expansion of agriculture in southeastern South America.

3. What are the connections between ozone layer depletion, ozone depleting substances and climate change?

Climate change influences the stratospheric ozone layer, its depletion, and its recovery. Increases in carbon dioxide in the atmosphere lead to a reduction in stratospheric temperatures and a change in circulation strength, both of which have an effect on ozone recovery. The cooling of the upper stratosphere will likely lead to higher ozone concentrations in the future. This will be a key factor for stratospheric ozone recovery towards the end of this century. Finally, the destruction of stratospheric ozone has led to changes in tropospheric climate. The strongest impacts are in the Southern Hemisphere where the summer tropospheric circulation has changed in response to the Antarctic lower stratospheric cooling resulting from ozone depletion.

Major Finding 3.1

An emerging connection between the ozone layer depletion and climate is the introduction of the non-ozone depleting HFCs in place of ODS.

Many HFCs are potent greenhouse gases and their potential influence on climate is a concern.

4. What did we gain by implementing the Montreal Protocol?

A key question to be answered is: What did we gain by implementing the Montreal Protocol? The answers to this question include how the Montreal Protocol influenced the course of the stratospheric ozone layer in the late 20th and early 21st centuries and the impact it will have on ozone in the future; how the levels of UV radiation have changed and will change in the future; and the side benefits for climate.

Major Finding 4.1

The ozone layer will recover in the 21st century.

Highlight 4.1.1

With complete adherence to the Montreal Protocol and its amendments, the levels of ODS should slowly decrease by about 0.6% per year during the rest of 21st century. In response to this decrease in ODS, the Arctic and global ozone layer should return to the benchmark 1980 levels around mid-century, and somewhat later for the Antarctic ozone hole.

Highlight 4.1.2

As controlled ozone-depleting substances decline, the evolution of the stratospheric ozone layer in the second half of the 21st century will depend largely on atmospheric abundances of CO_2, N_2O and CH_4.

N_2O and CH_4 will influence the changes in ozone more via their chemical interactions rather than their role as climate gases.

Major Finding 4.2

The surface levels of UV radiation will decline with the recovery of the stratospheric ozone layer.

Highlight 4.2.1

As the ozone layer recovers, UV-B radiation over the Antarctic is expected to decrease, broadly back to the same levels before the onset of ozone depletion.

Highlight 4.2.2

Smaller decreases in UV-B radiation are also expected outside the Antarctic.

This is due partly to the recovery of the ozone layer and partly to changes in cloud and atmospheric aerosols as a consequence of changes in climate and air pollution, although many of these changes remain hard to quantify and may show large geographical variation. The penetration of UV radiation into the oceans, lakes and rivers is affected by changes in UV-absorbing matter in these waters, which are increasing in many regions due to the effects of climate change. This may have long-term effects on UV radiation in aquatic ecosystems.

Highlight 4.2.3

Predicting the effects of future changes in UV radiation is complicated by factors beyond just stratospheric ozone.

Major Finding 4.3

The Montreal Protocol has delivered important co-benefits for climate.

Most ODS are also powerful greenhouse gases so that their regulation under the Montreal Protocol has had an important side benefit to climate change by reducing emissions of this class of global greenhouse gases.

Highlight 4.3.1

In 2010, the decrease of annual ODS emissions under the Montreal Protocol was estimated to provide about five times the climate benefit compared with the annual emissions reduction target for the first commitment period (2008–2012) of the Kyoto Protocol.

Without the Montreal Protocol, ODS would have contributed to climate forcing about 40% of that by CO_2 by 2020. This is to be compared with the climate forcing contribution from ODS of roughly 20% of the effect of CO_2 today and a slightly smaller contribution by 2020 (Figure 9). Phaseout of ODS is in contrast to the other greenhouse gases, which are all increasing, and will lead to the slow decrease in the forcing by ODS during the rest of the century.

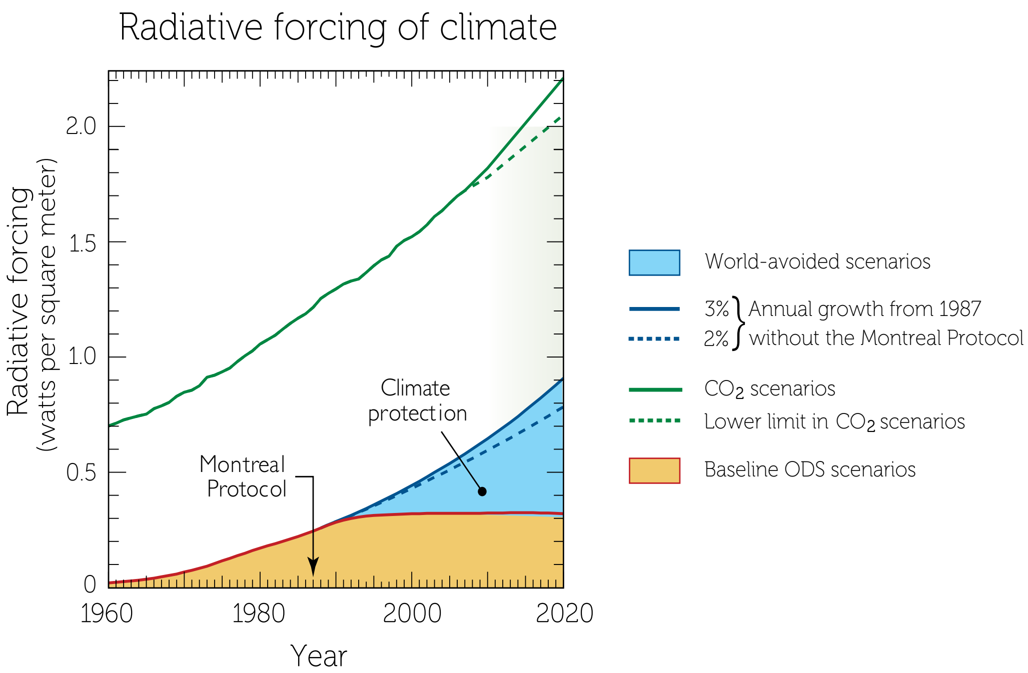


Figure 9. The influence of ODS on climate compared to that of CO_2 between 1960 (when ODS were essentially unused and absent in the atmosphere) and 2020. The influence on climate is measured using Radiative Forcing, which approximates to how these gases force climate to change. The gains made by controlling ODS is shown by the blue area, which is the difference between what the forcing would have been in the absence of the Montreal Protocol and with the Protocol. (Adapted from: Twenty Questions and Answers About the Ozone Layer: 2014 Update, Scientific Assessment of Ozone Depletion: 2014, WMO/UNEP Report, ISBN:978-9966-076-02-1.)

5. The world we avoided: What would the world be like in the absence of the Montreal Protocol?

While evaluating what the world is like because of the Montreal Protocol, it is important to assess what the world would have been like in its absence. Our understanding has evolved such that we can make a good assessment of this hypothetical future world, which could have been reality without the Montreal Protocol.

Major Finding 5.1

Today: Without a successful Montreal Protocol, today's world would have higher ODS levels, greater ozone depletion, and higher UV levels (Figure 10).

It has been three decades since the first actions were taken to protect the stratospheric ozone layer. But what would the world have been like today if these actions were not taken?

Highlight 5.1.1

It has been estimated that ODS levels would have been about 2.5 times larger than what is present today, leading to an additional 80 Dobson Units (20%) of Antarctic ozone depletion, with major Arctic ozone depletions.

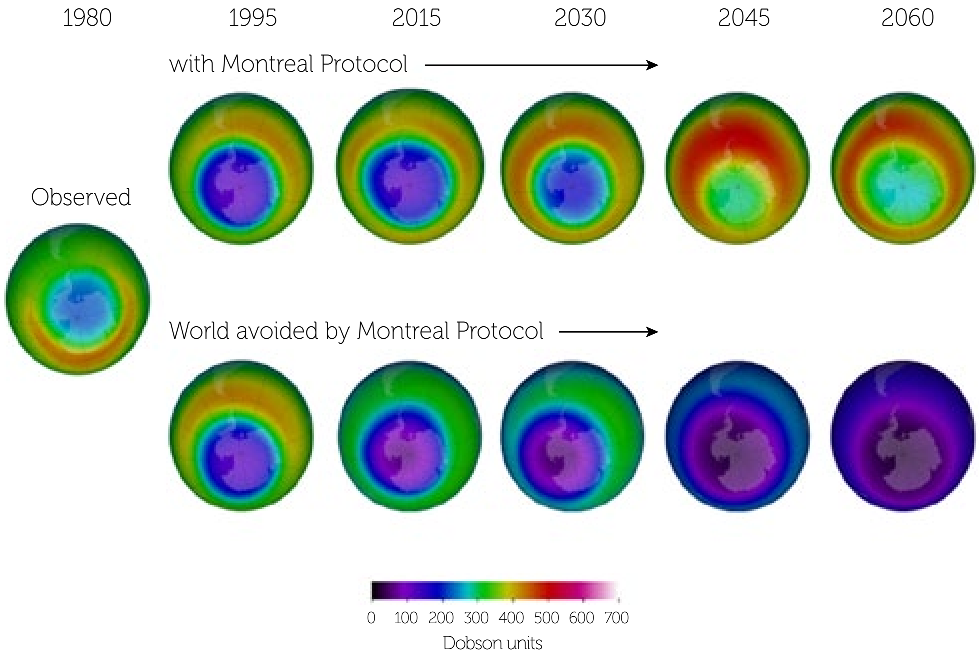


Figure 10a. The evolution of the Antarctic ozone hole with and without the Montreal Protocol. (From Newman et al. Atmos. Chem. Phys., 9, 2113–2128, doi:10.5194/acp-9-2113-2009, 2009)

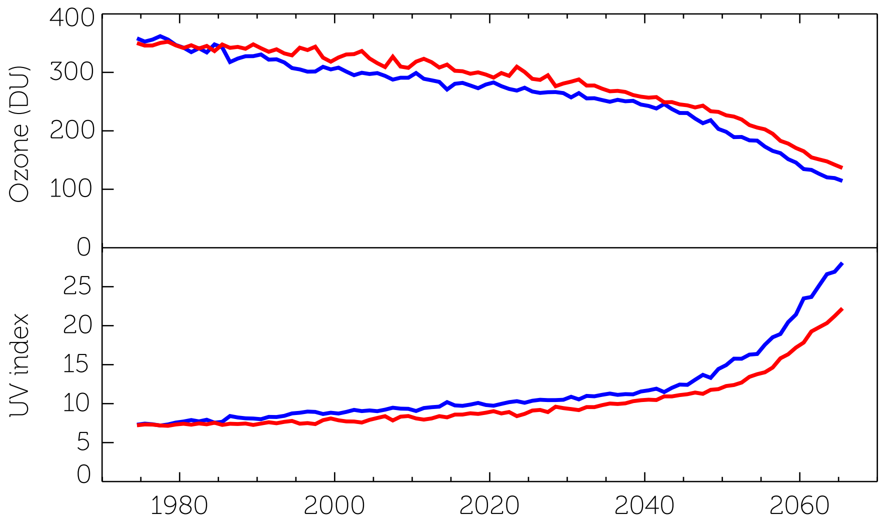


Figure 10b. The summer ozone and UV Index changes for 50°N (red) in July and 50°S (blue) in January from 1974 to 2065 that would likely have occurred in the absence of the Montreal Protocol. (Adapted from UNEP, Environmental Effects of Ozone Depletion: 2014 Assessment, United Nations Environment Programme ISBN 978-9966-076-04-5)

Highlight 5.1.2

Large effects of ozone depletion on human health and biota might not yet have been evident.

By 2015, the impact on crops and natural ecosystems would likely have been relatively small. Skin cancers occurring in 2015 would mainly have been the result of exposure to UV radiation in the 1980s and 1990s, well before significant increases in UV radiation had occurred. One model of skin cancers in the USA and NW Europe suggests that the incidence of skin cancers might have increased by 5-10% by 2015.

In summary, by 2015 those living in this hypothetical world might not have been aware of large effects of ozone depletion in their day-to-day lives. However, increases in UV radiation would already have been having hidden effects (e.g., damage at the cellular level). Those hidden effects would have led to increased cancer incidence and eye damage later in the century, as well as a wide range of environmental impacts.

Major Finding 5.2

Beyond 2015: If the Parties had failed to implement the Montreal Protocol, the consequences of ODS emissions would have continued through the coming decades.

Highlight 5.2.1

The continued accumulation of ODS in the absence of the Montreal Protocol would have led to a collapse of the global stratospheric ozone layer by the mid-21st century.

For example, global total ozone would have decreased from about 315 Dobson Units (DU) in 1974 to about 100 DU by 2065, or by about 66%.

Highlight 5.2.2

Without a successful Montreal Protocol, the climate effects from higher ODS levels and from depletion of the ozone layer would have been larger.

Because ODS are also effective greenhouse gases (as noted above), increasing ODS concentrations would have rivaled the effects of CO_2 on global warming. The combined effects of lower-stratospheric cooling by continued large ozone layer depletion and tropospheric warming from increased ODS emissions would then have led to much stronger climate changes in both the Southern and Northern Hemispheres in the 21st century. Modeling studies indicate that avoided tropospheric warming would be over 2°C in the tropics, 6°C in the Arctic, and about 4°C in the Antarctic by 2070 compared with 2000. This is of comparable magnitude to future greenhouse gas warming in many climate change simulations according to the Intergovernmental Panel on Climate Change (IPCC). Global warming over the next few decades would likely have been double that found in the absence of the Montreal Protocol, with large changes in precipitation.

Highlight 5.2.3

Model simulations show that without the Montreal Protocol, UV-B radiation at the Earth's surface in the second half of this century would have reached levels far beyond anything experienced in human history, with associated implications for human health, agriculture, construction material, and ecosystems.

Correspondingly, the UV index would have exceeded 35 in the tropics, and 5-15 at the sunlit northern polar cap, which would have been similar to values in the subtropics and tropics as measured in 2000 (Figure 11). As a consequence, it has been calculated that the Montreal Protocol will have prevented approximately two million cases of skin cancer per year worldwide by 2030, allowing for the lag time between exposure to UV radiation and the development of skin cancer.

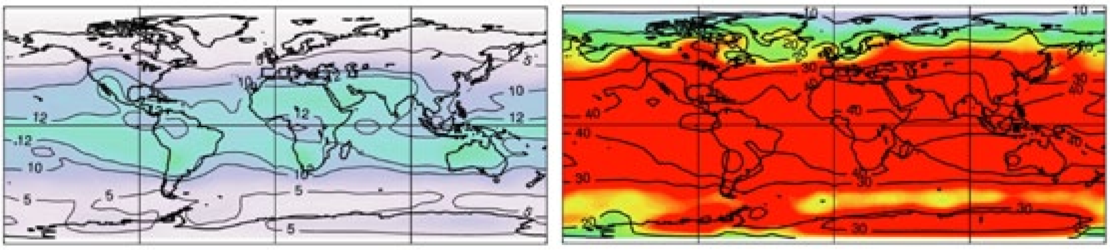


Figure 11. UV index in the current world, left panel, and the world avoided in 2090, right panel. Note that regions shown in red exceed the maximum UV index (25) currently experienced on Earth. Reproduced with permission from Egorova et al., 2013, Montreal Protocol Benefits Simulated with CCM SOCOL. Atmospheric Chemistry and Physics, 13: 3811-3823.

Much greater damage to human health would have been expected to result from the large and widespread ozone depletion that would have occurred mid-century had the Montreal Protocol not been successful. A recent model estimates that, in the USA alone, the Montreal Protocol and its amendments will prevent a total of 275-330 million cases of skin cancer and more than 20 million additional cataract cases by the early 2100s.

We cannot yet quantify the wider impacts of ozone depletion in the absence of the Montreal Protocol, but the expected reduction in plant growth across all crops and ecosystems would have had profound effects on food security and the function of ecosystems. The effect of these very large ozone depletions on aquatic ecosystems, air and water quality and materials remains unquantified, but would have likely been substantial.

While precise quantification of these avoided impacts is difficult, it is clear that the Montreal Protocol has prevented catastrophic changes, which could have been evident by mid-century. It can be argued that the world would never have allowed this to happen and that action would have eventually been taken. However, any delay would have led to ozone losses that would have been larger and would have persisted longer than have already occurred.

6. Looking ahead: What are the challenges?

The Montreal Protocol has successfully avoided a catastrophe for the stratospheric ozone layer, human health and the environment. It will succeed in returning the ozone layer to its 1980 levels in the 21st century.

The Protocol drove the transition away from the use of substances with a high potential to deplete the ozone layer. Replacement chemicals and technologies, which are less damaging to ozone or, better still, cause near-zero ozone depletion, were progressively introduced. The consequence is that the levels of ODS in the atmosphere have now started to decline and there are early signs of ozone layer recovery. An added benefit is that the reduction of the atmospheric abundance of ODS, which are also greenhouse gases, has also led to a substantial climate benefit. However, some important challenges for the Montreal Protocol still remain.

Major Finding 6.1

The destruction of banks is an option with diminishing returns to accelerate ozone layer recovery.

"Banks" of ODS are those gases that have already been produced and/or used but not yet emitted to the atmosphere. Leakage of ODS from installed equipment, or release of ODS stocks to the atmosphere could contribute to ozone depletion, and negatively impact climate. However, the opportunity to realise potential ozone and climate benefits from destroying ODS from banks is now declining. Most products containing ODS (e.g., appliances with limited life-cycle) have either already been destroyed or will be in the waste stream by 2020. Although there are mechanisms for providing credits for destruction of ODS, they are not widely used. Also, regulatory requirements or economic incentives have not been sufficient to avoid emissions altogether.

Major Finding 6.2

HFCs are benign to the ozone layer but some are potent greenhouse gases and continued increases in their use could lead to a significant negative climate impact.

To minimize the impact on the ozone layer and climate, ODS replacements would ideally have zero ODP and low GWP. Many technologies are already implemented with these characteristics, and a number of possible new low-GWP chemicals are now also being considered.

Nonetheless, the transition away from ODS has resulted in increased use of high-GWP HFCs. Indeed, the rapid current and future growth in the atmospheric abundances of these high-GWP HFCs has given rise to concerns about their possible climate impact.

Highlight 6.2.1

The future emissions of HFCs could lead to a radiative forcing that is roughly 40% of that resulting from future emissions of CO_2 by 2050.

HFCs currently constitute less than 1% of the global radiative forcing from climate. However, if the use of the current mix of HFCs were to continue following a business-as-usual scenario, increasing demand based on current market trends could significantly offset the climate benefit already achieved by the Montreal Protocol (Figure 12).

Highlight 6.2.2

However, the use of low-GWP HFCs as alternatives to both ODS and high-GWP alternatives could help to maintain a negligible contribution to climate over the coming decades.

The impact of HFC mitigation on future climate change needs to consider carefully a future commitment to climate forcing by the HFC banks; the HFC bank size represents a substantially larger fraction of the cumulative HFC production and emission than was the case for CFCs in the 1980s.

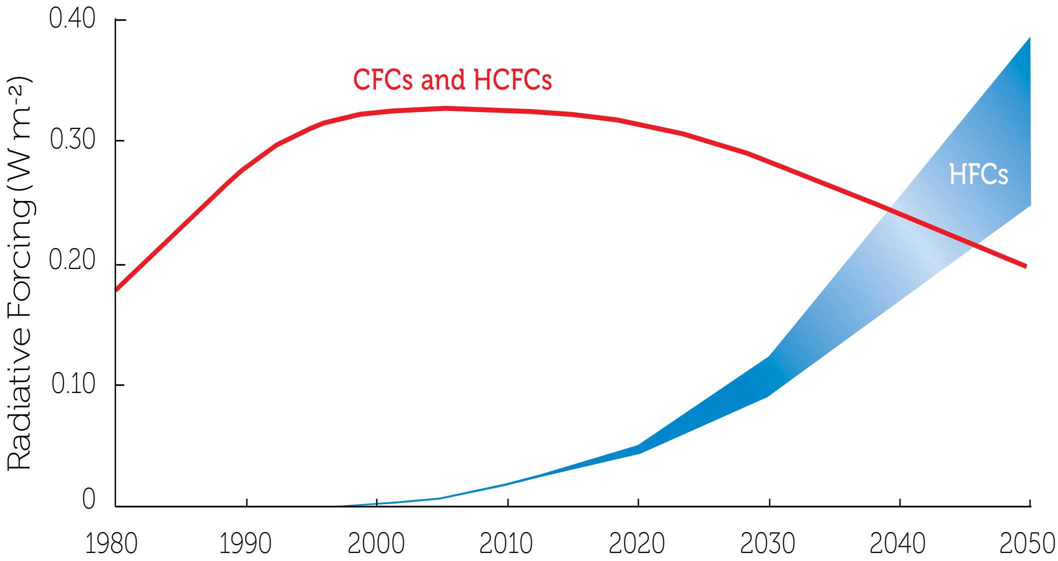


Figure 12. The climate forcing by CFCs and HCFCs (red line), as measured by their radiative forcing, from 1980 to 2050. Currently CFCs and HCFCs contribute about 0.33 Wm^{-2} to climate forcing, and their contribution will decrease. However, continued use of high GWP HFCs could offset the gains made by phasing out ODS, as shown by the blue area. Alternatives to low GWP HFCs – both in kind and not in kind replacements – will maintain the gains made by the Montreal Protocol to climate. (Adapted from: Assesment for Decision-Makers: Scientific Assessment of Ozone Depletion: 2014, WMO Global Ozone Research and Monitoring Project- Report No. 56, 2015, ISBN: 978-9966-076-00-7.)

The continued rising global demand for refrigeration and air conditioning equipment represents both important environmental protection opportunities and challenges. Efforts focused on ensuring that low-GWP options are available and technically proven at the earliest opportunity will be likely to inspire investment confidence.

Another concern associated with HFCs, and especially the shorter-lived HFOs, is that they could break down in the environment to produce trifluoroacetic acid (TFA), which accumulates in the environment. The concentration of TFA, which is toxic to a wide range of organisms is several orders of magnitude higher than the concentrations that have been measured, or expected for the current levels of usage. Levels of TFA, which persists in the environment, need careful monitoring in the future with large use of HFCs.

Major Finding 6.3

Shepherding the ozone layer to its recovery: Regular assessments are crucial for monitoring and assessing the achievements of the Montreal Protocol in terms of its impact on ODS, depletion of the ozone layer, the resulting effects of changes in UV radiation on human health and ecosystems, and the challenges of transitioning to alternatives and technologies across the various sectors of use.

It will be important to monitor sector and technology-specific challenges to fully assess potential impacts, including ozone layer recovery and climate. These challenges include remaining uses of ODS in specific sectors, uncontrolled and growing ODS uses, increasing use of high-GWP alternatives and emerging options for the use of more climate-friendly alternatives.

The stratospheric ozone layer is changing not only in response to the reduction in ODS but also because of other factors. These include a variety of natural factors, such as volcanic emissions, meteorological variability and natural changes in solar insolation that can all affect the ozone layer across a range of timescales. Climate change also impacts the ozone layer by changing the temperature and circulation of the stratosphere. UV radiation can be affected by clouds, changes in ice and snow cover, air pollution, and the properties of surface waters, which are all influenced by climate change. Understanding the effects of climate change on the ozone layer and UV radiation are thus key components of monitoring the success of the Montreal Protocol. Change in non-ODS greenhouse gases, CO_2, CH_4 and N_2O, is likely to be the dominant factor controlling the ozone layer in the second half of this century.

Major Finding 6.4

Continuing to learn from past lessons is essential for the continued success of the Montreal Protocol.

The ozone layer is fragile – if compressed to sea level pressure and standard temperature, it would only be 3mm thick – and the impact of only a few parts per billion of potent ODS could have been devastating. Our experience of the last few decades is that it can be damaged by human actions within short timescales. The sustained success of the Protocol hinges on continued vigilance by the Parties to fulfill their commitments and prevent any future actions that threaten to nullify the ozone and climate benefits achieved under the agreement. Success also depends on continuing the lessons of collaboration, leadership, innovation, and shared investment in our global environment that was the promise made to future generations under the Protocol.

List of Acronyms:

CCl_4 . . . . Carbon tetrachloride
CFC . . . . Chlorofluorocarbon
CH_4 . . . . Methane
CO_2 . . . . Carbon dioxide
COPD . . . . Chronic obstructive pulmonary disease
DU . . . . Dobson units
EESC . . . . Effective equivalent stratospheric chlorine
GHG . . . . Greenhouse gas
GWP . . . . Global warming potential
HCFC . . . . Hydrochlorofluorocarbon
HCFO . . . . Hydrochlorofluoroolefin
HFC . . . . Hydrofluorocarbon
HFE . . . . Hydrofluoroether
HFO . . . . Hydrofluoroolefins
IPCC . . . . Intergovernmental Panel on Climate Change
MB . . . . Methyl bromide
MCF . . . . Methyl chloroform
N_2O . . . . Nitrous oxide
ODS . . . . Ozone depleting substances(s)
QPS . . . . Quarantine and Pre-Shipment
RAC . . . . Refrigeration and Air Conditioning
TFA . . . . Trifluoroacetic acid
UV . . . . Ultraviolet
UVI . . . . UV Index

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