The Discovery in the 1980s of a Hole Over the Antarctic Stratospheric Ozone Layer.
Discovery that led to the most successful global environmental policy

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Abstract. The stratospheric ozone layer has been the centre of scientific interest for many decades for its fundamental role in the protection of any form of biological life on Earth’s surface from damaging Sun’s ultraviolet radiation (UV). From the 1970s there was suggestion in the scientific literature that inert gaseous pollutants have the potential to deplete the stratospheric ozone layer. A study in 1974 suggested that chlorine monoxide (ClO•) produced from dissociated Chlorofluorocarbons (CFCs) might deplete ozone. In 1985 researchers at the British Antarctic Survey discovered the ozone hole in Antarctica, and NASA’s satellite measuring the total column ozone from the Total Ozone Mapping Spectrometer (Limb Infrared Monitor of the Stratosphere, NIMBUS 7) confirmed the 1985 event. The news came as a surprise to many scientists and send worrying signs to environmental organizations and authorities. The discovery of the mechanisms by which the CFCs initiated ozone depletion was also very important that led to Prof. F. Sherwood Rowland, Mario J. Molina and Paul J. Crutzen who was a pioneer in stratospheric ozone research (Max Plank Institute of Chemistry, Germany) to share the 1995 Nobel Prize in Chemistry. In response to the dramatic discovery of the Antarctic ozone depletion the Montreal Protocol (15.9.1987) was a global agreement to protect the stratospheric ozone layer by phasing out the production and consumption of ozone-depleting substances CFCs. In 1989, 12 EU nations agreed to ban the production of all CFCs by the end of the century. Despite the initial doubts of CFCs contribution to the problem, the Montreal Protocol was the most successful environmental regulation and to date is the only UN treaty ever that has been ratified by every country on Earth 197 UN Member States. It phases down the consumption and production of the Ozone Depleting Substances (ODS) in a step-wise manner, with different timetables for developed and developing countries. The 2019 documents (WMO, UNEP, US NOAA, NASA and the European Commission) presented the advances in scientific understanding of ozone depletion and the gradual recovery in the last decades. The Northern Hemisphere (Arctic) mid-latitude total column ozone is expected to return to 1980 abundances in the 2030s. The Southern Hemisphere (Antarctic) mid-latitude ozone hole is expected to gradually close, with springtime total column ozone returning to 1980 values in the 2060s.
Introduction: Protective role of Earth’s stratospheric ozone layer

The Earth is the only planet in the solar system with a gaseous atmosphere that can protect and sustain biological life in the aquatic and terrestrial environments. The atmospheric blanket of gases not only contains the air that organisms breathe but also protects life from the blasts of heat and radiation (especially ultra violet, UV) emanating from the sun. The Earth’s atmosphere contains 78% nitrogen (N₂), 21% oxygen (O₂), 0.93% Argon (Ar) and 0.04 % carbon dioxide (CO₂). Additionally, the atmosphere plays an important role by warming the planet during the day and cools the planet at night. The Earth's atmosphere is about 480 kilometers (km) thick, but most of it is within 16 km from the surface.¹,²

![Layers of the Atmosphere](image)

**Figure 1.** The Earth is surrounded by three atmospheric layers: the troposphere up to 11 km, the stratosphere 11-50 km and the mesosphere region in the 50-80 km. The ozone layer is a very thin layer 20-25 km as part of the stratosphere and protects all biological organisms from the damaging UV radiation (in particular UV-B and UV-C) from the Sun. The ozone layer contains less than 10 parts per million of ozone.

Ozone in the lower tropospheric layer is mainly a secondary photochemical pollutant. But in the upper atmosphere ozone exists naturally at very low concentrations. It is estimated that there are only 3 molecules of ozone for every ten million air molecules. 90% of the planet's ozone is in the
"ozone layer" which exists in the lower level (20-25 kilometres above sea level) of the stratosphere.

Ozone is a triatomic molecule (O$_3$) that is formed in the stratosphere by breaking oxygen molecules (O$_2$) with the aid of the high energetic solar UV-B and UV-C radiation in the upper layers of the atmosphere into two atoms of oxygen each carrying one single electron (free radicals) (O$^\bullet$). These free radical oxygen atoms are highly energetic and react with a molecule of oxygen (O$_2$) forming ozone (O$_3$).

Ozone is also naturally broken down in the stratosphere by sunlight and by a chemical reaction with various compounds containing nitrogen, hydrogen and chlorine. These chemicals all occur naturally in the atmosphere in very small amounts. The UV-B wavelengths of ultraviolet (240-310 nm) are strongly absorbed by ozone, which breaks down as a result and reforms into molecular oxygen again. Up to 98% of the sun's high-energy ultraviolet light (UV-B and UV-C) are absorbed by the stratospheric ozone layer through a series of reactions that initially destroy ozone but then are reformed. The global exchange between atmospheric ozone and oxygen is on the order of

Figure 2. Ozone (O$_3$) is created in the stratosphere, when highly energetic solar rays strike molecules of oxygen (O$_2$) and cause to split apart in two atoms of oxygen carrying one free electron each (free radical). The high energy oxygen atom (O$^\bullet$) collides into another O$_2$ forming ozone (O$_3$).
300 million tons per day continuously changing concentrations of the two gases.\textsuperscript{3,4}

\[ \text{O}_3 + h\nu_{(240-310 \text{ nm})} \rightarrow \text{O}_2 + \text{O}\cdot \]

\[ \text{O}_2 + h\nu \rightarrow 2 \text{O}\cdot \]

\[ \text{O}\cdot + \text{O}_2 \rightarrow \text{O}_3 \]

**The crucial role of Ozone in the stratosphere and biological organisms on Earth**

Ozone is found in two different regions of the Earth’s atmosphere. The majority, 90%, of natural ozone resides in the stratosphere, in a very thin layer between 11 and 17 kilometers above the Earth’s surface, called the ozone layer. Another 10% of ozone is found in the lower region of the atmosphere (called troposphere) as a secondary photochemical pollutant which is formed from a series of reactions of exhausts gases of vehicular traffic and other gaseous pollutants. This ozone (called “bad ozone”) is also a key component of photochemical smog, a serious environmental problem in the atmosphere of many cities around the world.\textsuperscript{5}

The stratospheric ozone (called “good ozone”) plays a very important role in protecting life on Earth from ultraviolet radiation (especially UV-B, UV-C) from the sun. The UV radiation is highly damaging to biological molecules and tissues. Life on Earth would have been under threat if ozone layer did not exist billions of years ago. Also, the absorption of ultraviolet radiation by ozone creates a source of heat, which actually forms the stratosphere itself. Ozone plays a key role in the temperature structure of the Earth’s atmosphere. Without the filtering action of the ozone layer, more of the Sun’s UV-B radiation would penetrate the atmosphere and would reach the Earth’s surface. Experimental studies of plants and animals and clinical studies in humans have shown harmful effects of excessive exposure to UV-B radiation.\textsuperscript{6}

The planet Earth remains the only place in the universe known to harbour biological life. Paleomineralogists discovered substantial numbers of fossils 3.5-2.5 billion years ago that gave a very clear indication of
abiogenesis through reactive organic and inorganic molecules. The age of the Earth is about 4.54 billion years and the earliest evidence of life on Earth dates from at least 3.5 billion years ago (Archean period, 4-2.5 billion years), estimated from fossilized remains in various parts of the Earth. Initially, life forms were very small, one cell organisms, anaerobic and their metabolism was extremely simple supporting few basic anaerobic reaction and energy from breaking chemical bonds of organic molecules.\textsuperscript{7,8}

Oxygen (O\textsubscript{2}) production on Earth started over two billion years ago by the splitting of water molecules by the sun and more significantly, through the photosynthesis of blue-green algae in the oceans. Over millions of years, O\textsubscript{2} began to accumulate in Earth’s atmosphere. Ozone also began to form through photochemical dissociation in which O\textsubscript{2} molecules absorb UV radiation, producing two single oxygen molecules (O). The single oxygen and O\textsubscript{2} molecules can then react with each other to form ozone (O\textsubscript{3}). Around 600 million years ago, a thin ozone layer formed that was capable of protecting biological life from harmful wavelengths of UV radiation (wavelengths between 200-300 nm). The ozone layer plays this important role until now.\textsuperscript{9}

![Figure 3](image)

**Figure 3.** Example of the microfossils discovered in a sample of rock recovered from the Apex Chert. 3.5 billion-year-old piece of rock in Western Australia are the oldest fossils ever found and indeed the earliest direct evidence of life on Earth. Courtesy of Prof. Schopf JW research pictures. The Cambrian Period (+543 million years ago) is the first geological time period of the Paleozoic Era (the “time of ancient life”). This period marked a dramatic burst of evolutionary changes in life, known as the “Cambrian Explosion” that produced amazing aerobic organisms.
The obvious question is what happened to life before the formation of the ozone layer in the stratosphere? To protect the sensitive biological structures, living organisms only existed in the oceans where the water was deep enough to shield organisms from UV radiation, but shallow enough for photosynthesis to occur. The aquatic environment, water (H\textsubscript{2}O), with its exceptional property to be lighter as ice that floats on the top of liquid watery phase protected life from the frozen conditions for millions of years, providing at the same time soluble materials for energy and nutrition.

When the ozone layer became thick enough to shield organisms from the harmful spectrum of UV radiation (around 600 million years ago), there was a massive diversification of life, known as the Cambrian Explosion. During the Cambrian Explosion, many complex multicellular organisms evolved in the oceans. Marine organisms became mobile and were able to live in shallower areas of the ocean with greater sunlight exposure. Around 420 million years ago, ozone levels were high enough to allow for organisms to survive on land, without any shielding from water.\textsuperscript{10-12}

![Figure 4](image)

**Figure 4.** The first terrestrial life migrated out of the water about 430 million years ago, in the midst of a period known as the "Cambrian Explosion of Life"--an evolutionary heyday when favorable conditions (formation of ozone layer) allowed life to swell and branch into most of the major forms in existence today. During this time, a group of freshwater plants inched their way onto muddy shores and into swamps and watery lowlands, and true land plants evolved from there. Before that, there was nothing living on the land (because of the damaging effects of UV radiation).
The first organisms that spent some time on land were probably algae and fungi that lived in intertidal zones where the water levels fluctuated with the rising and falling of the tides. Eventually, primitive plants evolved as the first completely terrestrial organisms. At this point, the stratospheric ozone layer was still relatively thin and plants were thought to have developed UV screening compounds such as scytonemin to provide them with additional UV protection. The first animals to colonize land around 450 million years ago were arthropods such as myriapods (millipedes and centipedes), arachnids, and ancestors of modern insects.\textsuperscript{13,14}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{myriapods.png}
\caption{Myriapods. The fossil record of myriapods reaches back into the late Silurian, although molecular evidence suggests a diversification in the Cambrian Period. Some Cambrian fossils exist resembling myriapods. The oldest unequivocal myriapod fossil is of the millipede \textit{Pneumodesmus newmani} (428 million years ago).}
\end{figure}

\textbf{How the ozone hole was formed over in Antarctica}

The ozone layer is spread like blanket all over the Earth at an altitude of 11-17 km filtering the damaging UV from Sun and in this respect plays a substantial protective role of all biological organisms. Antarctica is the only place on Earth where it's reliably cold enough for an ozone hole to form. The ozone hole was discovered by scientists in 1985 over Antarctica. The ozone hole is an annual thin spot that forms in the stratospheric ozone layer over Antarctica in mid-September and October. Scientists did not know about this phenomenon but it was detected by satellite pictures. First researchers at the British Antarctic Survey discovered the ozone hole in 1985, and NASA's
satellite estimates of total column ozone from the Total Ozone Mapping Spectrometer (Limb Infrared Monitor of the Stratosphere, NIMBUS 7) confirmed the 1985 event, revealing the ozone hole’s continental scale.

Figure 6. In May 1985 reporting in Nature, scientists Joe Farman, Brian Gardiner and Jonathan Shanklin (British Antarctic Survey) described their observations of large losses of ozone over Antarctica. The British Antarctic Survey (BAS, with over 450 staff), a component of the Natural Environment Research Council, world-leading interdisciplinary research in the Polar Regions. Its skilled science and support staff is based in Cambridge, UK.

The discovery of the hole in the atmospheric ozone layer send worrying signals to the scientific community and environmental organizations. Finally, the importance of the ozone layer helped to establish one of the most successful global environmental policy of the 20th century. The scientists of the British Antarctic Survey Joe Farman, Brian Gardiner and Jonathan Shanklin reported (1985) large decreases in stratospheric ozone levels over the Antarctic stations of Halley and Faraday.15

The confirmation of stratospheric ozone depletion was recorded by the Total Ozone Mapping Spectrometer (TOMS) onboard. The false-colour view of total ozone over the Antarctic pole as purple and blue colours are where there is the least ozone, and the yellows and reds are where there is more ozone. It is calculated from the area on the Earth that is enclosed by a line with a constant value of 220 Dobson Units. NASA began measuring Earth’s stratospheric ozone layer by satellite in 1979.
Scientists had theorized since the 1970s about the chemistry that could lead to stratospheric ozone depletion. In 1985 scientists from the British Antarctic Survey shocked the world when they announced the discovery of a huge hole in the ozone layer. The special satellite U.S. NIMBUS 7 passed over Antarctica and recorded the ozone hole [NASA and the National Oceanic and Atmospheric Administration (NOAA)].

The ozone hole over Antarctica (Southern pole) doesn’t exist year round: it is seasonal and changes under the extremely cold conditions in the area.

Figure 8. Special satellite photographs of the Stratospheric ozone concentrations in spring 2016 in the Southern (left, September 19–26) and Northern (right, March 21-27) Hemispheres. Each year, ozone amounts drop below 220 Dobson Units—the threshold that marks the start of an ozone hole—across a large area of Antarctica. Northern Hemisphere (Arctic pole) values are rarely that low. National Oceanographic NOAA Climate.gov image based on satellite ozone data provided by NOAA.
Farman and other scientists of the British Antarctic Survey suggested in the 1980s that the ozone hole is associated with reactive chemical substances, such as chlorofluorocarbons (CFCs, Freon). These industrial substances produced in large amounts are used in aerosol spray cans and as cooling devices in fridges and air conditioners. They are gases, heavier than air, but escaping in the atmosphere are promoted upwards very easily.

When chlorofluorocarbons escape from refrigerators, air conditioners, aerosol cans or when are rejected as waste can reach the stratosphere with atmospheric turbulent air movements. The CFC's as gasses are diffused into the top of the ozone layer and are exposed to intense ultraviolet light (especially UV-B, UV-C), which leads only to dissociation of carbon-chlorine bonds forming a chlorine radical (Cl•). The bond of C-F fluorine with carbon is stronger and do not break easily with UV. This is the initiation step for the propagation chain reaction. The chlorine radical produced, Cl• is a highly energetic and reactive molecule (free radical) because of the single electron, and in a second step attacks ozone molecules, and at each cycle destroys 3 ozone molecules. The ClO• (chlorine-oxygen radical) is also highly reactive and entering the chain reaction destroys more ozone molecules.

Free radical reactions that decompose ozone

\[
\text{Initiation} \quad \text{F-Cl} \quad \text{hv} \quad \text{F-Cl}^* + \text{Cl}^* \\
\text{Propagation} \quad \text{Cl}^* + \text{O}_3 \quad \text{ClO}^* + \text{O}_2 \\
\text{ClO}^* + \text{O}_3 \quad \text{Cl}^* + 2\text{O}_2
\]
It is estimated that in cold atmospheric conditions, each chlorine radical produced destroys 100,000 molecules of ozone before the chain is terminated. Thus, it is the radical chain of chlorine free radicals process that makes CFC’s potentially so dangerous in destroying ozone, even in something as vast as the ozone layer in the stratosphere.

The chemical chain reactions that destroy ozone molecules have been investigated in laboratory tests and the important findings transformed the fields of atmospheric science and chemical kinetics. The importance of ozone layer and its extremely protective and unique role for life on Earth led to the most important and successful global change in environmental policy.

Already two studies ten years earlier, in 1974, suggested that chlorine monoxide (ClO•) produced from breaking the C-Cl bond with UV radiation of chlorofluorocarbons (CFCs) might similarly deplete ozone. In 1985 the Nimbus -7 spectrometer recorded the spring Antarctica ozone hole.18

Although the estimated projections on the problem of the ozone hole in connection with the man-made CFCs (Freon) escaping in the stratosphere did not look very extensive, the discovery at polar latitudes shocked the scientific community. There was a big debate among scientists at the time of the discovery of the Antarctica ozone hole if the CFCs can be responsible for the depletion. Another mystery was why the hole appears in September, at the end of Southern Hemisphere of winter and beginning of spring. Researchers found that during the cold, dark southern winter, clouds of ice form and float in the stratosphere. In the spring the Sun rises at the end of Southern Hemisphere winter melting slightly the watery ice clouds releasing watery surfaces that act as mirrors and catalyze chemical dissociation reactions. These catalytic cloud surfaces degrade CFCs gases, releasing “free radicals” of chlorine (Cl•). A single chlorine-containing free radical can catalyze the destruction of thousands of ozone molecules. Ozone destruction usually peaks in mid-October. Ozone loss diminish or stop gradually in late spring as the polar vortex weakens. Temperatures rise, and fewer clouds form. Ozone-rich air from lower latitudes mixes back into the polar stratosphere, and the ozone hole disappears until the next spring.19-21
Figure 9. The International Day for the Preservation of the Stratospheric Ozone Layer is now marked each year on 16 September to maintain awareness of the human impact on our environment.

Depletion of ozone and the Nobel Prize for Chemistry (1995)


Figure 10. Professor FS Rowland and Dr Mario Molina (from Mexico) at the University of California, Irvine, in 1974. Molina’s experimental research was directed to study dissociation mechanisms of Chlorofluorocarbons and their involvement in the depletion of the stratospheric ozone layer.
Research by Prof. Rowland and Dr. Molina (postdoctoral fellow) and their publication in Nature (1974) fell like a scientific bombshell, because from one hand the CFCs were important industrial chemicals with fundamental uses in refrigerators and in air conditioning (important electrical utilities) and in the other hand the importance of the ozone layer for life on Earth. For decades, the scientific community did not realize the destructive side of these chemicals as they rise into the atmosphere. The repercussions of the discovery would be felt around the world. It set off fierce debates, some scientists objected that CFCs were responsible, but the facts were very clear and very soon led to a global environmental treaty restricting the use of a broad class of chemicals, and changed the way humans viewed their impact on Earth's environment through the extensive use of industrial chemicals.

At the time, Chlorofluorocarbons (CFCs) and Bromofluorocarbons (BrCFs) were in wide use in refrigeration, air conditioning, aerosol spray cans and in fire extinguishers. CFCs (most common Freon-12) are low toxicity, inert, and inflammable. Millions of kilograms of CFCs were produced for the needs of refrigeration, air conditioning. In the 1960s, fluoroalkanes and bromofluoroalkanes were recognized as being highly effective fire-fighting materials. By the early 1970s, CFCs were in widespread use, and worldwide production of the compounds had reached nearly one million tons per year, representing roughly a $500 million slice of the chemical industry.

But the discovery of ozone depletion mechanisms through the free radical reactions due to chlorofluorocarbons dissociation by UV radiation at the stratospheric region was an important part of research collaboration among researchers from various institutions and the value of scientific investigations and new technological instruments in satellites orbiting the Earth and collecting atmospheric data. Antarctica is a region in which countries, like UK and USA, keep substantial teams of scientists. But at the same time the discovery in the laboratory of the CFCs involvement was another big success of scientific research and ingenuity that guided the decision of the Nobel Prize and led to professors F. Sherwood Rowland, Mario J. Molina and Paul J. Crutzen who was a pioneer in stratospheric ozone
research (Max Plank Institute of Chemistry, Mainz, Germany) to share the 1995 Nobel Prize in Chemistry.

Figure 11. Paul Crutzen, Mario Molina and Sherwood Rowland shared the Nobel Prize for Chemistry in 1995 for their atmospheric chemistry research, particularly the formation and decomposition of ozone.

The Montreal Protocol for substances that deplete the stratospheric ozone layer

The Montreal Protocol, finalized in 15.9.1987, was a global agreement to protect the stratospheric ozone layer by phasing out the production and consumption of ozone-depleting substances. Although there were many doubts and debates in the beginning for the role of CFCs in ozone depletion the scientific facts were overwhelming.

By 1987, in response to a dramatic seasonal depletion of the ozone layer over Antarctica, diplomats in Montreal forged a treaty, the Montreal
Protocol, which called for drastic reductions in the production of CFCs. On 2 March 1989, 12 European Community nations agreed to ban the production of all CFCs by the end of the century. In 1990, diplomats met in London and voted to significantly strengthen the Montreal Protocol by calling for a complete elimination of CFCs by the year 2000. By the year 2010, CFCs should have been completely eliminated from developing countries as well.\textsuperscript{22}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{image.png}
\caption{The Montreal Protocol (1987) was very successful and to date is the only UN treaty ever that has been ratified by every country on Earth - all 197 UN Member States.}
\end{figure}

At the time, the arguments for the importance of the stratospheric ozone layer was that it filters out harmful ultraviolet radiation (UV-B), which is associated with an increased prevalence of skin cancer and cataracts, reduced agricultural productivity, and disruption of marine ecosystems. The Montreal Protocol is despite the problems was successful and to date is the only UN treaty ever that has been ratified by every country on Earth - all 197 UN Member States decided to support the replacement of CFCs.

The Montreal Protocol phases down the consumption and production of the different Ozone Depleting Substances (ODS) in a step-wise manner, with different timetables for developed and developing countries. Under this treaty, all parties have specific responsibilities related to the phase out of the different groups of ODS, control of ODS trade, annual reporting of data, national licensing systems to control ODS imports and exports, and other matters. Developing and developed countries have equal but differentiated responsibilities, but most importantly, both groups of countries have binding,
time-targeted and measurable commitments. The Protocol includes various provisions related to control measures, calculation of control levels, control of trade with non-Parties, special situation of developing countries, etc. The substances controlled by the treaty are Chlorofluorocarbons (CFCs), Halons, other fully halogenated CFCs, carbon tetrachloride (CCl₄), methyl chloroform (CH₃Cl), Hydrochlorofluorocarbons (HCFCs), methyl bromide (CH₃Br) and Hydrofluorocarbons (HFCs).

The Multilateral Fund for the Implementation of the Montreal Protocol was established in 1991 to provide financial and technical assistance to developing country parties to the Montreal Protocol. It supported over 8,600 projects including industrial conversion, technical assistance, training and capacity building worth over US$3.9 billion.

The parties to the Montreal Protocol recognized (in 2007) the potential benefits to the Earth’s climate by accelerating the phase out of HCFCs. Because it was found that Hydrochlorofluorocarbons (HCFCs) are gases and nearly 2,000 times more potent than CO₂ in terms of its global warming potential. Developed countries have been reducing their consumption of HCFCs and will completely phase them out by 2020. Developing countries agreed to start their phase out process in 2013 and are now following a stepwise reduction until the complete phase-out of HCFCs by 2030.²³

Replacement substances for Chlorofluorocarbons (CFCs)

The substances that replaced the CFCs for the needs of refrigeration, air conditioning etc, were Hydrofluorocarbons HFCs, where the Chlorine was eliminated and was replaced with Hydrogen. These substances were introduced as non-ozone depleting alternatives (their ozone depletion properties are very limited) to support the timely phase out of CFCs and HCFCs. HFCs are now widespread in air conditioners, refrigerators, aerosols, foams and other products. HFCs do not deplete stratospheric ozone. However, there is a downside to the use of HFCs -- they are very potent greenhouse gases. HFC-134a, also known as R-134a, for example, which is used in automobile air conditioning units, is 1430 more active than the
"classic" greenhouse gas carbon dioxide (CO₂). Overall HFC emissions are growing at a rate of 8% per year and annual emissions are projected to rise to 7-19% of global CO₂ emissions by 2050. Uncontrolled growth in HFC emissions therefore challenges efforts to keep global temperature rise at or below 2°C this century. Urgent action on HFCs is needed to protect the climate system.²⁴,²⁵

The Parties to the Montreal Protocol reached agreement at their 28th Meeting of the Parties on 15 October 2016 in Kigali, Rwanda to phase-down HFCs. Countries agreed to add HFCs to the list of controlled substances, and approved a timeline for their gradual reduction by 80-85% by the late 2040s. The first reductions by developed countries are expected in 2019. Developing countries will follow with a freeze of HFCs consumption levels in 2024 and in 2028 for some nations. There are various alternatives to commonly used HFCs are listed: Natural refrigerants, HFCs with lower GWP (global warming potential), such as R32, Hydrofluoroolefins (HFOs), and HFC-HFO blends. The R32 refrigerant is also known as difluoromethane. This gas is poised to replace the other gaseous substances such as R-410A and R-407C as the preferred gas due to its lower Global Warming Potential (GWP). Its chemical formula is CH₂F₂. As a result of the Montreal Protocol, the R-410A and R-407C are refrigerant blends that are used to replace ozone depletion refrigerants such as R22 as both of these gaseous have zero ODP (Ozone Depletion Potential).

Given all of these factors, the Montreal Protocol is considered by environmental protection practitioners to be one of the most successful environmental agreements of all time. What the parties to the Protocol have managed to accomplish since 1987 is unprecedented, and it continues to provide an inspiring example of what international cooperation at its best can achieve.²⁶

The recovery of ozone layer under the Montreal Protocol

The full Scientific Assessment of Ozone Depletion (2019) shows that actions taken under the Montreal Protocol have led to decreases in the atmospheric abundance of controlled ozone-depleting substances (ODSs)
and the start of the recovery of stratospheric ozone. The quadrennial (every four years) report is the 9th in a series of assessments prepared by many dozens of the world’s leading atmospheric scientists. It is compiled under the auspices of World Meteorological Organization (WMO), the UN Environment Programme (UNEP), the US National Oceanic and Atmospheric Administration (NOAA), the National Aeronautics and Space Administration (NASA) and the European Commission. The report documents the advances in scientific understanding of ozone depletion, and is based on longer observational records, new chemistry-climate model simulations, and new analyses over the past four years of concentrations of stratospheric ozone layer in various parts of the Earth, particularly in Antarctica.

![Environmental Effects and Interactions of Stratospheric Ozone Depletion, UV Radiation, and Climate Change](image)

**Figure 13.** The 2018 report, “Environmental Effects and Interactions of Stratospheric Ozone Depletion, UV Radiation, and Climate Change: 2018 Assessment Report”, also known as the “ninth Quadrennial Assessment”. The full report can be downloaded directly from the UNEP website ([https://ozone.unep.org/science/assessment/eeap](https://ozone.unep.org/science/assessment/eeap)). The 381-pages report captures the latest scientific understanding on impacts of ozone layer depletion. The report places strong emphasis on the novel challenge of interactive effects of ozone depletion and climate change on human health and the environment. The report was prepared by over 250 international scientists working on the special chapters.

The most important highlights of the report in 2018 are:

a. Atmospheric abundances of both total tropospheric chlorine and total tropospheric bromine from long-lived ODSs controlled under the Montreal Protocol have continued to decline since the 2014 Assessment.
b. The Antarctic ozone hole is recovering, although continues to occur every year. As a result of the Montreal Protocol much more severe ozone depletion in the polar regions has been avoided.

c. Outside the polar regions, upper stratospheric ozone has increased by 1–3% per decade since 2000.

d. Ozone layer changes in the latter half of this century will be complex, with projected increases and decreases in different regions. Northern Hemisphere mid-latitude total column ozone is expected to return to 1980 abundances in the 2030s, and Southern Hemisphere mid-latitude ozone to return around mid-century (2050-2060).

e. Stratospheric ozone in the northern hemisphere is projected to return to healthy levels in the 2030s, southern hemisphere (Antarctica) ozone in the 2050s, and polar regions--where depletion is most severe--in the 2060s.²⁷,²⁸


**Figure 14.** NASA is contacting regular measurements and its report has revealed that in 2019 the hole in the ozone layer in Antarctica is now the smallest on record since its discovery in 1985. It has shrunk to 3.9 million square miles and is likely to heal fully by 2060, new evidence shows. To put this into perspective, during normal weather conditions, the hole is usually around 8 million square miles at this time of year (September). NASA, 21/10/2019 [https://www.nasa.gov/feature/goddard/2019/2019-ozone-hole-is-the-smallest-on-record-since-its-discovery].

Every 16th of September the world celebrates the Montreal Protocol, often dubbed the world’s most successful environmental agreement. The treaty (1987) is slowly but surely reversing the damage caused to the ozone
layer by industrial gases such as chlorofluorocarbons (CFCs). The ozone layer above Antarctica is recovering. As ozone-destroying gases are phased out, the annual ozone hole is generally getting smaller – a rare success story for international environmentalism. 2019 celebrates “32 Years and Healing”; a commemoration of the international commitment to protect the stratospheric ozone and the climate, which has led to the phase-out of 99% per cent of ozone-depleting chemicals.

Scientific research on the substances that deplete the stratospheric ozone and the effects of the Montreal Protocol recorded some very interesting results:

a. Global emissions of ozone-depleting substances (CFCs and other polychlorinated substances) have declined by more than 98% since 1986 (the year before international action was agreed)

b. The Montreal Protocol (and later amendments) was adopted in 1987 — signed by all UN nations then all 197 countries. The developed and developing countries were allowed to phase out their ozone-depleting chemicals with different dates for completion.

c. The Ozone layer thickness declined slowly in the 1980s and 1990s. The Antarctic ozone hole which was much larger in size from the Arctic hole grew substantially from the 1980s through to the early 2000s then this trend largely stabilized and in the last 29 years scientist observed clear signs of recovery. It is hoped that if the trend continues the Antarctic ozone hole will be healed in the 2060 and the ozone concentration will return to normal conditions.

d. The normal stratospheric Ozone layer will absorb most of the damaging ultraviolet (UV) radiation that reaches Earth’s surface and reduce the risk of skin cancer to humans, particularly at higher latitudes (especially for people living in mountainous areas). Also, ozone will protect plants and crops from damaging UV radiation.

e. The global shift away from ozone-depleting substances has also had co-benefits on the reduction of greenhouse gas emissions.
Conclusions

The scientific evidence of stratospheric ozone depletion over Antarctica in the 1980s was one of the most successful environmental regulation from monitoring trends and conditions in the Earth’s atmospheric environment. The evidence was so strong and important that forced all United Nations 197 member states, along with civil societies, academics and industry, to come together for a negotiated practical solution. The Montreal Protocol of 1987. The discovery of the stratospheric ozone hole over Antarctica was the result of a successful scientific research and prediction 10 years earlier (1974) for the role of industrially produced chlorofluorocarbons (CFCs) as refrigerants in millions of tons depleting ozone through free radical mechanisms. Then in 1985 scientists of the British Antarctic Survey discovered the actual hole and subsequently it was detected beyond doubt by NIMBUS-7 satellite (NASA’s satellite Total Ozone Mapping Spectrometer) revealing the ozone hole’s continental scale. The Montreal Protocol helped to phase out ozone-destroying gases (CFCs) and replace them with much less damaging industrial products. The result was that in 30 years, the annual ozone hole (over Antarctica and other stratospheric areas) started to get smaller – a rare success story for international environmentalism. In 2019 humankind celebrates “32 Years and Healing”; a commemoration of the international commitment to protect the stratospheric ozone and the climate under the historic Montreal Protocol, which has led to the phase-out of 99% per cent of ozone-depleting chemicals. At the same time the protective role of stratospheric ozone layer was restored to protect life on Earth from the damaging UV radiation (e.g. reduction in skin cancer risk). Scientific monitoring in the last 30 years observed clear signs of ozone recovery and if trends continue with Arctic and Antarctic holes to be healed completely in 2030 and 2060 respectively. Outside the polar regions, upper stratospheric ozone has increased by 1–3% per decade since 2000.

The Montreal Protocol continues to provide an inspiring example of what international cooperation among countries at its best can achieve, for the protection of the environment, ecosystems and life on Earth.
References