How the Montreal Protocol Put the Stratospheric Ozone Layer on the Path to Recovery and Delayed Climate Tipping Points That Would Have Forced Earth Further Beyond Planetary Boundaries

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Abstract

The framework, introduced in 2009 by co-author Professor Johan Rockström and colleagues, defines Planetary Boundaries as the safe operating thresholds for nine critical processes that maintain Earth system stability and resilience. The stratospheric ozone layer is one of the nine processes, and it is highlighted as the first and only example of a planetary system imperilled by humans yet pulled back towards health in the coming decades by collective action of scientists, consumer boycotts, public policy, and technical innovation. This paper explains how policymakers, facing an existential risk from fluorocarbon emissions, listened to science and acted at a global level with adoption of the Montreal Protocol on Substances that Deplete the Ozone Layer (Montreal Protocol) that, along with complementary actions by citizen and corporate leaders, avoided health and environmental hazards of stratospheric ozone depletion. The paper also explains how the Montreal Protocol has delayed climate tipping points through 1) the *phaseout* of ozone-depleting substances (ODSs) that are also powerful greenhouse gases (GHGs), 2) the ongoing *phasedown* of non-ozone-depleting hydrofluorocarbon (HFC) GHGs, and 3) the associated protection of aquatic and terrestrial carbon sinks from ultraviolet (UV) radiation. The Montreal Protocol is proof that humans can organize to protect the global commons against exceeding planetary boundaries. The paper shows how it is possible to restore the health of other planetary boundaries beyond stratospheric ozone and climate by using the Montreal Protocol's successful model of trusted scientific and technical wisdom, deep human connections, and a commitment to fairness.

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1. Introduction to Stratospheric Ozone Depletion

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 kilometres (6 miles) above the surface. About 90% of atmospheric ozone is contained in the stratospheric ozone layer … Twenty Questions and Answers About the Ozone Layer.

Salawitch et al. 2023.

Stratospheric ozone shields Earth from the harmful effects of ultraviolet (UV) radiation originating from the sun. UV radiation increases skin cancer and cataracts, suppresses the human immune system, damages agricultural and natural ecosystems, degrades aquatic and terrestrial carbon sinks, and deteriorates the built environment (Andersen and Gonzalez 2023; EEAP 2022; Andersen et al. 2021; Hunter, Saltzman, and Zaelke 2021; Young et al. 2021; Albrecht and Parker 2019; Andersen et al. 2018; Jacobs 2014; Andersen and Sarma 2002; DeSombre 2000; Percival 2006).

In the early 1970s, Professor Paul J. Crutzen (co-author with Rockström (2009a and 2009b) of the pioneering Planetary Boundaries framework) warned that nitrogen oxide (NO_x) from human activity could deplete stratospheric ozone and produce ground level ozone (Crutzen 1970; 1972; 1974). In 1971, Dr. James E. Lovelock warned that chlorofluorocarbons (CFCs) were accumulating in the atmosphere (Lovelock 1971). In 1974, Dr. Mario J. Molina and Professor F. Sherwood Roland warned that fluorocarbons could significantly deplete stratospheric ozone (Molina and Rowland 1974) and called for a boycott of CFC aerosol products such as hairspray, deodorant, and household pesticides (Andersen and Sarma 2002). And in 1975, Professor Veerabhadran Ramanathan warned that most ozone-depleting substances (ODSs) also force climate change (Ramanathan 1975). Citizens in North America and Scandinavia responded to the ozone and climate warnings with boycotts of CFC aerosol products, which motivated the United States and then Canada, Denmark, Japan, Norway, Sweden, and Taiwan to ban or restrict sales, and Mexico to voluntarily transition to ozone-safe products (Andersen and Gonzalez 2023).

Then in 1984, Shigeru Chubachi reported that the Japanese Syowa Antarctic station measured unusually low stratospheric ozone during the early 1980s (Chubachi 1984); and in 1985, Joseph C. Farman, Brian G. Gardiner, and Jonathan D. Shanklin warned of the Antarctic Ozone Hole during the Austral Spring (Farman, Gardiner, and Shanklin 1985) and Farman confidently speculated the cause must be CFCs.

Thinning of the Antarctic stratospheric ozone layer harms regional ecosystems (Smith et al. 1992) and diminishes global stratospheric ozone as air from lower latitudes mixes with polar air, posing risks to human health and prosperity (EEAP 2022; WMO et al. 2022). Environmental activists, corporate executives, policymakers, and scientists responded to the Antarctic Ozone Hole by using the 1985 Vienna Convention for the Protection of the Ozone Layer as the framework for creating the 1987 Montreal Protocol on Substances that Deplete the Ozone Layer (Montreal Protocol) (Miller 2025; Andersen and Gonzalez 2023; Andersen and Sarma 2002; Benedick 1998; Tolba and Rummel-Bulska 1998).

2. Introduction to the Planetary Boundaries Framework

Johan Rockström, Will Steffen, Katherine Richardson, and others have defined planetary boundaries for nine interconnected processes critical for maintaining Earth system stability and resilience (Rockström et al. 2024; Richardson et al. 2023; Rockström et al. 2023; Rockström et al. 2021; Steffen et al. 2015; Rockström et al. 2009a; Rockström et al.2009b).[2] The Planetary Boundaries framework elaborates the safe and just operating conditions that would continue global environmental functions and life-support systems similar to those experienced over the past approximately 10,000 years of the Holocene Epoch (Steffen et al. 2011a; Steffen et al. 2011b; Steffen et al. 2005). In 2024, the Potsdam Institute for Climate Impact Research, the Planetary Guardians, and other partners collectively inaugurated an annual Planetary Health Check (Caesar et al. 2024; Boyle 2023).

The nine planetary boundaries include the interconnected systems of biosphere, climate, oceans, and stratospheric ozone (Figure 1). Six of the nine boundaries have already been breached. The once precarious stratospheric ozone layer is recovering through the work of scientists, citizens, and businesses all operating within the boundaries of the Montreal Protocol. The Montreal Protocol's success alone has protected the climate more than most other global efforts (England and Polvani 2023; WMO et al. 2022; Hunter, Saltzman, and Zaelke 2021; Goyal et al. 2019; Borgford-Parnell et al. 2015; Velders et al. 2007).

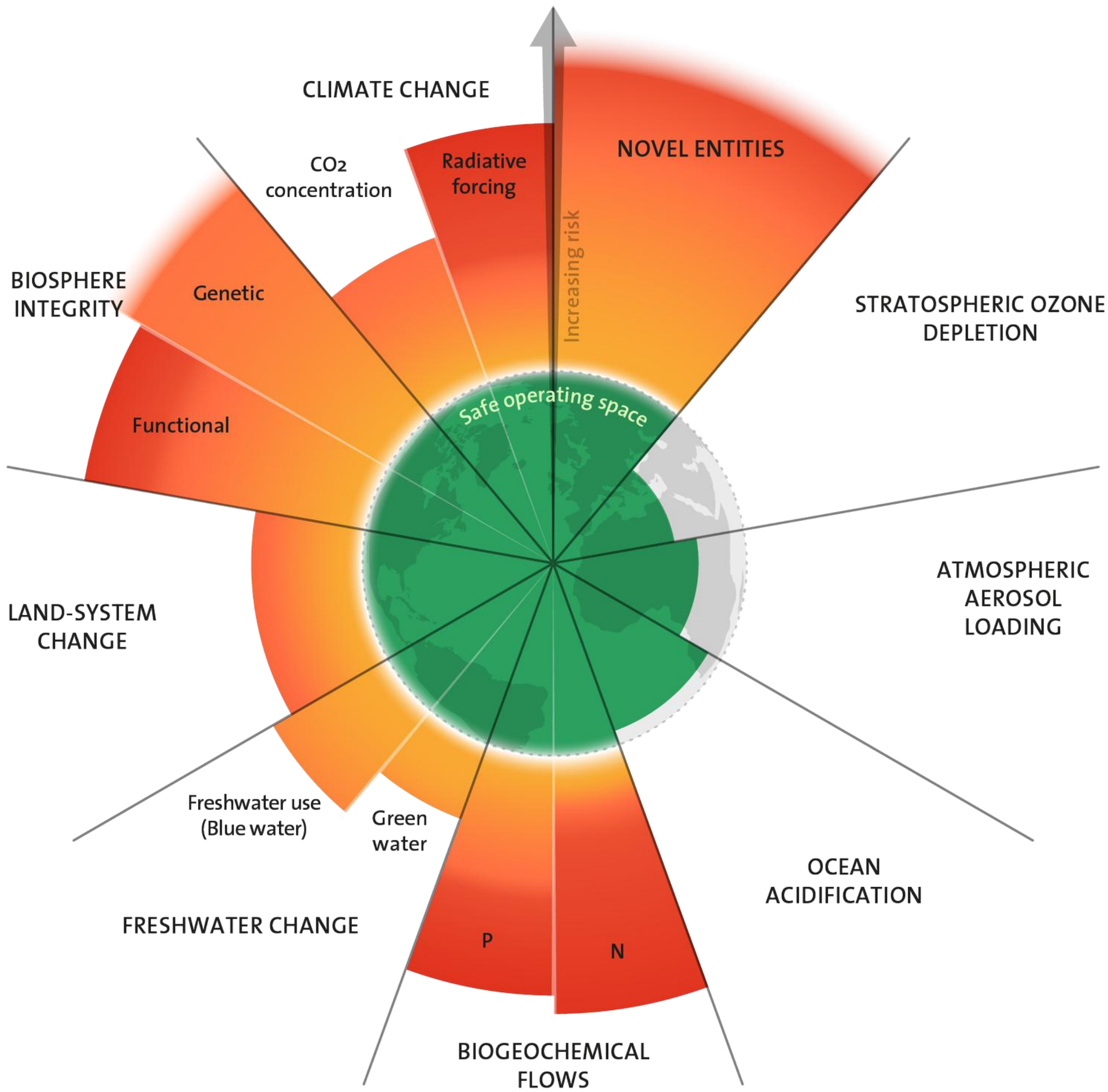


Figure 1. The Planetary Boundaries 2023 Update

Source: Azote for Stockholm Resilience Centre, based on analysis in Richardson et al. 2023. Licensed under CC BY-NC-ND 3.0.

3. Climate Tipping Points

The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) defines a tipping point as a "critical threshold beyond which a system reorganizes, often abruptly and/or irreversibly" (IPCC 2022). Lenton et al. (2008) and Nakicenovic et al. (2016) identify nine global and seven regional tipping elements and their climate tipping points. Ripple et al. (2024) calculate that the first five are likely to be crossed at 1.5 °C, a temperature likely within three to five years (Forster et al. 2025).

Tipping points can be brought about when a small or large disturbance causes a proportionally large and essentially irreversible change in the system. Tipping points exist in tipping element systems (Figure 2), which have at least two stable states (e.g., a rainforest can tip-over into a degraded savanna state, or a stable ice sheet can tip-over into a permanently melted state). The different states are "locked" into their basins of attraction through feedbacks. For example, a rainforest is held in a stable humid-tropical state through the moisture recycling feedback of a complete canopy cover and high humidity levels, which enables the forest system to generate some 40% of its own rainfall. A rainforest is pushed across its tipping point (triggered by heat increase, loss of forest cover, loss of biodiversity) when the self-moistening feedback is shifted to a self-drying feedback. A self-drying feedback subsequently leads to forest die-back, more frequent wildfires, and a general trend toward less rainfall. The system has tipped over into a new basin of attraction and gets permanently locked in a degraded bush savanna-like state. This means that tipping points are always associated with shifts in feedbacks. From a climate perspective, pushing tipping elements across tipping points leads to a dangerous shift from systems being dominated by negative (dampening/cooling) feedbacks to positive (self-amplifying/warming) feedbacks (Ripple et al. 2024; Zhong and Rojanasakul 2024; Biermann et al. 2020).

Arctic warming can force a domino-like cascade of climate tipping points (Lenton et al. 2023; Armstrong-McKay et al. 2022; NSIDC 2022; Wunderling et al. 2021; Lenton et al. 2019) (see Figure 2):

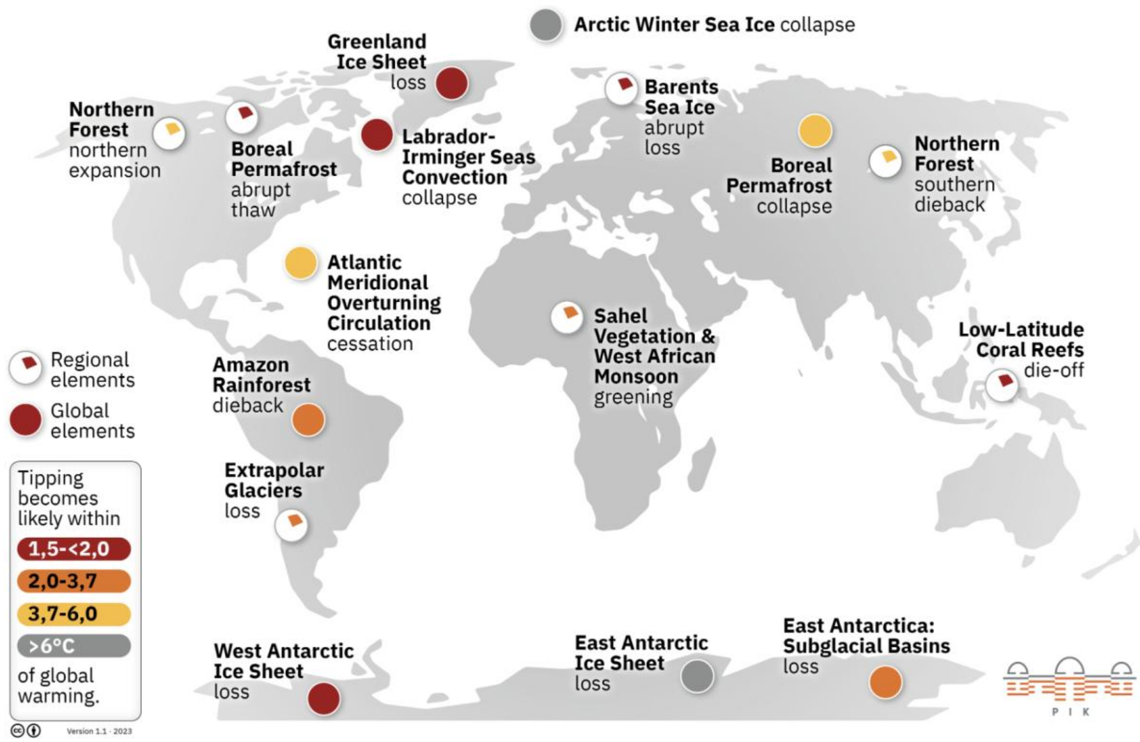
- Arctic sea ice reflects heat, but as sea ice melts and its surface area shrinks, the amount of heat absorbed by the darker ocean increases, causing more ice to melt in a self-amplifying feedback loop (Pistone, Eisenman, and Ramanathan 2014; 2019).

- A warming Arctic accelerates the melting of the Greenland Ice Sheet, which is already the largest single contributor to the rate of global sea level rise (King et al. 2020) and may be close to its tipping point of ice loss (IPCC 2023; Boers and Rypdal 2021).

- The melting of the Greenland Ice Sheet contributes to the weakening of the Atlantic Meridional Overturning Circulation (AMOC) (Golledge et al. 2019), an ocean current that circulates heat and nutrients from the South to the North Atlantic and returns colder water from the North to the South Atlantic (NOAA 2023).

- The collapse of the AMOC, while unlikely, would have catastrophic impacts across the entire world, leading to an overall accelerating in global warming, while triggering abrupt cooling in Northern Europe by up to 15 °C (27 °F) (van Westen et al. 2024) and shifting monsoon patterns across Asia and the Southern Hemisphere, imperilling food and water security (Hansen et al. 2025; Smolders et al. 2024; Ditlevsen and Ditlevsen 2023; IPCC 2023; Wang et al. 2023; IPCC 2022; Orihuela-Pinto et al. 2022).

- Arctic warming is triggering abrupt thawing of Arctic permafrost (Natali et al. 2021; Walker et al. 2019), a layer of soil and sediment that when frozen sequesters nearly twice the amount of greenhouse gases (GHGs) than is already present in the atmosphere (Wang et al., 2023; Miner et al., 2022).



The geographical distribution of global and regional tipping elements, color-coded according to the best estimate for their temperature thresholds, beyond which the element would likely be 'tipped'. Figure designed at PIK (under cc-by licence), based on Armstrong McKay et al., Science (2022).

Figure 2. Global Warming-Vulnerable Climate Tipping Points

Source: PIK n.d.: https://www.pik-potsdam.de/en/output/infodesk/tipping-elements

4. The Anthropocene Epoch

Professor Paul J. Crutzen, the Nobel Prize-winning chemist who, with Dr. Mario J. Molina and Professor F. Sherwood Rowland, warned of stratospheric ozone depletion, was the first to propose a new geological epoch named the *Anthropocene*. This epoch starts around 1950, when humans accelerated their significant adverse impact on Earth. It is defined by the iconic hockey stick graphs of Northern Latitude temperature increase and atmospheric carbon dioxide increase (the Keeling Curve), which are reproduced in Figures 3 and 4 and are indicative of accumulating long-lived and short-lived climate pollutants (LLCPs and SLCPs) that threaten climate and other planetary boundaries.

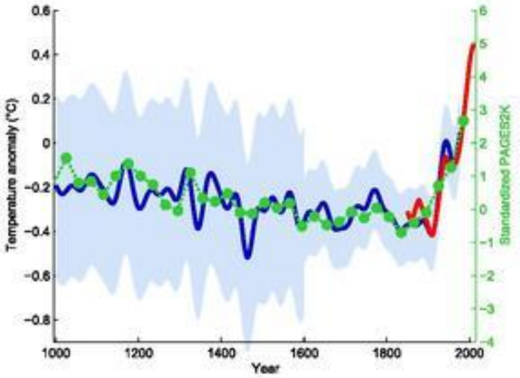


Figure 3. Iconic Hockey Stick Graph: Increase in Northern Latitude Temperature

Source: Mann, Bradley, and Hughes 1999.

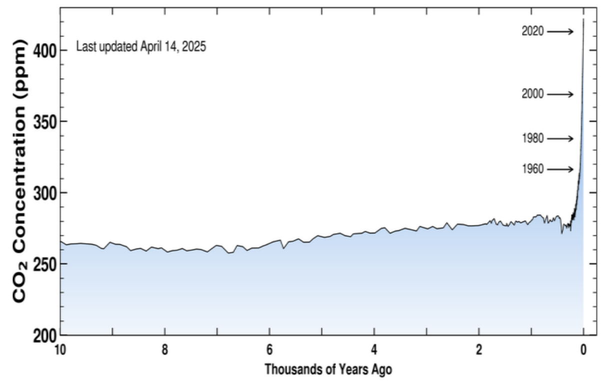


Figure 4. Increase in Global CO_2 Abundance

Source: Keeling Curve, Scripps 2025.

The Anthropocene name was agreed upon by Earth system scientists (Anthropocene Working Group 2024) but was not adopted by the geological community (IGUS and ICS 2024). Nevertheless, the Anthropocene signifies entering a new era where human actions comprise the large forces of change on planet Earth, surpassing natural forcings like solar cycles, volcanic eruptions, and earthquakes. Fortunately, humans also have the capacity to work together to solve problems and limit the negative consequences of prior activities.

5. The Montreal Protocol Has Already Delayed Reaching Climate Tipping Points

While the Montreal Protocol is widely appreciated for putting the ozone layer on the path to recovery, less appreciated is the fact that the Montreal Protocol also delayed climate tipping points because most ODSs are powerful GHGs. In addition, the 2016 Kigali Amendment requires a phasedown in production and consumption of hydrofluorocarbons (HFCs) that were once necessary as temporary replacements for some important ODS uses but are no longer needed because environmentally and technically superior replacements are available or will soon be available. While these HFCs have very low ozone-depletion potential and are typically lower global warming potential (GWP) than the CFC chemical substances they replaced, they can have comparable or higher GWP than the HFCs that they replaced and are still unsustainable GHGs, often with trifluoroacetic acid (TFA) atmospheric degradation considered under some definitions to be per- and poly-fluoroalkyl substances (PFAS) known as “everywhere and forever chemicals” (Andersen and Gonzalez 2023; Molina et al. 2009; Velders et al. 2009; Velders et al., 2007). Without global controls, HFCs were projected to contribute up to 0.5° C of global surface warming by the end of the century (Xu et al. 2013) with up to 0.2–0.4 ° C of warming avoided by the Kigali phasedown (Velders et al. 2022; WMO 2022).

This paper expands the scope of understanding within the Planetary Boundaries framework of how action to protect stratospheric ozone helped on three occasions to delay climate tipping points while significantly protecting the stratospheric ozone boundary and demonstrating the critical interconnections between planetary boundaries:

> The first delay in crossing climate tipping points was through Molina and Rowland's warning in *Nature* (Molina and Rowland 1974) and a subsequent CFC aerosol product boycott so successful that replacements were implemented before governments in Canada, Denmark, Japan, Norway, Sweden, Taiwan, and the United States banned or restricted sales. Ozone-safe replacements for boycotted products and regulated markets penetrated other global markets because of environmental concern and competitive prices (Miller 2025; Andersen and Gonzalez 2023).
>
> The second delay in crossing climate tipping points came from the Montreal Protocol phaseout of ODSs that are powerful GHGs and would have had a very significant impact on speeding up climate change. There was also another flow-on benefit as enterprises that better appreciated the importance of a sustainable Earth increased the energy efficiency of their manufacturing processes and upgraded their products with new technology (Andersen, Sarma, and Taddonio 2007).
>
> The third delay in crossing climate tipping points resulted from the phasedown of HFCs under the Kigali Amendment to the Montreal Protocol and from the increase in energy efficiency of cooling equipment and thermal insulating foam from the Kigali Decision (Dreyfus et al. 2020; Xu et al. 2013).

Figure 5 data show the actual carbon dioxide equivalent and CFC-11 chlorine equivalent emissions of ODSs with steady growth until 1975, when Rowland and Molina called for an aerosol product boycott. Emissions were stable from 1975 until 1984, when aerosol uses continued to drop but fluorocarbon producers offset that loss of sales with promotion of new uses, such as CFC-113 for aerospace and electronics applications. Then from 1985 to 1987, total emissions increased at a high rate until the Montreal Protocol was signed in 1987. Leadership companies abandoned trust in the environmental acceptability of CFC-11 and began impressive reductions even before the Montreal Protocol entered into force on 1 January 1989.

From 1955–2005, ODS emissions were responsible for about 30% of global warming (Sigmond et al. 2023; Velders et al. 2022; Morgenstern et al. 2008; Velders et al. 1997)

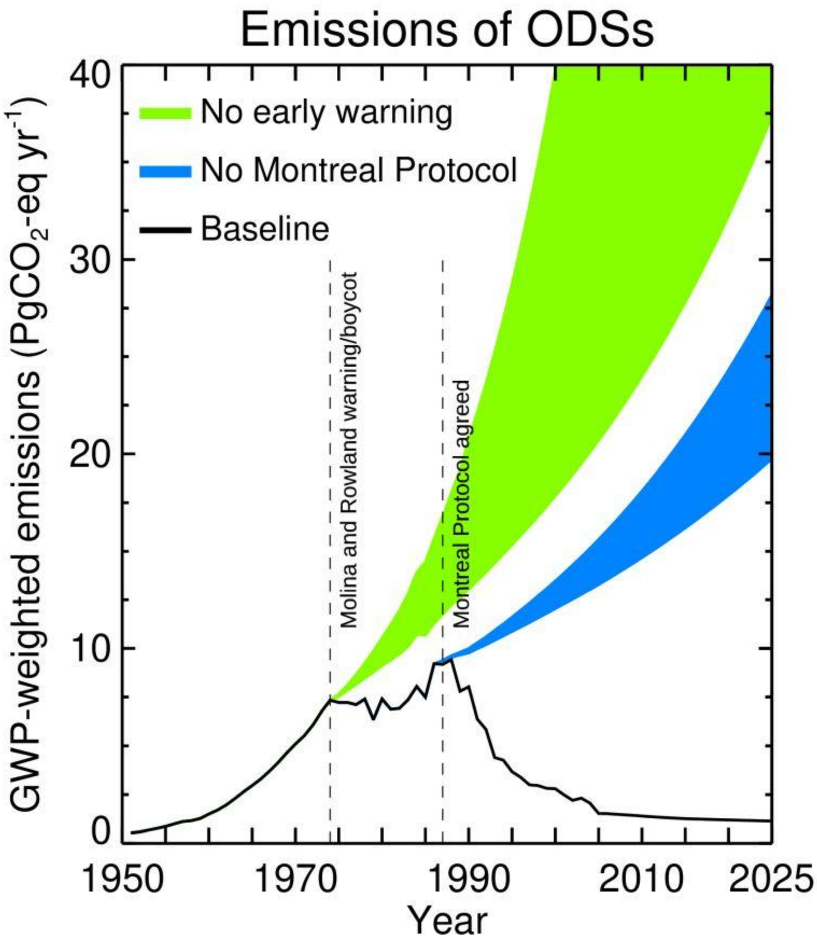


Figure 5. Impact of the 1974 Molina and Rowland ozone depletion warning and call for boycott and of the 1987 signing of the Montreal Protocol

Source: Updated from Velders et al., 2007.

By phasing out ODSs that are also GHGs, the Montreal Protocol has avoided 0.1–0.2 °C to date of global average surface warming and 0.2–0.6 °C in the Arctic and will avoid 0.5–1.0 °C of global surface warming by mid-century (Garny et al. 2022).

The Montreal Protocol Scientific Assessment Panel (SAP) estimates that Montreal Protocol phaseout of ODS production and consumption has avoided at present-day (average over years 2015–2024) approximately 0.1–0.2 °C global surface warming (with an ensemble weighted mean of 0.17 °C ± 0.06 °C) and 0.2–0.6 °C Arctic surface warming (ensemble weighted mean of 0.45°C ± 0.23°C) (Garny et al. 2022).

By the mid-21st century (average over years 2041–2060) the Montreal Protocol controls will avoid approximately 0.5–1.0 °C global surface warming (ensemble weighted mean of 0.79 °C ± 0.24 °C) (Goyal et al. 2019; Virgin and Smith 2019; Young et al. 2021) and 0.5–1.0 °C of global surface warming avoided by mid-century (Garny et al. 2022), compared to an extreme scenario with an uncontrolled increase in ODSs of 3 to 3.5% per year (WMO 2022).

The globally averaged radiative forcing (RF) from the years 2005–2065 is approximately half that of uncontrolled production and consumption without the Montreal Protocol (Virgin and Smith, 2019).

6. Collaboration Strategy from the Montreal Protocol Can Protect Other Planetary Boundaries

Some of the most successful people in the world all have a secret power: their partnerships.

Jean Oelwang, 2022

The work of Jean Oelwang and colleagues has documented that many of the most important transformations of the last half-century were accomplished through a combination of deep personal connections, a compelling purpose, and an unstoppable sense of urgency that made great things happen. Oelwang's findings are based on interviews of the changemakers, influencers, and policy actors in a wide range of impact campaigns, including protecting the ozone layer, ending Apartheid, ending smallpox in India, and other collective human achievements.

Oelwang (2022) and Penelope Canan and Nancy Reichman (2002) researched how the champions of the Montreal Protocol coalesced, planned, and then implemented fast action to save the ozone layer while respecting differentiated responsibilities, advocating for a start and strengthen approach, emphasizing learning by doing, and creating clear global goals and targets. In dozens of interviews, Canan, Oelwang, and Reichman confirmed that the community of ozone champions existed before the signing of the Montreal Protocol in September 1987 and that this community thrives today. Progress is driven by a group of committed leaders and a rotating and replenished cadre of visionaries who are deeply involved in the day-to-day operation of the United Nations Environment Programme (UNEP) Ozone Secretariat; Multilateral Fund for the Implementation of the Montreal Protocol (MLF); United Nations Development Programme (UNDP), UNEP, UNIDO, and World Bank implementing agencies; Scientific, Environmental Effects, and Technology and Economics Assessment Panels (SAP, EEAP, TEAP); national ozone units (NOUs); and environmental and industry non-governmental organizations (NGOs).

The Montreal Protocol is proof that humans *can* organize to protect the global commons against exceeding planetary boundaries and is a case study of governments and industry working together to accomplish planetary miracles. The Montreal Protocol community fosters honesty and openness in diplomatic negotiations, where delegates respect each other and take the time to solve every country's concerns (Andersen and Gonzalez 2023; Oelwang 2022; Molina et al. 2009; Andersen, Sarma, and Taddonio 2007; Andersen and Sarma 2002; Canan and Reichman 2002; Benedick 1998; Tolba 1985).

> *Isn't it a responsibility of scientists, if you believe that you have found something that can affect the environment, isn't it your responsibility to do something about it, enough so that action actually takes place?*
>
> F. Sherwood "Sherry" Rowland in 1997

If not us, who? If not now, when?

Age-old admonition often repeated by Professor Rowland

Sherry was proud to defend ozone depletion science and proud of advocating the precaution of a ban on CFC aerosol products. He showed me that if we believe in the science ... we should speak out when we feel it's important for society to change.

Mario J. Molina in 2012

7. The United Nations' Redoubled Call to Climate Action

2023 was the warmest year in 125,000 years (Abnett and Dickie 2023), with 1.2 °C (2.16 °F) observed global warming (UK Met Office n.d.). And 2024 was hotter than 2023, with the last 11 years comprising the hottest 11 on record[1] (NASA 2025; NOAA 2025a; 2025b). This prompted the United Nations (UN) Secretary General to call for action on extreme heat.

Humanity has opened the gates of hell. Horrendous heat is having horrendous effects. Distraught farmers watching crops carried away by floods. Sweltering temperatures spawning disease. And thousands fleeing in fear as historic fires rage.

UN Secretary-General António Guterres, 2023

Billions of people are facing an extreme heat epidemic—wilting under increasingly deadly heatwaves, with temperatures topping 50 degrees Celsius around the world.

UN Secretary-General António Guterres, 2024

This call to action urges global authorities to move quickly, decisively, and collaboratively. New thinking using the Planetary Boundaries framework can bring Anthropocene Earth back into balance by taking lessons from the Montreal Protocol on how the stratospheric ozone was put on the path to recovery by mid-century, with healing of the Antarctic Ozone Hole as early as 2035 (Wang et al. 2025; Chipperfield and Bekki 2024; Lickley et al. 2024; Andersen and Gonzalez 2023; Velders et al. 2022; Weber et al. 2022; Braesicke et al. 2018; Carpenter et al. 2018; Dhomse et al. 2018; Stone et al. 2018; Kuttippurath and Nair 2017; Steinbrecht et al. 2017; Solomon et al. 2016; Nair et al. 2015; Mäder et al. 2010; Angell and Free 2009; Weatherhead and Andersen 2006; Yang et al. 2006; Zanis et al. 2006; Hadjinicolaou, Pyle, and Harris 2005; Newchurch et al. 2003; Reinsel et al. 2002).

8. The Montreal Protocol is the Most Successful Multilateral Environmental Agreement

[T]he single most successful international agreement to date has been the Montreal Protocol.

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[1] Hottest first: 2024, 2023, 2016, 2020, 2019, 2015, 2017, 2022, 2021, 2018, and 2014.

Former UN Secretary-General Kofi Annan

[The] Montreal Protocol stands out. The manner in which this instrument for repairing and recovering the Earth's protective shield has been financed and implemented serves as an inspiring example of what is possible.

Former UN Secretary-General Ban Ki-moon

The Montreal Protocol—a triumph of collaboration between science, governments, multilaterals, and business—transformed entire industries, invested in science to track and understand the problem, and phased out 99% of ozone-depleting substances. Scientists now predict the ozone layer will largely be restored by 2060. If there's but one lesson to glean from the ozone example, it's this: changing course isn't a solo endeavour. It requires constant vigilance and radical collaboration.

Sir Richard Branson (Branson 2023)

[The Montreal Protocol is] a masterclass in international science-diplomacy, showing what is possible, even in a divided world.

Nature 2025

The Montreal Protocol is the most successful multilateral agreement (MEA) thanks to strong leadership, collaboration, fast action, and a shared vision and purpose to protect Earth and its inhabitants from an existential threat. The reasons for this success include: 1) universal ratification driven by a proactive Ozone Secretariat under the authority of UNEP; 2) actions driven by findings of the respected Scientific, Environmental Effects, and Technology and Economic Assessment Panels (SAP, EEAP, and TEAP, respectively)—the 1987 Montreal Protocol controlled only a dozen substances but was frequently amended over time to phase out almost 100; 3) universal membership by all 198 United Nations States; 4) strong compliance with control measures; 5) financial and technical support for developing countries through the MLF; 6) climate protection greater than all other efforts combined—because most ODSs are also potent GHGs; and 7) regulations requiring that replacements for products made with or containing ODSs must have superior technical and environmental performance, as incidental and intentional measures have promoted increases in energy efficiency, worker and product safety, community and global health, and quality of life (Miller 2025; Andersen and Gonzalez 2023; Andersen, Sarma, and Taddonio 2007; Parson 2003; Andersen and Sarma 2002; Benedick 1998; Litfin 1994; Tolba and Rummel-Bulska 1998; Tolba 1985).

9. The Start and Strengthen Approach

The 1987 Montreal Protocol was signed by just 24 countries and the European Union on 16 September 1987 and had been signed by only 46 countries when it entered into force 1 January 1989. The Montreal Protocol started modestly with basic production and consumption control measures only on a few CFCs and halons. It was then promptly and continuously strengthened by Amendments adding more controlled substances and bolstered by Adjustments accelerating the pace of phaseout as elaborated on Table 1 and Figure 6. Four out of five Amendments have already achieved universal ratification with the fifth, the 2016 Kigali Amendment, well on the way to that distinction.

Table 1. Fast Precautionary Actions Under the Montreal Protocol

Year	**Year(s) Since Last Action**	**Action**	**Controlled Substance(s)** (a dozen ODS controlled in 1987 strengthened by *Amendment* to almost 100 ODS, and accelerated in phaseout by *Adjustment*)
1985		Vienna Convention	Framework for the Montreal Protocol
1987	2	Montreal Protocol	CFCs (Annex A, Group I), halons
1989	2	Entry into Force	46 Parties @ Entry into Force
1990 MOP2*	1	London Amendment and Adjustment with MLF A5 Finance	CFCs (Annex B, Group I), methyl chloroform, carbon tetrachloride
1992 MOP4	2	Copenhagen Amendment and Adjustment	HCFCs, methyl bromide, hydrobromofluorocarbons
1995 MOP7	3	Vienna Adjustment	Article 5 Basic Domestic Needs
1997 MOP9	2	Montreal Amendment and Adjustment	Methyl bromide trade measures
1999 MOP11	2	Beijing Amendment and Adjustment	Bromochloromethane Production controls on HCFCs
2007 MOP19	8	Montreal Adjustment	Accelerating the HCFC phaseout to protect ozone and climate
2016 MOP28	9	Kigali Amendment and Energy-Efficiency Decision	HFCs
2018 MOP30	*	Quito Adjustment	Annex C, Group 1 substances
2023 MOP 35	7	US$1 Billion 3-yr Funding Stop Dumping Decision**	ODSs and HFCs

MOP = Meeting of the Parties to the Montreal Protocol

* The Quito Adjustment corrected an oversight in the Kigali Amendment and is not counted here as a precautionary action.

** Decision to Stop the Dumping in Article 5 (developing country) Parties of new inefficient cooling equipment with obsolete ozone-depleting and climate forcing refrigerants with “shared responsibility” of exporting and importing Parties.

Source: Andersen and Gonzalez 2023, updated by authors 2024. See also Ferris 2025.

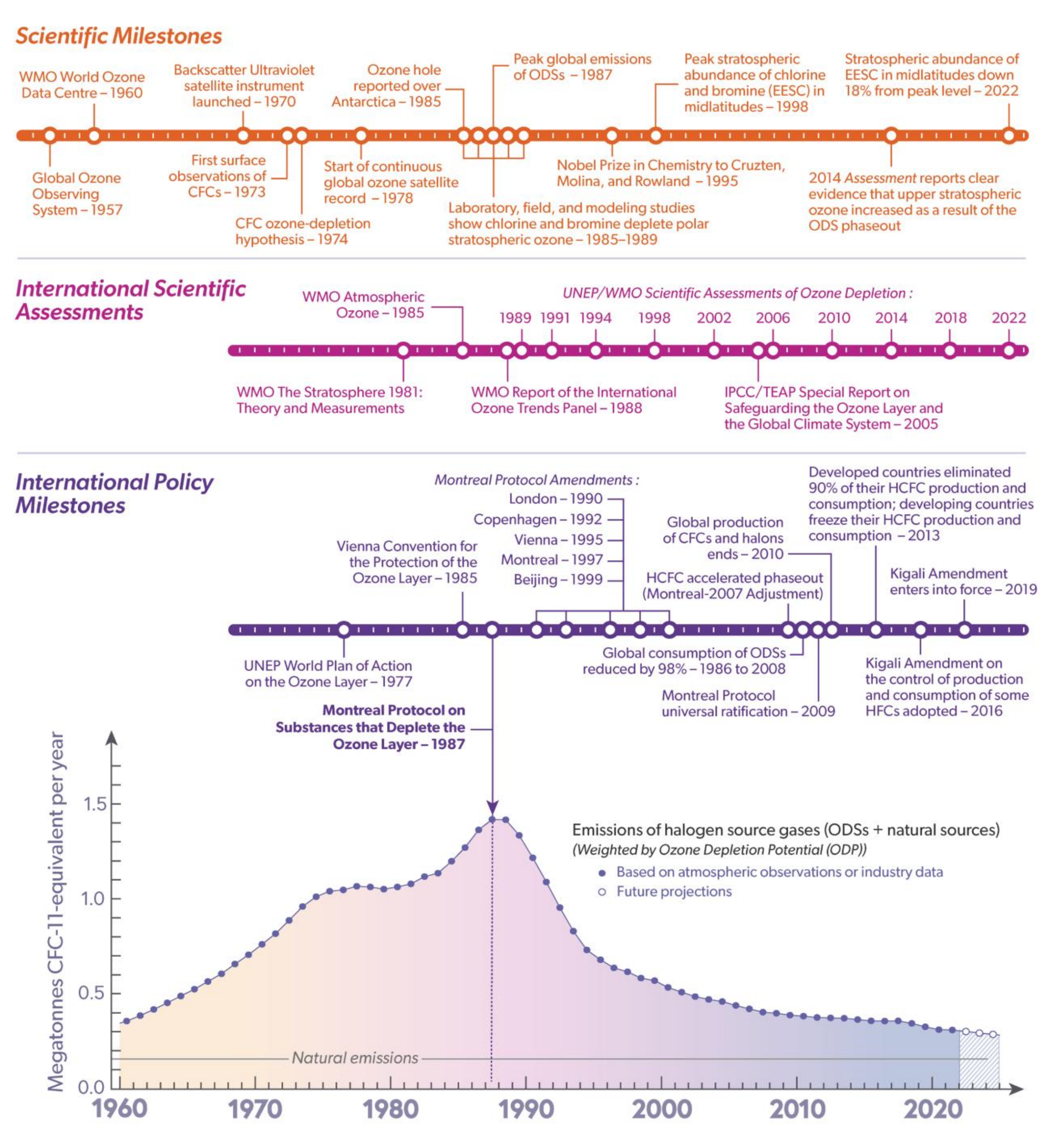

Figure 6. Stratospheric Ozone Depletion and Policy Milestones

Source: Salawitch et al. 2023.

10. Ozone and Climate Worlds Avoided and World Enjoyed through Montreal Protocol Fast Action

Without a protective ozone layer in the atmosphere, animals and plants could not exist, at least upon land.

The Nobel Prize committee (Royal Swedish Academy of Sciences 1995)

Many papers have explored the ozone and climate "world avoided" (Willi et al. 2021; Newman and McKenzie 2020; Forster et al. 2012; Newman et al. 2009; Morgenstern et al. 2008; Miller and Andersen 1996; Prather et al. 1996; Slaper et al. 1996).

- What if the boycotts and national bans of CFC cosmetic and convenience aerosol products as urged by Molina and Rowland starting in 1975 had never happened?
- What if the 1987 Montreal Protocol was never agreed or was strengthened at a slower pace?

The unresolvable challenge of answering "what-if" questions is that it is impossible to know if and when other scientists would have been as confident and persuasive to policymakers as Molina and Rowland were in warning of stratospheric ozone depletion, and Farman, Gardiner, and Shanklin were in warning of the Antarctic Ozone Hole (Canan et al. 2015; Daniel et al. 2010; DeSombre 2000.) For example, George P. Shultz, US Secretary of State, persuaded President Ronald Reagan based on his trust of Rowland and Molina, and precaution but not scientific certainty (Biello 2013):

I remember when, in the Reagan administration, we found that the ozone layer was in danger of depleting. Most scientists thought it was happening; some questioned it, but they all agreed that, if it happened, it would be catastrophic. I talked with President Reagan a lot about it, and I said, "We should take out an insurance policy," and the Montreal Protocol came about as a result of that. It turned out that the scientists who were worried were right, and we acted in the nick of time.

George P. Shultz (Mecklin 2021)

Most recently, Willi et al. (2021) estimated the environmental and health benefits if policymakers had acted more immediately on the ozone and climate warnings of Crutzen, Molina, Rowland, and Ramanathan. The red line on Figure 7 is the realized increase in equivalent effective stratospheric chlorine (EESC), which is a metric used to quantify the ozone-depleting potential of the chlorine and bromine released from ODSs and HFCs, considering factors like their transit time in the stratosphere and their photochemical degradation. The green line is the lower EESC that would have realized with faster action once warned by scientists. Notice that stratospheric ozone would have recovered to 1978 levels (2000 parts per trillion by volume - pptv) about 12 years earlier than now expected.

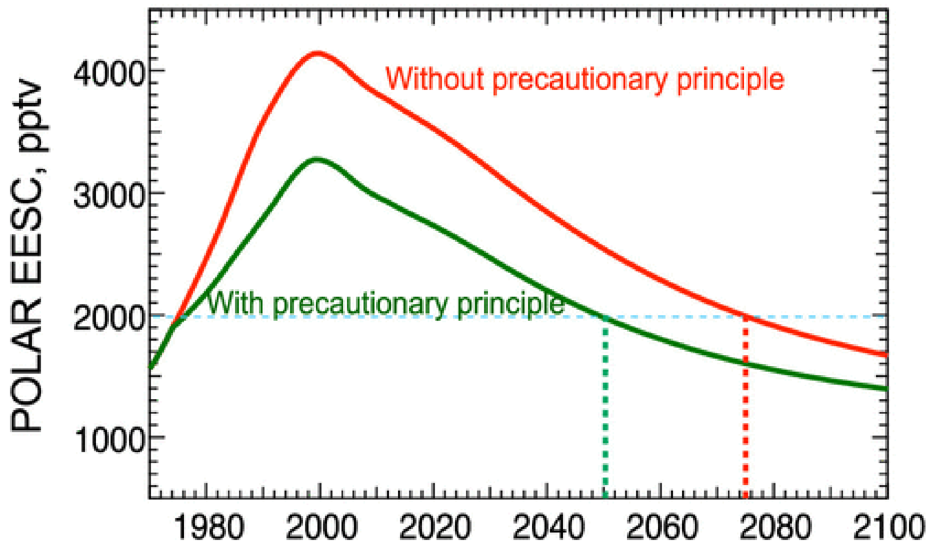

Figure 7. Benefits of Earlier CFC Substitution

Source Willi et al. 2021.
Equivalent effective stratospheric chlorine (EESC) is a metric that quantifies the combined effect of chlorine and bromine on stratospheric ozone depletion (see Salawitch et al., 2023; Engel et al., 2018; Newman et al., 2007).

If ozone and climate warnings had come even a decade later, climate forcing from ODSs could have equalled or exceeded the forcing of CO_2. Earth would certainly have passed climate tipping points beyond which recovery would not likely be possible within human time dimensions (Andersen and Gonzalez 2023; Sigmond et al. 2023; Miller, Zaelke, and Andersen 2021; Velders et al. 2009; Velders et al. 2007; Slaper et al.,1996) (Figure 8).

Ozone and climate tipping points may be abrupt, irreversible, and dangerous, with catastrophic implications for humanity.

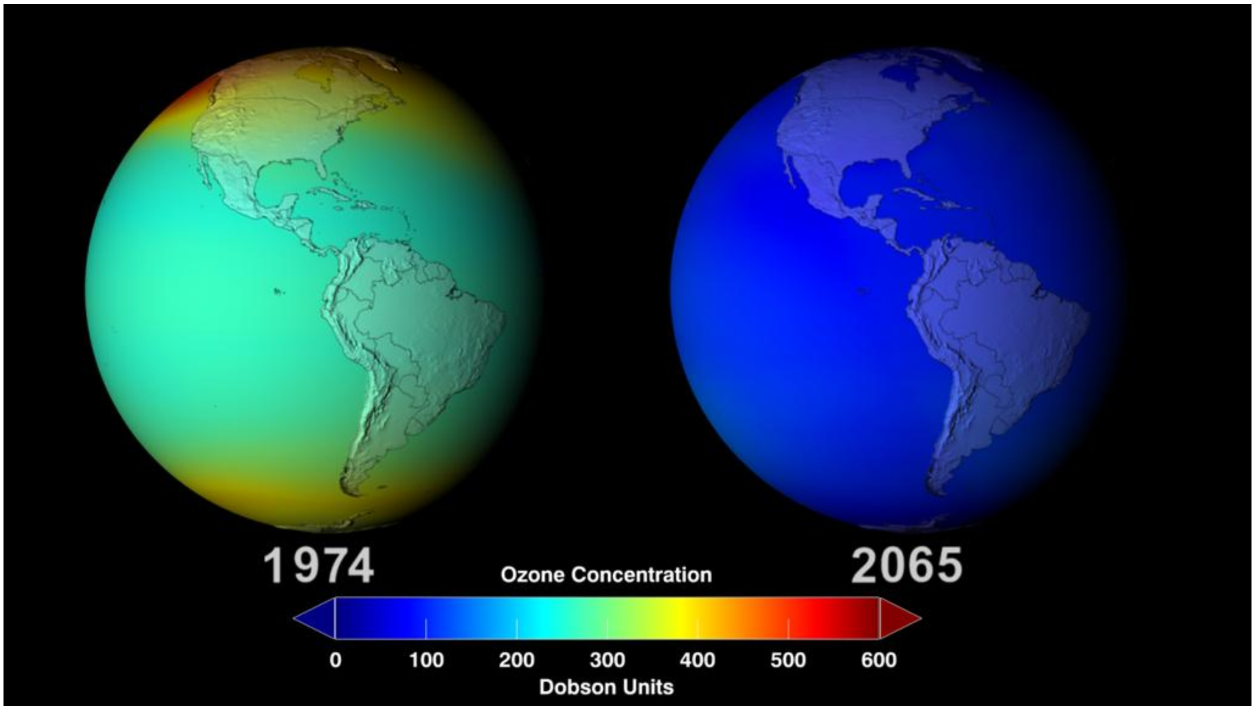

Figure 8. Ozone "World Avoided" Thanks to the Montreal Protocol
Source: Ogden 2023.
1974: Before Antarctic Ozone Hole
2065: Projected without Montreal Protocol

11. The Montreal Protocol Success by the Numbers

> Severe depletion of the Antarctic ozone layer is seasonal … when ozone is often completely destroyed over a range of stratospheric altitudes, thereby reducing total ozone by as much as two-thirds at some locations. This severe depletion creates the "ozone hole"… (that) far exceeds the size of the Antarctic continent.
>
> *Twenty Questions and Answers About the Ozone Layer: 2022 Update* (Question/Answer #10, Salawitch et al. 2023.)

> [T]he overall abundance of ozone-depleting substances (ODSs) in the atmosphere has been decreasing for the past two decades. If the nations of the world continue to comply with the provisions of the Montreal Protocol, the decrease will continue throughout the 21st century. However, it is only after mid-century that the abundance of ODSs is expected to fall to values that were present before the Antarctic ozone hole was first observed in the early 1980s, due to the long atmospheric lifetime of these gases.
>
> *Twenty Questions and Answers About the Ozone Layer: 2022 Update* (Question/Answer #15, Salawitch et al. 2023.)

> [U]ltraviolet radiation at Earth's surface increases as the amount of overhead total ozone decreases because ozone absorbs ultraviolet radiation from the Sun.” [S]urface ultraviolet radiation has increased in large geographic regions in response to ozone depletion.
>
> *Twenty Questions and Answers About the Ozone Layer: 2022 Update* (Question/Answer #16, Salawitch et al. 2023.)

> Ozone depletion and global climate change are linked because both [ODSs] and their fluorocarbon chemical substitutes are [GHGs]. The best estimate is that stratospheric ozone depletion has led to a small amount of surface cooling. Conversely, increases in tropospheric ozone and other greenhouse gases lead to surface warming. The effect on global climate change from stratospheric ozone depletion is small compared to the warming from the greenhouse gases responsible for observed global climate change. Since the early 1980s, the Antarctic ozone hole has contributed to changes in Southern Hemisphere surface climate through effects on the atmospheric circulation.
>
> *Twenty Questions and Answers About the Ozone Layer: 2022 Update* (Question/Answer #17, Salawitch et al. 2023.)

Stratospheric ozone depletion is a classic example of incremental environmental, health, and economic impacts that become harder to solve because many anthropogenic chemical substances have atmospheric lifetimes greater than a century. Scientists worried that merely halting chemical emissions was not enough for recovery in a foreseeable future and that ozone could decline below a point of no return.

12. Planetary Boundary Metrics of Stratospheric Ozone Recovery

The Japan National Institute for Polar Research first reported the Antarctic Ozone Hole in 1984 (Chubachi 1984), but this finding was unappreciated until 1985 when scientists from the British Antarctic Survey raised the alarm and attributed the ozone hole to ODSs (Jones 1988; Farman, Gardiner, and Shanklin 1985). Afterward, Parties to the Montreal Protocol strategically defined stratospheric ozone recovery as the elimination of ozone hole; the Protocol would have accomplished its ozone mission when the ozone hole was no longer observed. This simple metric enabled the use of iconic ozone graphics that communicate success in any language to citizens of all ages and backgrounds.

13. An Advanced Metric for Measuring Total Ozone

Scientists soon developed the equivalent effective chlorine (EECl) metric as a predictor for total column ozone (TCO). EECl determines the potential of ODSs to destroy stratospheric ozone, as follows:

- The ozone depletion potential (ODP) of a substance is calculated by comparing its percent column depletion of ozone at steady state to the percent column depletion from CFC-11 at steady state. This measures a substance’s effectiveness at removing ozone.

- The atmospheric abundance of each ODS is multiplied by its ODP.

TCO is the metric for the amount of ozone in a column of air that extends from the Earth's surface to the top of the atmosphere. TCO is typically measured in Dobson Units (DUs), where one DU is 2.687 ×1016 molecules/cm^2. The ozone mass deficit (OMD) is the amount of ozone that would need to be added to the atmosphere to increase the ozone levels over the Antarctic Ozone Hole to 220 DU, the pre-Antarctic Ozone Hole level (Bodeker and Kremser 2021).[3]

After considerable deliberation, scientists began publishing estimates of ozone recovery to the pre-Antarctic Ozone Hole condition (Salawitch 2023; Chipperfield et al. 2017; Chipperfield et al. 2015; Chipperfield et al. 2006).

> *Recovery of ozone in the upper stratosphere is progressing. Total column ozone (TCO) in the Antarctic continues to recover, notwithstanding substantial interannual variability in the size, strength, and longevity of the ozone hole. Outside of the Antarctic region (from 90°N to 60°S), the limited evidence of TCO recovery since 1996 has low confidence. TCO is expected to return to 1980 values around 2066 in the Antarctic, around 2045 in the Arctic, and around 2040 for the near-global average (60°N-60°S).*
>
> WMO Montreal Quadrennial Ozone Assessment 2022

The logic driving these estimates of TCO recovery is that the EECl was within "safe operating space" of the planetary boundary just before the Antarctic Ozone Hole. A shortcoming of that logic is that the absence of the Antarctic Ozone Hole is not proof that stratospheric ozone is resilient or at an abundance most optimal for life on Earth.

ODSs have been emitted in large amounts since commercial introduction of CFCs in 1930, and some ODSs persist in the atmosphere for more than 100 years. New ODS were invented, patented, and marketed in a rapidly expanding range of commercial applications until curtailed by the Montreal Protocol in the 1990s and beyond.[4]

An alternative description would be to characterize stratospheric ozone depletion to be "in remission" but not "cured" of hazardous fluorocarbon emissions. This Planetary Boundary framework avoids the questionable presumption that Earth will ever be as it was before the Anthropocene epoch.

14. Success in Protecting Stratospheric and Climate Planetary Boundaries and the Way Forward with Deep Personal Connections to Sustainable Earth

Nine planetary boundaries have been identified as critical for maintaining Earth system stability and resilience. The stratospheric ozone layer is the only planetary boundary once threatened by human activities (chlorinated and brominated fluorocarbon emissions) that is being pulled back toward health. An extraordinary co-benefit of protecting stratospheric ozone is the head start in protecting climate. This paper has explained in detail how scientists, governments, industry, and citizens worked together with deep personal connections under the United Nations Montreal Protocol on Substances that Deplete the Ozone Layer. Although the other eight planetary boundaries are still under grave threat from unsustainable human activity, the story of collaborative fast action to stabilize stratospheric ozone provides clear lessons and hope for climate, oceans, and other planetary boundaries. (Rockström et al. 2024; Richardson et al. 2023; Rockström et al. 2023; Attenborough and Rockström 2021; Rockström et al. 2021; Steffen et al. 2015; Rockström et al. 2009a; Rockström et al. 2009b).

The lessons from the success of the Montreal Protocol in bringing the stratospheric ozone back to a safe planetary boundary operating space can guide protection of the climate and the other seven planetary boundaries still under grave threat from unsustainable human activity. The Montreal Protocol also shows the interdependency of the boundaries and the opportunity for leveraged impact on all boundaries. It shows that we can be guardians of the entire planet. An essential proof, as the only way we will have a safe landing on climate change is by taking a whole planet approach.

15. Acronyms and Abbreviations

AR-4	IPCC Assessment Report Four (typically the GWP values in regulations)
AR-6	IPCC Assessment Report Six
CFC	chlorofluorocarbon
CO_2	carbon dioxide
CPSC	US Consumer Products Safety Commission
DU	Dobson Unit
EEAP	Environmental Effects Assessment Panel (Montreal Protocol)
EECl	equivalent effective chlorine
EESC	equivalent effective stratospheric chlorine
EU	European Union
FDA	US Food and Drug Administration
GHG	greenhouse gas
GWP	global warming potential
HCFC	hydrochlorofluorocarbon
HFC	hydrofluorocarbon
IGSD	Institute for Governance & Sustainable Development
IPCC	Intergovernmental Panel on Climate Change
LLCP	Long-lived climate pollutant
SLCP	Short-lived climate pollutant
MLF	Multilateral Fund for the Implementation of the Montreal Protocol
NOAA	National Oceanographic and Atmospheric Administration (USA)
MOP	Meeting of the Parties to the Montreal Protocol
NASA	National Aeronautics and Space Administration (USA)

NGO	non-governmental organization
NOU	national ozone unit
MEA	multilateral environmental agreement
NO_x	nitrogen oxide
NRDC	National Resources Defense Council
ODP	ozone-depletion potential
ODS	ozone-depleting substance
OMD	ozone mass deficit
PPTV	parts per trillion by volume
SAP	Scientific Assessment Panel (Montreal Protocol)
TEAP	Technology and Economic Assessment Panel (Montreal Protocol)
TCO	total column ozone
UN	United Nations
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNIDO	United Nations Industrial Development Organization
US	United States
USA	United States of America
UV	ultraviolet

16. Authors

Dr. Stephen O. Andersen, co-author of a 1974 assessment of the impact of ozone depletion and climate change on northern latitude grain yields, founder of TEAP and Co-Chair from 1989–2012, Deputy Director of the United States Environmental Protection Agency (US EPA) Stratospheric Protection Division, and Liaison to the US Department of Defense on Stratospheric Ozone and Climate. Stephen created the first EPA voluntary partnerships and with EPA colleagues created and managed the US EPA Stratospheric Ozone and Climate Protection Awards. He is currently the Director of Research at the Institute for Governance & Sustainable Development (IGSD).

Dr. Suely Carvalho, Co-Chair of TEAP from 1993–2001, Director of the Montreal Protocol and Director of the Chemicals Unit at the United Nations Development Programme (UNDP) from 2001–2013, where she coordinated implementation of ODS technology conversion and technical assistance projects in over 100 developing countries. Suely has held numerous other senior positions protecting ozone and climate for more than 35 years.

Sylvia A. Earle, Planetary Guardian, marine biologist, oceanographer, explorer, author, and lecturer. She has been a National Geographic Explorer at Large since 1998 and holds the record for deepest walk on the sea floor. She founded Mission Blue, an organization dedicated to protecting the ocean from threats of climate change, pollution, habitat destruction, invasive species, and the dramatic decrease in ocean fish stocks.

Marco González, Executive Director of the Montreal Protocol Ozone Secretariat from 2002–2013, secured universal ratification and the 2007 HCFC Adjustment that evolved the Montreal Protocol into a climate treaty.

Jean Oelwang, Founding CEO of Virgin Unite, the Planetary Guardians, and Plus Wonder. She is a B Team Leader and sits on the Advisory Council for The Elders and multiple boards. Jean's debut book, *Partnering: Forge the Deep Connections that Make Great Things Happen*, reveals how successful people became great leaders through the building of strong relationships, and includes a case study of the deep connections of the people who brought stratospheric ozone back from the planetary boundary danger zone.

Dr. Johan Rockström, Director of the Potsdam Institute for Climate Impact Research and Professor in Earth System Science at the University of Potsdam. He led the development of the Planetary Boundaries framework that guides human development in the current era of rapid global change, including risks of climate and other tipping points.

Dr. Guus J. M. Velders, Professor of Air Quality and Climate Interactions at Utrecht University (Netherlands) and senior scientist at the National Institute for Public Health and the Environment (RIVM), Bilthoven. Dr. Velders was selected as one of *Nature*'s 10: Ten people who mattered in 2016 and the same year selected as *Time* magazine's 100 most influential people in the world.

Durwood Zaelke, Founding President of IGSD, which is based in Washington, DC, and Paris. He focuses on fast mitigation strategies to protect the climate, including reducing short-lived climate pollutants (HFCs, black carbon, methane, and tropospheric ozone), as first described in *Reducing Abrupt Climate Change Risk Using the Montreal Protocol and Other Regulatory Actions to Complement Cuts in CO_2 Emissions*, by Mario J. Molina, Durwood Zaelke, Veerabhadran Ramanathan, Stephen O. Andersen, and Donald Kaniaru in *Proceedings of the National Academy of Science*s (8 December 2009).

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Appendix A: 1970s CFC Warning and Boycott, Label, and Ban Timeline

~1970 to ~1974	
	Professor Paul J. Crutzen and colleagues warn that nitrogen oxides can deplete stratospheric ozone and force climate change.
1971	
April	James E. Lovelock warns that CFCs are accumulating in the atmosphere.
1974	
June	Dr. Mario J. Molina and Professor F. Sherwood Rowland warn that CFCs can deplete stratospheric ozone.
September	Rowland & Molina call for boycott of CFC aerosol products.
November	The Natural Resources Defense Council (NRDC) petitions the US Consumer Products Safety Commission (CPSC) to ban CFC aerosol products.
1975	
February	An episode of the popular American television situation comedy *All in the Family* dramatizes that CFCs will "destroy the ozone layer and kill us all."
June	Oregon bans aerosol products containing CFCs effective 1977. S. C. Johnson announces it will phase out CFCs from its aerosol products.
July	Sherwin Williams, Bristol Myers, and Mennen announce they will phase out CFCs from aerosol products.
August	CFC-free aerosol product manufacturers launch campaigns disparaging CFCs. New York requires warning label on CFC aerosol products.
October	Professor Veerabhadran Ramanathan warns that CFCs are powerful GHGs.
1976	
October	US Food and Drug Administration (FDA) proposes "an orderly transition out of CFC aerosol products" and an interim warning label.
1977	
December	Sweden bans CFC aerosol products effective 1979; German and Swiss aerosol product associations agree to 30% reduction from 1976 baseline by 1979.

1978 and beyond	
	US bans CFCs for most convenience, cosmetic, food, household pesticide, and in many medical uses (but with exceptions for metered-dose inhalers (MDIs) as therapy for asthma and chronic obstructive pulmonary disease). Canada, the Netherlands, Norway, and Taiwan ban CFCs in aerosol products.
	Mexico aerosol producers—to compete with aerosol products produced in the United States at lower cost with hydrocarbon propellants—joins with the government of Mexico to promote transition to ozone-safe products.

Source: Andersen and Gonzalez 2023; Andersen, Sarma, and Taddonio 2007; Andersen and Sarma 2002

Appendix B: Glossary of Terms

The **Antarctic Ozone Hole** is a thinning of ozone in the stratosphere over the Antarctic each spring due to the chlorine and bromine from manufactured and natural ODSs and the specific meteorological conditions over the Antarctic.

The **Anthropocene Epoch** is a proposed unit for the most recent period in Earth's geographical history when human activity started to significantly impact Earth's climate and ecosystems.

The **Built Environment** includes human-made or modified landscapes, structures, and infrastructure systems (including energy, health care, national security, safety, and transportation) for living, working, and recreation.

Cosmetic and Convenience CFC Aerosol Products include spray deodorants and perfumes, hairsprays, and residential pesticides where the only purpose of the propellent is push-button ease. Contrast that with medical aerosol products like metered-dose inhalers (MDIs) that deliver medicine deep into the lungs without harm or technical aerosol products like streaming pesticide dispensers that allow killing of pests dangerous to health and safety far from the exterminator and without the risk of fire (e.g., hornets in electric switch boxes).

Equivalent Effective Stratospheric Chlorine (EESC) is a metric used to quantify the combined effect on stratospheric ozone of chlorine and bromine released from ODSs, taking into account the effects of atmospheric chemical lifetime, mixing ratios, age-of-air dependent fractional release values, and an age-of-air spectrum.

Ozone Tipping Points, like climate tipping points, are a consequence of the long-lasting presence of ODSs in the stratosphere. Even when emissions cease, it takes decades for the Antarctic Ozone Layer to vanish (estimated at about 2066) and decades more for the ozone layer to fully recover to the natural conditions before humans manufactured synthetic ODSs (i.e., when manufactured ODSs are below detectible atmospheric abundance). Consider also that some ODSs degrade to chemical substances such as trifluoroacetic acid (TFA) and TFA salts with lifetimes of centuries.

Planetary Boundaries are the safe limits for harmful human impact on the nine critical processes that together maintain stability of resilient Earth.

Start and Strengthen describes the Montreal Protocol's genesis and evolution after initially imposing controls on just a portion of two classes of chemicals, chlorofluorocarbons (CFCs) and bromochlorofluoromethanes (halons). Subsequently, the Protocol has been strengthened by Amendments requiring ratification by a specified number of Parties to control almost 100 ODSs categorized as carbon tetrachloride (CTC), CFCs, halons, hydrobromofluorocarbons (HBFCs), hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), and methyl bromide. It is also strengthened by Adjustments, which just require the consensus of all Parties. Note that halons are a group of organic compounds containing carbon, fluorine, bromine, and sometimes chlorine; e.g., the chemical formula for Halon 1301 is CBrF3 (Bromotrifluoromethane) and for Halon 1211, CBrClF2 (Bromochlorodifluoromethane).

Tipping Points for Climate are conditions beyond which changes in part or parts of the climate system become self-perpetuating and may lead to abrupt, irreversible, and consequential impacts for humanity (Armstrong-McKay et al. 2022).

Universal Treaty Ratification occurs when all UN States have ratified a treaty. Note that over time, some States have divided (e.g., North and South Korea, East and West Germany, Bangladesh and India, Czech Republic and Slovakia); some states have combined or reunited (e.g., East and West Germany); and some states are removed (e.g., The Republic of China) or added (e.g., South Sudan). Universal ratification can thus be lost over time and then restored by ratification.

Appendix C: Supporting Documentation

- ✓ World Avoided by Boycott of CFC Aerosol Products and the Montreal Protocol; and
- ✓ World Enjoyed by Superior ODSs and HFCs Replacements[2]

A comprehensive accounting of the full benefits of phasing out ODSs and phasing down HFC includes 1) the damages ***avoided*** to planetary boundaries and the built environment by restoring the ozone layer to natural balance and by reducing GHG emissions from applications using ODSs, and 2) the benefits ***enjoyed*** to planetary boundaries beyond ozone and climate from the economically, technically, and environmentally superior replacements for ODSs and HFCs that also replaced toxic and hazardous chemical substances without ozone or climate effects. This framework in analogous to how NASA's space program significantly benefits United States and global economies and quality of life by advancing science and fostering innovation and technology transfer (Zelalem, Drucker, and Sonmez 2024).

When Dr. Mario J. Molina and Professor F. Sherwood Rowland in 1974 warned that CFC emissions could destroy the ozone layer that protects Earth against UV radiation, the quantification by scientists of the potential damage triggered the market and policy response that has so far phased out over 99% of almost 100 ODSs previously used in about 240 applications. And when Guus J. M. Velders, David W. Fahey, John S. Daniel, Mack McFarland, and Stephen O. Andersen in 2009 warned that HFC emissions could push the atmosphere beyond climate tipping points again, it was quantification of benefits that triggered the Kigali phase down Amendment (Andersen, Gonzalez, and Sherman 2022).

To make the case for protecting the ozone layer, environmental activists and scientists concentrated on the assessment and quantification of the most obvious risks associated with increased exposure to UV that had the highest public response, namely, increased skin cancer and cataracts. Much later, the assessments were expanded to account for less obvious or less familiar risks, such as damage to agricultural and natural ecosystems, suppression of the human immune system, damage to the built environment[3], and climate change. Most recently, environmental effects scientists have calculated the avoided damage to aquatic carbon sinks (Jarníková et al. 2025; Häder 2000; Häder et al. 2015; and Häder et al. 1998) and terrestrial carbon sinks (Young et al. 2021). Not yet fully quantified is the damage avoided to biodiversity, species extinction, and to the built environment.

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[2] This supplemental material is updated from Chapter 6 "World Avoided, World Enjoyed" in Andersen and Gonzalez, 2023.

[3] The "built environment" that is damaged by UV includes composites, concrete, fabric, paints and stains, plastics, and wood.

Benefits of the World Avoided

Without a protective ozone layer in the atmosphere, animals and plants could not exist, at least upon land.

Professors Mario Molina and F. Sherwood Rowland.

Source: Royal Swedish Academy of Sciences 1995. https://www.nobelprize.org/prizes/chemistry/1995/press-release/.

The year is 2065. Nearly two-thirds of Earth's ozone is gone – not just over the poles, but everywhere. The infamous ozone hole over Antarctica, first discovered in the 1980s, is a year-round fixture, with a twin over the North Pole. The UV radiation falling on mid-latitude cities like Washington DC is strong enough to cause sunburn in just five minutes. DNA-mutating UV radiation is up more than 500 percent, with likely harmful effects on plants, animals, and human skin cancer rates. In the 2050s … ozone levels in the stratosphere over the tropics collapse to near zero in a span of six years … the rapid, near-total ozone destruction is similar to what happens over Antarctica today.

Newman et al., 2009.

This (ODS phaseout) …has protected millions of people from skin cancer and cataracts over the years since. It allowed vital ecosystems to survive and thrive. It safeguarded life on Earth. And it slowed climate change: if ozone-depleting chemicals had not been banned, we would be looking at a global temperature rise of an additional 2.5°C by the end of this century. This would have been a catastrophe.

UNEP Montreal Protocol Ozone Secretariat 2022.

The "World Avoided" metric used to quantify the benefits of halting the use of ODS and HFC greenhouse gases compares the impacts of the ODS and HFC atmospheric concentrations that would have occurred had there been no scientific warnings and no consumer and policy response with the actual use and emissions under the Montreal Protocol ODS phaseout and HFC phasedown.

For example, an Environment Canada study (Armstrong 1998) presented at the Tenth Meeting of the Parties to the Montreal Protocol in 1997 estimated that benefits to agriculture, forest, fisheries, and the built environment exceeded the total cost of Montreal Protocol implementation by US$ 235 billion as elaborated in Table C-1Table C-1. Global benefits and costs of the Montreal Protocol phaseout, 1987–2060 (Armstrong 1998).

Table C-1. Global benefits and costs of the Montreal Protocol phaseout, 1987–2060 (Armstrong 1998)

Health Benefits (not monetized)	
Avoided cases of non-melanoma skin cancer	19,100,000
Avoided cases of melanoma skin cancer	1,500,000
Avoided skin cancer deaths	1,300,000
Avoided case of cataracts	129,000,000
Environmental Benefits (monetized)	
Avoided agriculture, forest, and fisheries	US$ 429 billion
Avoided damage to the built environment	US$ 30 billion
Total Monetized Benefits	US$ 459 billion
Cost of Montreal Protocol Implementation	US$ 235 billion*
Net Benefits + Health Benefits	US$ 224 billion

**1997 US dollars, discounted over 1997–2060*

Consider also that without the consumer boycotts and the Montreal Protocol ODS phaseout, plants exposed to extreme UV radiation would have experienced reduced photosynthesis and growth. This would have resulted in an estimated 325-690 billion tonnes less CO_2 held in carbon sinks by the end of this century, causing an additional rise in temperature of 0.5° to 1.0° C (Young et al. 2021).

Skin Cancer Incidences Compared

When compared with a "No Depletion" scenario, defined as ozone un-depleted with cloud characteristics similar to the 1960s throughout, excess incidence (yearly cases) of skin cancer per million people of the "Full Compliance with phaseout of controlled substances under the Montreal Protocol" scenario is in the following ranges: New Zealand: 100–150, Congo: 0–10, Patagonia: 20–50, Western Europe: 30–40, China: 90–120, Southwest USA: 80–110, Mediterranean: 90–100 and Northeast Australia: 170–200. This is up to 4% of total local incidence in the Full Compliance scenario in the peak year.

For the United States alone, when compared with a scenario of no controls on ODS emissions, the amended and adjusted Montreal Protocol is expected to avoid 432 million cases of keratinocyte cancer and 11 million cases of melanoma, a total of 443 million cases of skin cancer avoided in the United States during the lifetimes of people born in 1890 to 2100. Over the same time period, the United States will avoid 800,000 deaths from keratinocyte cancer and 1.5 million from melanoma, for a total of 2.3 million avoided skin cancer deaths thanks to the Montreal Protocol. In addition, 63 million cataract cases will be avoided (US EPA 2020).

It is important to note that the benefits of the Protocol far exceed the costs to industry and consumers, even when the principal benefits of avoiding skin cancer and cataracts are unquantified (Barrett 2003).

So far, the impact of ODSs used in plastics manufacturing and the impact of plastics use, disposal, and terrestrial and atmospheric fate are unquantified. Furthermore, consider that the impact of the high-GWP ODSs on climate has been mostly unappreciated along with the extraordinary climate benefits of the 85% of ODS replacements that are not-in-kind technical solutions (Velders et al. 2007; 2009).

The World Enjoyed by the ODS phaseout is also significant proof of the merit of the Montreal Protocol. In most cases, the replacement technology was environmentally superior in every respect, typically satisfying updated safety standards that were more stringent, and unnoticeably different in cost of ownership (Andersen, Sarma, and Taddonio 2007). For example, CFC propellants and solvents for cosmetic and convenience aerosol products were mostly replaced with hydrocarbons (ODP~0; $GWP_{100\text{ yr. IPCC AR-4}}$ <1); CFC-12 refrigerants for motor vehicle air conditioners (ODP~1; $GWP_{100\text{ yr. IPCC AR-4}}$ =10,200) were mostly replaced with HFC-134a (ODP~0; $GWP_{100\text{ yr. IPCC AR-4}}$ =1300). In addition, no-cost or low-cost alternatives and substitutes for ozone-depleting solvents phased out by the Montreal Protocol (carbon tetrachloride, CFC-113, and methyl chloroform) also replaced hazardous fossil fuel and chlorinated solvents not controlled by the Montreal Protocol.

Indicative List of Superior Replacement Technology

- ✓ The benefits *enjoyed* to planetary boundaries beyond ozone and climate from the economically, technically, and environmentally superior replacements include improvements in product performance, safety, and sustainability. In some cases, replacements for ODSs also replaced toxic and hazardous chemical substances that do not deplete stratospheric ozone and force climate.
- ✓ Replacement MDIs for treatment of asthma and chronic obstructive pulmonary disease (COPD) are far more precise in therapeutic dose from the first puff to the last.
- ✓ Replacement ethylene oxide hospital sterilization offers a choice of higher efficacy against increasing dangerous bacteria and viruses, faster sterilization during emergencies when medical device inventory is limited, and lower doses of the hazardous ethylene oxide active sterilizing ingredient.[4]
- ✓ No-clean soldering replaced soldering cleaned in vapour degreasers using CFC-113. No-clean soldering (inherently safe flux is used to solder in controlled atmosphere) produces

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[4] CFC-12 as a flammability inerting agent (ODP~1; $GWP_{100\text{ yr. IPCC AR-4}}$ =10,200) was replaced with HCFC-124 (ODP~0.022; $GWP_{100\text{ yr. IPCC AR-4}}$ ~609).

solder joints with near-zero failure over the life of the product and far less hazardous lead solder dross. Near-zero failure is particularly valuable for safety systems in a wide range of civilian, industrial, and military applications. No-clean soldering facilitated the phasedown of lead solder and inspired super-integration of electronics with fewer components, lighter weight for lower carbon footprint, and even greater reliability (Andersen and Zaelke 2002).

- ✓ Replacement refrigeration and air-conditioning equipment has higher energy efficiency, reliability, and technical performance.
- ✓ In the complete redesign of refrigerators for ozone-safe refrigerants, engineers revisited the science of food preservation and adopted combined optimal temperature and humidity, allowing refrigerators to safely preserve food longer with reduced nutrition loss while using less energy.
- ✓ Some replacements for ODS refrigerants produce less vibration and noise, which is an advantage for refrigeration and air-conditioning equipment in occupied spaces and to avoid sonic targeting in military applications.
- ✓ Through financial incentives from higher refrigerant cost savings and government regulations against intentional venting, refrigerant containment and smaller refrigerant charges reduce ozone-depleting and GHG emissions. Professional organizations such as the Mobile Air Climate Systems Association (MACS), SAE International, and Underwriters Laboratories supported the industry through standards on precision leak detection, less permeability of flexible hoses, and improved joint seals.
- ✓ Containment, recovery, and recycling of refrigerants to avoid emissions also improves the weight and volume precision of recharge that achieves the highest possible cooling capacity and energy efficiency. For instance, the recovery of refrigerants during service of automobile air conditioners and the recharge by weight allows greater precision than with the obsolete technology of sight glass and pressure gauges. Precise refrigerant charge sustains energy efficiency and prolongs equipment's useful life and reliability.
- ✓ Air-conditioner engineers updated the science of comfort based on temperature, humidity, and airflow as well as targeted cooling rather than controlled ambient temperature only, resulting in faster comfort at less energy use and higher occupant alertness and creativity.
- ✓ Computer facilities with instantaneous transfer of operations to backup facilities proved far more cost-effective than paying for the faint hope that ODS halon would control fire without material damage to computer equipment or business interruption.
- ✓ Polyurethane thermal insulating foam blown with hydrocarbons, CO_2, and water have excellent flowability for moulding cases and panels with very low densities. Due to superior foam finishing, with fewer voids and foam defects, modern foams can achieve insulation performance comparable to foam previously made with CFCs, HCFCs and HFCs.

- ✓ Near-zero-waste manufacturing helps protect the environment by turning all inputs into valued product and avoiding disposal of unusable resources that may otherwise become hazardous waste.

- ✓ Toxic and ozone-depleting methyl bromide—classified as a biocide because it "*kills every lifeform in every life stage*"—was replaced with safer integrated pest control using natural methods and less hazardous chemical controls. Phasing out methyl bromide eliminated landfill waste from plastic tarping used to contain methyl bromide on soil long enough to achieve pest kill rates, halted methyl bromide fumigation that sometimes drifted into neighbourhoods or schools or to where farmers or farm labour were exposed, and reduced risk accidental release from natural disasters, criminal activity, or terrorism.

Source: Andersen and Gonzalez 2023; Andersen et al. 2018; Andersen, Sarma, and Taddonio 2007

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[1] Co-authors Dr. Stephen O. Andersen, Suely Carvalho, and Marco González earned the 2023 Planetary Guardian Award; other award winners that year included Dr. Mario J. Molina, Dr. F. Sherwood Rowland, Jonathan Shanklin, and Dr. Helen Tope.

[2] The Stockholm Resilience Center (SRC 2024) at Stockholm University identifies the pioneering publications on Planetary Boundaries as Rockström et al. (2009a and 2009b); Steffen et al. (2015) and Richardson et al. (2023). It is noteworthy that the 28 co-authors of Rockström 2009a and 2009b are identical; that Paul J. Crutzen, who shared the 1995 Nobel Prize in Chemistry with Mario J. Molina and F. Sherwood Rowland for warning of stratospheric ozone depletion, is one of the co-authors of Rockström et al. (2009a and 2009b); that Veerabhadran Ramanathan was first to warn that ozone-depleting CFCs are potent greenhouse gases; and that Katherine Richardson, Johan Rockström, and Will Steffen are co-authors on all four identified pioneering publications.

[3] See NASA Ozone Watch for the daily progression of the various ozone statistics comparing the climatology, including annual plots of statistics for monthly means.

[4] Probably the last ODS invented was HCFC-225 (in 50% HCFC-225ca / 50% HCFC-225cb ODP=0.029; $GWP_{100\text{-}yr}$ =347) conceived in 1986 as a replacement for CFC-113 (ODP=0.82; $GWP_{100\text{-}yr}$ =6530) and used as a non-flammable, low toxicity solvent in vapor degreasing of electronics and precision parts. The Japanese company Asahi responsibly marketed HCFC-225 only for socially important applications when no other in-kind or not-in-kind replacement satisfied essential technical performance criteria.