The Antarctic Ozone Hole: A Unique Example of the Science and Policy Interface

Susan Solomon and Marie-Lise Chanin

ABSTRACT. The discovery of an unexpected large depletion of the Antarctic ozone layer in the 1980s attracted the attention of scientists, policymakers, and the public. The phenomenon quickly became known as the "ozone hole." Observations established that the ozone losses were driven primarily by human-made compounds, chlorofluorocarbons and bromocarbons, whose chemistry is particularly enhanced for ozone loss under the extreme cold conditions of the Antarctic. Systematic long-term data of Antarctic total ozone date back to the 1950s at several international stations, and these key records owe their existence to the International Geophysical Year in 1957–1958 as well as to the Antarctic Treaty System. Although ozone depletion is greatest in the Antarctic, significant depletion has also been observed in the Arctic and at midlatitudes in both hemispheres. Ozone depletion enhances the ultraviolet light at the planet surface and thereby can damage ecosystems and some crops as well as increasing the incidence of human eye cataracts and skin cancer. These concerns led policymakers to agree to the Montreal Protocol on Substances that Deplete the Ozone Layer (Montreal Protocol) in 1987, and progressive advances in understanding the Antarctic ozone hole were important for the considerations by policy over the next 10 years that ultimately led to controls that have essentially phased out the production of chlorofluorocarbons and bromocarbons. Chlorofluorocarbons not only deplete ozone, but they are also greenhouse gases that contribute to climate change. It is not widely appreciated that the phaseout of the chlorofluorocarbons under the Montreal Protocol has probably contributed about five times more to mitigation of climate change than has occurred due to the Kyoto Protocol to the United Nations Framework Convention on Climate Change (Kyoto Protocol) to date. Thus, the Antarctic ozone hole and the subsequent scientific understanding and policy process have played key roles not only for ozone protection but also for climate protection.

INTRODUCTION

A distinguishing feature of the twentieth century was the recognition of the fact that human activities are changing the Earth's atmosphere. Carbon dioxide, methane, and chlorofluorocarbon concentrations have increased, causing people around the world to come to a new realization: the atmosphere is vast but finite. There are now so many people on this planet that some of the gases we release are affecting the composition of our atmosphere. The most striking illustration of the concurrent development of scientific theory, observation, and

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societal implications of atmospheric change has been the depletion of the Earth's protective ozone layer, and this remarkable change has been most pronounced in the most remote place on the planet: Antarctica.

ANTARCTIC OBSERVATIONS OF OZONE: A BELLWETHER FOR THE PLANET

The first identification of a human impact on the ozone layer was possible as a result of the commitment to long-term monitoring of Antarctica that began in the International Geophysical Year (IGY) in 1957–1958, when continuous, year-round observations of ozone were begun at multiple sites around the continent. The IGY was a cornerstone in global monitoring of the atmosphere not only in Antarctica but worldwide, and the establishment of this baseline system of scientific study was among the factors that bolstered both the success of the Antarctic Treaty dialogue at that time and the attraction of many young scientists into their careers. Among the key scientists who participated in the revision of the Antarctic Treaty in the 1980s was Jacques Cousteau, who argued for a treaty that would continue to consider Antarctica as a continent devoted to science and preservation of nature. These elements combined to produce the scientific capabilities that led to many advances, among them the discovery of the ozone hole.

In 1985, scientists from the British Antarctic Survey reported that the October Antarctic ozone content had decreased by almost half compared, e.g., to the measurements taken there in the first two decades after the IGY (Farman et al., 1985). This change was far greater than the natural variations observed at Halley in monthly averaged ozone. Data from three key stations are shown in Figure 1, illustrating how the international research programs in Antarctica undertaken by numerous nations around the time of the IGY complemented one another in jointly providing independent evidence of an unprecedented change in Antarctic total ozone.

Chlorofluorocarbons and bromocarbons produced by man were suspected as a possible cause. Ozone depletion leads to more ultraviolet light falling on the planet surface, which can cause damage to the DNA of plants and animals. The Antarctic ozone hole therefore raised the important question of whether or not similar processes could occur in other locations, particularly middle and low latitudes. Among other impacts, damage to certain ecosystems, crops, and human health (including cataracts and some types of skin cancers) are enhanced when ozone is reduced, making global ozone losses a matter of societal concern (see, e.g., United Nations Environment Programme, 1999).

Within a few years, aircraft and ground-based observations were carried out that measured not just Antarctic ozone but also a broad suite of chemicals, both manmade and natural, that can affect it (de Zafra et al., 1987; Solomon et al., 1987; Anderson et al., 1989; Waters et al., 1993). As a result of the work of hundreds of researchers, it is now well established that ozone depletion is pronounced in Antarctica because it is, indeed, the coldest place on Earth, which gives rise to chemical processes profoundly different from those occurring in warmer environments.

The extreme coldness of the Antarctic stratosphere allows chemical reactions to occur on and in the surfaces of polar stratospheric clouds that rapidly liberate reactive chlorine from chemically inert reservoirs, making the chlorine from chlorofluorocarbons much more damaging to ozone than it would otherwise be (Solomon et al., 1986). The most rapid ozone loss occurs in Antarctica during September because both cold temperatures and sunlight are involved in the chemistry of Antarctic ozone depletion. The depletion occurs over a particular range of altitudes from about 12 to 25 km because this is the height range where the polar stratospheric clouds occur. The structure of this depletion is shown in Figure 2, and it is one of the important pieces of evidence showing a "fingerprint" of the ozone hole that provides the evidence supporting the understanding that the depletion is driven by chlorofluorocarbon chemistry (see the review by Solomon, 1999, and references therein).

Ups and downs in the depth and size of the ozone hole from one year to another depend mainly on how cold or warm it is each year (see, e.g., World Meteorological Organization (WMO), 2007). Loss of ozone affects the temperature in the stratosphere too: less ozone leads to a colder stratosphere (Ramaswamy et al., 2001, and references therein). Strong cooling in Antarctica in turn affects the wind pattern in the troposphere and even at the ground and is one of the factors that has caused some parts of Antarctica to get colder while other parts have gotten warmer over about the past three decades (Gillett and Thompson, 2003). Thus, ozone depletion also affects the pattern of Antarctic surface climate change. Indeed, the discovery that Antarctic ozone depletion could couple to surface climate via circulation changes is a new process in chemistry-climate linkages. In addition, it has long been known that stratospheric ozone depletion could introduce a cooling effect on global surface climate. However, the

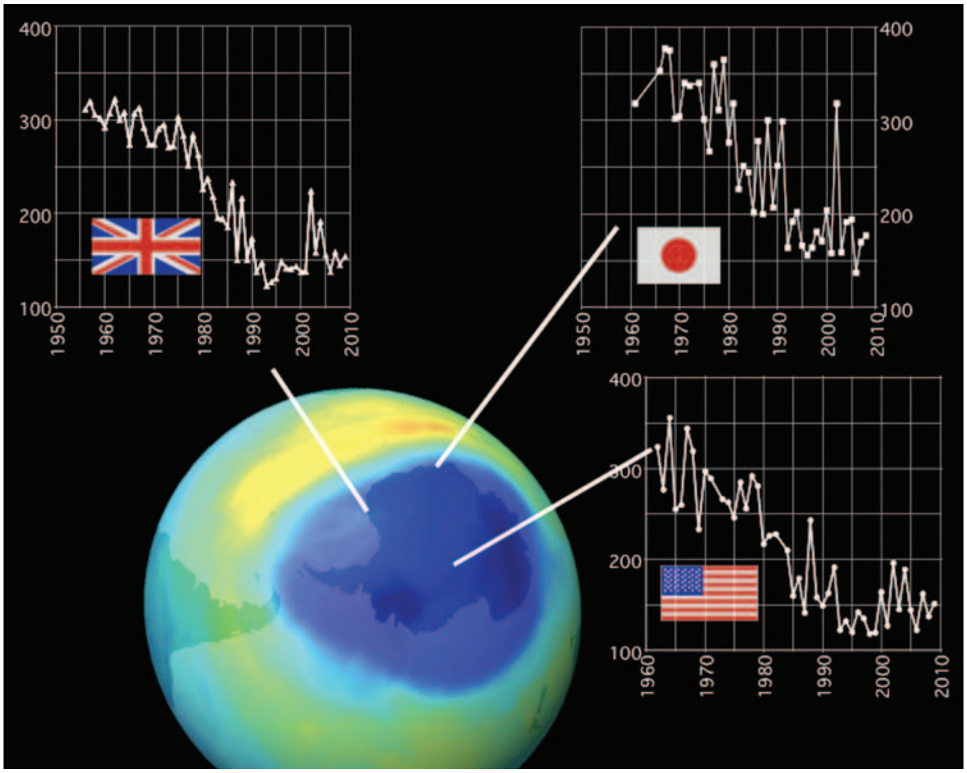

FIGURE 1. October monthly mean total ozone records (in dobson units) from (top left) Halley, (top right) Syowa, and (bottom right) South Pole stations, with the latter being the mean of the second half of the month only because of the limited availability of sunlight needed to make measurements there. Data for Syowa are available at the World Ozone and Ultraviolet Data Center (WOUDC), and those for the South Pole are available at the NOAA Earth System Research Laboratory, Global Monitoring Division, ftp archive; the Halley data are courtesy of J. D. Shanklin, available at the British Antarctic Survey Web site (http://www.antarctica.ac.uk). A satellite ozone map for 6 September 2000 is also shown (courtesy of NASA).

halocarbons that cause ozone depletion are also potent greenhouse gases that contribute importantly to warming along with other compounds including carbon dioxide, methane, and nitrous oxide; see Figure 4 and the discussion below.

CONTRASTS BETWEEN THE ARCTIC AND ANTARCTIC

A logical next question is whether or not ozone depletion is also occurring in the Arctic. The answer is yes, but the changes are smaller there, primarily because the Arctic stratosphere is warmer than the Antarctic, particularly in spring. Most important is that the Arctic stratosphere generally warms up sooner than the Antarctic does. This in turn means that the overlap between the cold temperatures that cause clouds to form and the sunlight that returns to the polar regions in spring is less effective in the north than in the south. However, some studies have highlighted an important aspect of natural variability: the spring Arctic stratosphere can sometimes be very cold. In unusually cold years, more Arctic ozone depletion is, indeed, observed. Figure 3 shows that the ozone losses in the Arctic were most pronounced in the mid- to late 1990s (which were colder than average in the Arctic), but these Arctic ozone depletions were still considerably smaller than those found in the Antarctic. Figure 3 also underscores the fact that whereas there are many sites where some Arctic ozone data have been taken for shorter periods, there is only one station in the High Arctic (Resolute, Canada) where a continuous record extends back to the IGY. In contrast, there

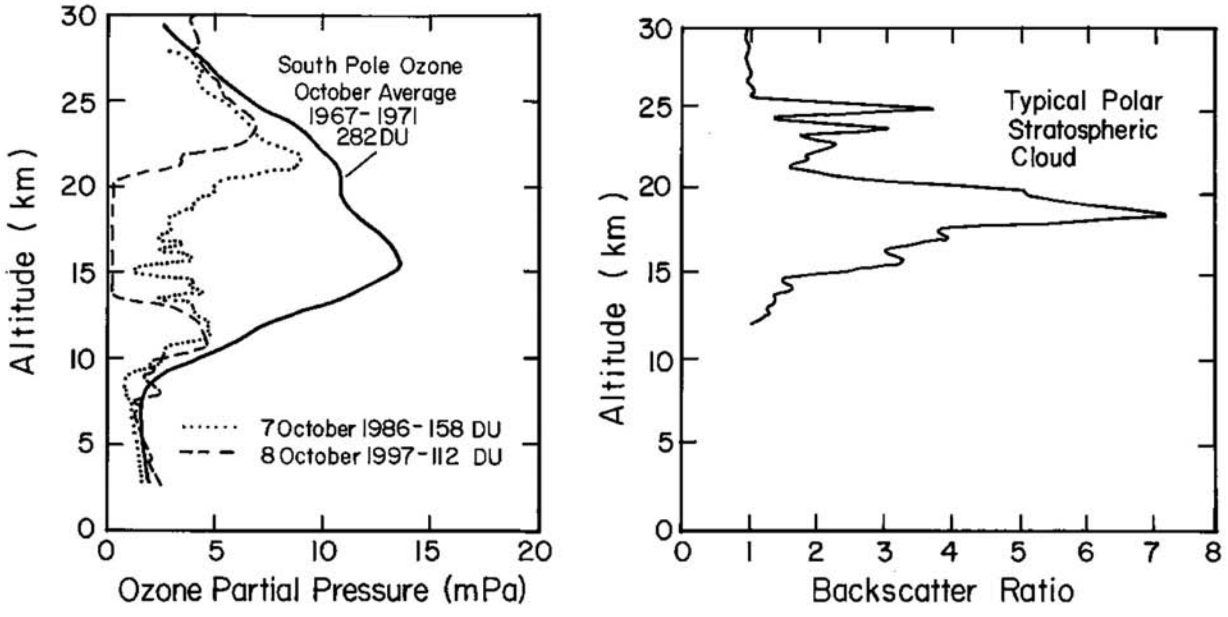

FIGURE 2. (left) Observations of the vertical profile of ozone observed at the South Pole during October in the late 1960s and early 1970s, contrasted with those of 1986 and 1997. Total ozone (dobson units) is indicated for each profile. (right) Typical polar stratospheric clouds observed at the South Pole are shown. From Solomon (1999).

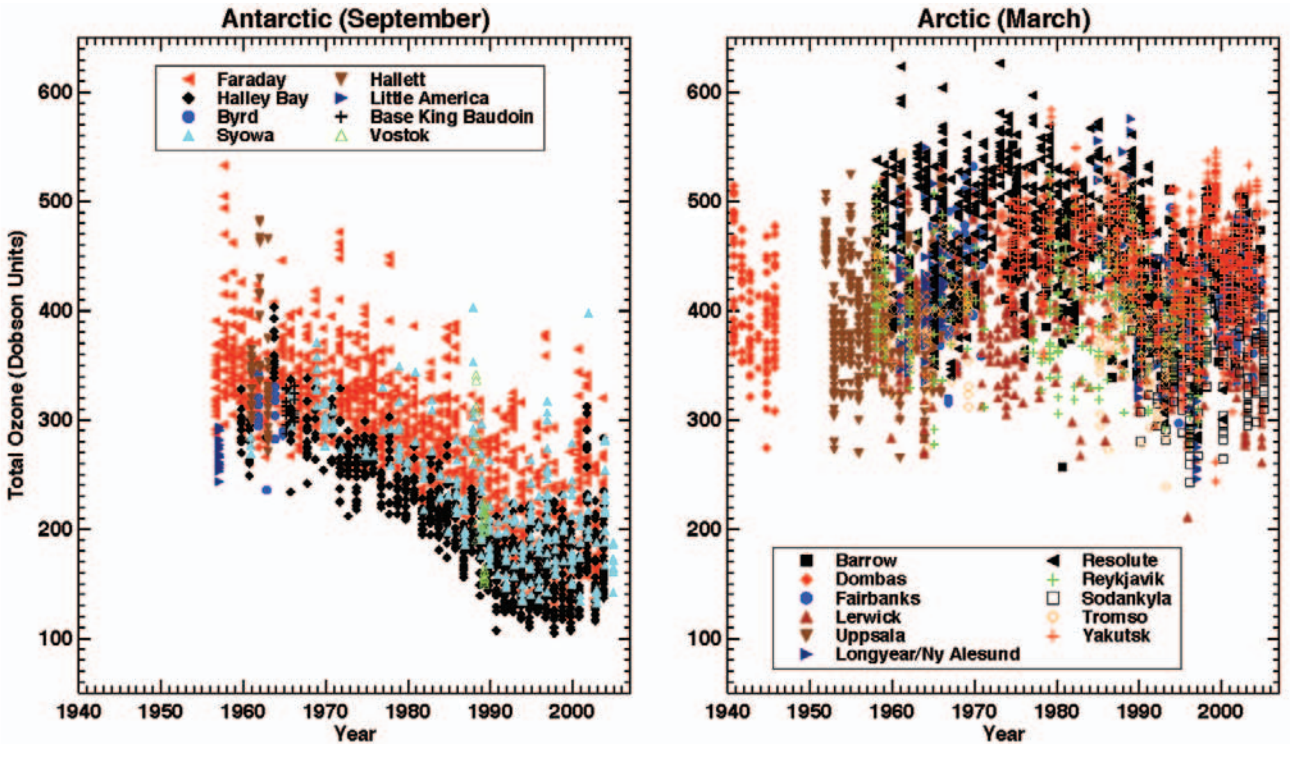

FIGURE 3. Observations of daily total column ozone (left) in Antarctica in September and (right) in the Arctic in March. Some records have been offset in time slightly for clarity. From Solomon et al. (2007).

are four sites with such records in the Antarctic, again attesting to the importance of the IGY and to the way in which the interface of science and policy in protecting the Antarctic also facilitated Antarctic science, especially systematic monitoring. Indeed, as the world looks forward to the future of the ozone layer and its interactions with climate change, the Antarctic Treaty can serve as model in preserving required data records, but no such international provisions fully cover the Arctic at present. Further, the question of whether the Arctic stratosphere might become colder or warmer in the future due to climate changes has been raised (see WMO, 2007), introducing the issue of whether or not Arctic ozone depletion could worsen in coming decades, at least in some years.

GLOBAL OZONE CHANGES AND GLOBAL POLICY AGREEMENT: THE MONTREAL PROTOCOL

Ozone changes are happening at midlatitudes too. Here again, there is evidence that these ozone changes are not natural. Observations suggest that human use of chlorofluorocarbons and other ozone depleting substances is the fundamental cause of the midlatitude ozone depletions and that reactions on surfaces are also significant in enhancing these ozone losses, albeit less so than in the polar regions (WMO, 2007).

As a result of concerns about our changing ozone layer, a handful of governments agreed the landmark 1987 Montreal Protocol, which started with modest controls on chlorofluorocarbons and bromocarbons but over the next two decades was joined by nearly every country in the world (the only UN treaty with full participation) and strengthened by amendments and adjustments to phase out dozens of additional ozone-depleting substances worldwide (Andersen and Sarma, 2002). The chief U.S. negotiator of the Montreal Protocol has written a memoir that discusses the key factors in the negotiation of the agreement (Benedick, 1998) and has emphasized a leading role played by the United States along with others, including Canada, Norway, and Sweden. Benedick (1998) suggests that the Montreal Protocol would likely have been agreed in 1987 even if the Antarctic ozone hole had not been discovered. It is, however, useful to note that the original Montreal Protocol required only that global chlorofluorocarbon production and consumption be reduced by 50% and that bromocarbon production and consumption not exceed the rates prevailing in the 1980s (i.e., emissions were to remain frozen at the rates occurring at that time). If that had been the only policy action taken, these gases would have continued to increase in the atmosphere, and massive amounts of ozone depletion would eventually have occurred in the Arctic; indeed, even the tropical ozone layer would have exhibited dramatic depletion at certain altitudes by about the 2050s (Newman et al., 2009).

The Montreal Protocol's precepts included a provision calling for review of the science, technology, and economics of the ozone depletion issue and revision over time, and it is evident that the subsequent amendments and adjustments to the Montreal Protocol that were agreed, e.g., in 1990 and 1992 were influenced by advances in understanding the science, in particular the science of the Antarctic ozone hole (see WMO, 2007; Newman et al., 2009). These revisions to the Montreal Protocol took the form of successive advancements of phaseout dates of production and consumption of ozone-depleting chemicals used in various sectors (e.g., solvents, refrigeration, airconditioning, fire extinguishing, etc.) as substitute chemicals and processes were found. Global emissions of chlorofluorocarbons today are near zero, and the concentrations of the chlorofluorocarbons already in the atmosphere are starting to decrease in response to this unprecedented global agreement. But the chlorofluorocarbon that is already in our atmosphere is very stable; it is destroyed only by very slow processes and lives for 50–100 years. This means that although the ozone layer is expected to eventually recover, the chlorofluorocarbon that is already present will continue to destroy ozone from one pole to the other well into the middle of the twenty-first century (WMO, 2007).

INTERACTIONS BETWEEN THE MONTREAL AND KYOTO PROTOCOLS

Observations of chlorofluorocarbons attest to the fact that global compliance with the Montreal Protocol has been highly successful (WMO, 2007). Although efforts are continuing to ensure a full understanding of residual emissions, it is clear that these are extremely small compared to the large amounts annually released prior to the protocol.

The chlorofluorocarbons that effectively deplete the ozone layer are also potent greenhouse gases and thereby contribute to global climate change. Emissions of greenhouse gases are considered under another global protocol, the Kyoto Protocol, but ozone-depleting substances are not included in its provisions because they are covered separately under the Montreal Protocol. Recent studies have drawn attention to the fact that the emissions of chlorofluorocarbons have made surprisingly important contributions to warming of the Earth's climate (see Intergovernmental Panel on Climate Change, 2005; Velders et al., 2007). By the late 1980s, just before the Montreal Protocol was signed, the emission of chlorofluorocarbons was equivalent to about 7.5 gigatonnes (Gt) of CO_2, and the emission of CO_2 itself from fossil fuel burning was about 22 Gt in that year, as shown in Figure 4. If there had not been a Montreal Protocol, continued growth in chlorofluorocarbons at the rates prevailing in the late 1980s would have led to a warming contribution of more than 10 Gt of CO_2 equivalent emission by 2009 (Figure 4); offsets due to cooling from ozone depletion and increased emissions of substitute gases (such as hydrochlorofluorocarbons) are included in this best estimate and amount to a few gigatonnes of CO_2 equivalent. But because of the Montreal Protocol, emissions of chlorofluorocarbon in 2009 were near zero, implying that the Montreal Protocol has already averted the emission of about 10 Gt per year of CO_2 equivalent (see Figure 4 and Velders et al., 2007). In contrast, the Kyoto Protocol calls for a global reduction of emissions of CO_2 and other greenhouse gases of about 2 Gt per year. Thus, the Montreal Protocol and the underlying science of Antarctic ozone depletion have not only protected the ozone layer but also made a contribution to protection of the climate that is about five times larger than the current provisions of the Kyoto Protocol. In closing, we emphasize that the Antarctic ozone hole serves as a remarkable example of the many ways in which the research conducted because of the Antarctic Treaty System has had far-reaching effects on science, on the environment, and on the global formulation of policy.

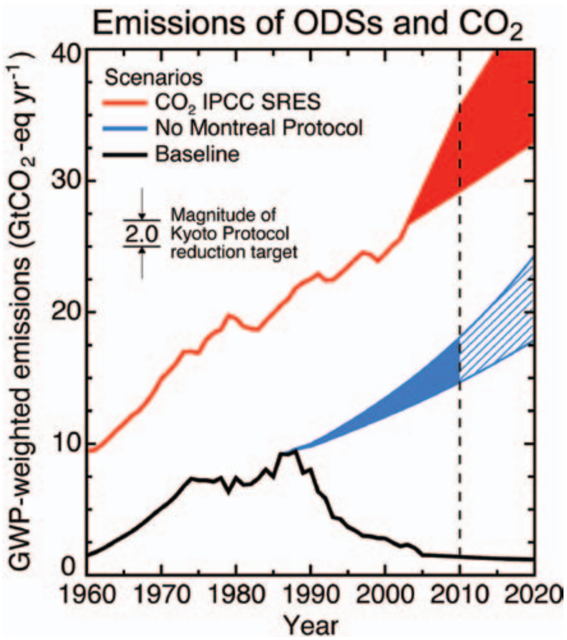

FIGURE 4. Global warming potential (GWP)–weighted emissions for the period 1960–2020. Calculated GWP-weighted emissions (100-year time horizon) are shown (see WMO, 2007). All emissions are normalized by their direct GWPs to equivalent Gt CO_2. The indirect contribution to the GWP due to ozone depletion, which is thought to be ≈20% (see text), is not included in these figures. The shaded blue region reflects a range of 2%–3% for assumed annual production increases in ozone-depleting substances in the absence of the Montreal Protocol after 1987. The CO_2 emissions for 1960–2003 are from global fossil fuel and cement production. Shown for reference is the magnitude of the reduction target of the first commitment period of the Kyoto Protocol, which is based on a 1990–2010 projection of global greenhouse gas emission increases and the average reduction target for participating countries. Adapted from Velders et al. (2007), kindly provided by the authors.

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