2004

Blue Planet Prize

Dr. Susan Solomon (U.S.A.)

Senior Scientist,
Aeronomy Laboratory, National Oceanic and
Atmospheric Administration

Dr. Gro Harlem Brundtland (Norway)

Chairman WCED (World Commission on
Environment and Development)
Former Prime Minister of Norway
Director-General Emeritus, WHO

Air on Gaia:
The earth is wrapped with a robe. Thanks to it, we are able to sustain our daily activities. From some point in time, human activities went too far impairing it. In 2004 the opening film instilled us with a hint to consider the future of the global environment, the ways toward development that enables us to sustain the environment.

Their Imperial Highnesses Prince and Princess Akishino at the Awards Ceremony

His Imperial Highness Prince Akishino congratulates the laureates

Dr. Hiroyuki Yoshikawa, chairman of the Selection Committee explains the rationale for the determination of the year's winners

Hiromichi Seya, chairman of the Foundation delivers the opening address

The prizewinners receive their trophies from Chairman Seya

Dr. Gro Harlem Brundtland

Dr. Susan Solomon

Howard H. Baker Jr., Ambassador of the United States of America to Japan and Åge Bernhard Grutle, Ambassador of Norway to Japan, congratulate the laureates

The prizewinners at the Congratulatory Party.

Profile

Dr. Susan Solomon

Senior Scientist,
Aeronomy Laboratory, National Oceanic and Atmospheric Administration

Education and Academic and Professional Activities

1956	Born on January 19 in Chicago, Illinois
1977	Bachelor of Science degree in chemistry at the Illinois Institute of Technology
1981	Doctoral degree in chemistry from the University of California, Berkeley
1981	Research Chemist, the Aeronomy Laboratory of the National Oceanic and Atmospheric Administration (NOAA)
1985	Adjoint Professor, Department of Astrophysical, Planetary and Atmospheric Sciences, University of Colorado
1988	Program Leader, Middle Atmosphere Group of the Aeronomy Laboratory, NOAA
1990-present	Senior Scientist, Aeronomy Laboratory, NOAA
1992-present	Member, National Academy of Sciences
1995-present	Foreign Associate, French Academy of Sciences
2000	American Meteorological Society Carl-Gustaf Rossby Research Medal
2000	National Medal of Science

The ozone hole over Antarctica attracted a high degree of interest among the global environmental issues in the late 20th century due to concerns that stratospheric ozone layer depletion would increase the amount of harmful ultraviolet light on earth. Prior to the discovery of the Antarctic ozone hole, theories suggested that the ozone layer might be depleted by a few percent in a century, but the issue came to the fore with the dramatic discovery of a much larger and rapid depletion. Dr. Solomon was the leading scientist in identifying the mechanism that created the Antarctic ozone hole. She and her colleagues put forth a theory involving heterogeneous chemical reactions of chlorine on the surfaces of the particles found in very cold clouds in the Antarctic stratosphere. She then conducted observations in Antarctica over two expeditions in 1986 and 1987, and succeeded in providing key evidence for her theory. This research played a leading role in identifying the process by which the surfaces of clouds produced by the extremely low temperatures of Antarctica couple with increased atmospheric chlorine due to human use of chlorofluorocarbons (CFCs) to deplete ozone at unprecedented rates. Dr. Solomon's findings provided one of the scientific cornerstones for the amendments of the Montreal Protocol leading instead to a ban on CFCs beginning in 1990, and thus contributed significantly to the protection of the ozone layer.

After studying chemistry at the Illinois Institute of Technology, Dr. Solomon majored in atmospheric chemistry at the University of California, Berkeley, where she received her doctoral degree in 1981. After her graduate work, she joined the National Oceanic and Atmospheric Administration, and she has continued her research on the atmosphere there ever since.

In the mid 1980s, it was revealed that a dramatic depletion of the ozone over Antarctica had been detected in the springtime from September to October beginning in the late 1970s. The ozone depletion was very extensive in both space (covering the entire Antarctic continent) and magnitude (up to about half of the ozone was depleted in comparison to pre-1970 levels). Dr. Solomon became deeply interested in these findings, and presented a theory hypothesizing the causes of depletion based on heterogeneous chemical reactions involving the unusual clouds that are created under the atmospheric conditions of extremely low temperature of minus eighty degrees Celsius, specific over Antarctica (polar stratospheric clouds).

Dr. Solomon theorized that the reaction of hydrochloric acid and chlorine nitrate, which does not occur significantly in the gas phase, might take place extremely rapidly on the icy surfaces of the particles in the polar stratospheric clouds, thereby producing nitric acid and chlorine. She further hypothesized that as the sun first rose with the arrival of spring in Antarctica, the chlorine would dissociate through photolysis, producing reactive chlorine atoms and related molecules such as chlorine monoxide and chlorine dioxide. These reactive forms of chlorine destroy the ozone with dramatic efficiency. Dr. Solomon's theory is considered groundbreaking not only for identifying the mechanisms that produced the chlorine radicals directly related to ozone depletion, but also for explaining the high concentration of reactive chlorine compounds in the atmosphere.

At the end of August 1986, chosen as the leader of the observational expedition team at the tender age of thirty, she set out to Antarctica aiming to verify the existence of ozone hole and clarify the mechanism of its formation. The team measured the ozone depletion by several methods, and they also measured key chemicals that gave insight into the cause. The measurements of active chlorine revealed that there was approximately a hundred times more of the substance than could be explained through gas-phase chemistry. This finding was a definitive indication of the involvement of heterogeneous chemistry as put forth in Dr. Solomon's theory. The following year, she led a second expedition to Antarctica, where the team found that the depletion of the ozone had worsened compared to the previous year.

Dr. Solomon has authored two books as well as having written or co-written over 150 papers. In her most recent book, *The Coldest March*, she wrote about the tragic expedition of a team led by British explorer Robert Falcon Scott, who succeeded in reaching the South Pole but perished on their return. Through extensive studies of the records from the expedition and more recent meteorological data, Dr. Solomon investigated the reasons for their demise and illustrated that their downfall was brought on by the rare misfortune of exceptionally frigid climate conditions. Further, she provided throughout the book a wonderful account of the individual explorers of the Scott team as they trekked through Antarctica, bringing to life their personalities, challenges, and legacies.

As a scientist, Dr. Solomon is deeply interested in making a contribution to society, and

values the important role that science can play in areas such as environmental issues. Through the application of science, she continues to work towards protecting the society from the dangers that arise from ignorance by shedding light on the nature and reasons for environmental problems.

Environmental Issues and Science:
Some Thoughts on Roles and Stages

Dr. Susan Solomon

"Believe one who has proved it. Believe an expert."   Virgil, in the Aeneid.

What is the role of science in environmental issues? Most people would readily agree that presentation of the best possible technical information is the obvious answer. But how does it preserve that status? How does it best communicate it to non-specialists?

Science can be the light of the world. In my opinion, it lights the world best when it is framed in a broader context of the other diverse challenges and inputs to societal change. What can reasonably be considered to be fact is one side of this. It is also important to consider where facts begin to fade into the genuine role of opinion, and the non-scientific elements of societal choices.

Consider the application of this line of thinking to the issue of ozone depletion. The depletion of the ozone layer over Antarctica and its chemical cause is now well-established through numerous independent measurements. There is no debate about the time scale of the gases that are responsible. The chlorofluorocarbons that cause the ozone hole live in the atmosphere for decades to centuries depending upon the species, so any effects that occur will last for many years. The elements of scientific understanding progressed quickly in the case of ozone depletion, from the initial ideas of the mid-1970s to the discovery of the Antarctic ozone hole in the mid 1980s and demonstration of its cause within a few years. Technology was also quick in the development of efficient and effective substitutes for nearly all applications, which include refrigeration, air conditioning, and foam blowing among others.

It is clear that a reduced ozone layer leads to more ultraviolet light at the ground. There are no significant winners from more ultraviolet light; rather there are risks to ecosystems, and to human health. There are matters unrelated to physical science involved when the issue of how large a risk to society or to ecosystems is acceptable or unacceptable is considered. But there can be little debate that increased risk of skin cancer and cataracts are serious matters to those who may end up contracting such health problems. Thus the potential impacts were also easy to describe and readily understood by the public and policymakers alike.

A wise colleague has noted that there are three stages to any environmental issue: credibility (is the change real? Can we prove why it is happening?); manageability (what are the options for dealing, or not dealing, with the changes and what would be the outcomes?); and finally accountability (have the options been effectively implemented, and are the desired outcomes occurring). In the case of the depletion of the ozone layer, the credibility stage began in the mid-1970s when the issue was first brought to global attention and it progressed rapidly, particularly following the discovery and explanation of the unexpected Antarctic ozone hole.

Between about 1985 and 1990 there was swift and convincing scientific demonstration of a very large effect and its explanation.

The manageability stage started in about the late 1970s, when international actions began to consider phaseouts of chlorofluorocarbons, at least in some applications such as spray cans. Substitutes first began to be used for the molecules responsible for the depletion. Policies accelerated quickly following the success of the credibility stage in demonstrating increasing clarity connecting observed changes to chlorofluorocarbons. By the late 1990s, agreements were in place globally, and production of the chlorofluorocarbons and halons that cause ozone depletion had dropped dramatically. But the ozone manageability stage involved more than science. It also involved economics, public policy, values, and technology, all as elements in the mix of influences. And in my own view, science lights the world best when it is acknowledged that these aspects go beyond its purview. That's not to say they are not important or that they do not draw in part upon science, but they clearly also involve different considerations to which science is an input but not the sole determinant. I would suggest that science provides the best service to society and the best credibility for the scientific process when these distinctions are clear.

Each scientist involved in such issues has a challenge to consider in deciding upon the way he or she will deal with the components of the problem that go beyond their expertise, and in deciding which matters go beyond scientific evidence into the realm of values and personal opinion. Some people ask if it's difficult, or even if it is possible, to separate scientific evidence from opinion. I don't believe it is difficult at all for a good scientist to do this – in fact it is fundamental to what scientists do each and every day as they weigh what they can say from a careful analysis of information, and separate that from what they wish were known. It is a fundamental aspect of the scientific process and the scientific ethic that has been a bedrock for hundreds of years of research across every field of scientific endeavour. History holds innumerable demonstrations of how effectively this has functioned in the past. Today is no different, nor are environmental issues different.

Now we're mainly in the accountability stage for ozone, the stage of understanding whether the chlorofluorocarbons are decaying as they should be due to reductions in production of CFCs worldwide, and whether the ozone layer is hence recovering as it should. Important progress has already been made, as observations worldwide have confirmed that the abundances of many of the chemicals responsible for ozone depletion are declining. This stage is not expected to progress to completion quite so swiftly, because the chemicals in question will remain in our atmosphere for many decades as already noted. The rate of ozone depletion has certainly slowed down, and it's fair to say that the ozone layer has at least stabilized on average. Perhaps it's helpful to think of the analogy with a person having a disease that has been making them progressively sicker and sicker each year. The first sign of progress is not getting worse anymore, and the next is genuine improvement, a start on the path to recovery. That step may be happening at certain altitudes and latitudes, and is probably just around the corner for the global ozone layer.

Unlike many other environmental pollution issues, the chlorofluorocarbons that are causing ozone depletion are often used in applications where they are intended to be largely

contained, such as refrigerators, air conditioners, and foams: It is the leakage of the gases out of these 'banks' that causes release to the atmosphere. It has recently been suggested that there is probably more chlorofluorocarbon remaining in 'banks' worldwide than was thought. Slow releases of these 'banks' would be expected to increase future ozone depletion above what it would otherwise have been. So a new scientific issue for the accountability period is to understand how much material is scattered throughout the world and how much leaking is occurring. A new policy and manageability question is therefore whether to consider further steps to limit releases from banks. An interesting analogy is also whether to more deeply consider the fate of current and future banks of other molecules – such as hydrofluorocarbons now used as substitutes for the chlorofluorocarbons in many applications. The hydrofluorocarbons don't deplete the ozone layer but they do contribute to climate change, and their use as substitutes in such applications implies a growing bank. So the understanding gained in this stage has linkages to another environmental issue. This reflects the success of policy regarding ozone depletion, which has virtually eliminated the use of these molecules in emissive applications such as spray cans, and has led to greater and greater care in containment of the gases in applications where it is precisely the containment that is the goal (such as in an air conditioning system). Perhaps ironically, the increased attention paid to avoiding emission implies a shift that challenges policy. Whereas use of such molecules in emissive or very leaky ways implied a great deal of emission but a limited bank, as emissions have been reduced and attention to environmental issues has led to less and less leaky systems, the new issue that arises is the fate of the banks that will therefore be built up through continuing production. Containment coupled with continuing use implies a buildup of a bank – and a new challenge for policy in considering not just what is emitted now but what is in the bank and how much of that may be emitted (or not emitted) in future.

Now I'd like to briefly turn to the issue of climate change. The carbon dioxide that is the primary cause of climate change lives in our atmosphere for more than a century. Such a long lifetime implies that each generation's choices about emissions of carbon dioxide will affect the climate of many future generations. We may choose to make different choices about risking something if we know that if we make a mistake we can put it back the way it was in a few months versus a case where it takes centuries or more to restore.

Scientific information also provides strong evidence for a substantial human influence on current climate. In addition to a warmer climate (by about 0.6°C on average over the 20th century), there is also evidence for other changes, such as increased heavy rainfall and changes in circulation patterns. How "dangerous" are climate changes now and in the future, and for whom, is a question increasingly being asked.

Research on the impacts of climate change is an active field. There is debate about the magnitude of the impacts and the degree to which adaptation can occur. Some evidence suggests that there could be both winners and losers. There is also debate about technologies and costs. In climate change today, the world is deeply immersed in both the credibility and manageability phases. They are occurring more strongly in parallel than they did for the ozone issue, in part because of the realization brought about by the story of ozone that long time scales are involved in reversing any changes once they are observed.

So one factor that we as a global society are now wrestling with is how to balance our scientific confidence in human effects upon how climate is changing or may change in the future as well as the impacts of those changes with the fact that if any changes do happen they're going to be with us for many decades – they will not be easily or quickly reversed, and that's a key dimension in our changing view of environmental risk, which involves perspectives as well as science. People take out individual health, fire, or flood insurance by considering the magnitude and duration of consequences along with assessment of the magnitude of the risk. Even if every risk could be well defined and quantified, different people are likely to have different perceptions of acceptable levels of risk – for themselves, for their children, and for future generations. It is sometimes asserted that the climate change problem is terribly complicated, and that poor communication with the public occurs as an inevitable result. But perhaps the complication lies not with the science but with its role in the broader backdrop of questions of risk and world views. As societies wrestle with the credibility and manageability of the climate change issue, a key challenge for science is to illuminate the evidence and the risks as clearly as possible, while recognizing that science is one input among several to a challenging set of policy questions.

Lecture

Ozone Depletion and Climate Change:
A Personal Journey from Pole to Pole

Dr. Susan Solomon

1. Introduction

I am honored and humbled to receive this wonderful award. I thought that the best way to show my deep appreciation for this great honor would be to try to make this lecture something that would reflect the Asahi Glass Foundation's wise commitment to advancing environmental understanding, particularly the understanding of how environmental changes can reach beyond national borders, beyond generations, and sometimes beyond the edge of scientific imagination. The story of the depletion of the ozone layer involves many phases: phases of matter (gas, solid, and liquid), phases of scientific discovery, and phases of public awareness and global policy decisions. I will touch upon all of those phases in telling you of my own part in the story of Antarctic and global ozone depletion. A broader review citing the many important contributions by other scientists worldwide can be found in Solomon (1999). Finally, in closing I will briefly present personal reflections on some parallels and differences between ozone depletion and climate change issues.

Stratospheric ozone represents a layer of vital protection for life on the earth's surface, because it shields the planet from harmful ultraviolet light in a way no other atmospheric molecule can. Yet ozone is easily attacked by other chemicals, as was underscored in the 1970s when concerns began regarding the possibility of ozone depletion due to chlorofluorocarbons (CFCs). At first, this came as a surprise since chlorofluorocarbons were known for their largely unreactive character at low altitudes, giving safety and stability when used in applications as diverse as blowing of insulating foams, refrigeration, and as propellants in spray cans. Although the chlorofluorocarbons have lifetimes in our atmosphere ranging from about half a century to as many as several centuries depending upon which gas is considered (CFC-11, CFC-12, CFC-113, CFC-114, CFC-115, etc.), these seemingly benign gases can transform through chemistry, leading to massive ozone loss. This led to changes in scientific thinking and a related challenge to policy: heightened recognition that human beings sometimes make chemicals that can affect our environment over a period far outlasting the generation that produced them. Similar issues arise for a number of greenhouse gases (see Table 1), a point that will be discussed further below. How much ozone depletion could these long-lived CFCs produce? Through what chemistry? Where in altitude and latitude?

Table 1: Atmospheric lifetimes (years) of selected chlorofluorocarbons and non-chlorofluorocarbon greenhouse gases

Chlorofluorocarbons		Non-chlorofluorocarbon greenhouse gases	
CFC-11	45	Carbon dioxide	≈150
CFC-12	100	CH_4	12
CFC-113	85	N_2O	114
CFC-114	300	SF_6	3200
CFC-115	1700	CF_4	50000

Chlorofluorocarbons are not stable everywhere: as they rise up into the stratosphere above about 10-15 kilometers, photochemical processes driven by harsh sunlight break them down to produce chlorine atoms. A portion of these chlorine atoms can be converted to safe reservoirs such as chlorine nitrate and hydrochloric acid, making the partitioning of chlorine between specific chemicals (Cl versus HCl, for example) of paramount importance to the impact on ozone. Insofar as the released chlorine is converted to relatively unreactive reservoirs such as HCl for example, ozone depletion is limited, but insofar as the chlorine remains in more reactive forms such as Cl, ozone can be destroyed by catalytic cycles. Much of my work has focused on the ways that chlorine partitioning can be radically affected by surface reactions involving solids and liquids, leading to far greater ozone destruction than previously thought.

The ozone chemistry understood prior to the mid-1980s all involved reactions of gas molecules with one another and with sunlight: it was believed that ozone depletion was driven by chemical reactions occurring exclusively in the gas phase. That chemistry was expected to lead to maximum ozone loss in the rarified air of the upper stratosphere, on the upper side of the ozone layer near 40 kilometers. By 1983, a United States National Research Council report projected that continued use of chlorofluorocarbons at then-current rates would probably lead to depletion of the total global ozone layer by about 3% in about a century. Some argued that this was a small effect, far in the future, and subject to large uncertainties - arguments that are frequently echoed today in discussions of global warming.

2. Poles Apart: The Unexpected Ozone Depletion At the Ends of the Earth
2.1 The Antarctic Ozone Hole
In the mid-1980s, a remarkable change in understanding of ozone occurred when scientific work at the bottom of the world documented an unprecedented and unexpected depletion of Antarctic ozone, restricted to the spring season. Ozone appeared to be depleted not by a few percent but by about a third, not in the far future but just a few years after the NRC said little would occur for a century. It was a surprise to many that these initial observations came from

ground-based methods at isolated research stations on the world's coldest continent. It was quickly realized that an error in data analysis approaches had impeded the satellites from seeing what the ground-based stations had documented so thoroughly through years of dedicated effort.

Only three sites on the vast continent at the bottom of the world have archived long-term high-quality measurements of ozone since at least the 1970s: the British station at Halley, the Japanese station at Syowa, and the American station at the South Pole. Figure 1 shows the time series of October mean total ozone measurements provided by those three stations. The British data display less variability than the others from year to year, so that as early as 1985 it was clear that ozone was behaving strangely at Halley. A key factor in the observed variability from site to site is the movement of the southern polar stratospheric vortex. At both poles, wintertime cooling leads to very cold conditions at high latitudes, while considerably warmer conditions prevail at lower latitudes. This temperature gradient in turn is linked to a vast wind system that encircles the cold polar air, a vortex. But the vortex can be disturbed by atmospheric waves, similar to the waves that move weather systems across both hemispheres, gracing the images in television weather forecasts. The British station at Halley is located inside the cold Antarctic vortex more often than the Japanese station at Syowa, which sometimes displays ozone levels characteristic of air outside the vortex. The frequency and intensity of these waves play substantial roles in determining the inter-annual variability of ozone concentration and ozone loss both locally (e.g., Syowa versus Halley) and on the larger scale (from one year to another inside the vortex).
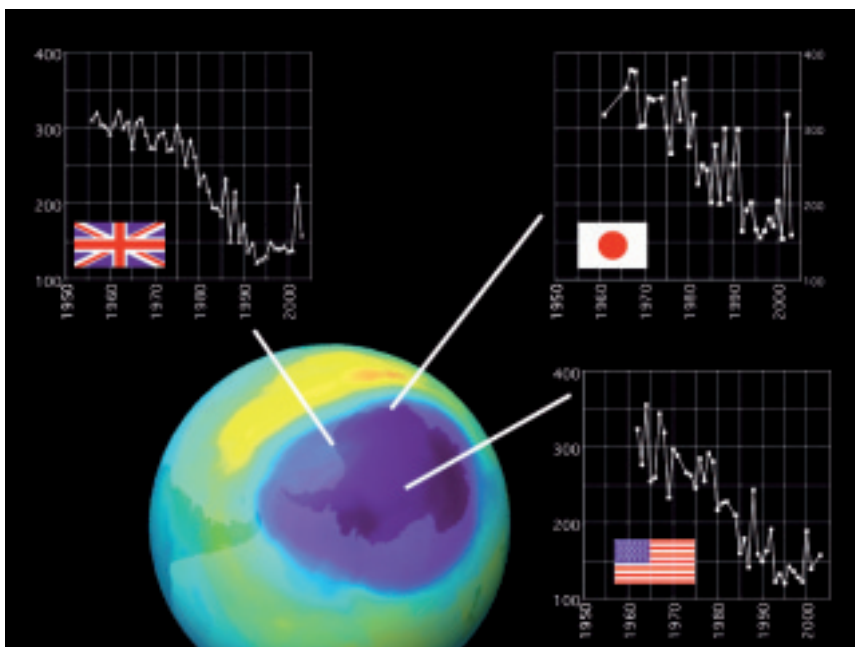

Figure 1. October monthly mean total ozone records (in Dobson Units) from Halley (upper left), Syowa (upper right), and the South Pole (lower right); the data are available at the World Ozone and Ultraviolet Data Center. A satellite ozone map for September 6, 2000 is also shown (courtesy NASA). The satellite map shows that Syowa is located very close to the edge of the vortex on this particular day.

At Syowa station and at the South Pole, measurements of the vertical profile of the ozone depletion in the 1980s suggested anomalous behavior in Antarctic spring at a specific and surprising range in altitude. The change was occurring not at the very top of the ozone layer near 40 kilometers as expected from gas-phase chlorine chemistry, but at an entirely different height range from about 10-20 kilometers, just where the most ozone is to be found (*see Figure 2*). This move of the center of action is why about a third of the total ozone was being depleted then, and today the depletion often exceeds half of the total integrated total ozone layer. It was clear that this ozone depletion was not just larger than what had been imagined, but totally different in character. A massive change in scientific understanding was needed to explain this change in ozone depletion from global to polar, and from 40 kilometers down to 10-20 kilometers.
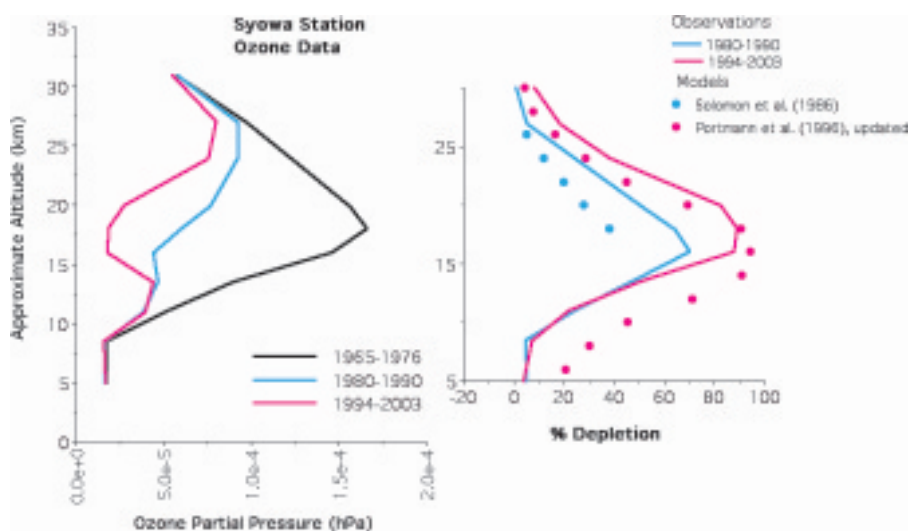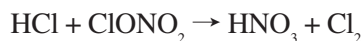

Figure 2. October ozone profiles are shown at the latitude of Syowa station (left), averaged for 1965-1976 showing a normal ozone layer observed before the ozone hole developed, as well as the averages for 1980-1990 and 1994-2003, illustrating the progressive deepening of the ozone depletion there. Model calculations are presented in the right hand panel, where the percent ozone depletion versus altitude derived from the data are compared to models including surface chemistry, as first presented in Solomon et al. (1986) and updated to present from the model presented in Portmann et al. (1996).

2.2 A New Mechanism of Antarctic Ozone Depletion

My colleagues and I suggested that an entirely different kind of chemistry might be responsible for the ozone hole: not gas-phase chemistry but surface reactions (also called heterogeneous reactions). We suggested that these could occur on the icy polar stratospheric clouds that form in the extremely frigid conditions of Antarctica in winter and spring, at altitudes near 10-20 kilometers. In particular, we noted that the densities of chlorine species capable of catalytically destroying ozone could only be appreciably enhanced at these key altitudes if both the HCl and $ClONO_2$ reservoirs were severely reduced, and we suggested that this could occur through the following reaction occurring via surfaces of polar stratospheric clouds:

$$HCl + ClONO_2 \rightarrow HNO_3 + Cl_2$$

The Syowa ozonesonde data were among the observations that helped our development of this new picture. Figure 2 shows the October mean ozone profile measured at Syowa over various time periods, along with our early model calculations as presented in Solomon et al. (l986) and updated model calculations we described a decade later (Portmann et al., 1996). Our early model did not extend below about 18 kilometers, nor did it include all of the chemical cycles that are now known, but our suggested surface chemistry did capture the most essential features of the process, particularly the movement of the ozone loss region down from 40 kilometers to the very heart of the ozone layer.

Why does the ozone loss occur in October, rather than earlier in the Antarctic winter? We emphasized that one more step was needed: such a process could not deplete ozone until sunlight was also available (e.g., to dissociate molecular chlorine, Cl_2). Thus, we suggested that surface reactions could render chlorine from chlorofluorocarbons much more damaging towards ozone than had been imagined based on gas phase chemistry, that those surface reactions would occur most effectively in Antarctica because of cold conditions that lead to stratospheric clouds, and that rapid ozone destruction occurred in spring when sunlight returned to the polar cap (Solomon et al., 1986). This surface chemistry implied large perturbations not only to Cl_2 and Cl, but also to a suite of related chlorine molecules that interchange rapidly among each other (including chlorine monoxide, ClO and chlorine dioxide, OClO) and can engage in rapid ozone destruction. It is now nearly two decades since the Antarctic ozone hole was discovered, and in that time a series of measurements of many different chemicals has confirmed this change of phase from gas to surface chemistry (see references in Solomon, 1999).

2.3 Observational Evidence: Verifying the Role of Chlorofluorocarbons and Surface Chemistry

In 1986, I was privileged to lead an expedition to the Antarctic that was able to make some of the first measurements that tested this chemistry, involving four different research groups. Here I'll focus on the measurements that my own group carried out of ozone, nitrogen dioxide, and chlorine dioxide. Chlorine dioxide was a particularly important early measurement because that molecule is proportional to Cl and ClO, and its detection could provide a direct indication of whether or not polar stratospheric clouds were indeed liberating chlorine. The proposed surface chemistry also converts reactive nitrogen to nitric acid, which impedes the reformation of $ClONO_2$ and thereby further enhances the ozone loss. This reduces nitrogen dioxide concentrations and makes that molecule a critical indicator in the chemistry as well. Indeed, as we emphasized in Solomon et al. (l986), the products of the surface chemistry are as important as the reactants. Finally, observations of ozone itself using visible light from the ground were useful in verifying the ozone hole reported by other methods such as the ultraviolet absorption method used at Halley, Syowa, and the South Pole.

We used a spectrograph to collect light from the sun, the sky, and the moon, and ana-

lyzed the spectrum in wavelengths from about 400 to 450 nm (blue light) to search for the distinct fingerprints of absorption due to ozone, nitrogen dioxide, and chlorine dioxide, which remove as little as a few percent or even a few tenths of one percent of the incoming light, making detection a challenge (Mount et al., 1986; Solomon et al., 1987; see also Sanders et al., 1993; Miller et al., 1999). Like Syowa station, the American site at McMurdo where we did our work is sometimes under the stratospheric polar vortex and sometimes outside it, so we sampled both Antarctic and sub-Antarctic air. We were able to arrive at McMurdo in late August before the sun was above the horizon, and hence before substantial ozone loss begins at that location. One of the stunning experiences of my life in science was to witness the ozone levels drop at McMurdo during September 1986. Ozone fell from about 300 Dobson Units when we arrived in Antarctica in late August 1986 to under 200 Dobson Units by late September, and the disappearance of a third of the total ozone supported the observations of others regarding the veracity of the ozone hole and its seasonality. The falling ozone was accompanied by a spectacular enhancement in chlorine dioxide (*Figure 3*). In late August and September under cold conditions, chlorine dioxide was about 50-100 times greater than gas-phase chemistry can explain, so this data pointed towards surface reactions involving chlorine as the likely cause of the ozone hole. The nitrogen dioxide was in contrast extremely low, as also expected from polar stratospheric cloud chemistry. As temperatures rose, the chlorine dioxide disappeared and the nitrogen dioxide increased, again as expected. Thus the seasonal behavior of both molecules supported the theory of the key role of surface chemistry in perturbing the composition of the Antarctic stratosphere, leading to rapid ozone loss.
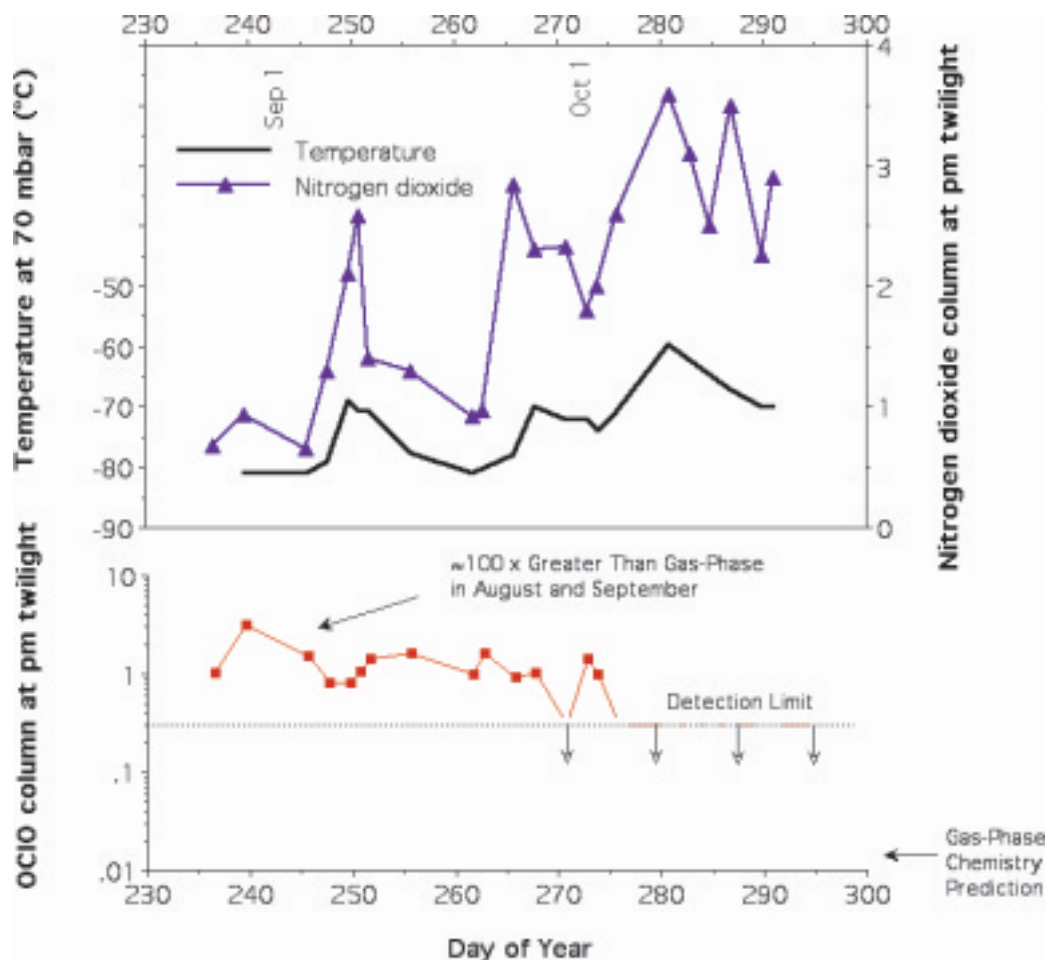
Figure 3. Daily evening twilight observations of chlorine dioxide (OClO) and nitrogen dioxide (NO_2) at McMurdo Station in 1986, from Solomon et al. (1987) and Mount et al. (l987). Temperatures at 70 mbar (about 18 km) are also shown for comparison, illustrating the low NO_2 and very high OClO in August and September, as well as the links of higher NO_2 and lower OClO to incursions of warmer air (e.g., around day number 250). As temperatures warmed in October, OClO disappeared and NO_2 increased to typical stratospheric levels.

We made measurements of chlorine dioxide using direct moonlight as well as the scattered light from the twilight sky. Having both the nighttime and twilight measurements was a further test of the chemistry due to the large diurnal cycle of this molecule, and Figure 4 shows how differently the nighttime chlorine dioxide behaved in Antarctica compared to what was observed by us at other latitudes where polar stratospheric clouds do not occur, for example in Colorado. In the lunar data, we also measured enhancements of about a factor of 100 above gas-phase chemistry predictions. Further, as the moon rose or set, we were able to measure its systematic behavior with changing lunar angle. Because the slant path through the atmosphere increases as the moon approaches the horizon, the amount of chlorine dioxide we observe in the path through the atmosphere to the moon increases in a well-defined way dur-

ing a night of observations. That provides an important check on the measurements, one that I have always felt was a simple but elegant way to confirm the data (albeit at times challenging to the observer, particularly when adjusting instruments throughout the frigid Antarctic night at surface temperatures below -40°C).
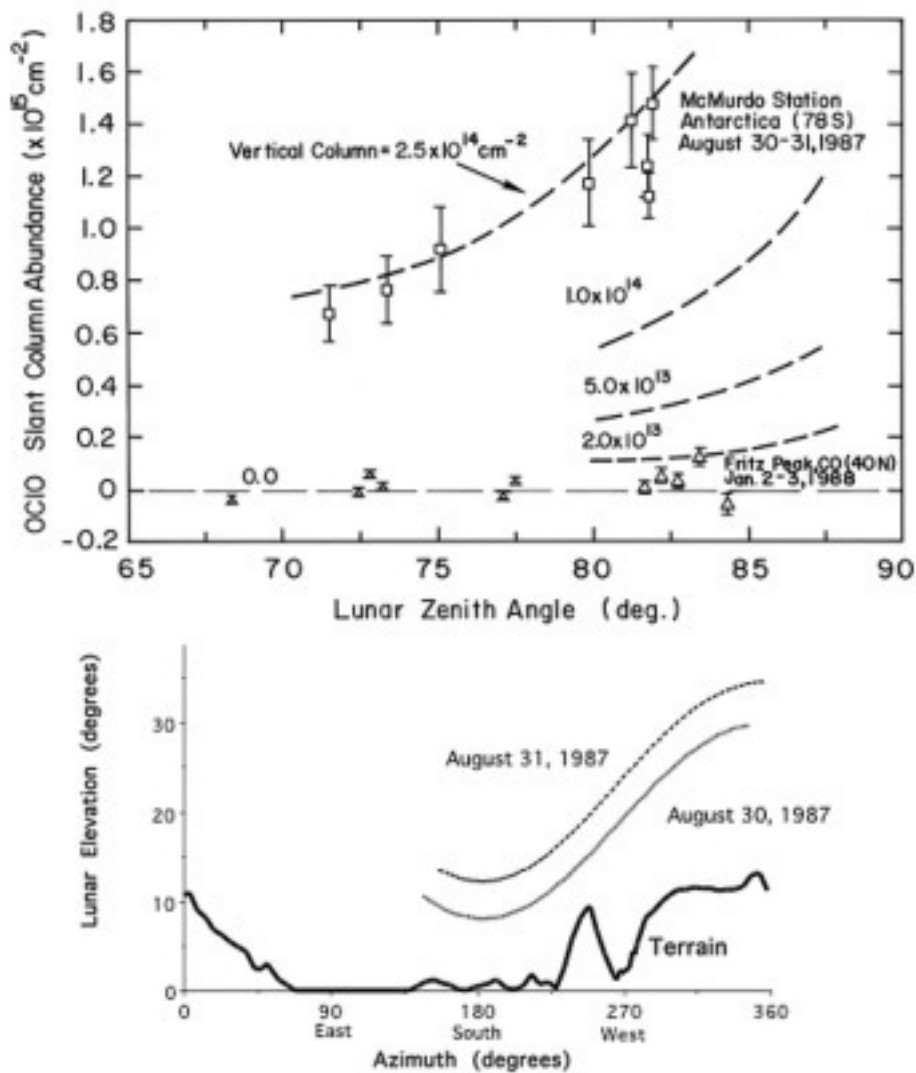
Figure 4. Observations of nighttime OClO (top) using the direct light of the moon as a light source. The position of the moon at our laboratory is shown in the bottom panel. The OClO changes with lunar angle (upper panel), and the observations at McMurdo systematically followed the expected behavior throughout the night. In contrast, OClO levels are below the detection limit of the instrument in Colorado in winter as illustrated.

2.4 First Measurements in the Arctic

Having seen that chlorine dioxide was greatly enhanced in Antarctica, my colleagues and I went north to Thule, Greenland in January 1988 to search for enhanced chlorine chemistry there. Using the moon as the light source, we were able to see the first clear signs that chlorine dioxide was also significantly enhanced in the north compared to gas-phase chemistry (Solomon et al., 1988). The levels of chlorine dioxide that we observed in Greenland that year were not as large as in the Antarctic. That might be generally expected since the Arctic stratosphere in winter is nearly always warmer than the Antarctic. As in Antarctica, Arctic polar ozone loss depends upon the overlap between chemical perturbations due to cold temperatures, associated polar stratospheric clouds, and sunlight. In recent years, substantial Arctic ozone depletion has been observed in some especially cold years, but the depletion is not as large as in the Antarctic. A key factor in the difference is that Arctic temperatures nearly always warm up in spring much earlier than in the Antarctic, limiting the overlap between sunlight and cold temperatures and cutting off the ozone depletion.

3. New Phases in Understanding Surfaces: Liquid Particles and Volcanoes

At the time of discovery of the ozone hole, it was thought that polar stratospheric clouds were composed entirely of solid particles, mainly water ice. But in addition to the solid phase, we now know that the liquid phase is also important to stratospheric chemistry, and the solid and liquid particles of the stratosphere contain additional chemical species besides water. Indeed, polar stratospheric cloud surfaces can even be composed of supercooled liquids. Liquid sulfuric acid and water particles, and nitric acid hydrates and solutions are part of the family of varieties of surfaces that contribute to polar stratospheric clouds. All of these surfaces are now known to drive much of the same surface chemistry, and this has relaxed the threshold for enhanced ozone loss related to surface chemistry from a picture in which temperatures had to be extremely cold (to allow water ice to form) to a far more widespread phenomenon affecting latitudes outside the polar regions. A key factor is the availability of water in and on the surfaces, which affects their reactivity (Hanson et al., 1994; Solomon, 1999). These considerations also appear to have important effects on the interannual variability of polar ozone depletion, as I will now describe.

By the late 1980s, several scientists began to conduct laboratory studies to examine whether some of the surface chemistry that takes place on solid polar stratospheric clouds might also occur on the liquid surfaces that are known to be present throughout much of the lower stratosphere. These are composed mainly of sulfuric acid and water. Further, their abundances can be greatly enhanced after explosive volcanic eruptions, which can deposit large amounts of sulfur dioxide at stratospheric altitudes. The sulfur dioxide oxidizes to form sulfuric acid, which in turn increases stratospheric particle sizes and surface area. My colleagues and I have made several contributions to the understanding of liquid phase chemistry in the stratosphere, particularly regarding the role of volcanic effects.

Laboratory studies by multiple groups have shown that the surface reaction between HCl and $ClONO_2$ that is so important on solid polar stratospheric clouds can also occur on liquid surfaces, albeit with a rate that is a strong function of temperature. Other important sur-

face chemistry can also occur on liquid surfaces (such as the hydrolysis of N_2O_5 and $BrONO_2$) and these also enhance ozone depletion.

With several colleagues, I conducted a number of modeling studies of this new liquid phase chemistry. We first showed that such reactions probably played a significant role in driving mid-latitude ozone loss after the eruption of the Mexican volcano El Chichon in the early 1980s (Hofmann and Solomon, 1989), thereby influencing the early detection of changes in northern hemisphere mid-latitude ozone due to manmade chlorine. While the discovery and explanation of the Antarctic ozone hole was important to policy deliberations, the identification and explanation of ozone loss at mid-latitudes probably helped inspire further action by policymakers to reduce emissions of CFCs. At that time, the future amount of CFCs was projected to continue to increase in the atmosphere, and we postulated that more ozone loss could occur if a large eruption were to occur in the presence of these increased levels of chlorine. The eruption of Mt. Pinatubo in the Philippines in 1991 provided a test. Observations revealed widespread mid-latitude ozone loss after the eruption of Pinatubo in the northern hemisphere. However, there was no obvious southern mid-latitude ozone loss at that time, an observation that stands today as a key challenge to present understanding. Nevertheless, observations of nitrogen dioxide, chlorine monoxide, and other chemicals in both hemispheres do support the view that important ozone-destroying surface reactions indeed occur on liquid surfaces in the mid-latitude stratosphere following major volcanic eruptions.

My colleagues and I argued that volcanic surfaces can also be important in polar regions, because there too they can enhance the amount of surface area available to drive the chemistry, making the polar stratospheric clouds even more abundant and effective (Solomon et al., 1993; Portmann et al., 1996). We suggested that reactions on volcanic surfaces might have played a very important role in the onset of observable Antarctic ozone loss in the early 1980s, after the eruption of the Mexican volcano El Chichon. We also argued for larger depletions following Pinatubo in the early 1990s, and in the Arctic (Solomon et al., 1996; Solomon et al., 1998). Figure 5 shows our calculations of how the combined effects of increasing chlorine and modulation of polar stratospheric clouds by volcanic activity probably affected the Antarctic ozone record, enhancing the depletion after the two major eruptions in the early 1980s and early 1990s compared to what likely would have occurred if no volcanoes had erupted.

Figure 5 suggests that the lives of many scientists, and the evolution of international policy, could have been quite different without the eruption of El Chichon in the early 1980s: it likely would have taken several more years before the effects of chlorine would have been large enough to produce a clearly detectable ozone hole without the enhancements due to the volcanic aerosols. But as we contemplate the ways in which human-produced chlorine is influenced by temperature and by volcanoes, it is helpful to underscore that there was no measurable ozone depletion after earlier eruptions such as that of Mt. Agung in 1966 or Mt. Fuego in 1974. Cold temperatures, solid polar stratospheric clouds, and liquid volcanic particles are all factors that modulate the ozone depletion, but the fundamental cause of the loss is the large increase in ozone-destroying chlorine and bromine caused by human use of chlorofluorocarbons and, to a lesser extent, bromocarbons.
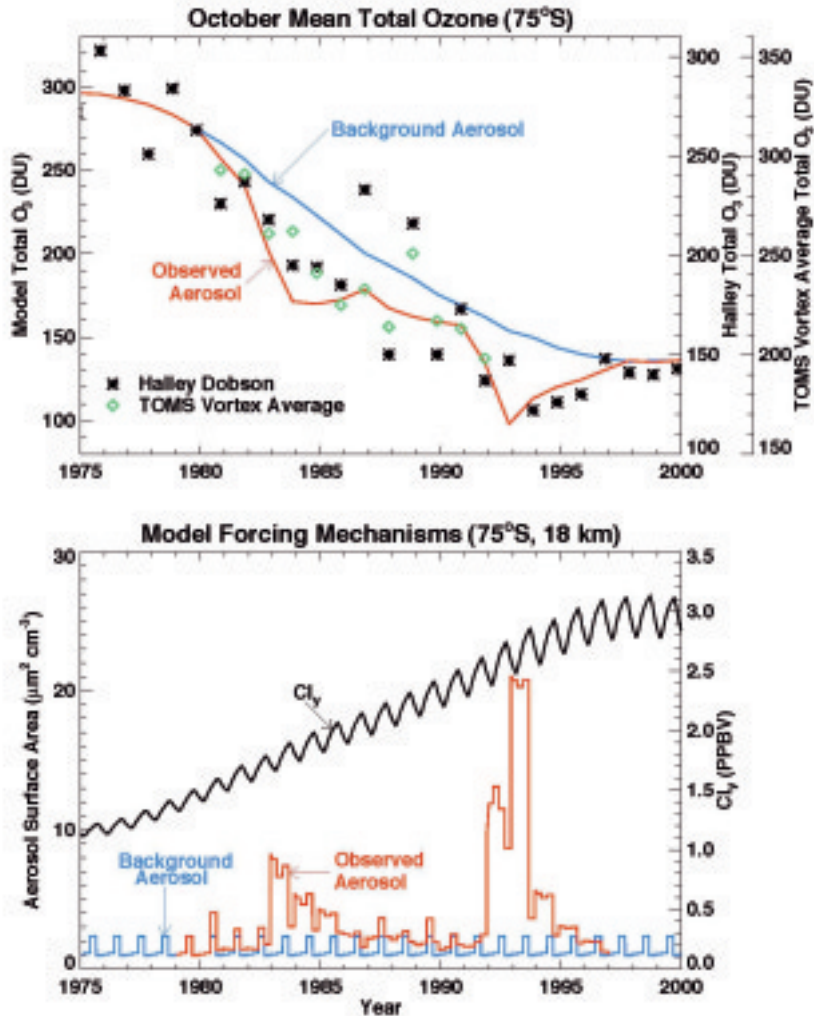
Figure 5. The top panel shows the evolution of the October monthly mean ozone at 75S. Total ozone measurements from Halley and from satellite data averages over the vortex are compared to model results run with and without considering observed aerosol surface area variations, updated from Portmann et al. (l996). The bottom panel shows the factors which produced the model results: increasing active chlorine (Cly) due to CFC emissions and aerosol surface areas determined from satellite data. The eruptions of the volcanoes El Chichon in the early 1980s and Pinatubo in the early 1990s are reflected in large enhancements in polar stratospheric cloud surface areas as shown.

Thus it has been my privilege to be involved in multiple phases of understanding of ozone loss chemistry in modeling and in observations. The picture has evolved from the gas-phase alone to solids and liquids. Further, the understanding of liquid phase chemistry has led to an evolution of thinking from extreme cold to less extreme, expanding both the processes that must be considered and where they can occur in altitude and latitude. Today our ozone layer is greatly depleted in the Antarctic, with some modulation from year to year depending upon meteorological conditions and volcanic activity. Arctic ozone is also depleted, by as much as about 25% in cold years, and the ups and downs of meteorological variability are extremely important in modulating the ozone loss from one year to another. Southern mid-latitudes display more depletion than the north, and there are questions about the roles of inter-annual and interdecadal changes in meteorology for mid-latitude ozone changes, but there is significant depletion of about 5-8% at mid-latitudes of both hemispheres. Thus, much of the world's population now lives under a reduced ozone shield and a greater level of ultraviolet exposure than we did a generation ago. An important scientific question regarding mid-latitude ozone loss is the dilution of ozone-depleted air from higher latitudes, and the extent to which surface chemistry occurring on cold air outside the polar regions may spread to lower latitudes, enhancing the ozone loss.

4. Reflections on Ozone Depletion, Climate Change, and the Role of Science in Environmental Decision-Making

Policymakers met repeatedly to discuss evolving findings on ozone depletion during the late 1980s and 1990s, and progressively developed global agreements to reduce and eventually to phase out the emissions of the responsible gases. Today the global annual emissions of CFCs have dropped by more than 90% compared to their peak values, demonstrating the effectiveness of those policies. But the concentrations of the CFCs are dropping only very slowly, because the cleansing of the atmosphere is limited by the lifetimes. For example, CFC-113 was used primarily as a solvent, and other chemicals and processes have now taken its place in those applications nearly worldwide, so that its global emissions are now close to zero. But with an atmospheric lifetime of about 80 years, even the complete cessation of emissions can only result in a slow decay at about 1% per year for this gas. Thus, the solvents used for example during the boom in electronics in cleaning component chips in the 1980s, leading to the modern lifestyle we enjoy today, will remain in our atmosphere and continue to deplete ozone for many decades.

I would now like to briefly sketch some ideas about scientific parallels and differences between ozone depletion and climate change, and I emphasize that these thoughts are purely personal reflections.

Ozone depletion and climate change are different phenomena. Although the loss of ozone does have an influence on surface climate, perhaps even a very significant influence in the Antarctic (see, e.g., Thompson and Solomon, 2002), it is not the primary cause of global climate change. In fact, it leads to a cooling rather than a warming. Rather, global warming is primarily driven by increases in carbon dioxide. But carbon dioxide is a gas with an average atmospheric lifetime of more than a century, just like some of the chlorofluorocarbons (see

Table 1). Thus both of these environmental issues involve substances that last longer than a human lifetime, so both issues are a legacy that people are giving to their children and grand-children. They challenge us to think beyond ourselves, to a longer-term view of the role of each generation, its footprint on the lives of the next, and even its footprint on civilization.

For both ozone depletion and climate change, well understood physical or physical/chemical processes can be identified that imply that these gases surely do influence the atmosphere – in the case of the CFCs, by increasing chlorine and depleting ozone; in the case of carbon dioxide by altering the planetary energy budget, increasing the retention of radiant energy by the planet and hence leading to a warmer world.

For both ozone depletion and climate change, observations of the gases causing the changes come from sites around the world, and in ice cores, and these clearly reveal the role of man in driving today's concentrations upward – in the case of carbon dioxide, to levels higher than they have been in at least a half a million years.

In the case of ozone depletion, human-made chlorine undergoes chemistry, particularly surface chemistry, that leads directly to large ozone losses.   The processes involved are not greatly dependent on how the atmosphere evolves (possible feedbacks) as depletion occurs. But in the case of climate change, the scientific problem is challenging because the feedbacks are known to be large, and may include stabilizing as well as destabilizing mechanisms. Climate change increases surface temperatures and water vapor. The enhanced water vapor can further enhance global warming, but just how much enhancement occurs depends sensitively on the amount and the vertical profile of the change. Further, climate change may lead to changes in cloudiness that reflect more radiation out to space (causing a stabilizing cooling effect), or absorb more radiation (enhancing the warming).   So the role of numerous large feedbacks is critical for climate, making it a different scientific challenge than the large direct impact of ozone depletion.

The strongly seasonal nature of the ozone depletion and its chemistry in Antarctica has greatly facilitated its detection and attribution to CFCs. Because the Antarctic ozone hole opens up every year, and is accompanied by dramatic changes in many chemicals that we can observe using multiple techniques (such as chlorine dioxide and nitrogen dioxide as discussed in this paper), the relationship between chlorine chemistry and the ozone depletion can be demonstrated in just a single season of observations – as it was in the 1980s.   If we had not done those measurements at that time, we could go to Antarctica now and in just one season could show why the ozone there drops so quickly and dramatically. Global warming is a slow and pervasive phenomenon, requiring careful measurements over many decades. It requires consummate attention to long-term measurements rather than a short campaign. And it is much harder to measure all of the factors that are important (such as clouds, sea surface temperatures, water vapor, particulates, etc.) Thus the jigsaw puzzle of related observational evidence is far more difficult to assemble.

There is strong evidence that the global average temperature of the Earth increased during the 20th century, by about 0.6°C. Further, most of the globally averaged warming of the past 50 years is attributable to human activities.   Some regions have been subject to larger trends, while others have experienced smaller changes or even localized cooling.   Regional

variability in climate is a well-known phenomenon, and there is ample evidence for regional-scale fluctuations in the past. How are the observed regional changes linked to the global mean change, and how much confidence can we place in projections for the future at both global and smaller scales? This is a key scientific challenge, but I would suggest that it shows why global warming is an even bigger societal challenge. That is because it represents yet another way in which global warming challenges us to think beyond ourselves: to consider not just what is occurring or may occur in our own backyards, but also those of our neighbors, as well as those of people very far away, across huge gulfs of mountains, oceans, economies, and cultures.

Like ozone depletion, some key problems for climate change may relate to ice. Formation and melting of ice relating to global warming is a phenomenon that merits careful attention, because small changes in temperature can have important effects on phases of matter: solid versus liquid. While Antarctic sea ice trends have not yet been conclusively demonstrated, Arctic sea ice has declined in the past few decades, and dramatic changes have been noted in some recent years. Snowpack and glaciers are also changing in many areas, with the potential for large effects on water resources. Finally, the melting of the ice on the Greenland or the West Antarctic ice sheets is a critical question for future climate change. The great ice sheets have not always held as much water as they do today, and the consequences of that for global sea level in the geologic past thousands of years ago were very large. Many scientists are asking whether the Greenland ice sheet could melt due to global warming, with a related rise in sea level of perhaps 3-6 meters. An interesting scientific question is whether it is the Arctic or Antarctic polar ice sheet that is more likely to change in a warmer world. The possibility of changes in processes relating to ice at the two poles is a key vulnerability in the climate system – perhaps ironically, the same issue that has been a cornerstone of the ozone problem and of my own scientific career.

But the possibility of stabilizing influences on ice and snow must also be carefully evaluated: could increased snowfall in a warmer wetter world with altered storm tracks compensate for rising Greenland temperatures, leaving the ice unchanged? Perhaps we will be lucky and the competing influence of more melt will be exactly balanced, or even overbalanced in some places, by more snow. That implies that a critical issue in climate change is evaluation of the risk.

Science is an important input to societal choices about risk, but decisions about risk are seldom made through science alone. They involve considerations ranging from science, to cultural values, to economics, to diplomacy and beyond. For both science and policy a key question is how to use science objectively, so that future history books will document that humankind dealt with climate change as wisely as I believe that it did with ozone depletion. As I have emphasized in this lecture, that will challenge us to think very deeply, and very far beyond ourselves: across generations and around this beautiful blue planet that is home to all of us.

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Major Publications

Dr. Susan Solomon

Books:

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Journal Publications:

Dr. Susan Solomon was named the third most highly cited geoscientist in the world during the decade of the 1990s by Science Watch in December, 2001. Her publication record is as follows:

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