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State of Japanese Research on the Ozone Layer

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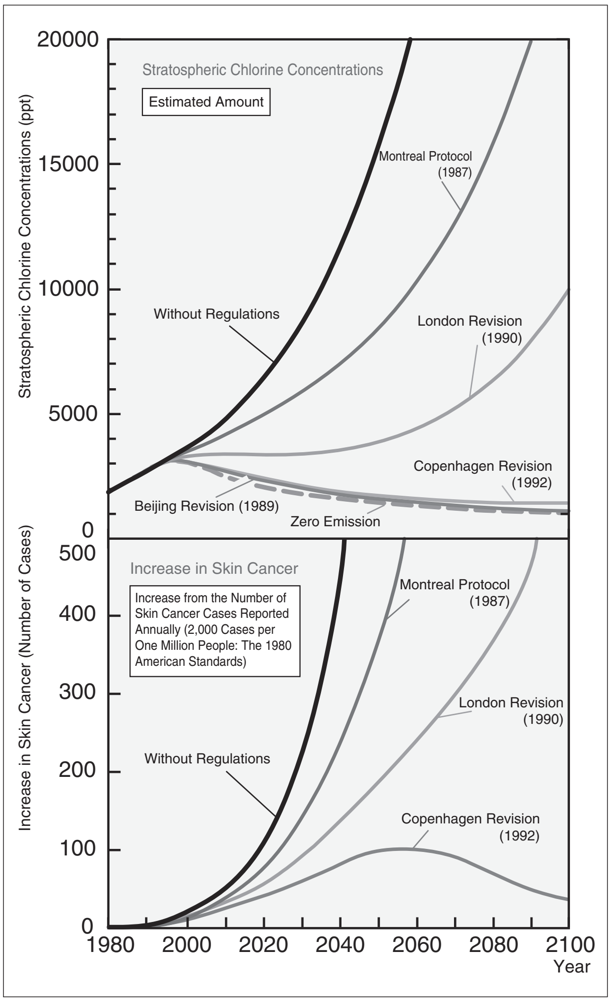
1 Introduction

Chlorofluorocarbons (hereinafter referred to as “CFCs”), which were invented as chemical compounds with great potential, later turned out to be involved in ozone depletion. A series of measures to protect the ozone layer have thus been put in place through an international cooperative framework, namely the Montreal Protocol and its amendments and adjustments. As a result, stratospheric chlorine concentrations are expected to decrease dramatically in the 21st century compared to the predicted levels without regulation of CFCs (see the upper part of Figure 1). The ozone layer problem, therefore, is considered the first instance where a global environmental problem has been successfully solved. In other words, this particular problem is now treated as if it were a thing of the past. However, quite a few problems remain, one of which concerns the need to carefully observe and monitor the effects of climate change and chemical substances other than CFCs.

In fact, a closer look at the predicted increase in the incidence of skin cancer reveals a very different situation. The lower part of Figure 1 shows an increase in the number of patients with skin cancer, which can be attributed to ozone depletion. Particularly notable is its incidence, which is expected to peak around 2060. This estimate is based on the assumption that the number of patients with skin cancer will increase if the effects of ultraviolet radiation accumulate over a lifetime. Only the rate of increase is peaking now. In short, we cannot be assured that the threat of ozone depletion is behind us, even if the depletion has peaked. With these factors in mind, this article features the state of the ozone layer, exploring the direction in which recent research efforts on this subject are heading.

Figure 1 : Past-Present-Future Scenario of Stratospheric Chlorine Concentrations (Upper Figure) and Future Scenario of Increase in Skin Cancer due to Ozone Depletion (Lower Figure)[1]



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2 Factors affecting ozone changes in the stratosphere

CFCs are not the only substances that deplete the ozone layer. Other culprits include organic chlorine and bromine compounds and methyl bromide, which release chlorine and bromine into the stratosphere; nitrogen oxides such as NO and NO_2 (NOx) produced by oxidization of N_2O (a greenhouse gas); and hydrogen oxide such as OH and HO_2 (HOx) which are produced from methane and water vapor in the stratosphere. While methane itself moderates ozone depletion, stratospheric water vapor (partly produced by methane oxidization) increases polar stratospheric clouds, one of the causes of the ozone hole. NO_2, meanwhile, mitigates the polar ozone depletion in the Arctic and Antarctic in winter and spring.

Ozone depletion is not caused only by chemical changes. For instance, an increase in greenhouse gases results in a rise in ground-level air temperatures, while it lowers the temperature in the stratosphere and above; this may contribute to strengthening of the ozone hole in the Antarctic stratosphere and ozone depletion in the Arctic region, and at the same time weaken ozone depletion in the upper stratosphere (at an altitude of about 40km). Changes in large-scale wave activity (planetary waves) in the troposphere cause unusual weather patterns in the troposphere and the stratosphere, and have a significant impact on ozone transfer in the stratosphere (from the tropics to the high latitudes) as well as on the size of the ozone hole. In other words, tropospheric and stratospheric changes due to unusual weather patterns affect the ozone layer, changes in which then affect weather patterns. An increase in sulfate aerosols in the stratosphere due to volcanic eruption also depletes the ozone layer. The factors affecting ozone changes mentioned above are summarized in Table 1 (present trends in the factors are shown in the table).

2-1 Two ozone depletion mechanisms

Two major mechanisms are involved in ozone depletion due to chemical reactions. One is a mechanism where chemical compounds (CFCs, halons, etc.) that release chlorine and bromine into the stratosphere deplete ozone through gas-phase reactions, a phenomenon that was predicted in 1974 in the theory presented by Molina and Rowland. The other is depletion involving heterogeneous reactions in which surface reactions in clouds and aerosols play a major role, such as the depletion occurring in the Antarctic ozone hole. The former is important in the upper stratosphere (at an altitude of about 40 km), and the latter in the lower stratosphere (at an altitude of 15-20 km), with the latter posing a

Table 1 : Factors Affecting the Ozone Layer and Resulting Changes in Ozone Amount

Factors affecting the ozone layer	Upper stratosphere (altitude of about 40km)	Middle stratosphere (altitude of about 30km)	Lower stratosphere (altitude of below 20km)
Substance			
CFCs, Halons, etc.	—	—	—
NOx (produced from N_2O)	—	—	+
HOx	—	—	—
Methane	+	+	+
Water Vapor			—
Climate change			
Drop in stratospheric temperatures	+		— (Polar in spring)
Rise (fall) of the tropopause			— (+)
Decrease (increase) in the intensity of large-scale wave activity in the troposphere			— (+)
Increase in stratospheric aerosols due to volcanic eruption		+	—

+ : Factors increasing stratospheric ozone —: Factors decreasing stratospheric ozone greater threat to the ozone layer. Details of these two mechanisms are explained in the following sections.

(1) Mechanism of ozone depletion in the upper stratosphere due to gas-phase reactions

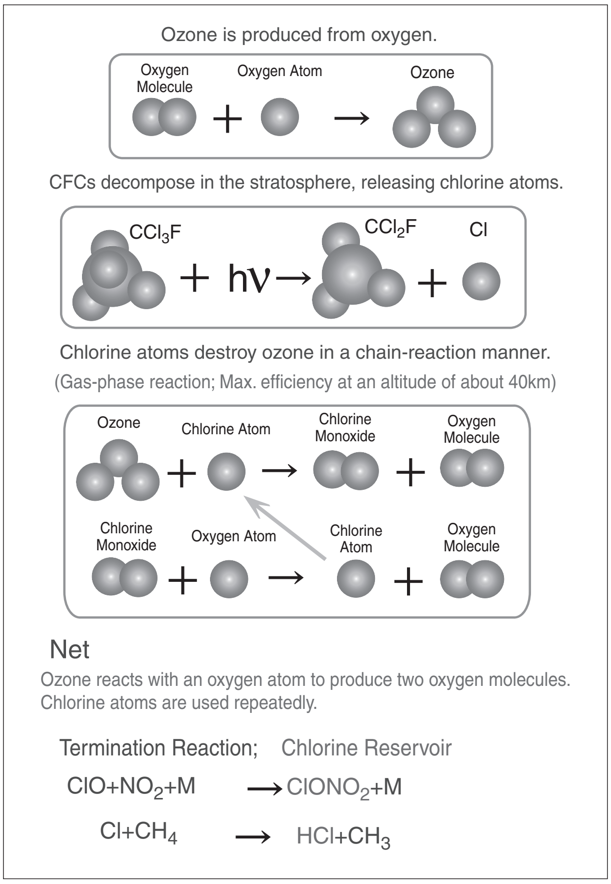
The short-wavelength ultraviolet radiation in the stratosphere decomposes substances such as CFCs, resulting in the release of chlorine atoms, which react with ozone to produce chlorine monoxide (ClO). Chlorine monoxide subsequently reacts with an oxygen atom to produce an oxygen molecule and a chlorine atom, which in turn reacts with ozone. This catalytic cycle, which converts an ozone molecule and an oxygen atom into two oxygen molecules, consists of relatively simple gas-phase reactions involving only gaseous molecules, radicals and atoms. Ozone depletion through this mechanism is efficient in the upper stratosphere (at an altitude of about 40 km), where concentration of oxygen atoms is high. This catalytic cycle, however, is not permanent; chlorine and chlorine monoxide, through reactions with methane and nitrogen dioxide, are incorporated into "chlorine reservoirs" such as HCl and $ClONO_2$, thereby losing their activity. Most of the chlorine atoms in the upper stratosphere take the form of HCl. In this case, chlorine depletes the ozone, while methane and nitrogen dioxide mitigate the depletion.

A similar catalytic reaction cycle is possible with Cl replaced by NO. It was this catalytic reaction cycle involving NO that frustrated a project for a supersonic jet traveling through the stratosphere; it occurs most significantly in the middle stratosphere (at an altitude of about 30 km), with NO_2 depleting the ozone layer.

(2) Mechanism of ozone depletion in the lower stratosphere involving heterogeneous reactions; cause of the Antarctic ozone hole

The second mechanism of ozone depletion is that involving "heterogeneous reactions" that occur on the surface of liquid and solid particles (clouds and aerosols), a typical phenomenon observed in the ozone hole.

Figure 2 : Mechanisms of Ozone Formation and the Gas-phase Catalytic Reaction Cycle through Chlorine Atoms Released from CFCs



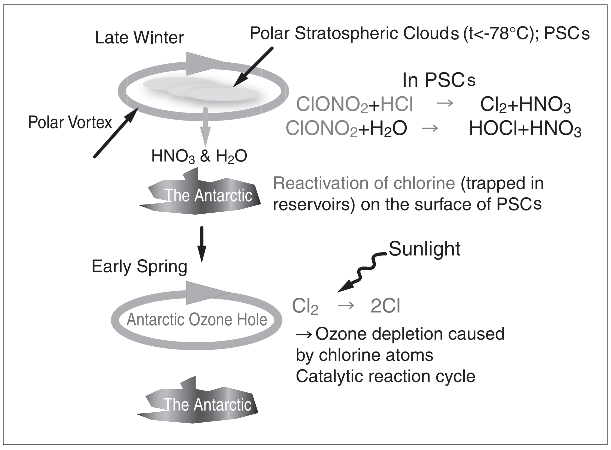
This cycle terminates, with chlorine atoms and chlorine monoxide converted into reservoirs.

While heterogeneous reactions are known as the mechanism responsible not only for the ozone hole but also for ozone depletion caused by stratospheric aerosols (originating from volcanic eruption) and cirrus clouds, this article focuses on the mechanism of the ozone hole. In winter and spring, a strong west wind blows in the Arctic and Antarctic stratospheres; this is the circumpolar stratospheric jet steam called a "polar vortex." In the Antarctic region in particular, this polar vortex covers an area more than twice the size of the Antarctic Continent. (Refer to the website of the National Institute for Environmental Studies for a daily polar-vortex forecast[2].) Since the air inside and outside the vortex does not mix well, the temperature inside the vortex tends to drop; "polar stratospheric clouds" (PSCs) build up if the temperate drops below minus 78 degrees Celsius (195 degrees Kelvin). Under these conditions, chlorine reservoirs (HCl, $ClONO_2$, etc.) that prevent ozone-depleting catalytic reaction cycles are converted into active chlorine species such as chlorine molecules on the surface of PSCs. These chlorine molecules, if exposed to sunlight in spring, decompose into chlorine atoms, which continue destroying ozone through catalytic reaction cycles until ozone levels drop to nearly zero.

Ozone depletion through this mechanism is most efficient in the ozone-rich lower stratosphere. Thus, under the current situation where stratospheric chlorine levels are peaking, the ozone hole grows if stratospheric temperatures drop, creating areas with temperatures below minus 78 degrees Celsius (195 degrees Kelvin), conditions suitable for the formation of PSCs. An increase in stratospheric water vapor at a given temperature creates ideal conditions for the development of PSCs. It also contributes to the expansion of the ozone hole because it lowers stratospheric temperatures.

In the Arctic region, the area in which PSCs develops, there are dramatic changes from year to year. The Arctic polar vortex is relatively weak and tends to meander, which is why temperatures are higher in the Arctic than in the Antarctic. It sometimes splits, with the air inside spreading throughout the mid-latitudes. The Arctic polar vortex does not remain over the Arctic Ocean; it spreads as far as Northern Europe and Siberia, sometimes extending its reach into London and Paris. In fact, a split vortex is occasionally observed in the sky above Hokkaido in Japan. The Arctic vortex, therefore, interacts closely with the mid-latitudes, which raises the temperature of the air inside the vortex. In the meantime, global-scale planetary waves that develop in the troposphere and spread out to the stratosphere force the vortex to meander. Large-scale mountains such as the Alps, the Himalayas and the Rockies, and the non-symmetric distribution of continents and seas together produce large-scale waves in the troposphere, which propagate into the stratosphere to produce planetary waves. For this reason, planetary waves in the northern hemisphere are much stronger than those in the southern hemisphere. Ozone depletion is less serious in the Arctic than in the Antarctic because the Arctic stratosphere is not as cold as the Antarctic stratosphere.

Figure 3 : Mechanism of Ozone Depletion in the Ozone Hole



Although planetary waves also affect the Antarctic ozone hole, their impact is much less significant in the southern hemisphere; this is why the ozone hole continues to grow every year in the Antarctic. In 2002, however, the Antarctic polar vortex was seriously distorted because of extremely strong planetary waves. Coupled with higher Antarctic stratospheric temperatures, the ozone hole was much smaller and disappeared earlier. “An extreme weather event in the stratosphere” was the cause of this phenomenon; it is by no means a “sign of ozone layer recovery.” In fact, the year 2003 saw the second largest ozone hole area ever observed.

2-2 Climate change and stratospheric ozone

The relationship between “climate change” and “stratospheric ozone” can be summarized as follows:

- A decrease in the stratospheric ozone affects the climate (Cooling in the troposphere).
- Climate change affects the ozone layer (A variety of effects are possible, including extreme weather events in the stratosphere).

Although there is a feedback effect between these two phenomena, they can be better understood if separated. Carbon dioxide, methane and N_2O, major culprits of climate change, are expected to increase for the time being, warming the troposphere and cooling the stratosphere. Stratospheric temperature decreases because the earth radiates more infrared radiation toward space in response to an increase in greenhouse gases. CFCs are both ozone-depleting substances and greenhouse gases that are on the decrease, while CFC substitutes (HFC and PFC) and SF_6 are greenhouse gases with no ozone-depleting properties. Controlling their emission, however, largely depends on countermeasures taken in the future. How climate change affects the ozone layer remains uncertain, but several effects on the stratospheric ozone are expected through changes in ozone distribution due to variations in transport in the stratosphere, changes in the amount of water vapor drifting up to the stratosphere, and unusual weather patterns in the stratosphere. The following are details of these phenomena.

(1) The impact of CFCs and ozone layer changes on the climate

Stratospheric ozone depletion due to CFCs and the resulting decrease in ozone levels in the lower stratosphere reduce atmospheric temperature since less infrared and ultraviolet radiation is absorbed by ozone. At the same time, the downward infrared radiation at the tropopause decreases, which in turn cools the troposphere. This effect, however, is less powerful than global warming caused by CFCs, and hence the release of CFCs results in net global warming. On the other hand, a decrease in CFCs leads to the recovery of the ozone layer, thereby raising tropospheric temperature, but this effect is smaller than that reducing global warming caused by the decrease of CFCs. Note that global warming due to an increase in CFC substitutes (particularly HFC and PFC) should be considered here. The net global warming over the next several decades, therefore, depends on how well CFCs are replaced by substances with lower global warming potentials.

(2) The impact of climate change on the ozone layer

The impact of climate change extends throughout the global climate system, affecting the ozone layer in a variety of ways. Among others, the following are considered essential:

- Tropospheric warming and stratospheric cooling due to an increase in greenhouse gases: lower stratospheric temperatures may result in a long-lasting Antarctic ozone hole and the development of an Arctic ozone hole (At the same time, ozone levels will increase in the upper stratosphere).
- Extreme weather events in the stratosphere may develop in both frequency and intensity due to changes in global-scale wave activity, particularly planetary waves, a result of climate change, which could affect the stratospheric ozone layer. Moreover, changes in transport in the stratosphere may alter ozone distribution.
- The inflow and outflow to and from the stratosphere of substances that could affect the chemical and radiative environment of the stratosphere may change. Specifically, they include water vapor and its precursors (formed by the union of methane and hydrogen, etc.), N_2O, chlorine and bromine compounds, and the precursors of stratospheric aerosols (sulfur dioxide, OCS, etc.).
- The amount of stratospheric ozone flowing into the troposphere may change (It is expected to increase, according to the results of some model calculations).

(3) Trends in international research on the relationship between the ozone layer and global climate change

The ozone layer, a heat source for the stratosphere, determines the vertical temperature distribution of the stratosphere and mesosphere. Therefore, it controls not only the chemical environment but also the climate/weather of the stratosphere. Thus, changes in the ozone alter climate/weather in the stratosphere, which also affects climate/weather in the troposphere because the stratosphere is part of the atmospheric climate system. The World Climate Research Program (WCRP) includes a project called the “Stratospheric Processes and their Role in Climate” (SPARC), which is an international cooperative project for studying the interactions between stratospheric changes (ozone depletion, increase in water vapor, drop in temperature, etc.) and climate change.

It is becoming clear that the tropopause (the bottom of the stratosphere) is not a simple boundary, which has created a research area named "upper troposphere and the lower stratosphere" (UTLS) that studies the unique chemical and dynamic-meteorological phenomena near the tropopause. This particular research area is considered an important part of SPARC since it addresses water vapor variability in the tropical tropopause region, ozone depletion involving cirrus clouds, global warming and ozone depletion caused by aircraft emissions, and inflow and outflow of ozone to and from the troposphere.

3 Observed changes and trends in the ozone layer

3-1 Global ozone amount

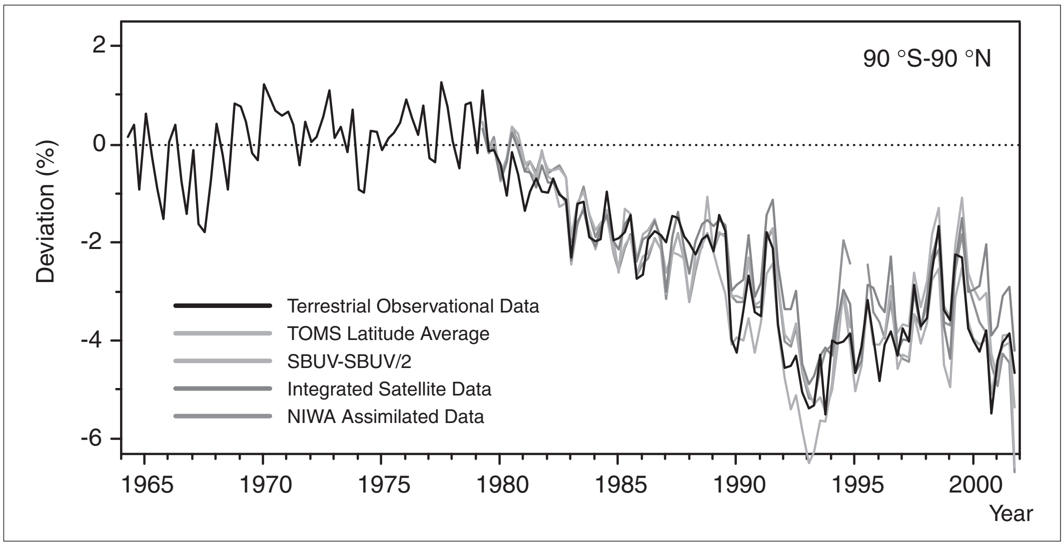
Figure 4 shows changes in the amount of global ozone over the past four decades. It should be noted here that the unit of "amount of global ozone" refers to the thickness of the ozone (at ground level up to the upper atmosphere) compressed at a pressure of one atmosphere and zero degrees Celsius. The ozone layer is, so to speak, a "3-mm-thick space suit," so called because its global average thickness is about 3 mm. With the measurement accuracy of the total ozone being three digits, the thickness of the ozone layer is expressed in centimeters and is then multiplied by 1,000, a unit called the "Dobson Unit (DU)" or "milli-atmosphere centimeter (m atm-cm)." Incidentally, the global average of the total ozone currently stands at 300 DU (m atm-cm). As shown in Figure 4, the total ozone continued to decrease in 1980 and in 1990, and the years 1992 and 1993 saw a record low, down 5% from pre-1980 levels, probably due to Mt. Pinatubo, which erupted in June 1991. It began to increase thereafter, and the upturn continued into 1999. However, the average amount in 1997 and in 2001 was down 3% from the pre-1980 levels.

Table 2 shows changes in ozone levels by region and season. The total ozone (between 1997 and 2001), when compared with pre-1980 levels (the average between 1964 and 1980), was down 3% and 6%, respectively, in the northern and southern mid latitudes. A significant decrease was observed in the northern hemisphere in winter and spring, while the southern hemisphere saw a decrease of the same magnitude throughout the year.

3-2 Detection of "early signs of recovery" in the upper stratospheric ozone

As shown in Figure 1, stratospheric ozone concentrations peaked around 1997 and decreased gradually thereafter. With this phenomenon verified, a new research area is emerging: efforts to detect "signs of recovery" in the ozone layer based on observational data.

Figure 4 : Long-term Changes in Total Ozone



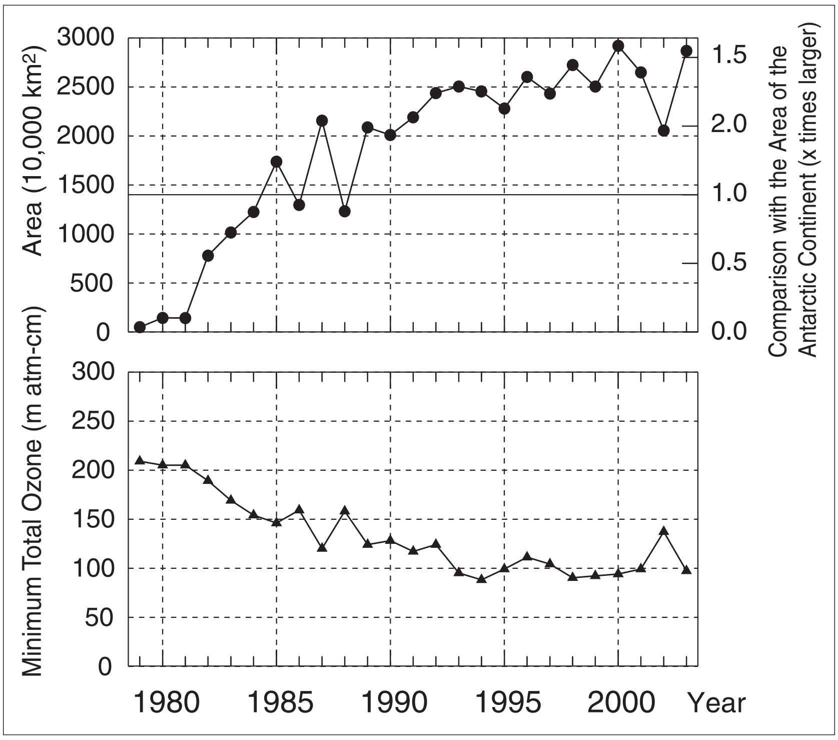
"Changes" removes known natural fluctuations in the total ozone such as seasonal variation, solar activity and quasi-biennial oscillation (QBO). Data obtained through five measurement/analytical methods are shown in the chart[1].

Table 2 : Decrease in Total Ozone (Pre-1980 Levels*1 versus Average between 1997 and 2001)[1,3]

	Full-year Basis	Winter to Spring	Summer to Fall
Global Average	3%		
Tropical Region (25°N - 25°S)	No Significant Decrease Observed	No Significant Decrease Observed	No Significant Decrease Observed
Northern Mid Latitudes (35°N - 60°N)	3%	4%	2%
Southern Mid Latitudes (35°S - 60°S)	6%	6%	6%

*1 Average of total ozone between 1964 and 1980 (winter to spring, and summer to fall).
*2 "Changes" removes known natural fluctuations in the total ozone such as seasonal variation, solar activity and quasi-biennial oscillation (QBO).

Figure 5 : Changes in Ozone Hole Area (Top) and Minimum Total Ozone in Ozone Hole (Bottom) between 1979 and 2003[4]



The upper stratosphere, where no heterogeneous reactions occur, is the region in which these signs can be detected most easily. Researchers at NASA, therefore, focused attention on the upper stratosphere and analyzed data on ozone and hydrogen chloride (HCl) concentrations, using satellite sensors. The results they announced were that HCl concentrations increased linearly before 1997, resulting in a linear decrease in ozone concentrations, while the pace of the increase began to slow after 1997. The "first step towards the recovery of the ozone layer" has been detected, according to the researchers[5].

3-3 Trends in the Antarctic ozone hole

Figure 5 shows changes in the Antarctic ozone hole area (the area with a total ozone level of less than 220 DU), the minimum total ozone (the lowest of the "minimum daily total ozone" in a year, i.e., the "minimum total ozone" in each year). In 2002, stratospheric temperatures were high, the ozone hole was small, and the minimum total ozone was high. This phenomenon can be attributed to unusually strong planetary waves that distorted the polar vortex; air flowed into the vortex and raised its temperature, which mitigated ozone depletion. In 2003, by contrast, the ozone hole grew to match the size observed in 2000, and the minimum total ozone remained low. The minimum total ozone has been relatively stable since around 1993, while the ozone hole area has been increasing since 1995. With the size of the hole almost matching that of the vortex core, however, there is little room left for the hole to grow further.

3-4 "Ozone hole-type" ozone depletion in the Arctic

Ozone depletion of the same magnitude as in the Antarctic ozone hole takes place in the Arctic polar vortex during winter and spring. In 2000, for instance, more than 70% of the total ozone was lost at an altitude of about 18 km. Figure 6 shows changes in the average total ozone between 1979 and 2003 (in March and April, in the area from 60 to 90 degrees north latitude); it decreased dramatically in the 1990s and picked up slightly thereafter. The significant fluctuation, however, makes it difficult to discern long-term trends.

3-5 Changes in solar UV radiation at ground level

Solar UV radiation at ground level changes dramatically depending on the amount of total ozone, clouds, etc. It has been only a decade or so since high-accuracy observations of solar UV radiation started in Japan (around 1990). Moreover, the eruption of Mt. Pinatubo, which resulted in a considerable decrease in ozone levels around 1993, makes it difficult to discern long-term trends in solar UV radiation. In the southern hemisphere, on which the impact of the eruption was much smaller, the total ozone continued to decrease throughout the 1990s. Figure 7 shows changes in the total amount of

Figure 6 : Changes in Total Ozone in Northern High Latitudes (from 60 to 90 Degrees North Latitude)in March and April[4]

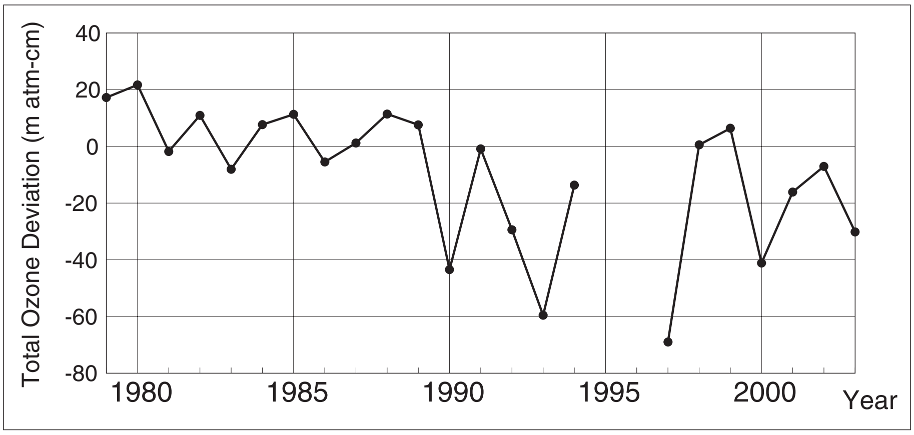
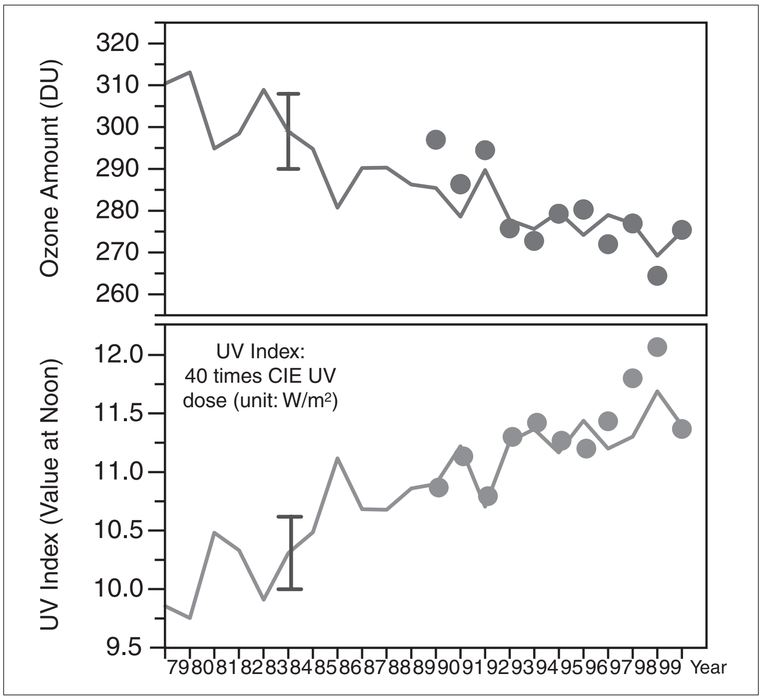


Figure 7 : Amount of Ozone (Top) and UV Radiation (Bottom) in Lauder, New Zealand, in Summer[1]



ozone and UV radiation (at ground level) in New Zealand; there is a clear anti-relationship between the decrease in the total ozone and the increase in UV radiation, which has reached a potentially dangerous level.

4 Prospects for the ozone layer

The "Scientific Assessment of Ozone Depletion: 2002[1]" includes a prediction of Antarctic ozone holes and the Arctic ozone depletion in spring, based on the current scenario of protecting the ozone layer through regulatory measures and other scenarios of greenhouse gases (carbon dioxide, methane, etc.), using three-dimensional models called "chemical climate models," which take climate change effects into account. According to this prediction, the Antarctic ozone layer will begin to recover around 2010 (not in 2000 as generally thought), but roughly in accordance with the scenario in Figure 1, while in the Arctic climate change will not produce "an ozone hole." It should be noted, however, that the current chemical climate models for the stratosphere have yet to be improved because they do not give full consideration to "other factors[6]."

Global-scale forecasts for the ozone layer, calculated by two-dimensional models (latitude and altitude), are also available, the results of which show that the ozone layer will recover almost in accordance with the scenario[1]. As in the case of the three-dimensional models, there is room for improvement in these two-dimensional models, as most of them do not fully take into account important factors such as an increase in water vapor, a decrease in stratospheric temperature, and dynamic/chemical processes in the polar regions.

5 Outstanding issues and challenges

The "ozone layer" is a fairly mature research area that is increasingly becoming an exact science. In fact, models used for data analysis well reproduce observational data. However, several issues and challenges remain, some of which are described below.

(1) It is necessary to continue observing and monitoring whether the ozone layer is recovering and whether UV radiation at ground level is decreasing according to the scenarios. If there are deviations from the scenarios, our understanding should be corrected.

(2) The impact of ozone depletion caused by "other factors" (excluding CFCs) should be elucidated. "Other factors" include an increase in stratospheric water vapor, a decrease in stratospheric temperature, an increase in N_2O, changes in atmospheric circulation, and wave activity due to climate change.

(3) The interaction betwesen the stratosphere and the troposphere should be predicted, and the impact of stratospheric changes on the chemistry of the troposphere should be elucidated.

(4) It is necessary to find out how much of the impact of UV radiation accumulates in the body, how much the damaged tissue can be repaired, and whether the incidence of skin cancer will continue to increase until 2060 as predicted.

6 Japanese and Western approaches to ozone layer research

Ozone layer research began to gain momentum in the 1920s, with Dobson inventing a spectrophotometer (Dobson Spectrophotometer) to measure the latitudinal distribution of the total ozone. Observation and research activities have since made great progress in shedding light on the mechanisms of the ozone layer. Specific achievements include improvements in observation through the "Dobson Spectrophotometer" and "Ozonesonde," taking the opportunity provided by the International Geophysical Year (1957-1958); the launching of TOMS (Total Ozone Monitoring Spectrometer) in 1979 by the U.S.; the discovery of the Antarctic ozone hole (1984-1986) and intensive observations to elucidate its mechanisms; and intensive observations to elucidate the mechanisms of "ozone hole-type" ozone depletion in the Arctic. Further improvements have been made through the launching of UARS (Upper Atmospheric Research Satellite) in 1991 by the U.S., the establishment of the Network for the Detection of Stratospheric Change (NDSC) in 1991, and the launching of ADEOS (Advanced Earth Observing Satellite) in 1996 by Japan. In the next five years or so, Envisat (a European Earth observation spacecraft launched in 2002) and EOS AURA (a U.S. Earth observation satellite launched in 2004) will most likely be the primary data suppliers.

Ozone layer research was originally designed to figure out latitudinal ozone distribution, understand the behavior of ozone as a tracer of atmospheric circulation, and investigate stratospheric transport models. In short, the research was in the discipline of meteorology. However, a series of breakthrough discoveries, ozone depletion (caused by CFCs) in 1974 by Molina and Rowland, the Antarctic ozone hole between 1984 and 1986, and decreasing ozone levels in the northern mid-latitudes in 1988, paved the way for modern ozone layer research as part of the approach to global environmental issues. Particularly shocking was the discovery of the Antarctic ozone hole.

6-1 Western approaches to the Antarctic ozone hole and research on the ozone layer

The U.S. took immediate action to investigate the Antarctic ozone hole, with NASA playing a leading role in implementing a series of national projects such as a pioneering small-scale ground-based observation in 1986 and an intensive and comprehensive observation involving airborne instruments in 1987, which found that:

- Chlorine atoms released from CFCs play a major role in creating the Antarctic ozone hole.
- Heterogeneous reactions taking place on the surface of the particles of polar stratospheric clouds play a central role in the ozone depletion mechanisms taking place in the Antarctic ozone hole.

Susan Solomon, who won the 2004 Blue Planet Prize, focused on heterogeneous reactions to shed light on the mechanisms behind the ozone hole, spearheading intensive observations implemented in the Antarctic in 1986. She not only took a lead in establishing a theory but also participated in outdoor observations in freezing Antarctic conditions[7]. With the sense of mission that comes from the seriousness of the problem and a sense of responsibility for the U.S. tracking down the cause of the ozone hole (and perhaps driven by intellectual curiosity), US researchers and the members of a support team seemed to have cultivated a strong sense of teamwork, as they would have felt if they had been on the battlefield or Olympic athletes in team sports. In the course of these efforts, the National Science Foundation (NSF) and NASA contributed substantially to organizing an open forum for researchers and making flexible budgetary arrangements.

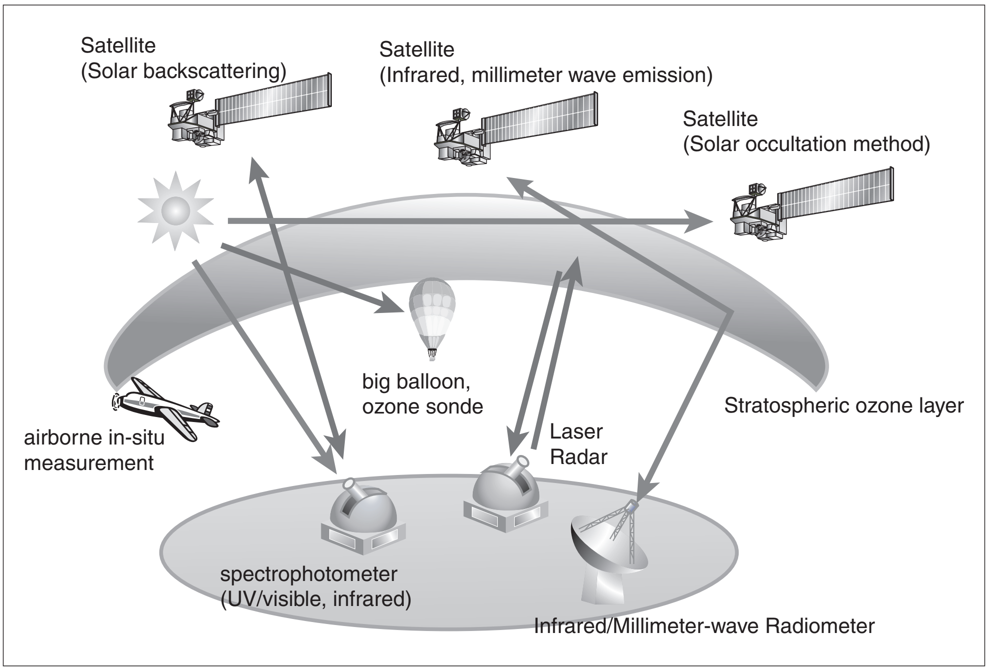
A European researcher told me back in 1987 that "We, European researchers, will focus on the Arctic, leaving the Antarctic to our US counterparts who are fully committed to it." In fact, European countries, although not as quick as the U.S. in taking action, jointly established a system for intensive observations, with each of them offering its specialty. At the same time, each country's budget was incorporated into the EU's budgetary framework, which resulted in intensive observation programs implemented four times during the period from 1991 to 2000. A system led by John Pile, a modeling researcher at Cambridge University, worked effectively in these programs, while observational data, the results of model calculations, auxiliary data, and analysis software were made readily available at a data center set up in Norway. In short, ozone layer research, which had been an "individual match" both in the U.S. and in Europe before the discovery of the ozone hole, developed into a "team sport" afterwards.

The U.S. launched the Upper Atmosphere Research Satellite (UARS) in 1991, which served as a major supplier of data on the ozone layer throughout the 1990s. While satellite observations are basically a "team sport," a broad base of "data users" who participate in "individual matches" came into existence. In line with this, a ground-based remote sensing observation network operated mainly by researchers was established in 1991 to complement satellite observations. Using laser-radar, microwave, infrared and visible/ultraviolet spectrometers, this network, called the Network for the Detection of Stratospheric Change (NDSC), has long been conducting unique observations together with satellite observations and ozone observations as part of meteorological observations in mutually complementary form. While it still contributes to verifying data provided by Envisat and EOS AURA, financial problems abound: a lack of long-term budgets for observations and budget cuts in research activities.

6-2 Japan's ozone layer research

Until the 1980s, Japan's ozone layer research efforts were focused on ozone observations as part of meteorological observations (by the Meteorological Agency), theoretical approaches to stratospheric dynamics from the viewpoint of atmospheric dynamics (by universities, etc.), and observations based on upper atmosphere research. These together have played a part in shedding light on the mechanisms of the sudden warming phenomenon in the stratosphere and in discovering the Antarctic ozone hole. Japanese researchers contributed in no small measure to ozone layer research, as systematic approaches were not widely adopted by researchers in other countries also. With the ozone hole discovered, however, research systems in the U.S. and Europe changed completely, which resulted in systematic research activities, a framework for "team sports." Unfortunately, flexible, systematic approaches were difficult in Japan in those days. It was not that "Japan took to the field to play an individual match, only to be smashed by a team gearing up for a team sport." Japan knew that it was going to be a team sport; it simply could not or did not organize a team. For one, both the Arctic and the Antarctic were much too far from Japan. The government's compartmentalized budgets, moreover, made it possible for each institution to conduct research individually without organizing an "All-Japan Team." In the end, Japan chose to participate in joint research programs with the U.S. and European counties, which was an appropriate, albeit forced, decision under circumstances where Japan's Western counterparts had established a "team sport" framework early on, considering "ozone depletion" as their own problem. More to the point, particular emphasis was placed on sensors on board ADEOS (particularly ILAS, the Improved Limb Atmospheric Spectrometer) in accordance with the priority order of stratospheric observation and research activities, which also turned out to be a good decision. Specific

Figure 8 : Satellite-borne, airborne and ground-based observations of ozone layer



achievements include:

- During the eight-month observation period, ILAS (a device of the Ministry of Environment) on board ADEOS (Japanese name: Midori) gathered comprehensive data on the Arctic ozone depletion (ozone hole-type depletion) and the relationship between ozone depletion and polar stratospheric clouds or nitrogen oxides, some of which produced important scientific findings through analysis by researchers at home and abroad[8].
- Long-term observational data have been accumulated, contributing to NDSC, etc. The National Institute for Environmental Studies (NIES) has been observing the vertical ozone distribution since 1988, using an ozone laser radar. The Solar Terrestrial Environment Laboratory of Nagoya University is observing chlorine and nitrogen compounds at Moshiri and Rikubetsu in Hokkaido, using FTIR and a visible spectrometer. The Meteorological Research Institute and the Communications Research Laboratory (the present National Institute of Information and Communications Technology) conducted laser radar observations of aerosols in Canada and New Zealand. In the Antarctic region, stratospheric observations at the Showa Station, led by the National Institute of Polar Research (NIPR), played a major role in discovering the ozone hole. In the Arctic region, meanwhile, NIPR and other parties conducted PSCs observations in Ny-Alesund, Svalbard, while Nagoya University, Tohoku University, the National Institute of Information and Communications Technology, etc., observed aerosols and trace constituents in the stratosphere above Alaska. NIES and other parties have been engaged in intensive observations of the Arctic ozone layer since 1995 (led by European countries) as well as joint research with Russia[9].
- Japan is now on a par with its Western counterparts in observation technologies using millimeter/sub-millimeter radiometers[10]. Its technological resources in developing and manipulating laser radar and aerosol/nitrogen-oxide sensors on board balloons and aircraft are also highly appreciated.
- Hokkaido University, Kyoto University and Kyushu University achieved a breakthrough in the analysis of stratospheric dynamics, such as analyses of data provided by UARS.
- With respect to the development of future prediction models for the ozone layer, a "proactive strategy" was adopted in the early 1990s to develop a stratospheric chemistry model based on the "CCSR/NIES General Circulation Model." The purpose was to create a three-dimensional model that was then considered "unpractical" because of the computation time involved. This strategy bore fruit: in the WMO and UNEP "Scientific Assessment of Ozone Depletion: 2002," the prediction of the future polar ozone depletion involving the effects of climate change by this model was treated as one of the most advanced results. It was possible because a large group committed to developing the "CCSR/NIES General Circulation Model" has been active.

With an "ample budget" (not a "modest budget") provided, albeit a compartmentalized one, and a handful of full-time researchers committed to observation activities, a team comprising dozens of staff members could be organized, which would enable Japan to take part in a "team sport." The ILAS team for ADEOS was one such example. It is unfortunate that the observation lasted for only eight months and that ADEOS-II malfunctioned and ceased to function prematurely. Neither the Arctic nor the Antarctic was a "remote place" for the ILAS team because ILAS was a satellite sensor specifically designed for high-latitude observations. The ADEOS projects, for that matter, had a relatively large budget and full-time researchers.

It is still uncertain whether a national project can be designed and launched in a year or so to address an emerging environmental problem such as the ozone hole. Japan's decision to cooperate with its Western counterparts turned out to be a good one, but it was not the consequence of comprehensive and open discussion among Japanese researchers; it was the choice for obtaining budgets from competent authorities. In relation to this, the absence of an open forum that transcends the boundaries of research areas and competent authorities has been a major issue. What is important now is that it has been overcome. Moreover, it is imperative that researchers improve themselves so that they can take advantage of an array of opportunities that can serve as an open forum (e.g., academic societies and Japanese committees on international research programs). The situation, however, has improved since 1986, with the Council for Science and Technology Policy in place to take the "initiative," which facilitates cooperation between government agencies. The next challenge is to fund the council properly to ensure flexible and dynamic research activities.

7 Towards the development of Japan's ozone layer research

While Europe's Envisat and the U.S.'s EOS AURA (satellites equipped with stratosphere-monitoring sensors) are gathering observational data, there are few options left for researchers engaged in observation and data analysis in Japan, which does not have a stratosphere-monitoring sensor of its own. In the short term, they are expected to pursue research efforts in the framework of "international cooperation," taking advantage of their specialty, while in the long term, it is necessary to capitalize on their own data that will accumulate over a long period. Super computers and Earth simulators are available for modeling researchers, and there are quite a few qualified researchers in this research area in Japan who together are expected to make satisfactory achievements.

The Earth Observation Summit II was held in Tokyo this April, and a 10-year plan for earth observations is in the pipeline. In Japan, a working group on earth observations was set up in the Council for Science and Technology Policy, and an ad-hoc group on the global environment is mapping out a long-term plan for global environment observations including ozone layer observations. With this as a backdrop, it is essential that "outstanding problems" be addressed and long-term approaches including international cooperation be maintained, based on the government's proactive measures. With respect to ozone depletion, the focus should be on "whether it is recovering according to our understanding," rather than on "whether it recovers or not." To this end, a strategic monitoring system should be created, and the following are suggested, with particular emphasis on observation activities:

(1) Evaluate the possible effects of "other factors" (substances other than chlorofluorocarbons that are not regulated by the Montreal Protocol) on the ozone layer, and incorporate the evaluation results into models for accurate prediction.

(2) Prepare a budget and create a system to support long-term observations of the ozone layer (including advanced observations that should be implemented by researchers). This is a means to monitor whether the ozone layer is really recovering according to the prediction based on a scenario of reducing chlorofluorocarbons, etc.

(3) Create a system (a data center), with a budget earmarked for it, to store long-term observational data, analyze variations or long-term changes in the subjects observed, accumulate models and their implementation results, and facilitate data utilization.

(4) Develop atmospheric chemistry sensors onboard satellites (a sensor that can monitor the concentrations of atmospheric constituents and meteorological parameters of the stratosphere and the troposphere, simultaneously and separately, is a promising means of keeping track of the stratospheric ozone layer and regional air pollution along with its impact on tropospheric air quality, and to gather information on interactions between the troposphere and the stratosphere).

A system should be in place to create an open forum attended by researchers and supported by flexible budgetary arrangements so that immediate action can be taken to address emerging environmental problems such as the Antarctic ozone hole.

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