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NASA Ozone Depletion Averted This Year

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TO: Ms. Katie McGinty
for Senator Gore

FROM: Dr. Robert T. Watson

**THE ATTACHED REPORT IS EMBARGOED UNTIL
1:00p.m. TODAY.**



National Aeronautics and
Space Administration
Washington, D.C. 20546

Brian Dunbar
NASA Headquarters, Washington, D.C.
(Phone: 202/453-1547)

April 30, 1992

Jessie Katz
Goddard Space Flight Center, Greenbelt, Md.
(Phone: 301/286-5566)

James H. Wilson
Jet Propulsion Laboratory, Pasadena, Calif.
(Phone: 818/354-5011)

NASA SPACECRAFT FINDS LARGE ARCTIC OZONE DEPLETION AVERTED THIS YEAR

A rise in stratospheric temperatures in late January apparently prevented severe ozone depletion from occurring in the Arctic this year, says a scientist at NASA's Jet Propulsion Laboratory, Pasadena, Calif. The temperature increase is thought to eliminate polar stratospheric clouds, microscopic ice particles that can sustain high levels of CIO and lead to the large and fast ozone depletion characteristic of the Antarctic.

An alarming spread of chlorine monoxide (CIO), the dominant form of chemically active chlorine that destroys ozone, was detected in January over Greenland, the north Atlantic, northern Europe and Russia by the Microwave Limb Sounder (MLS) on NASA's Upper Atmosphere Research Satellite (UARS).

When the MLS continued its monthly northern hemisphere observations in mid-February, the CIO was reduced from mid-January, said Dr. Joe Waters, Microwave Limb Sounder principal investigator at JPL. Although the January data indicated severe ozone depletion was possible during the northern winter of 1991-92, Waters said his recent ozone data indicate that it did not occur. However, because the sources of chlorine are long-lived in the stratosphere, ozone depletion remains a threat in future years.

"This tells me that conditions in the upper atmosphere are in a very delicate balance," said Waters. "With so much chlorine in the stratosphere, a slight temperature difference can make an enormous difference in the potential for ozone depletion."

In February, "lesser abundances of CIO were detected," said Waters. "These were still very much at an unwanted level and of substantial concern. But they were not at the levels we saw in January which, had they persisted, could have led to a substantial northern ozone depletion this year."

Scientists believe most of the chlorine in the stratosphere is from the release of commercially produced chlorofluorocarbons (CFCs). A delicate combination of sunlight, ice clouds and weather conditions can initiate reactions that lead to ozone depletion. The CFCs are also believed to be involved worldwide in a slower chain of reactions that are eroding ozone on a global scale, and do not require the special conditions inside a polar "hole."

- more -

In the Antarctic, said Waters, conditions are regular enough that scientists can predict with some confidence the annual formation of an ozone hole. In the south, winter stratospheric winds blow mainly in an east-west direction and form a vortex, or circular air pattern, around the Antarctic. The vortex inhibits warmer air from entering polar regions.

"The air in this vortex gets very, very cold in the southern winter with no sunlight," said the atmospheric scientist. "So when sunlight arrives around early September, both conditions -- cold and sunlight -- are present that, in an atmosphere which has already been loaded with chlorine monoxide, can lead to an ozone hole." The southern ozone hole generally persists through October and dissipates in November or December as the air warms and the vortex breaks up.

The scenario is not so simple in Earth's northern hemisphere, where the more complex pattern of continents and oceans cause circulation patterns with a more variable and less intense northern vortex.

Because the northern circulation patterns are more complicated than in the south, "We cannot yet predict details of ozone depletion in the northern polar vortex," said Waters. "We know the season when severe ozone depletion might be expected, but it's like predicting hurricanes -- you may know the general season, but you can't predict the exact time, location and severity. The problem will grow as more chlorine is added to the atmosphere."

Although the northern winter is over for this year, the scientist said he plans to continue monitoring the global situation, closely watching his satellite data for years to come.

The UARS spacecraft, launched Sept. 12, 1991, carries 10 instruments to study the chemistry, dynamics and energetics of the upper atmosphere. Its mission is to provide scientists the first comprehensive, three-dimensional global picture of the upper atmosphere, including the processes of ozone depletion.

UARS is managed by NASA's Goddard Space Flight Center for the Office of Space Science and Applications. JPL, with collaboration from organizations in the United Kingdom, developed and operates the Microwave Limb Sounder.

- end -

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JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
PASADENA, CALIF. 91109. TELEPHONE (818) 354-5011

PHOTO CAPTION TOP April 30, 1992
P-40216c

Abundances of stratospheric chlorine monoxide (ClO) in a layer centered near 20 km (65,000 feet) altitude during the winter of 1991-92, measured by the Microwave Limb Sounder on NASA's Upper Atmosphere Research Satellite (UARS). ClO is the dominant form of chemically active chlorine that destroys stratospheric ozone.

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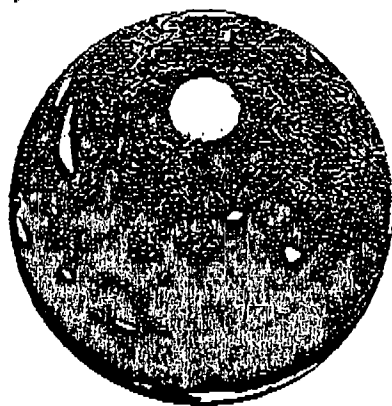
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PICTURE CAPTION TOP April 30, 1992
P-40224

Average arctic-vortex abundances of chlorine monoxide (ClO) and ozone, measured in a layer centered near 20 km (65,000 feet) altitude by the Microwave Limb Sounder aboard NASA's Upper Atmosphere Research Satellite, compared with minimum temperatures in the same region obtained from NOAA's National Meteorological Center. The measurements are plotted against time through the winter of 1991-92. ClO is the dominant form of chemically active chlorine that destroys stratospheric ozone.

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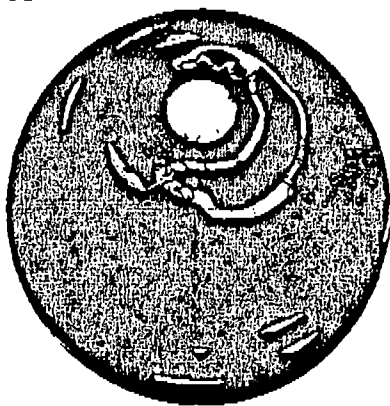
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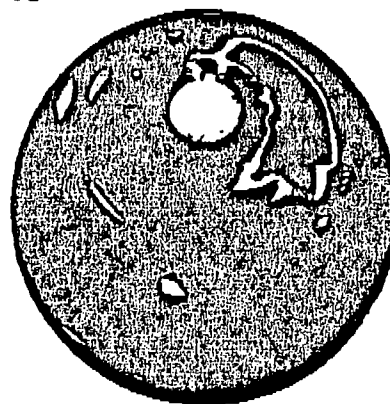
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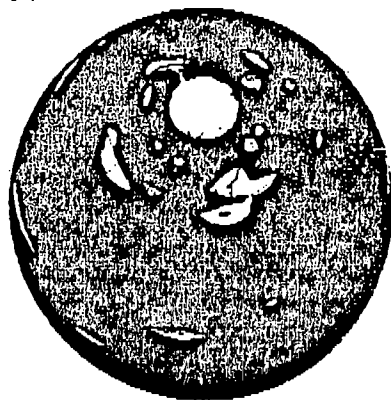
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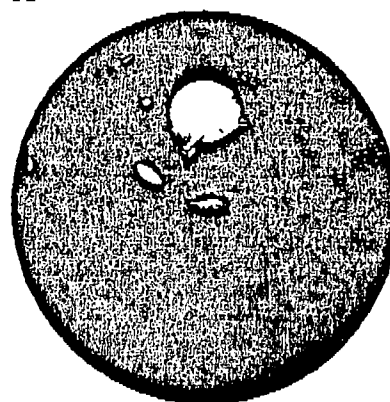
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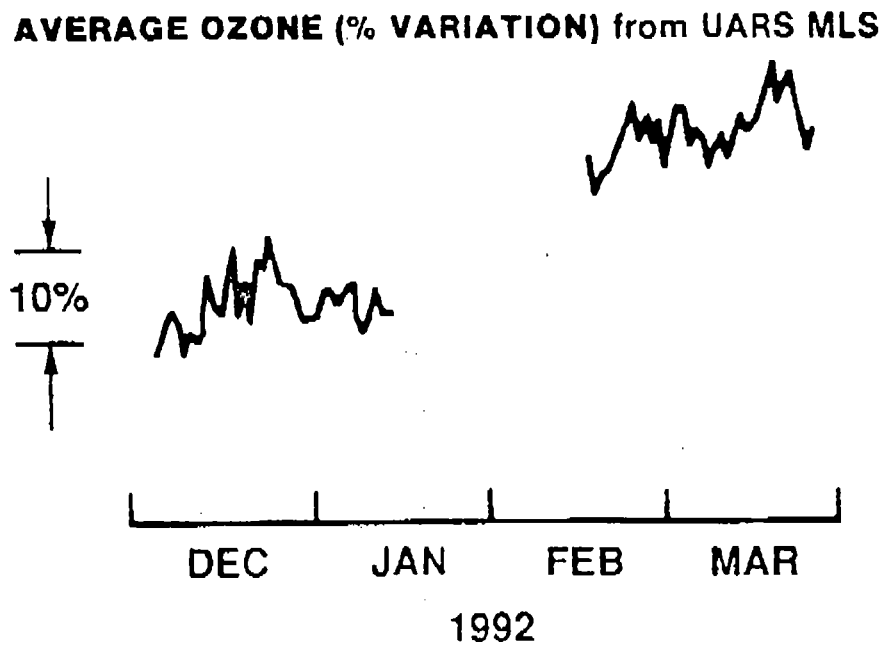
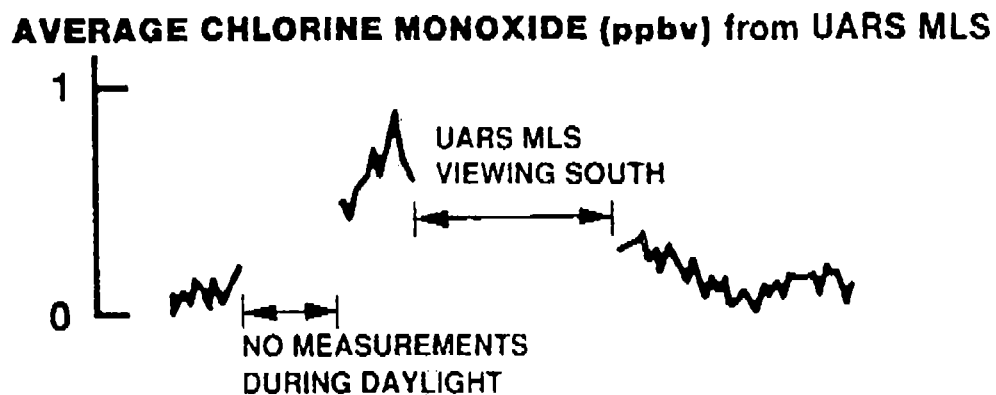
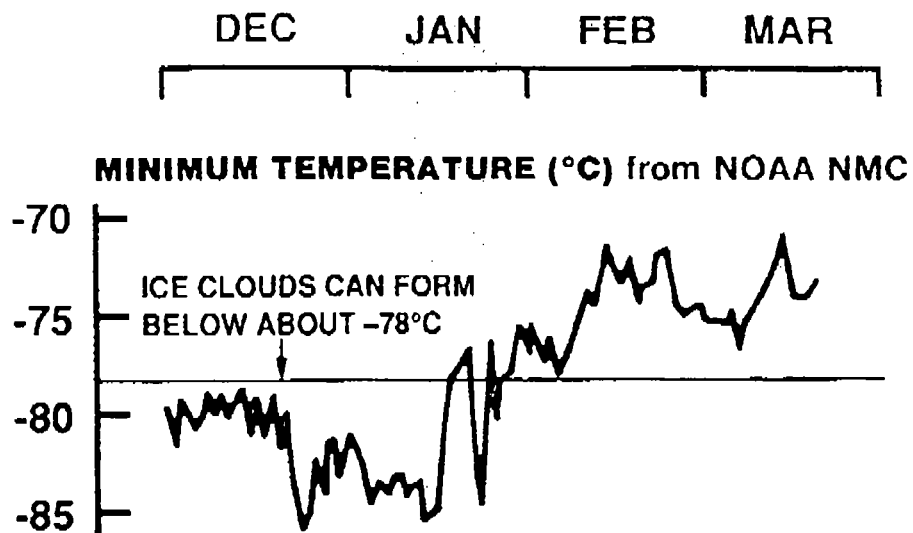


less than 0.4

0.4 to 0.8

more than 0.8

ClO abundance (parts per billion) at 20 km height





National Aeronautics and
Space Administration
Washington, D.C. 20546

TOMS SHOWS NORTHERN HEMISPHERE OZONE DECLINING

Preliminary results from the Total Ozone Mapping Spectrometer (TOMS) aboard the Nimbus-7 satellite indicate that through mid-March 1992, the total amount of Northern Hemisphere ozone was low or lower than any year in the TOMS record, which extends to 1978. Scientists at NASA's Goddard Space Flight Center, Greenbelt, Md., report that a phenomena similar to the Antarctic ozone "hole" did not develop this year in the Northern Hemisphere.

In this photograph, eight false-color TOMS images show the February monthly average ozone levels in two four-year periods (1979 - 1982, top panels, and 1989 - 1992 bottom panels). The color scale (bottom) indicates low total ozone as blues/purples with high total ozone as red/green. The black region in the center of each image is the polar night, where TOMS does not make measurements.

Usually there is a substantial build-up of total ozone in northern mid-to high-latitudes during late winter and early spring. TOMS measurements show that this winter's build-up of high total ozone values was unusually weak, approximately 10 to 15 percent lower than in previous years.

Reduced ozone in 1992 (bottom right) is indicated by the scarcity of the relatively high ozone values (50 to 70 degrees North, approximately Canadian latitudes). This contrasts with the higher ozone values (reds and greens) shown in the earlier years. Total ozone values from tropics up to 40 degrees North were close to normal. Ozone depletion comparable to what occurs in the Antarctic would have been indicated by total ozone values significantly below 200 Dobson Units.

The Goddard-managed Nimbus-7 TOMS has been operating since November 1978 and has collected more than 13 years of total ozone data. The TOMS data from the Russian Meteor-3 satellite, launched in August 1991, are consistent with that of the Nimbus-7 TOMS.

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TOMS total ozone

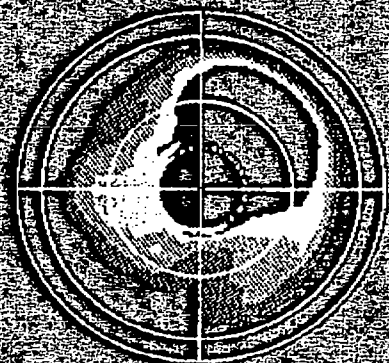
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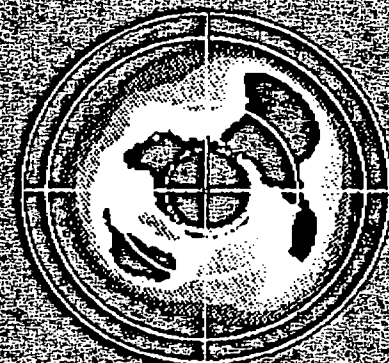
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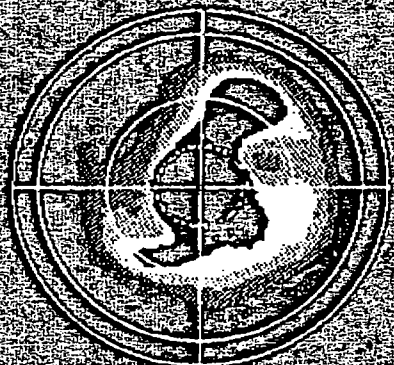
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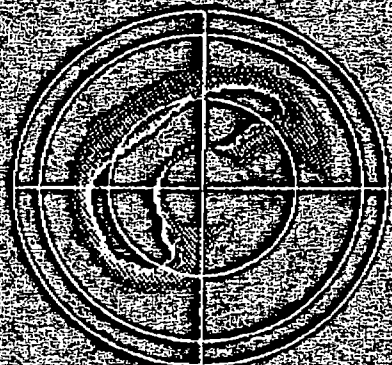
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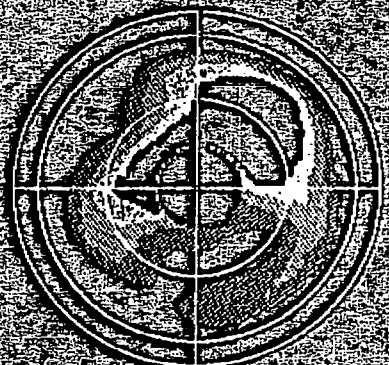
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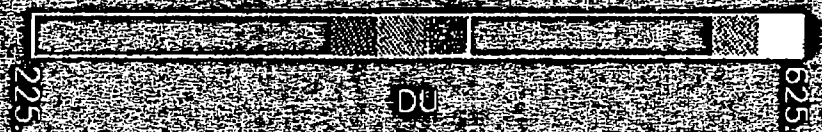
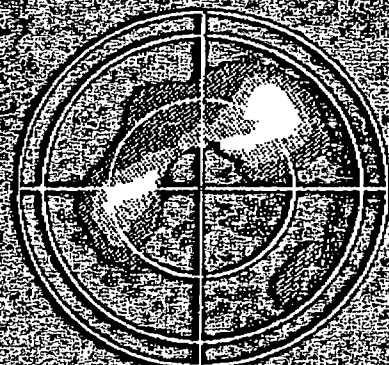
TOMS 2/90



TOMS 2/91



TOMS 2/92



PRESS BRIEFING

END OF MISSION STATEMENT

SECOND AIRBORNE ARCTIC STRATOSPHERIC

EXPEDITION

AASE-II

PART ONE: PREAMBLE

PART TWO: MISSION SUMMARY

PART THREE: MISSION RESULTS

APPENDIX: GLOSSARY

NASA HEADQUARTERS

30 APRIL 1992

PART ONE PREAMBLE

30 APRIL 1992

This statement has been prepared by scientists of the second Airborne Arctic Stratospheric Expedition (AASE-II). The mission was staged over a period of eight months from Moffett Field, California; Fairbanks, Alaska; Anchorage, Alaska; Stavanger, Norway; and Bangor, Maine. The mission used two aircraft to study the lower stratosphere: a high altitude ER-2 aircraft for *in situ* observations and a long-range DC-8 for remote sensing observations. This summary represents the preliminary conclusions of the scientists at the end of the flight series.

The issue of ozone depletion is of widespread public concern. Hence, policy makers and the public should be kept abreast of the advances in scientific understanding. It is in this spirit that we report our provisional interpretation of new data concerning stratospheric ozone in the Northern Hemisphere. A comprehensive interpretation of our findings will be forthcoming after a series of scientific meetings and the publication of peer-reviewed scientific papers.

BACKGROUND TO THE MISSION

In 1985, a large and unanticipated decrease in the abundance of ozone over Antarctica was reported by the British Antarctic Survey. Public concern was heightened in 1988 and again in 1991 by ground and satellite observations that showed ozone at northern mid latitudes in the winter had decreased 6-8% between 1979 and 1990. It is critical to recognize that while ozone exhibits considerable natural variability, decreases in ozone overhead without other offsetting atmospheric changes result in increased ultraviolet radiation reaching the Earth's surface. Biological and medical studies suggest that the accumulated exposure to these increases produce deleterious effects on mankind and other living organisms.

Predicting ozone loss in the Earth's stratosphere over the next decade requires detailed knowledge of both chemical and transport processes. Two types of scientific investigation provide guidance for policy decisions: (1) mechanistic studies linking cause and effect, which serve as the foundation of our ability to look forward in time, and (2) global-scale studies of trends of atmospheric change. Improved understanding of mechanism and process was the focus of the second Airborne Arctic Stratosphere Expedition (AASE-II).

The research phase described here, which began in August, 1991, is a continuation of episodic aircraft flights into the antarctic, arctic and mid-latitude stratosphere. More than one hundred flights have been made during the last five years by the ER-2 and DC-8, encompassing all latitudes from the

South Pole to the North Pole. Results from the first of these aircraft campaigns, the Airborne Antarctic Ozone Experiment (AAOE) over Antarctica in 1987, demonstrated that chlorofluorocarbons (CFCs) released into the atmosphere caused dramatic springtime ozone erosion over the Antarctic. Those studies pinpointed chlorine monoxide and bromine monoxide as the species responsible for controlling the *rate* of ozone destruction and further indicated the importance of polar stratospheric clouds (PSCs) in producing chemical transformations that facilitate such destruction. In 1989, the first Airborne Arctic Stratospheric Expedition (AASE-I) was staged from Stavanger, Norway. During that mission, ER-2 flights into the arctic stratosphere revealed that chlorine monoxide and bromine monoxide were present at concentrations comparable to those observed over Antarctica in 1987. However, since the degree of ozone loss depends both on the ClO/BrO concentrations and on the *duration* of the elevated levels, the shorter period of cold temperatures in the Arctic diminishes the impact on ozone.

AASE-II is comprised of four major program elements: a high altitude ER-2 aircraft, a long-range DC-8 aircraft, extensive meteorological predictions and analyses, which include an array of computational programs to correlate and interpret the aircraft observations, and finally, the Total Ozone Mapping Spectrometer (TOMS) on the Nimbus-7 satellite, which monitored the global distribution of total ozone. The instrument packages on the two aircraft measured an array of the chemical species and other atmospheric parameters that are associated with the mechanisms that determine the distribution of ozone.

Meteorological analyses from the NOAA National Meteorological Center (NMC) provided the historical context, analysis and predictive capability for temperature, pressure and wind fields for the northern hemisphere during the field deployment.

Three questions define the principal mission objectives for AASE-II:

1. Will significant erosion of stratospheric ozone occur over the Arctic as stratospheric chlorine levels increase during the next decade?

2. What are the causes of mid-latitude stratospheric ozone decreases in late fall through early summer, revealed over the past decade by ground and satellite observations?

Finally, given the eruption of Mt. Pinatubo in June of 1991, we address a another issue:

3. What effect do volcanoes have on the chemical processes that govern stratospheric ozone? In particular, could volcanic aerosols modify depletion of stratospheric ozone associated with industrial halocarbons?

PART TWO: AASE-II SUMMARY STATEMENT

- The chemical composition of the stratosphere was highly perturbed at northern latitudes this winter. Most of the chlorine released from CFCs in the stratosphere, where it resides as chemically stable inorganic chlorine (HCl and ClONO_2), was converted to the reactive form (ClO). This transformation, observed in a sequence of flights, began in mid-December and was complete by mid-January. Concentrations of ClO were observed by the ER-2 to increase during January, exceeding 1500 pptv on January 20th. Appearance of high ClO concentrations correlated with the disappearance of HCl and with the onset of temperatures cold enough to form polar stratospheric clouds (PSCs). The onset of cold temperatures, high ClO , and the loss of HCl had been predicted based on laboratory measurements and was observed simultaneously in specific air masses for the first time in AASE-II.

- Meteorological conditions over the Arctic this winter were characterized by a period from mid-December to the third week of January when minimum temperatures dropped below the threshold for PSC formation at ER-2 altitudes. This period was shorter than average. An analysis of HCl , ClONO_2 , NO , NO_2 , HONO_2 and ClO concentrations from this mission, in the context of more than one hundred aircraft flights over the last five years, implies that ClO levels in excess of 1000 pptv should emerge at high latitudes in January during typical or colder years for the next two decades.

- Temperatures warmed abruptly within the vortex the third week of January. The decline of ClO commenced as expected when temperatures warmed above the PSC threshold. ClO dropped slowly: by mid-February concentrations from 700 to 1000 pptv were typical in the vortex. The decline of ClO continued into late March.

- Calculations based on the observed concentrations of HCl , ClONO_2 , NO , NO_2 , HONO_2 , ClO and BrO in the arctic vortex in January and February indicate approximately 20% ozone removal between 15 and 20 km. Using data for ozone and tracers from the aircraft, evidence for comparable ozone removal was observed over a more limited altitude range. The percentage total column ozone loss is estimated to be about one half the percentage observed between 15 and 20 km. In the calculations, ozone removal is due in about equal measure to reactions involving chlorine and bromine.

- The amount of ozone destroyed in a given year is controlled by two factors: (1) total chlorine and bromine concentrations in the stratosphere, both of which are increasing annually; (2) the timing and vertical extent of temperatures below the threshold for PSCs. If temperatures had remained cold into the third week of February, which has occurred several times in the

last decade, greater amounts of ozone would have been destroyed. The loss of ozone in winter 1991/1992, while significant, should not be described as an "ozone hole," a term coined to denote the sharp transition to dramatically suppressed O_3 levels over Antarctica. In this hemisphere, it is essential to focus on the more broadly distributed erosion of ozone at both mid and high latitudes.

- During 1992, the Total Ozone Mapping Spectrometer (TOMS) satellite measurements show that the hemispheric ozone average during January, February, and most of March was lower than any previous year in the TOMS record. TOMS measurements also showed that total ozone values in the mid-latitude maximum during February were 10-15% lower than any previous year in the TOMS record. The processes responsible for this ozone decrease are under investigation.

- The mission revealed strong evidence for the influence of sulfate aerosols on stratospheric chemistry, particularly outside the polar vortex. Natural sulfate particles appear to suppress concentrations of NO and NO_2 , leading to enhanced concentrations of ClO and BrO . The highest concentrations of ClO and BrO outside the vortex were observed in winter at high latitudes. The results are consistent with the view, expressed in the recent UNEP report, that ClO and BrO are likely to be implicated in recent reductions of column ozone amounts observed over midlatitudes. The largest changes in midlatitude ozone levels are observed in late winter and occur in the same altitude regions where ClO and BrO are elevated throughout the winter.

- The eruption of Mt. Pinatubo increased abundances of natural sulfate aerosol particles, potentially amplifying the effects of reactions which take place on the surfaces of particles. No significant direct injection of chlorine by the volcano was observed. There was no evidence for significant influence of Pinatubo aerosols on the chemistry of the polar vortex. In the vortex, the removal of NO , NO_2 , and HCl , and the large enhancements of ClO appear to be triggered by formation of PSCs.

- Enhanced sulfate loading from Mt. Pinatubo may affect regions of the atmosphere where the fractional conversion resulting from pre-Pinatubo aerosol loading is incomplete, which is increasingly true at lower latitudes and at altitudes above 20 km. Column amounts of NO_2 were observed by the DC-8 to be notably depressed at mid-latitudes this year, as compared to past years. Ozone levels were reduced within the Pinatubo aerosol layers in the tropics.

PART THREE MISSION RESULTS

REVIEW OF SCIENTIFIC RESULTS FROM

AASE-II

Results from this mission are presented in a question and answer format and are drawn from observational data, diagnostic calculations, and an extensive analysis of the region's meteorology. Four sections address, in order: the approach to quantifying ozone loss, mission results obtained at arctic latitudes, issues surrounding the thinning of ozone at mid latitudes, and finally, the process used to establish the conclusions cited in this briefing. A glossary of terms and a list of scientific participants in the mission appear in the appendix.

General Approach

(1) How did this mission seek to determine and understand ozone losses?

The natural abundance of ozone varies with altitude, latitude, and season, reflecting patterns in chemical production and loss, and dynamical transport of ozone. Measurements of O_3 alone are not sufficient to define the degree of chemical destruction within a specific region. This is particularly true in the middle and high latitudes of the northern hemisphere, where the natural variability of ozone is very large. Hence, this mission has utilized four complementary approaches for diagnosing ozone loss:

Simultaneous, in situ observations of ozone, winds and atmospheric chemical tracers (N_2O , CFC-11, CH_4), combined with global maps from the NOAA National Meteorological Center (NMC) of stratospheric circulation patterns along with computed dynamical tracers and air parcel trajectories. The in situ observations and global analyses provide the information to define the atmospheric motion. Research over the past five years has demonstrated the importance of placing ozone observations in an analytical framework, whereby ozone changes resulting from atmospheric motion can be differentiated from chemical loss.

Observations of chemical species both directly responsible for ozone destruction in the stratosphere (ClO, BrO, and NO₂), and indirectly responsible (HCl, ClONO₂, HONO₂, H₂O, total reactive nitrogen) through linking chemical reactions. Studies in the Antarctic have shown that ClO and BrO concentrations determine the rate of catalytic ozone loss within the airmass in which they are measured. Laboratory studies provide fundamental data defining chemical reaction rates, absorption cross-sections, and molecular structures.

Global maps of total ozone by the Total Ozone Mapping Spectrometer (TOMS) on board the Nimbus-7 satellite. A comparison of measurements taken during this mission with established historical values of ozone developed for the northern hemisphere over the 13-year lifetime of TOMS provides insight into the global distribution of ozone change.

Vertical cross sections of ozone and aerosols from the Differential Absorption Lidar (DIAL) aboard the DC-8 aircraft. The aircraft was used to search for regions inside the vortex with unusual vertical profiles of ozone that might suggest correlation between ozone loss and either the Pinatubo aerosol or polar stratospheric clouds (PSCs).

Arctic Latitudes

(2) What did the mission reveal concerning the chemical composition of the arctic lower stratosphere?

These studies, in conjunction with the AASE-I investigation of the arctic vortex in January and February of 1989, demonstrate that the conversion of inorganic chlorine (HCl and ClONO₂) to ClO does not require unusual conditions. We believe that ClO mixing ratios exceeding 1000 parts per trillion by volume (pptv) will emerge annually by mid-January throughout the lower stratospheric vortex, except during unusually warm years.

Through the course of twenty-five ER-2 flights and nineteen DC-8 flights, encompassing latitudes from the southern tropics to the pole, the seasonal evolution in concentration of the reactive radicals ClO, BrO, and NO, and of the less reactive chlorine reservoirs, HCl and ClONO₂, has been observed from the fall, prior to PSC formation, through winter to the beginning of spring.

The dramatic changes observed in the chlorine composition of the arctic lower stratosphere may be divided into three phases:

(i) *Prior to and during the onset of PSCs:* At high latitudes, ClO was in the range of 30-50 pptv in October and increased to 130 pptv (at northern latitudes) in mid-December. These values are significantly greater than expected, based on models that do not take proper account of reactions on aerosols. *In situ* measurements of HCl are lower than expected from model calculations (even those with aerosol reactions) throughout the period.

(ii) *Winter occurrence of PSCs:* After the onset of PSC temperatures, ClO increased to 500 pptv in the vortex in mid-December. Conversion of inorganic chlorine to ClO was observed inside the vortex by the ER-2 in December, 1991, and January, 1992, as large losses in HCl (reductions of as much as 1000 pptv) occurring simultaneously with large increases in ClO. In early January, ClO levels regularly approached 1000 pptv, increasing to 1500 pptv by the third week. These ClO levels represent a large fraction of the available inorganic chlorine in the stratosphere and are the highest values observed by the ER-2 in either hemisphere. Using back trajectory analysis, air parcels with low levels of HCl and high levels of ClO were found to have experienced temperatures at or below those required for PSC formation within a few days prior to sampling. Conversely, air parcels showing no evidence of chlorine conversion had not recently experienced PSC formation temperatures. Column measurements of HCl and ClONO₂ from the DC-8 were low inside the vortex, with a maximum ClONO₂ amount at the edge of the vortex in January. In January and February, 1992, there was little evidence for the irreversible removal of total reactive nitrogen, $\text{NO}_y = \text{HNO}_3 + \text{N}_2\text{O}_5 + \text{NO}_3 + \text{NO}_2 + \text{NO}$.

(iii) *Disappearance of PSCs:* Following a minor warming event in late January, temperatures rose above the PSC threshold and high ClO concentrations at ER-2 altitudes began to decline just inside the vortex, approaching 1000 pptv by mid February, and dropping to 200 pptv by late March. With the decrease in ClO after the cessation of PSCs, HCl and ClONO₂ were observed to increase, the latter more rapidly. The springtime decline of ClO and the resulting formation of ClONO₂ arises from the increased production of NO₂ from nitric acid released from PSCs as sunlight returns.

Concentrations of BrO between 4 and 8 pptv, accounting for 20-40% of the total inorganic bromine, were observed. These concentrations were not significantly affected by the occurrence of PSCs, nor did they vary significantly throughout the period of observation.

In situ observations of NO were combined with those of ozone and ClO to estimate NO_x ($= \text{NO} + \text{NO}_2$) in sampled air parcels. The value of NO_x/NO_y is used as an index of partitioning within the NO_y reservoir. Throughout the mission, when ClO levels were elevated, NO_x/NO_y values were suppressed at high latitudes. The depletion of NO and NO_2 within the NO_y reservoir is consistent with low photolysis rates of nitric acid at high latitudes in conjunction with the conversion of NO_x to nitric acid, via surface reactions on aerosols.

(3) What is the evidence for ozone loss in the Arctic?

Ozone loss was analyzed in the vortex for altitudes below 20 km. Calculations based on the observed time evolution of ClO, BrO, HCl, ClONO_2 , NO and NO_2 in the vortex in January and February predict ozone losses of approximately 20% between 15 and 20 km, consistent with observed ozone and tracer data obtained by the aircraft. The magnitude of total ozone loss was limited by the brevity and timing of the period during which temperatures remained below the PSC threshold (-78°C). These losses are quite significant but should not be described as an ozone hole.

Historical observations of the seasonal cycle in polar ozone indicate that from October through March, descent of ozone-rich air in the vortex substantially increases ozone in the lower polar stratosphere, particularly in the 15-20 km region. Changes in ozone at a particular altitude represent a balance between: (a) increases resulting from an influx of ozone from lower latitudes and higher altitudes, and (b) losses due to chemical destruction. Observations of ozone, referenced to both the H_2O and CFC-11 tracer fields, indicate net local decreases of ozone of about 20% in the 16-17 km range, while the balance at higher altitudes results in a small net increase in ozone. Although these results are preliminary, they are consistent with model calculations and with the DC-8 observations between 15 and 18 km.

Simultaneous observations of O_3 , ClO, BrO and total reactive nitrogen (NO_y) in the antarctic vortex during the period of rapid ozone erosion in 1987 established the relationship between chlorine monoxide and bromine

monoxide concentrations and the rate of ozone loss. The AASE-II series of ER-2 flights detailed the time evolution of ClO and BrO concentrations within the arctic vortex from early January through mid-March. Using ozone destruction rates derived from antarctic analysis, calculations based on AASE-II data predict ozone losses of approximately 20% between 15 and 20 km altitude, consistent with observations. The amount of ozone lost from the total column depends upon the vertical extent of the amplified ClO/BrO concentrations. Calculations suggest that the total ozone column decreases by approximately half the percentage change that occurs between 15 and 20 km. Calculations guided by the simultaneous observation of ClO, BrO, HCl, ClONO₂, NO and NO₂ during January through March also predict that more ozone loss would have occurred if the period over which temperatures remained below the PSC threshold (-78°C) extended well into February, as they have in approximately half of the last ten years.

4) How did the meteorological conditions of the 1991/92 Arctic vortex compare with those of previous years?

Global meteorological analyses show that the period of cold temperatures (specifically, temperatures below the nitric acid trihydrate (NAT) phase transition at -78 °C, allowing PSC formation) was significantly shorter than normal at and below ER-2 cruise altitude.

Temperatures obtained from the NOAA National Meteorological Center were used to determine the climatology of the northern hemisphere. As during most northern winters, stratospheric temperatures in 1991/92 were cold enough for formation of PSCs but were not cold enough for extensive water ice particle formation. During a 39-day period from mid-December to mid-January, temperatures were intermittently low enough to form PSCs at the 20 km level. A minor stratospheric warming in mid-January raised temperatures above the PSC limit. This 39-day period contrasts with a 79-day period in 1988/89, and a 68-day range during an average winter.

The stratospheric polar vortex developed in early fall and reached maximum intensity in mid-winter. The 1991/92 polar vortex was not unusually strong, but did persist for an unusually long period (early April). The years 85/86, 87/88, 89/90, and 91/92 were each characterized by a persistent polar vortex.

(5) Did the presence of Mt. Pinatubo aerosol have significant impact on the chemical composition of the polar vortex?

The abundance of reactive chlorine in the Arctic vortex was dominated by reactions occurring on PSCs, rather than by reactions on either volcanic or background sulfate aerosols.

The high abundances of ClO (in excess of 500 pptv) are linked to the advent of PSCs. Trajectory studies (the tracing of air mass motion backward in time from the point of observation by the ER-2) reveal that air masses characterized by (i) very high concentration of ClO, (ii) nearly complete removal of HCl, and (iii) changes in the particle size distribution, were several days earlier within regions characterized by temperatures below the PSC formation threshold. Trajectory analyses of immediately adjoining air masses that showed no such perturbations in ClO, HCl, or particle size distribution indicated that these air masses were not within regions with temperatures below the PSC formation threshold. While we believe that reactions on liquid aerosols are important, conversion of inorganic chlorine (HCl and ClONO₂) to ClO on PSCs is substantially faster, masking any reactions on background aerosols. This conclusion holds even for surface area enhancements of a factor of 30, characteristic of the Mt. Pinatubo cloud.

Lidar observations from the DC-8 showed that the Pinatubo aerosols were concentrated at and below the typical ER-2 flight altitudes inside most of the vortex. The ER-2 encountered the main aerosol layer from Pinatubo at the lowest altitudes in the descent profiles within the vortex. Pinatubo aerosols at high altitudes (up to 26 km) did not reach northern high latitudes soon enough to be entrained within the vortex upon its formation in early winter.

Air outside of the vortex was observed by the DC-8 instruments to move through cold regions, in which both NAT and ice clouds were forming. This air, with only brief exposure time to PSCs, was highly depleted in HONO₂, ClONO₂, and HCl. Air that had moved only through warmer regions of the Pinatubo cloud exhibited near-normal mid-latitude abundances of HONO₂, ClONO₂, and HCl. These observations not only show that PSCs are more important for processing the air than are warm volcanic clouds, but also that a single rather brief exposure to PSCs is capable of significantly processing the air.

(6) Are future arctic ozone losses likely?

Analysis of results from both arctic airborne missions, AASE-I in 1989 and AASE-II in 1991/92, have isolated two key variables that determine the amount of ozone destroyed in any given year. The first is the amount of chlorine and bromine present in the stratosphere. The second is the timing and vertical extent over which temperatures in the vortex remain below the PSC threshold (-78°C).

The two AASE missions have demonstrated that a large fraction of all inorganic chlorine (HCl and ClONO_2) in the stratosphere is converted to ClO and its dimer whenever the temperature in a particular region of the vortex reaches the PSC threshold (-78°C). Therefore, the concentration of reactive chlorine following PSC processing is proportional to total chlorine loading. Additionally, in the absence of NO_x , reactive bromine is proportional to the bromine loading. Knowledge of the ClO and BrO concentrations within the vortex allows the determination of the rate of ozone loss.

These missions in conjunction with the antarctic mission in 1987 have further demonstrated that the total amount of ozone lost in the vortex in any given year (for which the total chlorine and bromine loading are specified) depends foremost on the timing and vertical extent of temperatures within the vortex that remain below the PSC threshold (-78°C). The reason is at least twofold: (i) PSCs retain nitric acid, preventing the reintroduction of NO_2 , which converts ClO back to the more stable form of chlorine, ClONO_2 ; and (ii) PSCs recycle HCl and ClONO_2 back into ClO . The amount of ozone removed is sensitive to the amount of NO_2 reintroduced because ClO is removed primarily by reaction with NO_2 to form ClONO_2 . For example, at a current total chlorine loading of 3500 pptv, if vortex temperatures remain below PSC threshold until the fourth week of January, calculations consistent with observed levels of HCl , ClO , BrO , NO , NO_2 , ClONO_2 and HONO_2 predict that approximately 20% of the ozone will be destroyed by the chlorine and bromine cycles at ER-2 altitudes. The impact on total column ozone depends upon the vertical extent of the cold region and for typical temperature profiles ranges from one quarter to one half the fractional loss at ER-2 altitudes. If in future years temperatures remain below PSC threshold until the fourth week of February, a circumstance that has occurred a number of times in the last decade, ozone loss will increase substantially.

Mid Latitudes

(7) What did the mission reveal concerning the chemical composition of the mid-latitude stratosphere?

The mission revealed strong evidence for the influence of sulfate aerosols on stratospheric chemistry from several new, independent sets of measurements. These include:

ClO abundances near 20 km that are a few times larger than gas-phase chemical model predictions but in broad agreement with models including surface reactions of N_2O_5 on sulfate aerosols.

Observations that NO concentrations are many times smaller than gas-phase chemical model predictions, again in broad agreement with models including surface reactions on sulfate aerosols.

In addition to their absolute values, both the seasonal and latitudinal variations observed in ClO and NO conflict with gas-phase model predictions but are consistent with our understanding of the impact of sulfate aerosols. In particular, the ClO increased substantially from summer to winter, in direct contradiction to gas-phase chemistry.

Observations of NO_2 column abundances that are significantly lower than those obtained in 1989 under comparable conditions. This suggests important effects from the added sulfate aerosols present in the stratosphere this year due to the eruption of Mt. Pinatubo, notably an increased altitude range over which heterogeneous processes convert NO_2 to nitric acid and a resulting increase in ClO.

The mission also provided important information on the abundances, trends, and origin of stratospheric chlorine, bromine, and fluorine.

Measurements of long-lived tracers show that the total chlorine and total bromine entering the tropical lower stratosphere is about 3.5 ppbv and 20 pptv, respectively, of which 2.9 ppbv of chlorine and about 8 pptv of bromine are manmade. In addition, column measurements of HF and HCl, made in 1989 and 1991, suggest that stratospheric fluorine and chlorine have been increasing by about 10% and 5% per year, respectively, consistent with releases of manmade compounds.

(8) What does the Total Ozone Mapping Spectrometer (TOMS) show with respect to this year's ozone distribution?

During 1992, TOMS measurements show that the hemispheric ozone average during January, February and most of March was lower than any previous year in the TOMS record. TOMS measurements also showed that total ozone values in the mid-latitude maximum were 10-15% lower than any previous year in the TOMS record. The mechanisms responsible for this situation are currently under study.

The Total Ozone Mapping Spectrometer (TOMS) instrument aboard the Nimbus 7 satellite has collected more than 13 years of total column ozone data, beginning in November 1978. TOMS data have been vital for the monitoring of the Antarctic ozone hole and more recently for quantifying changes in the ozone layer in the northern hemisphere.

Usually there is a substantial build-up of total column ozone in northern mid latitudes during the late winter and early spring. TOMS measurements show that this build-up of high total ozone values was unusually weak this winter. Specifically, total ozone values in the northern mid-latitude maximum were 10-15% lower compared to previous years. The mechanisms responsible for this reduction in ozone are currently under study.

To date in 1992, TOMS measurements show that the hemispheric ozone averages were as low or lower than any previous year in the TOMS record. However, the very lowest values of total ozone were similar to those found in previous years.

(9) To what extent do the results of this mission contribute to our understanding of the observed long-term decrease of mid-latitude ozone?

The results from this mission, particularly the observations of HCl, NO, NO₂, ClO, BrO and the tracers N₂O and CFC-11, support the conclusion, stated in the recent UNEP Report, that decreases in ozone are associated with increases in chlorine and bromine in the lower stratosphere.

Ozone changes at mid latitudes result from the combined influence of (i) chemical loss by chlorine, bromine, hydrogen and nitrogen catalytic cycles, and (ii) dynamical redistribution of ozone through the seasonal cycle. Observations of HCl, ClO, BrO, NO, NO₂ and the tracers N₂O and CFC-11 obtained during AASE-II have defined for the first time the relative importance with respect to ozone loss of the major nitrogen, chlorine and bromine cycles in the lower stratosphere (15-20 km). These observations show that while a number of catalytic cycles contribute to the balance between ozone production and loss in the lower stratosphere, chlorine and bromine reactions have a significant and perhaps dominant role in the ozone loss budget. In addition, observed concentrations of NO, ClO and BrO highlight the critical importance of the bromine cycle to increasing ozone loss rates of ozone at mid latitude.

Models that are consistent with the simultaneously observed concentrations of HCl, ClO, BrO, NO, NO₂ and ClONO₂ predict long term ozone losses, primarily as a result of reactions involving ClO and BrO. These models are in general agreement with the observed ozone decrease at mid latitudes reported by ground-based and satellite data over the decade of the 1980s. It is important to note that major contributions to the balance between ozone chemical production/loss and dynamical redistribution through the seasonal cycle extend from 15 to 30 km and that the AASE-II results are focussed primarily on the altitude interval from 15 to 20 km.

(10) To what extent was the observed chemical composition in mid latitudes and the tropics influenced by the eruption of Mt. Pinatubo?

The eruption increased the natural abundances of sulfate particles, thereby potentially amplifying the effects of heterogeneous reactions. No evidence has been found for significant chlorine injections. At mid and high latitudes, the chemical perturbation that could be traced to Pinatubo was a suppressed mid-latitude NO₂ column concentration. Ozone levels in the tropics also were found to be reduced within the Pinatubo aerosol layers.

The TOMS instrument observed a stratospheric SO₂ injection from the eruption of Mt. Pinatubo which exceeded that measured or estimated from any other eruption in the past century. TOMS observed the SO₂ to decline quickly as it was converted to sulfuric acid particles. The optical depth (which is proportional to the column surface area of the particles) of the resulting global scale volcanic cloud was found by instruments on the DC-8 to be greater than that of the 1982 El Chichon eruption. The column surface area in

the volcanic cloud exceeded the surface area of background aerosols by a factor of about 20 to 40 in the tropics and about 10 to 20 in the arctic vortex. DC-8 lidar measurements showed that the region of significantly enhanced surface area extended from the local tropopause up to about 26 km in the tropics, to about 22 km at northern mid latitudes, and to about 18 km in the arctic vortex. ER-2 observations showed that local surface areas were enhanced by factors of 20-30 at mid latitudes over non-volcanic levels. ER-2 and DC-8 particle analyses showed the volcanic cloud was dominated by submicron sized sulfuric acid particles.

Volcanic eruptions can potentially inject significant quantities of chlorine into the stratosphere. Measurements made in the Pinatubo cloud revealed that the eruption could have perturbed stratospheric chlorine levels by no more than about 5%, which is the equivalent of about one year's anthropogenic contribution to rising stratospheric inorganic chlorine levels. Although DC-8 column data do show a 5% yearly rise in inorganic chlorine over the past several years due to the anthropogenic contribution, no measurable contribution to stratospheric chlorine was observed in the dispersed Pinatubo cloud. Likewise, ER-2 measurements of HCl inside and outside of the volcanic cloud at mid latitudes did not show any evidence of enhanced stratospheric chlorine resulting from the Pinatubo eruption. No enhancement in stratospheric water vapor resulting from Mt. Pinatubo was observed.

Numerous theoretical studies have suggested the potential for volcanic eruptions to affect mid-latitude ozone levels. The proposed mechanism involves reactions occurring on the surface of sulfuric acid particles (which deplete NO_x). The depleted NO_x in turn, would lead to an increase in ClO through gas phase chemical processes and the ClO would destroy ozone. The reactions depleting NO_x are very efficient even on the background stratospheric aerosols and therefore stratospheric NO_x is not expected to decrease in direct proportion to increased aerosol loading. We found that NO_2 columns in the Arctic vortex, although low, were not lower than in 1989. At high latitudes outside the vortex the NO_2 column was slightly lower than in 1989. These results are in line with expectations that the volcanic cloud would have little impact on high latitude NO_x levels, which are already driven quite low by background sulfate aerosols. At mid latitudes, column NO_2 values were lower than in previous years, reflecting both (i) the increased altitude range over which heterogeneous conversion of NO_x to nitric acid took place within the volcanic cloud, and (ii) the higher concentrations of NO_2 (resulting from the faster photolysis rates of nitric acid) at lower latitudes that were thus sensitive to enhanced heterogeneous conversion to nitric acid on aerosol surfaces.

It is not clear whether the volcanic sulfate aerosol, which will be removed from the stratosphere by natural processes over the next few years, will

increase the amount of mid-latitude ozone depletion that is expected to occur over this period due to rising inorganic chlorine levels from anthropogenic sources.

The DC-8 lidar measurements in the tropics showed a negative correlation between the presence of the Pinatubo aerosols and ozone levels compared to satellite climatology for that region. The maximum amount of the decrease was about 20% near the center of the Pinatubo layer at 23 km. These results agree with ozone changes across the Pinatubo layer found in ozonesonde data from the tropics.

(11) Have we learned anything new about the impact of aircraft exhaust on the stratosphere?

The importance of heterogeneous reactions on sulfate aerosols has been verified by these aircraft studies. Thus, the impact of additional NO_x on ozone in the lower stratosphere is expected to be much smaller than previously predicted and may now be closer to that simulated with the most recent global assessment models that include heterogeneous sulfate-layer chemistry.

SCIENTIFIC PROCESS

(12) What was the scientific process involved in coming to the above conclusions?

The above conclusions were based on a group synthesis of the viewpoints of more than 80 scientists involved in the AASE-II campaign. The observations and simulations involved in this mission have built upon a rich research heritage, including updated laboratory kinetic studies of gas and surface reactions. The ER-2 and DC-8 aircraft and many of the instruments have been involved in over a hundred stratospheric research flights. The methods and results are contained in numerous peer-reviewed journal publications including three special issues. The science team included both experimentalists and theorists, whose experience and background embraces chemistry and chemical modelling, physics, meteorology, and large-scale dynamics. In designing the mission and interpreting the data, the efforts of the principal investigators were augmented by an advisory and review group. The details of the results of the current campaign will be published in the peer-reviewed literature.

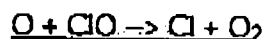
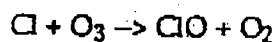
PART FOUR: APPENDIX

A. GLOSSARY OF TERMS

AEROSOLS -- Small, suspended particles in the atmosphere. Most stratospheric aerosols contain sulfur, emitted naturally (e.g., by volcanoes) or as a result of human activities (e.g., by burning fossil fuels)

AIRMASS -- an arbitrarily defined mass or volume of air whose movements as an identifiable entity can be tracked for periods of days.

CATALYTIC CYCLE -- a set of reactions in which one of the reacting species (the catalyst) is regenerated. For example,



the net result of many catalytic cycles of atmospheric interest is the destruction of ozone.

CHLORINE: Organic chlorine, Inorganic chlorine and Reactive chlorine -- *Organic chlorine* is that component of the total chlorine budget that is emitted at the Earth's surface in the form of chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs) and methyl chloride (CH_3Cl). In the presence of ultraviolet light that the organic chlorine compounds see only when they reach the stratosphere, these compounds break down and are irreversibly converted via additional chemical reactions to *inorganic chlorine*, principally HCl and ClONO_2 . Oxidation reactions involving HCl release chlorine atoms that can react with ozone molecules to form chlorine monoxide. The principal form of *reactive chlorine* is the chlorine monoxide molecule that can take part in catalytic cycles. By these catalytic cycles, one chlorine monoxide molecule can destroy several hundred thousand ozone molecules.

CHLORINE MONOXIDE DIMER -- a compound (ClOOCi) formed by the combination of two molecules of chlorine monoxide. Its stability at low temperatures allows it to persist in the polar stratosphere in the winter. When broken down by solar radiation, it releases free chlorine atoms that can participate in ozone depletion.

CHLOROFLUOROCARBONS (CFCs) -- compounds consisting of chlorine, fluorine, and carbon that are very stable in the troposphere. Their degradation by solar radiation in the stratosphere releases chlorine atoms, a process that contributes to ozone depletion. Some CFCs persist in the troposphere for decades; their only known loss is the slow upward mixing into the stratosphere.

COLUMN ABUNDANCE OR COLUMN CONCENTRATION -- A measure of the total number of molecules in the Earth's atmosphere above a given area, usually a square centimeter. For example, instruments on the DC-8 aircraft can measure the total number of molecules in the atmosphere per square centimeter above the aircraft. The TOMS instrument on the Nimbus 7 satellite can measure the total number of ozone molecules per square centimeter in the Earth's stratosphere by looking down at the Earth.

FLUOROCARBONS -- a class of chemical compounds that includes chlorofluorocarbons, hydrochlorofluorocarbons, and hydrofluorocarbons. All of these compounds have been used (or have the potential of being used) in important applications including refrigeration, air conditioning, insulating materials, medical products, and the cleaning of electronic components.

GAS PHASE CHEMISTRY -- chemical reactions occurring between isolated atoms or molecules in the gas phase (in contrast with heterogeneous chemistry).

HETEROGENEOUS CHEMISTRY -- chemical reactions occurring on the surfaces of atmospheric particles. The conversion of nonreactive or reservoir chlorine to reactive or active chlorine involves heterogeneous chemical reactions on the surface of polar stratospheric clouds.

HYDROCHLOROFLUOROCARBONS (HCFCs) -- compounds consisting of hydrogen, chlorine, fluorine, and carbon, which have much shorter lifetimes in the troposphere than chlorofluorocarbons. Hence, only a fraction of the HCFCs emitted to the atmosphere are transported to the stratosphere where they can release chlorine and contribute to ozone depletion.

HYDROFLUOROCARBONS (HFCs) -- compounds consisting of hydrogen, fluorine, and carbon that, like HCFCs, are destroyed naturally in the lower atmosphere and hence have much shorter lifetimes in the troposphere than chlorofluorocarbons. Since these compounds do not contain chlorine, they do not contribute to ozone depletion.

NO_x (NITROGEN OXIDES) -- a term used to collectively represent the compounds nitric oxide (NO) and nitrogen dioxide (NO₂). These molecules can participate directly in catalytic cycles that destroy ozone.

NO_y (ODD NITROGEN) -- a collective designation for the sum of NO_x and all oxidized nitrogen species that represent sources or sinks of NO_x through processes that occur on short time scales. Hence, NO_y includes NO, NO₂, N₂O₅ (dinitrogen pentoxide), HONO₂ (nitric acid), ClONO₂ (chlorine nitrate), and CH₃COO₂NO₂ (peroxyacetyl nitrate or PAN). Although N₂O is a source of NO_x in the upper atmosphere, it is not normally included in the list of NO_y compounds.

OZONE -- a molecule made up of three oxygen atoms (O₃). Nearly 90% of the Earth's ozone resides in the stratosphere and is referred to as the ozone layer. Ozone absorbs ultraviolet-B (UVB) radiation (290-320 nm) and is the primary shield against UVB reaching the ground.

OZONE DEPLETION -- Ozone is continually being created and destroyed in the stratosphere by a variety of chemical reactions. Because of the dependence of these reactions on temperature and sunlight, there are large natural seasonal and latitudinal variations in ozone. Chemical ozone loss, or depletion, occurs when the rate of ozone destruction exceeds that of production. There are also significant changes in ozone throughout the various regions of the stratosphere due to meteorological transport or air movement.

OZONE HOLE -- a term adopted to describe the visual impression obtained from satellite imagery of the significant seasonal depletion of ozone over Antarctica each spring. Ozone depletion is much less severe in the northern hemisphere. The higher natural variability of ozone in the arctic polar region makes it more difficult for significant ozone loss in this region to have the appearance of a distinct depression or "hole."

OZONE LAYER -- the region of the stratosphere between approximately 15 and 40 kilometers (about 10 and 25 miles) that contains the bulk of the atmosphere's naturally occurring ozone.

POLAR STRATOSPHERIC CLOUDS (PSCs) -- microscopic particles of water ice or nitric acid hydrates (nitric acid plus water) that form within the polar vortex under very cold temperatures. The formation of water ice requires colder temperatures than does nitric acid trihydrate (NAT). Chemical reactions occur on the surfaces of PSCs, converting inorganic chlorine into reactive forms, principally ClO, thereby leading to ozone depletion in the polar regions.

POLAR VORTEX -- the region of stratospheric air poleward of the high latitude circumpolar jet stream. The degree of "isolation" provided to air within the vortex helps to develop the extremely cold temperatures that are necessary for the formation of polar stratospheric clouds (PSCs).

RESERVOIR COMPOUNDS -- a designation referring to the compounds of lower reactivity within a particular chemical class. Both hydrochloric acid (HCl) and chlorine nitrate (ClONO_2) are reservoir compounds in the chlorine family. Through gas phase chemistry and photolysis, these inorganic forms of chlorine are slowly converted into reactive chlorine compounds that can rapidly destroy ozone. Through heterogeneous chemistry, this conversion is much more rapid.

STRATOSPHERE -- the layer of the Earth's atmosphere lying immediately above the troposphere and extending to an altitude of approximately 50 kilometers (about 30 miles). Temperatures in the stratosphere increase with increasing altitude and, hence, mixing between different altitudes is very slow.

TRACERS -- atmospheric compounds typically having fairly long photochemical lifetimes (such as nitrous oxide, N_2O , methane, CH_4 , and CFC-11, CFCI_3). They are used to map the motions of the atmosphere and thereby help in distinguishing between the causes of changes in the concentrations of shorter lived compounds.

TRAJECTORY ANALYSIS -- the tracing of air mass motions backward in time from the point of observation. Such analysis permits a diagnosis of the conditions and processes that led to the observed air mass composition and properties.

TROPOSPHERE -- the lowest layer of the atmosphere, extending from the Earth's surface to an altitude of between 8 and 15 kilometers (about 5 and 10 miles). Because the temperature of the troposphere decreases with increasing altitude, air within this region is well mixed.



National Aeronautics and
Space Administration
Washington, D.C. 20546

Glossary of Ozone Terms

Aerosols: Small droplets in the atmosphere, typically including sulfur, emitted naturally (e.g., by volcanoes) or as a result of human activity (e.g., by burning fossil fuels). Aerosols are also formed by chemical processes involving other natural constituents of the atmosphere.

Air mass: an arbitrarily defined volume of air whose movements as an identifiable entity can be tracked for hours or days.

Chlorine, chlorine monoxide, chlorofluorocarbons: Chlorine is currently the major contributor to the destruction of stratospheric ozone. Much of the chlorine that reaches the upper atmosphere is emitted at the Earth's surface in the form of chlorofluorocarbons (CFCs), chemicals that are used in electronics, refrigeration, air conditioning and foam insulation. In the presence of ultraviolet light, CFCs break down, freeing chlorine atoms. The free chlorine atoms can react with an ozone molecule to form one molecule of chlorine monoxide and one of oxygen. The chlorine monoxide molecules can take part in catalytic cycles leading to further ozone destruction by reacting with oxygen atoms, chlorine monoxide, bromine monoxide or hydroperoxyl radicals. Through these catalytic cycles, one chlorine atom can destroy several hundred thousand ozone molecules.

Column: a vertical "core sample" of atmosphere looking either from the top down or from the bottom up.

Gas-phase chemistry: Chemical reactions occurring between free, isolated atoms or molecule of gases in the atmosphere, as opposed to *heterogeneous* chemistry, which occurs on surfaces.

Halogen: Refers to the elements bromine, chlorine, fluorine and iodine, which exist in the free state as diatomic (two-atom) molecules. The inactive form of a halogen is a *halide*. The halogens chlorine and bromine are the most effective chemical destroyers of ozone.

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Halons: Organic compounds containing carbon, bromine and other halogens but no hydrogen. The bromine released from halons act upon ozone in a manner similar to chlorine. Fire-suppressants are a common source of halons.

Halocarbons: Chemicals derived from carbon-hydrogen compounds (hydrocarbons), in which halogens have replaced all or part of the hydrogen atoms.

Heterogeneous chemistry: Chemical reactions occurring on the surfaces of aerosols or particles in the atmosphere. The conversion of non-reactive chlorine to reactive chlorine involves heterogeneous chemical reactions on the surface of polar stratospheric clouds (see entry below).

Hydrochlorofluorocarbons (HCFCs): Compounds containing, hydrogen, chlorine, fluorine and carbon. The presence of hydrogen gives these compounds shorter lifetimes in the troposphere. Only a small portion of HCFCs reach the stratosphere, where they can release chlorine and contribute to ozone depletion. HCFCs are potential substitutes for CFCs.

Hydrofluorocarbons (HFCs): Compounds consisting of hydrogen, fluorine and carbon. Like HCFCs, they are destroyed naturally in the lower atmosphere. Since these compounds do not contain chlorine, they do not contribute to ozone depletion. HFCs are potential substitutes for CFCs.

Model: A computer program that uses mathematical formulas to simulate a complex phenomenon, e.g., ozone depletion. A one dimensional atmospheric model computes the chemical composition of the atmosphere as a global average that varies only with altitude. A two dimensional atmospheric model calculates chemical composition changes with both altitude and latitude.

Ozone: A molecule made up of three atoms of oxygen (O_3). An ozone molecule absorbs ultraviolet-B (UVB) radiation (wavelength of 290-320 nanometers) and is the primary shield that stops UVB from reaching the ground. When exposure to light or reaction with chemicals such as chlorine releases one oxygen atom from the ozone molecule, the resulting oxygen molecule (O_2), does not absorb UVB.

Ozone depletion: A variety of chemical reactions continually produce and destroy ozone in the stratosphere. Because these reactions are very sensitive to temperature and sunlight, ozone concentrations can vary greatly from season to season and latitude to latitude. There are also significant changes in ozone throughout the various regions of the stratosphere due to the natural movement of large air masses.

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Ozone hole: This term was adopted to describe the visual impression obtained from satellite imagery of the significant ozone depletion that occurs over Antarctica in the austral spring. The "hole" generally refers to the area of most severe depletion, which appears well defined within the polar vortex. The term "hole" is a misnomer; currently, Antarctic ozone can be reduced by as much as 50 percent but does not disappear completely anywhere.

The "hole" disappears when the Antarctic atmosphere warms enough to break up the polar vortex and stop the formation of polar stratospheric clouds. Chlorine reverts to inactive forms, and, as the vortex breaks up, ozone-rich air flows in to replenish the ozone layer over the Antarctic.

Ozone depletion is currently much less severe in the northern hemisphere. Ozone levels are naturally much more variable over the Arctic, and therefore it is more difficult for significant ozone loss in this region to have the appearance in satellite images of a distinct depression or "hole".

Ozone layer: The major abundance of the Earth's ozone, which resides in the stratosphere. Ninety percent of atmospheric ozone lies between 9 and 30 miles altitude, with the maximum concentration centered between 15 and 20 miles altitude. If compressed to one atmosphere pressure (the pressure of the Earth's atmosphere at sea level) at 32 degrees Fahrenheit, the ozone layer would be approximately one-eighth of an inch (3 millimeters) thick.

Polar Stratospheric Clouds: Microscopic particles of water ice or nitric acid hydrates that form within the polar vortex under very cold temperatures. On the surfaces of these clouds, chemical reactions convert inactive forms of chlorine into reactive forms, leading to ozone depletion in the Earth's polar regions.

Polar Vortex: A cold mass of air that forms in the stratosphere over each pole in the winter. The vortex is relatively isolated from air at lower latitudes by the eastward jet stream winds that circulate around the poles at high latitudes. (Seen from above each pole, the winds would appear to move counterclockwise around the North Pole and clockwise around the South Pole.) Cold temperatures within the vortex permit the formation of polar stratospheric clouds.

Reservoir compounds: Compounds within a chemical class that are relatively less reactive than others in the class. Hydrochloric acid (HCl) and chlorine nitrate (ClONO₂) are chlorine reservoir compounds that through gas-phase chemistry and photolysis (the disintegration of molecules by light) convert into reactive compounds that release free chlorine atoms. Through heterogeneous chemistry, (e.g., on polar stratospheric clouds), this conversion is much more rapid.

Stratosphere: The region of the atmosphere above the troposphere, beginning at an altitude of 6 to 9 miles. In the stratosphere, temperature

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increases as altitude increases due to the absorption of radiation by ozone. Mixing between regions of the stratosphere is relatively slow.

Tracers: Atmospheric compounds that have fairly long photochemical lifetimes (e.g., nitrous oxide, methane, CFC-11). These chemicals are used to map the motions of the atmosphere to help distinguish between the causes of changing concentrations of shorter-lived compounds (e.g., air-mass movement vs. chemical destruction).

Tropopause: The boundary between the troposphere and stratosphere. Between the Earth's surface and the tropopause, temperature decreases as altitude increases. Above the tropopause, temperature increases as altitude increases because of the absorption of radiation by ozone.

Troposphere: The lowest layer of the atmosphere, the troposphere extends from the Earth's surface to a height of 6 to 9 miles. It contains 90 percent of the Earth's atmosphere and is well mixed by weather systems. The temperature of the troposphere decreases with height.

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