Preface

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Introduction

Ozone screens the Earth from the biologically harmful effects of solar ultraviolet radiation and is a radiatively active gas in both the UV and the IR portions of the solar spectrum. Changes in global ozone amounts impact both greenhouse warming and the exposure of the Earth's biota to UV radiation [*WMO,* 1999]. Hence, a precise understanding is needed of how changing atmospheric composition (e.g., aircraft emissions or other anthropogenic trace gas releases) affects ambient levels of ozone. This requires a thorough understanding of the chemical and transport processes that control ozone in the stratosphere.

The polar stratosphere is a unique region for ozone because of the cold temperatures and continuous darkness in winter and the warmer temperatures and continuous daylight in summer. In winter, stratospheric temperatures are quite cold, typically dropping below 195 K at 50 hPa (see e.g., *Coy et al.* [1997a]). These cold winter temperatures enable a variety of chemical reactions to occur on polar stratospheric cloud particles [*Poole and Pitts,* 1994; *Peter,* 1997]. The continuous daylight in polar summer produces a much different chemical environment than is observed in mid-latitudes or the tropics [*Johnston,* 1975; *Farman et al.,* 1985; *Fahey and Ravishankara,* 1999]. The summer polar temperatures in the polar lower stratosphere are relatively warm (e.g., generally greater than 230 K) and the mean circulation is easterly(e.g., see *Wu et al.,* [1984]). In addition, eddy flux quantities (such as heat flux) show that the transport is considerably weakened (again, see *Wu et al.,* [1984]). Weakened dynamics results in a much reduced transport of ozone from the tropical photochemical production region into the Arctic lower stratosphere [*Wu et al.,* 1987; *Gettelman et al.,* 1997]. However, significant wave effects have been observed in ozone and other trace gases [*Park and Russell,* 1994], implying important roles for both photochemical and transport effects [*Luo et al.,* 1997].

Ozone abundances show a distinct seasonal cycle in areas away from the tropical ozone production region. At northern high latitudes, ozone column amounts peak in spring and reach minimum values in late summer/early fall [*Dobson et al.,* 1929; *London et al.,* 1976; *Bojkov,* 1988; *Krueger,* 1989] (see Figure 1). This spring-to-fall Arctic decrease was first recognized following the pioneering spectrophotometer measurements of Dobson and his colleagues [*Dobson et al.,* 1929]. The decrease is attributed to an increased role of NO_x catalytic cycles in ozone destruction during periods of prolonged solar illumination at summer polar latitudes [*Johnston,* 1975] and reduced poleward transport of ozone. Increased NO_x also moderates the effectiveness of the Cl_x (= Cl + ClO) and HO_x (= OH + HO_2) ozone loss cycles [*Brühl et al.,* 1998]. However, model simulations of this decrease have generally overestimated ozone in the polar region [*Chipperfield,* 1999]. The winter-to-spring build-up of ozone was originally ascribed to a mean poleward and downward transport effect by *Brewer* [1949] and *Dobson* [1956], and later refined with the development of the "transformed Eulerian mean" circulation [*Edmon et al.,* 1980; *Dunkerton et al.,* 1981]. While conventional meteorological data have been used to validate the winter build-up of ozone at high latitudes, less progress has been made in validating the photochemical loss of ozone over the course of the summer.

Figure 1

The POLARIS mission was designed to investigate the photochemical and transport processes that cause the summer polar decreases in stratospheric ozone. The mission primarily utilized the NASA ER-2 high-altitude aircraft and balloon platforms while based in Fairbanks, Alaska. Additional data were obtained with ground-based instruments, satellites, and sondes. Measurements included meteorological variables; long-lived tracers for assessing summertime transport questions; reactive species within the reactive nitrogen (NO_y), halogen (Cl_y), and hydrogen (HO_x) reservoirs; and aerosols. These stratospheric measurements were made at mid- to high latitudes in spring and summer. The observations have been used to constrain various stratospheric computer models in order to evaluate summertime ozone changes due to chemistry and transport.

The POLARIS mission follows-on and builds-upon 15 years of NASA sponsored aircraft measurement campaigns. A number of instruments aboard the NASA ER-2 have been regularly utilized on these campaigns since the Stratosphere Troposphere Exchange Project (STEP) in April-May 1984 [*Russell, P. B., et al.,* 1993]. This long instrument heritage has led to significant improvements of the measurements. For example, the NOAA NO/NO_y instrument's measurement of NO_2 during the 1993 Stratospheric Photochemistry, Aerosols and Dynamics Expedition (SPADE) had an uncertainty of 30-60% [*Gao et al.,* 1997] which was improved to 10-30% by the time of the POLARIS campaign [*Del Negro et al.,* this issue].

Over the last 15 years there has also been a significant expansion of the measured variables aboard the NASA ER-2. For example, the 1984-87 STEP campaign included no measurements of chlorine compounds; a measurement of the ClO radical was added for the 1987 Airborne Antarctic Ozone Experiment (AAOE) [*Anderson et al.,* 89]; a measurement of HCl was added for the 1992 second Airborne Arctic Stratospheric Expedition (AASE-II) [*Webster et al.,* 1994]; and a $ClONO_2$ measurement was added for POLARIS [*Stimpfle et al.,* this issue]. Whole air samples [*Flocke et al.,* this issue] and gas chromatograph measurements [*Ray et al.,* this issue; *Romashkin et al.,* this issue] provided a near complete capability of stratospheric chlorine measurements.

This 15-year heritage of campaigns also provides a temporal record of the evolving stratosphere. Measurements made during the 1992-1993 SPADE campaign, the 1994 Airborne Southern Hemisphere Ozone Experiment / Measurements for Assessing the Effects of Stratospheric Aircraft (ASHOE/MAESA), and the 1995-1996 Stratospheric Tracers of Atmospheric Transport (STRAT) missions provide a data set for analyzing the temporal evolution of the stratosphere [*Andrews et al.,* this issue; *Flocke et al.,* this issue; *Ray et al.,* this issue; *Romashkin et al.,* this issue].

Following this introduction to the POLARIS mission are sections that describe the mission logistics, provide highlights of the separate deployment phases, describe the science topics included in the papers accompanying this Special Section, and summarize the overall mission.

Mission description

The principal measurement platforms for POLARIS were the NASA ER-2 aircraft and balloons. Four balloons were flown, two providing correlative measurements for the Japanese Advanced Earth Observing Satellite (ADEOS), and one flight each of the NASA Observations of the Middle Stratosphere (OMS) in-situ and remote payloads. Small balloons also were used for ozone sondes throughout the mission.

Spatial and temporal coverage

The 35 ER-2 and 4 balloon flights during the POLARIS campaign covered the entire summer period and latitudes from the equator to the pole (see Table 1). Figure 1 Table 1 displays the flight tracks of the NASA ER-2 (black lines) superimposed on an image of the total ozone amounts from the Earth Probe Total Ozone Mapping Spectrometer (TOMS) instrument. The three deployment phases of POLARIS are seen as the groupings of the black lines in Figure 1 and are also noted in Table 1. The phases occurred in April–May (Phase I), June–July (Phase II), and September (Phase III). The 35 flight included 19 flights from Fairbanks, Alaska (65°N), 3 from the NASA Ames Research Center (ARC) (37°N), one flight flown to 3°S from Barbers Point, HI (21°N), seven transit flights, as well as 4 January 1997 test flights of the $ClONO_2$ instrument from ARC. The region of continuous (24-hour per day) sunlight is indicated by the white line in Figure 1. Deployment Phase I occurred after continuous daylight began at the north pole, Phase II was timed to the summer solstice when continuous daylight was covering the maximal amount of the polar area, and Phase III was timed to cover the disappearance of continuous polar daylight at summer equinox.

The altitudes sampled during POLARIS extended from the surface to approximately 20 km for the ER-2, and up to 30 km for the ADEOS and OMS balloon flights. Figure 2 displays the altitude profiles of the ER-2 and balloon flights (thin white lines). These altitude profiles are superimposed on ozone density contours as derived from the ozone sondes launched from Fairbanks. The three phases of POLARIS are seen again in the groupings of the lines over the course of the summer period. The ADEOS and OMS balloon flights are labeled on the figure, and are also differentiated from the ER-2 flights by the greater maximum altitudes. Figure 2

The POLARIS flights covered latitudes from 3°S to 90°N (see Table 1). Figure 3 Figure 3 shows the three POLARIS deployment sites, the latitudinal/longitudinal extent of all mission flights, and the May–September 1997 average of TOMS total ozone. ADEOS and OMS balloon flights were launched from Fairbanks and generally landed near to Fairbanks depending on wind speeds. Ozone sondes were launched at the University of Alaska in Fairbanks throughout the April to September period and with higher frequency during the deployment phases [*Lloyd et al.,* this issue]. The launch dates are indicated by the dark triangles at the bottom of Figure 2. These sondes provided near-continuous monitoring of overhead ozone amounts over the course of the three POLARIS deployments.

During the June–September period, the polar region is surrounded by a maximum of ozone near 55°N as is apparent in Figure 1 and 3 (see e.g., *Godson,* [1960]). Fairbanks is located poleward of this maximum, and in a region where ozone temporally decreases by a large amount between spring and fall. Hence, POLARIS was staged from Fairbanks because of the proximity to the region of continuous sunlight, the ozone spatial structure, and the region of large spring to fall ozone change.

The evolving meteorological fields influenced the planning of ER-2 flight paths and launch opportunities for the balloons. Because clearance into Russian-controlled airspace was difficult to obtain, flights were also restricted to the western hemisphere. The extent of solar exposure received by an air mass in the preceding five to ten days was an important parameter in the selection of air masses to be sampled on ER-2 flights. This and other flight planning tools were utilized to sample solar exposure gradients and maximum possible values.

Airborne payloads

The list of POLARIS instruments, measured parameters, measurement techniques, and references are listed in Table 2. This payload provides measurements of radical, reservoir, and source gases in all of the major stratospheric families (chlorine, bromine, nitrogen, oxygen, and hydrogen). In addition, measurements were made of the UV and visible solar spectrum, particle number and size, and meteorological variables. The POLARIS ER-2 payload was expanded over that of previous missions with the addition of both in situ and remote measurements. New in situ measurements included $ClONO_2$ and an additional measurement of NO_2 [*Perkins et al.,* 1999]. The $ClONO_2$ measurements are the first to be made in situ in the stratosphere [*Stimpfle et al.,* this issue]. New remote measurements are those of the submillimeter limb sounder (SLS). With the exception of the SLS instrument, the payload in Table 2 was flown on all POLARIS flights. SLS and a small subset of the full payload were flown on the ER-2 transit flights between Moffett Field, CA, and Fairbanks between the Phase I and II, and Phase II and III deployments.

Table 2

The POLARIS OMS activities made use of a remote sensing payload and an in-situ measurements payload (see Table 3). The in-situ payload focused on measurements of long-lived trace gases for investigating stratospheric transport issues. The remote payload combined an in situ ozone measurement with the long-path absorption measurements of the MkIV Fourier transform interferometer (FTIR) (see Table 3). The MkIV FTIR measured a wide range of radicals, reservoir species, and long-lived trace

Table 3

gases.

The ADEOS correlative balloon flights included two payload configurations, both including remote and in situ instruments (see Table 4). The payloads were flown on 30 April 1997 and 8 May 1997. Table 4

Ground-based observations

Ground-based measurements of ozone column amounts were provided by two spectrophotometers at Fairbanks (Table 4) during and between the deployment phases in conjunction with the UV and visible radiation measurements made on the ER-2 [*Lloyd et al.,* this issue]. Between deployment phases, the MkIV FTIR instrument was also used on the ground at Fairbanks to measure column abundances of many of the molecules listed in Table 4.

Satellite investigations

Relating the POLARIS observations to satellite and ground-based measurements was important to establishing an overall understanding of the evolution of polar ozone from spring to fall. Satellite and ground station measurements of ozone form the backbone of the global ozone monitoring system [*WMO,* 1999]. The Earth Probe TOMS, ADEOS TOMS, the Upper Atmosphere Research Satellite (UARS) Halogen Occultation Experiment (HALOE), the UARS Microwave Limb Sounder (MLS), and Stratospheric Aerosol and Gas Experiment (SAGE II) instruments all provided ozone measurements that contributed to POLARIS field and analysis activities (see Table 4).

In addition, HALOE and SAGE II measured other species that were measured by the ER-2 and balloon instrument payloads, for example, NO_2 (see Tables 2, 3, and 4).

Theoretical investigations

Accurate meteorological forecasts and theoretical modeling of the stratosphere were important aspects of the POLARIS mission. Meteorological forecasts by the GEOS-1 model of the NASA/GSFC Data Assimilation Office [*Coy et al.,* 1997a; *Coy et al.,* 1997b] and the Australian Bureau of Meteorology's Global Assimilation and Prediction (GASP) model [*Waugh et al.,* 1998] were used in the detailed flight planning of the ER-2. GEOS-1 analyses were used to compute air mass trajectories [*Schoeberl et al.,* 1993; *Newman and Schoeberl*, 1995; *Fairlie et al,* this issue]. National Centers for Environmental Prediction (NCEP) data were used to detail the summer evolution of the stratospheric meteorological conditions [*Rosenlof,* this issue]. In addition, satellite cloud images and forecast data were used to forecast the movement of cirrus cloud systems that can dehydrate the tropical upper troposphere [*Jensen et al.,* 1996]. This cloud information was combined with the meteorological information, gravity wave forecasts [*Bacmeister et al.,* 1994], and a mesoscale model [*Hitchman et al.,* this issue] for planning high resolution sampling of the upper troposphere and lower stratosphere (see the multiple level flights indicated in Table 1).

Models of the chemical [*Salawitch et al.,* 1994; *Kawa et al.,* 1997] and photolysis fields [*Swartz et al.,* this issue] provided a basis for comparison to observations. These chemical models were also used with the meteorological forecasts to plan flights. The predictions and post-flight comparisons to data have been subsequently utilized to refine our understanding of the stratosphere.

Forecasting air motions in the winter stratosphere is principally done using potential vorticity (PV) and temperatures [*Tuck et al.,* 1989; *Waugh et al.,* 1998]. During summer, the weak easterly circulation, lack of a well defined vortex, and lack of a distinctive cold air region makes accurate forecasting difficult. However, the unusual persistence of the winter polar vortex allowed the usage of GEOS-1 [*Coy et al.,* 1997a; *Coy et al.,* 1997b; *Fairlie et al,* this issue] and PV fields to plan ER-2 flight tracks in the first phase of POLARIS.

Because photochemical active species are dependent on the extent and duration of the continuous sunlight, new forecast products were developed to find air masses that had undergone continuous sunlight for extended periods. These "solar exposure fields" utilized GEOS-1 model forecast information to calculate the time that air parcels had been exposed to sunlight with solar zenith angles less than 92°. The fields were calculated using a grid of points with an isentropic trajectory model [*Newman and Schoeberl*, 1995; *Schoeberl and Newman,* 1995; *Fairlie et al,* this issue] that integrates the amount of sunlight encountered by an air mass over a 10 day period. As an example, the flight of 13 May is superimposed on the solar exposure field in Figure 4. The flight Figure 4 was planned to cross an air mass which was moving southward from the pole to North America. This air had received nearly continuous exposure to sunlight for 10 days. The flight track bearing was slightly east of north to further encounter an air mass that recently traveled northward from the eastern hemisphere. All of the POLARIS "photolysis" flights (see Table 1) were planned using these solar exposure fields.

Deployment Descriptions

Phase I: April–May. This ER-2 flight series covered a latitude range from 13°N to 90°N at cruise altitudes near 20 km in the lower stratosphere (see Table 1). On most flights, vertical coverage extended from approximately 15 to 21 km at selected latitudes. Vertical profiles were obtained between cruise altitude at approximately 20 km and the surface at the two deployment sites, ARC (37°N) and Fairbanks (65°N).

A number of POLARIS objectives were achieved during this phase. First, the ER-2 penetrated the northern polar vortex on 26 April 1997 during a flight that reached the north pole. In the spring of 1997, the polar vortex had unusually low ozone that persisted for an exceptionally long period (see *Newman et al.* [1997], *Fioletov et al.* [1997], and *Donovan et al.*, [1997]). Second, the ER-2 completed flights that separately included a sunrise (30 April 1997) and sunset (9 May 1997) at high latitudes in the stratosphere. The data indicated unusual asymmetries in the behavior of hydrogen radicals at low-angle solar illumination [*Wennberg et al.,* 1999]. Third, the ER-2 sampled stratospheric air masses that had experienced continuous sunlight for periods ranging from 1 to 12 days (2, 6, and 13 May 1997; see *Del Negro et al.* this issue). These flights revealed important observational-model (photochemical steady-state and trajectory) discrepancies with respect to NO_x concentrations (for example, see *Gao et al.* [1999]). Fourth, there were two successful launches of the ADEOS correlative balloon payloads on 30 April [*Jucks et al.,* this issue] and 8 May 1997 [*Toon et al.,* this issue, 1999a].

Phase II: June–July. With the ER-2 based solely in Fairbanks during Phase II, the latitude survey range extended from 47.7°N to 90°N in the lower stratosphere (see Table 1). Vertical coverage to 21 km in the Fairbanks region was quite good because of dedicated flights on 30 June 1997 and 10 July 1997 that included a number of flight legs at specific altitudes in the upper troposphere and lower stratosphere. In addition, vertical profiles were obtained over the 15- to 20-km altitude range near 47.7°N and 90°N.

POLARIS objectives achieved during this phase included sampling of mid-summer polar air that had undergone continuous solar exposure for an extended period [*Del Negro et al.,* this issue]; OMS balloon flights using the in situ and MkIV FTIR payloads to altitudes in excess of 30 km (performed coincidentally with ER-2 flights [*Toon et al.,* this issue, 1999a]); and sampling of winter polar vortex fragments in mid-summer [*Herman,* 1998; *Hurst et al.,* 1999; *Fairlie et al,* this issue].

Phase III: September. Phase III ER-2 flights included latitudes extending from 90°N to 3°S in the lower stratosphere (see Table 1). Both sunrise and sunset flights in late summer were conducted over the Fairbanks region, similar to those flown in Phase I. In addition, a midday solar zenith angle flight was flown, providing a nearly full scan of solar zenith angles from sunrise to sunset in similar air masses.

As the final component of this phase, the ER-2 transited to Barbers Point, Hawaii, performed a flight to slightly south of the equator, and returned to ARC. Vertical profiles from the ground to 21 km occurred at Fairbanks, Hawaii, and ARC, with profiles over the 15- to 20-km altitude range near 3°S and 90°N. These tropical vertical profiles complete a time series of measurements extending back 1994 to 1997 [*Andrews et al.,* this issue].

POLARIS Science topics

This collection of Journal of Geophysical Research papers is the first to interpret the POLARIS data set in a comprehensive manner. These papers address stratospheric ozone abundances and its changes; the photochemical role of aerosols and soot; details of the photochemistry of reactive species; stratospheric transport and the correlations of long-lived species; and measurement intercomparisons. Data from ground-based instruments and those on the ER-2 aircraft, balloons, satellites, and sondes are included, thereby representing the full range of available observational data. In addition, many papers rely directly or indirectly on meteorological analyses. Box models, trajectory models, and 2-D and 3-D photochemical transport models are widely used to add value to the observations. Finally, these papers are augmented by several published separately since the end of the POLARIS field campaign [*Herman,* 1998; *Gao et al.,* 1999; *Osterman et al.,* 1999; *Wennberg et al.,* 1999; *Hurst et al.,* 1999; *Hintsa et al.,* 1999; *Nevison et al.,* 1999].

The most extensive observations available for POLARIS are those of ozone in column and profile abundances. Each data set clearly marks the late spring-to-summer decline in ozone amounts [*Lloyd et al.,* this issue; *Pierce et al.,* this issue; *Toon et al.,* this issue, 1999a; *Toon et al.,* this issue, 1999b]. Intercomparisons show good systematic agreement among the various data sets [*Lloyd et al.,* this issue; *Toon et al.,* this issue, 1999a; *Toon et al.,* this issue, 1999b].

The ozone observations form the basis for addressing an important objective of POLARIS: Are the observed summer ozone decreases consistent with our understanding of transport and chemical processes? With the papers included here, a fully consistent picture has yet to emerge [*Pierce et al.,* this issue; *Rosenlof,* this issue; *Toon et al.,* this issue, 1999a; *Hitchman et al.,* this issue]. In general, ozone amounts throughout the stratosphere represent a balance of transport and photochemical production and destruction processes. The combination of models and observations confirm the role of photochemistry in summer ozone decreases at high latitudes [*Gao et al.,* 1999; *Wennberg et al.,* 1999; *Del Negro et al.,* this issue; *Drdla et al.,* this issue; *Pierce et al.,* this issue; *Stimpfle et al.,* this issue]. The transport contributions are calculated from the meteorological analyses [*Rosenlof,* this issue] (the residual circulation usually brings air to high latitudes from lower latitudes), or deduced as a difference between the net ozone change and calculated photochemical change [*Pierce et al.,* this issue]. These photochemical calculations include the effects of small-scale mixing [*Fairlie et al,* this issue]. Column ozone amounts also change as a result of synoptic waves disturbing the tropopause region [*Hitchman et al.,* this issue].

The large number of long-lived and radical species measured during POLARIS provide an unprecedented opportunity to diagnose photochemical processes and measure trace species abundances in the summer high latitude stratosphere [*Gao et al.,* 1999; *Osterman et al.,* 1999; *Wennberg et al.,* 1999; *Hurst et al.,* 1999; *Hintsa et al.,* 1999; *Del Negro et al.,* this issue; *Jucks et al.,* this issue; *Randeniya et al.,* this issue; *Sen et al.,* this issue; *Stimpfle et al.,* this issue; *Swartz et al.,* this issue; *Drdla et al.,* this issue]. A highlight of the results are the analyses of the partitioning of the NO_y and Cl_y reservoirs. The enhanced and uninterrupted solar illumination at summer high latitudes increases the abundance of NO_x within the NO_y reservoir and the associated catalytic ozone loss [*Gao et al.,* 1999; *Del Negro et al.,* this issue]. Comparisons using box models constrained by observations and other models showed unsatisfactory agreement when using currently recommended kinetic rate coefficients. More recent measurements of the rates of the gas-phase reactions of OH with NO_2 and HNO_3 by *Brown et al.,* [1999] and *Dransfield et al.,* [1999] have substantially improved the agreement in most comparisons [*Gao et al.,* 1999; *Wennberg et al.,* 1999; *Del Negro et al.,* this issue]. The sunrise and sunset flights revealed the need for an additional HO_x source in current models. The source could be the long-wavelength ($>$ 650 nm) photolysis of HNO_4 [*Wennberg et al.,* 1999]. The NO_y analyses benefited from two in situ measurements of NO_2 on board the ER-2 aircraft which showed good agreement throughout the mission and were consistent with the NO observations [*Del Negro et al.,* this issue]. The evaluations of the partitioning within the Cl_y reservoir demonstrate a good understanding throughout the lower stratosphere [*Flocke et al.,* this issue; *Randeniya et al.,* this issue; *Romashkin et al.,* this issue; *Sen et al.,* this issue; *Toon et al.,* this issue, 1999a]. New in situ measurements of $ClONO_2$ on the ER-2 aircraft were an important addition to these analyses [*Stimpfle et al.,* this issue]. An analysis of the hydrogen budget also shows good agreement with our theoretical expectations in the lower stratosphere [*Hurst et* *al.*, 1999].

Measurements of the UV-visible radiation combined with measurements of radical species demonstrate the accuracy of our understanding of photolytic processes. Photolysis rates for NO_2 are derived independently using both CPFM measurements and chemical measurements [*Swartz et al.*, this issue; *Del Negro et al.*, this issue]. The comparisons show good agreement ($< 20\%$), and can be used to test the photolysis sensitivity to surface albedo, clouds, temperature, and ozone profiles [*Swartz et al.*, this issue; *Del Negro et al.*, this issue].

Aerosols play a lesser role in the chemistry of the summer stratosphere because N_2O_5 formation becomes negligible in regions of continuous solar illumination [*Farman et al.*, 1985; *Gao et al.*, 1999; *Osterman et al.*, 1999]. However, the summer stratosphere provides a unique opportunity to evaluate sulfate aerosol processes at warm temperatures (> 210K) [*Drdla et al.*, this issue]. Measurements of soot particles on the ER-2 aircraft [*Strawa et al.*, this issue] suggest that reactions on soot particles do not have a significant role in controlling the partitioning with the NO_y reservoir in agreement with previous studies [*Gao et al.*, 1998].

Special features of the POLARIS mission are the sampling of air from tropical latitudes in late spring and late summer and from the Arctic vortex in late April. These new data from aircraft and balloons extend data sets acquired in previous missions and with other platforms (see e.g., *Wofsy et al.*, [1994] and *Volk et al.*, [1996]). The papers here use these new data sets in part to address transport of air into the tropics and within high latitudes [*Andrews et al.*, this issue; *Flocke et al.*, this issue; *Ray et al.*, this issue; *Rex et al.,* this issue; *Romashkin et al.,* this issue]. Tropical and mid-latitude measurements of species with a wide range of lifetimes were used to quantify the rate of transport of air from mid-latitudes to the inner tropics. The results indicated more rapid transport into the tropics than found in earlier studies [*Flocke et al.,* this issue]. Measurements of CO_2 were used to evaluate the vertical age distribution in the tropical lower stratosphere [*Andrews et al.,* this issue]. SF_6 and CFC observations were used in a unique analysis to estimate the fraction of air in the mid-latitudes lowest-most stratosphere which is from the tropical troposphere and from the stratospheric overworld [*Ray et al.,* this issue]. With long-lived tracer correlations of CH_4, NO_y, and N_2O, mixing processes associated with the Arctic polar vortex were clarified with a specific emphasis on validating the occurrences of denitrification [*Rex et al.,* this issue]. Correlations and age-of-air information were also used to clarify how stratospheric abundances of methyl chloroform are changing in response to changes in tropospheric emission rates [*Romashkin et al.,* this issue].

Summary

The POLARIS mission was conducted over the course of the 1997 summer. The flights covered the polar lower stratosphere at latitudes from the equator to the North Pole. The thirty-five ER-2 aircraft, two OMS balloon flights, and two ADEOS correlative balloon flights provide an unprecedented glimpse of polar summer chemistry, dynamics, and radiation.

The natural decrease of ozone over the course of the summer has been well documented by ground and satellite observations. The chemistry and dynamics of the summer period have only been partially understood from a theoretical basis and limited satellite observations. The new POLARIS observations have firmly grounded our historic ozone observations and model predictions with a large body of new observations. These papers address key issues concerning the photochemistry and transport in the stratosphere and provide important new details on the causes underlying changes in summer ozone amounts.

A highlight of the photochemical investigations is the detailed comparison of radical and reservoir measurements with models. These results initially revealed important discrepancies and agreements in our understanding of stratospheric chemistry. These observations encouraged new laboratory measurements, which have led to revised reaction rate recommendations that significantly improve model agreement with observations. These improvements provide greater confidence in our predictions of future stratospheric change.

POLARIS and other NASA sponsored missions are described at the NASA Ames Earth Science Division Project Office web site (http://cloud1.arc.nasa.gov/). The POLARIS data set and data sets from all the mission prior to POLARIS are available on CD-ROM by request from the NASA Ames Earth Science Division Project Office.

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References

Anderson, J. G., W. H. Brune, S. A. Lloyd, D. W. Toohey, S. P. Sander, W. L. Starr, M. Loewenstein, and J. R. Podolske, Kinetics of O_3 destruction by ClO and BrO within the Antarctic vortex - an analysis based on in situ ER-2 data, *J. Geophys. Res., 94,* 11480–11520, 1989.

Andrews, A. E., K. A. Boering, B. C. Daube, S. C. Wofsy, E. J. Hintsa, E. M. Weinstock, and T. P. Bui, Empirical age spectra for the lower stratosphere from in situ observations of CO_2: Implications for stratospheric transport, *J. Geophys. Res., this issue,* 1999.

Bacmeister J. T., P. A. Newman, B. L. Gary, and K. R. Chan, An algorithm for forecasting mountain wave-related turbulence in the stratosphere, *Weather and Forecasting, 9,* 241–253, 1994.

Barath, F. T., M. C. Chavez, R. E. Cofield, D. A. Flower, M. A. Frerking, M. B. Gram, W. M. Harris, J. R. Holden, R. F. Jarnot, W. G. Kloezeman, G. J. Klose, G. K. Lau, M. S. Loo, B. J. Maddison, R. J. Mattauch, R. P. Mckinney, G. E. Peckham, H. M. Pickett, G. Siebes, F. S. Soltis, R. A. Suttie, J. A. Tarsala, J. W. Waters, W. J. Wilson, The Upper Atmospheric Research Satellite Microwave Limb Sounder Instrument, *J. Geophys. Res., 98,* 10751–10762, 1993.

Baumgardner, D., J. E. Dye, B. Gandrud, and K. Barr, Refractive indices of aerosols in the upper troposphere and lower stratosphere, *Geophys. Res. Lett., 23,* 749–752, 1996.

Boering, K. A., B. C. Daube, S. C. Wofsy, Jr., M. Loewenstein, J. R. Podolske, and E. R. Keim. Tracer-Tracer Relationships and Lower Stratospheric Dynamics: CO_2 and N_2O Correlations During SPADE. *Geophys. Res. Lett., 21,* 2567–2570, 1994.

Boering, K. A., B. C. Daube, S. C. Wofsy, Jr., M. Loewenstein, J. R. Podolske, and T. J. Conway, Stratospheric transport rates and mean age distribution derived from observations of atmospheric CO_2 and N_2O, *Science 274,* 1130–1343, 1996.

Bojkov, R. D., Ozone variations in the northern polar region, *Meteorol. Atmos. Phys., 38,* 117–130, 1988.

Brewer, A. W., Evidence for a world circulation provided by the measurement of helium and water vapour distribution in the stratosphere, *Quart. J. Roy. Met. Soc., 75,* 351–363, 1949.

Brown, S. S., R. K. Talukdar, and A. R. Ravishankara, Reconsideration of the rate constant for the reaction of hydroxyl radicals with nitric acid, *J. Phys. Chem., 103,* 3031–3037, 1999.

Brühl, C., P. J. Crutzen, and J. U. Grooß, High-latitude, summertime NO_x activation and seasonal ozone decline in the lower stratosphere: Model calculations based on observations by HALOE on UARS, *J. Geophys. Res., 103,* 3587–3597, 1998.

Coy, L., E. R. Nash, and P. A. Newman, Meteorology of the polar vortex: Spring 1997, *Geophys. Res. Lett., 24,* 2693–2696, 1997a.

Coy, L., and R. Swinbank, Characteristics of stratospheric winds and temperatures produced by data assimilation, *J. Geophys. Res., 102,* 25763–25781. 1997b.

Chipperfield, M. P., Multiannual simulations with a three-dimensional chemical transport model, *J. Geophys. Res., 104,* 1781–1805, 1999.

Del Negro, L. A., D. W. Fahey, R. S. Gao, S. G. Donnelly, E. R. Keim, J. A. Neuman, R. C. Cohen, K. K. Perkins, L. C. Koch, R. J. Salawitch, S. A. Lloyd, M. H. Proffitt, J. J. Margitan, R. M. Stimpfle, G. P. Bonne, P. B. Voss, P. O. Wennberg, C. T. McElroy, W. H. Swartz, T. L. Kusterer, D. E. Anderson, L. R. Lait, and T. P. Bui, Comparison of modeled and observed values of NO_2 and $J(NO_2)$ during the POLARIS mission, *J. Geophys. Res., this issue,* 1999.

Denning, R. F., S. L. Guidero, G. S. Parks and B. L. Gary, Instrument Description of the Airborne Microwave Temperature Profiler, *J. Geophys. Res., 94,* 16757–16765, 1989.

Dobson, G. M. B., Origin and distribution of polyatomic molecules in the atmosphere, *Proc. Roy. Soc. London, Series A, 236,* 187–193, 1956.

Dobson, G. M. B., D. N. Harrison, and J. Lawrence, Measurements of the amount of ozone in the Earth's atmosphere and its relation to other geophysical conditions, *Proc. Roy. Soc. London, Series A, 122,* 456–486, 1929.

Donovan, D. P., H. Fast, Y. Makino, J. C. Bird, A. I. Carswell, J. Davies, T. J. Duck, J. W. Kaminski, C. T. McElroy, R. L. Mittermeier, S. R. Pal, V. Savastiouk, D. Velkov, and J. A. Whiteway, Ozone, column ClO, and PSC measurements made at the NDSC Eureka observatory (80N, 86W) during the spring of 1997, *Geophys. Res. Lett., 24,* 2709–2712, 1997.

Dransfield, T. J., K. K Perkins, N. M. Donahue, J. G. Anderson, M. M. Sprengnether, and K. L. Dermerjian, Temperature and pressure dependent kinetics of the gas-phase reaction of the hydroxyl radical with nitrogen dioxide, *Geophys. Res. Lett., 25*, 687–690, 1999.

Drdla, K., R. F. Pueschel, A. W. Strawa, R. C. Cohen, and T. F. Hanisco, Microphysics and chemistry of sulphate aerosols at warm stratospheric temperatures, *J. Geophys. Res., this issue,* 1999.

Dunkerton, T. J., C. P. F. Hsu, and M. E. McIntyre, Some Eulerian and Lagrangian diagnostics for a model stratospheric warming, *J. Atmos. Sci., 38,* 819–843, 1981.

Edmon, H. J., B. J. Hoskins, and M. E. McIntyre, Eliassen-Palm cross sections for the troposphere, *J. Atmos. Sci., 37,* 2600–2616, 1980.

Elkins, J. W., D. W. Fahey, J. M. Gilligan, G. S. Dutton, T. J. Baring, C. M. Volk, R. E. Dunn, R. C. Myers, S. A. Montzka, P. R. Wamsley, A. H. Hayden, J. H. Butler, T. M. Thompson, T. H. Swanson, E. J. Dlugokencky, P. C. Novelli, D. F. Hurst, J. M. Lobert, S. J. Ciciora, R. J. McLaughlin, T. L. Thompson, R. H. Winkler, P. J. Fraser, L. P. Steele, and M. Lucarelli, Airborne gas chromatograph for in situ measurements of long-lived species in the upper troposphere and lower stratosphere, *Geophys. Res. Lett., 23,* 347–350, 1996.

Fahey, D. W., K. K. Kelly, G. V. Ferry, L. R. Poole , J. C. Wilson, D. M. Murphy, M. Loewenstein, and K. R. Chan, In situ aerosol measurements of total reactive nitrogen, total water, and aerosol in a polar stratospheric cloud in the Antarctic, *J. Geophys. Res., 94,* 11,299–11,315, 1989.

Fahey, D. W., and A. R. Ravishankara, Summer in the stratosphere, *Science, in press,* 1999.

Fairlie, T. D., R. B. Pierce, J. A. Al-Saadi, W. L. Grose, J. M. Russell, III, M. H. Proffitt, and C. R. Webster, The contribution of mixing in Lagrangian photochemical predictions of polar ozone loss over the Arctic in summer 1997, *J. Geophys. Res., this issue,* 1999.

Farman, J. C., R. J. Murgatroyd, A. M. Silnickas, and B. A. Thrush, Ozone photochemistry in the Antarctic stratosphere in summer, *Quart. J. R. Met. Soc., 111,* 1013–1028, 1985.

Fioletov, V. E., J. B. Kerr, D. I. Wardle, J. Davies, E. W. Hare, C. T. McElroy, and D. W. Tarasick, Long-term ozone decline over the Canadian Arctic to early 1997 from ground-based and balloon observations, *Geophys. Res. Lett., 24*, 2705–62708, 1997.

Flocke, F., R. L. Herman, R. J. Salawitch, E. Atlas, C. R. Webster, S. M. Schauffler, R. A. Lueb, R. D. May, E. J. Moyer, K. H. Rosenlof, D. C. Scott, D. R. Blake, and T. P. Bui, An examination of chemistry and transport processes in the tropical lower stratosphere using observations of long-lived and short-lived compounds obtained during STRAT and POLARIS, *J. Geophys. Res., this issue,* 1999.

Gao, R. S., D. W. Fahey, R. J. Salawitch, S. A. Lloyd, D. E. Anderson, R. Demajistre,

C. T. McElroy, E. L. Woodbridge, R. C. Wamsley, S. G. Donnelly, L. A. DelNegro, M. H. Proffitt, R. M. Stimpfle, D. W. Kohn, S. R. Kawa, L. R. Lait, M. Loewenstein, J. R. Podolske, E. R. Keim, J. E. Dye, J. C. Wilson, and K. R. Chan, Partitioning of the reactive nitrogen reservoir in the lower stratosphere of the southern hemisphere: Observations and modeling, *J. Geophys. Res., 102,* 3935–3949, 1997.

Gao, R. S., B. Karcher, E. R. Keim, and D. W. Fahey, Constraining the heterogeneous loss of O_3 on soot particles with observations in jet engine exhaust plumes, *Geophys. Res. Lett., 25,* 3323–3326, 1998.

Gao, R. S., D. W. Fahey, L. A. Del Negro, S. G. Donnelly, E. R. Keim, J. A. Neuman, E. Teverovskaia, P. O. Wennberg, T. F. Hanisco, E. J. Lanzendorf, M. H. Proffitt, J. J. Margitan, J. C. Wilson, J. W. Elkins, R. M. Stimpfle, R. C. Cohen, C. T. McElroy, T. P. Bui, R. J. Salawitch, S. S. Brown, A. R. Ravishankara, R. W. Portmann, M. K. W. Ko, D. K. Weisenstein, and P. A. Newman, A comparison of observations and model simulations of NO_x/NO_y in the lower stratosphere, *Geophys. Res. Lett., 26,* 1153–1156, 1999.

Gettelman, A., J. R. Holton, and K. H. Rosenlof, Mass fluxes of O_3, CH_4, N_2O and CF_2Cl_2 in the lower stratosphere calculated from observational data, *J. Geophys. Res., 102,* 19149–19159, 1997.

Godson, W. L., Total ozone and the middle stratosphere over arctic and sub-arctic areas in winter and spring, *Q. J. Roy. Met. Soc., 86,* 301–317, 1960.

Hara, K., T. Kikuchi, K. Furuya, M. Hayashi, and Y. Fujii, Characterization of Antarctic aerosol particles using Laser Microprobe Mass spectrometry, *Environmental Sci. Tech., 30,* 385–391, 1996.

Herman, R. L., D. C. Scott, C. R. Webster, R. D. May, E. J. Moyer, R. J. Salawitch, Y. L. Yung, G. C. Toon, B. Sen, J. J. Margitan, K. H. Rosenlof, H. A. Michelsen, and J. W. Elkins, Tropical entrainment time scales inferred from stratospheric N_2O and CH_4 observations, *Geophys. Res. Lett., 25,* 2781–2784, 1998.

Hitchman, M. H., M. L. Buker, and G. J. Tripoli, Influence of synoptic waves on column ozone during Arctic summer 1997, *J. Geophys. Res., this issue,* 1999.

Hintsa, E. J., E. M. Weinstock, J. G. Anderson, R. D. May, and D. F. Hurst, On the accuracy of in situ water vapor measurements in the troposphere and lower stratosphere with the Harvard Lyman-α hygrometer, *J. Geophys. Res., 104,* 8183–8189, 1999.

Hurst, D. F., G. S. Dutton, P. A. Romashkin, P. R. Wamsle, F. L. Moore, J. W. Elkins, E. J. Hintsa, E. M. Weinstock, R. L. Herman, E. J. Moyer, D. C. Scott, R. D. May, and C. R. Webster, Closure of the total hydrogen budget of the northern extratropical lower stratosphere, *J. Geophys. Res., 104,* 8191–8200, 1999.

Jensen, E. J., O. B. Toon, L. Pfister, and H. B. Selkirk, Dehydration of the upper troposphere and lower stratosphere by subvisible cirrus clouds near the tropical tropopause, *Geophys. Res. Lett., 23,* 825–828, 1996.

Johnson, D. G., K. W. Jucks, W. A. Traub, and K. V. Chance, Smithsonian stratospheric far-infrared spectrometer and data reduction system, *J. Geophys. Res., 100,* 3091–3106, 1995.

Johnston, H. S., Global ozone balance in the natural stratosphere, *Rev. Geophys. Space Phys., 13,* 637–649, 1975.

Jost, H., M. Loewenstein, L. Pfister, J. J. Margitan, A. Y. Chang, R. J. Salawitch, and H. A. Michelsen, Laminae in the tropical middle stratosphere: Origin and age estimation, *Geophys. Res. Lett., 26* 4337–4340, 1998.

Jucks, K. W., D. G. Johnson, K. V. Chance, W. A. Traub, and R. J. Salawitch, Nitric acid in the middle stratosphere as a function of altitude and aerosol loading, *J. Geophys. Res., this issue,* 1999.

Kawa, S. R., P. A. Newman, L. R. Lait, M. R. Schoeberl, R. M. Stimpfle, D. W. Kohn, C. R. Webster, R. D. May, D. Baumgardner, J. E. Dye, J. C. Wilson, K. R. Chan, and M. Loewenstein, Activation of chlorine in sulfate aerosol as inferred from aircraft observations, *J. Geophys. Res., 102,* 3921–3933, 1997.

Kerr, J.B.W., et al., The Automated Brewer Spectrophotometer, in Atmospheric Ozone, *Proc. of the Quad. Ozone Symp.*, Halkidiki, Greece, edited by C.S. Zerofos and A. Ghazi, 396–401, D. Reidel, Hingham, Mass., 1985.

Komhyr, W.D., R.A. Barnes, G.B. Brothers, J.A. Lathrop, and D.P. Opperman, Electrochemical concentration cell ozonesonde performance evaluation during STOIC 1989, *J. Geophys. Res., 100,* 9231–9244, 1995.

Krueger, A. J., The global distribution of total ozone: TOMS satellite measurements, *Planet. Space Sci., 37,* 1555–1565, 1989.

Lloyd, S., W. H. Swartz, T. Kusterer, D. Anderson, C. T. McElroy, C. Midwinter, R. Hall, K. Nassim, D. Jaffe, W. Simpson, J. Kelley, D. Griffin, D. Nicks, B. Johnson, R. Evans, D. Quincy, S. Oltmans, P. Newman, R. McPeters, G. Labow, L. Moy, C. Seftor, G. Toon, B. Sen, and J.-F. Blavier, Intercomparison of total ozone observations at Fairbanks, Alaska during POLARIS, *J. Geophys. Res., this issue,* 1999.

London, J., R. D. Bojkov, S. Oltmans, and J. I. Kelly, Atlas of the global distribution of total ozone, July 1957–June 1967, *National Center for Atmosphere Research, NCAR/TN113+STR,* Boulder, CO, 1976.

Luo, M., J. H. Park, K. M. Lee, J. M. Russell, and C. Brühl, An analysis of HALOE observations in summer high latitudes using airmass trajectory and photochemical model calculations, *J. Geophys. Res., 102,* 16145–16156, 1997.

May, R. D., Open-path, near-infrared tunable diode laser spectrometer for atmospheric measurements of H_2O, *J. Geophys. Res., 103,* 19161–19172, 1998.

McCormick, M.P., SAGE II: An overview, *Adv., Space Res., 7,* 219–226, 1987.

McElroy, C.T., A spectroradiometer for the measurement of direct and scattered solar irradiance from on-board the NASA ER-2 high-altitude research aircraft, *Geophys. Res. Lett., 22,* 1361–1364, 1995.

McPeters R. D., and G. J. Labow, An assessment of the accuracy of 14.5 years of

Nimbus-7 TOMS Version 7 ozone data by comparison with the Dobson network, *Geophys. Res. Lett., 23,* 3695–3698, 1996.

Murcray, F. J., J. R. Starkey, W. J. Williams, W. A. Matthews, U. Schmidt, P. Aimedieu, and C. Camy-Peyret, HNO_3 profiles obtained during the EASOE campaign, *Geophys. Res. Lett., 21,* 1223–1226, 1994.

Nevison, C. D., S. Solomon, and R. S. Gao, Buffering interactions in the modeled response of stratospheric O_3 to increased NO_x and HO_x, *J. Geophys. Res., 104,* 3741–3754, 1999.

Newman, P. A., and M. R. Schoeberl, A reinterpretation of the data from the NASA stratosphere-troposphere exchange Project, *Geophys. Res. Lett., 22,* 2501–2504, 1995.

Newman, P. A., J. F. Gleason, R. D. McPeters, and R. S. Stolarski, Anomalously low ozone over the Arctic, *Geophys. Res. Lett., 24,* 2689–2692, 1997.

Osterman, G. B., B. Sen, G. C. Toon, R. J. Salawitch, J. J. Margitan, J. F. Blavier, D. W. Fahey, and R. S. Gao, Partitioning of NO_y species in the summer Arctic stratosphere, *Geophys. Res. Lett., 26,* 1157–1160, 1999.

Park, J. H., and J. M. Russell, III, Summer polar chemistry observations in the stratosphere made by HALOE, *J. Atmos. Sci., 51,* 2903–2913, 1994.

Perkins, K. K., T. F. Hanisco, R. C. Cohen, L. C. Koch, R. M. Stimpfle, P. B. Voss, G. P. Bonne, E. J. Lanzendorf, J. G. Anderson, P. O. Wennberg, R. S. Gao, L. A. Del Negro, R. J. Salawitch, C. T. McElroy, E. J. Hintsa, M. Loewenstein, and

T. P. Bui, An examination of the NO_x-HNO_3 system in the lower stratosphere: Insights from in situ measurements during periods of continuous sunlight, *J. Geophys. Res.,* submitted, 1999.

Perliski, L. M., S. Solomon, and J. London, On the interpretation of the seasonal variations of stratospheric ozone, *Planet. Space Sci., 37,* 1527–1538, 1989.

Peter, T., Microphysics and heterogeneous chemistry of polar stratospheric clouds, *Ann. Rev. Phys. Chem., 48,* 785–822, 1997.

Pierce, R. B., J. A. Al-Saadi, T. D. Fairlie, J. R. Olson, R. S. Eckman, W. L. Grose, G. S. Lingenfelser, and J. M. Russell, III, Large-scale stratospheric ozone photochemistry and transport during the POLARIS campaign, *J. Geophys. Res., this issue,* 1999.

Podolske, J. and M. Loewenstein, Airborne tunable diode laser spectrometer for trace-gas measurement in the lower stratosphere, *Appl. Opt., 32,* 5324–5333, 1993.

Poole L. R., and M. C. Pitts, Polar stratospheric cloud climatology based on Stratospheric Aerosol Measurement-II observations from 1978 to 1989, *J. Geophys. Res., 99,* 13083–13089, 1994.

Proffitt, Michael H. and Richard J. McLaughlin, Fast-response dual-beam UV absorption ozone photometer suitable for use on stratospheric balloons, *Rev. Sci. Instrum., 54,* 1719–1728, 1983.

Pueschel, R. F., K. G. Snetsinger, J. K. Goodman, O. B. Toon, G. V. Ferry, V. R.

Oberbeck, J. M. Livingston, S. Verma, W. Fong, W. L. Starr, and K. R. Chan, Condensed nitrate, sulfate, and chloride in Antarctic stratospheric aerosols, *J. Geophys. Res., 94,* 11271–11284, 1989.

Ray, E. A., F. L. Moore, J. W. Elkins, G. S. Dutton, D. W. Fahey, H. Vomel, S. J. Oltmans, and K. H. Rosenlof, Transport into the Northern Hemisphere lowermost stratosphere revealed by in situ tracer measurements, *J. Geophys. Res., this issue,* 1999.

Randeniya, L. K., I. C. Plumb, and K. R. Ryan, NO_y and Cl_y partitioning in the middle stratosphere: A box model investigation using HALOE data, *J. Geophys. Res., this issue,* 1999.

Rex, M., R. J. Salawitch, G. C. Toon, B. Sen, J. J. Margitan, G. B. Osterman, J.-F. Blavier, R. S. Gao, S. Donnelly, E. Keim, J. Neuman, D. W. Fahey, C. R. Webster, D. C. Scott, R. L. Herman, R. D. May, E. J. Moyer, M. R. Gunson, F. W. Irion, A. Y. Chang, C. P. Rinsland, and T. P. Bui, Subsidence, mixing and denitrification of Arctic polar vortex air measured during POLARIS, *J. Geophys. Res., this issue,* 1999.

Romashkin, P. A., D. F. Hurst, J. W. Elkins, P. R. Wamsley, F. L. Moore, and G. S. Dutton, The effect of the tropospheric trend on the stratospheric tracer-tracer correlations: methyl chloroform, *J. Geophys. Res., this issue,* 1999.

Rosenlof, K., Estimates of the seasonal cycles of mass and ozone transport at high northern latitudes, *J. Geophys. Res., this issue,* 1999.

Russell, III, J. M., L. L. Gordley, J. H. Park, S. R. Drayson, W. D. Hesketh, R. J. Cicerone, A. F. Tuck, J. E. Frederick, J. E. Harries, and P. J. Crutzen, The Halogen Occultation Experiment, *J. Geophys. Res., 98,* 10777–10798, 1993.

Russell, P. B., L. Pfister, and H. B. Selkirk, The tropical experiment of the Stratosphere-Troposphere Exchange Project (STEP)—science objectives, operations, and summary findings, *J. Geophys. Res., 98,* 8563–8589, 1993.

Salawitch, R. J., S. C. Wofsy, P. O. Wennberg, R. C. Cohen, J. G. Anderson, D. W. Fahey, R. S. Gao, E. R. Keim, E. L. Woodbridge, R. M. Stimpfle, J. P. Koplow, D. W. Kohn, C. R. Webster, R. D. May, L. Pfister, E. W. Gottlieb, H. A. Michelsen, G. K. Yue, M. J. Prather, J. C. Wilson, C. A. Brock, H. H. Jonsson, J. E. Dye, D. Baumgardner, M. H. Froffitt, M. Loewenstein, J. R. Podolske, J. W. Elkins, G. S. Dutton, E. J. Hintsa, A. E. Dessler, E. M. Weinstock, K. K. Kelly, K. A. Boering, B. C. Daube, K. R. Chan, and S. W. Bowen, The diurnal-variation of hydrogen, nitrogen, and chlorine radicals—implications for the heterogeneous production of HNO2, *Geophys. Res. Lett., 21,* 2551–2554, 1994.

Sasano, Y., M. Suzuki, T. Yokota, and H. Kanzawa, Improved Limb Atmospheric Spectrometer (ILAS) for stratospheric ozone layer measurements by solar occultation technique, *Geophys. Res. Lett., 26,* 197–200, 1999.

Schauffler, S. M., E. L. Atlas, F. Flocke, R. A. Lueb, V. Stroud, and W. Travnicek, Measurements of bromine containing organic compounds at the tropical tropopause, *Geophys. Res. Lett., 25,* 317–320, 1998.

Schoeberl M. R., S. D. Doiron, L. R. lait, P. A. Newman, and A. J. Krueger, A simulation of the Cerro Hudson SO_2 cloud, *J. Geophys. Res., 98,* 2949–2955, 1993.

Schoeberl, M. R., and P. A. Newman, A multiple level trajectory analysis of vortex filaments, *J. Geophys. Res., 100,* 25801–25815, 1995.

Scott, D. C., R. L. Herman, C. R. Webster, R. D. May, G. J. Flesch, and E. J. Moyer, Airborne Laser Infrared Absorption Spectrometer (ALIAS-II) for In situ Atmospheric Measurements of N_2O, CH_4, CO, HCl, and NO_2, *Applied Optics, 38,* 4609–4622, 1999.

Scott, S. G. , T. P. Bui, K. R. Chan, and S. W. Bowen, The Meteorological Measurement System on the NASA ER-2 aircraft, *J. Atmos. Oceanic Technol., 7,* 525–540, 1990.

Sen, B., G. B. Osterman, R. J. Salawitch, G. C. Toon, J. J. Margitan, J.-F. Blavier, A. Y. Chang, R. D. May, C. R. Webster, R. M. Stimpfle, G. P. Bonne, P. B. Voss, K. K. Perkins, J. G. Anderson, R. C. Cohen, J. W. Elkins, G. S. Dutton, D. F. Hurst, P. A. Romashkin, E. L. Atlas, S. M. Schauffler, and M. Loewenstein, The budget and partitioning of stratospheric chlorine during the 1997 Arctic summer, *J. Geophys. Res., this issue,* 1999.

Stachnik, R. A., J. C. Hardy, J. A. Tarsala, J. W. Waters, and N. R. Erikson, Submillimeter heterodyne measurements of stratospheric ClO, HCl, O_3, and HO_2: First results, *Geophys. Res. Lett., 19,* 1931–1934, 1992.

Stimpfle, R. M., R. C. Cohen, G. P. Bonne, P. B. Voss, K. K. Perkins, L. C. Koch, J. G. Anderson, R. J. Salawitch, S. A. Lloyd, R. S. Gao, L. A. Del Negro, E. R. Keim, and T. P. Bui, The coupling of $ClONO_2$, ClO and NO_2 in the lower stratosphere from in situ observations using the NASA ER-2 aircraft, *J. Geophys. Res., this issue,* 1999.

Strawa, A. W., K. Drdla, G. V. Ferry, S. Verma, M. Yasuda, R. J. Salawitch, R. F. Peuschel, R. S. Gao, S. D. Howard, P. T. Bui, M. Loewenstein, J. W. Elkins, K. K. Perkins, and R. Cohen, Carbonaceous aerosol (soot) measured in the lower stratosphere during POLARIS and its role in stratospheric photochemistry, *J. Geophys. Res., this issue,* 1999.

Swartz, W. A., S. A. Lloyd, T. L. Kusterer, D. E. Anderson, C. T. McElroy, and C. Midwinter, A sensitivity study of photolysis rate coefficients during POLARIS, *J. Geophys. Res., this issue,* 1999.

Toon, G.C., The JPL MkIV Interferometer, *Optics and Photonics News, 2,* 19–21, 1991.

Toon, G. C., J.-F. Blavier, B. Sen, J. J. Margitan, C. R. Webster, R. D. May, D. Fahey, R. Gao, L. Del Negro, M. Proffitt, J. Elkins, P. A. Romashkin, D. F. Hurst, S. Oltmans, E. Atlas, S. Schauffler, F. Flocke, T. P. Bui, R. M. Stimpfle, G. P. Bonne, P. B. Voss, and R. C. Cohen, Comparison of MkIV balloon and ER-2 aircraft measurements of atmospheric trace gases, *J. Geophys. Res., this issue,* 1999a.

Toon, G. C., J.-F. Blavier, B. Sen, R. J. Salawitch, G. B. Osterman, J. Notholt, M. Rex,

C. T. McElroy, P. A. Newman, and J. M. Russell, III, Ground-based observations of Arctic O_3 loss during spring and summer 1997, *J. Geophys. Res., this issue,* 1999b.

Tuck, A. F., R. T. Watson, E. P. Condon, J. J Margitan, and O. B. Toon, The planning and execution of ER-2 and DC-8 aircraft flights over Antarctica, August and September, 1987, *J. Geophys. Res., 94,* 11181–11222, 1989.

Volk, C. M., J. W. Elkins, D. W. Fahey, R. J. Salawitch, G. S. Dutton, J. M. Gilligan, M. H. Proffitt, M. Loewenstein, J. R. Podolske, K. Minschwaner, J. J. Margitan, K. R. Chan, Quantifying transport between the tropical and mid-latitude lower stratosphere, *Science, 272,* 1763–1768, 1996.

Vömel, L, H., M. Rummukainen, R. Kivi, J. Karhu, T. Turunen, E. Kyro, J. Rosen, N. Kjome, and S.J. Oltmans, Dehydration and sedimentation of ice particles in the Arctic stratospheric vortex, *Geophys. Res. Lett., 24,* 795–798, 1997.

Waugh, D. W., J. M. Sisson, and D. J. Karoly, Predictive skill of an NWP system in the southern lower stratosphere, *Q. J. Roy. Meteor. Soc., 124,* 2181–2200, 1998.

Webster, C.R., R.D. May, C.A. Trimble, R.G. Chave and J. Kendall, Aircraft (ER-2) Laser Infrared Absorption Spectrometer (ALIAS) for In-situ Stratospheric Measurements of HCl, N_2O, CH_4, NO_2, and HNO_3, *Applied Optics, 33,* 454–472, 1994.

Weinstock, E. M., E. J. Hintsa, A. E. Dessler, J. F. Oliver, N. L. Hazen, J. N. Demusz, N. T. Allen, L. B. Lapson, and J. G. Anderson, A new fast response photofragment fluorescence hygrometer for use on the ER-2 and Perseus remotely piloted aircraft, *Rev. Sci. Instrum., 65,* 3544–3454, 1994.

Wennberg, P. O., R. J. Salawitch, D. J. Donaldson, T. F. Hanisco, E. J. Lanzendorf, K. K. Perkins, S. A. Lloyd, V. Vaida, R. S. Gao, E. J. Hintsa, R. C. Cohen, W. H. Swartz, T. L. Kusterer, and D. E. Anderson, Twilight observations suggest unknown sources of HO_x, *Geophys. Res. Lett., 26,* 1373–1376, 1999.

Wennberg, P. O., R. C. Cohen, N. L. Hazen, L. B. Lapson, N. T. Allen, T. F. Hanisco, J. F. Oliver, N. W. Lanham, J. N. Demusz, and J. G. Anderson, Aircraft-borne, laser-induced fluorescence instrument for the in situ detection of hydroxyl and hydroperoxyl radicals, *Rev. Sci. Instr., 65,* 1858–1876, 1994.

Wilson, J. E., E. D. Blackshear, and J. H. Hyun, The function and response of an improved stratospheric condensation nucleus counter, *J. Geophys. Res., 88,* 6781–6785, 1983.

World Meteorological Organization (WMO), Scientific Assessment of Ozone Depletion: 1998, *World Meteorological Organization Report 44,* 1999.

Wofsy, S. C., R. C. Cohen, and A. L. Schmeltekopf, Overview—the Stratospheric Photochemistry Aerosols and Dynamics Expedition (SPADE) and Airborne Arctic Stratospheric Expedition-II (AASE-II), *Geophys. Res. Lett., 21,* 2535–2538, 1994.

Wu, M.-F., M. A. Geller, J. G. Olson, and E. M. Larson, A study of global ozone transport and the role of planetary waves using satellite data, *J. Geophys. Res., 92,* 3081–3097, 1987.

Wu, M.-F., M. A. Geller, J. G. Olson, and M. E. Gelman, Troposphere-stratosphere (surface–55km) monthly general circulation statistics for the northern hemisphere—four year averages, *NASA tech. memo., 86182*, pp. 138, 1984.

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Figure 1. Values of total column ozone from the Total Ozone Mapping Spectrometer (TOMS) instrument on the Earth Probe satellite shown as a function of time and latitude during 1997 (figure adapted from *Lloyd et al.,* this issue). Column values are measured in Dobson Units (DU, m-atm cm) and contour lines are separated by 15 DU. No observations are available for the white open areas at high latitudes. The dark vertical lines represent ER-2 flight tracks during POLARIS. The thick white line denotes the boundary of continuous daylight.

Figure 2. Ozone as a function of time and pressure altitude (pressure) during the April to September period of 1997. Ozone amounts are measured in Dobson Units per kilometer (DU km^{-1}). Contours are separated by 2 DU km^{-1}. Observations are from ozone sondes launched from Fairbanks, Alaska, (65°N) on dates marked by yellow triangles at the bottom of the figure (see *Lloyd et al.,* this issue). The thin white vertical lines represent the altitude of ER-2 flights during POLARIS. The thin white lines extending to the top of the image represent the ADEOS and OMS balloon flights. The white horizontal line represents the tropopause.

Figure 3. TOMS total ozone averaged from May 1997 through September 1997 [*Lloyd et al.,* this issue]. Column values are measured in Dobson Units (DU, m-atm cm) with the color scale at the bottom of the figure. Fairbanks, AK, was the principal POLARIS basing site, with a series of test flights from NASA/Ames, and a single flight to the equator flown from Barber's Point, HI. All of the POLARIS ER-2 flights are shown in black.

Figure 4. Solar exposure field for 13 May 1997 on the 450 K isentropic surface. The colors represent the fraction of time spent by an air parcel in sunlight over the 10-day period 03-13 May (see scale on left). The ER-2 flight of 13 May is superimposed on this field as the thick black line running slightly east of due north. High values of solar exposure are correlated with high values of NO_x/NO_y [*Gao et al.,* 1999].

Table 1. POLARIS Flight Log

Date	Type	Flight Hours	POLARIS Flight	Lat.	Comments
			Phase I		
970416	ER-2	2.00	97-01	35°- 38°N	check flight
970418	ER-2	5.00	97-02	36°- 38°N	check flight
970422	ER-2	7.75	97-03	14°- 38°N	south survey from ARC
970424	ER-2	6.00	97-04	37°- 66°N	Transit ARC to FAI
970426	ER-2	8.00	97-05	65°- 90°N	N. Pole—Into vortex
970430	ER-2	6.50	97-06	64°- 65°N	Sunrise
970430	ADEOS	8.77	429N	65°N	Correlative balloon
970502	ER-2	7.58	97-07	65°- 71°N	Photolysis—Canada
970506	ER-2	6.83	97-08	65°- 79°N	Photolysis—Canada
970508	ADEOS	8.55	431N	65°N	Correlative balloon
970509	ER-2	6.17	97-09	64°- 65°N	Sunset
970511	ER-2	4.92	97-10	62°- 65°N	Multiple level
970513	ER-2	6.67	97-11	65°- 85°N	Photolysis—North
970515	ER-2	5.33	97-12	65°- 37°N	Transit FAI to ARC

Table 1. (continued)

Date	Type	Flight Hours	POLARIS Flight	Lat.	Comments
			Phase II		
970623	ER-2	5.25	97-13	37°- 65°N	Transit ARC to FAI
970626	ER-2	7.75	97-14	55°- 77°N	Photolysis—North
970629	ER-2	6.75	97-15	48°- 65°N	Photolysis—South
970630	OMS	5.78	435N	65°N	In situ balloon
970630	ER-2	4.58	97-16	63°- 67°N	OMS comparison
970704	ER-2	8.25	97-17	48°- 71°N	Photolysis—North/South
970707	ER-2	8.00	97-18	65°- 90°N	Photolysis—North
970708	OMS	6.93	436N	65°N	MkIV balloon
970710	ER-2	5.50	97-19	64°- 65°N	Multiple level
970712	ER-2	5.50	97-20	65°- 37°N	Transit FAI to ARC
			Phase III		

Table 1. (continued)

Date	Type	Flight Hours	POLARIS Flight	Lat.	Comments
970902	ER-2	5.50	97-21	37°- 65°N	Transit ARC to FAI
970908	ER-2	7.75	97-22	65°- 86°N	Photolysis
970910	ER-2	0.50	97-23	64°- 65°N	Abort after takeoff
970911	ER-2	4.25	97-24	64°- 65°N	Sunset flight
970914	ER-2	6.40	97-25	64°- 65°N	Sunrise
970918	ER-2	8.00	97-27	65°- 90°N	Photolysis—North Pole
970919	ER-2	7.30	97-28	64°- 65°N	East/West
970921	ER-2	7.33	97-29	65°- 21°N	Transit FAI to BP
970923	ER-2	8.00	97-30	21°N - 3°S	South survey
970925	ER-2	6.00	97-31	21°- 37°N	Transit BP to ARC

Table 2. POLARIS ER-2 Instrument Payload

Instrument	Measurements	Technique	References
H_2O	H_2O	Lyman-α hygrometer	[*Weinstock et al.*, 1994]
HO_x	OH, HO_2	Chemical titration and laser-induced fluorescence	[*Wennberg et al.*, 1994]
$ClONO_2$	$ClONO_2$, ClO	Resonance fluorescence, chemical titration, and thermal dissociation	[*Stimpfle et al.*, this issue]
NO_2	NO_2	Laser-induced fluorescence	[*Perkins et al.*, 1999]
WAS	hydrocarbons, halocarbons, organic nitrates	Whole air canister sample with laboratory analysis by gas chromatography and mass spectrometry	[*Schauffler et al.*, 1998]
CO_2	CO_2	Non-dispersive infrared absorption	[*Boering et al.*, 1994]

Table 2. (continued)

Instrument	Measurements	Technique	References
MMS	P, T, winds	aircraft probes and pressure ports	[*Scott et al.*, 1990]
ACATS	CFC-11, CFC-12, CFC-13, CH_3CCl_3, CCl_4, Halon 1211, SF_6, H_2, N_2O, CH_4	Gas chromatography, electron capture detection	[*Elkins et al.*, 1996]
MASP	particle number, size (0.4–10 μm diameter)	Light scattering by individual particles	[*Baumgardner et al.*, 1996]
NO_y	NO, NO_2, NO_y	NO-O_3 chemiluminescence combined with photolysis for NO_2, catalysis for NO_y	[*Fahey et al.*, 1989]
MTP	temperature profiler	Microwave radiometer	[*Denning et al.*, 1989]

Table 2. (continued)

Instrument	Measurements	Technique	References
ATLAS	N_2O	Tunable diode laser absorption	[*Podolske and Loewenstein,* 1993]
H_2O	H_2O	Open path, far-infrared absorption	[*May,* 1998]
CPFM	solar radiation	UV and visible spectroradiometer	[*McElroy,* 1995]
O_3	O_3	Ultraviolet light absorption	[*Proffitt and McLaughlin,* 1983]
SLS	O_3, H_2O, HNO_3, ClO	Submillimeter-wave emission spectroscopy	[*Stachnik et al.,* 1992]
APS	particle number, size (>0.1 μm diameter)	Wire impaction and electron microscope analysis	[*Pueschel et al.,* 1989]
ALIAS	HCl, N_2O, CH_4, CO	Tunable diode laser absorption	[*Webster et al.,* 1994]

Table 2. (continued)

Instrument	Measurements	Technique	References
CNC	condensation nuclei	Particle growth followed by light scattering	[*Wilson et al.*, 19983]
FCAS	particle number, size (0.08–2 μm diameter)	Light scattering by individual particles	[*Wilson et al.*, 19983]

Table 3. POLARIS OMS Balloon Observations

Instrument	Measurements	Technique	References
		OMS in situ payload	
CO_2	CO_2	Non-dispersive infrared absorption	[*Boering et al.*, 1996]
LACE	CFC-11, CFC-12, CFC-13, SF_6	Gas chromatography with electron capture detection	[*Elkins et al.*, 1996]
ARGUS	N_2O, CH_4	Tunable diode laser absorption	[*Jost et al.*, 1998]
O_3	O_3	Ultraviolet absorption	[*Proffitt and McLaughlin*, 1983]
H_2O	H_2O	Frost-point hygrometer	[*Vömel et al.*, 1997]
ALIAS II	N_2O, CH_4	Tunable diode laser absorption	[*Scott et al.*, 1999]
		OMS remote payload	

Table 3. (continued)

Instrument	Measurements	Technique	References
MkIV	O_3, N_2O, HNO_3, NO_2, CH_4, H_2O, CO, CFC-11, N_2O_5, H_2O_2, HOCl, $ClONO_2$, HCl, HF, CFC-12, NO, HNO_4, OCS, HCN, CCl_4, CF_4, COF_2, $CHFCl_2$, CH_3Cl, C_2H_2, C_2H_6, O_2, N_2, H_2CO, HCOOH, HDO, SF_6, CFC-113, CH_3Cl	Solar infrared absorption	[*Toon,* 1991]
O_3	O_3	Ultraviolet absorption	[*Proffitt and McLaughlin,* 1983]

Table 4. POLARIS Collaborative Measurement Programs and Platforms

Instrument	Measurements	Technique/Satellite	References
	ADEOS Correlative Balloon Measurement – 30 April 1997		
Aerosol	particle size and number	Filter/impactor measurements	[*Hara et al.,* 1996]
O_3	O_3	Ultraviolet absorption	[*Proffitt and McLaughlin,* 1983]
SLS	O_3, N_2O, HNO_3, HO_2, ClO, HCl	Submillimeter limb sounder	[*Stachnik et al.,* 1992]
FIRS-2	O_3, N_2O, HNO_3, NO_2, H_2O, N_2O_5, OH, HO_2, H_2O_2, HOCl, $ClONO_2$, HCl, HF	Far-infrared spectrometer	[*Johnson et al.,* 1995]
	ADEOS Correlative Balloon Measurement – 8 May 1997		
CAESR	O_3, HNO_3, CH_4, CFC-11,	Mid-infrared remote thermal emission	[*Murcray et al.,* 1994]

Table 4. (continued)

Instrument	Measurements	Technique/Satellite	References
	CFC-12, N_2O_5, aerosol	grating spectrometer	
MkIV	CO_2 and 22 of the 33 species listed in table 3	Solar infrared absorption	[*Toon,* 1991]
Aerosol	particle size and number	Filter/impactor measurements	[*Hara et al.,* 1996]
	POLARIS correlative ground and ozonesonde measurements		
ozonesondes	P, T, O_3	Electrochemical cell	[*Komhyr et al.,* 1995]
Brewer	O_3	UV spectra	[*Kerr et al.,* 1985]
Dobson	O_3	Differential UV	[*Lloyd et al.,* this issue]
MkIV	See table 3	Solar infrared absorption	[*Toon,* 1991]

Table 4. (continued)

Instrument	Measurements	Technique/Satellite	References
	POLARIS Satellite Measurement Investigations		
SAGE II	O_3, NO_2, aerosols	ERBS	[*McCormick,* 1987]
TOMS	column O_3	Earth Probe	[*McPeters and Labow,* 1996]
HALOE	O_3, NO, NO_2, H_2O, CH_4, HCl, HF	UARS	[*Russell, J. M., et al.,* 1993]
MLS	O_3, HNO_3, ClO	UARS	[*Barath et al.,* 1993]
ILAS	O_3, HNO_3, NO_2, N_2O, H_2O, CFC-11, CH_4, aerosols	ADEOS	[*Sasano et al.,* 1999]