

PHOTOCHEMISTRY OF OZONE LOSS IN THE ARCTIC REGION IN SUMMER (POLARIS)

End of Mission Statement

December 1997

D. W. Fahey
NOAA Aeronomy Laboratory
Boulder, Colorado

P. A. Newman
NASA Goddard Space Flight Center
Greenbelt, Maryland

POLARIS Project Scientists

This summary is a compilation of research and activities performed by the investigators of the **Photochemistry of Ozone Loss in the Arctic Region in Summer (POLARIS)** aircraft campaign. The campaign was based at the NASA Ames Research Center, Moffett Field, California; Fort Wainwright U. S. Army Base, Fairbanks, Alaska; and Barbers Point Naval Air Station, Hawaii between March and September 1997. The mission was co-sponsored by NASA's Office of Mission to Planet Earth and Office of Aeronautics.

Introduction

The POLARIS aircraft campaign was designed to understand the seasonal behavior of polar stratospheric ozone as it changes from very high concentrations in spring down to very low concentrations in autumn. This behavior has been attributed to an increased role of NO_x catalytic cycles for ozone destruction during periods of prolonged solar illumination such as occur at high latitudes during summer. The detail with which current photochemical models can describe this large natural change in ozone serves as an indication of how well the role of increased stratospheric NO_x from anthropogenic sources can be quantified.

The campaign primarily utilized the NASA ER-2 and balloon platforms based in Fairbanks, Alaska to make measurements of select species within the reactive nitrogen (NO_y), halogen (Cl_y), and hydrogen (HO_x) families; aerosols; and other long-lived species in the lower and middle stratosphere. The POLARIS campaign included a total of 30 ER-2 flights and 3 balloon flights in 3 deployment periods in 1997: 17 April to 15 May, 24 June to 13 July, and 3 to 27 September.

The flight dates for each are included in the Appendix. These measurements along with computer models of the atmosphere as well as meteorological and satellite data are being used to evaluate spring-summer-fall ozone changes due to chemistry and transport at high latitudes.

The POLARIS web page (<http://cloud1.arc.nasa.gov/polaris/index.html>) provides additional details on the mission, including overview, goals, logistics, schedule, platform payloads, and science and support team members. The POLARIS flight logs and science and support team lists are included in the Appendix.

Deployment Descriptions

Phase I

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. On most flights, vertical coverage extended from ~15 to 21 km at selected latitudes. Several vertical profiles were obtained between cruise altitude and the surface at the two deployment sites, NASA Ames Research Center (37°N) and Fairbanks (65°N).

This flight series achieved a number of science goals including: 1) penetration into the northern polar vortex on 26 April 1997 (the polar vortex had unusually low ozone and persisted for an exceptionally long period during the spring of 1997; see *Geophysical Research Letters*, 24, at http://www.agu.org/pubs/toc/gl/gl_24_22.html for a series of articles describing these low ozone values); 2) completion of both sunrise (30 April 1997) and sunset (9 May 1997) flights at high latitudes in the stratosphere, with the data indicating unusual asymmetries in trace-gas behavior in low-angle illumination; 3) penetration into stratospheric air masses that had experienced continuous sunlight for periods ranging from 1 to 12 days (2, 6, and 13 May 1997) and that revealed important observational-model (photochemical steady-state and trajectory) discrepancies with respect to NO_x concentrations; and 4) a launch of the Advanced Earth Observing System (ADEOS) Validation Campaign balloon payload.

Phase II

With the ER-2 based solely in Fairbanks during Phase II, the latitude survey range extended only from 47.7°N to 90°N in the lower stratosphere. Vertical coverage to 21 km in the Fairbanks region was quite good because of stacked flights on 30 June 1997 and 10 July 1997, with vertical profiles over the 15- to 20-km altitude range near 47.7°N and 90°N.

This flight series achieved a number of science goals including: 1) sampling of midsummer polar air that had undergone continuous solar exposure for an extended period; 2) Observations from the Middle Stratosphere (OMS) balloon flights using the *in situ* and MkIV solar absorption interferometer payloads to altitudes in excess of 30 km (performed coincidentally with the ER-2); and 3) sampling of winter polar vortex fragments in midsummer.

Phase III

Phase III ER-2 flights included latitudes extending from 90°N to 3°S in the lower stratosphere. 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 on 19 September 1997, providing a nearly full scan of solar zenith angles from sunrise to sunset.

As the final component of this phase, the ER-2 transited to Barbers Point, Hawaii on 21 September 1997, performed a flight to slightly south of the equator on 23 September 1997, and returned to Ames on 25 September 1997. Vertical profiles from the ground to 21 km occurred at Fairbanks, Hawaii and NASA Ames Research Center, with profiles over the 15- to 20-km altitude range near 3°S and 90°N.

POLARIS Science Summary

Ozone Evolution during the Summer of 1997

The total ozone values during 1997 generally followed the typical summer evolution. Figure 1 displays longitudinally (zonally) averaged total ozone between November 1996 and October 1997 as observed by the Earth Probe Total Ozone Mapping Spectrometer (TOMS) satellite instrument. Superimposed on the plots are the POLARIS ER-2 flight tracks over the course of the deployment (blue lines). The TOMS satellite data display the very strong mid-latitude maximum of ozone during the northern spring. Note also the anomalous polar low of ozone in late March and April 1997 (see *GRL* articles referred to earlier). POLARIS flights nearly sampled the entire equator-to-pole ozone gradient at an altitude of about 20 km during the first deployment. The TOMS data show the April polar low quickly recovered to normal high values in May. As the season evolved, total ozone gradually decreased in the mid- to high latitudes, with the largest decreases in the polar region. This differential decrease led to the development of the normal summer polar low and mid-latitude belt of high ozone. The second POLARIS deployment sampled the period of greatest total ozone decline during late June, and covered the region of the mid-latitude belt of high ozone. The final POLARIS deployment in September sampled the polar region during the period of minimum ozone values in the Northern Hemisphere annual cycle.

In situ sampling of ozone occurred over the entire POLARIS period via the ER-2, ozone sondes, and the OMS flights. Remote sensing measurements of ozone were conducted from both ground and balloon observations. Figure 2 displays ozonesonde profile data taken over the course of the summer period at Fairbanks, Alaska (triangles at bottom indicate sonde launch dates) with ER-2 flights superimposed as white lines, and the tropopause indicated by the thick white line. The contours of ozone partial pressure decrease over the course of the summer period. For example, 16-nbar contours are apparent during April, but only values of ~12 nbar are present during September. Ozone levels above ~28 km show small changes over the entire period, while the tropopause shows rather minor variations. These ozone partial pressure decreases are reflected in the decrease of total ozone concentrations during summer as observed by TOMS in Figure 1, and illustrate how the ozone changes are confined to the lower stratosphere.

1997 Northern Summer Meteorology

The meteorological situation was generally consistent with climatology. The spring (April and early May) was anomalous because of the persistence of the winter polar vortex. Figure 3 displays zonally averaged winds for the Northern Hemisphere as determined from the Goddard Space Flight Center (GSFC) Goddard Earth Observing System-Stratospheric Transport of Atmospheric Tracers (GEOS-STRAT) analyses over the course of the POLARIS period. The temperatures are superimposed as dashed lines, while the tropopause is superimposed as the thick blue line. POLARIS ER-2 flights during the respective months are indicated by the white lines.

Westerly stratospheric winds (solid lines) during April 1997 were much stronger than expected, since the polar vortex usually breaks down in late March or early April. The first POLARIS flight to the north pole on 26 April 1997 was able to reach just inside the northern polar vortex. The zonal monthly mean gives a somewhat distorted picture, since the vortex was offset into the Eastern Hemisphere over northern Siberia, and the winds considerably weakened over the course of the month. By mid-May, the vortex had deteriorated, with winds slowed to their normal easterly circulation (dotted lines). By June, the stratosphere was generally dominated by easterlies, although atmospheric waves of considerable amplitude extended into the stratosphere over the course of the deployment. By the final phase of the deployment in September, polar winds were beginning to make the transition to the winter westerly circulation. The descending westerly phase of the quasi-biennial oscillation (QBO) dominated the tropical circulation during the entire POLARIS period. These descending westerlies are seen at the equator above 30 hPa in April, and centered at about 50 hPa in September.

Twice-daily balloon observations at Fairbanks show the descent of the easterly winds during the early-May period. Figure 4 displays zonal winds from these sondes over the course of the POLARIS period over Fairbanks (contours are 10 m s^{-1} with westerly winds as solid lines, and easterly winds as dashed lines). The disappearance of the strong westerly winds is just apparent at the end of April, with the corresponding appearance of the normal summer easterlies. The westerlies reappear over Fairbanks in August, just prior to the third POLARIS deployment.

In addition to the general wind behavior, note that the variability of the winds decreases quite dramatically with altitude. At altitudes near the tropopause, the day-to-day variation of the zonal wind is quite large. At higher altitudes this variation is markedly less. Because of the easterly winds in the stratosphere, synoptic-scale waves cannot penetrate into the middle stratosphere, and wind variability falls off with increasing altitude. This lessening of wind variability results in reduced mixing by these synoptic systems. Based on this type of wind variability, mixing ought to be strongest near the tropopause, and significantly decrease at altitudes above $\sim 400 \text{ K}$.

Air will remain on an isentropic surface in the absence of any diabatic heating processes. Typical diabatic heating rates are quite small during the summer period, hence the cross isentropic mass flux should be small. The diabatic heating rates have been calculated for the entire summer period over the polar region (see Figure 5). At the start of the first POLARIS deployment, diabatic heating rates (thin solid lines denote positive values while the thin dotted lines denote negative values) were positive because of the colder polar temperatures resulting from the persistent vortex. This situation quickly changed, and there were generally small diabatic cooling rates in the polar

region. Typical values of diabatic cooling were approximately -0.5 K/day or about 15 K per month isentropic change. Since ozone has a vertical gradient of ~0.02 ppmv/K in the lower stratosphere, this diabatic cooling rate leads to an ozone increase of ~0.3 ppmv over a 1-month time scale, representing an ~15% increase of ozone on the 480-K isentropic surface solely from downward diabatic advection.

Observations Highlights

- Stratospheric Nitrogen Chemistry

NO, NO₂, and total odd nitrogen were measured during all three of the POLARIS deployments. The measurements of the ratio NO_x/NO_y (NO_x = NO + NO₂) were consistently higher than modeled (photochemical steady-state, trajectory, and three-dimensional (3-D)) values throughout the POLARIS campaign. Flights in May and September that revisited the same air mass several times over the course of five hours provide important information on the possible explanations for this discrepancy. Specifically, we made observations that provide information on the rates of N₂O₅ formation after sunset, N₂O₅ photolysis at sunrise, and on the rate of change of NO_x during the afternoon. Simultaneous observations of OH in the afternoon provide further restrictions on the possible mechanisms for the unexpectedly high NO_x. Models that reproduce the observations may be more sensitive (exhibit greater ozone loss) to added nitrogen oxide such as might occur via the emissions from aircraft than the current generation of models. However, buffering by HO_x and halogens modify the NO_x impact on ozone, and complicate the issue of whether additional NO_x from aircraft will increase ozone loss.

The NO_x/NO_y ratio changed dramatically over the three phases of the mission. NO_x/NO_y ratios varied from 0.07 to 0.28 and maximized around summer solstice when periods of photolysis were nearly continuous at high latitudes over the course of the day. These observations are consistent with a reduction in heterogeneous N₂O₅ hydrolysis due to the suppression of N₂O₅ formation. In addition, the concentration of BrONO₂ is reduced around summer solstice due to higher photolysis loss, which further reduces formation of HNO₃.

The NO₂ measurements from the laser-induced fluorescence instrument compared well with the photolysis-chemiluminescence measurements. In addition, these observations compared well with simple, constrained models based on measurements of NO, ozone, and the solar radiation field. Small differences in calibration between the two measurement approaches will be evaluated in the laboratory over the next few months.

While the NO_x/NO_y ratio is poorly represented by most models, the observed NO₂/NO ratio is accurately predicted using a photochemical steady-state model. Photolysis of NO₂ (i.e., J(NO₂)) is derived from standard photolysis models using satellite data, ER-2 constituent observations, and Ultraviolet-Visible (UV-Vis) observations from the Composition and Photodissociative Flux Measurement (CPFV) instrument. These rates show some discrepancies, but generally agree to within 5%. Calculations of J(NO₂) at high solar zenith angles (SZA) (89° < SZA < 91°) have been evaluated using *in situ* measurements of NO_x and ozone. It was found that the height of clouds beneath the ER-2 can affect the calculated value of J(NO₂) at high SZAs by as much as 20%. With

cloud height values derived from satellite observations, the calculated $J(\text{NO}_2)$ values agree well with those derived from NO_x and ozone measurements.

- Ozone Loss Rates

Preliminary calculations using *in situ* measurements of NO_x , HO_x , and ClO show that NO_x dominates the destruction of ozone in the summer Arctic stratosphere, with significant contributions from the HO_x cycles. Calculations of mid-latitude spring ozone loss rates during the Stratospheric Photochemistry, Aerosol, and Dynamics Expedition (SPADE) campaign showed that HO_x catalysis was the dominant ozone loss process. Near the summer solstice, the ozone destruction rate due to NO_x reached 13% per month, compared to 5% per month by HO_x and halogen cycles combined. The net ozone change reached -16% per month during that period.

Estimates of ozone loss (without production) have been computed using the GSFC 3-D chemical transport model (CTM) which is driven by winds derived from the Data Assimilation Office (DAO) GEOS data assimilation system (DAS). Figure 6 displays these ozone loss rates (percent per month) as a function of latitude and time on the 525-K isentropic surface over the course of the POLARIS campaign (white lines show latitudinal range of POLARIS flights). Shown are total loss rates from all species (top), NO_x (middle panel), and HO_x (lower panel). Ozone losses in the model are principally driven by HO_x and NO_x chemistry. The NO_x catalytic loss exceeds that of the HO_x cycles at polar latitudes. These loss processes are largest in the polar region during periods of continuous sunlight in midsummer during the second POLARIS deployment, and fall to smaller values in the third deployment.

The net photochemical change of ozone using a photochemical steady-state model was -10 to -15% per month near 20 km, peaking during Phase I and at high latitudes during Phase II. The altitude range of net photochemical loss of ozone extended to ~24 km for the first MkIV flight during May, and extended to ~30 km for the second flight during July. The net photochemical loss rate of ozone is sensitive to the production rate of ozone, which increases as overhead ozone column falls and as the noontime solar zenith angle experienced by an air mass falls. Indeed, changes in the net photochemical change of ozone between various phases of POLARIS, and as a function of latitude during a specific phase, are driven as much by a variation in ozone production as by changes in NO_x . Both the ozone loss rates based on radical measurements, and the model based ozone loss rates generally were consistent with the observed ozone decreases over the course of the summer.

- Stratospheric Chlorine Budget

The payload of the ER-2 includes a number of measurements of chlorine-containing species, including ClO ; HCl ; ClONO_2 , CFC-11, CFC-12, CFC-113, CCl_4 , and CH_3CCl ; plus a number of other halocarbons. These observations represent a large fraction of both the organic and inorganic chlorine reservoirs in the lower stratosphere. The ClONO_2 instrument provided its first measurements during the POLARIS deployments.

ER-2 measurements of ClO, HCl, and ClONO₂ are very consistent with measurements of organic chlorine compounds. In addition, the measured ratio of ClO/ClONO₂ is in excellent agreement with the modeled photochemical steady-state value. The sum of the inorganic chlorine species, ClO, ClONO₂, and HCl, is in excellent agreement with the value inferred from organic chlorine measurements from the Airborne Chromatograph for Atmospheric Trace Species (ACATS) and Whole Air Sampler (WAS) instruments. These measurements place exacting constraints on our understanding of the chemical mechanisms involved in chlorine partitioning, and suggest that our current understanding of stratospheric chlorine chemistry is very good.

In addition to the ER-2 observations, MkIV and Far-Infrared Spectrometer (FIRS) balloon-borne observations during Phases I and II also showed excellent agreement with our understanding of chlorine partitioning. The new *in situ* ER-2 measurements of ClONO₂ obtained during POLARIS add great confidence to our understanding of processes that regulate reactive chlorine at 20 km, and are entirely consistent with these balloon-borne remote measurements of ClONO₂ obtained by MkIV and FIRS.

- Sunrise and Sunset Flights and HO_x Chemistry

Early summer sunrise/sunset flights were conducted during the first POLARIS deployment, while late summer sunrise/sunset flights were flown in the third deployment. These observations will be of value in addressing the diurnal chemistry of radicals in the lower stratosphere. In particular, the flights confirm the important role of the heterogeneous reaction of BrONO₂ + H₂O in explaining the behavior of HO_x, since concentrations of OH and HO₂ are significantly higher at high solar zenith angle than expected. The observations of HO_x radicals during the third deployment are very consistent with observations made during Phase I, suggesting that our current understanding of diurnal HO_x chemistry in the lower stratosphere is quite good.

- Polar Vortex Samples

Unusually low ozone values were observed in March 1997 inside the polar vortex by the Earth Probe TOMS, ADEOS TOMS, and Upper Atmosphere Research Satellite (UARS) Halogen Occultation Experiment (HALOE) satellite instruments. Because of these unusual observations, the first POLARIS flight from Fairbanks on 26 April 1997 was directed at making measurements inside the stratospheric polar vortex. The ER-2 flight went on a direct path from Fairbanks to the north pole. Meteorological forecasts showed that the edge of the polar vortex was near the pole, with the bulk of the vortex offset into the Eastern Hemisphere. The vortex edge was observed near the pole, based upon various trace gas observations (e.g., methane, N₂O, SF₆, NO_y, and CO₂). Nitrous oxide (N₂O) dropped to ca. 80 parts per billion by volume (ppbv), while other chemical and particle tracers showed comparable behavior. Measurements made inside the vortex on this flight did indeed show low values of ozone with respect to long-lived tracers such as nitrous oxide. The most convincing evidence for a polar ozone deficit was observed in the polar dive on this flight, between 400 and 470 K. Measurements of ozone deep within the vortex were inaccessible because the stationary position of the vortex was beyond the permitted ER-2 operational flight region.

- Midsummer Vortex Fragments

Long-lived trace-gas measurements during the second POLARIS deployment showed anomalously low values in a relatively narrow layer near 20 km. A particular filament sampled by the ER-2 showed N₂O values down to 50 ppbv. The OMS payload also made measurements in this anomalous layer and in a higher layer at ~30 hPa. These layers are too vertically narrow to be observed by satellite instruments (such as Stratospheric Aerosol and Gas Experiment (SAGE) or HALOE). Three-dimensional transport model predictions of such layers have been previously described in the literature, but have heretofore been unobserved. The layers appear to be remnants of the polar vortex following the late spring breakup. These observations indicate that vortex fragments can survive at least two months following vortex breakup. Previous analysis using an advection-diffusion model together with SPADE ER-2 data and trajectory calculations, suggested that during spring, vortex filaments are mixed into the background field within 25 to 30 days (Vaugh *et al.*, 1997). Preliminary results indicate that during summer the time scale for the large-scale flow to reduce the scale of these filaments down to mixing scales is twice as large as during winter/spring.

- Ozone Transport Effects

Ozone changes on a potential temperature surface are not solely a result of photochemistry. As was observed in the second POLARIS deployment, transport significantly altered the CO₂-N₂O relationship for values of N₂O less than 200 ppbv. The CO₂ data suggest that features of the ozone-N₂O correlation plots are due primarily to end-point mixing between vortex remnants and mid-latitude air.

Long-lived tracer-tracer relationships are relatively independent of potential temperature. Hence, CO₂ data suggest that a significant region of middle stratospheric air at high latitudes was not significantly affected by transport during the summer, although the influence of transport on ozone is difficult to define accurately because gradients between mid- and high latitudes are weak. However, the persistence of winter vortex remnants well into the summer (see previous item) provides direct support for the idea that high-latitude air is isolated from lower latitudes.

Tracer correlations from the WAS in the lower stratosphere suggest that the Arctic stratosphere was dynamically isolated during the spring-through-autumn period of POLARIS. One example of this behavior was the relatively slow increase inferred for hydrochlorofluorocarbons (HCFCs) (e.g., HCFC-141b) in the 20-km region compared to temporal increases in the troposphere and the stratospheric increases found during the STRAT missions at lower latitudes.

Survey flights to the tropics in early summer and late summer show the development of a very strong latitude gradient in long-lived trace gases such as N₂O, CO₂, SF₆, H₂O, and CH₄. This gradient development indicates that these long-lived trace gases were continuously injected into the tropical stratosphere, but had not intruded into the high latitudes.

- Stratospheric Transport

The mean age of air provides extremely important information for our understanding of the stratosphere, and an important test of transport in two-dimensional (2-D) and 3-D models. The mean age also provides a measure of the time that high-speed civil transport (HSCT) exhaust will spend in the stratosphere. The mean age of air observed over Fairbanks on 20 June was 6.8 years. This air is older than calculated by models, indicating that at high summertime latitudes, HSCT exhaust will likely accumulate in greater amounts than models currently predict.

Tracer-tracer correlations obtained from aircraft and balloons show clear differences among tropical, mid-latitude, and polar vortex air. These differences are pronounced in correlation diagrams for species such as CH₄, N₂O, and CFC-11. These correlation diagrams show evidence of mixing between the tropics and mid-latitudes, and between the polar vortex and mid-latitudes.

- Gravity Wave Mixing

The POLARIS wind measurements on all three deployments were dominated in the vertical profiles by inertia-gravity waves with peak-to-peak amplitudes of about 10 m/s. The correlations of these wind fluctuations with tracer profiles were generally quite low, consistent with the generally accepted idea that these waves are NOT responsible for the major filamentation of trace constituents in the stratosphere. Horizontal excursions associated with inertial period fluctuations of these amplitudes are at most ~100 km, creating relatively small perturbations of trace-gas profiles. A number of observed small “dents” in the tracer profiles were associated with these wind fluctuations.

Weak turbulence (as indicated by high-frequency vertical wind fluctuations) was correlated with strong vertical shears associated with the inertia-gravity waves. This observation, and the small dents in the tracer profiles related to the waves, suggests that the role of inertia-gravity waves in the summer Arctic stratosphere is to generate some of the mixing that breaks down the strong tracer filaments.

An interesting case arose on 10 July 1997, where a fortuitous and unplanned change in the flight path caused the aircraft to fly back and forth through a breaking mountain wave. Notably, the turbulence in this case was five times greater than in the strongest inertia-gravity wave case. Also, the amplitude of the mountain wave decreased to very small values at the highest flight leg, indicating that the mountain wave energy is absorbed by the decreasing very weak winds in the summer Arctic stratosphere.

- Organic Fluorine Growth Rate

Analysis of air from tropospheric samples collected in the Northern Hemisphere by L. Heidt and W. Pollock of the National Center for Atmospheric Research (NCAR) allowed a reasonable definition of the growth rate of selected organic fluorine gases since 1977. Preliminary examination of the measurements from POLARIS, still underway as of this writing, indicate concentration distributions in the stratosphere that are consistent with measured tropospheric growth rates. As a result, HFC-143a (CH₃CF₃) appears to have tropospheric growth rates and

mixing ratios of sufficient magnitude that this compound could be used as another independent tracer of stratospheric age, in addition to SF₆ and CO₂.

- Particle Observations

The Focused Cavity Aerosol Spectrometer-Condensation Nucleus Counter (FCAS-CNC) data contain many interesting features, including aircraft plumes and large increases in nuclei-mode particle concentrations near 20 km in mid-latitudes not associated with any obvious plumes or tracer fluctuations. These regions of unexpectedly high particle concentration are unprecedented in our measurement record and will be investigated further.

Preliminary analysis of samples indicates that the sulfate aerosol concentration is in agreement with estimates for this region of the atmosphere. Soot, as collected on wire impactor samples, is found at concentrations one to two orders of magnitude less than sulfate aerosol. The soot results will be used to evaluate the potential role of soot surface reactions in the partitioning of reactive nitrogen and ozone loss rates.

Figure Captions

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 latitude during 1997. Contour lines are labeled in Dobson Units (DU, m-atm cm) and separated by 25 DU. No observations are available for the white open areas at high latitudes. The dark vertical lines represent ER-2 flight tracks during POLARIS.

Figure 2. Values of ozone in nbar as a function of altitude and pressure during the April to September period of 1997. Contours are separated by 2 nbars. Observations are from ozone sondes launched from Fairbanks, Alaska, (65°N) on dates marked by triangles at the bottom of the figure. The thin white vertical lines represent the altitude range of ER-2 flights during POLARIS. The thick white horizontal line represents the tropopause.

Figure 3. Vertical distribution of winds and temperatures as function of latitude and month during POLARIS. Zonally averaged winds for the Northern Hemisphere are determined from the Goddard Space Flight Center (GSFC) Goddard Earth Observing System-Stratospheric Transport of Atmospheric Tracers (GEOS-STRAT) analyses over the course of the POLARIS period (thin solid (westerly) and dotted (easterly) lines, units of m s⁻¹, contour interval of 5 m s⁻¹). The temperatures are superimposed as dashed lines, while the tropopause is superimposed as the thick blue line. POLARIS ER-2 flights during the respective months are indicated by the white lines.

Figure 4. Vertical distribution of zonal winds over Fairbanks, Alaska (65°N) as a function of time during POLARIS as observed with twice-daily balloon soundings. Contours are in intervals of 10 m s⁻¹ with westerly winds as solid lines and easterly winds as dashed lines. The tropopause is shown as the thick white line and POLARIS ER-2 flights are indicated by the white vertical lines. The thin dot-dash lines are potential temperature contours in K.

Figure 5. Vertical distribution of diabatic heating rates as a function of northern latitudes for each month of POLARIS. Thin solid lines denote positive values, thin dotted lines denote negative values, and thick solid lines denote zero heating rate. Contours intervals are 0.5 K day^{-1} . The tropopause is shown as the thick blue line and POLARIS ER-2 flights are indicated by the white lines. The long dashed lines indicate potential temperature in K with contour intervals of 100K.

Figure 6. Estimates of ozone loss (without production) using the GSFC 3-D chemical transport model (CTM) as driven by winds derived from the Data Assimilation Office (DAO) GEOS data assimilation system (DAS). Ozone loss rates in percent per month are shown as a function of latitude and time on the 500-K isentropic surface over the course of the POLARIS campaign where the white vertical lines show the latitudinal range of POLARIS flights. Loss rates are shown for all species (top), NO_x (middle panel), and HO_x (lower panel).

Instrument Investigator Summaries (alphabetical by PI)

Water Vapor - Harvard University

J. G. Anderson, E. J. Hintsa, and E. Weinstock

With the POLARIS mission, the Harvard water vapor instrument completed its fifth year of operation and its fourth mission. During the first deployment, electrical and optical problems led to lower quality data on some of the flights. By the last two flights in May, all problems were fixed and the instrument worked well for the remainder of the mission. Even for the early flights, however, a preliminary analysis suggests that the lower quality data suffered from loss of precision but not loss of accuracy.

On the flight of 26 April 1997 into the polar vortex, no dehydration was observed in the vortex air. In the summer deployment, patches of older air, presumably remnants from the vortex, were frequently observed. These had very low residual methane and correspondingly high water vapor, the highest we have ever observed for air unaffected by the seasonal cycle in water vapor. From analysis of tracer-tracer correlations we expect to be able to improve our understanding of stratospheric transport and the hydrogen budget.

The tropical flight from Hawaii (23 September 1997) was a success. Air which had entered the stratosphere in the summer, with higher water vapor, was observed in the vertical profile at the equator. The measurements appeared to be relatively free of mixing with mid-latitude air. This data will help us to fill a gap in measurements of the seasonal cycles of water and CO_2 in the tropics, important for understanding strat/trop exchange and vertical velocities in the tropics.

The stacked flights were also successful, with clear observations of tropospheric air mixed into the lowermost stratosphere (middleworld). Finally, intercomparison with the new Jet Propulsion Laboratory water instrument showed very good agreement in the stratosphere (well within 10% in a preliminary analysis), and comparable long-term precision when plotted against a different tracer (such as N_2O). Since post-flight calibrations and analysis are continuing for both instruments, these last conclusions are strictly preliminary.

Chlorine Nitrate (ClONO₂)

J. G. Anderson, R. Stimpfle, and R. Cohen

A new instrument measuring ClONO₂, ClO, NO₂, and BrO was deployed during POLARIS. The instrument adds significantly to the capability of the ClO/BrO instrument that it replaced. The size and weight of the components measuring ClO and BrO were dramatically reduced without affecting sensitivity or reliability. ClONO₂ is measured by thermal dissociation to ClO and NO₂ followed by ClO detection. NO₂ is detected by laser-induced fluorescence (LIF).

The LIF NO₂ results compare well with the photolysis-chemiluminescence approach used by the NOAA Aeronomy Lab group and with models based on measurements of NO, ozone, and the solar radiation field, enhancing the credibility of all three approaches. Small differences in calibration between the two measurement approaches will be evaluated in the laboratory over the next few months.

Measurements of ClONO₂ are remarkably consistent with measurements of ClO, HCl, and organic chlorine compounds. In particular, the measured ratio of ClO/ClONO₂ is in excellent agreement with the photochemical steady-state value. The sum of the inorganic chlorine species (ClO, ClONO₂ and HCl) is in excellent agreement with a value inferred from total organic chlorine measurements. These measurements rule out several of the explanations for the anomalously low values of HCl observed during SPADE and ASHOE/MAESA and place exacting constraints on our understanding of the chemical mechanisms involved in chlorine partitioning.

Observations of the ratio NO_x/NO_y disagreed with models consistently throughout the POLARIS campaign. The measured values of NO_x were consistently higher than these model estimates. Models that reproduce the NO_x observations may be more sensitive (exhibit greater ozone loss) to added nitrogen oxide such as might occur via the emissions from aircraft than the current generation of models. Flights in May and September that revisited the same air mass several times over the course of 5 hours provide important information on the possible explanations for this discrepancy. Specifically, we made observations that provide information on the rates of N₂O₅ formation after sunset, N₂O₅ photolysis at sunrise, and on the rate of change of NO_x during the afternoon. Simultaneous observations of OH in the afternoon provide further restrictions on the possible mechanisms for the unexpectedly high NO_x.

High-Altitude OH Experiment (HO_x)

J. G. Anderson, P. O. Wennberg, T. F. Hanisco, and E. J. Lanzendorf

The HO_x instrument measures OH and HO₂ from the nose of the ER-2. Just prior to POLARIS, the HO_x instrument was extensively modified to replace the aging YAG laser system. The HO_x instrument functioned well during POLARIS with complete data sets obtained on most of the flights. The third deployment was a noticeable exception when the HO_x instrument failed to obtain useful data on the two sunrise flights and during much of the southern survey flight from Hawaii. Nevertheless, the HO_x data obtained are of high quality and the missing flights will not strongly impact scientific analysis of the POLARIS data set.

Preliminary Scientific Findings

- Concentrations of OH and HO₂ are significantly higher at high solar zenith angles than expected. Analysis suggests that either the hydrolysis of bromine nitrate (BrONO₂) occurs at a rate significantly faster than suggested by laboratory study [D. R. Hanson and E. R. Lovejoy, *Science*, 267, 1326, 1995] or there exists another error or omission in the kinetic database [W. B. DeMore *et al.*, *Chemical Kinetics and Photochemical Data for Use in Stratospheric Modeling: Evaluation Number 12*, JPL Publication 97-4, 1997].
- During POLARIS, the observed NO_x/NO_y ratio was consistently higher than expected. In the polar regions which do not experience night during the summer, reaction of OH with NO₂ is thought to be the most important source of nitric acid (HNO₃). The larger-than-expected concentration of NO_x is even more difficult to understand because the concentration of OH was higher than expected on some flights. Further analysis should help identify the possible cause of the discrepancy in both HO_x and NO_x in the high polar latitudes. The higher concentrations of HO₂ and NO₂ mean that ozone loss occurs faster than expected in this region.

Trace Gas Measurements during POLARIS from the Whole Air Sampler (WAS)

E. Atlas, F. Flocke, R. Lueb, and S. Schauffler

The main science objectives of the WAS experiment during POLARIS were to: 1) quantify organic halogen source gases to evaluate chlorine and bromine budgets and partitioning; 2) use trace gases of different sources, chemistry, and lifetimes to investigate mixing processes and dynamics in the Arctic region; 3) continue to define the temporal evolution of HCFC concentrations in the lower stratosphere; and 4) investigate the distribution and correlation of long-lived organic fluorine compounds.

During the POLARIS missions, the WAS was located in the mid-body of the right wing superpod and was configured to collect 29 samples per flight. With the exception of the first southern survey flight from Ames at the beginning of the first POLARIS deployment, the WAS successfully collected samples during all flights. Approximately 700 samples were collected during the 3 POLARIS deployments. After each flight, samples were sent to the NCAR laboratory for analysis of trace gas composition. The samples were analyzed for all the major (and most of the minor) chlorofluorocarbons (CFCs), HCFCs, halons, methyl halides, chlorinated solvents, methane, C₂ - C₅ alkanes, and C₁ - C₃ alkyl nitrates. A series of samples were also measured for long-lived organic fluorine gases, including C₂F₆, C₄F₈, CH₃CF₃, CHF₃, and CFC-114a. After trace gas analysis was complete at NCAR, residual air in selected canisters was sent to K. Boering and colleagues for isotopic analysis of CO₂, N₂O and CH₄.

Measurements of the halogen source gases allowed a complete characterization of the organic halogen contribution to total chlorine and total bromine in the POLARIS region. These data can be used to estimate the inorganic chlorine content of the lower stratosphere by comparison with the estimated total organic chlorine content entering the stratosphere through the tropical tropopause. During POLARIS, direct measurements of the inorganic chlorine were made with the Aircraft Laser Infrared Absorption Spectrometer (ALIAS) instrument (HCl) and with the Harvard/Berkeley laser fluorescence instrument (ClONO₂ and ClO). Preliminary analysis of the chlorine budget from

indirect calculations based on total chlorine and organic chlorine showed good agreement with the direct measurement of inorganic chlorine species. For the bromine budget, estimates of inorganic bromine were available only from the measurements of organic bromine and comparison to total organic bromine entering the stratosphere. We suggest, however, that this analysis is somewhat more uncertain than that for chlorine because of the variability of short-lived organic bromine gases which can constitute a significant fraction of organic bromine in the lowermost stratosphere.

Tracer correlations in the lower stratosphere suggest that the Arctic stratosphere was dynamically isolated during the spring through autumn period of POLARIS. One example of this behavior was the observation of the relatively slow increase in HCFCs (e.g., HCFC-141b) in the 20 km region compared to temporal increases in the troposphere and the stratospheric increases observed during the STRAT missions at lower latitudes. Another interesting behavior observed in organic halogens, and virtually all other tracer species, during POLARIS was the mixing of vortex filaments with the surrounding atmosphere. This process is characterized by a mixing line of younger to older air compared to the curvature in the correlations of tracers in the surrounding atmosphere. Understanding this mixing process has implications for understanding ozone loss in terms of the chemistry and dynamics of the region.

A pilot study of long-lived organic fluorine compounds was conducted during POLARIS to examine consistency of age predictions using a combination of long-lived tracers with different tropospheric growth rates. Analysis of air from tropospheric samples collected in the Northern Hemisphere by L. Heidt and W. Pollock of NCAR allowed a reasonable definition of the growth rate of selected organic fluorine gases since 1977. Preliminary examination of the measurements from POLARIS indicate concentration distributions in the stratosphere which are consistent with measured tropospheric growth rates. It is found that HFC-143a (CH_3CF_3) appears to have tropospheric growth rates and mixing ratio of sufficient magnitude that this compound could be used as another independent tracer of stratospheric age, in addition to SF_6 and CO_2 .

Multiangl e Aerosol Spectrometer Probe (MASP)

D. Baumgardner, B. Gandrud, and T. Onasch

Summary of Instrument Performance over Deployments

Just prior to the beginning of the POLARIS mission, the MASP was installed on the ER-2 left superpod. The location selected for the external mount was based on model output of the flow around the superpod done at NASA Ames and the data system was repackaged to fit into a 19-inch rack mount. The mounting changes were necessary because the spear pods are no longer in use on the ER-2. The MASP is equipped with a pitot-static system for measuring air velocity immediately aft of the sample volume. With the MASP mounted in the spear pod as it was previously, this velocity measurement agreed very closely with the aircraft true air speed. During POLARIS, the MASP airspeed was lower than the aircraft speed by $\sim 40 \text{ m s}^{-1}$. We would like to explore the source of this difference during a future test flight as it is not due to pressure transducer calibration.

From the first test flights through the Phase II missions, the MASP experienced some type of power surge problem when the aircraft went to maximum thrust immediately prior to takeoff. This would cause the “fail” to turn on, the pilot would recycle power, and for most of the flights the

MASP would take data after that. This meant the loss of data during most of the ascents during Phase I and II but the majority of the level flight data is available.

Between Phase II and III, we made some additional changes in the MASP data system that eliminated the power surge problem at takeoff. Therefore, ascent data is available for PHASE III flights. During Phase III there were selected times with the sun directly in front of the ER-2 when the MASP data is corrupted by sunlight getting into the inlet of the instrument. These time periods are minor and they will be removed from the archive data set.

Preliminary Scientific Results

The MASP measures particles over the nominal size range from 0.4 to 30 microns in diameter. The number concentration of particles observed in that size range varied little at flight altitude over the course of the 3 phases of POLARIS (0.4 to 0.6 particles cm^{-3}). There are some minor changes in the size distribution which result in changes in the surface area and volume during the mission. The modest surface area and volume changes need further examination.

When the various flights at the end of Phase III from polar to the equator latitudes are combined, the data do not show much gradient or hint of volcanic activity in terms of number concentration. However, there are changes in surface area and volume which warrant further work. The data from the 26 April 1997 show very clearly the loss of concentration, surface area, and volume within the remnant of the polar vortex the ER-2 crossed on that day. Penetration of vortex remains on other days show this same trend, but not as strongly, since the 26 April 1997 flight made the deepest penetration into the vortex.

There was an interesting event on 13 May 1997 when MASP shows elevated concentration (20 times), surface area (10 times), and particle volume (5 times) above background values. This occurred between ~ 77380 UT s and 77850 UT s in the descent portion of the vertical profile at the north end of the flight track. Although values above over background are in the range of what would be expected from a cirrus cloud, the ambient temperature and measured water vapor show the local conditions are $\sim 40^\circ\text{C}$ warmer than the frost point. An examination of the forward- to backscatter ratio from the MASP indicates that these particles are very aspherical and quite different than the rest of the particles observed on that day. The NASA Ames group (A. Strawa, K. Drdla, and R. Pueschel) had a wire impactor exposure during this period and the collected particles during this event are very different from the particles collected on exposed wires before and after the event. Rather than the usual sphere like sulfuric acid type particles, the wire impactor samples show columns which are 3 to 6 microns in length. K. Drdla has suggested that these unusual particles might be a hydrate of sulfuric acid which could be stable in the warm summer polar stratosphere. This event will receive continued attention and a submission for publication is likely to result from that work.

High-Sensitivity Fast-Response CO₂ Analyzer: ER-2 and OMS Balloon Platforms

K. A. Boering, S. C. Wofsy, S. Alex, A. Andrews, and B. C. Daube

Objectives

The objectives of the CO₂ measurements were to:

- Determine the age of stratospheric air in the polar stratosphere, using data from a balloon ascent and ER-2 flights, with particular attention to data obtained in remnants of the winter polar vortex. The distribution and transport of natural and anthropogenic trace gases throughout the lower stratosphere are directly related to the mean age. For example, quantifying the accumulation of exhaust products from stratospheric aircraft is facilitated by such a determination. Hence, we sought to obtain (via the CO₂ measurements) a critical test of model predictions for mean age. Some stratospheric models predict that the polar regions would constitute a stagnation zone with air significantly older than elsewhere in the stratosphere; others have rather modest values for mean age.
- Define the contributions of transport to changes in ozone observed over the course of POLARIS. One of the principal goals of POLARIS was to detect and quantify chemical removal of ozone over the summer pole. To achieve this goal, independent information on the influence of transport was needed. Measurements of CO₂ through the season provided a test of the underlying paradigm of isolation of the air in this region from the rest of the globe, i.e., that changes in ozone due to transport were small relative to chemical changes in ozone.
- Examine exchange of air between the tropics and high latitudes in the middleworld and near-tropopause region over the summer pole. Global mixing at these altitudes has major significance for assessing the impact of present subsonic aviation and future supersonic aircraft on stratospheric composition. The seasonal variation of CO₂ provides an ideal probe of meridional exchange, enabling definitive tests of the conclusion from previous observations that meridional exchange is rapid between the tropics and polar regions at these altitudes.
- Measure the vertical propagation and attenuation of the seasonal signal for CO₂ in the tropics during the northern summer season to define the vertical advection velocity and dispersion in this season. These data were intended to fill out our picture of tropical upwelling from previous ER-2 and balloon missions, providing fundamental physical quantities for the stratosphere, and to set the stage for the follow-on OMS observations.

Results

- Effects of Transport on Apparent Ozone Loss

Preliminary analysis of CO₂ observations in combination with N₂O and other long-lived tracers provided an excellent probe to distinguish the influence of transport on ozone mixing ratios in the summer polar region from changes in ozone due solely to *in situ* photochemical processes.

Air with low values of CO₂ and N₂O was observed in deployments I and II from the ER-2, both over Fairbanks and near the pole, and in deployment II from the OMS platform, from the tropopause up to altitudes above 27 km. We interpret these anomalous parcels as remnants of air having descended a long distance in the polar vortex, or mixing of remnants with ambient air.

In April/May, the relationship between CO₂ and N₂O in vortex remnants was curvilinear for N₂O < 200 ppbv whereas in June/July, there had been significant mixing between vortex remnants and the ambient atmosphere, as revealed by a straightening of the relationship. In addition, potential temperatures for these vortex remnants mixtures in June/July were higher than those for the vortex fragments in April/May for given tracer concentrations.

Because transport has significantly altered the long-lived tracer-tracer relationships for these values of N₂O (N₂O < 200 ppbv), it is not valid to interpret ozone changes on a potential temperature surface as solely due to photochemistry. The CO₂ data provide a simple interpretation of ozone-N₂O correlation plots as primarily due to end-point mixing between vortex remnants and mid-latitude air. In the July deployment, loss of ozone in these remnants could possibly be inferred by accounting for changes in potential temperature.

The CO₂ data suggested that a significant slice of middle stratospheric air (200 < N₂O < 270 ppbv) was not significantly affected by transport during the summer, although the influence of transport on ozone is difficult to define accurately because the contrast between mid- and high latitudes is not strong. However, the persistence of vortex remnants well into the summer provides direct support for the idea that this air is significantly isolated from lower latitudes.

From the above, it appears as a preliminary result that significant chemical removal of ozone could be quantified for both the vortex remnants and for middle-stratospheric air.

- Mean Age of Stratospheric Air

Mean ages were derived from the time lag between observed CO₂ values, corrected for CH₄ oxidation, using our observed stratospheric boundary condition for CO₂ mixing ratios entering the stratosphere. In April/May, mean ages of air for N₂O < 200 ppbv exceeded 4 years, ~0.3 years older than obtained from observations in earlier campaigns at mid-latitudes.

The oldest age from the OMS platform was 6.8 years, obtained at 32 km over Fairbanks on 30 June 1997. This result is older than found in most 2-D and 3-D models, but does not confirm very old air as expected in a stagnation zone.

Observations of mean ages indicate that exhaust products from stratospheric aviation will accumulate to higher levels than predicted by models with mean ages of < 4 years in the polar stratosphere.

- Global Transport Rates near the Tropopause

For all three deployments, CO₂ mixing ratios for values of N₂O greater than 275 ppbv evolved in a manner similar to the observed evolution of CO₂ at mid-latitudes from previous campaigns: the

seasonal and long-term variations in CO₂ entering the lower tropical stratosphere rapidly propagated poleward. Thus, quasi-horizontal transport from lower latitudes was significant over the entire time period, in contrast to the isolation of the summer polar region observed at higher altitudes. This region of the lower polar stratosphere is not isolated during the summer months. There is no obvious way to infer photochemical changes in ozone at these altitudes using POLARIS data.

- Tropical Ascent and Dispersion

The mean ascent rate of air in the tropics was determined to be 0.29 K/day (or 0.15 mm s⁻¹ ± 27%) from vertical profiles of CO₂ and potential temperature on 23 September 1997 over the equator. Comparison with rates from other time periods shows this velocity to be slightly less than that obtained in late October 1994 (0.19 mm s⁻¹ ± 18%) and early November 1995 (0.21 mm s⁻¹ ± 18%), and significantly less than that obtained in February 1996 (0.31 mm s⁻¹ ± 25%). We conclude that mean upwelling velocities are larger in northern winter than during the equinox seasons and northern summer, consistent with calculations of the diabatic circulation.

These advection rates apply between the tropical tropopause and ~18 km, at the point of entry of air to the stratosphere, providing a strong constraint on the mass flux into the stratosphere. Simultaneous constraints on mass fluxes and mean ages, obtained from CO₂, N₂O, and potential temperature observations by instruments on the ER-2, represent an important new diagnostic for diffusive transport in 2-D models.

Quantifying Stratospheric Transport Processes Using Isotopic Analyses of Trace Gases

K. A. Boering, E. Atlas, M. Bender, M. H. Thiemens, and S. C. Wofsy

For the POLARIS mission, a pilot study was undertaken to measure the abundance and distribution of oxygen, carbon, and nitrogen isotopes in stratospheric and upper tropospheric CO₂, N₂O, and CH₄ on a hemispheric scale using residual air from the ER-2 WAS canisters. The premise for the study is that these new isotope observations offer the promise of distinguishing and quantifying the roles of advective vs. dispersive transport processes in the stratosphere, particularly when air from the upper stratosphere or mesosphere is involved (i.e., in investigations of descent of air at the poles or of mixing of older mid-latitude air into the tropics in the lower stratosphere). From December 1996 to September 1997, approximately 200 samples were collected which, after laboratory analyses, will increase the number of available isotopic measurements of stratospheric species by one to two orders of magnitude and will represent the first set of isotopic observations to be made in conjunction with simultaneous measurements of the concentrations of numerous other trace species, rather than in isolation, and over a wide range of latitudes.

Results for the oxygen isotopic composition of stratospheric CO₂ from 11 air samples collected during the first deployment (April/May 1997) demonstrate the usefulness and unique features of this new tracer and the ability to successfully retrieve the stratospheric oxygen isotopic compositions from the WAS canisters. The fractionation of oxygen in CO₂ showed enrichment in the heavy isotopes that is independent of the mass difference between the isotopes, with ¹⁷O = ¹⁷O

- 0.52* ^{18}O ranging from 0.5 to 5.0 per mil (with a measurement precision of 0.1 per mil). In addition, a compact anti-correlation of ^{17}O with simultaneous measurements of N_2O was observed from N_2O of 305 ppbv down to 90 ppbv, the lowest value observed during the first deployment. When coupled with 13 measurements of ^{17}O in upper stratospheric and mesospheric CO_2 from a rocket-borne cryogenic whole air sampler by Thiemens *et al.* [*Science*, 270, 969, 1995] (which ranged from 5 to 12 per mil for N_2O values from 90 to 2 ppbv), it is clear that the negative correlation of ^{17}O with N_2O is curvilinear, with a dramatic increase in ^{17}O for $\text{N}_2\text{O} < 90$ ppbv. Thus, ^{17}O tracer characteristics are distinctively different from those of tracer concentrations measured from the ER-2; its source is stratospheric rather than tropospheric (as it is for the tracers CO_2 , N_2O , and CH_4) and the magnitude of fractionation increases with altitude in the middle and upper stratosphere (where CO_2 , N_2O , and CH_4 mixing ratios show little variation). Its unique curvilinear relationship with N_2O is ideal for investigating the descent and mixing of air into the lower stratosphere from the upper stratosphere and mesosphere; quantification of descent over the course of the POLARIS observation period awaits analyses of samples from the second and third POLARIS deployments.

Meteorological Measurement System (MMS)

T. P. Bui, L. Pfister, S. W. Bowen, D. Bui, E. Moore, and T. Trias

Instrumentation Performance during POLARIS

The ER-2 MMS measures the primary meteorological variables along the flight track of the ER-2 aircraft at 5 Hz, including pressure, temperature, and the 3-D wind vector. The instrument has undergone very few changes since the last major experiment (STRAT), and that maturity is reflected in the instrument performance. High-quality data is available for the entire length (or nearly so) of 31 flights during POLARIS, including 4 ferry flights between Ames and Fairbanks that did not include much of the POLARIS payload. With the exception of one flight, which was scrubbed partly because of the failure of the MMS data acquisition computer on the ground, there were no instrument failures during the POLARIS deployment. The MMS INS did fail several times and was not fully reliable until the September deployment. For those flights, the aircraft INS (Litton 92) was used, resulting in a small degradation in the wind measurements.

Science Summary

The most important feature of the *in situ* winds during all three POLARIS deployments was the dominance of inertia-gravity waves in the vertical profiles. These waves had significant wind amplitude (up to 10 m per second peak-to-peak) and very small temperature amplitude, which indicated that the frequencies were very close to the inertial period. The correlations of these wind fluctuations with tracer profiles were generally quite low, consistent with the generally accepted idea that these waves are NOT responsible for the major filamentation of trace constituents in the stratosphere. Given that the horizontal excursion associated with inertial period fluctuations of these amplitudes is at most ~100 km, this is not surprising.

There were a number of cases where small “dents” in the tracer profiles were associated with the wind fluctuations. Also, weak turbulence (as indicated by high frequency vertical wind fluctuations) was correlated with strong vertical shears associated with the inertia-gravity waves.

These two observations suggest that the role of inertia-gravity waves in the summer Arctic stratosphere is to generate some of the mixing that breaks down the strong tracer filaments.

An interesting case arose on 10 July 1997, where a fortuitous and unplanned change in the flight path caused the aircraft to fly back and forth through a breaking mountain wave. Notably, the turbulence in this case was five times greater than in the strongest inertia-gravity wave case. Also, the amplitude of the mountain wave decreased to very small values at the highest flight leg, indicating that the mountain-wave energy is absorbed by the decreasing very weak winds in the summer Arctic stratosphere.

Airborne Chromatograph for Atmospheric Trace Species (ACATS-IV)

J. W. Elkins, R. E. Dunn, G. S. Dutton, D. F. Hurst, F. L. Moore, P. Romashkin, and P. R. Wamsley

Instrument Performance

The ACATS-IV instrument [Elkins *et al.*, 1996] was modified for POLARIS to measure 11 trace gases at a more frequent sampling rate that resulted in ~30% more data than for the flights during the STRAT mission. The weight of ACATS-IV also was reduced by 5.5 kg by using state-of-the-art pressure and flow controllers. We added a new molecule, chloroform (CHCl_3), a trace gas with an atmospheric lifetime of ~0.7 year. These improvements yielded *in situ* measurements of CFC-11, CFC-12, CFC-113, CHCl_3 , CH_3CCl_3 , CCl_4 , halon-1211, CH_4 , and H_2 once every 120 seconds and of N_2O and sulfur hexafluoride (SF_6) once every 240 seconds. ACATS measures ~80% of the total organic chlorine species and ~15% of the total inorganic bromine. Unmeasured trace gases of organic halogen (CH_y , where the halogen atom, H, is either Br or Cl) were estimated using a measured gas that was common to both WAS and ACATS for measurements or model-estimated values [Woodbridge *et al.*, 1995; Wamsley *et al.*, 1998]. In either case, this measured value is multiplied by the ratio (of mixing ratios) of the unmeasured gas of interest to the common measured gas. SF_6 can be used to “date” the air to within 3 months (1 yr), because it has a long lifetime in the atmosphere (~3200 years) and thereby relatively no atmospheric sink. The mean age of the air parcel can be calculated from the SF_6 measured stratospheric mixing ratio and tropospheric trend (6.7% yr^{-1}) [Geller *et al.*, 1997]. Tropospheric trends of the individual halogen species and the mean age of the air mass permitted a calculation of the total halogen atom (H_{Total}) that enters the stratosphere through the tropopause. Using conservation of mass, the difference, $\text{H}_{\text{Total}} - \text{CH}_y$, gave the total inorganic halogen atom mixing ratio (H_y). For the first time, we included data files after each flight for the mean age of the air mass, and total bromine and chlorine that included estimates for the stratospheric total input, inorganic, and organic components. Data were obtained by ACATS-IV on all 26 flights of the POLARIS mission.

Preliminary Scientific Results

The most remarkable scientific result of the POLARIS mission for the trace gases is the observation of low mixing ratios in a number of patches or filaments of polar stratospheric air at ER-2 altitudes in summer. Small filaments like these are not easily detected using remote sensing from the ground or satellites, so very little is known about them. Previously, these low mixing ratios were observed as late as 6 May 1993 in the mid-latitude stratosphere during the SPADE

mission [Vaugh *et al.*, 1997; Newman *et al.*, 1996]. These filaments are thought to result from the breaking up of the winter polar vortex in early spring. Polar vortex air was briefly encountered near the pole on the 6 May 1997 flight. Considerably lower mixing ratios were measured from the flights of 26., 29, and 30 June, and 4, 7, and 10 July 1997 at ER-2 altitudes (55 hPa or between 19 and 21 km). The Lightweight Airborne Chromatograph Experiment (LACE), a gas chromatograph similar to ACATS-IV that flew on the OMS *in situ* balloon payload launched 30 June 1997, confirmed that the air with the low mixing ratios observed on the ER-2 aircraft probably descended from altitudes between 26 and 30 km (15 to 18 hPa). The late mixing of polar vortex air into midsummer has important implications to the transport models used to calculate ozone depletion.

Comparisons of the ACATS nitrous oxide (N₂O) mixing ratios against those from ATLAS were within a few percent of each other for the first and second deployments. This means that the ACATS-IV values of N₂O can be used for those flights where ATLAS experienced problems during the third deployment. Our calculation of Cl_y agreed within experimental errors with the sum of the inorganic chlorine species of HCl, ClONO₂, and ClO measured independently by other instruments. This result means that our understanding of the chemistry involved with chlorine destruction of stratospheric ozone is well understood.

References

- 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. P. 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.
- Geller, L. S., J. W. Elkins, R. C. Myers, J. M. Lobert, A. D. Clarke, D. F. Hurst, and J. H. Butler, Tropospheric SF₆: Observed latitudinal distribution and trends, derived emissions and interhemispheric exchange time, *Geophys. Res. Lett.*, *24*, 675-678, 1997.
- Newman, P. A., L. R. Lait, M. R. Schoeberl, M. Seablom, L. Coy, R. Rood, R. Swinbank, M. Proffitt, M. Loewenstein, J. R. Podolske, J. W. Elkins, C. R. Webster, R. D. May, D. W. Fahey, G. S. Dutton, and K. R. Chan, Measurements of polar vortex air in the midlatitudes, *J. Geophys. Res.*, *101*, 12879-12891, 1996.
- Wamsley, P. R., J. W. Elkins, D. W. Fahey, G. S. Dutton, C. M. Volk, R. C. Myers, S. A. Montzka, J. H. Butler, A. D. Clarke, P. J. Fraser, L. P. Steele, M. P. Lucarelli, E. L. Atlas, S. M. Schauffler, D. R. Blake, F. S. Rowland, W. T. Sturges, J. M. Lee, S. A. Penkett, A. Engel, R. M. Stimpfle, K. R. Chan, D. K. Weisenstein, M. K. W. Ko, and R. J. Salawitch, The distribution of halon-1211 in the upper troposphere and lower stratosphere and the 1994 total bromine budget, *J. Geophys. Res.*, *103*, 1513-1526, 1998.
- Vaugh, D. W., R. A. Plumb, J. W. Elkins, D. W. Fahey, G. S. Dutton, M. Loewenstein, J. R. Podolske, E. Keim, K. Boering, S. C. Wofsy, M. H. Proffitt, K. K. Kelly, C. R.

Webster, R. D. May, K. R. Chan, P. A. Newman, and L. R. Lait, Mixing of polar vortex air into middle latitudes as revealed by tracer-tracer scatter plots, *J. Geophys. Res.*, *102*, 13119-13134, 1997.

Woodbridge, E. L., J. W. Elkins, D. W. Fahey, L. E. Heidt, S. Solomon, T. J. Baring, T. M. Gilpin, W. H. Pollock, S. M. Schauffler, E. L. Atlas, M. Loewenstein, J. R. Podolske, C. R. Webster, R. D. May, J. M. Gilligan, S. A. Montzka, K. A. Boering, and R. J. Salawitch, Estimates of total organic and inorganic chlorine in the lower stratosphere from *in situ* and flask measurements, *J. Geophys. Res.*, *100*, 3057-3064, 1995.

Lightweight Airborne Chromatograph Experiment (LACE)

J. W. Elkins, D. W. Fahey, R. E. Dunn, G. S. Dutton, R. J. McLaughlin, F. L. Moore, E. A. Ray, and T. L. Thompson

Instrument Performance

LACE is a two-channel gas chromatograph (GC) that measures chlorofluorocarbons CFC-11 (CCl_3F), CFC-12 (CCl_2F_2), and CFC-113 ($\text{CCl}_2\text{F-CClF}_2$), as well as Halon-1211 (CBrClF_2) and sulfur hexafluoride (SF_6) once every 70 seconds. LACE is similar to the ACATS instrument [Elkins *et al.*, 1996], but is built to operate under ambient air conditions instead of inside the pressurized and temperature-controlled environment of ER-2 aircraft's Q-bay. The LACE instrument, as part of the OMS balloon payload, had one flight on 30 June 1997 during the POLARIS mission. During this flight, the GC sample loops did not come to a steady-state pressure prior to the time of injection. Tropospheric mixing ratios were mainly affected, initially yielding higher than expected values. However, calibration curves of the GC response to differential sample loop pressure were generated in the laboratory and were used to correct the data throughout the flight.

Preliminary Scientific Results

The mean age of sampled air parcels can be estimated with measurements of SF_6 , because it has a long atmospheric lifetime (~ 3200 years) and a nearly linear growth rate ($6.7\% \text{ year}^{-1}$). LACE measures $\sim 50\%$ of the total organic chlorine species and $\sim 15\%$ of the total organic bromine in the stratosphere. With the additional input of 2-D model results and observed correlations between long-lived species, the LACE data will be used to estimate total bromine and chlorine at each altitude of the flight.

One of the most important lessons from our OMS balloon launch from POLARIS in Fairbanks was the observation of the remnants of the Arctic polar vortex which broke up earlier in March 1997 (see ACATS write-up). Figure 7 shows the tracer-tracer correlation for observations of CFC-12, a long-lived gas (lifetime ~ 100 years), versus CFC-11, a shorter lived gas (~ 40 years) from the LACE instrument. The figure includes LACE data from 30 June during POLARIS; from a mid-latitude flight over Ft. Sumner, New Mexico on 21 September 1996; and from a tropical flight over Juàzeiro do Norte, Brazil on 14 February 1997; as well as POLARIS data from the ER-2 ACATS instrument on 29 and 30 June. Curves of LACE CFC-12 versus CFC-11 mixing ratios for the polar and mid-latitude flights should be coincident because of strong mixing in the extratropical

regions. The curves are in agreement except for CFC-11 mixing ratios below 70 pptv. In that range, a mixing line appears connecting low (<10 ppt) and higher (70 ppt) values. A similar mixing line appears in the correlation of ACATS data from 29 and 30 June. A mixing line on a correlation plot is a result of the atmospheric mixing of two air masses that have CFC-11 and CFC-12 abundances defined by the end points of the mixing line [Newman *et al.*, 1996; Waugh *et al.*, 1997]. Continued atmospheric mixing will remove the mixing line from the correlation plot leaving the more general curve found by LACE at mid-latitudes. Clearly, the correlation is not typical of mid-latitude flights as might be expected during POLARIS. The mixing event also provided measurements of CFC-12 that were much lower than expected at ER-2 altitudes in the summer. These long lasting remnants of the polar vortex coinciding with the presence of large ozone depletion in the Arctic spring show why we should continue observational efforts in the Arctic. The CFC-12 versus CFC-11 curve for the tropical flight of LACE (14 February 1997) is very different than that of the mid-latitude and polar flights because the average age of the air is lower in the tropics because of strong vertical advection and continual mixing of air from mid-latitudes into the tropics [Volk *et al.*, 1996]. At ER-2 altitudes, approximately 50% of tropical air is estimated to have come from mid-latitudes. Thus, at these altitudes, the conceptual picture of transport in the tropics is one that resembles a “leaky pipe.”

References

- 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. P. 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.
- Newman, P. A., L. R. Lait, M. R. Schoeberl, M. Seablom, L. Coy, R. Rood, R. Swinbank, M. Proffitt, M. Loewenstein, J. R. Podolske, J. W. Elkins, C. R. Webster, R. D. May, D. W. Fahey, G. S. Dutton, and K. R. Chan, Measurements of polar vortex air in the midlatitudes, *J. Geophys. Res.*, *101*, 12879-12891, 1996.
- 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, and K. R. Chan, Quantifying transport between the tropical and mid-latitude lower stratosphere, *Science*, *272*, 1763-1768, 1996.
- Waugh, D. W., R. A. Plumb, J. W. Elkins, D. W. Fahey, G. S. Dutton, M. Loewenstein, J. R. Podolske, E. Keim, K. Boering, S. C. Wofsy, M. H. Proffitt, K. K. Kelly, C. R. Webster, R. D. May, K. R. Chan, P. A. Newman, and L. R. Lait, Mixing of polar vortex air into middle latitudes as revealed by tracer-tracer scatter plots, *J. Geophys. Res.*, *102*, 13119-13134, 1997.

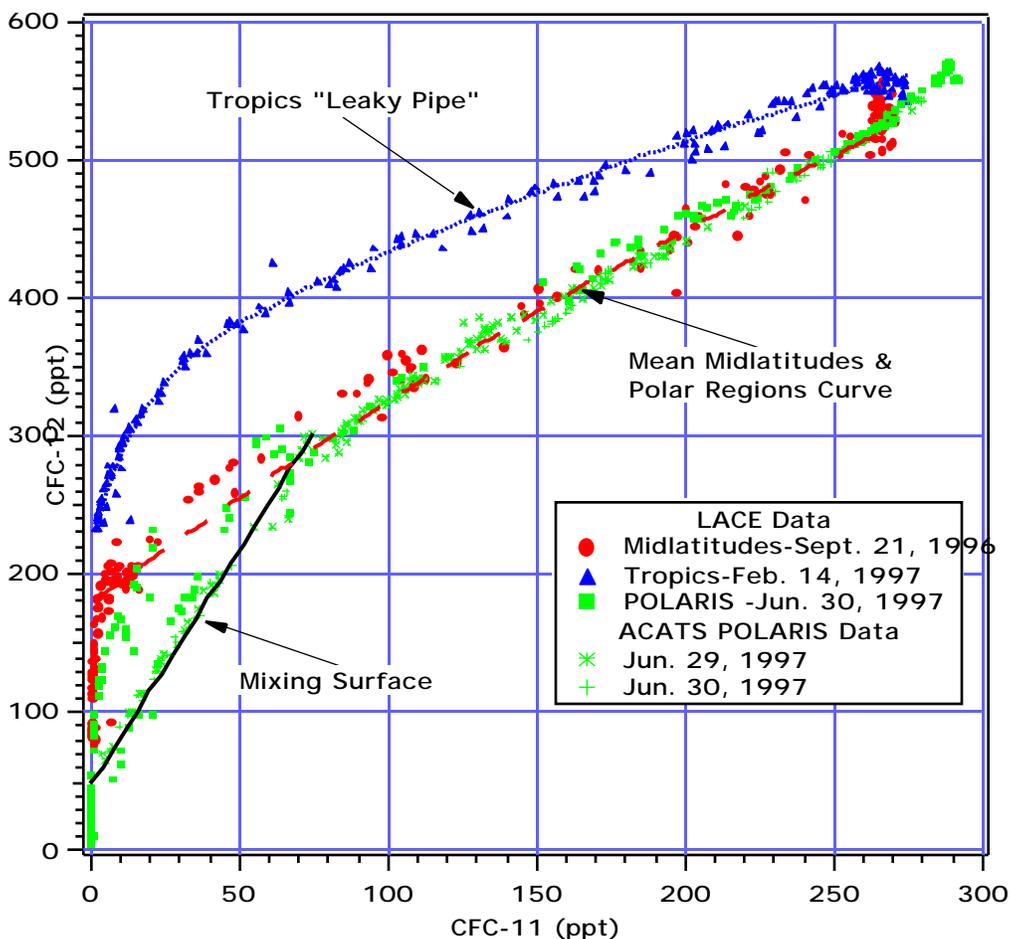


Figure 7. Tracer-tracer correlation plot of CFC-12 versus CFC-11 from LACE on the OMS gondola for flights on 21 September 1996 (mid-latitudes), 14 February 1997 (tropics), and 30 June 1997 (POLARIS, polar regions). Also included are ACATS data from POLARIS flights of the ER-2 aircraft on 29 and 30 June 1997. Dotted line indicates tropical data resulting from the “leaky pipe”, dashed line indicates mean mid-latitudes and polar regions curve, and solid line indicates conservative mixing in the region with endpoints for (CFC-11, CFC-12) between (69, 285) and (1, 48) ppt.

Reactive Nitrogen (NO/NO₂/NO_y)

R.-S. Gao, L. A. Del Negro, S. G. Donnelly, E. R. Keim, J. A. Neuman, L. Teverovskaia, T. L. Thompson, and R. H. Winkler

The NO/NO₂/NO_y instrument performed satisfactorily throughout the entire mission. The sensitivity for all three channels of the instrument has been improved by approximately 70% relative to previous missions. The NO₂ channel background measurement has been improved leading to more accurate NO₂ data.

The fractional contribution of NO_x to NO_y changed dramatically over the duration of the mission. NO_x/NO_y ratios varied from 0.07 to 0.28 and maximized around summer solstice when periods of photolysis were nearly continuous over a diurnal cycle. These observations are consistent with a reduction in heterogeneous N_2O_5 hydrolysis due to the suppression of N_2O_5 formation. In addition, the concentration of BrONO_2 is reduced around summer solstice due to higher photolysis loss, which further reduces formation of HNO_3 .

Preliminary data show that the photochemical steady-state approximation accurately predicts the observed NO_2/NO ratio, which is consistent with results from the Airborne Southern Hemisphere Ozone Experiment/Measurements for Assessing the Effects of Stratospheric Aircraft (ASHOE/MAESA) mission. However, the values of NO_x/NO_y in current photochemical models are less than the observed values by as much as a factor of two, contrary to ASHOE/MAESA polar winter results. Several possible mechanisms have been proposed including inaccurate rate constants, heterogeneous reactions on carbon aerosols that are not accounted for in the models, and inhibited heterogeneous reactions due to freezing of sulfuric acid aerosols. A simplified model was developed specifically for testing those mechanisms systematically. At this stage, none of the proposed mechanisms provides results that are consistent with the observed data, although reducing the $\text{OH} + \text{NO}_2$ reaction rate constant by 50% brings the calculated NO_x/NO_y values to within $\pm 50\%$ of the measured data.

The preliminary calculations using *in situ* measurements of NO_x , HO_x , and ClO show that the rate of ozone destruction by NO_x is indeed higher than that by HO_x and halogens in the Arctic region in summer. Around the time of the summer solstice the ozone destruction rate due to NO_x reached 13% per month, compared to 5% per month by HO_x and halogen cycles combined. The net ozone change reached -16% per month during that period.

Calculations of $J(\text{NO}_2)$ at high solar zenith angles ($89^\circ < \text{SZA} < 91^\circ$) have been evaluated using *in situ* measurements of NO_x and ozone for the first time. It was found that the cloud height can affect the calculated value of $J(\text{NO}_2)$ at high SZAs by as much as 20%. With cloud height values derived from satellite observations, the calculated $J(\text{NO}_2)$ values agree well with those derived from NO_x and ozone measurements.

The correlation plots of NO_y with N_2O data obtained during POLARIS exhibit features of nonlinearity and scatter that are unusual compared to previous data sets obtained with the ER-2. For N_2O values greater than 200 ppbv, the correlation is fairly linear over the time period studied and exhibits a small seasonal change with a minimum slope of 0.060 occurring in June and July. This minimum is consistent with the predictions based on data obtained during earlier ER-2 missions (STRAT, ASHOE/MAESA). For N_2O values less than 200 ppbv, and in particular for potential temperatures greater than 500 K, the correlation exhibits much larger changes and has significant nonlinearity during the April-to-June time period. Possible causes include the incomplete mixing out of the previous winter's polar vortex. However, the POLARIS data set alone cannot be used to determine whether the changes are due to denitrification or extreme diabatic descent occurring in the vortex. Comparison with the NO_y - N_2O data set obtained with the MkIV balloon-borne solar occultation interferometer in Fairbanks in May suggest, if the scatter is due to descent, the sampled air began the winter at altitudes over 30 km.

Microwave Temperature Profiler (MTP)

B. Gary

Summary of Instrument Performance

The MTP/ER-2 operated during all POLARIS flights, including the test and ferry flights (30 in all). A noisy filter caused 26% data loss for one flight (10 July), and up to 5% losses on other July flights; the problem was identified and repaired before the third deployment. The first and third deployments produced nearly 100% good data.

Preliminary Scientific Results

The principal MTP result is that the Arctic summer lower stratosphere has a very suppressed level of mesoscale vertical motions. Mesoscale fluctuation amplitude (MFA), defined as the root mean square (RMS) departure of isentrope altitude from synoptic-scale filtered altitude, was typically 60 m during July and September. Before POLARIS the smoothest region/season that MTP had encountered was winter-time oceans in both the Arctic and Antarctic, with MFA of 120 m. Land terrain for Arctic, Antarctic, and CONUS exhibit MFA of 160 m, and mountainous Arctic, Antarctic, and CONUS exhibit MFA of 40 m.

A secondary MTP result is the observation during the vortex flight (26 April) that the “temperature field vortex edge” was approximately 1.8° of latitude equatorward of the tracer edge (ozone/ N_2O , N_2O , CO_2 , H_2O , $ClONO_2$) for both ingress and egress. Isentrope surfaces (below ~ 500 K) exhibited an abrupt slope change at 82.2° latitude, whereas tracers exhibited their abrupt change at 84.0° (which was also the wind maximum location). This difference in location of “tracer vortex edge” and “temperature field vortex edge” has been seen on many occasions beginning with the Second Airborne Arctic Stratospheric Expedition (AASE II) in 1992.

MTP did not detect temperature anomalies associated with filaments of air having tracer mixing ratios belonging to other latitudes. This contrasts with previous MTP detections of the model-predicted pattern “warm on top, cold on bottom” associated with filaments traveling equatorward during ASHOE/MAESA and STRAT. The fact that neither this pattern, nor its opposite (for filaments traveling poleward) were detected, might argue that either high diabatic heating rates overcame potential vorticity (PV)-conserving temperature anomalies, or PV changes were partitioned to the wind field instead of the temperature field.

Argus: Dual-Channel N_2O and CH_4 Lightweight Tracer Instrument

M. Loewenstein, J. Grose, and H. Jost

During the POLARIS campaign a single flight of the OMS balloon payload was carried out on 30 June 1997 from Fairbanks. This flight represented an opportunity to intercompare tracer fields measured on the balloon and on the ER-2 as well as to extend these measurements to higher altitudes on a one-time basis. Several significant findings emerged from the Argus data acquired on this flight:

- Filaments, apparently remnants of the Arctic winter polar vortex, were observed at 2 places in the profile, 55 and 32 hPa. These narrow structures were characterized by low N₂O (about 50 ppb) and a polar vortex-like correlation of CH₄:N₂O. The very low N₂O values observed in these filaments provide strong evidence that they were advected from the polar vortex before or during its breakup and have maintained their identity with little or no mixing for a period of about two months.
- A near-simultaneous flight of the ER-2 on 30 June provided measurements of N₂O by the ATLAS instrument which are in excellent agreement with the Argus N₂O measurements made as part of the OMS payload. The ER-2 also observed the lower of the two vortex filaments (55 hPa) seen by the OMS payload.
- The age of the air observed at the top of the OMS balloon profile near 32 km, in excess of 6 years, is the oldest air sampled by tracer instruments in the STRAT campaigns. Age determinations from flight data of this type will provide important input to models that attempt to predict age of air and, therefore, the residence time and fate of HSCT exhaust injected into the mid-latitude stratosphere.

Airborne Tunable Laser Absorption Spectrometer (ATLAS)

M. Loewenstein, J. Greco, J. Grose, and J. R. Podolske

Phase I

The nitrous oxide tracer field was inhomogeneous due to an intense and prolonged vortex activity in the preceding northern winter, which led to record low ozone column densities.

During the polar flight (26 April) a vortex fragment was encountered at altitude before the pole, N₂O dropped to ca. 80 ppbv and also other chemical and particle tracers showed the same behavior.

The ozone/N₂O correlation was very scattered, showing points “above” the mid-latitude correlation, which is indicative of air transported from the subtropics. The correlation bent over towards lower ozone values at ~3200 ppbv ozone, close to the expected value for this date. Curiously, the air sampled right after take-off appeared below the mid-latitude ozone/N₂O correlations and also in the CO₂/N₂O correlation as a “fork” in the otherwise compact correlation. This thin layer with obviously different tracer abundances was observed during many flights in Phase I.

- Performance of ATLAS

From the very first test flight and during the entire POLARIS mission ATLAS revealed oscillations in the second harmonic detection signals, in both the reference and signal (White-cell) channels. The period of oscillations varied from flight to flight and ranged from 12 seconds to ~1 minute. The amplitude was ~10% at the most. All attempts to resolve this problem, which ATLAS had never shown before, failed; neither shielding the connector cables nor adjustments of the Phase Sensitive Detector phases were successful. The oscillations were never seen in the laboratory

(either with a 60-Hz or a 400-Hz power supply for the GSE) and could not be reproduced in during a ground power test at the aircraft with other instruments located in the right pod turned on and off. Furthermore, no correlation between the occurrence of the oscillations in flight and the turn-on time of the WAS pump could be established. An engine test on the ground at the very end of the Phase I deployment revealed the oscillations seen in flight. A connection between the new ER-2 engine and the ATLAS problem was an obvious conclusion of this test.

Efforts Following Phase I

The time between the deployments was used to perform an additional engine test at Ames in order to measure the power supplied by the new engine in terms of RMS voltage of the three AC phases and their frequencies and the voltage of the DC (28V) supply. A “dummy” load equivalent to the power which ATLAS uses during flight (~1000 W) was connected to a junction box especially built for this power test. A battery-powered voltmeter, oscilloscope, and chart recorder were used to monitor the power supply. During an approximately 20-minute engine test the three 400-Hz and 120-V phases appeared to be very clean, but the 28-V DC had periodic oscillations of ~4 V on top of it. The frequency was ~2 kHz. It remains puzzling how these oscillations could have affected ATLAS, since the DC 28-V supply is used in the instrument only up to the J-Box next to the electronics box and since the frequency is very high. Although frequency beating with 2 kHz used in ATLAS for phase-sensitive detection could result in the low frequency observed in these oscillations, the mechanism of the introduction of the 2 kHz frequency from the 28-V DC power supply into the electronic box is still not obvious and radiative coupling is only a speculation. To make things even worse, we learned that the ER-2 engine or generator was modified between the end of POLARIS Phase I and our power test at Ames, thus the conclusions of this test may be invalid for the effects seen during Phase I.

Phase II

The N₂O tracer field was homogenous with the exception of a layer at Fairbanks latitude with a filament of vortex air, which showed N₂O values down to 50 ppbv.

An important intercomparison between the ER-2 and OMS payloads was done during the OMS balloon launch. The N₂O intercomparisons between ATLAS and ARGUS were very good, certainly well within the error estimates of the two instruments. The ozone/N₂O correlation in the polar flight bent over at lower ozone values, ca. 2500 ppbv ozone, than during Phase I, as expected. This reduction in ozone in the ER-2 altitude region is most likely due to *in situ* chemistry, although large scale transport from lower latitudes (quasi horizontal) cannot be completely neglected, as evidenced for example by mixing lines in the NO_y/N₂O correlations. This partitioning into *in situ* chemistry vs. large-scale transport needs the utmost attention during the upcoming data analyses.

The observation of this unusual filament of vortex air over Fairbanks (and actually the OMS payload detected one at altitudes well above the maximum ER-2 altitude) during every flight in this Phase II deployment may allow us to quantify smaller scale isentropic mixing with adjacent air.

The dependence of the N₂O changes with sharp gradients in solar exposure time, as targeted during several flights, seems to be expectedly low, but this also needs further analysis.

- Performance of ATLAS

The oscillations remained in the flight data and changing the 2-kHz frequency board did not solve the problem. The intercomparisons with ACATS were excellent again and the agreement with ALIAS was better than in Phase I.

Phase III

No unusual observation of the N₂O tracer field was made.

During a small segment of the polar flight, ozone and N₂O were positively correlated.

The transit from Fairbanks to Hawaii revealed an N₂O gradient at ~35°N latitude and the tropical flight out of Hawaii showed two distinct vertical profiles (take-off and landing vs. dive at the equator). This also appeared in the CO₂/N₂O correlation as a change towards higher correlation slope in the tropics.

And, of course, the ozone/N₂O correlation during this tropical flight revealed again the change of slope as the aircraft flew into the deep tropical region, as observed during STRAT. But the “isolation” between mid-latitudes-subtropics and the tropics was much more pronounced than during any flight in STRAT (November 1995, February 1996, August 1996, and December 1996).

- Performance of ATLAS

Again the oscillations remained in the flight data, but the effect of an optical etalon in the White-cell degraded the data a little more, which made an optical realignment necessary. Even though the data looked very good in the laboratory, the etalon effect in flight always increased. Because the etalon effect during the polar flight increased so much that it became evident in the N₂O data, the error margins had to be raised to 15 ppbv for this flight's data.

The N₂O intercomparisons between ATLAS and ACATS degraded substantially during Phase III and the intercomparison between ALIAS and ACATS was partly better. Nevertheless, it should be noted that during one or two flights ACATS was substantially lower than ATLAS and ALIAS.

Summary Statement on the Data Quality and Accuracy of the Preliminary Data in the Archive

In summarizing the overall data quality, the N₂O error bars remain at 9 ppbv and are not effected by the oscillations, since the latter cancel to the first order because the ratio between the signal and reference channels is used and the oscillations are common to both.

The temperature difference between reference and White cell was reduced to 4 to 5°C just prior to POLARIS as compared to 6 to 8°C before the modifications of ATLAS. Although this reduces the

size of the thermal corrections to the raw data, the resultant improvement in flight accuracy has been largely offset by the oscillations in the raw signals.

The calibration factor for correcting preliminary data of Phases I and II will be ~0.985 but during Phase III presumably a different calibration factor for each flight will have to be applied in the light of the comments above on ATLAS performance during this phase.

Water Vapor - Jet Propulsion Laboratory

R. D. May

Instrument Performance

This water vapor (H₂O) instrument worked well on every POLARIS flight during the first two deployments, and throughout the third deployment until the ferry flight from Alaska to Hawaii. During ascent at ~400 hPa an electrical event caused the computer to reboot, and also caused the laser to fail. The exact cause of this event is unknown, and there appears to be no damage of any kind to any other component of the instrument. However, a kink in the main power cable (from the 28V converter shared with ALIAS) was observed back at JPL and a momentary short may have occurred (although this is speculation).

Preliminary Results

No anomalous behavior in H₂O volume mixing ratios in the stratosphere was observed during POLARIS. High values (near 6 ppmv) observed on numerous occasions in older air present at ER-2 altitudes via descent are consistent with increased methane oxidation. Of particular interest to us are the ER-2 wake intercepts, and the very low H₂O values observed at the hygropause during the first POLARIS mission.

Composition and Photodissociative Flux Measurement (CPFM)

C. T. McElroy, D. V. Barton, R. Hall, J. C. McConnell, M. J. Prather, C. Midwinter, and K. Nassim

The Composition and Photodissociative Flux Measurement experiment uses a miniature UV-Vis diode array spectrophotometer to make spectroradiometric measurements of the radiation field in the vicinity of the ER-2. Measurements of the horizontal irradiance and of the apparent surface brightness in the limb and nadir directions are used to estimate the flux of radiation into a volume of air at the ER-2 location. These data are used to derive a number of products which are used to define the radiation environment of the aircraft. The derived products include the column amount of ozone above the aircraft and the estimated J-values for the reactions:



and



The first of these is very important for understanding the ratio of NO to NO₂ in the atmosphere while the second reaction is the major daytime source of excited oxygen in the stratosphere. The subsequent reaction of excited oxygen with water vapor is the largest source of the OH radical in the lower stratosphere.

Brewer Ozone Spectrophotometer number #007 was operated at both Fairbanks and Barbers Point to provide total column ozone, Umkehr profiles, and ultraviolet radiation measurements. The ground-based column measurements are used to verify the calibration of the CPFM instrument. The ground-based and airborne ozone column data are of particular importance for the POLARIS missions since the ozone amounts at high latitudes can be highly variable and since the TOMS data can be unreliable, particularly at large solar zenith angles, because of surface reflectivity issues and because of the unusual vertical distributions of ozone which can occur in the Arctic. Since both the Brewer and the JPL MkIV interferometer were operated at Fairbanks throughout the summer, an excellent data set comparing Brewer UV-absorption ozone total column data with infrared absorption results has been compiled. These data will form the basis for a publication on the subject which may prove to be the best of its kind. The ground-based Brewer ozone data are available on the NASA/Ames archive as ground based "TO" files.

Environment Canada also provided ozonesonde support for POLARIS by making extra ozonesonde ascents from Canadian northern stations during the POLARIS deployments. These data, and other Canadian sonde data, have also been archived at NASA/Ames.

The UV-VIS instrument operated well throughout all of the POLARIS science flights and provided excellent ozone column data. The preliminary data from most flights are usable in all product forms (spectra, fluxes and J-values) already, but reprocessing with an improved aircraft geometry model will improve the accuracy of the data. Generally, very good agreement between the CPFM data and modeled J-values have been seen for the POLARIS mission when accurate ozone distributions and total column data are available.

The new all-sky digital camera system installed during the STRAT project was operational throughout all of the POLARIS flights and data were obtained during all but one flight. These data have already shown their value in helping to define the nature of the reflecting surface below the aircraft in the Arctic, where satellite visible and infrared (IR) imagery cannot always distinguish between large albedos from ice surface reflectivity and from cloud tops. It has been shown that the images can be used to improve the quantitative estimates of the nadir and limb brightness contributions of the total J-values calculated from CPFM data. These corrections should soon be available operationally as part of the J-value processing.

A particularly interesting new product from the CPFM nadir spectra radiance data is now being computed. Observations from the first POLARIS deployment have been analyzed using the UV-Vis Differential Optical Absorption Spectroscopy (DOAS) technique and have revealed that large amounts of BrO (0.6 to 1.5E15 molecules cm⁻²) existed in the free troposphere at the time of the 26 April 1997 flight.

Ozone Profiles from Fairbanks, Alaska in Support of the POLARIS Mission

S. Oltmans, D. Jaffe, and B. Johnson

A team consisting of scientists from NOAA/Climate Monitoring and Dynamics Laboratory (CMDL) and the University of Alaska were funded by NASA to provide vertical profiles of ozone over Fairbanks using the standard balloon-borne electrochemical sensors. Between April and October 1997, 37 successful ozone profiles were obtained and the data made available to the POLARIS in near real-time using the worldwide web (http://zorba.uafadm.alaska.edu/chem/ozone/O3_dat.html).

Dual-Beam UV-Absorption Ozone Photometer (Ozone)

M. H. Proffitt, K. Aikin, and J. J. Margitan

The instrument performed well during all 25 flights beginning with the 22 April 1997 survey flight south from Ames and ending with the return ferry flight from Barbers Point on 25 September 1997. The only instrument problems encountered were on a few flights out of Fairbanks, when ~5 minutes of data were lost due to data system failure. On these flights the pilot noticed the fail light was lit and restarted the instrument using the pilot's instrument control panel. These failures could not be duplicated on the ground and their source has not been determined.

Phase I

It was hoped that remnants of the extensive polar ozone loss that had occurred within the 96-97 Arctic vortex might be observed in late April. Although evidence for an ozone deficit was found in the ozone-N₂O data, extensive loss was not, due in part to the position of the region of high PV (the vortex remnant) which was not accessible to the ER-2. Additionally, based on previous Arctic missions (AASE and AASE II), the flight levels of the ER-2 may have been too high to observe the region containing the greatest evidence for previous ozone loss (below 440 K). There was one dive to 400 K during this phase (26 April 1997), with a dive near the pole. During this flight, the most convincing evidence for previous ozone loss was observed, particularly between 400 K and 470 K. Except near Fairbanks (takeoffs and landings), flight profiles otherwise remained above 440 K.

Phase II

Ozone-N₂O distributions were very different from those found during other seasons and from those found at other latitudes. At the upper theta levels, ozone was generally much lower than observed during any other season, and in particular during Phase I. This was not so evident at the lowest levels (<420 K). N₂O values were also very low at the upper levels. Some combination of summertime ozone loss combined with the 1996/97 polar losses and local isentropic mixing most likely account for these distributions rather than dynamical processes alone.

Phase III

The average values for N₂O have increased substantially above 460 K and ozone has increased ~10% relative to N₂O at all levels. The changes in the ozone-N₂O distributions may be explained by decreases in summertime loss rates and isentropic mixing of mid-latitude air (higher ozone and N₂O) with the high-latitude air observed during Phase II. The ferry flight to Barbers Point encountered tropical air at ~38°N and the ER-2 remained in tropical air during the remainder of the flight. The flight to the equator was entirely in tropical air with ozone-N₂O distributions virtually identical to those found during OMS-Brazil on 14 February 1997.

Submillimeterwave Limb Sounder (SLS)

R. A. Stachnik

The SLS instrument, a remote sensor measuring ozone, H₂O, N₂O, HCl, HNO₃ and ClO, was flown during POLARIS on the ER-2 Ames-Fairbanks transit flights on 15 May, 23 June, 12 July, and 2 September 1997. All three radiometer and spectrometer systems worked well on all flights, except for the 637-GHz receiver (HCl, ClO) on 15 May. During these flights the instrument recorded full “limb-scan” emission spectra every 75 seconds. These have been interpreted to produce a set of vmr profiles for the above constituents covering the altitude range from 15 to 35 km along the flight track.

Preliminary Science Results

Comparison of the SLS ozone field (latitude vs. altitude) for 23 June 1997 shows good agreement in magnitude and latitude gradient with that observed by NOAA14 Solar Backscatter Ultraviolet Spectrometer (SBUV)-2. SLS ozone for the 12 July flight is also in good agreement with the OMS ozone photometer profile (balloon flight on 8 July). Comparisons with HALOE zonal means for May through July show 1-sigma agreement at pressures greater than 10 hPa. Above 10 hPa, the HALOE ozone is significantly higher (~15%) than SLS or balloon ozone. Comparisons with TOMS columns and MLS are planned. Correlation plots of ozone vs. N₂O (both SLS data) show more curvature (decreased negative slope) at low N₂O (N₂O < 100 ppbv) for latitudes > 55°N on flights 23 June and 12 July as compared with data for 15 May and 2 September. Profiles for H₂O and HCl showed no significant latitude gradient along the flight track.

Ames Particle Measurement System (APS)

A. W. Strawa, K. Drdla, G. Ferry, and R. Pueschel

The APS had a successful POLARIS mission. An automated control system for the instrument was designed, fabricated, and flown during the mission. Its excellent performance will afford investigators with more flexibility in future aerosol sampling. A total of 162 samples were taken of stratospheric aerosol and are currently being analyzed on the electron microscope.

Preliminary analysis of samples indicates that the sulfate aerosol concentration is in agreement with estimates for this region of the atmosphere. Soot also has been collected on our samples. The potential exists for heterogeneous chemistry on soot particles to affect the NO_x/NO_y ratio and the

partitioning of the reactive nitrogen budget. Because of this, we are in the process of refining our measurements and exploring the link between soot and ozone chemistry.

JPL MkIV Interferometer

G. C. Toon, J.-F. Blavier, and B. Sen

Balloon Observations

The MkIV interferometer performed two balloon flights from Fairbanks in support of POLARIS. In both flights the MkIV instrument worked flawlessly and obtained high-quality spectra, which provided vertical profiles of over 30 different gases including H₂O, ozone, N₂O, CO, CH₄, NO, NO₂, HNO₃, HF, HCl, OCS, H₂CO, HOCl, H₂O₂, HNO₄, N₂O₅, ClONO₂, HCN, CH₃Cl, CF₄, CF₂Cl₂, CFCI₃, CCl₄, COF₂, C₂H₆, C₂H₂, CHF₂Cl, HCOOH, HDO, and SF₆.

On the evening of 7 May, MkIV was launched from Fort Wainwright on a 24-million cubic feet (MCF) balloon and obtained sunrise observations the following morning (8 May) from 38 km altitude. This flight was also in support of the ADEOS Validation Campaign and the payload included the Cold Atmospheric Emission Spectral Radiometer (CAESR) instrument of the University of Denver (Murcray). The long duration of this sunrise (120 minutes as compared with 35 minutes typically from Ft. Sumner, NM), provided data of very high quality and vertical resolution. Profiles were obtained over the 8- to 37-km altitude range with a vertical resolution of about 2 km. These profiles exhibit good agreement with closely collocated ER-2 measurements and with the OMS balloon payload launched the following month. In particular, tracer correlations (e.g., N₂O-O₃ and N₂O-CH₄ show excellent consistency with the *in situ* measurements.

On the evening of 7 July, the MkIV was launched from Fairbanks on an 11-MCF balloon. Since the sun does not rise or set sufficiently in midsummer at the latitude of Fairbanks to perform an occultation, data were taken on ascent and descent, with minimal time being spent at float (35-km altitude). Essentially, the sun was made to rise and set by the vertical motion of the balloon rather than by the Earth's rotation. With the late evening launch, the solar zenith angles remained large (84 to 92°) throughout the entire flight, providing good vertical resolution and high sensitivity to trace species. Two sets of profiles were obtained from this flight, the ascent profiles covering the 8- to 32-km altitude range and the descent profiles covering the 10- to 32-km range. This payload also carried the *in situ* ozone photometer (Margitan and Chang) and the Canadian Sun-Photospectrometer (McElroy), which is similar to the ER-2 CPFM instrument.

The main relevance of the MkIV balloon observations to POLARIS is that they sampled the stratosphere at the altitudes where the largest ozone loss occurs, which are above the altitudes attainable by the ER-2 aircraft. Furthermore, the MkIV measures all the main radicals and reservoirs of NO_x, whose catalytic removal of ozone dominates in the high-latitude summer. Modeling efforts (Salawitch and Osterman) reveal that ozone loss rates calculated as a function of altitude from these MkIV observations of NO_x agree well with the ozone loss profiles actually observed. Furthermore, both the budget and partitioning of the chlorine species measured by MkIV showed excellent agreement with the model.

Ground-Based Observations

In addition to the two balloon flights, the MkIV instrument also made 48 days of ground-based observations from Fairbanks between mid-March and mid-September. From these spectra vertical column abundances were obtained for 24 different species, including ozone, HF, HCl, ClONO₂, NO, NO₂, HNO₃, CO₂, CO, N₂O, CH₄, C₂H₂, C₂H₆, and NH₃.

The MkIV ground-based observations of ozone exhibit excellent agreement with the TOMS and the Brewer instruments, and reveal that a third of the column ozone present in late March was lost by September. The MkIV observations of HF and other stratospheric tracers show almost constant abundances during the same period, indicating minimal ascent or descent of stratospheric air and that the loss of column ozone therefore could not be due to transport processes.

Aircraft Laser Infrared Absorption Spectrometer (ALIAS)

C. R. Webster, R. L. Herman, R. D. May, K. Modarress, E. Moyer, and D. C. Scott

The ALIAS Instrument

The Aircraft Laser Infrared Absorption Spectrometer (ALIAS) instrument produced simultaneous measurements of N₂O, CH₄, CO, and HCl, sampling the latitude range 0° to 90°N, over the region from the upper troposphere to lower stratosphere in flights out of California, Alaska, and Hawaii. The instrument was flown in the same configuration as in the previous STRAT mission, but with reduced weight resulting from the removal of ancillary plumbing associated with active isokinetic flow control.

The Flights

Despite instrument failure during both test flights, the ALIAS instrument performed very well during all three phases of the POLARIS deployments, producing data on 23 out of 24 flights, and with complete data sets for all four gases on about 75% of those flights. No data were collected during the southern survey flight on 22 April.

Excellent HCl data were obtained on 21 out of 24 flights, with data loss on 22 April, 13 May, and 10 July. For the high-latitude flights which sampled low-N₂O air that experienced low-temperature processing, the data quality was excellent. Further data processing is required for the September flights at low latitudes, because interferences at the lowest altitudes due to nearby water lines require careful removal. ALIAS N₂O and CH₄ data were collected on 22 out of 24 flights, with data loss on 22 April and 10 July. The quality of these tracer data sets was somewhat diminished for Phase III of the mission. Excellent CO data were collected on 23 out of 24 flights, with data loss during the flight of 22 April. For a few flights, CO data sets are partial with data loss on ascent or descent. The CO data of the flight of 6 May appear low.

The Tracers N₂O and CH₄

The POLARIS mission offered the opportunity to extend the CH₄ vs. N₂O correlation database and further determine to what extent the tracer-tracer relationships can be used to characterize air

masses and distinguish tropical, mid-latitude, and vortex air. This framework provides a reference frame for quantitatively determining the rates of transport and mixing between different regions of the stratosphere and between the stratosphere and troposphere.

The ALIAS N₂O measurements were compared with those from ATLAS and ACATS during many of the flights. In addition, ALIAS CH₄ data were compared with those from ACATS. During the POLARIS mission all three N₂O measurements and the two CH₄ measurements agreed better than in previous missions. Least-squares fits to the N₂O data show high correlation (> 0.95) between ALIAS/ATLAS/ACATS measurements; one-sigma standard deviation between ALIAS/ATLAS N₂O is ~6 ppbv (2%) with systematic differences in slope/intercept of less than 4%. The ACATS measurements correlate similarly with ALIAS and ATLAS, showing deviations of ~10 ppbv (3%) and slope/intercept differences of less than 3%.

The ALIAS and ACATS measurements of CH₄ show excellent agreement (correlation coefficient 0.98), with one-sigma standard deviations of ~2%, and slope/intercept differences of a similar amount. There is a tendency for ACATS measurements of tropospheric CH₄ to be higher than those of ALIAS.

Correlations of ALIAS N₂O vs. ALIAS CH₄ during the POLARIS deployments were generally consistent with correlations from previous missions (STRAT and ASHOE/MAESA) and, with this correlation alone, sampled air masses could be identified as air of either mid-latitude or vortex origin. Correlations of CH₄ vs. N₂O observed in vortex flights, such as those during Phases I and II, agreed well with similar observations from both STRAT 1995/96 and SPADE 1993.

Our ER-2 N₂O vs. CH₄ tracer-tracer database is extended and complimented by the six successful balloon flights of ALIAS II on the OMS platform. In particular, the ALIAS II data extend the correlations to higher altitudes, which is important for distinguishing tropical air whose correlation departs from that of mid-latitudes at altitudes well above the ER-2 cruising altitude. There was excellent agreement between ALIAS II and ALIAS N₂O and CH₄ during the 30 June intercomparison flights.

Carbon Monoxide (CO)

During the POLARIS mission, the ALIAS CO database was extended in time and season, with data quality comparable to or higher than previous missions. The CO data set from the ER-2 is now extensive enough that mean mixing ratio contours are being generated and compared with 2-D model simulations to identify the dependence of its production and loss terms on latitude and altitude, where seasonal dependencies can clearly be extracted.

ALIAS CO over Alaska had a very sharp gradient at the tropopause, typically starting at 80 to 115 ppbv 0.5 km below the tropopause (determined by Bruce Gary (MTP)), and decreasing to only 30 to 40 ppbv by 1.0 km above the tropopause. This reflects the lack of ascent across the high-latitude tropopause. Although the minimum in the CO tropospheric seasonal cycle nominally occurs in July to August at mid- and high latitudes, extremely high CO (up to 180 ppbv) was observed in the upper troposphere in June and July POLARIS flights due to forest fires.

At potential temperatures greater than 480 K, CO is in photochemical steady state with mixing ratios ranging from 10 to 15 ppbv, depending on the temperature history. On the southern survey flight of 23 September, the CO mixing ratio was ~60 ppbv at the tropical tropopause. This is consistent with the observed CO during the STRAT southern surveys.

Carbon monoxide is a sensitive probe of air which has been in the stratosphere for less than six months or so, and we are using it as a tool for understanding atmospheric transport from the tropics to mid-latitude lower stratosphere. In model calculations underway, the photochemistry of CO along the flight track is constrained by simultaneous measurements of CO and CH₄ from ALIAS, OH from the HO_x instrument, NMHC from the NCAR WAS experiment, and model Cl and O(¹D) from the Salawitch PS files.

Hydrochloric Acid (HCl)

ALIAS provided excellent HCl data throughout most of the POLARIS mission. The agreement between the ER-2 ALIAS HCl measurements and those of the MkIV Fourier Transform Infrared (FTIR) balloon instrument flown at similar times from Alaska is excellent, and gives confidence in our ability to extend the aircraft data sets to higher altitudes where appropriate.

With the new ClONO₂ measurements by Harvard, the POLARIS mission provided the first opportunity to test the inorganic chlorine partitioning from simultaneous measurements of ClO, ClONO₂ (Harvard), and HCl (ALIAS). Initial results show that the agreement between the sum ClO + ClONO₂ + HCl and the measured Cl_y is remarkably good. In flights where the ClONO₂ varies as expected, the HCl is seen to compensate to maintain the integrity of the sum.

HCl vs. N₂O correlations were captured for the low background aerosol conditions characteristic of POLARIS. The mid-latitude HCl measurements show HCl/Cl_y values of ~70 to 80% that are consistent with low-aerosol data from earlier missions, and contribute to the long-term database that indicates an HCl/Cl_y ratio increasing with time as the aerosol loading diminishes. One important observation under investigation is that at the very low surface areas encountered during sampling of vortex air, the HCl/Cl_y fraction is seen to diminish significantly. If low-temperature sulfate heterogeneous chemistry is responsible, this observation may be related to the longer times these air parcels have experienced low temperature conditions, albeit at lower surface areas.

Focused Cavity Aerosol Spectrometer (FCAS) and Condensation Nuclei Counter (CNC)

J. C. Wilson, C. A. Brock, and J. M. Reeves

Performance Summary

The FCAS and CNC performed well throughout the POLARIS campaign. Data were lost only during flight 10 July, when FCAS data were not recorded for the last third of the flight due to a computer problem. The MACS impactor system collected approximately 15 particle samples per flight. A small fraction of these samples will be analyzed for individual particle morphology and composition by analytical transmission electron microscopy.

Preliminary Results

The data contain many interesting features, including aircraft plumes and large increases in nuclei-mode particle concentrations near 20 km in mid-latitudes not associated with any obvious plumes or tracer fluctuations. These regions of unexpectedly high particle concentration are unprecedented in our measurement record and will be investigated further. Measurements in air with polar vortex characteristics show the expected enhancements in small particle concentration due to the vortex aerosol source. Similarly, data in the tropics show high concentrations of small particles characteristic of the tropical tropospheric particle source.

Measurements outside of vortex and tropical airmasses near 20 km altitude show relatively low and constant values of particle surface concentrations ($\sim 1.2 \mu\text{m}^2 \text{cm}^{-3}$). These surface areas still exceed our estimates of the pre-Pinatubo values which were near $0.8 \mu\text{m}^2 \text{cm}^{-3}$.

Preliminary studies using the POLARIS data set suggest that particulate sulfate mass concentrations increase as N_2O decreases from tropospheric values to values near 225. This increase can be compared with *in situ* and satellite measurements of carbonyl sulfide (OCS) vs. N_2O to help constrain the stratospheric sulfur budget. Very preliminary calculations indicate that the measured decrease in OCS as air enters the stratosphere is mirrored by a proportional increase in particulate sulfate. This suggests that there is sufficient OCS to account for the observed stratospheric sulfate layer. Additional tropical measurements would strengthen this argument.

Particle size distributions were found to vary with stratospheric age. In high N_2O air, a significant fraction of the aerosol surface and volume was provided by particles with diameters near 1 micron. The proportion of surface and volume provided by these particles in the low N_2O air seen at high latitudes was much smaller. The sedimentation velocities of these particles is significant and their sedimentation is likely to impact the distribution of sulfate in the stratosphere. Current models do not contain these larger particles.

Theory Team Summaries (alphabetical by PI)

Non-Hydrostatic Modeling of Summer Stratospheric Mixing Processes for POLARIS

M. H. Hitchman and M. Buker

Model Performance

The University of Wisconsin Non-Hydrostatic Modeling System (UW-NMS) is being used to study mixing processes in the summer stratosphere. Our goals include: a) to carry out high-resolution numerical simulations for each POLARIS campaign, b) to quantify the transport contribution to column ozone loss via mixing into the troposphere, c) to compare ER-2 and idealized UW-NMS tracer distributions and variability, and d) to make simulation results available to the POLARIS community. The University of Wisconsin team participated in the Phase II and III field deployments at Fort Wainwright. Since the UW-NMS model is set up to be initialized from global European Center for Medium Range Weather Forecasting (ECMWF) meteorological

analyses, our commitment was to carry out these runs when the data are available, with an approximate three-month lag relative to real time. For the Phase II deployment, we ran a simulation initialized for a synoptic situation from July 1991 which was analogous to the real situation on 8 July 1997. The run featured high-resolution topography, idealized initial tracer distributions, particle trajectories, VIS-5D animation, and various gravity wave diagnostics. The PI presented this simulation at a science meeting to demonstrate the utility of the UW-NMS and highlight scientific issues. For the Phase III deployment, we attempted near-real-time simulations in the field. We wrote a 4-D interpolation code to ingest fields from NCEP's ETA model for initialization and successfully integrated the model. This type of data, however, is available only to 50 hPa, which is near ER-2 flight levels. We then sought to blend Goddard Assimilation data on top, to extend the initialization upward to 35 km. Despite vertical smoothing attempts, the model "rang" quite vigorously due to differences between the two data sets. We tried several different transition altitudes with no better results. We concluded that it is imperative to have a single data set for initialization. Regarding possible future near-real-time support in the field, NCEP initialization works quite well up to 50 hPa. Another option is to fix the lower boundary condition incompatibility between the Goddard Assimilation data and the UW-NMS. To fulfill our commitments to the POLARIS effort we are relying on the standard ECMWF initialization. We expect to make results available to the community for Phases I and II by November 1997 and to carry out the Phase III simulation in December 1997. Additional software development carried out for POLARIS includes interpolation to ER-2 flight tracks in the evolving model fields for comparing tracer distributions and variability and for studying the contribution of gravity waves to this variability. A pseudo-ozone field was also initialized on surfaces of constant potential vorticity in the model. The ozone loss rate is assumed to be zero above the tropopause and infinite below the tropopause. This allows for estimation of the loss of column ozone via entry into the troposphere. Other tracers were initialized with strong vertical gradients near 19 km to emphasize deformation by air motions at small and large scales near the flight track altitude.

Preliminary Scientific Results

The rise in tropopause altitude of several kilometers from spring to early fall reduces total column ozone by a significant amount. This occurs via "sloping convective" mixing associated with traveling synoptic waves with periods of several days, and via occasional direct convective encroachment associated with thunderstorms, which were observed flying into Fairbanks in the July campaign. These traveling tropospheric systems significantly influence tracer distributions up to ~16 km. Modeled gravity waves help mix air between the stratosphere and troposphere as poleward-ascending warm air encroaches over Alaska in a warm frontal situation. Quantitative estimates of the loss of model pseudo-ozone confirm this transport effect on column ozone. Trajectory calculations further support the pathways of vertical exchange near the tops of these tropospheric systems.

At higher levels, UW-NMS simulations support the concept that the fascinating layered structures of chemically "old" air embedded within "new" air is a result of large-scale differential advection. Nevertheless, these simulations focus on the Alaska region and time scales of a few days or less. Therefore, to draw any firm conclusions it will be necessary to initialize tracers on the domain boundary from larger-scale simulations such as those performed by Pierce and co-workers. Synoptic-scale confluence and mesoscale disturbances such as gravity waves clearly influence the

modeled tracer fields at most levels, and constitute essential transport ingredients necessary for bringing reactants into proximity.

POLARIS Radical and Ozone Continuity Equation Simulations

S. R. Kawa, A. R. Douglass, J. F. Gleason, P. A. Newman, and R. S. Stolarski

All model simulations proposed for POLARIS were completed successfully. The 3-D global, full chemistry and transport model (CTM) was run at near-real-time for the period 25 March 1997 to 10 October 1997. Plots of CTM output for the POLARIS flights were produced and displayed. Three-dimensional model ozone fields calculated with simplified chemistry and forecast wind fields were generated and made available for flight planning and analysis. Finally, simulations of chemistry-along-trajectories were run for each POLARIS flight. Results from these runs will be put on the POLARIS archive.

The most prominent preliminary findings from this work are 1) excess ozone in the CTM relative to observations and 2) reduced NO_x/NO_y in either the CTM or trajectory chemistry models compared to the measured ratio. The causes for these discrepancies are under examination. Note also that modeled HO_x generally underestimates the measurements, but whether this is an independent problem or related to the above is not yet clear. The comparison of model simulations and observations also yielded a number of positive comparisons including NO/NO_2 , location of NO_x/NO_y gradients, and tracer gradients, e.g., N_2O , NO_y , and H_2O .

Contribution to Data Analysis Using the AER 2-D Assessment Model

M. K. W. Ko, J. Rodriguez, M. Danilin, C. Scott, and D. Weisenstein

Summary of Model Performance over the Deployments

The role of the AER team was to analyze the data in the context of their implications to the photochemical and dynamical components of our assessment model. Previous intercomparisons, both model-model comparisons and model-measurement comparisons, have greatly increased our confidence in the mechanisms used in current assessment models. POLARIS provided measurements in a region and during a season previously untested, when the photochemical contribution to the ozone budget is expected to be the largest and the relative importance of the different catalytic cycles different from previous samplings. We performed a number of diagnostic calculations using the AER 2-D assessment model appropriate for the seasons corresponding to the three POLARIS deployments. These results were communicated to the other team members during meetings in each of the deployments.

Preliminary Scientific Results

For the long-lived sources gases, the measured concentrations are larger than those calculated by the AER model. For the downward diffusing species (e.g., HCl), the measured concentrations are smaller than the model. One possible explanation is that the downward circulation in the AER model may be too strong, at least between May and September. The calculated seasonal trends in the tracer data (source gases and ozone) derived from the three deployments are in good agreement

with the AER model results. This gives us some confidence that the seasonal cycles simulated in the AER model are approximately correct.

Future Activities

We will use the POLARIS data in the Models and Measurements Workshop to compare with results from other models. We will derive a set of criteria based on the POLARIS measurements for testing other models.

Meteorological Support for POLARIS

P. A. Newman, L. R. Lait, S. R. Kawa, L. Moy, M. R. Schoeberl, and A. M. Thompson

Performance over the Deployments

This proposal provided real-time support for aircraft flights, with post flight ancillary products. In general, data transmission, flight planning software, and ancillary products were provided in a timely and efficient manner. The close collaboration with the proposal for 3-D chemical transport modeling (R. Kawa) and the Data Assimilation Office proposal (S. Strahan) provided a unique convergence of meteorological tools and modeling capabilities. Both met products and trajectories were generally of good quality in comparison to ER-2 observations. Assessment and analysis of these products will continue over the course of the next year.

The most-used of the GSFC data exchange files are the "BT" files. We calculated isentropic back trajectories of parcels located initially at regular intervals along the flight track for each POLARIS flight. As 3-D gridded meteorological wind analyses are used to trace the parcel histories, other meteorological fields are interpolated to the parcel locations. The trajectories provide a useful history of the temperatures and solar exposure, for example, experienced by the parcels over the past ten days before being intercepted by the aircraft. The POLARIS BT files contain latitude, longitude, pressure, temperature, potential vorticity, and solar zenith angle at regular time intervals along each parcel's trajectory.

Meteorological fields for the flight period itself were also provided for each POLARIS flight. These were supplied as the "XS" and "FA" exchange files. The FA files contain Ertel's potential vorticity, temperature, geopotential height, zonal wind, and meridional wind, all interpolated to the flight track. Total ozone (and associated quantities, such as reflectivity) from the EP and ADEOS TOMS were routinely calculated following the flight track and submitted for each POLARIS flight.

In addition to the numeric data supplied in the BT, FA, XS, AD, and EP files, standard plots of meteorological fields have been placed into the archives. Horizontal maps of modified potential vorticity (on several isentropic surfaces) and TOMS total ozone (for both ADEOS and EP) have been submitted as PostScript files.

During Phase II (22 June 1997 through 12 July 1997), approximately 295 automailer jobs were run for five mission participants, and 527 jobs were run for seven members of the balloon-borne instrument teams operating alongside the POLARIS group. Of these, the majority were used to obtain plots of meteorological fields, with trajectory model runs coming in second.

Preliminary Scientific Results

- Ozone Evolution during the Summer of 1997

The ozone values during 1997 generally followed typical of the summer period. The TOMS data showed a normal very strong mid-latitude maximum of ozone during the northern spring. However, a late spring polar low of ozone developed in late March and April 1997, and persisted into the first week of the first POLARIS deployment. This April polar low quickly recovered to the normal high values, and ozone levels in the polar region slowly decreased over the course of the summer. As the season evolved, total ozone gradually decreased in the mid- to high latitudes, with the largest decreases in the polar region. The second POLARIS deployment sampled the period of greatest total ozone decline during late June. The final POLARIS deployment in September sampled the polar region during the period of lowest total ozone values.

- 1997 Northern Summer Meteorology

The meteorological situation was generally consistent with the expectations, with the beginning of summer as slightly anomalous because of the persistence of the winter polar vortex. Stratospheric winds were much stronger than expected during the late-April period. The first POLARIS flight to the North Pole on 26 April 1997 was able to penetrate the northern polar vortex as determined from measurements, and confirmed by the GEOS-STRAT potential vorticity calculations. By mid-May, the vortex had broken down, and winds had relaxed to their normal easterly circulation. By June, the stratosphere was generally dominated by easterlies, although atmospheric waves of considerable amplitude extended into the stratosphere over the course of the deployment. By the final phase of the deployment in September, winds were beginning to transition to the winter westerly circulation. The westerly winds in the tropics above 100 hPa are indicative of the westerly phase of the quasi-biennial oscillation (QBO) that dominated the tropical circulation during the entire POLARIS period.

Radiative and Photochemical Modeling for POLARIS

S. Lloyd, D. Anderson, T. Kusterer, and B. Swartz

Our primary data product to the POLARIS Science Team is a set of photolysis rate coefficients or J-values for photochemical reactions of interest in the lower stratosphere and upper troposphere, calculated along the ER-2 flight track for each flight during the POLARIS campaign (posted as JV exchange files on the data archive). These calculated J-values can be compared with those obtained with Environment Canada's Composition and Photodissociative Flux Measurement (CPFM) instrument aboard the ER-2 and with J-values calculated from observed species concentrations. They can also be incorporated into photochemical models used by a variety of instrument groups and other theory groups in their data analysis.

Radiation field calculations are only as good as the inputs to these models. Therefore, a considerable portion of our effort was spent to acquire and assess the quality of the input model atmosphere used, with emphasis placed on an accurate description of the total column ozone and partial column above the ER-2 along the flight tracks. We worked cooperatively with other groups to provide additional data products, in particular with NASA Goddard to acquire higher resolution

(level 2) TOMS total ozone data than used in prior ER-2 missions (posted as EP and AD exchange files), and with the University of Alaska at Fairbanks Geophysical Institute to coordinate their launching of ozone sondes simultaneous with each ER-2 flight (posted as FB exchange files). Analysis of these ozone datasets, as well as Environment Canada's Brewer spectroradiometer data (posted as TO exchange files), allowed us to establish the seasonal trend of diminishing total ozone over Fairbanks during the POLARIS campaign (a decrease of almost 30 Dobson Units each month), as well as a composite climatology of pressure, temperature and ozone profiles for each deployment. Ozone variability was found to be greatest at altitudes between the tropopause and ER-2 cruise altitude.

Our JV files list J-values calculated using TOMS total ozone data and climatological profiles obtained from the ozonesonde dataset for comparison with the J-values obtained with the CPFM *in situ* spectroradiometer data. While there were significant discrepancies in the J-values produced by our group and those observed by the CPFM instrument and calculated by another theory group (Salawitch *et al.*) during ASHOE/MAESA (often 50% differences for $J(\text{NO}_2)$ and factors of 2 to 3 for $J(\text{O}_3)$), working cooperatively with these groups in the field during POLARIS has significantly reduced these differences in the radiation field to the level of the uncertainties in the cross sections/quantum yields (typically within 5% for $J(\text{NO}_2)$ and better than 25% for JO_3). This excellent agreement between the CPFM and two independently calculated radiation field models provides a validation of the CPFM dataset, which holds the advantage of finer spatial resolution than the TOMS satellite data, as well as simultaneity with the *in situ* trace species observations. We have, therefore, calculated a comparable set of J-values (JU exchange files) which use the CPFM observations of overhead ozone and effective surface albedo as inputs, which agrees well with the calculations of Salawitch *et al.*

The largest remaining uncertainties in the J-value calculations are our knowledge of the cloud and surface reflectivity beneath the ER-2. The fish-eye camera flown with the CPFM and Advanced Very High Resolution Radiometer (AVHRR) data have proven valuable when trying to distinguish between surfaces of comparable surface reflectivity in the polar region, i.e., ice cover and low-lying clouds. Further analysis of the O_2 A-band at 762 nm using the CPFM dataset should allow for another data product, an estimate of the effective cloud top altitude along the ER-2 flight track.

One of the most important scientific questions that can be directly addressed by our radiation field calculations (and validated by the POLARIS dataset) is the sensitivity of certain J-values to input conditions: total ozone, ozone profile, season or solar zenith angle, effective surface albedo, cloud height and atmospheric refraction. The wide range of geography and seasons covered by the POLARIS mission will allow us to assess the relative importance of each of these factors, with an emphasis placed on J-values for the important species ozone, NO_2 , HNO_3 and ClONO_2 .

POLARIS Surface and Satellite Meteorology

L. Pfister, S. Gaines, M. Legg, K. Pagan, and H. B. Selkirk

Performance during POLARIS

The purpose of the Meteorological Satellite Team in the POLARIS project is to provide and interpret tropospheric meteorological information that is relevant both to the mechanics of getting

ER-2 flights off the ground and to the interpretation of the stratospheric chemical and dynamical data obtained by the aircraft.

In the field, the most immediate purpose was to provide the Project Scientist with surface weather information for appropriate planning of flights, and cloud altitude information to minimize the interference of cloud particles with instrument performance. Overall, the surface weather for all three deployments was very benign for ER-2 operations, as expected from climatology. Only one flight was scrubbed due to weather. Obtaining cloud-free flights in the tropopause, however, proved to be more difficult. The low tropopause resulted in one of the stacked flights being partially in clouds.

The major tools of the meteorological satellite portion of our effort, including the Ames Satellite Ground Station, and ancillary data gathering and processing efforts, worked well during the deployments. We have successfully archived GOES-9, AVHRR, and Geostationary Meteorological Satellite (GMS)-5 data covering the deployment periods.

Science Summary

Among our products is the evaluation of surface reflectivity in the visible range along the flight track, an important component of the NO/NO₂ ratio. The values derived from the AVHRR satellite were in good agreement with values measured on the aircraft, a result that speaks well for both approaches.

Water vapor imagery (5 to 6 microns) on the geostationary satellite is valuable in interpreting tropospheric dynamics. On the 11 May stacked flight, tracer measurements showed a transition from stratospheric to tropospheric air near Anchorage, consistent with features in the water vapor imagery that showed air flowing northward from low latitudes.

On the tropical flight of 23 September, there was a large convective system at 3°S, at the southern terminus of the ER-2 flight track. The cloudtop temperatures during the flight were as cold as 200 K, though they may have been colder before the flight. The aircraft penetrated the tropopause at ~15.85 km and 1°S, with water vapor mixing ratios of 5.7 ppmv, equivalent to a frost point of ~194 K. Winds at the tropopause were from the southeast at ~10 to 15 m per second, i.e., from the direction of the large convective system. Still, it appears that the sampled air was probably not directly injected through the nearby convective clouds, since the cloudtop temperatures were 8 K warmer than the frost point based on observed water vapor. Back trajectories indicate that the air in the dip came from the eastern tropical Pacific. The Panama region and Mexican coast are regions of strong convection, with frequent observations of cloudtop temperatures in the 194-K range at this time of year.

HALOE Airmass Trajectory and Photochemical Modeling Studies for the POLARIS Campaign

R. B. Pierce, J. A. Al-Saadi, R. S. Eckman, T. D. Fairlie, W. L. Grose, J.-U. Grooss, G. S. Lingenfelser, J. R. Olson, and J. M. Russell III

Scientific Objective

The scientific objective of this modeling study was to investigate the large-scale distribution of stratospheric catalytic ozone loss during the Northern Hemisphere summer. The vertical and meridional distribution of ozone loss in the Northern Hemisphere was examined during each of the three POLARIS deployments using the Langley airmass/photochemical model initialized with near-real-time observations by the UARS HALOE instrument. Due to the anomalously late 1997 final warming, and unusually low total column ozone values in the 1997 Northern Hemisphere vortex, HALOE airmass modeling studies also focused on potential Northern Hemisphere springtime ozone loss processes prior to and during the first POLARIS deployment.

Model Performance

The POLARIS HALOE airmass modeling effort by the NASA Langley Research Center (LaRC) theory team was significantly more successful than originally anticipated. Coordination with the HALOE data processing team at NASA LaRC allowed for near real-time access (2-to 3-day lag) to HALOE retrievals (including enhanced aerosol products) prior to and during each of the POLARIS deployments. Coordination with the DAO at NASA Goddard allowed for real-time access to GEOS assimilated and forecast winds and temperatures used in HALOE airmass forecasts. This coordination allowed our team to produce an initial HALOE airmass forecast, valid for the first part of each deployment, prior to arrival in Fairbanks. A subsequent updated forecast was conducted during each of the deployments. Results of these forecasts were compared with *in situ* measurements from the ER-2 on a flight-by-flight basis. Preliminary scientific results of these intercomparisons were presented during the mission flight discussions. Daily Lagrangian forecasts of daylight fraction, material line evolution, and ER-2 range ring deformation were also conducted and supplied to the project scientists for assistance in flight planning.

Preliminary Scientific Results

- Phase I

One of the objectives of the first deployment was to sample air within the polar vortex prior to the 1997 final warming to characterize the distribution of ozone within the polar vortex. This objective was accomplished on the 26 April 1997 vortex flight. Comparisons between *in situ* ozone mixing ratios and HALOE airmass forecasts, represented as a function of methane on the flight day, showed very good agreement for methane mixing ratios that characterize the vortex and mid-latitude airmasses. Ozone within the vortex was found to be significantly depleted relative to expected values for the observed methane mixing ratios. The HALOE airmass forecast predicted higher ozone mixing ratios than were observed in the collar region of the vortex. Inclusion of a parameterization for subgrid-scale mixing processes (n-member mixing with an efficiency based on

the grid-scale deformation field) significantly improved the agreement within the vortex collar region.

A second objective was to characterize the relationship between NO_x/NO_y and the time an air mass has spent in sunlight (daylight fraction), since the summertime ozone loss is believed to be dominated by NO_x -driven loss processes. HALOE air mass predictions of NO_x/NO_y vs. daylight fraction were generally in good agreement with *in situ* estimates, with peak ratios above 0.22. However, these peak ratios occurred within vortex air masses and not for mid-latitude air masses as indicated by estimates from *in situ* ER-2 data.

- Phase II

A key highlight of the second deployment was the sampling of filaments of very low N_2O and low CH_4 air masses by both the ER-2 and OMS Balloon payload. Low $\text{N}_2\text{O}/\text{CH}_4$ mixing ratios identify air which has originated from much higher altitudes and indicates that either remnants of the polar vortex have persisted through mid June or air has relatively recently descended from aloft. HALOE air mass forecasts during the second deployment also showed indications of low CH_4 filaments. Ozone vs. CH_4 comparisons between the HALOE air mass predictions and *in situ* observations on the 26 June 1997 flight showed remarkable agreement, and indicate that the subgrid-scale mixing parameterization in the HALOE air mass predictions is able to represent both strong mixing (final warming) and weak mixing (midsummer) periods.

A second highlight of the second deployment was the comparison of hemispheric distributions of transport and photochemical contributions to ozone tendencies inferred from the HALOE air mass predictions with results from the Garcia and Solomon 2-D model. Preliminary comparisons showed that the inferred transport from the HALOE air mass predictions is consistent with the 2-D model results; namely, a near balance between photochemical production and poleward transport in the subtropics during most of the period, and a net loss at polar latitudes during the summer, because photochemical loss dominates over poleward transport of air with high ozone mixing ratios. Further work must be done in characterizing the distribution of diabatic heating for the trajectory calculations before this work is completed.

- Phase III

During the final deployment, modeling results from all three deployments were compiled to produce a HALOE air mass forecast valid over the duration of the POLARIS mission (19 March 1997 to 15 September 1997). This compilation of the individual HALOE air mass runs provided a clear picture of the large scale evolution of Northern Hemisphere ozone production/loss processes at ER-2 flight altitudes (500 K).

Net photochemical production was highest (near 0.7 ppmv/month) in the tropics (10°N) during Phase I, followed the sun poleward during Phase II to near 20°N , and then returned to 10°N by Phase III.

Net photochemical destruction rates showed peaks of slightly larger than 0.2 ppmv/month during both the first (near 60°N) and second (near 80°N) deployments. The destruction during the first

deployment was dominated by HO_x driven loss processes while the peak destruction during the second deployment was dominated by NO_x driven losses. The ozone loss during the final deployment was also NO_x dominated but somewhat weaker than in either of the previous deployments. Peak NO_x driven ozone losses were associated with HALOE air mass predictions of NO_x/NO_y ratios of larger than 0.2 and 5-day daylight fractions greater than 80-90%.

Photochemistry of Ozone during Polar Summer

R. J. Salawitch

Model Performance over the Deployments

We have two standard model products: photolysis rates along the flight track of the ER-2, and calculated concentration of reactive gases assuming photochemical steady state (PSS) over a 24-hour period. Secondary model products, such as photolysis rates along Lagrangian trajectories that intersect the flight track of the ER-2, or calculated concentration of gases along trajectories, are available upon request. The photolysis rates model product is constrained by *in situ* measurements of overhead ozone column, ozone concentration, and temperature, as well as to satellite measurements of total column ozone, reflectivity, and cloud height, and balloon and ozonesonde measurements of ozone profiles. The PSS product is constrained by many long-lived tracers and precursors measured onboard the ER-2 (e.g., ozone, H₂O, CH₄, NO_y, etc.). We also provide similar products in support of the balloon flights that were part of POLARIS.

Our model performed well during POLARIS. We have initiated upgrades in our computational speed through the acquisition of a faster CPU, a much better FORTRAN compiler than the native SUN compiler, and improvements in our code that allow us to conduct simulations at much higher temporal resolution than we have used in the past. We are also able to now conduct simulations constrained by measured NO, as well as measured NO_y. The NO simulations are run in an iterative manner, treating NO_y as a free parameter, and have been particularly important for analyzing measurements of OH and HO₂. Additionally, our model output was used extensively during POLARIS to assist the flight planning efforts of the project scientists.

Photolysis rate (SP*) files were submitted to the data archive soon after each flight was completed. The SP* files have recently been updated into a “provisional final” version on the archive. An e-mail message has been distributed to the POLARIS community describing, among other things, how the ozone column over the ER-2 was estimated for each flight. This process involved difficult decisions concerning whether or not to use the CPFM measurement of overhead ozone. We also described in that e-mail message an unsettling systematic discrepancy of 5% for the photolysis rate of NO₂ calculated using our model compared to estimates provided to the data archive by Steve Lloyd *et al.* The two models should agree to better than 5% for J(NO₂). We hope to work closely with Steve Lloyd to resolve this discrepancy.

To date, our PSS model results have been shared with the POLARIS community through production and distribution of “lots of plots”. We will submit PSS model result files to the data archive for each flight (so-called PS* files). The PS* files contain calculated concentration of every gas considered in our model, as well as rates for all important source and sink terms for ozone, HO_x, NO_x, HNO₃, HCl, and ClONO₂. We anticipate the PS* files will be quite useful for

facilitating comparison of theory and observation by the experimental PIs, and will also hopefully serve as a useful for starting point for comparing results from different photochemical models.

Preliminary Scientific Results

Note: The preliminary conclusions based on analysis of balloon-borne data have benefited greatly from the contributions of Geoff Toon, Jim Margitan, Bhaswar Sen, and Greg Osterman at JPL, and Ken Jucks, Dave Johnson, Wes Traub, and Kelly Chance at SAO.

The observed ratio of NO_x to NO_y is larger than theory by 15 to 40% for the vast majority of air masses sampled by the ER-2. Since the Harvard measurement of NO_2 is 20% to 25% larger than the NOAA measurement of NO_2 (defined here as NO_2 noaa), the largest discrepancies are seen using the Harvard measurement of NO_2 (NO_2 harv) to define NO_x .

Fairly good agreement exists between theory and observation of the NO/NO_2 ratio at 20 km using NO_2 noaa. The observed ratio is lower than expected if NO_2 harv is used. However, the situation concerning NO/NO_2 is “murky”: there are larger than expected (e.g., 5%) differences in the photolysis rate of NO_2 calculated by two radiative transfer models, and the CPFM measurement of $J(\text{NO}_2)$ agrees more closely with NO/NO_2 noaa than NO/NO_2 harv during Phase III, but agrees more closely with NO/NO_2 harv during Phase II. Problems in the NO/NO_2 ratio may indicate that a revision to the rate of $\text{NO} + \text{O}_3$ is necessary. This reaction is of vast importance to stratospheric ozone and is not known to better than 20% from existing laboratory observations near 220 K. It is difficult to make progress on NO_x/NO_y until the situation concerning the partitioning of NO/NO_2 is better understood, because a major sink for NO_x is the reaction of $\text{OH} + \text{NO}_2$, and we are unclear whether or not the concentration for NO_2 found in our model is realistic. Therefore it is imperative that the POLARIS team work together to better define whether or not a problem exists in the NO/NO_2 ratio.

A preliminary analysis of balloon-borne observations obtained by the MkIV FTIR using solar occultation reveals discrepancies in the NO/NO_2 ratio at 20 km consistent with the comparison between theory and NO/NO_2 harv on the ER-2. Also, the NO_x/NO_y ratio measured by MkIV exceeds theory at 20 km by an amount similar to the discrepancy indicated by the ER-2 measurements. The discrepancy between theory and observation of NO_x/NO_y is reduced for increasing altitude, suggesting the possibility that heterogeneous reactions on soot could be responsible. However, a reduction in the rate of $\text{OH} + \text{NO}_2 + \text{M} \rightarrow \text{HNO}_3 + \text{M}$ might also explain the observations. More work remains to identify the cause of the discrepancy in NO_x/NO_y .

Despite the problems described above between theory and observation of the NO_x/NO_y ratio, certain properties of this ratio predicted by models were observed. For example, models suggested NO_x/NO_y would increase by about a factor of 2 with increasing latitude during polar summer, with the ratio leveling off for latitudes with continuous solar exposure. The increase in NO_x/NO_y occurs because air masses that do not experience darkness are unable to form of significant amounts of N_2O_5 , and thus the $\text{N}_2\text{O}_5 + \text{H}_2\text{O}(\text{sulfate})$ sink for NO_x ceases to occur. The observed shape of NO_x/NO_y vs. latitude agrees fairly well with theory. This provides an unmistakable signature for the occurrence of $\text{N}_2\text{O}_5 + \text{H}_2\text{O}(\text{sulfate})$.

The observed concentrations of OH and HO₂ are simulated extremely well by a model constrained by measured NO (necessary to properly simulate the OH to HO₂ ratio). This provides strong confidence that we have a good understanding of the budget and partitioning of HO_x. Also, these comparisons demonstrate models used to study the NO_x/NO_y ratio have realistic levels of OH, critical due to the importance of the OH + NO₂ and OH + HNO₃ reactions in setting the partitioning of NO_x relative to NO_y.

Extraordinarily good agreement was seen for the partitioning and budget of the Cl_y family of gases measured both by instruments aboard the ER-2, as well as the MkIV and FIRS balloon-borne instruments. The level of agreement between the measured and modeled ratio of ClONO₂ to HCl, for example, is much better than published uncertainties in the relevant kinetic terms would suggest. The new *in situ* measurements of ClONO₂ obtained during POLARIS add great confidence to our understanding of processes that regulate reactive chlorine at 20 km, and are entirely consistent with the remote measurements of ClONO₂ obtained by MkIV and FIRS.

The observed variation of OH and HO₂ with solar zenith angle during several sunrise and sunset flights provides an unmistakable signature for the occurrence of the sulfate heterogeneous reaction BrONO₂ + H₂O. Better agreement between data and model is exhibited assuming a reaction probability of close to 1.0 for this reaction, similar to the JPL 97-4 recommendation of 0.8. However, the Hanson formula for the rate of this reaction, based on laboratory measurements not quite at stratospheric conditions, suggests a slower reaction probability close to 0.3. Our understanding of the variation of OH and HO₂ at high SZA would benefit from better laboratory definition of the rate of BrONO₂ + H₂O(sulfate), as well as the absorption cross sections of HOBr.

Ozone loss rates calculated using a model that simulates well observed OH, HO₂, NO, NO₂, NO_x, and ClO reveals loss of ozone during polar summer is dominated by NO_x, with non-negligible contributions from the HO_x cycles. Similar conclusions are reached based on analysis of MkIV balloon-borne data. Interestingly, the total loss rate of ozone near 20 km is rather insensitive to whether the model is constrained by measured NO or NO_y due to buffering of the HO_x and halogen cycles as NO_x rises. Of course the distribution of the total ozone loss rate among the various catalytic families is quite sensitive to whether NO or NO_y is used to constrain the model.

The net photochemical loss rate of ozone found using the model was 10 to 15% per month near 20 km, peaking during Phase I and at high latitudes during Phase II. The altitude range of net photochemical loss of ozone extended to about 24 km for the first MkIV flight during May, and extended to about 30 km for the second flight during July. The net photochemical loss rate of ozone is sensitive to the production rate of ozone, which increases as overhead ozone column falls and as the noontime solar zenith angle experienced by an air mass falls. Indeed, changes in the net photochemical loss rate of ozone between various phases of POLARIS, and vs. latitude during a specific phase are driven as much by a variation in ozone production as by changes in NO_x.

The decline in the concentration of ozone observed during the three phases of POLARIS near 20 km was consistent with the calculated net photochemical loss rates described above. Similarly, reductions in the profile of ozone observed by the balloon-borne instruments and ozonesondes agree well with changes expected based on the MkIV data. In particular, the balloon and sonde data show changes in the profiles of ozone occurred mainly below 24 km prior to early July, as

expected based on the MkIV data. Later in summer, changes in profiles of ozone occurred at higher altitude, again consistent with the net removal rate of ozone inferred from the MkIV measurements obtained during July.

Interpretation of Observations of Ozone, NO_y, and Other Trace Gases during POLARIS Using a Two-Dimensional Chemical/Dynamical Model

S. Solomon and C. Nevison

The goal of this study is to compare results of the Garcia-Solomon 2-D model to observed tracers, radicals, and ozone loss rates calculated by the semi-empirical method. We first established a methodology for comparing model results to POLARIS data which involves interpolating model results, which are calculated on constant pressure surfaces, to the variable pressures along the POLARIS flight track, and extrapolating and averaging observed radicals over a diurnal cycle for comparison to diurnally averaged model results. Preliminary comparisons show generally reasonable agreement for ozone and long-lived tracers such as N₂O, but a tendency for the model to underestimate the observed NO_x/NO_y ratio by about a factor of 2. Semi-empirical ozone loss rates are not yet available for comparison; however, the model more or less correctly reproduces the observed decrease in ozone from May to September. Future work will involve continuing the comparisons between model and observations and examining the effect of uncertainties in the NO_x/NO_y ratio on modeled ozone in a global context.

Flight Planning and Constituent Modeling for the POLARIS/STRAT Campaign Using the GEOS-1 Data Assimilation System

S. E. Strahan, A. R. Douglass, K. Ekers, S. R. Kawa, D. Lamich, G. P. Lou, and R. B. Rood

The NASA/GSFC DAO has provided forecasts and meteorological analyses as the principal flight planning tools for the three POLARIS deployments. The data products are near real-time analyses and five-day forecasts. The assimilation system used is the GEOS-DAS vc5.4/oi1.5, also known as the "STRAT" assimilation, which uses rotated poles. There were two runs each day, the early run starting about 10:30 EDT and the final run starting at 20:30 EDT.

The meteorological fields of DAO GEOS-DAS were not only used for flight planning by mission scientists, but were also used to drive the 3-D GSFC chemical transport model, which was run in a chemical forecasting mode during these deployments. The assimilation products have also been used by other POLARIS theory team members. For example, the GEOS-DAS stratospheric products have been used by the University of Wisconsin team for a regional model/data study.

The quality of the forecast and analyzed temperatures was generally very good, with RMS errors typically less than 1 K in the analyses. Wind forecasting, however, proved to be difficult in the Arctic region in summer. Because Arctic summer is a season of very light winds, with u and v often less than 5 m s⁻¹, a forecast wind with a 3- to 4-m s⁻¹ error can represent a 100% or greater error. In the winter, this magnitude of wind error on top of a mean zonal wind of, say, 40 m s⁻¹, represents a much smaller error. As a result of this, trajectories calculated for flight planning were less useful than in the past (i.e., on deployments with greater mean winds). It is hoped that this

opportunity to compare the assimilation analyses with high spatial resolution wind data from the ER-2 may lead to the identification of the cause(s) of the wind errors.

SAGE II and HALOE Data Analysis and Modeling in Support of the POLARIS Campaign

A. F. Tuck, S. J. Reid, and K. H. Rosenlof

During the POLARIS mission we:

- Calculated zonally averaged large scale diabatic transport and ozone fluxes into high-latitude regions of the lower and middle stratosphere using HALOE and MLS data in conjunction with a radiative transfer model. Comparisons with values estimated from 2-D (Solomon-Garcia) and 3-D (LaRC) models showed our estimates of the advective flux of ozone to be larger than in the models, but with a similar seasonal cycle. Further work will use satellite data and assimilated winds to estimate the isentropic component of ozone flux into high latitudes during the POLARIS period.
- Compared HALOE ozone with ER-2 ozone and found excellent agreement.
- Began work using a chemical trajectory model to examine both the role of overtone photolysis of HNO_3 and HNO_4 and heterogeneous reactions on carbon aerosols in the HO_x and NO_x budget.
- Began work analyzing possible typhoon influences on constituent profile measurements during the tropical portion of the last POLARIS phase.
- Worked on comparing MTP lapse rate signatures with ozone anomalies, in the context of similar comparisons between MST radars and lidars.

We intend to continue to pursue the above noted topics, and also do 3-D trajectory runs to look for the source of various anomalous measurements throughout the POLARIS campaign.

CRC-SHM Meteorological and Chemical Modeling of the POLARIS Measurements

D. W. Waugh, K. R. Ryan, R. J. Atkinson, T. M. Hall, I. C. Plumb, and L. Randeniya

During all three deployment stratospheric analyses, forecasts, and output from high-resolution trajectory calculations (including reverse domain filling calculations of PV and “Solar Exposure”) from the Australian Bureau of Meteorology's Global Assimilation and Prediction Scheme (GASP) were provided to mission scientists for flight planning.

Also, files containing 10-day isentropic back trajectories, using GASP analyses, from the ER-2 flight paths have been submitted to the POLARIS archive. The format of these files, and the endpoints of the trajectories (= the starting points of the back trajectories), are the same as the BTyymmdd.EA1 files (which contain back trajectories using analyses from the GSFC DAO system). Comparison of calculations (e.g., chemical box-model calculations) using the two

different sets of trajectories should give some indication of the sensitivity of any results to using different meteorological analyses.

Post-flight analysis is being performed using the CRC photochemical box model to calculate the production and loss processes for ozone in the air masses sampled during the three POLARIS deployments. Preliminary analysis indicates that the NO_x and HO_x catalytic cycles constitute the dominant photochemical loss mechanisms for ozone during the summer at northern high latitudes. This is in accordance with present understanding of the chemistry in this region.

Table 1 lists the calculated ozone loss rates due to the NO_x , HO_x , and halogen cycles for sampled air in the latitudes poleward of 65°N for flights from each deployment. In general, the calculated ozone loss rates in the air masses sampled increase with latitude and altitude, and larger values are calculated for the altitudes near 20 km and latitudes near 85°N which correspond to highest cruise altitudes and the northernmost latitudes reached by these flights. The calculated ozone loss rates decrease with season, with a significant decrease between July and September. The relative contributions to the calculated ozone loss rates from various catalytic cycles depend in general on the latitude, the altitude, and the period of the flight deployment.

While the measured compositions of transient species are in general agreement with those predicted by the box model, there are some important differences in the measured and predicted concentrations of key species in the ozone catalytic loss cycles. It was found that the partitioning calculated by the model for NO_y species does not agree with the measurements. For a significant number of flights the NO_x/NO_y ratio (where $\text{NO}_x = (\text{NO} + \text{NO}_2)$) calculated by the model is 15 to 20% smaller than the measured ratio. For the flight of 9 September 1997, the range of the model calculated NO_x/NO_y ratio is 5 to 10% compared to the measured values of 10 to 15%. On the other hand, model predictions of the NO/NO_2 ratio generally agree well with the measured values. The significantly smaller values of NO_x/NO_y ratio observed for the air masses which were exposed to periods of night is well described by the model which includes sulfate aerosol reactions of N_2O_5 and BrONO_2 . For the majority of the flights studied, the model predicted concentrations of ClONO_2 and HCl agree well with measurements.

The values of the OH/HO_2 ratio derived from the box model are also smaller than the measured values. The OH/HO_2 ratio depends directly on the NO concentration. When the measured NO concentrations are used in place of the calculated NO concentrations to estimate this ratio, much better agreement with the measurements is obtained.

Analysis of TOMS records from 1980 to the present day is in progress to determine to what extent our present understanding of chemistry at high latitudes in summer can explain the observed changes in ozone throughout this period.

We are also examining the time scale for mixing of ex-vortex air into mid-latitudes following the break up of the vortex. Measurements from flights during Phase II show distinct regions with the characteristics of vortex air (e.g., low concentrations of tropospheric source gases) indicating that vortex fragments can survive at least two months following vortex break up. Previous analysis using an advection-diffusion model together with SPADE ER-2 data and trajectory calculations indicated that during spring vortex filaments are mixed out within 25 to 30 days (Vaugh *et al.*,

1997). We are currently performing a similar analysis of mixing during POLARIS deployments. Preliminary results show that strain rate during summer is half that during winter/spring, indicating that during summer the time scale for the large-scale flow to reduce the scale of filaments down to mixing scales is twice that during winter/spring.

Table 1. Model calculated zone loss rates, local photochemical removal rate, and relative contribution of different catalytic cycles for air sampled poleward of 65°N

Flights (date: YYMMDD)	Ozone loss rates (cm ⁻³ s ⁻¹)	Local removal rate (%/month)	% contribution from		
			NO _x	HO _x	Halogen
970506, 970513	1.0-3.0 e5	3-16	50-60	20	10-15
970707	0.5-2.5 e5	3-16	50-60	20	10-15
970909	0.2-1.0 e5	1.5-6	25-30	30-35	30-35

References

Waugh, D. W., R. A. Plumb, J. W. Elkins, D. W. Fahey, G. S. Dutton, M. Loewenstein, J. R. Podolske, E. Keim, K. Boering, S. C. Wofsy, M. H. Proffitt, K. K. Kelly, C. R. Webster, R. D. May, K. R. Chan, P. A. Newman, and L. R. Lait, Mixing of polar vortex air into middle latitudes as revealed by tracer-tracer scatter plots, *J. Geophys. Res.*, *102*, 13119-13134, 1997.

Analysis of Ozone Changes during POLARIS Using SAGE II Data and Trajectory Calculations

H. A. Michelsen and S. C. Wofsy

Introduction

The goal of POLARIS is to understand the mechanisms controlling stratospheric ozone abundances in the mid- to high northern latitudes during summer. To achieve this goal we must identify photochemical and dynamical factors, and define the interplay between transport and chemistry, that contribute to ozone seasonal changes in these regions. Photochemical models will be used to aid in the analysis of *in situ* measurements of nitrogen, hydrogen, and halogen oxide radical concentrations, complemented by measurements of concentrations of radical precursors, reservoir species, and aerosols.

Model Performance during the Mission

Unfortunately SAGE II data were not available during the mission. Nevertheless, photochemical steady-state calculations were helpful in analyzing data throughout the mission, despite severe network problems during the first deployment.

Preliminary Scientific Results

Tracer correlations derived from Atmospheric Trace Molecule Spectroscopy (ATMOS) observations proved to be extremely useful in identifying air mass origins for both ER-2 and balloon measurements, particularly for the first two deployments during which filaments of vortex air were encountered. ATMOS observations appear to be quantitatively consistent with *in situ* measurements for this mission.

Future Work

ER-2 data will be analyzed using meteorological observations and trajectory models with embedded photochemistry computations to understand the recent photochemical history (i.e., within ~10 days prior to encounter) of air observed during POLARIS. Back-trajectory calculations will be supplemented by analyses based on tracer correlations and compared with those from previous aircraft and balloon campaigns and ATMOS shuttle missions. SAGE II ozone concentration and aerosol abundance measurements made throughout the Northern Hemisphere will provide essential information on the large-scale context for interpreting changes observed by the ER-2 during POLARIS. In particular, the combination of global-scale ozone and aerosol measurements should allow approximate identification of the history of air masses on time scales longer than 10 days at ER-2 altitudes. Since SAGE II measures the vertical profile of ozone, these measurements can also be used to provide values of column ozone above the aircraft.

Appendix

POLARIS ER-2 Flight Log

Requested Flight Hours: 190.00
Augment (5/97): 40.00
Total: 230.00

<u>DATE</u> (YYMMDD)	<u>Sortie</u>	<u>POLARIS ft.</u>	<u>Flt. time</u>	<u>Pilot</u>	<u>Comments</u>
<i>Test Flights</i>					
970106			2.00		CIONO ₂ test flight
970108			6.00		CIONO ₂ test flight
970112			6.00		CIONO ₂ test flight
970114			6.00		CIONO ₂ test flight
Subtotal:	20.00 hours				
<i>Phase I</i>					
970416	97-081	97-01	2.00	Collette	2-hr check flight
970418	97-082	97-02	5.00	Nystrom	5-hr check flight
970422	97-083	97-03	7.75	Porter	8-hr south survey from Ames
970424	97-085	97-04	6.00	Collette	Transit Ames to Ft. W.
970426	97-086	97-05	8.00	Nystrom	8-hr to NP/into vortex
970430	97-087	97-06	6.50	Collette	SZA flight (2:10-08:45)
970502	97-088	97-07	7.58	Nystrom	Photolysis - Canada
970506	97-089	97-08	6.83	Collette	Photolysis - 2 dips, Canada
970509	97-090	97-09	6.17	Collette	Sunset flight
970511	97-091	97-10	4.92	Nystrom	Stack flight
970513	97-092	97-11	6.67	Collette	Photolysis
970515	97-093	97-12	5.33	Collette	Return transit Ft. W. to Ames
Subtotal:	72.75 hours				
Cumulative:	92.75 hours				

Phase II

970623	97-115	97-13	5.25	Broda	Transit Ames to Ft. W.
970626	97-116	97-14	7.75	Porter	Photolysis - 77°N-54°N, 2 dips
970629	97-117	97-15	6.75	Broda	Photolysis - South to 53°N, 2 dips
970630	97-118	97-16	4.58	Porter	OMS intercomparison
970704	97-119	97-17	8.25	Porter	Photolysis - north/south
970708	97-120	97-18	8.00	Broda	Photolysis to NP, Broda 2000 hours
970710	97-121	97-19	5.50	Broda	Stairstep
970712	97-122	97-20	5.50	Porter	Return transit Ft. W. to Ames

Subtotal: 51.58 hours
Cumulative: 144.33 hours

Phase III

970902			5.50	Barrilleaux	Transit Ames to Ft. W.
970905			0.00		Canceled - control panel problem
970906			0.00		Canceled - autopilot problem
970907			0.00		Canceled - autopilot problem
970908	97-152	97-22	7.75	Nystrom	Photolysis flight
970909			0.00		Abort sunset - autopilot
970910	97-153	97-23	0.50	Barrilleaux	Abort after takeoff - autopilot
970911	97-154	97-24	4.25	Nystrom	Sunset flight
970912			0.00		Abort sunrise - fog
970913			0.00		Open House
970914	97-155	97-25	6.40	Barrilleaux	Sunrise (HO _x fail)
970915	97-156	97-26	6.70	Nystrom	Sunrise (HO _x fail)
970917			0.00		Abort photolysis - MMS fail
970918	97-157	97-27	8.00	Barrilleaux	Photolysis - North Pole
970919	97-158	97-28	7.30	Porter	East-west constant altitude
970921	97-159	97-29	7.33	Nystrom	Transit Ft. W. to Barbers Pt.
970923	97-160	97-30	8.00	Broda	South survey (2nd dive aborted)
970925	97-161	97-31	6.00	Nystrom	Return transit Barbers Pt. to Ames

Subtotal: 62.23 hours
Cumulative: 206.56 hours

POLARIS Balloon Flight Log

970430	ADEOS payload
970508	ADEOS - MkIV payload
970630	OMS <i>in situ</i> payload
970704	MkIV payload
970708	OMS <i>in situ</i>

POLARIS Principal Investigators

POLARIS ER-2 Aircraft Instruments

J. Anderson and E. Hints	Harvard University	Water Vapor (H ₂ O)
J. Anderson, R. Stimpfle, and R. Cohen	Harvard University Harvard University University of California, Berkeley	Chlorine Nitrate (ClONO ₂)
J. Anderson and P. Wennberg	Harvard University	High-Altitude OH Experiment (HO _x)
E. Atlas	National Center for Atmospheric Research	Whole Air Sampler (WAS)
D. Baumgardner and B. Gandrud	National Center for Atmospheric Research	Multiangle Aerosol Spectrometer Probe (MASP)
K. Boering and S. Wofsy	Harvard University	High-Sensitivity Fast-Response CO ₂ Analyzer
P. Bui	NASA Ames Research Center	ER-2 Meteorological Measurement System (MMS)
J. Elkins	NOAA Climate Monitoring and Diagnostics Laboratory	Airborne Chromatograph for Atmospheric Trace Species (ACATS)
R.-S. Gao	NOAA Aeronomy Lab	Reactive Nitrogen (NO/NO _y)
B. Gary	Jet Propulsion Laboratory	Microwave Temperature Profiler (MTP)
M. Loewenstein	NASA Ames Research Center	Airborne Tunable Laser Absorption Spectrometer (ATLAS)
T. McElroy	Atmospheric Environment Service/ Canada	Composition and Photodissociative Flux Measurement (CPFM)
R. May	Jet Propulsion Laboratory	Water Vapor (H ₂ O)

M. Proffitt and J. Margitan	NOAA Aeronomy Lab Jet Propulsion Laboratory	Dual-Beam UV-Absorption Ozone Photometer (O ₃)
R. Stachnik	Jet Propulsion Laboratory	Submillimeterwave Limb Sounder
A. Strawa	NASA Ames Research Center	Ames Particle Measurement System (APS)
C. Webster	Jet Propulsion Laboratory	Aircraft Laser Infrared Absorption Spectrometer (ALIAS)
J. Wilson	University of Denver	Focused Cavity Aerosol Spectrometer (FCAS) and Condensation Nuclei Counter (CNC)

Observations from the Middle Stratosphere (OMS) Balloon Instruments

K. Boering and S. Wofsy	Harvard University	Carbon Dioxide (CO ₂)
J. Elkins	NOAA Climate Monitoring and Diagnostics Laboratory	Lightweight Airborne Chromatograph Experiment (LACE)
M. Loewenstein	NASA Ames Research Center	Argus
J. Margitan	Jet Propulsion Laboratory	Dual-Beam UV-Absorption Ozone Photometer (O ₃)
S. Oltmans	NOAA Climate Monitoring and Diagnostics Laboratory	Water Vapor (H ₂ O)
C. Webster	Jet Propulsion Laboratory	Aircraft Laser Infrared Absorption Spectrometer II (ALIAS II)

Theoretical Modeling Projects, Ancillary Measurements, and Mission Support

M. Hitchman	University of Wisconsin
R. Kawa	NASA Goddard Space Flight Center
M. Ko	Atmospheric and Environmental Research, Inc.
L. Lait	NASA Goddard Space Flight Center
S. Lloyd	Johns Hopkins University
L. Pfister	NASA Ames Research Center
R. Pierce	NASA Langley Research Center
R. Salawitch	Jet Propulsion Laboratory
S. Solomon	NOAA Aeronomy Laboratory
S. Strahan	NASA Goddard Space Flight Center
A. Tuck	NOAA Aeronomy Laboratory
D. Waugh	Monash University (Australia)
S. Wofsy	Harvard University

Operations Management

J. Barrilleaux	NASA Ames Research Center
A. Cartledge	NASA Ames Research Center

ER-2 Pilots

J. Barrilleaux	NASA Ames Research Center
K. Broda	Lockheed
W. Collette	Lockheed
J. Nystrom	Lockheed
D. Porter	Lockheed

Project Office

D. Fahey	NOAA Aeronomy Laboratory	Project Scientist
P. Newman	NASA Goddard Space Flight Center	Project Scientist
S. Hipskind	NASA Ames Research Center	Project Manager
M. Craig	NASA Ames Research Center	Deputy Project Manager
K. Wolfe	Computer Sciences Corporation	Project Coordinator
Q. Allison	SIMCO	Logistics Coordinator
S. Gaines	Sterling Software	Data Exchange and Archive/Network Manager

Program Management

M. Kurylo	NASA Headquarters and National Institute of Standards and Technology	Program Scientist/UARP Manager
R. Lawrence	NASA Goddard Space Flight Center	AEA Project Manager
R. Kawa	NASA Goddard Space Flight Center	AEA Project Scientist
J. Kaye	NASA Headquarters	ACMAP Manager
J. Huning and G. Shelton	NASA Headquarters	Airborne Science Office Program Managers
E. Condon	NASA Ames Research Center	Atmospheric Observations Mgr.
P. DeCola	Johns Hopkins University and NASA Headquarters	Assistant UARP Manager