An overview of the SOLVE-THESEO 2000 campaign

Paul A. Newman
NASA Goddard Space Flight Center, Greenbelt, Maryland, USA

Neil R. P. Harris
European Ozone Research Coordinating Unit, Cambridge, United Kingdom

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Abstract. Between November 1999 and April 2000, two major field experiments, the SAGE III Ozone Loss and Validation Experiment (SOLVE) and the Third European Stratospheric Experiment on Ozone (THESEO 2000), collaborated to form the largest field campaign yet mounted to study Arctic ozone loss. The main scientific aims of SOLVE-THESEO 2000 were to study (a) the processes leading to ozone loss in the Arctic vortex and (b) the effect on ozone amounts over northern mid-latitudes. The campaign included satellite, heavy lift balloon launches, 5 different aircraft, ground stations, and scores of ozonesondes. Campaign activities were principally conducted in 3 intensive measurement periods: early-December 1999, late-January 2000, and early-March 2000. Observations made during the campaign showed that temperatures were unusually cold in the polar lower stratosphere over the course of the 1999–2000 winter. These cold temperatures resulted in the formation of extensive polar stratospheric clouds (PSC) across the Arctic. Heterogeneous chemical reactions on the surfaces of the PSC particles produced high levels of reactive chlorine within the polar vortex by early January. This reactive chlorine catalytically destroyed about 60% of the ozone in a layer near 20 km between late-January and mid-March 2000.

1. Introduction

Between November 1999 and April 2000, two major field experiments, the NASA-sponsored SAGE III Ozone Loss and Validation Experiment (SOLVE) and the European Union-sponsored Third European Stratospheric Experiment on Ozone (THESEO 2000), collaborated to form the largest field campaign yet mounted to study Arctic ozone loss. The main scientific aims of SOLVE-THESEO 2000 were to study (a) the processes leading to ozone loss in the Arctic vortex and (b) the effect on ozone amounts over northern mid-latitudes. A further aim was to validate measurements from the third Stratospheric Aerosol and Gas Experiment (SAGE III) instrument. Unfortunately, SAGE III was not launched on schedule and so this goal was not achieved. However, measurements from several satellite instruments are being used in conjunction with SOLVE-THESEO 2000 data for scientific and validation studies. SOLVE-THESEO 2000 involved research aircraft, balloons, ozonesondes, ground-based and satellite instruments, which were augmented by meteorological and chemical models. In all, more than 500 scientists from over 20 countries (the European Union, Canada, Iceland, Japan, Norway, Poland, Russia, Switzerland and the United States of America) were involved. Descriptions of the SOLVE-THESEO 2000 activities and the early findings were published in the SPARC newsletter [*Newman,* 2000; *Harris et al.,* 2001a].

Arctic ozone loss has been extensively studied since the discovery of the Antarctic ozone hole [*Farman et al.,* 1985]. The simple fact that such a large area of depleted ozone existed immediately raised the question of whether a similar phenomenon could occur over the Arctic, closer to the heavily populated areas of Asia, Europe and North America. The confirmation that the ozone loss was caused by chlorine and bromine chemistry underlined the importance of the question. As a result a number of large scientific campaigns have investigated ozone loss in the Arctic stratosphere during winter and spring. These include the Airborne Arctic Stratospheric Experiment (AASE, 1987), European Arctic Stratospheric Ozone Experiment (EASOE, 1991-92), Airborne Arctic Stratospheric Experiment (AASE 2, 1991/92), Second European Stratospheric Arctic and Mid-latitude Experiment (SESAME, 1994/95), Photochemistry and Ozone Loss in the Arctic Region In Summer (POLARIS, 1997), and Third European Stratospheric Experiment on Ozone (THESEO, 1998/99).

There have also been a number of smaller, focused campaigns investigating processes such as Polar

Stratospheric Aerosol Experiment (POLSTAR, 1997) and Airborne Polar Experiment (APE-POLECAT, 1997). These campaigns have been complemented by longer-term observations from ground stations (e.g. the stratospheric composition measurements made within the Network for the Detection of Stratospheric Change (NDSC) and the ozone and meteorological observations made within the WMO-GAW network) and from a number of satellites (e.g., TOMS, MLS, HALOE, SAGE, GOME, and POAM). Such continuity of observation is important, since a striking feature of Arctic ozone loss has been its large interannual variability. Multi-year records give the perspective with which to interpret results from individual, intensively studied winters.

The processes which lead to Arctic ozone loss have thus been closely studied and, qualitatively, they are fairly well understood. During October and November, a westerly circulation of winds develops in the stratosphere. This circumpolar vortex is the dominant feature of the stratospheric circulation during the Arctic winter and is the counterpart of the much more stable and long-lived Antarctic vortex. During the long periods of darkness at high latitudes in winter, the Arctic vortex radiatively cools, and at sufficiently low temperatures (195 K or below), polar stratospheric clouds (PSC) can form. Heterogeneous chemical reactions occur on the surface of the PSC particles. These reactions convert relatively inactive chlorine compounds such as HCl and $ClONO_2$ into active forms such as ClO which can lead to rapid chemical destruction of ozone in the presence of sunlight. This ClO catalytic ozone loss is deactivated by the reaction of ClO with NO_2 to re-form $ClONO_2$. As this ClO gradually reverts back to the inactive forms, the ozone destruction slows down. These processes largely take place in the Arctic vortex. As the vortex breaks down, ozone-depleted air is mixed with mid-latitude air.

Levels of chlorine and bromine in the Arctic are high enough to cause large ozone losses if the meteorological conditions are cold enough for formation of PSCs, particularly during late February and March. There is a large interannual variability in the dynamics and temperature of the Arctic stratosphere, and large ozone losses have occurred in the colder winters but not in the warmer ones. Modeling studies suggest that the changes in climate will cause a further cooling of the stratosphere which could lead to enhanced PSC formation and a longer-lived Arctic vortex. Both of these mechanisms would cause a greater future occurrence of winters with large Arctic ozone losses. An improved understanding of the dynamic, radiative and chemical processes involved is required to increase confidence in model studies of the possible future atmosphere.

The main results of SOLVE-THESEO 2000 are being published in two special sections of JGR [1st vol number; this issue]. In this paper we present an overview of the campaign. In the rest of the introduction, the scientific goals of the campaign are described. In section 2, the full scope of the mission is described with details about the timing and coverage, the platforms (aircraft, balloons, ground-based stations and satellites) and instruments involved, and the meteorological and modelling support activities. A brief outline of the main results to date is given in section 3.

Each element of the chain of processes involved in chemical ozone loss needs to be understood quantitatively if the future evolution of ozone over the Arctic and the northern mid-latitudes is to be accurately assessed. Based on the simple picture given above, the scientific aims can be divided into four main categories: (1) Transport and dynamics, (2) Formation and composition of PSCs, (3) Improved quantification of the activation and deactivation of ClO_x, and (4) Empirical and modelled calculations of chemical ozone loss.

These more detailed aims are now considered in turn.

1.1. Transport and Dynamics

Understanding the transport and dynamics of the development and break-up of the Arctic vortex, needed to fully constrain the chemical evolution, requires precise large scale observations over at least one Arctic winter. In situ observations of the Arctic stratosphere during the early and mid winter have been relatively sparse. It was important to study this period in detail because the dynamical evolution of the vortex during this period has a major significance in terms of the chemical and dynamical behavior in the January to March period when nearly all the ozone loss takes place. For example, the amount of descent in the vortex resulting from radiative cooling determines the amounts of Cl_y, Br_y and NO_y in spring, while the temperature history determines the extent of PSC formation and, indirectly, the degree of denitrification.

The exchange of air between the polar vortex and the mid-latitudes is an important factor in the polar ozone budget. Further the carrying of low ozone air from the polar vortex into mid-latitudes can reduce mid-latitude ozone levels. In addition, while mid-latitude air is not easily carried into the polar vortex, occasionally, under disturbed stratospheric weather conditions, mid-latitude air can be entrained into the vortex, significantly changing the chemical composition of the vortex.

1.2. Formation and Composition of PSCs

PSCs provide both the surfaces for the heterogeneous reactions that result in ozone loss, but are also thought to both sequester and re-distribute (or remove) nitric acid and water from the stratosphere. The heterogeneous reaction rates on PSCs are known from laboratory measurements but are rather poorly constrained by observations because of the lack of observations. A wide number of questions are still open with respect to the types of PSCs and their composition. These questions were principally addressed during SOLVE-THESEO 2000 by direct measurements and analysis of the chemical and physical composition of PSCs. Information was needed on the temporal evolution of PSCs, in particular the nucleation of these particles and the evolution of their size distributions.

Important unknowns for PSCs are the spatial and horizontal morphologies of the PSC types, size distributions, and relationships to the broad temperature fields. These quantities are necessary for determining from broad scale model and analysis quantities parameterizations of type, size, and surface area in models. These parameterizations will be used to characterize the heterogeneous reaction rates and denitrification effects.

1.3. Improved Quantification of the Activation and Deactivation of ClO

Chlorine activation involves a number of science questions. First, what is the seasonal evolution of the particles and how does this evolution impact reaction probabilities over the winter season? Second, what is the chemical evolution of the nitrogen and chlorine budgets over the course of the winter due to repeated activation events? In particular, the impact of mesoscale temperature perturbations that result from mountain waves needs to be considered in addition to the activation events that result from synoptic scale systems. Additional questions involve the details of denitrification processes that extract reactive nitrogen from the lower stratosphere.

Our current understanding of the termination of the halogen catalyzed ozone loss depends on the reintroduction of NO_2 into the gas phase where it reacts with ClO to form the relatively long-lived $ClONO_2$. The NO_2 is formed by the photolysis of nitric acid.

The key chemistry questions involve: whether NO_2 is the principal gas for deactivating ClO; how the reservoir species ($ClONO_2$ and HCl) evolve following ClO deactivation; whether the formation of ClOOCl is a principal part of the loss mechanism; and what are the relative contributions among catalytic loss cycles to the overall ozone loss in the winter to spring period? A further important issue is how denitrification affects the chlorine deactivation processes and hence ozone loss.

1.4. Empirical and Modeled Calculations of Chemical Ozone Loss

A number of techniques for determining empirical estimates of chemical ozone loss rates in the Arctic vortex have been developed in recent years. Several of these techniques will be used during the 1999/2000 winter. It is important to examine the consistency of the empirical estimates with each other, as there has been considerable discussion of apparent inconsistencies between results from different winters.

Comparison of these empirical estimates of ozone loss with the losses calculated by models is another priority for SOLVE-THESEO 2000. Several studies have shown significant disagreements between the modeled and empirical estimates [*Becker et al.,* 2000; *Kilbane-Dawe et al.,* 2001], and these disagreements limit the confidence that can be placed in predictions of future losses. A particular puzzle has been the high ozone loss rates observed at the end of January [*Rex et al.,* 1999]. Thorough comparisons using a range of models are needed to understand better the conditions where these disagreements arise.

2. Mission Scope

The SOLVE-THESEO 2000 campaign was primarily conducted in 3 phases over the Arctic and mid-latitude region during the winter of 1999/2000. Most activities took place at Kiruna (67.9°N, 21.1°E), Sweden or the SSC Esrange facility near Kiruna, between mid-January and mid-March. During this period, 7 large balloons, 14 small balloons, and 3 long duration balloons carrying scientific payloads were launched successfully from Esrange. Two other small balloons were launched from the Norwegian station in Andoya. Aircraft measurements in the Arctic region were made on board the NASA ER-2, NASA DC-8, DLR Falcon, the CNRS/INSU ARAT, and the Swiss Air Force Learjet. There were simultaneous ground-based activities from the Scandinavian stations

(ALOMAR, Kiruna, Ny-Ålesund, Sodankyla, Harestua) throughout the winter. In coordinated activities, the aircraft often flew along upwind and downwind of the balloon flight path. Additional flights of ozonesondes were conducted at a number of sites across the northern hemisphere [*Rex et al.,* 2001], and ground measurements were made a number of Arctic and mid-latitude sites. The TOMS, GOME and POAM satellite instruments also made measurements of sunlit regions of the stratosphere through the winter. Meteorological support was provided by several meteorological organizations, some with representatives in the field (FU-Berlin, US NOAA/NCEP, US Naval Research Lab, NASA/GSFC Data Assimilation Office) to assist daily planning, and others through the provision of data (ECMWF, Météo-France, SMHI, UKMO and DWD). Modeling and theory support groups were essential for both the pre-mission planning and the daily operational planning.

2.1. Location and Timing

The SOLVE-THESEO 2000 campaign was designed for both extensive spatial coverage and fall-to-spring temporal coverage. In particular, the campaign was partitioned into 3 intensive measurement phases. The first phase was set in the early December period as the polar vortex set up, and as temperatures first fell below about 195 K (the nitric acid trihydrate saturation temperature). The second phase was chosen during the period when polar lower stratospheric temperature were coldest and the vortex was at its strongest. Because this phase was timed to the coldest period, expected formation of PSCs would lead to extensive conversion of chlorine into reactive forms. The final phase of SOLVE-THESEO 2000 was timed to the recovery period of the polar vortex as temperatures rose above 195K, the vortex decreased in strength, and perturbed chemistry began to recover.

The science requirements prescribed a need for regular and deep penetrations of the polar vortex along with good proximity to the coldest portion of the polar vortex. Kiruna, Sweden provided an ideal site for SOLVE-THESEO 2000's principal activities. The Arena Arctica hangar at the Kiruna airport was built in 1992 as a facility for accommodating large aircraft field projects on environmental issues. The total area of the facility is 5,700 m^2. In late January, this hangar simultaneously accommodated the NASA ER-2, NASA DC-8, and DLR Falcon. A second hangar was available for use by the ARAT and Lear Jet. The Arena also includes offices, labs and shared rooms such as a pantry, a meeting room, dressing rooms, and workshops. The lab and office space on either side of the hangar housed all of the investigators and instruments for the aircraft portion of the campaign.

Balloon operations were conducted at the Swedish Space Corporation's Esrange facility, which is approximately 40 km from Kiruna. This facility is able to launch balloons of up to 1,000,000 m^3. The facility includes a large 400 m by 250 m launch pad, a balloon control facility, and a laboratory and payload assembly building (the cathedral). In addition, Esrange includes accommodation and dining facilities to handle the large teams of scientists associated with the balloons. A second balloon launching facility, where 10,000 m^3 balloons were flown, was at the Norwegian Rocket Range at Andoya.

SOLVE/THESEO operations extensively covered the Arctic region. Plate 1 displays this operational region. Plate 1 The magenta line indicates the 2700 km distance from Kiruna, roughly the operational radius of ER-2 flights. Kiruna is located at the center of the image by the green star. Ozonesonde launch sites were widely distributed across the polar region (as indicated by the red points on Plate 1). In addition, ground-based instruments were located at a number of sites across the polar and mid-latitude region in support of SOLVE-THESEO 2000. The observational sites in the EU project Compilation of atmospheric Observations in Support of Satellite measurements over Europe (COSE) are shown as the blue points in Plate 1.

2.2. Platforms

The SOLVE-THESEO 2000 campaign had a mix of observational platforms that included satellites, ground stations, aircraft, and balloons.

2.2.1. Satellites. Satellite observations provided a wide view of the Arctic polar vortex over the course of the 1999/2000 winter. These observations were vital to following the hemispheric evolution of ozone, polar stratospheric clouds, and temperatures over the course of the winter. The satellite observations provided a first look at the basic structure of these fields. These maps assisted in the flight planning, day-to-day launch schedules, and real-time analysis of observations. Five satellite instruments were principally used during the campaign: GOME, POAM, HALOE, TOMS, and SAGE II.

2.2.1.1. POAM: The POAM III instrument was launched onboard the French SPOT 4 spacecraft on March 24, 1998, into a sun-synchronous 98.7°E inclination orbit (PI: R. Bevilacqua, NRL). The POAM III instrument is a nine-channel visible/near infrared photometer (352–1020 nm) for measuring trace constituents in the stratosphere using solar occultation. The POAM III measurements include O_3, H_2O, NO_2, and aerosol extinction. A detailed description of the POAM III instrument, and early validation results are given by *Lucke et al.* [1999]. POAM III makes 14 measurements per day in each hemisphere evenly spaced in longitude around a circle of latitude. The latitudes of the POAM occultations are shown in Plate 2 as the magenta line. Because of the polar vortex size, this sampling pattern allows POAM to obtain profiles both inside and outside the Arctic polar vortex on a daily basis throughout the winter. Plate 2

2.2.1.2. TOMS: The Total Ozone Mapping Spectrometer (TOMS) Instruments have been in nearly continuous orbit since late 1978. The first TOMS was launched aboard the Nimbus-7 spacecraft, while the latest TOMS on the Earth Probe satellite was launched on July 2, 1996. The TOMS instrument uses 6 wavelengths (360.0, 331.2, 322.3, 317.5, 312.5, and 308.6 nm) in the UV portion of the spectrum to derive total column ozone amounts. The side-to-side instrument scanning, combined with the 39$\times$39 km nadir field-of-view yields complete daily coverage of total ozone across the globe. Because the TOMS instrument requires backscattered solar radiation, observations are not available in polar night. Plate 2 displays the longitudinally averaged (zonal mean) TOMS observations over the period of October 1999 through April 2000. Measurements are not available for solar zenith angles greater than 82°.

2.2.1.3. GOME: The Global Ozone Monitoring Experiment (GOME) was launched on April 21, 1995 on board the second European Remote Sensing Satellite (ERS-2) [*Burrows et al.,* 1999, and references therein]. GOME is a nadir-scanning spectrometer that measures the solar radiation scattered by the atmosphere and the extra terrestrial solar irradiance in the ultraviolet and visible spectral region. The entire spectral region between 230 and 790 nm is observed at moderate spectral resolution of 0.2 to 0.4 nm in four individual linear detector arrays each having 1024 detector pixels. The field of view may be varied in size from 320$\times$40 km to 40$\times$40 km for a 1.5 s measurement. For O_3 profiling typically a 12 s swath corresponds to eight 1.5 s measurements or 960$\times$80 km. The ERS-2 orbit is a sun synchronous orbit having an equator crossing time of 10:30 AM. As a result GOME obtains full global coverage over a three-day period at the equator. As with TOMS, GOME relies on backscattered solar radiation, hence, it can only make measurements outside the region of continuous polar darkness. GOME products for the SOLVE-THESEO 2000 campaign include column O_3, BrO, NO_2, OClO, and H_2CO and O_3 profiles.

2.2.1.4. UARS HALOE: The HALogen Occultation Experiment (HALOE) was launched on board the Upper Atmospheric Research Satellite (UARS) on September 12, 1991 into a 57° inclined orbit (PI: J. M. Russell III). HALOE measures the absorption of solar energy due to stratospheric trace gases during spacecraft sunrise and sunset events. Vertical scans of the atmosphere are obtained by tracking the sun position during 15 sunrise and 15 sunset occultations per day. The instantaneous vertical field of view is 1.6 km. Daily retrievals are at approximately equal latitudes with a 24° longitudinal resolution. Latitudinal sweeps occur approximately once every 30 days. The HALOE altitude range is 15 to 60 or 130 km, depending on the species. Vertical profiles of O_3, H_2O, NO_2, temperature, and pressure are obtained using broadband techniques. Vertical profiles of HCl, HF, CH_4, and NO rely on gas filter radiometer techniques [Russell et al., 1993]. Aerosol extinction coefficient profiles and sulfate aerosol surface area densities (SAD) are inferred [*Hervig et al.,* 1996].

Version 19 (third public release) of the HALOE retrieval was used during SOLVE-THESEO 2000. HALOE made extensive observations of the early vortex formation during October and November 1999 with 18% of the northern hemisphere HALOE observations occurring within the Arctic proto-vortex. Plate 2 displays the HALOE occultations for both sunrise (blue crosses) and sunset (blue stars). During mid February through mid March HALOE returned to high northern latitudes and once again made vortex observations.

2.2.1.5. SAGE II: The SAGE II (Stratospheric Aerosol and Gas Experiment II) sensor was launched into a 57° inclination orbit aboard the Earth Radiation Budget Satellite (ERBS) in October 1984. During each sunrise and sunset encountered by the orbiting spacecraft, the instrument uses the solar occultation technique to measure attenuated solar radiation through the Earth's limb in seven channels centered at wavelengths ranging from 0.385 to 1.02 μm. The exo-atmospheric solar irradiance is also measured in each channel during each event for use as a reference in determining limb transmittances.

The transmittance measurements are inverted using the "onion-peeling" approach to yield 1-km vertical resolution profiles of aerosol extinction (at 0.385, 0.453, 0.525, and 1.02 μm), O_3, NO_2, and H_2O. The focus of the measurements is on the lower and middle stratosphere, although retrieved aerosol, H_2O, and O_3 profiles often extend well into the troposphere under non-volcanic and cloud-free conditions.

The sampling coverage for SAGE II varies in latitude from approximately 60°N to 80°S during the winter. The SAGE II measurements provide insight into the distribution of aerosol, O_3, and H_2O found at mid and low latitudes outside to polar vortex. A detailed description of SAGE II is provided by *McCormick et al.* [1979] and *Cunnold et al.* [1991].

2.2.2. Ground. A number of ground sites and instruments were involved in the SOLVE-THESEO 2000 campaign. These instruments provided continuous records of ozone and other trace gases over the entire course of the 1999-2000 winter. Table 1 lists the sites and observations. Table 1

2.2.3. Aircraft. Six aircraft were employed during the SOLVE-THESEO 2000 campaign. The SOLVE campaign provided the NASA ER-2 and the NASA DC-8, while the THESEO 2000 campaign provided the French ARAT, the DLR Falcon, the Swiss Learjet, and the French Mystère 20 aircraft.

2.2.3.1. ER-2: The NASA ER-2 is the civilian version of the famous U-2 spy plane. NASA has employed the ER-2 on numerous field campaigns. The aircraft is capable of flights at altitudes over 20 km (pressures less than 50 hPa) for durations up to 8 hours. The ER-2 was flown 13 times during the second and third deployments of the campaign, including transits into and from Kiruna. The aircraft is shown in Plate 3, with locations of the 17 instruments. The ER-2 instruments are listed in Table 2 along with the PI and home institutions. Plate 3 Table 2

2.2.3.2. DC-8: The NASA DC-8 was a commercial airliner that was converted into a flying laboratory. Like the ER-2, the DC-8 has been deployed on numerous field campaigns investigating stratospheric ozone. The aircraft is capable of flights to about 12 km for durations over 10 hours. The DC-8 was flown 22 times during the 3 deployments of the campaign. The aircraft is shown in Plate 4, with locations of the 17 instruments. The DC-8 instruments are listed in Table 3. Plate 4 Table 3

2.2.3.3. ARAT: The ARAT is a turbo-prop Fokker 27-MK 700 aircraft that carries the LEANDRE backscatter lidar (PI: C. David of Service d'Aéronomie-IPSL). The ARAT is capable of flight to approximately 5 km, and durations of 4 hours. The ARAT aircraft is a research facility jointly operated by the Institut National des Sciences de l'Univers (INSU-CNRS), the French Space Agency (CNES), the French National Weather Center (Météo-France), and the National Geographic Institute (IGN). LEANDRE is a backscatter lidar emitting

10 pulses per second at a wavelength of 532 nm. The backscattered signal is split into components polarized parallel and perpendicular to the laser emission. The ARAT flew on January 25, 2000 in coordination with the second PSC-Analysis balloon. Two flights were performed. The first flight was upstream towards Andoya, before PSC-Analysis gondola launch, while the second flight was directed southeastward between Kiruna and Rovaniemi. During this second flight, the position of the balloon was communicated in real time to the ARAT through the VHF station in Esrange, allowing the aircraft to track the balloon efficiently. PSCs were observed between about 20 and 25 km in altitude. The ARAT also flew on January 26 and 27, 2000.

2.2.3.4. Falcon: The DLR Falcon 20-E5 is a modified twin engine-jet business aircraft capable of flights to 13.7 km with a maximum endurance of up to 5 hours. The Falcon carried the OLEX lidar during the SOLVE-THESEO 2000 campaign. OLEX (PI: H. Flentje, DLR) measures ozone as well as depolarization- and wavelength-resolved backscatter of aerosol and PSCs. During SOLVE-THESEO 2000 a total of 8 science flights (including 2 transit flights) of the FALCON lidar were carried out during the second deployment. Three of them were mountain wave flights, the other three probed the NAT rock PSCs south of Spitzbergen. On January 27 the FALCON precisely tracked two balloons (HALOZ and TRIPLE), which carried various in situ aerosol probes. Plate 5 displays the DLR Falcon parked on the ramp outside of the Arena Arctica on January 31, 2000. Plate 5

2.2.3.5. Lear Jet: The Swiss Air Force Learjet carried a microwave radiometer (PI: N.Kämpfer, University of Bern). The measurements were made from March 8 to 14, 2000. This instrument recorded spectra of stratospheric water vapor at 183 GHz as well as ozone at 176 GHz. From these spectra, profiles were derived over an altitude range of roughly 20–70 km. Several flights were performed, including Kiruna to Iceland, from Kiruna to the North Pole, and from Kiruna to the North Atlantic. After the Arctic flights, the plane flew south to the Canary Islands to increase the latitude range of the measurements to the subtropics.

2.2.3.6. Mystère 20: The French Mystère 20 is a twin turbofan engine aircraft built by Dassault. The Mystère is capable of 3-hour flights to a maximum altitude of approximately 13 km, and a range of approximately 1800 km. During SOLVE-THESEO 2000, the Mystère carried the Alto ozone lidar (PIs: S.Godin and A.Hauchecorne, CNRS-SA/IPSL) which is a DIAL system capable of measuring ozone profiles from 1 km above the plane to about 20 km. The objective for the Mystère was to measure polar ozone filaments that were breaking off of the polar vortex. The Mystère was flown on February 28, March 7, March 26, and March 28, 2000 and was operated from Creil airport near Paris.

2.2.4. Balloons.

2.2.4.1. OMS in situ: The NASA OMS in situ payload was launched on November 19, 1999 and March 5, 2000, with both flights inside the Arctic vortex. In situ measurements of the vertical profiles of a range of atmospheric tracers were made. The OMS in situ gondola includes the following instruments: (1) The Airborne Laser Infrared Absorption Spectrometer (ALIAS-II), measuring HCl, NO_2, CO, CO_2, CH_4, N_2O (PI: C. Webster, JPL), (2) The Dual-beam UV in situ O_3 Photometer (PI: J. Margitan, JPL), (3) The High-Altitude Fast-Response CO_2 Analyzer (PI: S. Wofsy, Harvard), (4) The Lightweight Airborne Chromatograph Experiment (LACE) described by *Moore et al.* [2001], measuring CFC-11, CFC-12, CFC-113, halon-1211, $CHCl_3$, CH_3CCl_3, CCl_4, SF_6 and N_2O (PI: J. Elkins, NOAA/CMDL)

The Frost-Point Hygrometer was launched as a free flying package in parallel with the OMS in situ payload (PI: S. Oltmans, NOAA/CMDL)

2.2.4.2. OMS Remote: The OMS Remote payload consisted of two instruments. The JPL MkIV infra-red interferometer (PI: G.Toon, JPL) made profile measurements of a wide range of species in solar absorption mode by observing sunrise or sunset from a balloon. These included H_2O, O_3, N_2O, CO, CH_4, NO, NO_2, HNO_3, HNO_4, N_2O_5, H_2O_2, $ClNO_3$, HOCl, HCl, HF, COF_2, CF_4, SF_6, CFC-11, CFC-12, CCl_4, CH_3Cl, and CO_2. The Submillimeterwave Limb Sounder (SLS) is a heterodyne radiometer measuring thermal emission spectra (PI: R.Stachnik, JPL). It measured atmospheric profiles ClO, O_3, HCl, HNO_3, and N_2O. This payload made two flights, both inside the Arctic vortex. The first was early in the winter on December 3, 1999, and the second was on March 15, 2000 just prior to a major split in the vortex.

2.2.4.3. MIR: The Montgolfière Infrarouge (MIR) packages (PIs: J.-P. Pommereau, CNRS and F. Vial, CNES) are long duration balloon flights. The objective of the flights was to complement the measurements of 1999 by two new instrumented scientific MIR flights in the vortex as well as an additional technical MIR, all carrying payloads recovered in 1999. The two first MIRs were launched on the same day (February 18, 2000) when the vortex passed rapidly above Kiruna. They lasted for 2 and 18 days, both being automatically cut-down when reaching 55°N. Their payloads were recovered respectively in the Hudson Bay and in Belarus near Minsk. The third (technical) balloon failed during the initial ascent and no useful measurements were made. The data include temperature, pressure, altitude and IR radiation measurements every 15 minutes along the two flights, five CH_4 and H_2O profiles, and ten O_3, NO_2, and OClO profiles.

2.2.4.4. PSC analysis: The PSC analysis balloon borne payload was launched from Esrange on January 19 and 25, 2000 for detailed studies of PSC particles (see Plate 6). The payload consists of a mass spectrometer with an aerodynamic focusing lens for condensed phase chemical analysis (ACMS), and optical and CCN counters for measurements of PSC particle size distributions, backscatter sondes for observations of optical properties and physical phase, and a water vapour frost point hygrometer. The balloon altitude was controlled by CNES and on each flight the balloon went up and down, passing through PSC layers multiple times. Plate 6

2.2.4.5. HALOZ: A series of five small balloons carrying instruments to address the issue of halogen-catalyzed ozone loss (HALOZ) were launched from Kiruna, Sweden in between January and April 2000. A critical subset of species involved in ozone loss were measured in situ with lightweight instruments. ClO and BrO were measured using a resonance fluorescence instrument (PI: D. Toohey, Colorado Univ.); particle number and size distributions were measured by optical scattering (PI. T. Deshler, Univ of Wyoming); and CFC-11 was measured by the in situ gas chromatograph, DIRAC (PI: A. Robinson, Univ. of Cambridge). Ozone was measured by an ozonesonde. Two distinct payload configurations were used for maximum launch flexibility. The first, which consisted of all the instruments, was launched twice (January 19 and 27, 2000) when PSCs were observed visually. For the last three flights (March 1, March 8, and April 4), the particle instruments were removed. On March 1 and April 4, CFC-11 was measured by the DESCARTES grab-sampler (PI: H. Nilsson, IRF; and F. Danis, Univ. of Cambridge) rather than DIRAC. All flights took place inside the vortex.

2.2.4.6. TRIPLE: The TRIPLE payload included a ClO/BrO chemical conversion resonance fluorescence instrument (PI: F. Stroh, KFz Jülich), the cryogenic whole air sampler BONBON which measures a wide range of stable gases including N_2O, CFCs, CH_4, HCFCs, and SF_6 - chk) (PIs: A. Engel and U. Schmidt, Univ of Frankfurt), the Lyman-alpha hygrometer FISH, the filter UV radiometers, and an instrument measuring aerosol size distribution (PI of all three: C. Schiller, KFz Jülich). This payload was flown on January 27, 2000 and

March 1, 2000 from Esrange, separated by a few hours from the HALOZ flights.

2.2.4.7. LPMA/DOAS: The LPMA/DOAS payload was launched from Esrange by CNES on February 18, 2000. Solar absorption measurements were performed by the FTIR (Fourier Transform-InfraRed Spectrometer PI: C. Camy-Peyret, UPMC) and DOAS (Differential Optical Absorption Spectrometer PI: K. Pfeilsticker, Univ. Heidelberg) instruments. These spectrometers simultaneous measured vertical profiles of HCl, $ClONO_2$, CH_4, N_2O, HNO_3, NO_2, NO, O_3, and HF in the infrared spectral range and O_3, BrO, IO, NO_2, O_4, and OClO in the UV-visible spectral range.

2.2.4.8. SALOMON: SALOMON is a UV-visible spectrometer (350–700 nm) which uses the moon as the light source. The instrument (PI: M. Pirre, LPCE) measures the vertical distributions of O_3, NO_2, NO_3, OClO, aerosol extinction coefficients, and possibly OBrO. Two SALOMON flights were performed in different geophysical conditions, allowing a comparison of various aspects of the stratospheric polar chemistry to be made. The first flight was on January 23, 2000 at the edge of the vortex. The flight was stopped early for safety reasons and observations were made in the 13–20 km range. The second flight occurred on February 22, 2000. The measurements were made in warm conditions outside the polar vortex. The full moon-rise was observed, giving profiles between 16 and 30 km.

2.2.4.9. Micro-Radibal: Micro-Radibal is a balloon-borne instrument developed to study stratospheric aerosols and measures the radiance and polarisation of scattered sunlight at 730, 865, 1000, and 1620 nm (PI: C. Brogniez, U. Lille). The gondola rotates around a vertical axis and observations are made under various scattering angles during the ascent of the balloon. Micro-Radibal flew on January 26, 2000 from Esrange and made measurements between 13 and 23 km.

2.2.4.10. SAOZ balloon flights: The SAOZ (PIs: J-P. Pommereau, F. Goutail, CNRS-SA) is a UV-visible spectrometer that measures in the wavelength region between 300–600 nm. During SOLVE-THESEO 2000 there were 6 flights made inside the vortex and 2 flights made outside the vortex. The basic SAOZ provides O_3, NO_2, and OClO vertical profiles. A refined version, SAOZ-BrO, provided BrO and OClO vertical profiles on 3 flights inside the vortex, and on all flights outside vortex. One flight inside the vortex was made in parallel with a HALOZ flight, to allow a comparison with the ClO/BrO resonance-fluorescence instrument. In addition, tracer profiles were measured on all flights with either the DESCARTES or DIRAC instruments or the methane TDL instrument (Pis: R.Jones, Univ Cambridge and P. Woods, NPL). In total, DESCARTES made 11 flights during this winter, ten in conjunction with other instruments (OMS remote; HALOZ; OMS in situ; SAOZ) and one solo flight in early winter (November 11, 1999). DIRAC made four flights in conjunction with other instruments (three with HALOZ and one with OMS in situ). These flights with the OMS gondola were made so that measurements comparisons can be made.

2.2.5. Ozonesondes. During SOLVE-THESEO 2000, over 650 ozonesondes were launched from a network of 36 stations in 20 countries at mid and high latitudes in the northern hemisphere (see Plate 1). Many of these stations were underneath the Arctic vortex at various times, and so a high proportion of the ozonesondes made measurements inside the Arctic vortex. The ozonesondes were either part of regular programs or were launched in response to requests within the coordinated Match program or in conjunction with aircraft or balloon flights.

2.3. Flights and Launches

The SOLVE-THESEO 2000 campaign was divided into 3 intensive measurement phases. The flight log is shown in Table 4. Table 4

The principal deployment site was in Kiruna, Sweden (see Plate 1 to view operational region of SOLVE-THESEO 2000). Five aircraft were primarily staged from the Arena Arctica at the Kiruna airport, while all of the Mystère 20 flights were from a small airfield near Paris. The balloons were primarily flown from Esrange, though two additional SAOZ balloons were flown from Andoya, Norway (240 km northwest of Kiruna).

The aircraft flights indicated in Plate 7 cluster into the 3 phases of the campaign. The balloon flights are Plate 7
shown in Plate 8, superimposed on the polar vortex temperatures. As planned, the first phase sampled the polar Plate 8
vortex during the vortex formation phase as temperatures cooled below the NAT saturation temperature of 195 K. The second deployment occurred shortly after the coldest period during the 1999/2000 winter in the last two weeks of January. The final phase occurred as temperatures warmed to temperatures greater than 195 K.

2.4. Mission Forecasting

The aircraft platforms and balloon payloads discussed in the previous sections provided an enormous capability for understanding the Arctic polar vortex. However, such resources required careful coordination and direction for optimizing the scientific return. Optimized flights were determined using meteorological, chemical, and microphysical forecasting. A number of meteorological and theory groups participated in the SOLVE-THESEO 2000 campaign. Over the course of the campaign these groups held daily meetings at Arena Arctica and Esrange to discuss the evolving polar vortex and forecast its further evolution. In addition, tropospheric forecasts were used to determine flight conditions, particularly for the large balloon payloads and NASA ER-2.

2.4.1. Tropospheric forecasting. The surface weather forecasting for SOLVE-THESEO 2000 at the Arena Arctica was conducted by Dr. G. Forbes (The Weather Channel). Forecasting for the DC-8, ARAT, Falcon, and Lear Jet was relatively straightforward, since these aircraft have a near "all-weather" flight capability. However, the NASA ER-2 has rather severe weather restrictions. For example, the ER-2 requires runway cross winds to be less than 12 kts (6 m s^{-1}), wind chill temperatures greater than 31°C (242 K), good visibility, low ceilings, and a runway that is relatively free of ice and snow. Such conditions were satisfied relatively often in Kiruna, but were extremely difficult to forecast.

Surface forecasting at Esrange was handled by the U.S. National Science Balloon Facillity (NSBF) staff meteorologists (G. Rosenberger, J. Hobbie, and R. Mullenax) for the SOLVE OMS launches, and by CNES meteorologists (P. Dedieu and colleagues) for the THESEO 2000 launches. Because of the large size of these balloons, very light surface winds and very small vertical wind shears over the lowest few hundred meters are necessary for safe launches. Forecasting support was also provided by Esrange staff, and sounding balloon launches were handled by the Esrange balloon launch crew. Trajectory forecasts were an important aspect of these balloon launches. These trajectories ensured that the payloads were inside the vortex, and had the desired float times. For example, the second OMS remote launch required very accurate predictions of time to float (a heavy cirrus cover caused an unfavorable radiation environment). The NSBF meteorologists' use of the SINBAD model was critical in determining the launch window. Similarly, the accuracy of the ground wind forecasts from the Météo-France ARPEGE model and from SMHI were essential in the launch of the first PSC Analysis gondola. All of the trajectory and meteorological forecasts were prepared with considerable assistance by the Esrange Range Safety team (T. Hedqvist, S. Kemi, and B. Sjoholm).

2.4.2. Stratospheric forecasting. The forecasting for the stratosphere was carried out by a number of groups. These groups used standard meteorological analyses combined with specialized products to predict stratospheric temperatures, the position of the polar vortex, mountain wave amplitudes and turbulence, PSC microphysics, and the chemical composition of the stratosphere.

2.4.2.1. Stratospheric meteorology and mountain wave forecasting: A number of conventional meteorological forecasts and analyses were utilized for SOLVE-THESEO 2000 forecasting. These forecasts and analyses were routinely provided for flight planning and data analysis. Typically, the data were used to forecast the locations of cold temperature regions (for PSC flights), and for locating the position of the polar vortex. These analyses included GSFC Data Assimilation Office GEOS-3 output (PI: S. Strahan), the NCEP/CPC analyses and NCEP/MRF forecasts and analyses (PI: L. Lait), the NCEP/AVN output (PI: A. Tuck), the Australian Bureau of Meteorology's Global Assimilation and Prediction (GASP) system's analyses and forecasts (PI: D. Waugh), and the ECMWF forecasts and analyses (PI: G. Braathen, PI: A. Dörnbrack). The Météo-France ARPEGE model was used for stratospheric as well as tropospheric forecasting. The UKMO UARS analyses were also used to support the analysis of SOLVE-THESEO 2000 observations. Free University of Berlin subjective analyses of radiosondes were provided for analysis purposes (PI: B. Naujokat).

A number of specialized products were utilized for forecasting and analysis. High density trajectory model runs based on analyzed and forecast winds were used to predict air masses that had broken off of the polar vortex, had encountered PSCs, had persistently been in polar darkness, or had encountered upper tropospheric clouds. Such trajectory runs based on forecast and analysis products were produced using the NCEP and DAO forecasts (PI: L. Lait), the DAO data in combination with NCEP MRF analyses in the upper troposphere and lower stratosphere for studying water vapor transport (PI: H. Selkirk), the GASP data (PI: D. Waugh), and the MIMOSA model at CNRS (PI: A. Hauchecorne).

The Match project [*Rex et al.,* 2001] provided real-time trajectory analyses during the campaign. The main goal was to track and to forecast the motions of air masses that have been probed by ozonesondes and to enable subsequent ozone measurements within these air masses in a Lagrangian sense. Close coincident measurements of ozonesondes with the ER-2 instruments were also coordinated based on the ER-2 flight plans and short trajectory forecasts of the motions of the air masses probed along the envisaged flight track. After each ER-2 flight the motions of air masses probed along the actual flight track were tracked and forecast by continuously updated trajectory calculations over ten days. The positions of the air masses probed during previous flights were made available for flight planning and for the coordination of Lagrangian ozonesonde measurements.

Mountain-forced gravity waves are extremely important for understanding the evolution and formation of PSCs, but also for forecasting turbulence that posed a hazard to the NASA ER-2. Forecasts of mountain wave vertical displacement amplitudes, temperature amplitudes, and turbulence were provided using the Naval Research Laboratory Mountain Wave Forecast Model (MWFM) interfaced to forecast winds and temperatures from the DAO GEOS-2 forecasts and the U.S. Navy's NOGAP model forecasts (PI: S. Eckerman). Flow fields and temperature perturbation for the whole of Scandinavia were provided based upon the regional MM5 model (PI: A. Drnbrack). The 3D University of Wisconsin Non-hydrostatic Modeling System (UW-NMS) was used to investigate transport processes at the mesoscale to synoptic scale in the upper troposphere/lower stratosphere near Scandinavia. The 3DVOM is a finite-difference numerical code designed for high-resolution simulations (PI: S. Vosper). Finally, the flow fields and temperature perturbation over northern Scandanavia were also calculated using the 15 km resolution German Weather Service NWP model.

2.4.2.2 Chemical and radiative modeling

While the meteorology provided the broad strategy for the campaign, chemical and radiative models provided supplemental information for designing flight paths. Three 3-dimensional (3-D) chemical transport models (CTMs) were employed during SOLVE-THESEO 2000. The GSFC CTM uses DAO GEOS-2 meteorology to provide a full suite of trace gas measurements, including source gases, reservoir species, and radical species in all of the major families (PI: R. Kawa). The UK UGAMP SLIMCAT model is an isentropic 3-D CTM that uses UKMO meteorology to provide a full suite of trace gases (PIs: M. Chipperfield, Univ. Leeds; and J. Pyle, Univ Cambridge). The REPROBUS model is a full 3-D CTM that uses the Météo-France ARPEGE analysis and forecast winds to produce a complete set of stratospheric species (PI: F. Lefevre).

In addition to the 3-D models, a chemical trajectory model was run for each of the ER-2 flights (PI: R. Kawa), and for parcels within the polar vortex (PI: K. Drdla) using the GSFC trajectory model. A photochemical steady state model was heavily utilized for forecasting the behavior of radical species under a variety of conditions (PI: R. Salawitch). A radiative model was extensively used to provide photolysis rate coefficients or jvalues for photochemical reactions of interest in the lower stratosphere and upper troposphere, calculated along the ER2 and DC8 flight tracks for each flight (PI: S. Lloyd).

2.4.2.2. Microphysical modeling: Determining the evolution and properties of PSCs was a principal goal of the SOLVE-THESEO 2000 campaign. While temperature forecasts were the principal tools for locating prospective regions of PSC formation, microphysical models were employed for real-time analysis of the observations in order to re-direct our strategies while we were in the field. The Integrated Microphysics and Aerosol Chemistry on Trajectories (IMPACT) model was used to simulate PSCs and their impact on stratospheric chemistry (PI: K. Drdla). The MM5 results from the DLR were used with the Mainz microphysical box model [*Meilinger et al.,* 1995; *Tsias et al.,* 1997; *Carslaw et al.,* 1998] for calculation of PSC temporal evolution along air parcel trajectories.

3. Results

As described in section 2.1, the SOLVE-THESEO 2000 campaign was partitioned into 3 phases: (1) the early December polar vortex set-up period, (2) the very cold late January period, and (3) the vortex recovery period. As will be shown, all 3 phases were adequately covered as had been hoped. Ground-based, satellite and ozonesonde measurements provided continuous coverage throughout the winter, and filled the observational gaps between the deployments.

The first phase of SOLVE-THESEO 2000 was timed to occur in early winter as temperatures cooled to the point where PSCs would form. Balloon flights and the NASA DC-8 flights were prioritized to understand the initial conditions of the polar vortex prior to the occurrence of significant PSCs, and to measure some of the first appearances of PSCs. Initial flights of the DC-8 and the OMS remote payload did not reveal elevated levels of

ClO, suggesting that the first goal was achieved [*Bremer et al.,* 2001]. In addition, a number of early PSCs were detected by the DC-8 in flights over the high Arctic during the course of the first two week deployment.

The second phase was timed to occur in mid-winter when temperatures were at their coldest. The aircraft and balloon flights were all conducted during this cold period. All of the flights inside the polar vortex encountered air that had been chemically perturbed by PSCs. In addition, vast regions of the polar vortex were still cold enough in this late January period to contain PSCs.

The final campaign phase was set for the first two weeks of March to investigate the recovery of the polar vortex. Surprisingly, at the start of this period the polar vortex was quite strong and temperatures were still cold enough to form PSCs. Again, both chemically perturbed air and PSCs were measured inside the polar vortex during this phase.

3.1. Meteorological Background

The early stratospheric winter of 1999/2000 has been described in *Manney and Sabutis* [2000]. In this paper they point out the unusually cold early winter lower stratosphere, and describe the vortex evolution in 1999/2000 as typical. The breakup of the 1999/2000 lower stratospheric vortex occurred on April 11, 2000, slightly later than the average breakup date of March 29 [*Waugh and Rong,* 2001].

3.1.1. Temperatures. The temperature of the polar vortex over the course of the 1999/2000 winter has been shown in Figure 1 of *Manney and Sabutis* [2000]. The vortex averaged temperature is shown in Plate 8 of this paper with all of the SOLVE-THESEO 2000 balloon flights. The first balloon flights and the DC-8 flights occurred as the vortex was cooling below 195 K during the first phase of the campaign. Lidar temperature observations inside the vortex, ozonesondes, and conventional radiosondes all provided direct evidence of this cold polar vortex in the mid-to-lower stratosphere of the Arctic during this early winter phase.

Plate 8 shows that the coldest temperatures occurred in the first two weeks of January, immediately prior to the second phase of the campaign. Again, direct observations provide an independent validation of these cold lower stratospheric temperatures. Extensive measurements of PSCs were obtained during this second phase.

During the final phase of SOLVE-THESEO 2000, the polar lower stratospheric temperatures increase above

195 K. Again, Plate 8 displays this increase during the first two weeks of March. During the final flights of the DC-8 from Kiruna, temperatures were observed to be too warm for the formation of PSCs.

3.1.2. Vortex and jet evolution. The lower stratospheric polar vortex developed slowly during the 1999–2000 winter [*Manney and Sabutis,* 2000], reached its greatest strength in mid-January, and broke apart in mid-April [*Waugh and Rong,* 2001]. This evolution is illustrated in Plate 9 which displays the average wind on the 600 K isentropic surface following lines of equivalent latitude (equivalent to a zonal mean in a vortex centered coordinate system). In the mid-stratosphere, the polar night jet-core speed was greater than 20 m s^{-1} by early-November, 30 m s^{-1} by early-December, and 50 m s^{-1} by late-December. The polar vortex is the region contained by this polar night jet. This jet had three periods of deceleration: late-January to early-February as the jet narrowed in latitudinal dimension (indicated by D on Plate 9), mid-March as the jet decelerated and the polar vortex shrank (F on Plate 9), and early-April as a greatly reduced vortex disappeared completely (H on Plate 9). The first SOLVE-THESEO 2000 deployment took place as the vortex was rapidly accelerating (B on Plate 9). The second deployment occurred as the vortex decelerated and narrowed (D on Plate 9), while the third deployment occurred as the vortex was rapidly shrinking (F on Plate 9). The thick black line on Plate 9 shows the equivalent latitude of Kiruna on this 600 K isentropic surface. Generally, Kiruna's equivalent latitude is poleward of the jet core, hence Kiruna was usually inside the polar vortex over the course of the 1999/2000 winter. Kiruna is outside the vortex during mid-February and late-March (aside from the spin-up and break-down periods of the vortex). At lower stratospheric altitudes (e.g., 450 K), the vortex is more variable, and Kiruna was found to be frequently outside of the vortex.

Plate 9

The behavior of the polar night jet in Plate 9 can be broadly explained by examining the wave energy propagating out of the troposphere and into the stratosphere over the course of the campaign. The large wave events act to decelerate the jet, and warm the polar vortex [*Newman et al.,* 2001]. The wave energy that drives the circulation of the stratosphere is proportional to the eddy heat flux for large-scale waves (superimposed on Plate 9 as the white line, scale on the right hand side of the plate). There are 4 important bursts of wave energy (large eddy heat flux) that affect the stratosphere during the 1999/2000 winter. The first burst (indicated by A on Plate 9) acts to both retard the jet development and the radiative cooling of the polar region. The jet builds and the polar region cools as this first event falls off. The second burst (bracketed by C and E on Plate 9) acts to narrow the broad flow and warm the polar vortex from the cold early January temperatures. The third burst (indicated by F) warms the vortex above temperatures necessary for the formation of polar stratospheric clouds and considerably reduces the jet speed and vortex size. The fourth burst in early-April (H on Plate 9) completely breaks-up the vortex.

The potential vorticity evolution in the lower stratosphere generally follows the evolution of the polar night jet. Plate 10 displays a series of potential vorticity maps on the 450 K isentropic surface over the course of the winter (modified potential vorticity is used herein, see *Lait* [1994]). The letters in the titles of each map correspond to the letters shown in Plate 9. Both the November 23 (A) and Devember 2 (B) panels display the weak vortex that characterized the early lower stratospheric winter. The mid-December to early-March (C, D, E, F) vortex is quite strong and large, while the polar vortex in late March and early April was quite small (G and H). There are three periods of weak eddy heat flux shown on Plate 9 (C, E, and G). These three periods correspond to relatively symmetric polar vortices that are shown in Plate 10. Plate 10

3.1.3. Total ozone. Total ozone in the Arctic was quite low during spring of 2000. Plate 2 displays the zonal mean total ozone obtained by the Earth Probe satellite's TOMS instrument. During the February–April period, a low of ozone is distinctly observed in the Arctic that is co-incident with the polar vortex. Plate 11 displays the total ozone average for March over the Arctic region [updated from *Newman et al.,* 1997]. Total ozone for March 2000 was much lower than normal. Plate 11

3.1.4. Transport and dynamics. The evolution of the vortex and polar temperatures has been broadly described herein and more precisely in *Manney and Sabutis* [2000] and the NOAA Climate Prediction Center's Northern Hemisphere winter summary for 1999/2000 (see http://www.cpc.ncep.noaa.gov/products/stratosphere/winter_bulletins/nh_99-00/index.html). *Newman et al.* [2001] quantitatively and theoretically show that the cold stratosphere during the SOLVE-THESEO 2000 campaign was a result of weak tropospheric wave driving of the stratosphere. *Waugh and Rong* [2001] show the breakup date of the vortex as April 11, 2000.

This vortex breakup and the mixing of air into the mid-latitudes is modeled by *Piani et al.* [2001]. They show that above 420 K most of the air contained in the polar vortex is mixed and carried into low latitudes by the end of June, while air below 420 K was primarily contained in the polar region.

Godin et al. [2001] describe the appearance of polar air over the OHP site in Southern France. While the appearance of vortex air over OHP was relatively low compared to the previous 3 years, they estimate a 4% reduction of ozone in the 400–500 K layer as a result of low ozone filaments over OHP. *Hauchecorne et al.* [2001] used a high resolution isentropic model to estimate the transport of ozone to the mid-latitudes in filamentation events coming off of the polar vortex. They found that winters with strong and cold polar vortices are associated with relatively weak filamentation compared to active years when as much as 20% of the vortex is transported to mid-latitudes.

The polar vortex is chemically distinct from the mid-latitudes. Very large gradients of trace gas concentrations are observed in crossing the boundary of the polar vortex, forming chemical “fronts”. One of the principal gases used for diagnosing the behavior of the polar vortex is nitrous oxide (N_2O). *Hurst et al.* [2001] describe the development of a high-resolution, consistent, unified N_2O data set derived from the ER-2 in situ observations. Such a data set is critical for diagnosing the evolution of the vortex and understanding trace-tracer relationships. *Greenblatt et al.* [2001] use the N_2O observations to describe a technique for precisely defining the edge of the polar vortex.

While conventional meteorological observations and models describe the larger scale meteorology, mesoscale models are necessary to also describe the basic thermal structure of the stratosphere. In particular, such models are necessary to describe the smaller scale features that can lead to the formation of PSCs. *Dornbrack et al.* [2001] describe the model and observations of mountain wave forced PSCs that formed in late January in the Kiruna region.

3.1.5. Formation and composition of PSCs. Because the winter of 1999/2000 was cold, extensive PSCs were observed over the course of the SOLVE-THESEO 2000 campaign. Using POAM III measurements, *Bevilacqua et al.* [2001] give a description of the extent of the PSCs during the entire campaign and they contrast the 1999/2000 observations with previous years. In particular, PSCs were first observed by POAM in mid-November and were last observed on March 15, 2000.

In situ observations of PSCs were made by both aircraft and balloons during the campaign. *Fahey et al.*

[2001] describes the measurements of large nitric acid hydrate particles that were found over extensive portions of the polar vortex. These large nitric acid containing particles were found at temperatures above the frost point, and were large enough to considerably de-nitrify the stratosphere. *Voigt et al.* [2000] and *Schreiner et al.* [2001] report the first direct observations of the composition of PSCs by the Kiruna launched PSC gondola on January 25, 2001. This balloon observation showed that liquid ternary particles were seen near frost point, solid NAT near and slightly above NAT equilibrium, and a few large size NAT that were in thin cloud layers below the other cloud layers. *Luo et al.* [2001] discusses the fives types of PSCs observed by the NASA DC-8 Arotel instrument over the course of the SOLVE-THESEO 2000 campaign and derives some of the properties of these PSCs.

As a result of the sedimentation of these large nitric acid containing particles, extensive denitrification was observed in the polar vortex. *Popp et al.* [2001] report that the polar vortex has an average denitrification of 60%. While extensive denitrification was observed, only small dehydration was observed in the vortex. *Herman et al.* [2001] and *Schiller et al.* [2001] report episodes of dehydration of up to 0.5 ppmv. However, *Herman et al.* [2001] only report a 0.2–0.3 ppmv dehydration for the vortex as a whole.

New techniques for analyzing remotely sensed observations of PSCs have been developed from the SOLVE-THESEO 2000 campaign. The t-matrix technique utilized by *Luo et al.* [2001] derives microphysical properties of PSCs using the lidar observations, but assumes that the particles are spheroidal in shape. The finite difference time domain (FDTD) technique of *Reichardt et al.* [2001] derives microphysical properties of PSCs from lidar data assuming that the PSCs are irregular and hexagonal in shape. *Strawa et al.* [2001] derive a new technique for discriminating PSC type 1a and 1b using POAM III satellite observations.

PSC caused denitrification of the polar vortex by the large NAT particles is critical for future assessments of the stratosphere. A one-dimensional model of this denitrification has been developed by *Jensen et al.* [2001]. This study investigates the efficiency of denitrification under varying assumptions about temperature, number density, and NAD and NAT relative concentrations. *Carslaw et al.* [2001] simulates the history of the large NAT particles observed by *Fahey et al.* [2001] using isentropic trajectories based on ECMWF meteorological analyses.

3.1.6. Chemistry of the polar vortex. Chlorine and bromine are principally responsible for ozone loss in the polar vortex. The evolution of chlorine activation over the course of the winter was monitored by observations of OClO by the GOME satellite observations [*Wagner et al.,* 2001]. These observations showed strong activation starting around December 22, peaking in mid-February, with a steep decrease in mid-March and an ending around March 22. The 1999/2000 winter had the highest activation level of all of the winters observed by GOME since its launch in 1995. Observation of HCl and ClO by ASUR [*Bremer et al.,* 2001] showed relatively high levels of HCl in early December (first deployment), with low HCl and high ClO in January (second deployment), consistent with the activation on the extensive PSCs observed by POAM. In situ observations of ClO and Cl_2O_2 during the second deployment also showed a vortex that was fully activated [*Stimpfle et al.,* 2001]. Satellite observations by MLS showed good agreement with these results [*Danilin et al.,* 2001; *Santee et al.,* 2000]. Microwave ground measurements of ClO profiles at Ny Ålesund and Kiruna [*Klein et al.,* 2001; *Kopp et al.,* 2001] also show a highly activated vortex. These high levels of ClO persisted into the third SOLVE-THESEO 2000 deployment.

Heterogeneous reactions have been directly observed in numerous laboratory simulations, and these reactions are part of the basis for photochemical models of the stratosphere. *Hanisco et al.* [2001] reports measurements by the ER-2 inside a PSC that shows air being heterogeneously processed. Large perturbations of HO_x observations were found to be consistent with HOCl production via $ClONO_2+H_2O$ reaction.

Denitrification of the polar vortex makes NO_2 unavailable for reacting with ClO. Thus, denitrification allows ozone loss to persist, since NO_2 cannot deactivate the ClO catalytic loss process. *Gao et al.* [2001] show that the ozone loss rate is directly tied to the level of denitrification. They calculated ozone loss rates of 63 ppbv d^{-1} at 3–5 ppbv of NO_y and 43 ppbv d^{-1} for 7–9 ppbv of NO_y. *Davies et al.* [2001] use the SLIMCAT model to simulate both denitrification and its affect on ozone loss, showing that a 70% denitrification delays recovery by approximately 10 days.

3.1.7. Empirical and modeled calculations of chemical ozone loss. Ozone was a fundamental observation during SOLVE-THESEO 2000. As outlined in section 2.2, satellite, balloon, ground, and aircraft observations of ozone were carried out over the entire winter of 1999/2000. In particular, while the SAGE III satellite was not launched in time for the mission, this satellite instrument will have a similar orbit and measurements as the POAM III satellite instrument. *Lumpe et al.* [2001] compares ozone from POAM with

ER-2, MkIV, DOAS, Arotel, DIAL, and sondes. This comparison shows reasonably good agreement from the tropopause to the upper stratosphere, and provides confidence in the solar occultation measurements and our ability to monitor ozone with such a platform. *Randall et al.* [2001] uses these POAM observations to construct three dimensional ozone fields using a potential vorticity and potential temperature technique. *Danilin et al.* [2001] presents a another comparison technique that uses trajectories to show good agreement between instruments.

Precise ozone loss estimates are critical components to our understanding of stratospheric photochemistry. Theory and modeling have predicted large polar ozone losses under certain conditions in the Arctic. While a number of studies have been shown these losses in the last few years, the loss uncertainties have been large, and there were unresolved assumptions in those loss estimates. *Harris et al.* [2001b] discuss these loss estimates, and show generally good agreement amongst the Match technique, vortex sonde averages, MLS, HALOE, and REPROBUS (SAOZ, POAM) as long as the comparisons are precise. In particular, a number of papers in this issue and previous publications calculate ozone losses for the 1999/2000 winter. Table 5 lists loss estimates derived from the SOLVE-THESEO 2000 campaign. Table 5

Tremendous ozone loss occurred inside the Arctic polar vortex during the 1999/2000 winter. A number of studies have quantified the chemically driven ozone loss for air inside the vortex on March 12, 2000 at the 450 K isentropic level (see Table 5). The loss rates tend to cluster near 1.7 ppmv over this period with variations from 1.0 to 2.3 ppmv. Studies using data from instruments with coarse vertical resolution tend to have lower loss rates [e.g., *Bremer et al.,* 2001; *Klein et al.,* 2001; *Kopp et al.,* 2001]. The time period of estimate is also a source of differences between analyses. The MSX ozone losses [*Swartz et al.,* 2001] do not include the critical week in mid-March when losses were quite high, while the HALOE [*Müller et al.,* 2001] begins in December. The 2.3 ppmv loss derived from MLS data is the product of the 40 ppbv d^{-1} loss rate (derived from the first 2 weeks of February) and the 52-day period between January 20 and March 12 with the inclusion of a vertical descent correction of a 5 ppbv d^{-1} correction for vertical descent. Additional sources of differences include descent rate differences and averaging technique. When accounted for, the losses show reasonably good consistency and provide great confidence in our ability to quantify ozone loss inside the polar vortex. These large losses are similar to the ozone losses calculated by the SLIMCAT 3D CTM [*Sinnhuber et al.,* 2000].

4. Summary

The SOLVE-THESEO 2000 campaign was the largest and most comprehensive study of the polar lower stratosphere that has ever been conducted. The 1999/2000 winter was cold, and the deployment timing worked very near perfectly. The initial deployment occurred during this period of first appearance of temperatures cold enough for PSC formation. The second deployment occurred as cold temperatures covered extensive regions of the Arctic. The third period covered the disappearance of cold temperatures as the vortex began its break up.

The cold temperatures of the Arctic lower stratosphere during the 1999/2000 winter led to the formation of extensive layers of polar stratospheric clouds (PSC). While PSCs were observed during the December period, extensive PSCs were encountered during the second deployment by the various platforms of SOLVE-THESEO 2000. These extensive PSCs fully processed the air inside the vortex by mid-December. Temperatures tended to remain cold throughout the winter and into mid-March. Again, PSCs were observed by our platforms up to mid-March.

Activated chlorine levels were observed during the second and third deployments of SOLVE-THESEO 2000, but were not observed in the first deployment. The extensive measurements of chlorine species by a variety of instruments provides the most extensive and precise determination of the evolution of chlorine over the course of a single winter.

Because of the high amounts of ClO_x in the Arctic, and because of the persistence of PSCs into March, there were large chemical ozone losses in the lower stratosphere. Satellite, ozonesonde, in situ aircraft and balloon, and ground observations reveal that losses exceeded 60% in a layer of the lower stratosphere (460 K).

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P. A. Newman, Mail Code 916, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA. (newman@code916.gsfc.nasa.gov).

N. R. P. Harris,

Received ______________________

Plate 1. SOLVE-THESEO 2000 operations region. Kiruna, Sweden is noted at the center of the image with the green star. The magenta line indicates a distance of 2700 km from Kiruna. The blue dots indicate ground observation sites, while the red dots indicate ozonesonde sites. Also superimposed are 50 hPa January average temperature contours (1979–1999). On average, the coldest region of the lower stratosphere is centered on Spitzbergen.

Plate 2. Zonal mean total ozone from the TOMS instrument. The latitude of Kiruna is superimposed as the red line, the occultation latitude of the POAM observations is superimposed as the magenta line, and the sunrise (sunset) occultations of the HALOE instrument are superimposed as the blue crosses (stars).

Plate 3. NASA ER-2 with payload layout in front of the Arena Arctic in Kiruna, Sweden.

Plate 4. NASA DC-8 taking off from Kiruna with it's payload layout.

Plate 5. DLR Falcon with OLEX lidar.

Plate 6. PSC analysis balloon gondola with attached instruments.

Plate 7. Ozone mixing ratios (ppmv) from ozonesonde measurements at Ny-Ålesund. The broken lower white line indicates the tropopause, the middle white line shows the 380 K isentropic level, and the upper white line represents the 480 K isentropic level. The vertical lines represent the altitude coverage of the DC-8 (white), ER-2 (black), Falcon (orange), ARAT (red), Mystère (green), and Lear Jet (cyan) for their respective flight dates.

Plate 8. Average vortex temperature as a function of potential temperature. Height scale on the right axis is an estimate based upon a 6.5 km scale height. The average is computed over an equivalent latitude range from 75°–90°N using the UKMO data at each theta level from 350 to 900 K. The white vertical lines indicate balloon launches and symbols at the top indicating the balloon launch (see Table 4 and the payload section for details).

Plate 9. Mean wind parallel to lines of equivalent latitude on the 600 K isentropic surface (equivalent to a zonal mean in a vortex-centered coordinate system).

Plate 10. Potential vorticity on the 450 isentropic surface.

Plate 11. Total ozone averaged between 63°–90°N during the month of March for the northern hemisphere. Updated from *Newman et al.* [1997].

Table 1. Ground Instruments During the SOLVE-THESEO 2000 Campaign.

Site	(°N) Latitude	(°E) Longitude	Instrument	Profile	Column
Observatoire Haute Provence, France	43.94	5.71	lidar, SAOZ, Dobson, ozonesonde, DOAS	O_3, aerosol	O_3, NO_2, BrO
Plateau de Bure, France	44.63	5.90	microwave	ClO, O_3	. . .
Observatoire de Bordeaux, France	44.83	-0.52	SAOZ, Dobson, microwave, DOAS	O_3	O_3, NO_2, BrO
Jungfraujoch, Switzerland	46.50	8.00	SAOZ, EMCOR, FTIR	ClO	O_3, NO_2, CO, CH_4, HNO_3, N_2O, $ClONO_2$, HCl, HF
Bern, Switzerland	46.95	7.45	GROMOS	O_3	. . .
Zugspitze, Germany	47.42	10.98	FTIR	. . .	O_3, NO_2, CO, CH_4, HNO_3, N_2O, $ClONO_2$, HCl, HF
Garmisch, Germany	47.48	11.06	lidar	aerosol	. . .

Table 1. (continued)

Site	(°N) Latitude	(°E) Longitude	Instrument	Profile	Column
Cambridge, United Kingdom	52.00	0.00	DOAS	. . .	BrO
Bremen, Germany	53.00	9.00	DOAS	. . .	O_3, NO_2, BrO
Harestua, Norway	60.20	10.80	DOAS, FTIR, Dobson	O_3	O_3, NO_2, COF_2, $ClONO_2$, N_2O, OClO, BrO, HNO_3, ClO, HCl, HF
Salekhard, Russia	66.70	66.70	SAOZ	. . .	O_3, NO_2
Zhigansk, Russia	67.20	123.40	SAOZ	. . .	O_3, NO_2
Sodankyla, Finland	67.37	26.65	backscatter sonde, ozonesonde, SAOZ, Brewer	O_3, aerosol	O_3, NO_2
Kiruna, Sweden	67.84	20.41	DOAS, FTIR, MW, lidar	O_3, N_2O, CH_4,	O_3, N_2O, CH_4, HNO_3, NO,

Table 1. (continued)

Site	(°N) Latitude	(°E) Longitude	Instrument	Profile	Column
				HNO_3, NO, HCl, HF, ClO, aerosol	NO_2, $ClONO_2$, HCl, ClO, COF_2, HF, OClO, BrO
Andoya, Norway	69.30	16.00	lidar, ozonesonde, DOAS	O_3, aerosol	O_3, NO_2, OClO, BrO
Scoresbysund Greenland	70.48	-21.97	SAOZ	. . .	O_3, NO_2
Thule, Greenland	76.53	-68.74	ozonesonde, DOAS, SAOZ, backscatter sonde	O_3, aerosol	O_3, NO_2, OClO
Ny Ålesund, Spitsbergen	78.92	11.93	FTIR, SAOZ, lidar, DOAS, microwave, ozonesonde, backscatter sonde	O_3, aerosol, ClO	O_3, NO_2, OClO, BrO, CO, CH_4, HNO_3, N_2O, ClO, HCl, HF

Table 2. ER-2 Payload.

Instrument	Investigator	Institution	Measurements
ACATS	J. W. Elkins	NOAA/CMDL	CFC-11, CFC-12, CFC-113, CH_3CCl_3, CCl_4, halon-1211, $CHCl_3$, CH_4, H_2, N_2O, SF_6
ALIAS	C. Webster	JPL	HCl, CO, CH_4, N_2O
Argus	H. Jost	NASA/ARC	N_2O, CH_4
CIMS	P. Wennberg, F. Eisele	Cal. Tech., NCAR	HNO_3
$ClONO_2$	R. Stimpfle	Harvard U.	ClO, $ClONO_2$, Cl_2O_2, BrO
	S. Wofsy	Harvard U.	CO_2
CPFM	C. T. McElroy	AES-Canada	UV-visible spectra, column O_3, J values, albedo
FCAS, N-MASS Impactor	J. Wilson	U. Denver	.07–1 μm particles, 4–60 nm particles, particle composition, and structure
H_2O	E. Weinstock, R. Spackman	Harvard U.	H_2O

Table 2. (continued)

Instrument	Investigator	Institution	Measurements
HO_x	T. Hanisco, J. Smith	Harvard U.	OH, HO_2
JLH	R. Herman	JPL	H_2O
MASP	D. Baumgardner, B. Gandrud	NCAR	0.4 to 20 μm particles
MMS	T. P. Bui	NASA/ARC	T, P, U, V, W, position
MTP	M. Mahoney	JPL	temperature profiles
NO_2	K. Perkins, E. Lanzendorf	Harvard U.	NO_2
NO_y	D. Fahey, R. Gao	NOAA/AL	NO, NO_y
O_3	E. Richards	NOAA/AL	O_3
WAS	E. Atlas, S. Schauffler	NCAR	CFCs, hydrocarbons, halons, HCFCs, etc.

Table 3. DC-8 Payload.

Instrument	Investigator	Institution	Measurements
LASE	E. Browell	NASA/LARC	H_2O, aerosol backscatter profile
UV DIAL	E. Browell	NASA/LARC	O_3, aerosol profile
SAFS	R. Shetter	NCAR	actinic flux 280-535 nm, J values
ASUR	K. Kunzi	U. Bremen	profiles of ClO, HCl, N_2O, O_3, HNO_3, CH_3Cl, H_2O, HO_2, BrO
CIMS	A. Viggiano	AF Research Lab	SO_2, HCN, HNO_3
PMS	B. Anderson	NASA/LARC	0.1–3 μm particles, CN concentrations
O_3	M. Avery	NASA/LARC	O_3
Dew Point	J. Barrick	NASA/LARC	dew point
FTIR	W. Mankin	NCAR	columns of N2, H_2O, CO_2, CF_2Cl_2, HCN, N_2O, HCl, HDO, OCS, O_2, CO, $CFCl_3$, NO, HF, O_3, CH_4, NO_2, C_2H_6, HNO_3, $ClONO_2$
NO_y	Y. Kondo	U. Tokyo	NO, NO_y

Table 3. (continued)

Instrument	Investigator	Institution	Measurements
AEROTEL	T. McGee, J. Burris, C. Hostetler	NASA/GSFC, NASA/LARC	O_3, temperature, aerosol profile, aerosol scattering profile, backscatter, polarization
Solar Cam	C. Hostetler	NASA/LARC	solar images
DACOM	G. Sachse	NASA/LARC	CO, CH_4, N_2O
DLH	G. Sachse,	LARC/Ames	H_2O
	J. Podolske	LARC/Ames	H_2O
JLH	R. Herman	JPL	H_2O
ATHOS	B. Brune	Penn State	OH, HO_2
ClO, BrO	D. Toohey	U. Colorado	ClO, BrO
TOTCAP	L. Avallone	U. Colorado	O_3, total H_2O, CO_2, F11, F12, F113, halon-1211, CCl_4

Table 3. (continued)

Instrument	Investigator	Institution	Measurements
FCAS II, NMASS	J. Reeves	U. Denver	0.08–2 μm particles, 4–100 nm particles
MTP	M. Mahoney	JPL	temperature profiles

Table 4. Flight Log

Date	Platform	Flight Time	Minimum Latitiude	Maximum Latitude	Site	Comment	Maximum Altitude	Data In Base?
				Deployment 1				
1999-11-09	Descartes	...	...	...	Esrange	...	...	no
1999-11-17	SAOZ, Descartes	...	...	...	Andoya	...	27.0 km 14.1 hPa 682.4 K	yes
1999-11-19	OMS in situ	...	...	...	Esrange	...	...	...
1999-11-30	DC-8	9.90	34.87	78.07	Kiruna	transit	...	...
1999-12-02	DC-8	8.36	63.04	79.59	Kiruna	vortex survey	...	...
1999-12-03	Descartes, OMS-remote	...	...	...	Esrange	...	23.71 km 23 hPa	Descartes: yes
1999-12-05	DC-8	8.75	61.94	80.70	Kiruna	PSC survey	...	...
1999-12-07	DC-8	9.73	67.81	85.67	Kiruna	PSC survey	...	...

Table 4. (continued)

Date	Platform	Flight Time	Minimum Latitiude	Maximum Latitude	Site	Comment	Maximum Altitude	Data In Base?
1999-12-10	DC-8	8.53	67.51	82.83	Kiruna	Vortex survey	. . .	. . .
1999-12-12	DC-8	9.66	67.67	81.27	Kiruna	PSC survey	. . .	. . .
1999-12-14	DC-8	8.33	59.62	69.02	Kiruna	Vortex survey	. . .	. . .
1999-12-15	Descartes	. . .	. . .	. . .	Esrange	. . .	25.86 km	yes
1999-12-16	DC-8	10.48	34.91	78.18	Kiruna	transit	. . .	. . .
				Deployment 2				
2000-01-14	DC-8	10.00	34.88	78.18	Kiruna	transit	. . .	. . .
2000-01-14	ER-2	7.30	42.20	71.72	Kiruna	transit	. . .	. . .
2000-01-16	DC-8	10.04	60.15	82.00	Kiruna	PSC survey	. . .	. . .

Table 4. (continued)

Date	Platform	Flight Time	Minimum Latitiude	Maximum Latitude	Site	Comment	Maximum Altitude	Data In Base?
2000-01-19	HALOZ1, Dirac	?	?	?	Esrange	. . .	42 hPa 482 K	HALOZ1:No Dirac:yes
2000-01-19	PSC-Analysis	13768s	. . .	. . .	Esrange	. . .	17.01 hPa	yes
2000-01-19	ARAT	. . .	. . .	. . .	Kiruna	transit	. . .	. . .
2000-01-20	DC-8	9.77	62.20	89.35	Kiruna	PSC survey	. . .	. . .
2000-01-20	ER-2	8.04	65.26	89.11	Kiruna	PSC survey	. . .	. . .
2000-01-23	DC-8	10.32	58.57	73.77	Kiruna	vortex sunrise	. . .	. . .
2000-01-23	ER-2	5.65	58.727	3.86	Kiruna	vortex sunrise	. . .	. . .
2000-01-23	Salomon	?	66 (mean)	. . .	Esrange	. . .	18.2 km 59h Pa	yes

Table 4. (continued)

Date	Platform	Flight Time	Minimum Latitiude	Maximum Latitude	Site	Comment	Maximum Altitude	Data In Base?
2000-01-24	Falcon	...	...	...	Kiruna	transit	...	...
2000-01-25	DC-8	10.36	59.37	75.89	Kiruna	mountain waves	...	...
2000-01-25	Falcon	...	...	...	Kiruna	...	...	...
2000-01-25	micro-Radibal	...	...	...	Esrange	...	21.0 km 38h Pa	yes
2000-01-25	PSC-Analysis	13044s	...	...	Esrange	PSC flight	23.93 hPa	yes
2000-01-25	ARAT	...	...	...	Kiruna	PSC analysis	...	...
2000-01-26	ARAT	...	...	...	Kiruna	PSC analysis	...	...
2000-01-26	Falcon	...	...	...	Kiruna	...	...	...
2000-01-27	TRIPLE	16586s	...	...	Esrange	...	25.69 km	yes

Table 4. (continued)

Date	Platform	Flight Time	Minimum Latitiude	Maximum Latitude	Site	Comment	Maximum Altitude	Data In Base?
							18.94 hPa 618 K	
2000-01-27	HALOZ2 Dirac	. . .	. . .	. . .	Esrange	. . .	35 hPa 499 K	HALOZ2:no Dirac:yes
2000-01-27	Falcon	. . .	. . .	. . .	Kiruna	. . .	. . .	. . .
2000-01-27	ARAT	. . .	. . .	. . .	Kiruna	transit	. . .	. . .
2000-01-27	DC-8	9.71	51.48	68.00	Kiruna	edge survey	. . .	. . .
2000-01-27	ER-2	6.10	51.52	67.92	Kiruna	edge survey	. . .	. . .
2000-01-28	SAOZ, SAOZ-BrO, Descartes, CH_4/O_3sensor	. . .	. . .	. . .	Esrange	27 km 12.7 hPa 754 K	yes	

Table 4. (continued)

Date	Platform	Flight Time	Minimum Latitiude	Maximum Latitude	Site	Comment	Maximum Altitude	Data In Base?
2000-01-29	DC-8	10.78	34.91	78.18	Kiruna	transit	...	...
2000-01-31	ER-2	3.90	67.81	79.05	Kiruna	vortex survey	...	...
2000-01-31	Falcon	...	...	...	Kiruna	...	...	...
2000-02-02	ER-2	7.57	64.19	77.86	Kiruna	vortex survey	...	...
2000-02-02	Falcon	...	...	...	Kiruna	...	...	...
2000-02-03	ER-2	3.21	67.83	73.16	Kiruna	multiple level	...	...
2000-02-03	Falcon	...	...	...	Kiruna	...	...	...
2000-02-04	Falcon	...	...	...	Kiruna	transit	...	...
2000-02-09	SAOZ, SAOZ-BrO, Descartes,	...	...	...	Esrange	...	25 km 21.4 hPa	yes

Table 4. (continued)

Date	Platform	Flight Time	Minimum Latitiude	Maximum Latitude	Site	Comment	Maximum Altitude	Data In Base?
	CH_4/O_3sensor						632 K	
2000-02-13	SAOZ, SAOZ-BrO,	. . .	. . .	. . .	Esrange	. . .	26 km	yes
	Descartes						17.9 hPa	
	CH_4/O_3sensor						729 K	
				Deployment 3				
2000-02-18	LPMA/DOAS	. . .	. . .	. . .	Esrange	. . .	29.5 km	yes
2000-02-18	Mir1e	. . .	. . .	. . .	Esrange	. . .	. . .	some
2000-02-18	Mir2e	. . .	. . .	. . .	Esrange	. . .	. . .	some
2000-02-22	Salomon2e	. . .	. . .	. . .	Esrange	. . .	29 km	yes
							11.4 hPa	
2000-02-26	ER-2	7.46	62.93	84.80	Kiruna	vortex survey	. . .	. . .

Table 4. (continued)

Date	Platform	Flight Time	Minimum Latitiude	Maximum Latitude	Site	Comment	Maximum Altitude	Data In Base?
2000-02-27	Support Mir2	...	...	...	Esrange	...	...	...
2000-02-27	DC-8	10.25	34.88	78.18	Kiruna	transit	...	...
2000-02-28	Mystère	...	...	...	Paris	...	...	...
2000-02-29	techno.Mir3	...	...	...	Esrange	...	...	...
2000-03-01	TRIPLE	...	...	...	Esrange	...	21.7 hPa	...
2000-03-01	Descartes HALOZ3	...	...	...	Esrange	...	18.1 km 57h Pa	Descartes:yes, HALOZ:no
2000-03-03	DC-8	9.99	60.69	86.53	Kiruna	vortex edge	...	...
2000-03-05	DC-8	9.55	63.82	79.37	Kiruna	vortex survey	...	...
2000-03-05	ER-2	7.85	66.68	81.04	Kiruna	vortex survey	...	...

Table 4. (continued)

Date	Platform	Flight Time	Minimum Latitiude	Maximum Latitude	Site	Comment	Maximum Altitude	Data In Base?
2000-03-05	OMS in situ, Dirac, Descartes	...	...	...	Esrange	...	...	...
2000-03-07	O_3 Sensor Labs, SAOZ, Descartes	...	...	...	Esrange	...	27 km 9.7 hPa 820 K	yes
2000-03-07	Mystère	...	...	...	Paris	...	...	...
2000-03-07	ER-2	7.90	67.83	82.96	Kiruna	vortex survey	...	...
2000-03-08	DC-8	10.67	63.10	80.25	Kiruna	PSC survey	...	...
2000-03-08	HALOZ4, Dirac	...	...	...	Esrange	...	46 hPa 475 K	HALOZ4:no Dirac:yes

Table 4. (continued)

Date	Platform	Flight Time	Minimum Latitiude	Maximum Latitude	Site	Comment	Maximum Altitude	Data In Base?
2000-03-08	Learjet	...	...	...	Kiruna	Transit	...	...
2000-03-09	DC-8	9.92	57.40	80.14	Kiruna	...	...	...
2000-03-09	Learjet	...	...	...	Kiruna	Iceland flight	...	...
2000-03-10	Learjet	...	...	...	Kiruna	North Pole	...	...
2000-03-11	Learjet	...	...	...	Kiruna	Arctic Sea	...	...
2000-03-11	DC-8	8.78	67.58	80.09	Kiruna	vortex edge	...	...
2000-03-11	ER-2	7.97	58.60	75.08	Kiruna	vortex edge	...	...
2000-03-12	ER-2	7.44	65.27	79.46	Kiruna	vortex survey	...	...
2000-03-13	Learjet	...	...	...	Kiruna	Transit	...	...

Table 4. (continued)

Date	Platform	Flight Time	Minimum Latitiude	Maximum Latitude	Site	Comment	Maximum Altitude	Data In Base?
2000-03-15	DC-8	8.77	46.95	86.33	Kiruna	transit	...	...
2000-03-15	OMS remote	...	...	...	Esrange	...	...	...
2000-03-16	ER-2	9.02	42.21	67.81	Kiruna	transit	...	...
2000-03-25	SAOZ, Dirac, CH_4	...	...	...	Esrange	...	28 km K 12.3 hPa 837 K	SAOZ:yes Dirac:no, CH_4:yes
2000-03-26	Mystère	...	...	...	Paris	...	...	...
2000-03-28	Mystère	...	...	...	Paris	...	...	...
2000-04-03	SAOZ, Descartes	...	...	...	Andoya	...	26 km 11.9 hPa 822 K	yes

Table 4. (continued)

Date	Platform	Flight Time	Minimum Latitiude	Maximum Latitude	Site	Comment	Maximum Altitude	Data In Base?
2000-04-04	Descartes HALOZ5	...	...	...	Esrange	...	15.32 km 103 hPa 407 K	Descartes:yes, HALOZ5:no

Table 5. Polar Vortex Ozone Loss at 450 K on March 12 (estimated between January 20 and March 12, 2000)

Reference	(ppmv) O_3 Loss	(ppmv) Uncertainty	Data Set
Bremer et al. [2001]	1.05	±0.1	ASUR
Grant et al. [2001]	1.5	±0.3	LARC DIAL
Hoppel et al. [2001]	1.45	±0.2	POAM III solar occultation
Klein et al. [2001]	0.7[b]	±0.3	Ny Ålesund μm radiometer
Kopp et al. [2001]	1.1	±0.2	Kiruna FTIR O_3, N_2O, HF
	1.4	±0.6	μm O_3, FTIR N_2O, HF
	1.4	±0.2	KASIMA model
Lait et al. [2001]	1.7	±0.3	PV-θ analysis, ozonesondes
Müller et al. [2001]	2.2[e]	±0.3	HALOE, OMS
Rex et al. [2001]	1.7	±0.2	Match, ozonesondes
Richard et al. [2001]	1.8	±0.3	ER-2 tracer-tracer

Table 5. (continued)

Reference	(ppmv) O_3 Loss	(ppmv) Uncertainty	Data Set
Robinson et al. [2001]	1.35	±0.12	Dirac tracer-tracer
	1.10	±0.1	Descarte tracer-tracer
Salawitch et al. [2001]	1.36[d]	±0.21	OMS measurements
	1.76	±0.21	OMS balloon and ER-2 data
Santee et al. [2000]	2.3[c]	±0.6	UARS MLS
Schoeberl et al. [2001]	1.63	±0.3	vortex average ozonesondes
	1.3	±0.1	POAM III
	1.54	±0.15	forward trajectory
Sinnhuber et al. [2000]	1.7	±0.2	Ny Ålesund sonde, SLIMCAT model
Swartz et al. [2001]	1.0[a]	±0.08	MSX stellar occultation

All losses are corrected for descent unless otherwise noted.

[a]Estimate based upon ozone change between January 23 and March 4.

[b]Microwave radiometer has a 10 km vertical resolution.

[c]Loss rate (0.04 ppmv day^{-1}) estimated at 465 K between February 2 and 13, 2000, scaled for 52 days, with a 0.25 ppmv correction

for downward advection.

[d]Estimated for January 20 to March 5, 2000.

[e]Estimated between November 1999 and March 11–14, 2001.