Studies of the Antarctic Stratosphere During IPY

A. R. Klekociuk, Australian Antarctic Division, Australia (andrew.klekociuk@aad.gov.au)
M. C. Pitts, NASA Langley Research Center, USA (michael.c.pitts@nasa.gov)
S. P. Alexander, Australian Antarctic Division, Australia (simon.alexander@aad.gov.au)
C. David, L'Institut Pierre-Simon Laplace, France (christine.david@aero.jussieu.fr)
M. Snels, Institute of Atmospheric Sciences and Climate, Italy (m.snels@isac.cnr.it)
P. von der Gathen, Alfred Wegener Institute for Polar and Marine Research, Germany (peter.von.der.gathen@awi.de)

Introduction

The Antarctic stratosphere of today is distinctly different to that which existed when pioneering studies of stratospheric ozone and dynamics were undertaken during the International Geophysical Year (IGY; 1957-1958). Over the past 5 decades, temperatures in the lower and middle stratosphere have significantly cooled at southern polar latitudes (Randel et al., 2009), and since the early 1980s, the annual Antarctic ozone hole has been a dominant feature (WMO, 2007). Preparations for the IGY led to the expansion of the global radiosonde network and coordination and standardisation of ozone measurements. Both of these aspects produced lasting outcomes for atmospheric science by providing many of the initial baseline polar measurements against which modern records are compared. Through evaluation and attribution of the stratospheric change that has occurred since the IGY, with many led by SPARC initiatives, we now recognise the stratosphere as a key component of the Earth System, with important coupled responses to the climate at the Earth’s surface. This awareness, together with new capabilities for remote sensing and coupled chemistry-climate modelling, has been harnessed by projects within the second International Polar Year (IPY; 2007-2008) to advance stratospheric science.

In this article we provide a synopsis of IPY activities that are primarily related to the Antarctic stratosphere, and summarise the main features of the winter polar vortex and ozone holes of the IPY years.

Antarctic Stratospheric Projects and Measurements during IPY

The main foci for IPY stratospheric investigations are key topics currently being addressed by leading international collaborative research programs, in particular the World Climate Research Programme (WCRP), SPARC, the International Global Atmospheric Chemistry Project (IGAC), the Intergovernmental Panel on Climate Change (IPCC), and the Network for the Detection of Atmospheric Composition Change (NDACC). The important benefits created by IPY for stratospheric science have included the development of new links between individual national projects and larger international efforts, the promotion of interdisciplinary studies for the investigation of interrelations between the atmosphere and other components of the Earth system, and the application of bipolar studies to investigate the similarities and differences between the Antarctic and Arctic.

Participants in IPY have drawn on timely new capabilities that have been established during the last decade. These include satellites that are addressing global change issues (including the ACE, Aura, CALIPSO, CloudSat, COSMIC, Envisat, ODIN and TIMED missions), as well as new capabilities in Antarctic facilities and logistics, such as the establishment of the Concordia plateau station, real-time data streaming from Antarctica, and improved access to research stations. This work has also been assisted by well-established measurement programs, such as those operated by the Global Atmosphere Watch (GAW) of the World Meteorological Organisation (WMO) and NDACC.

Table 1 lists IPY endorsed projects with a significant stratospheric component. These are ‘umbrella’ activities that represent the synthesis of various projects that were collated from expressions of interest during the formulation of the IPY plan. Of these activities, ORACLE-O3 is specifically focused on the polar stratosphere. This activity draws on a variety of established measurement capabilities, which are summarised in Table 2. It also involves new approaches in synthesising observations and models, such as in the LOLITA-PSC, discussed in Section 4.

Broadly, the significant topics addressed for the Antarctic stratosphere during IPY are:

1. The detection and attribution of stratospheric change.

There is clear evidence of a reduction of ozone depleting substances (ODS) in the troposphere following international regulation on the production of these chemicals (WMO, 2007). During the IPY years, it is expected that stronger evidence will emerge as to the effect of ODS mitigation on the recovery of Antarctic stratospheric ozone. Attribution of any improvement in ozone levels requires quantification of a variety of factors, which include evaluation of stratospheric temperatures and dynamical variability, trace gas transport, changes in chemical cycles (influenced, for example, by water vapour and methane), and effects from the solar activity cycle and aerosols of tropospheric origin (e.g. from volcanoes and biomass burning). Through SPARC and SPARC-related initiatives, the international community is focusing on improving long-term projections of stratospheric ozone levels through the detailed study of ozone-related processes. This includes developing a greater understanding of stratospheric changes being brought about by increases in well-mixed greenhouse gases, and the coupling between these changes and long-term ozone recovery. These aspects have been assisted by coordinated physical measurements throughout the full depth of the Antarctic atmosphere during IPY, as well as by specific ozone studies such as those under the ORACLE-O3 activity.

2. Stratosphere-troposphere dynamical coupling.

Coupling between the stratosphere and troposphere influences atmospheric variability in the extratropics on time scales ranging...
from days to at least decades. Major modes of variability that influence the Antarctic atmosphere and other components of the Earth system include the Southern Annular Mode (SAM), the El-Nino Southern Oscillation (ENSO) and the Quasi-Biennial Oscillation (QBO). An area of current interest is gaining a deeper understanding of variability in SAM, which has components associated with wave-driven dynamics and radiative coupling from the Antarctic ozone hole, and tropospheric climate trends near Antarctica. IPY activities have provided additional data for examining variability in the extratropical atmosphere from atmospheric and meteorological measurement programs, and also from new measurements of the Southern Ocean (for example, under the Climate Variability and Predictability (CLIVAR) program of WCRP).

3. Science of the extratropical upper troposphere – lower stratosphere (UTLS). The extratropical UTLS is a highly coupled region that is influenced by interactions between radiation, dynamics, chemistry and microphysics. Ozone and water vapour are the most significant greenhouse gases in the UTLS, and are controlled by stratosphere-troposphere exchange, and by chemical processes associated with multiphase chemistry and cloud microphysics. During the IPY period, new high resolution vertical profile measurements for the UTLS became available; from the CALIPSO and CloudSat missions of cloud and aerosol properties from lidar and radar profiling, and from the COSMIC satellite constellation of temperature profiles from the GPS radio occultation technique. These specific capabilities are being applied to an IPY investigation of coupling in the Antarctic UTLS under the AC^2 and ORACLE-O3 activities. In situ measurements relevant to the UTLS were also advanced through use of the High-performance Instrumented Airborne Platform for Environmental Research (HIAPER) aircraft during early 2009 to obtain unique measurements in the upper troposphere from the Arctic to the Antarctic.

4. Atmospheric chemistry and climate. IPY has provided an opportunity to improve coordination and archiving of measurements that are important for climate model validation. This aspect is a focus of the SPARC-IPY activity, and is of benefit to the Chemistry-Climate Model Validation (CCMVal) initiative of SPARC. During IPY, additional support was provided by several nations for upper air measurements using radiosondes and ozonesondes. These measurements together with the improved polar coverage of high resolution vertical profiles from the GPS radio occultation technique (such as those provided by COSMIC) will be of assistance to current efforts in parameterising small scale processes (such as gravity waves) for climate models, such as those associated with CCMVal.

Table 1 – Antarctic stratospheric projects during IPY – This list was compiled from full proposals details at the IPY information portal http://classic.ipy.org/development/eoi/; Acronyms: PSC – Polar Stratospheric Cloud, CCM – Coupled Chemistry-climate Model, CTM – Chemistry and Transport Model
Table 2 – Antarctic and sub-Antarctic ground-based and in situ stratospheric measurements during IPY.

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<tr>
<th>Name</th>
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Notes: This table does not include UV instruments for surface radiation measurements or sun photometers for aerosol measurements. 1: Name denotes the country contribution to the Antarctic Treaty System. 2: MF radars measure winds from the upper stratosphere to mesosphere – lower thermosphere (MLT) region. MST radars measure winds from troposphere to lower stratosphere and upper mesosphere to MLT region. The two MST radars operated during the 2007/08 austral summer.

Data from: Table 2 – Antarctic and sub-Antarctic ground-based and in situ stratospheric measurements during IPY.
In the following sections we provide background information on Antarctic stratospheric conditions during IPY, and outline two sub-projects of ORACLE-O3.

**Characteristics of the Antarctic Stratosphere During IPY**

The IPY nominally ran from 1 March 2007 to 28 February 2009, however a number of projects collected measurements during 2006 and have also continued beyond February 2009 (particularly to capture complete information on the Arctic winter). Here we restrict our description of Antarctic stratospheric conditions primarily to the austral winters of 2007 and 2008, but also examine 2006 when some metrics of the Antarctic ozone hole achieved record levels.

Detailed summaries of Antarctic atmospheric conditions can be found in WMO Antarctic Ozone Bulletins (http://www.wmo.int/pages/prog/arep/gaw/ozone/index.html) and Winter Bulletins of the National Oceanic and Atmospheric Administration (http://www.cpc.ncep.noaa.gov/products/stratosphere/winter_bullets/). Additional information can be obtained from the annual summaries of the National Climate Data Center (http://www.ncdc.noaa.gov/oa/climate/research/monitoring.html) and annual instalments of the State of the Climate Report (http://lwf.ncdc.noaa.gov/oa/climate/research/state-of-climate/).

**The Polar Vortex**

A summary of zonal mean Antarctic temperatures for 2007 and 2008 based on measurements by the Microwave Limb Sounder (MLS) onboard the Aura satellite is shown in Figure 1 (colour plate IV). The stratosphere below 30 km altitude during the austral winter and early spring of 2008 was generally cooler than in 2007, and this can be seen qualitatively by examining the area bounded by the 200 K contour in both years. The average of the temperatures in Figure 1 between 12 km and 30 km from 1 June to 1 September was $0.8 \pm 0.1$ K lower in 2008 than in 2007. Overall, winter temperatures in the two years were cooler than the climatological average but generally well within the observed range since 1979.

During 2008, the Antarctic polar vortex was stronger, larger and more symmetric than in 2007, although not of record characteristics. Figure 2 shows the potential vorticity gradient in the lower stratosphere as a function of time and equivalent latitude for the 450 K potential temperature isentrope (near 70 hPa pressure, or 18 km altitude), derived from the United Kingdom Meteorological Office (UKMO) stratospheric assimilation. Equivalent latitude is derived using the method of Nash et al. (1996). The black contour denotes the equivalent latitude of Davis station (68.6°S, 78.0°E geographic). Additional blue contours show the location of the ‘inner’, ‘central’, and ‘outer’ limits of the vortex edge as defined by Nash et al. (1996).

![Figure 2: Potential vorticity gradient (expressed in potential vorticity units (PVU; 1 PVU = 10 ** K m ** kg ** s ** ) per degree of equivalent latitude) as a function of time and equivalent latitude for the 450 K potential temperature isentrope (near 70 hPa pressure, or 18 km altitude), derived from the United Kingdom Meteorological Office (UKMO) stratospheric assimilation. Equivalent latitude is derived using the method of Nash et al. (1996). The black contour denotes the equivalent latitude of Davis station (68.6°S, 78.0°E geographic). Additional blue contours show the location of the ‘inner’, ‘central’, and ‘outer’ limits of the vortex edge as defined by Nash et al. (1996).](http://www.cpc.noaa.gov/)

**Stratospheric Ozone**

The ozone holes of 2007 and 2008 were large, but not of record proportions, and had generally similar metrics to those in 2001 and 2005. Minimum total column ozone levels for the Southern Hemisphere are presented in Figure 3. In general, minimum values in the two years had a similar temporal behaviour, and were almost entirely within the minimum values for all years of observation. A feature of 2008 was the persistence of low ozone into December.

Poleward heat transport by planetary wave activity was markedly lower in 2007 compared with 2008. In the mid- and upper-stratosphere, the main planetary wave disturbances of 2008 occurred after the austral spring equinox, while activity in this region occurred throughout the winter and spring of 2007.
mass in Figure 4a and 4b, respectively. We use MLS ozone measurements to follow ozone loss within the darkness of the polar night, which is inaccessible to solar backscatter instruments such as OMI. In Figure 4a, the area where the partial column ozone is less than certain thresholds is used to illustrate differences in behaviour for the three years. The black time series, which shows the standard ozone hole area metric, is based on total column measurements and a threshold of 220 DU. The ozone hole area metric had an early start in 2007, and closely matched that in 2006. In contrast, the growth of the ozone hole was delayed in 2008, but overall was consistently larger than in 2007.

In the mid-stratosphere (‘Mid’ region of Figure 4a), the area metric began to arise 2-3 weeks earlier in 2007 than in the other two years. This appears to be related to generally low background ozone levels in the mid- and upper stratosphere that prevailed over the pole during the late winter of 2007 (Figure 4b). In 2006, the comparatively large and cold vortex appears to have been a factor in allowing depletion to occur rapidly through photochemistry at the illuminated edge of the vortex. Note that in Figure 4b, the geographic area considered also includes part of the ‘ozone collar’ that surrounds the vortex, and thus averages over regions of depleted ozone within the vortex and enhanced ozone transported from lower latitudes on the periphery of the vortex. The time series of Figure 4b show similar relative behaviour if the bounding latitudes are restricted to poleward of 65°S to lie generally within the vortex (not shown here).

In mid-September of 2007, wave forcing produced an obvious reduction in the ozone hole area, limiting any further rise in this metric and the overall significance of the ozone hole. This event, noted by Tully et al. (2008), occurred above the 50 hPa pressure level and was related to a disturbance of the upper vortex and poleward transport of ozone-rich air from the tropics.

In the lower stratosphere, the relative magnitude of ozone loss and the dates of onset and recovery for 2006, 2007 and 2008 are consistent with a colder vortex, associated with more ozone loss (in the absence of any significant change in the equivalent effective stratospheric chlorine (EESC) loading).

Polar Stratospheric Clouds

A key contributor to the overall level of ozone depletion are the surfaces made available by polar stratospheric clouds (PSC), which promote heterogeneous reactions. There is a close relationship between PSC coverage and temperature, with secondary effects due to dehydration and denitrification as winter progresses. As shown in Figure 1, the estimated region containing the nitric acid trihydrate (NAT) form of PSC based on thermodynamic considerations was somewhat larger in 2008 than in 2007. More important though are the lower temperatures apparent within the NAT frost-point contour for 2008. Measurements by the CALIOP lidar on the CALIPSO satellite, shown in Figure 5, show that PSC volume was larger during the winter of 2008 than for 2007, which is consistent with the relative temperatures and levels of ozone depletion between the two years.
Examples of Specific IPY Studies

Polar Ozone Loss (PO3L)

Following on from the European Arctic Stratospheric Ozone Experiment (EASOE) conducted in 1991/92, the ‘Match’ method of Lagrangian tracer evaluation was developed to analyse data from the large numbers of ozonesondes launched during the campaign. This approach endeavours to use ozonesondes to sample the same air parcels at two or more times, and thereby measure ozone loss rates. Subsequent to EASOE, further campaigns have involved coordination of the ozonesonde launches to take advantage of air parcel trajectory forecasts. The method has been used in 13 Arctic and 2 Antarctic campaigns (see Streibel et al., 2006, for recent Arctic results). The most recent campaigns, which were organised for IPY under PO3L, were conducted in 2007 (Antarctica, involving 9 sites; see Table 2), and 2007/08 (Arctic, involving 41 sites). The main aim of the Match approach undertaken during PO3L has been to provide new assessment of ozone loss rates in box and chemical transport models through comparison with observations. The outcomes of this work will be used to reassess the earlier campaign observations in the light of evolving EESC and polar temperatures.

Lagrangian Observations with Lidar Investigations and Trajectories in Antarctica and the Arctic of PSCs (LOLITA - PSC)

Understanding the formation and evolution of PSC particles is an important issue in evaluating stratospheric chlorine activation and subsequent ozone depletion. In this project, which was specifically developed for IPY, the ‘match’ approach used in PO3L has been applied for the first time to lidar measurements in the Antarctic lower stratosphere. Campaigns took place during the austral winters of 2006, 2007 and 2008 using ground-based lidars at the coastal sites of Dumont d’Urville, Davis and McMurdo (see Table 2) to measure PSC properties. Forward and backward trajectory calculations have been run with a variety of meteorological assimilations and trajectory physics to estimate times when air parcels measured at one lidar site are likely to overlap with measurements at second and subsequent sites.

In spite of the geographical separation between the sites and limitations in observing schedules imposed by weather, approximately 15% of observing sessions have yielded potential match cases within elapsed times of 5 days, of which approximately half have PSC detections at 2 or more sites. Work in progress involves extracting lidar-derived aerosol optical parameters for candidate ‘match’ parcels and combining these with similar data obtained from the CALIOP lidar on the CALIPSO satellite, as well as chemistry measurements by Aura, at intersecting measurement locations along the associated trajectories. This approach will provide a reference dataset for model-observation intercomparisons, with the specific aim of testing coupled transport-PSC microphysics box codes and trajectory retrievals. The outcomes of this work are anticipated in improving the parameterisation of aerosol properties in coupled-chemistry climate models, and demonstrating the use of this technique for other related studies, such as the evolution of aerosols produced by biomass burning.

Outlook

Now that the main observational phase of IPY has concluded, the scientific community is engaged in producing outcomes that will undoubtedly leave a new legacy for future research. As we have learned from IGY, appropriate cataloguing and archiving of the observational data from IPY is of paramount importance, and SPARC is playing a role in this regard. A key challenge is ensuring that the capabilities utilised during IPY, in terms of the ground-based, in situ and satellite measurement programs have continuity so that stratospheric processes can be followed through further annual cycles.

Acknowledgments

We thank Paul Krummel at CSIRO Marine and Atmospheric Research, Australia for producing Figure 3. Aura MLS data used in this study were acquired as part of the NASA’s Earth-Sun System Division and archived and distributed by the Goddard Earth Sciences (GES) Data and Information Services Center (DISC) Distributed Active Archive Center (DAAC). UKMO assimilated data were obtained from the British Atmospheric Data Center. We thank all Antarctic IPY field members for their contributions to the programs outlined here.
References


Derek M. Cunnold 10 July 1940 – 18 April 2009

Derek Martin Cunnold, of Dunwoody, Georgia died suddenly while playing tennis on April 18, 2009. He is survived by his wife of 43 years, Susan R. Cunnold, his daughters and sons-in-laws, Carolyn C. and Zachary T. Holcomb of Dunwoody and Alison C. and Christopher J. Boivin of Alpharetta, his son and daughter-in-law, David D. and Claudette S. Cunnold of Alpharetta, and three grandchildren, Andrew Cunnold, Sarah Holcomb, and Alexander Holcomb. He received B.A. and M.A. degrees in Applied Mathematics from St. John’s College, Cambridge, England and a Ph.D. in Electrical Engineering (Aeronomy) from Cornell University. Upon receiving his doctorate, he served as a Research Engineer at the Sylvania Electric Systems in Waltham, Massachusetts, a Research Fellow at the Harvard-Smithsonian Center for Astrophysics at Harvard University, and a Research Associate at Massachusetts Institute of Technology’s Department of Meteorology. For the next 27 years, Dr. Cunnold was a Principal Research Scientist, Acting Chair, and Professor at Georgia Institute of Technology’s School of Earth and Atmospheric Sciences. He was conferred Professor Emeritus in 2006. Dr. Cunnold was an internationally recognised and respected expert on the science of the Earth’s protective ozone layer, the use of satellite measurements and computer models to study this complex layer, and the interpretation of global atmospheric measurements to determine the sources and sinks of ozone-depleting and greenhouse gases. He was a co-founder of the international Advanced Global Atmospheric Gases Experiment that has observed these gases continuously over the globe for the past 31 years. He was one of a select number of contributors to “The Stratosphere 1981” (the very first of what has now become a series of international ozone assessments). Since then he has participated as a reviewer, contributing author, co-author, or lead author for (i) the 1988 Ozone Trends Panel Report; (ii) the 1994 NASA Special Publication of CFCs, Halons, and Related Species; (iii) the 1998 SPARC Assessment on Trends in the Vertical Distribution of Ozone; (iv) the 1991, 1994, 1998, 2002, and 2006 Scientific Assessments of Ozone Depletion; and (v) the 2005 IPCC/TAEP Special Report on Safeguarding the Ozone Layer and the Global Climate System. Dr. Cunnold received the NASA Medal for Outstanding Achievement in 1992 and was a member of nine NASA international satellite experiment teams.

He was an outstanding mentor for students and young scientists at both Georgia Tech and other institutions. His long-term collaborator, Professor Ron Prinn of MIT, comments that “Derek’s intelligence, insight, scientific achievements, unselfish service and quiet, wise and effective leadership will be deeply missed, but never forgotten, by me and his many scientific colleagues and admirers around the world”. Derek was a true gentleman whose family always came first. He enjoyed taking family vacations, travelling worldwide with his wife, and spending time with his grandchildren. He was an avid tennis player, golfer, and skier and was a generous supporter of the World Association of Girl Guides and Girl Scouts. His passing comes as a great loss for his family, friends, and scientific associates.

Mike Kurylo
Features of the Arctic Stratosphere during IPY

< Figure 11
Vortex-averaged (within a scaled PV contour, e.g. Manney et al., 2007) MLS (top to bottom) HNO₃, HCl, ClO and O₃ during the (left to right) 2006-2007, 2007-2008, and 2008-2009 Arctic winters.

Studies of the Antarctic Stratosphere During IPY

< Figure 1
Zonal mean temperature for the latitude range 85°S to 65°S as a function of time and altitude derived from Aura MLS version 2.2 retrievals. The individual profiles were converted to a uniform grid in geopotential height through linear interpolation before creating the daily zonal averages. Bias corrections have not been applied to individual measurements. The red contour delineates the NAT frost point evaluated using observed MLS temperature and mixing ratios of HNO₃ and H₂O. The dashed vertical lines mark the time of the austral spring equinox.