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 measurements 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

62706-1 SPARC Newsletter 33_2_Re14 14 8/20/2009 2:16:36 PM

Project Number	Project Name, (Short Name), Web Site	Country of Activity Leader	Location	Key Antarctic Stratospheric Investigations
99	Ozone layer and UV radiation in a changing climate evaluated during IPY, (ORACLE-O3), http://www.awi-potsdam.de/atmo/ORACLE-O3/index.html	Germany	Bipolar	* Precise quantification of polar ozone losses in both hemispheres.
				* Quantification of PSC distribution and micro-physical characteristics.
				* Measurements of key atmospheric quantities: ozone, water vapour, key ozone-related trace gases, wind and temperature.
				* Comparison of measurements with process-oriented models and CCMs for model validation and improvement.
180	Antarctic Climate and Atmospheric Circulation (AC^2)	USA	Antarctica	* Examination of key processes associated with the dynamics and chemistry of the upper troposphere and lower stratosphere including development PSCs.
				* Field observations and *in situ* measurements of chemical species.
				* Evaluation of transport and modulation of chemical species by large-scale dynamical processes.
217	The Structure and Evolution of the Polar Stratosphere and Mesosphere and Links to the Troposphere during IPY, (SPARC-IPY), http://www.atmosp.physics.utoronto.ca/SPARC-IPY/	Canada	Bipolar	* Collection and archival of Antarctic stratospheric data for use, for example, with CTMs and, comparison with the primary activity of the project which is focused on the Arctic polar vortex.

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

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-Ñino 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.

Site Name	Latitude	Longitude	Ozone-sonde[2]	Spectro-meters[3]	Dobson (D) or Brewer (B)	Lidar	Radar[4]	Details and other instruments	Countries Involved
Macquarie Island	54.4°S	159.0°E	X	UV/vis	D				Australia New Zealand
Marambio	64.2°S	56.6°W	M						Argentina
Vernadsky	65.3°S	64.3°W	X		D				Ukraine, UK
Dumont d'Urville	66.4ºS	140.0ºE	M	SAOZ		X		Rayleigh-Raman-Mie-DIAL lidars (ozone, temperature and aerosol backscatter/depolarisation troposphere-stratosphere)	France
Rothera	67.6°S	68.1°W	X	SAOZ					UK
San Martin	68.1°S	67.1°W			B				Argentina
Davis	68.6ºS	78.0ºE	M			X	MF, MST	Rayleigh-Raman lidar (temperature and aerosol backscatter troposphere-mesosphere)	Australia
Syowa	69.0ºS	39.6ºE	M	UV/vis	D	X	MF	- Micro-pulse lidar (aerosol backscatter/depolarisation in UTLS)	Japan
Zhong Shan	69.4ºS	76.4ºE	X		B	X			China
Neumayer	70.6ºS	8.3ºW	M	DOAS					Germany
Wasa[5]	73.0ºS	13.4ºW					MST		Sweden
Concordia	75.1°S	123.4°E	M	SAOZ		X		Micro-lidar (aerosol backscatter in UTLS)	France, Italy
Halley	75.6°S	26.6°W	X		D				UK
Belgrano	77.8°S	34.5 °W	M		B				Argentina
Arrival Heights McMurdo Scott Base	77.8ºS	166.7ºE	M	UV/vis DOAS FTIR	D	X	MF	- Backscattersondes - ClO microwave radiometer - Rayleigh-Raman-Mie lidar (temperature and aerosol backscatter/depolarisation troposphere-stratosphere)	New Zealand, USA, Italy, Germany
South Pole	90.0ºS		M		D	X	MF	- Micro-pulse lidar (aerosol backscatter/depolarisation in UTLS)	USA

Table 2 –Antarctic and sub-Antarctic ground-based and in situ stratospheric measurements during IPY[1].

Notes: [1]This table does not include UV instruments for surface radiation measurements or sun photometers for aerosol measurements. [2]M denotes ozonesonde stations participating in the 2007 Antarctic Match campaign. [3]Spectrometers for ozone and trace gases. [4]MF radars measure winds from the upper stratosphere to the mesosphere – lower thermosphere (MLT) region. MST radars measure winds from the troposphere to the lower stratosphere, and upper stratosphere to MLT region. [5]The Wasa MST radar operated during the 2007/08 austral summer.

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.noaa.gov/products/stratosphere/winter_bulletins/**). 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/**).

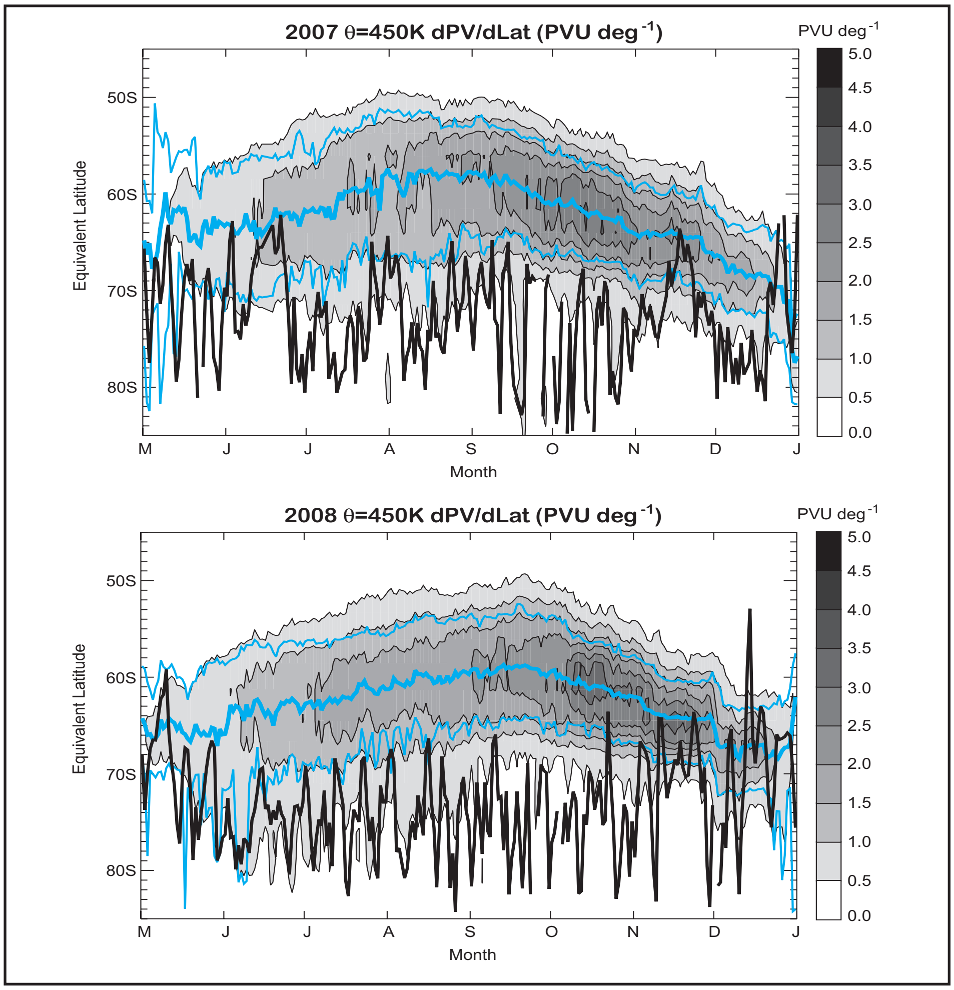


Figure 2: Potential vorticity gradient (expressed in potential vorticity units (PVU; 1 PVU = 10^{-6} K m^2 kg^{-1} s^{-1}) per degree of equivalent latitude) as a function of time and equivalent latitude for the 450 K potential temperature isentrope (near 70 hPa pressure, or 18 km altitude), derived 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).

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±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 both years. The selected potential temperature surface is within the region of maximum ozone loss during spring. During the 2008 winter, the edge of the vortex was generally further equatorward in the lower stratosphere than in 2007, and exhibited larger edge gradients related to stronger zonal flow. Davis station, which is typical of sites at the edge of East Antarctica, was more consistently inside the inner vortex edge during 2008. A notable feature was that the polar vortex in both years persisted through until 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.

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.

The evolution of ozone depletion in 2006, 2007 and 2008 is shown using metrics based on ozone hole area and total ozone

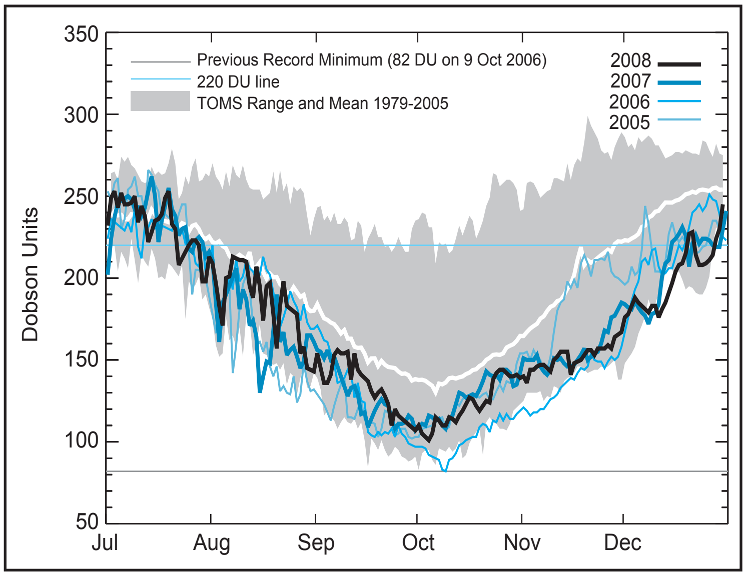


Figure 3. Daily minimum total column ozone for the Southern Hemisphere based on OMI and TOMS satellite data. The 2008 hole (OMI data) is indicated by the thick black line, the 2005, 2006 and 2007 holes (OMI data) by the light blue, cyan and thick blue lines respectively. The grey shaded area and white line show the 1979-2005 TOMS range and mean respectively.

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.

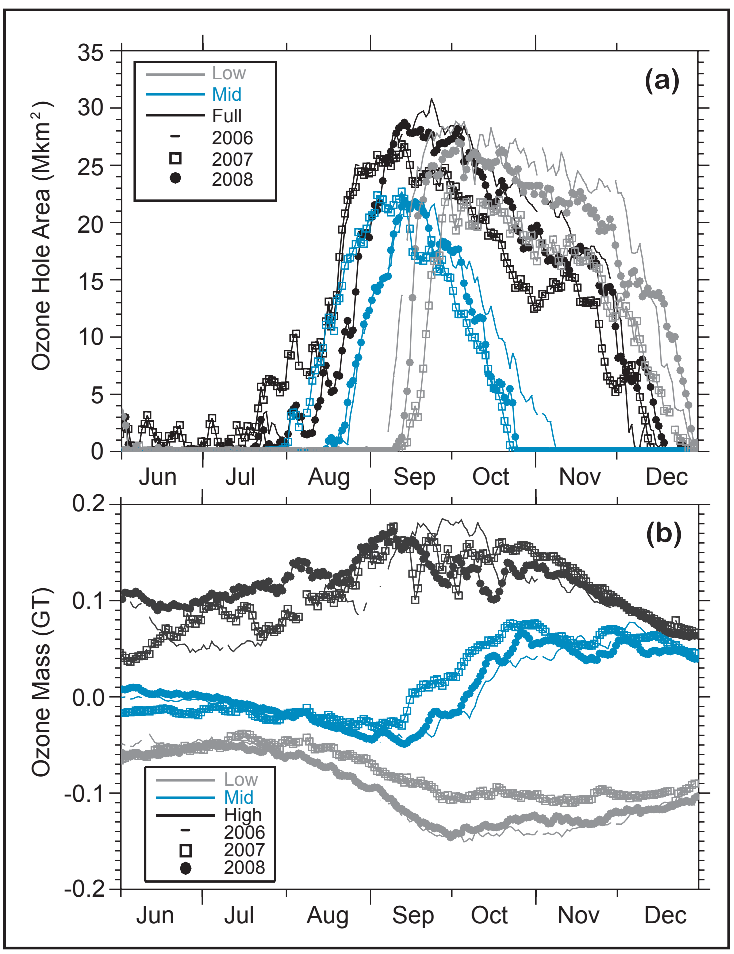


Figure 4: Analysis of gridded Aura MLS v2.2 ozone measurements south of 50°S for 2006-2008. (a) Time series of ozone hole area for three partial columns: 146-68 hPa ('low'), 46-10 hPa ('mid') and 464-0.1 hPa ('full'). Each time series represents the area where the partial column ozone amount, expressed in Dobson Units (DU), is less than the following thresholds: 25 DU ('Low'), 70 DU ('Mid') and 220 DU ('Full'). (b) Total ozone mass in three partial columns: 'Low' and 'Mid' from (a), and 7-0.01 hPa ('High'). Each time series has the associated value for 1 June 2006 removed. For clarity, the 'Low' time series values have been offset by -0.05 GT, while the 'High' time series values have been multiplied by 10, and then offset by +0.1 GT.

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.

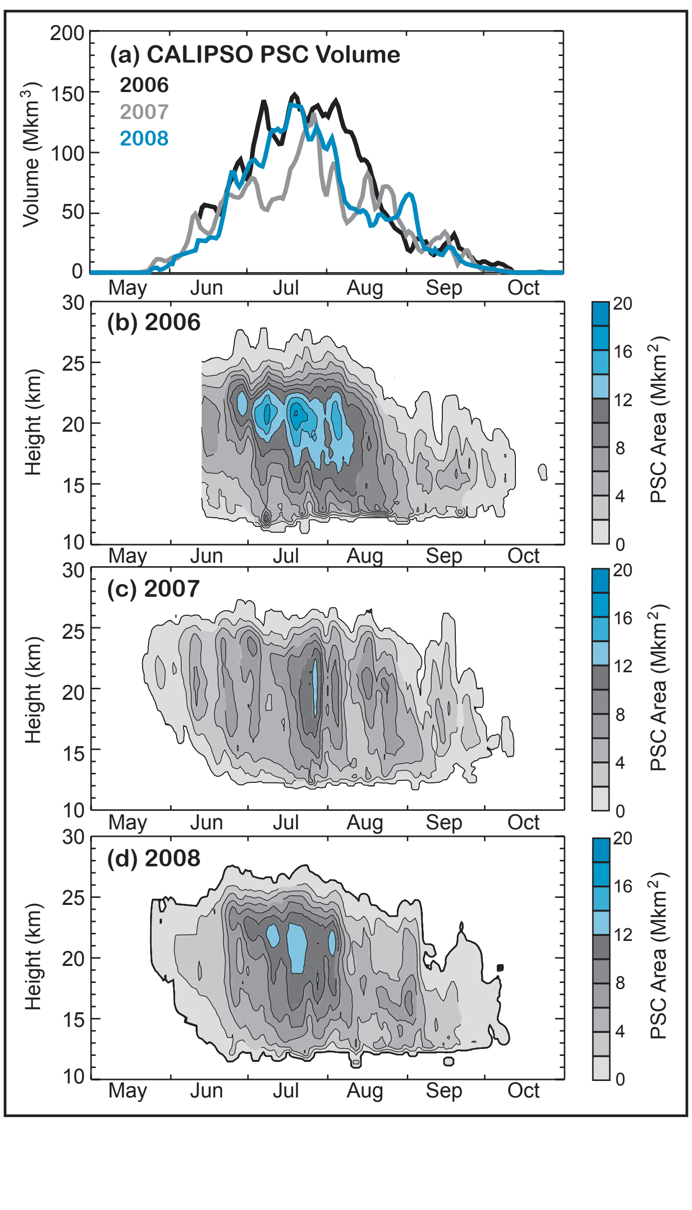


Figure 5: Daily PSC time series for Antarctica derived from the CALIPSO second generation PSC detection algorithm described by Pitts et al. (2009). (a) Time series of total PSC volume for 2006, 2007 and 2008. PSC area as a function of altitude for the (b) 2006, (c) 2007, and (d) 2008 seasons.

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

Nash, E.R., P.A. Newman, J.E. Rosenfield, and M.R. Schoeberl, An objective determination of the polar vortex using Ertel's potential vorticity, *J. Geophys. Res.*, **101** (D5), 9471-9478, 1996.

Pitts, M. C., L. R. Poole, and L. W. Thomason, CALIPSO polar stratospheric cloud observations: Second-generation detection algorithm and composition discrimination, *Atmos. Chem. Phys. Dis.*, **9**, 8121–8157, 2009.

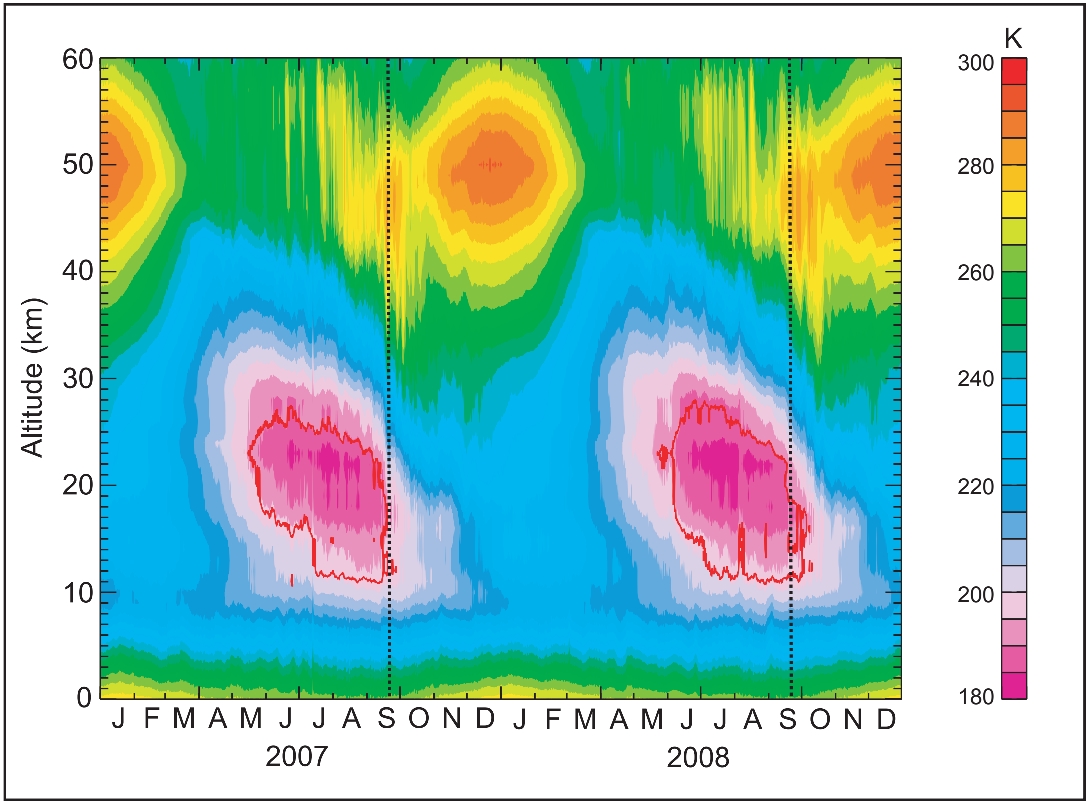
Randel, W. J., *et al.*, An update of observed stratospheric temperature trends, *J. Geophys. Res.*, **114**, D02107, doi:10.1029/2008JD010421, 2009.

Streibel, M., *et al.*, Chemical ozone loss in the Arctic winter 2002/2003 determined with Match, *Atmos. Chem. Phys.*, **6**, 2783–2792, 2006.

Tully, M.B. *et al.*, The 2007 Antarctic ozone hole, *Aust. Met. Mag*. **57**, 279-298, 2008.

WMO, World Meteorological Organization /United Nations Environment Programme (WMO/UNEP), Scientific Assessment of Ozone Depletion: 2006, Rep. 50, 572 pp., Geneva, Switzerland, 2007.

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 HNO_3 *and* H_2O*. The dashed vertical lines mark the time of the austral spring equinox.*