SPARC
STRATOSPHERIC PROCESSES AND THEIR ROLE IN CLIMATE
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Report on the 30th Session of the Joint Scientific Committee of the World Climate Research Programme

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The 30th meeting of the WCRP-JSC was held 6-9 April 2009 at the new Earth System Science Interdisciplinary Centre (ESSIC) at the University of Maryland, USA. The meeting was opened by the chair of the JSC and Director of ESSIC, Professor **Antonio Busalacchi**. Welcoming remarks were presented by **Stephen Halperin**, Dean of the College of Computer, Mathematical, and Physical Sciences at the University of Maryland and by **Mary Glackin**, Deputy Under Secretary of Commerce for NOAA.

In addition to the regular agenda items that were addressed during the meeting, there were two 30 minute science presentations by ESSIC scientists. One of these, presented by **Raghu Murtugudde**, provided an overview of the Chesapeake Bay Forecast System. The other, presented by **Sumant Nigam**, discussed hydroclimate variability over South Asia and the role of regional reanalyses. A third 30-minute presentation, on risk assessment from the perspective of users of climate information, was given by **Stephen Zebiak** of the International Research Institute for Climate and Society (IRI) of Columbia University.

Over-arching themes of JSC 30

The usual purpose of the annual JSC meetings is to review progress of the four core WCRP projects, panels and working groups over the previous year. However, the 2008 external review of the WCRP, commissioned by its Sponsors and the International Group of Funding Agencies of Global Change Research, and the related need to address future programmatic priorities and WCRP structural issues were the main overarching themes of the 30th meeting. To ensure effective discussion of these issues the meeting was structured differently from previous ones. The traditional (and sometimes exhausting) summary presentations of individual reports from projects, panels, and working groups were replaced with a single lead-off presentation on WCRP accomplishments over the 2005-2008 period on behalf of all projects, panels, and working groups by **Jim Hurrell** (CLIVAR co-chair) and **Ted Shepherd**. This presentation set the stage for the discussions of the WCRP review and long term plans that occupied the bulk of the meeting. The lead-off presentation was very effective in summarising the breadth and scope of

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WCRP activities and pointed to a number of key elements of the WCRP organisation and activities that have been central to its successes, as well as to lessons that can be drawn from the WCRP experience over the last two decades. The lion's share of the WCRP program is carried out through the core projects and the International Project Offices (IPOs), for these projects are seen as being fundamental to the success of the WCRP. Other key lessons include the value of focused objectives and targeted activities, and the importance of and value

ICSU International Council for Science
IOC

in engaging young scientists in ways that ensure that WCRP activities are key elements of their own research careers. In the discussion, the importance of the WCRP in national science programs was noted on several occasions. National funding agencies look to the WCRP for guidance on climate science issues and priorities.

Discussions on the WCRP review were led by A. Busalacchi and **Ghassem Asrar**, WCRP Director. In a brief presentation G. Asrar noted that the financial situation of the WCRP has improved within the past year and this will allow more effective support for WCRP workshops and meetings, as well as for JPS coordination activities.

A. Busalacchi drew attention to some of the key issues raised in the WCRP review, and pointed out the importance of addressing these as part of the planning for the near future (up to 2013) and longer - term activities of the WCRP. (The text of the review can be accessed at the ICSU website, **http://www.icsu.org**, its page on strategic reviews). Among the recurring concerns is the perception that, despite its notable achievements, the WCRP lacks visibility within key communities, notably within certain user communities, and particularly within developing countries. The WCRP review drew attention to this and recommended engaging these communities more effectively. This notwithstanding, the WCRP must continue its role as a key research program within the complex of international science activities and other global change programs.

In addition, A. Busalacchi noted the need to develop key elements of the WCRP program for the near and longer term as input to the World Climate Conference-3 that will be held in Geneva, 31 August-September 4, 2009. This process has started with the development of near-term (to 2013) draft plans for implementing the COPES strategic plan (discussed further below), but must also include articulation of high-level long-term objectives for the WCRP. The overall program for the JSC-30 meeting was designed to provide input for and to initiate this process. It included three round table discussions. The first of these included representatives from the WCRP international sponsors and funding agencies (WMO, IOC, ICSU, IGFA, NERC). The second included representatives from major agencies from the USA (NASA, NOAA, NSF), and the third included representatives from international partner programs (ESSP, START, CEOS, IGBP, GEO, IHDP, GCOS).

Participants in these round table discussions were asked to address some key questions: What impact has the WCRP had on their activities in the past? How should the WCRP evolve in the future? What are the expectations of the particular sponsoring program/agency in regard to the WCRP? While these discussions did underline the relevance of many of the programmatic and visibility issues that were raised in the WCRP review, a common and strong theme, particularly from the major science funding agencies (*e.g*. NERC, NOAA, NSF), was that the fundamental research role of the WCRP is of preeminent importance. This perspective was repeatedly stated by the major USA agency representatives, with numerous examples cited of the importance of WCRP project activities in national research programs. In particular the NASA participant (J. Kaye) noted the value and influence of the SPARC program in a wide range of NASA activities. Defining and maintaining an ambitious science agenda in the future emerged as a central theme of the input from the funding agency representatives in the round table discussions.

In addition to the round tables there were several organised discussions of WCRP long term planning that took place during the meeting. The first discussion focused on a tentative proposal for the post-2013 WCRP structure that emerged from the 29th JSC meeting in Arcachon, with further elaborations resulting from discussions within the JSC in the intervening period, presented as a white paper for discussion at JSC 30. The main features of this initial proposal included replacing the existing WCRP structure with one in which the main elements would be a small number of panels that would be oriented along methodological themes. Initially, there would be panels on (a) Earth system observations, analysis and data, (b) Earth system modelling, and (c) Earth system prediction, predictability, and applications. In the discussion many questions were raised about this proposal, its implications for a major reorientation of WCRP programs, and the effect that departing from the more topical themes-orientation of the existing projects might have on the scientific communities that have developed, and are fundamental for the successful achievement of WCRP objectives. This discussion set the stage for the breakout sessions that were held on the last two days of the meeting (discussed further below).

Near-term implementation of the COPES Strategic Plan

The major parts of the second and third day of the meeting were devoted to presentations of near-term (up to 2013) plans, and outlooks for the longer-term from core projects, panels, working groups and cross-cutting activities. The overall goal of these presentations, with supporting documents prepared beforehand, was to provide input into the WCRP COPES Implementation Plan that is being prepared and intended as input to the third World Climate Conference (WCC-3). A number of broad questions were posed in the guidelines that were set down for preparation of the documentation and presentations. These included summarising current and near future (to 2013) major activities, projecting activities that should be maintained beyond 2013, identifying (as currently conceivable) science questions beyond 2013, contributions to COPES themes and cross-cutting initiatives, and long-term legacy and outlooks.

SPARC Plans

T. Shepherd presented near-term plans and longer-term outlooks for SPARC. These were prepared on the assumption that SPARC will continue as an identifiable project within the WCRP to 2013 and beyond with its current overarching themes. While many of the current major activities within the SPARC program are likely to continue into the far future, the three that were identified as key components of a SPARC program beyond 2013 were
(a) chemistry-climate model validation,
(b) assessment of key uncertainties in measurements,
(c) linking various scientific communities.

The first of these is clearly identifiable as a continuation of the current CCMVal activity, which has become a major underpinning for both the WMO/UNEP ozone and IPCC assessments. The second addresses the need to provide expertise in order to keep track of latent or emerging uncertainties in measurements relevant for the stratosphere and upper troposphere (as has in the past led to

SPARC Reports, and recently to the laboratory-based AquaVIT hygrometer intercomparison). The third addresses the ongoing need to facilitate communication between the measurement and modelling communities, between dynamicists and chemists or microphysicists, and between the natural sciences and the end user communities. For example, the third activity has been and will be providing guidance to the measurement community on modelling needs, and in turn providing observational databases from the measurement community for use by modellers.

Many of the key science questions that are currently being addressed within SPARC will remain relevant beyond 2013. To highlight these, the SPARC presentation listed a number of topics that might appear on the agenda for a SPARC SSG meeting in 2013 (a number of which have been discussed at recent SSG meetings). In summary, it was noted that the perception of the importance of stratospheric processes in weather and climate prediction has emerged largely as a result of SPARC activities over the past decade. However, understanding and successfully modelling the key processes and characteristics of stratosphere-troposphere dynamical and chemical coupling is still emerging and will require continued focused activities similar to those within the current SPARC project.

Atmospheric Chemistry and Climate (AC&C) progress and plans

The WCRP/IGBP cross-cutting AC&C activity is jointly led by SPARC (on behalf of WCRP) and IGAC (on behalf of IGBP). In the past year, A. Ravishankara has stepped down as the SPARC Co-chair for this activity. Recently Martyn Chipperfield has agreed to become the Co-chair on behalf of SPARC. Phil Rasch remains as the Co-chair on behalf of IGBP.

Tom Peter summarised AC&C progress and projected future activities. Hitherto, Phase I activities have been predominant, a large part being coordinated modelling studies that build on the AC&C component activities: the main ones are currently CCMVal, AeroCom (Aerosol Model Intercomparison), and the new TropChem (tropospopheric chemistry modelling). Major goals are improving the representation of processes in chemistry-climate models, and contributing to IPCC assessments and WMO ozone assessments. To this end two AC&C activities are currently in the planning stage. The Scenarios, Sensitivity and Uncertainty activity will address the need of modelling groups that expect to contribute to future IPCC Assessments but either do not have the capability to create their own time-evolving distributions of short-lived species or would prefer to use a standard climatology. Among other things this activity would consider the creation of data sets that would be available to interested user groups. A second new activity will focus on bounding the role of black carbon in climate. The intent of this initiative is to produce a peer reviewed report on the topic with a first meeting of coauthors planned for August 2009.

The AC&C cross-cutting activity has built on historic links between IGAC and SPARC. These links remain strong. However, there has not been as much engagement of the CCMVal community in Phase I of AC&C as hoped for. Of course, the CCMVal groups have been fully occupied over the past year with CCMVal-2 simulations and the CCMVal report. The recent appointment of Martyn Chipperfield as AC&C co-chair is expected to result in enhanced engagement of both the CCMVal and European chemistry-climate modelling communities. Additionally, the joint SPARC SSG – IGAC SSC meeting that will be held in Kyoto in October, 2009 will serve to advance the AC&C activity as well as strengthen SPARC and IGAC interactions.

Future of the WCRP

Following the presentations from the individual components of the WCRP, three breakout groups were formed, all with cross-cutting membership, with each tasked to consider the same three questions: (1) What should be the function of WCRP? (2) What should be the main themes of WCRP? (3) What should be the structure of WCRP? The groups met for two hours, then their conclusions were presented in plenary and discussed. This format led to extremely constructive discussions. While each group approached the questions a bit differently, in the end there was a remarkable degree of consensus between them.

The result of this exercise was the emergence of a framework for revising/restructuring the WCRP in the longer-term future. As noted above, the current structure with the core projects as the major components will continue up to 2013. Beyond that time a new structure that builds on the strengths of the current one is envisaged. This will also have major central structured activities, analogous to the current core projects, organised under broad disciplinary themes that recognise major couplings and processes in the climate system (Land /Atmosphere, Ocean/Atmosphere, Cryosphere, Stratosphere/Troposphere). This was seen as best able to lead to an ambitious scientific agenda that would engage the next generation of scientists. It furthermore offers the advantage of allowing relatively straightforward connections to IGBP and to GCOS, key partners for WCRP, which are organised similarly. The issues of applications, communications, and outreach, identified as important for the future WCRP, will be addressed through a major interdisciplinary cross-cutting actvity that will also be a distinct structural feature of the future WCRP. Each of these structural features will be sustained by appropriate infrastructural elements, including project offices and support staff, in a manner similar to that which enables the current WCRP structure to function effectively.

The proposed Stratosphere/Troposphere activity would obviously be a natural evolution of SPARC, and a recognition that the stratosphere is an integral part of the climate system while having its own distinct character. So from a SPARC perspective, this development concerning the future of WCRP is seen to be a very positive one, which provides stability for future planning.

The JSC-30 meeting explicitly recognised that past achievements of the WCRP should be treasured, and that structural change *per se* – as long as the players are not exchanged – will not automatically improve WCRP's efficiency. This appreciation for the role and operation of the WCRP was shared by most participants, and in particular, by representatives from the WCRP international sponsors and funding agencies. The meeting ended on a very optimistic note, and all its participants felt energised to continue the work on defining the future of WCRP over the coming year. The 31st Session of the WCRP JSC will take place in Antalya, Turkey, in February 2010, in conjunction with the 15th Session of the WMO Commission for Climatology.

The SPARC Contribution to the Implementation Plan of the WCRP Strategic (COPES) Framework

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During the past year the WCRP core projects, panels and working groups have developed contributions toward an integrated plan for implementation of the WCRP's Coordinated Observing and Prediction of the Earth System (COPES) strategic framework. SPARC's contribution to this process has been informed and guided by discussions at the 2008 meeting of the SPARC SSG, as well as by interactions with the SPARC community in the period following initiation of the public discussion on the future of SPARC at the Fourth General Assembly. A broadly similar consultative process has been carried out within the whole of the WCRP following the 2008 meeting of the Joint Scientific Committee (JSC) (see the report in Newsletter No. 29), and has culminated in the production of the aforementioned implementation plan documents. As noted in the accompanying report in this issue of the Newsletter, these contributions were discussed in detail at the 2009 JSC meeting.

An integrated WCRP plan is now being developed based on these contributions from the core projects, panels and working groups. However, the integrated plan for the WCRP as a whole is likely to focus on the major features of the component contributions, with limited attention to details of the individual contributions. If it is to be an effective framework, an implementation plan must allow for change and evolution. Therefore, with this "living document" perspective in mind, we have decided to post the full version of the SPARC implementation plan contribution on the SPARC web site. The implementation plan document sets out details of SPARC plans and objectives. Here we provide a more concise summary of its key features. Instructions on accessing and viewing the SPARC implementation plan (IP) document are given at the bottom of this summary article.

The guidelines that were set out by the JSC requested that the implementation plan contributions should address questions and issues for the near-term (up to 2013) and attempt to identify key activities and themes that should be included in longer term (beyond 2013) planning.

To provide a perspective for both the near- and long-term, the SPARC contribution begins by setting out the overarching themes of the current SPARC program. These encapsulate issues of abiding importance, as well as serve to define the framework for the SPARC program at least up to 2013. Plans and projections in the SPARC contribution are based on the assumption that these overarching themes will also continue as the framework for longer-term future activities.

SPARC activities that should be maintained beyond 2013

The guidelines requested identification of a small number of key activities that should be continued into the indefinite future. In the SPARC contribution, the following were indicated as key longer-term activities and issues:

(a) Chemistry-climate model validation activities
(b) Assessments of key uncertainties in measurements
(c) Linking various scientific communities

As noted in the accompanying JSC report, and more fully in the IP document, the first of these is a continuation of the current CCMVal activity as a major underpinning for both the WMO/UNEP ozone and IPCC assessments; the second addresses the need to provide expertise in order to keep track of uncertainties in measurements; and the third addresses the ongoing need to facilitate communication between the various communities that are linked to SPARC, and contribute to and benefit from SPARC activities.

Key science questions for SPARC beyond 2013

The implementation plan must be able to address new questions and issues that emerge with evolving capabilities and interests of the climate science community. The SPARC contribution identifies some key science issues, some of an abiding nature and some that are emerging and may come to fruition in the next decade, that are relevant to SPARC:

- Quantify the interaction between ozone recovery and climate change
- Foster stratospheric science in climate accountability, mitigation and adaptation
- Investigate air quality aspects of the troposphere-stratosphere system
- Quantify the impact of solar variability (on all time scales) on climate
- Improve climate models *via* data assimilation and the use of mesoscale/cloud-resolving models
- Improve decadal stratospheric ozone pre dictability, seasonal climate predictability, and our understanding of climate variability in the stratosphere
- Improve chemistry-climate coupling in the stratosphere-troposphere system
- Quantify the role of the polar regions in global climate
- Quantify effects of future stratospheric change on the global carbon cycle
- Critically assess Geoengineering

Legacy and outlook beyond 2013

The evolution of the WCRP and its component projects in the intermediate and longer-term future is likely to build on the strengths of the current structure and program while broadening its perspectives and interactions with other major global change programs. Identifying strengths and abiding issues is fundamental to defining a framework for the future evolution of the WCRP and its components.

In the SPARC contribution, it is noted that, while the perception of the importance of stratospheric processes in weather and climate prediction has emerged largely as a result of SPARC activities over the past decade, understanding and successfully modelling the key processes and characteristics of stratosphere-troposphere dynamical and chemical coupling is likely to remain a central focus in the future.

Although the "recovery" of stratospheric ozone to pre-CFC levels is expected in the coming decades, detecting the signs of ozone recovery and understanding the influence of increasing GHG concentrations are issues of continuing major societal importance. Therefore, this was identified as a second issue that will continue to be of importance in the longer term.

The full version of the SPARC contribution to the implementation plan is available for viewing on SPARC web site (**http://www.atmosp.physics.utoronto.ca/SPARC/**). It can be viewed and comments posted by entering the 'SPARC Café'. This forum will remain active until the next SPARC SSG meeting, which will be held in October, 2009.

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SPARC-IPY and Beyond

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The International Polar Year 2007-2008 has now formally ended (as of March 31, 2009). As hoped, it has left a legacy of measurements and analyses that have engaged the scientific research community, and will continue to do so for some time in the future. As many readers of this issue of the SPARC Newsletter will know, the SPARC-IPY Activity entitled "The Structure and Evolution of the Polar Stratosphere and Mesosphere and links to the Troposphere during IPY" was an officially endorsed IPY Activity with links to several others.

SPARC-IPY was proposed on the basis of the understanding - much of it achieved under the auspices of the SPARC project - that the evolution of stratospheric ozone and other important and related atmospheric constituents in Polar Regions is tightly coupled to a wide range of processes acting within and outside the winter polar vortices, and through the entire region from the surface to the mesopause. The IPY program offered a unique opportunity to assemble a wide range of scientific expertise to study the Antarctic and Arctic Polar Vortices, the *loci* of key chemical and physical processes associated with ozone depletion and its eventual recovery, as well as key features of the dynamical coupling between the troposphere, stratosphere, and mesosphere in polar and sub-polar regions.

A major goal of the SPARC-IPY program was to document as completely as possible the dynamics and chemistry of the polar middle atmosphere during the IPY period. It was anticipated that achieving a unique synthesis of data on the polar middle atmosphere would require analysis of available research and operational satellite data, as well as ground-based and aircraft data. This would clearly also include data from new measurement systems, as well as from enhanced measurement programs with established systems. The intent of SPARC-IPY, in cooperation with related and linked IPY activities, was to facilitate such data acquisition, archiving and analysis activities. To complement results provided by new measurement programs, SPARC-IPY also included the collection and archiving of objective analysis products from major centres during the IPY period. This activity was undertaken and coordinated within the SPARC-DA activity. A description of it was published in Newsletter No. 29 (Polavarapu *et al*.,) and an update on it is included in this issue. SPARC-IPY has also encouraged work on data assimilation and intercomparison of assimilated data sets.

In addition to the research activities that were undertaken in the context of IPY, outreach activities were strongly encouraged within both national and international IPY programs. A number of outreach activities were undertaken as part of the SPARC-IPY Activity and these are documented on the SPARC-IPY web site (**http://www.atmosp.physics.utoronto.ca/SPARC-IPY/**). This site was initially created as a forum for informing participants in the SPARC-IPY activity of progress and new results. However, this site is now fully accessible and will be maintained for an indefinite period in the future as a means of informing the SPARC community of outcomes from IPY activities.

With the ending of the official IPY period it is appropriate to draw attention to what has been achieved and point to the legacy of IPY, as well as to ongoing issues of continuity and adequacy of observations and observing systems that will be needed in the future. This issue of the newsletter features two articles that provide overviews on observations and analyses of the Antarctic and Arctic stratosphere during the IPY period. They draw attention to some of the notable features that have been revealed as a result of the enhanced observational programs that were undertaken in the IPY period. These articles highlight satellite and ground-based observations and what has been revealed by them. A number of other research and analysis activities that were undertaken as part of SPARC-IPY and related activities have also produced interesting and valuable results that we hope to feature in articles in future issues of the newsletter.

Reference

S. Polavarapu *et al*., SPARC-IPY Update, SPARC Newsletter No. 29, 2007.

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Features of the Arctic Stratosphere during IPY

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Introduction

The International Polar Year (IPY) has provided the opportunity and the means to intensify and coordinate ground-based measurements from stations across the Arctic. The combination of ground-based measurements, complimented by satellite observations, affords a unique observational framework for studying atmospheric processes in the Arctic during the IPY period. Many of the ground-based stations are affiliated with the Network for the Detection of Atmospheric Composition Change (NDACC: **http://www.ndacc.org/**). NDACC stations typically have a suite of instruments, including lidars (for measuring ozone, water vapour, aerosol, and temperature profiles), microwave radiometers (ozone, water vapour, and ClO profiles), UV-visible spectrometers (ozone, NO_2, OClO and BrO columns), Fourier transform infrared (FTIR) spectrometers (columns of many species), Dobson and Brewer spectrophotometers (ozone columns), sondes (ozone and aerosol profiles), and UV spectroradiometers (UV radiation at the ground). Fourier transform infrared spectrometers provide a particularly valuable tool for characterising the chemical composition of the Arctic atmosphere, as they can measure both stratospheric and tropospheric species, such as ozone, HCl, HF, NO, NO_2, $ClONO_2$, HNO_3, N_2O, CO, CH_4, C_2H_6 and HCN. More information concerning the FTIR spectrometers within the NDACC can be found at **http://www.acd.ucar.edu/irwg**.

During IPY, satellite observations, particularly those focused on the polar winter middle atmosphere, provided details on the meteorology and insight into chemical and dynamical processes. The Aura Microwave Limb Sounder (MLS) (Waters *et al*., 2006) and the Atmospheric Chemistry Experiment - Fourier Transform Spectrometer (ACE-FTS) (Bernath *et al*., 2005) are two valuable sensors that provide daily measurements from which temperature and trace gas data have been extracted since 2004. These data sets cover the upper troposphere through the mesosphere.

This unique combination of ground-based and satellite observations are now being used to study and elucidate many dynamical and chemical features of the Arctic stratosphere and mesosphere. The purpose of this article is to provide a broad overview of the observations and highlight some of these features during the IPY period.

Dynamical features of the Stratospheric and Mesospheric Circulation during IPY

A number of recent studies of the planetary scale circulation during the IPY period have utilised temperature and geopotential height data determined from satellite observations. In addition, lidar measurements of density and temperature fluctuations enable identification of higher frequency, smaller-scale features in the upper stratosphere and mesosphere that are associated with gravity-wave propagation. In combination, these satellite and ground-based measurements have revealed a range of dynamical features and processes that have occurred in the Arctic stratosphere and mesosphere during the IPY period. Many of these features are manifestations of well known, *albeit* irregularly occurring, phenomena (such as stratospheric warmings) that have been studied in the past. However, as is noted repeatedly in this summary article, the coincidence of observations from satellite and ground-based systems during the IPY period has enabled identification and study of many of these features in greater detail than may have been possible in the past, or may be possible in the future if some of the observing systems do not continue to operate. This section will provide an overview of significant dynamical features of the Arctic winter stratosphere and mesosphere that have been identified in the IPY period.

Large-Scale Structure

The three winters 2006-2007, 2007-2008 and 2008-2009 represent a wide range of conditions in the highly variable Arctic winter stratosphere, though only 2008-2009 exhibits an extreme of Arctic variability (*e.g*. Manney *et al*., 2008a). **Figure 1** (colour plate I) shows zonal-mean zonal winds in the middle and upper stratosphere in each year. Both 2006-2007 and 2007-2008 were cold, relatively undisturbed winters (strong westerlies). A brief major stratospheric sudden warming[1] (SSW)

[1]An SSW is considered major when the zonal mean wind and temperature gradient pole-ward of 60°N change sign at 10hPa.

occurred in late February in both 2007 and 2008. After the SSW in February 2007, the vortex reformed and reestablished westerlies persisted through early April, resulting in an unusually late final warming. In 2008, the first major SSW was followed very closely by a "major final" warming (that is, a major warming leading directly into the final warming without recovery of westerlies in between), resulting in an early vortex breakup before mid-March. In January 2009, the strongest, most prolonged SSW on record occurred (*e.g*. Manney *et al*., in press); after this event, 10hPa winds returned to westerlies as a weak vortex was reestablished, and the final warming was late (as is typical after early major SSWs, *e.g*. Manney *et al*., 2005, 2008b), in early May. The overall evolution of the vortex prior to the SSWs at 10hPa is similar in both 2007 and 2008. However in the upper stratosphere (*e.g*. 1hPa), there were numerous brief wind reversals in 2008 prior to the major SSW. The prolonged major SSW in 2009 resulted in an ~10-day wind reversal in the upper stratosphere, after which very strong westerlies reappeared, indicating reformation of an unusually strong upper stratospheric vortex.

Figure 2 (colour plate I) shows the evolution of high latitude temperatures during the three winters. The polar winter stratopause (temperature maximum) is typically near 50 km, and shows considerable variability in temperature and position. Similar to the behaviour during the prolonged major SSW in 2006 (*e.g* Siskind *et al*., 2007; Manney *et al*., 2008a, b), the stratopause dropped dramatically, then broke down during the 2009 SSW; reformation of the stratopause at a very high altitude after the SSW was accompanied by enhanced descent and reestablishment of an unusually strong upper stratospheric vortex (Manney *et al*., in press), similar to 2006 (*e.g*. Siskind *et al*., 2007; Manney *et al*., 2008a, b); reformation of a strong vortex was seen in the development of strong westerlies at 1 hPa as shown in Figure 1. The brief major SSWs in February 2007 and 2008 had only a small effect on the stratopause location and temperatures, and, consistent with the occurrence later in the season, the vortex did not strongly reform (see Figure 1). In the lower stratosphere, temperatures in December and early January were lower in 2007-2008 and 2008-2009 than in 2006-2007; however, low temperatures persisted longest in 2007, until late February, as opposed to mid-February in 2008 and (because of the major SSW) late January in 2009.

Figure 3 (colour plate II) shows maps of scaled potential vorticity (sPV, see Manney *et al*., 1994 for details of scaling) in the lower (490K), middle (850K), and upper (1700K) stratosphere, and in the lower mesosphere or near the stratopause (2500K) from the GEOS-5 assimilated meteorological analyses. The date shown in each year is at the beginning of the major SSW, approximately the time when the 10 hPa zonal-mean winds reversed to easterly. SSWs are classified as vortex displacement or vortex split events (*e.g*. Charlton and Polvani, 2007); 2007 and 2008 provide examples of the first type (displacement) and 2009 of the second (split). SSWs typically develop from the top down (*e.g*. Andrews *et al*., 1987), and, consistent with this, the upper stratospheric and lower mesospheric vortex had already broken down by the date shown, and the lower stratospheric vortex, while strongly distorted, was still intact. In 2007 and 2008, the lower stratospheric vortex did not subsequently break down, as the influence of those brief major SSWs was not that deep; in 2009 the lower stratospheric vortex broke down completely in early February and never reformed (Manney *et al*., in press).

Figure 4 (colour plate II) shows ACE-FTS measurements of long-lived trace gases in the Arctic polar vortex during the IPY winters. The increase in CH_4 and N_2O and decrease in CO surrounding the late-December to January gap in vortex coverage is an artifact of the ACE-FTS sampling moving from vortex core (lower CH_4 and N_2O, higher CO) to vortex edge beforehand, and from edge to core afterwards (*e.g*. Manney *et al*., 2007, 2009). Other variations are consistent with the patterns seen in MLS measurements (*e.g*. Manney *et al*. (in press) show MLS vortex averaged CO and N_2O for 2009; Manney *et al*., 2009 show MLS and ACE vortex averages for the 2005-2006 winter). In December and early January, CO (and to some extent CH_4) show the early winter descent of mesospheric air into the polar vortex in each year, but the variations in the extent of the signature highlights the large interannual variability in descent (closely linked to temperature variability) and vortex isolation in the upper stratosphere. In 2009, that signature of confined descent is abruptly terminated in mid-January, at the start of the major SSW; as the upper stratospheric vortex reformed, a signature of strong confined descent was seen once again. Manney *et al*., (in press) show these features in MLS data, and very similar behaviour was seen in ACE-FTS and MLS data during the strong January 2006 SSW (Manney *et al*., 2009). A similar, but weaker, signature is seen during the brief February 2007 and February 2008 major SSWs; the stronger signature in 2008 results partly from mesospheric air having descended further into the stratosphere vortex before the SSW in that year, but also is consistent with the somewhat stronger SSW in 2008 than 2007 (*e.g*. Figure 1).

Harvey *et al*. (2002) have developed a methodology for depicting aspects of the three-dimensional structure and evolution of the polar vortex. **Figure 5** (colour plate III) shows snapshots for days corresponding to warming onsets during the year 2007, 2008, and 2009. Full animations may be viewed on the SPARC-IPY website (**http://www.atmosp.physics.utoronto.ca/SPARC-IPY/**).

Lidar Observations of Temperature in the Stratosphere and Mesosphere in the Arctic Winter

A network of five Rayleigh lidars has conducted soundings of the stratosphere and mesosphere during the IPY winters (*i.e*. 2007-2008, 2008-2009). The location of the lidars is shown in **Figure 6**. These lidars provide high-resolution measurements of temperature in the stratosphere and mesosphere, and have previously contributed to validation of the measurements from the Atmospheric Chemistry Experiment (ACE) satellite (Sica *et al*., 2008). **Figure 7** shows temperature profiles measured by the lidars in February 2009. The temperature profiles represent an average temperature measured over several hours at nighttime. The measurements at these high latitude sites highlight the longitudinal asymmetries in the circulation of the Arctic stratosphere and mesosphere (*e.g*. Thurairajah *et al*., 2009). Thurairajah *et al*. (2009) presents and compares a variety of temperature measurements from satellites, ground-based instruments, and *in situ* instruments in the Arctic with comparisons to the SPARC atlas. For 2009, measurements at Kühlungsborn, Germany (54°N, 12°E) show a temperature

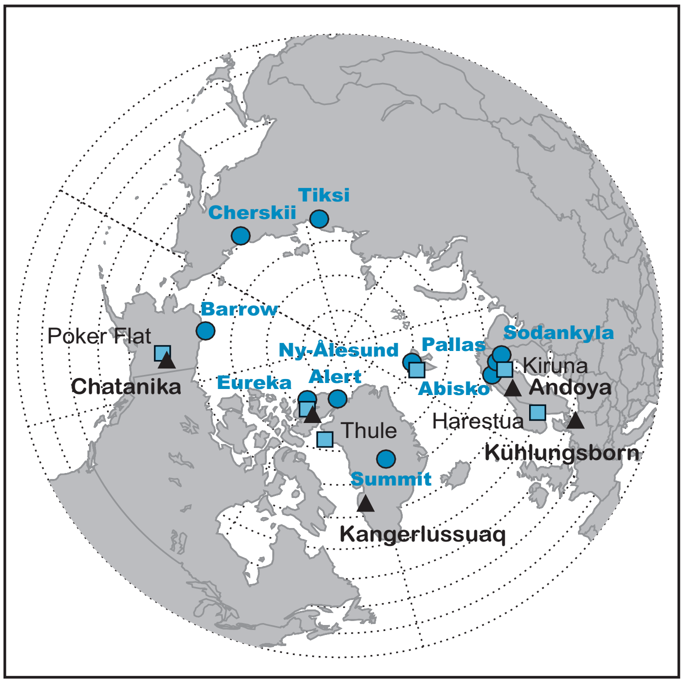

Figure 6. The locations of the IASOA observatories (cyan circles) and the six NDACC stations north of 60° that have FTIR spectrometers (blue squares). Eureka and Ny Ålesund are in both networks. The black triangles show the locations of a network of five Rayleigh lidar sites making ongoing measurements of the middle atmosphere during the IPY. Adapted from IASOA (http://www.iasoa.org).

profile similar to the climatology in the stratosphere and lower mesosphere, with a temperature enhancement in the upper mesosphere. The high latitude measurements at Chatanika, USA (65°N, 147°W), Andoya, Norway (69°N, 16°W), and Eureka (PEARL), Canada (80°N, 86°W) all show an upper stratosphere and lower mesosphere significantly colder than climatology. All four sites show a temperature enhancement in the upper mesosphere. At the highest latitude sites of Andoya and Eureka, the temperature profiles show the structure of an "elevated stratopause" with a cold stratosphere in 2004 and 2006 (Hauchecorne *et al*., 2007; Siskind *et al*., 2007) consistent with MLS measurements shown in Figure 2.

The presence of a separated winter stratopause in the polar region is currently understood as a manifestation of the dynamical coupling between the mesosphere and the lower atmosphere, particularly in association with wave driving that accompanies gravity-wave saturation (Hitchmann *et al*., 1989). It is often a pronounced wintertime feature in both the Antarctic and the Arctic. Its presence and role in the evolution of the stratosphere in the Arctic in recent winters has been noted in observational and modelling studies (Siskind *et al*., 2007, Hoffmann *et al*., 2007) where its strong coupling to stratospheric warmings has also been examined (Manney *et al*., 2008b). This coupling is also consistent with the role of gravity-wave driving in determining the structure of the polar winter stratopause. In this region, the gravity wave driving is most likely associated with upward-propagating orographically excited gravity waves. During stratospheric warmings, strong weakening or reversal of the zonal westerly winds in the stratosphere effectively filters these waves in the lower stratosphere. Removing the gravity wave forcing from the diabatic circulation in the mesosphere typically inhibits relaxation of the atmosphere in that region toward a radiative equilibrium state. Restoration of westerly winds, in association with stratospheric cooling following the warming, again permits upward propagation of these gravity-waves with the associated wave saturation and wave driving in the mesosphere.

Although this interpretation of the role of gravity wave driving is consistent with the observed behaviour of the polar winter stratopause, corroborating direct observations of the gravity wave activity and its variation in the upper stratosphere and mesosphere during and following stratospheric warming events are not usually reported. However, Rayleigh lidar observations yield measurements of the atmospheric density profile at 30-min resolution. The density measurements can be combined with the nightly temperature to yield measurements of the potential energy of the gravity-wave fluctuations (*e.g*. Wilson *et al*., 1991). **Figure 8** shows the relative density fluctuations measured by the Rayleigh lidar at Chatanika on February 11, 2008. **Figure 9** shows the gravity wave potential energies measured at three of the lidar sites in early 2008 (*i.e*. Kühlungsborn, Chatanika and Kangerlussuaq, Greenland). The gravity wave energies at Chatanika are generally lower than Kühlungsborn and Kangerlussuaq. Figure 9 also shows the magnitude of the stratospheric winds at these three sites in early 2008. The low wave energies at Chatanika are consistent with the weaker winds. Ray tracing studies have shown that the weaker winds associated with the Aleutian anticyclone result in blocking of

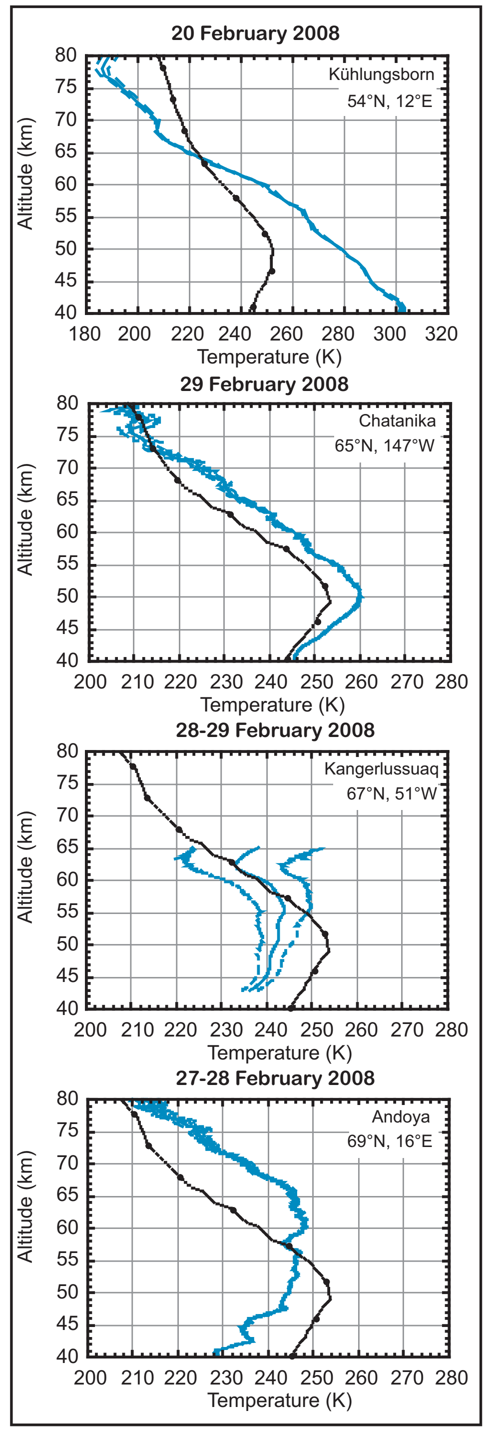

Figure 7. Rayleigh lidar temperatures (blue solid) plotted as a function of altitude from four northern hemisphere sites in February 2008. The uncertainty in the lidar measurements is also plotted (blue dashed). The SPARC reference atlas temperatures are plotted for comparison (black dashed with dot).

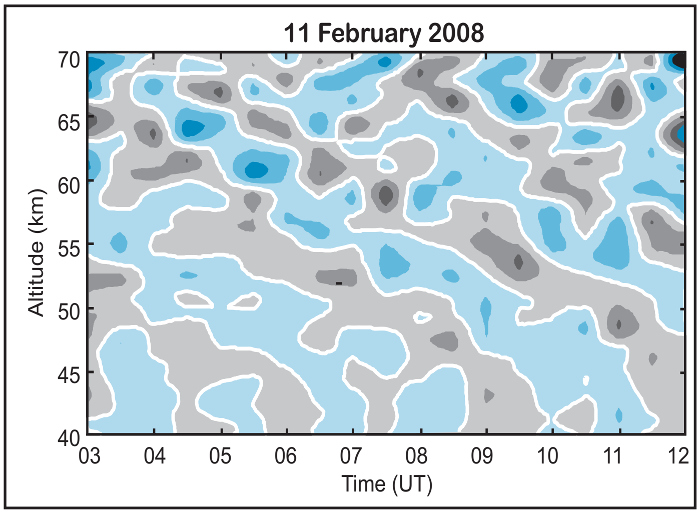

Figure 8. Relative density fluctuations as a function of time and altitude measured by Rayleigh lidar at Chatanika, Alaska (65°N, 147°W). The white contour marks the 0% fluctuation, 0–1% (light grey), 1–2% (medium grey), >2% (dark grey), 0–-1% (light blue), -1–-2% (medium blue) <-2% (dark blue). Data represents fluctuations with observed periods 1 h – 4 h, and vertical wavelengths 2 – 30 km.

upwardly propagating orographic gravity waves (*e.g*. Dunkerton and Butchart, 1984). Studies of the gravity wave activity in early 2009, to see how gravity wave activity is affected by the major change in the Arctic stratospheric circulation in February 2009, are in progress. Direct observations of the gravity wave activity will allow assessment of the role of gravity waves in the evolution of the Arctic winter stratopause as exemplified by formation of the "elevated stratopause" described by Siskind *et al*. (2007).

Stratospheric Chemistry during IPY

In the Arctic stratosphere, average ozone column amounts show high interannual variability, with low ozone values in late winter and spring during cold winters when the Arctic polar vortex breakup occurs late in spring, and high ozone values during warm winters with a disturbed vortex (WMO, 2007). Both dynamically-driven processes, such as those discussed here and chemically-driven processes such as heterogeneous chemistry and halogen activation contribute to variability in Arctic ozone. However, the extent to which each of these basic winter processes affect Arctic ozone varies strongly from year to year. Extreme ozone depletion has been observed when vortex temperatures were low enough to sustain polar stratospheric clouds over a period of few days, while little or no ozone loss was observed during warm winters with a disturbed vortex (WMO, 2007). The low temperatures of an extremely cold Arctic polar vortex may sustain polar stratospheric clouds and/or prolong their existence (*e.g*. Singleton *et al*., 2007) leading to substantial chlorine activation (Santee *et al*., 2008 and references therein). To investigate the influence of chemical processes on the stratospheric ozone distribution in the Arctic atmosphere, and to monitor the ozone recovery in the future, it is crucial to have continuous high-quality measurements of ozone and its related constituents in the stratosphere (WMO, 2007). While satellite-borne instruments provide near global coverage of the stratosphere with high spatial resolution, ground-based observations complement them with high temporal resolution that can be used to provide insight into local processes.

Satellite Measurements Across the Arctic

Aura MLS provides observations of many species important to polar process studies, including HNO_3, HCl, ClO, H_2O, and ozone, as well as long-lived tracers such as N_2O, that are important in assessing the relative effects of dynamical and chemical processes. MLS data have been used in numerous studies of polar processing, including studies of large ozone losses in the 2004-2005 winter (*e.g*. Manney *et al*., 2006, Singleton *et al*., 2007), examination of the effects of a vortex intrusion on polar processing (Schoeberl *et al*., 2006), and a comprehensive study of chlorine partitioning in several Arctic and Antarctic winters (Santee *et al*., 2008). **Figures 10** and **11** (colour plate III and IV) provide an overview of MLS observations of polar processing during the three IPY winters.

Figure 10 shows equivalent latitude[2] (EqL) time series of MLS HCl, ClO and ozone in the lower stratosphere (490K, ~50hPa, ~18km) during the past three winters. Black overlaid contours show the regions where temperatures - averaged around EqL contours - were below the approximate threshold for polar stratospheric cloud (PSC) formation; localised regions of temperatures low enough for PSC formation were present both before and after the periods indicated here (when the cold area was large enough to appear in this average). As noted in the previous section, low temperatures persisted longest in 2007, but were lower during the cold periods in 2008 and 2009. In each year, decreasing HCl and increasing ClO heralds activation of chlorine through reactions on PSCs. The patterns of both depressed HCl and enhanced ClO de-

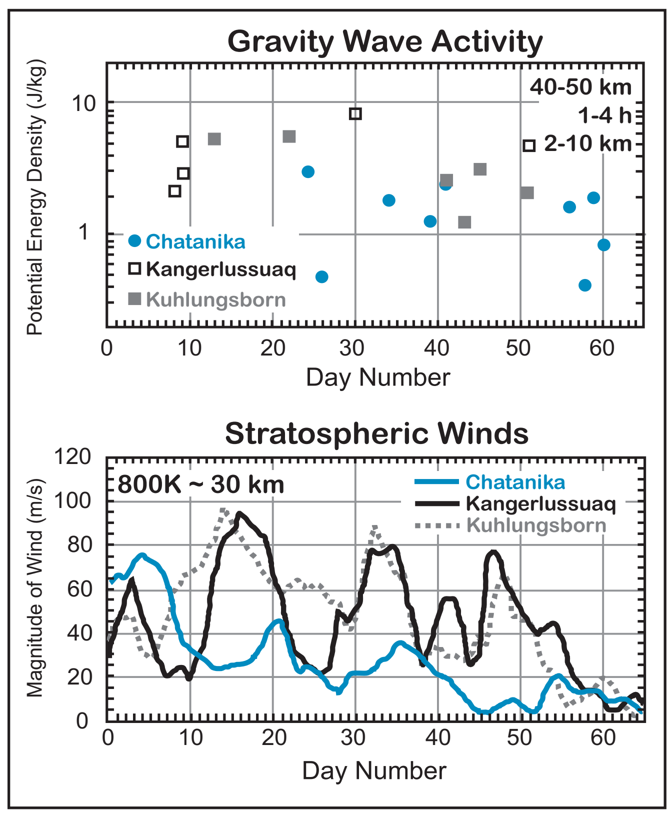

Figure 9. (Upper) Potential energy of gravity waves measured in early 2008 at Kühlungsborn (54°N, 12°E), Chatanika (65°N, 147°W) and Kangerlussuaq (67°N, 51°W) as a function of day number (1 = January 1). (Lower) Magnitude of 800K winds from (UK) Meteorological Office as a function of day number at corresponding locations.

[2]The latitude that would enclose the same area between it and the pole as a given PV contour, commonly used as a vortex-centered coordinate.

pend not only on the temperatures, but also on the location of the cold region with respect to the vortex and strong winds, which determines how extensively and where PSC-processed air is transported within the vortex (*e.g*. Manney *et al*., 2003). In addition, ClO enhancement occurs primarily in sunlit regions. Thus, the differences in patterns of chlorine activation depend on many aspects of the circulation. Substantial chlorine activation began in mid-late December in each year, with activated chlorine filling most of the vortex by late January in 2007 and 2008, and by mid-January in 2009. Similar timing of activation was seen in earlier winters observed by MLS (Santee *et al*., 2008).

The earlier extensive activation in 2009 is consistent with a more distorted, active vortex, of which larger portions experience sunlight, and throughout which processed air is transported more extensively. Similar early activation was seen in 2005-2006 in the active, distorted vortex prior to the January major SSW in that year (Santee *et al*., 2008). Chlorine activation was more complete in 2008 than in 2007, consistent with lower temperatures in 2008. Activation persisted until late March 2007, mid-March 2008, and was curtailed by mid-February 2009 as a result of the major SSW. In each year, vortex ozone begins to decline by late January to early February. Since transport processes (primarily descent in the vortex) tend to increase ozone, the decrease is an indication of chemical loss. In 2009, the decrease halts after a few weeks, as the vortex breaks up during the major SSW, so chemical loss was not extensive. Ozone continued to decrease through early March in 2007 and 2008, over a broader region and somewhat more quickly in 2008 than in 2007.

Figure 11 shows the vertical extent of observed polar processing in the three winters as vortex averages (within an sPV contour) of HNO_3, HCl, ClO and ozone in the lower through middle stratosphere. In the lower stratosphere, the averages after late February 2009 are not useful since the lower stratospheric vortex had broken up. Decreases in HNO_3 indicate sequestration in PSCs; the decreases do not appear very dramatic in these vortex averages because the region of sequestration (low temperatures) typically does not fill the vortex. The largest HNO_3 decreases in early 2008 indicate most extensive PSC activity in that year. HCl and ClO show the longest-lasting, most intense, and deepest vertical extent of chlorine activation in early 2008, with long-lasting activation also in 2007, and early deactivation in 2009 after the major SSW. The upward tilt of ozone contours indicates decreasing vortex ozone; this began in late January in 2007 and 2009, and in early February in 2008. In 2008, lower ozone values appear somewhat sooner at higher levels (near/above 20 km), consistent with chlorine activation extending to higher levels.

While the observed differences in ozone in the three IPY years appear consistent with differences in temperatures and chlorine activation, transport processes play such an important role in the distribution of Arctic ozone that separating dynamical and chemical effects, and thus quantifying chemical ozone loss, requires much more detailed analysis. Methods for doing so typically involve using either transport models or long-lived trace gas measurements to quantify transport (*e.g*. WMO, 2007). State-of-the-art data assimilation systems (such as GEOS-5, ECMWF and others in the SPARC-IPY database) provide high-quality winds for transport calculations; Aura MLS measurements of N_2O provide a long-lived tracer that is useful for assessing transport processes.

ACE-FTS on SCISAT provides measurements that complement those obtained by Aura MLS. Profiles of over 30 different species are retrieved from the ACE solar occultation spectra. These include species such as ozone, HCl, $ClONO_2$, HNO_3, and NO_2 that are valuable for studies of polar ozone chemistry and the long-lived species N_2O, CH_4 and HF that are needed to understand the transport of the air masses of interest. Prior to IPY, the ACE-FTS measurements from winter 2004-2005 were used to investigate partitioning of inorganic chlorine between the two reservoir species HCl and $ClONO_2$ (Dufour *et al*., 2006), and to study denitrification in the Arctic vortex using correlations with long-lived tracers (Jin *et al*., 2006). Enhancements in NO_x in the Arctic vortex, due to strong downward transport of NO produced by energetic particle precipitation, were studied by Randall *et al*. (2006) using winter 2006 observations from ACE-FTS. In the study by Santee *et al*. (2008), the HCl and ClO measurements from Aura MLS were combined with the $ClONO_2$ and HCl measurements from ACE-FTS and model results from the SLIMCAT chemical transport model to investigate chlorine partitioning during two Arctic and two Antarctic winters. In addition to the ACE-FTS tracer measurements during IPY that were discussed previously (Figure 4), a number of studies are under way using ACE-FTS results from IPY. These include interannual variability in ozone depletion using constituent and tracer measurements from ACE-FTS and MLS (Taylor *et al*., in preparation) and year-to-year differences in energetic particle precipitation enhanced NO_x in the Arctic vortex (Randall *et al*., submitted).

Ground-based Measurements Across the Arctic

The IPY project #196, International Arctic Systems for Observing the Atmosphere (IASOA: **http://www.iasoa.org**) aims to develop a legacy of continuous measurements from existing stations and the newly established intensive Arctic atmospheric observatories, with a focus on measurements of standard meteorology, greenhouse gases, atmospheric radiation, clouds, pollutants, chemistry, aerosols, and surface energy balances. The goal is to develop sufficient understanding to determine relative contributions of natural *versus* anthropogenic forces in shaping the nature of the Arctic atmosphere. Figure 6 shows the distribution of IASOA observatories, along with the six NDACC stations north of 60°N that have FTIR spectrometers.

The facility at Eureka is part of both networks, and comprises a Weather Station, run by Environment Canada, and the Polar Environment Atmospheric Research Laboratory (PEARL), run by the Canadian Network for the Detection of Atmospheric Change (CANDAC: **http://www.candac.org**). PEARL is a refurbishment of an existing laboratory for studying stratospheric ozone, but its mission has been extended to include air quality and climate issues. It is now home to more than 25 instruments that are being used to investigate chemical and physical processes in the atmosphere from the ground to 100 km. These include a range of *in situ* and remote sounding instruments including lidars, radars, spectrometers, radiometers, and samplers.

A new Bruker IFS 125HR FTIR spectrometer was installed at PEARL in July 2006 (Batchelor *et al*., in press). This instrument

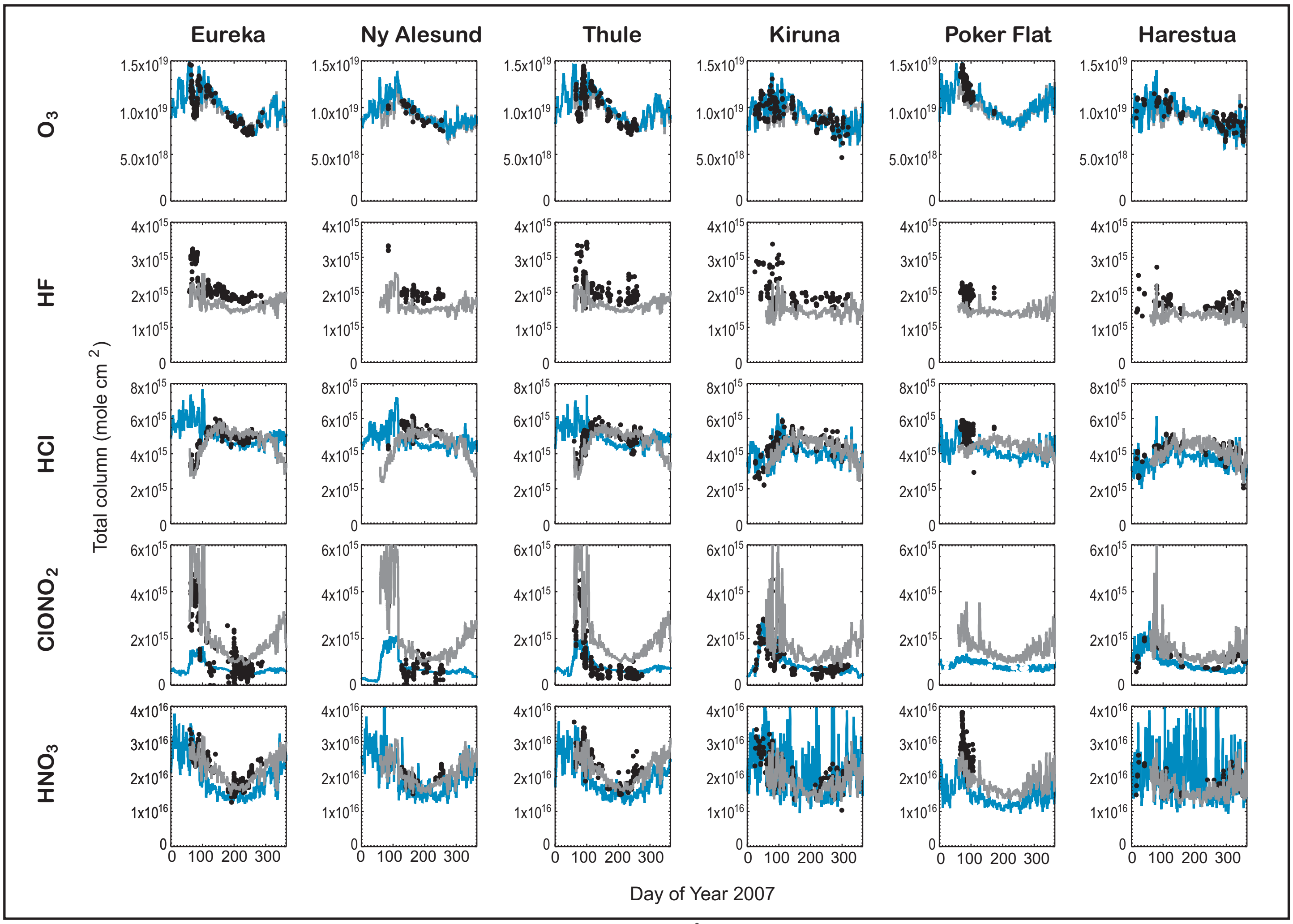

Figure 12. Total columns of ozone, HF, HCl, $ClONO_2$, and HNO_3 at Eureka, Ny Ålesund, Thule, Kiruna, Harestua, and Poker Flat during 2007. FTIR measurements (black circles), GEM-BACH model results (grey lines), and CMAM-DAS model results (blue lines) are shown.

is a very high spectral resolution commercial spectrometer, which is operated semi-autonomously throughout the sunlit parts of the Arctic year. It replaces a Bomem DA8 FTIR that was operated at Eureka by Environment Canada from 1993 to 2008. During the 2007 and 2008 IPY, measurements were made with ground-based FTIR spectrometers at PEARL and at five other NDACC stations around the Arctic. These stations are Eureka, Canada (80°N, 86°W); Ny Ålesund, Spitsbergen (79°N, 12°E); Thule, Greenland (77°N, 69°W); Kiruna, Sweden (68°N, 20°E); Poker Flat, Alaska (65°N, 147°W) and Harestua, Norway (60°N, 11°E).

Figure 12 shows the total columns of five key chemical species involved in stratospheric ozone depletion as measured at each station during 2007: ozone, the fluorine reservoir and tracer HF, chlorine reservoirs HCl and $ClONO_2$, and the nitrogen reservoir HNO_3. In addition, results are displayed from the IPY runs of two global chemistry-climate models[3] with assimilated meteorological variables (winds and temperatures) in the troposphere and stratosphere.

The measurements, in conjunction with dynamical analyses and derived meteorological products, are being utilised to better understand the composition of the Arctic stratosphere during IPY. The high level of variability associated with polar vortex dynamics is clear during the first 100 days of the year, with very different total columns observed at each station depending on whether the measurements are made inside or outside the vortex. Excellent agreement in the ozone columns is seen for both models. However, the CMAM-DAS fails to correctly partition chlorine species within the polar vortex. The high variability observed in the summer-time CMAM-DAS HNO_3 over the European stations Harestua, Kiruna and, to a lesser extent, Ny Ålesund, results from local NO_x emissions in the troposphere that contribute to the HNO_3 total column. This is not observed in the GEM-BACH HNO_3 column as there is no tropospheric chemistry in that model. In general, both models are seen to do a very good job of capturing the polar stratospheric chemistry, with the annual cycle of all of these gases comparing favorably to the FTIR measurements.

While this comparison is preliminary, it illustrates the strength of combining data from different observatories to obtain a more complete picture of the Arctic stratosphere. Polar vortex dynamics tend to dominate the observed columns, and dynamical analyses (not shown) are being used to characterise the underlying vortex conditions at each station. The measurements

[3]These results are available through the Stratospheric Processes and Their Role in Climate (SPARC) Data Center, http://www.sparc.sunysb.edu/): the Canadian Middle Atmosphere Model – Data Assimilation System (CMAM-DAS), and Environment Canada's Global Environmental Multiscale stratospheric model, run with the online BIRA (Belgian Institute for Space Aeronomy) Atmospheric CHemistry package (GEM-BACH)

and the models have a symbiotic relationship: the comparisons enable an assessment of how well the model runs are simulating chemical conditions near the poles (particularly for the meteorological data assimilated runs that have been generated for IPY), while the models, once verified, can contribute to the interpretation of the measurements. We are currently utilising these and other measurements in conjunction with the models and dynamical analyses to better understand conditions in the Arctic stratosphere during IPY.

Quantifying Arctic Chemical Composition in the Future

Continued observations of stratospheric composition are essential for ascertaining that the ozone layer is 'recovering' as expected, and for quantifying its progress and the impact of climate change on this recovery. In addition to observing the decrease in stratospheric halogens, global vertically-resolved composition profile observations are critical to quantifying changes in stratospheric dynamics and meteorology that can strongly modulate ozone layer recovery. Quantification of chemical ozone loss in the Antarctic and Arctic stratosphere requires the separation of complex chemical and dynamical influences on ozone, for which continued daily global vertically-resolved composition observations, including during polar night, are essential.

Our understanding of critical chemical, dynamical, and radiative processes in the stratosphere has advanced dramatically over the last two decades, thanks in large part to the wealth of composition observations from satellite, airborne, and ground-based instruments. However, the diversity and frequency of such observations is waning. Aircraft and balloon flights are less frequent than in previous years, and resources for ground-based observations are diminishing. The Arctic is a remote and difficult environment: maintaining stations and data records is an ongoing challenge. It is critical that we continue to acquire the long-term measurements that are the strength of ground-based instruments.

All of the satellites making stratospheric composition profile measurements are currently, or will shortly be, operating in "extended mission" (*i.e.*, beyond their design lifetimes). Plans for successor missions are sketchy at best, with the only confirmed stratospheric observations being ozone profiles measured by ultraviolet limb scatter (thus limited to daylight) from the OMPS (Ozone Mapping and Profiler Suite) instrument to launch on the NPOESS Preparatory Project (NPP) spacecraft no earlier than Spring 2011. The Japanese SMILES (Superconducting Submilimeter-wave Limb Emission Sounder) instrument to be installed on the International Space Station (ISS) in 2009 will make high precision microwave limb composition profile measurements in the stratosphere and mesosphere. However, observations are restricted to 38°S to 65°N, and the nominal "prime mission" duration is only one year. A significant gap in stratospheric observations is anticipated between NASA's Aura satellite and the expected successor Global Atmospheric Composition Mission (GACM). A similar gap between ESA's Envisat and Sentinel 5 missions is highly likely. The long and valuable record of high precision, high vertical resolution solar occultation observations from the Polar Ozone and Aerosol Measurement (POAM) and Stratospheric Aerosol and Gas Experiment (SAGE) series of instruments, and from the Halogen Occultation Experiment (HALOE) on UARS, is currently being extended only by the Canadian Atmospheric Chemistry Experiment Fourier Transform Spectrometer (ACE-FTS), and there are no confirmed plans for future occultation measurements.

Summary

In this article we have presented an overview of the Arctic wintertime stratospheric circulation and chemistry that has been revealed by ground-based lidar, FTIR spectrometer and satellite measurements that have become available during the IPY period. Of necessity this overview is broad and not detailed in its perspective. However, as noted in the references, a substantial amount of detailed work has already been published in peer reviewed journal articles and more will appear in forthcoming papers.

Much progress has been made toward preparing the comprehensive picture of the structure and evolution of the Arctic polar vortex that was originally envisaged as a major goal of SPARC-IPY and its linked IPY activities. It is clear that such a goal would have much less achievable in the absence of the coincidence of a critical combination of ground-based and satellite measurement systems and observations.

An extended record of stratospheric composition observations is critical for placing our understanding of the stratosphere and its future evolution on a sound scientific footing. We have drawn attention to the looming and profound gap in stratospheric composition observations from satellites. This is an issue of particular concern to the SPARC community.

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Studies of the Antarctic Stratosphere During IPY

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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

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	77.8ºS	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/**).

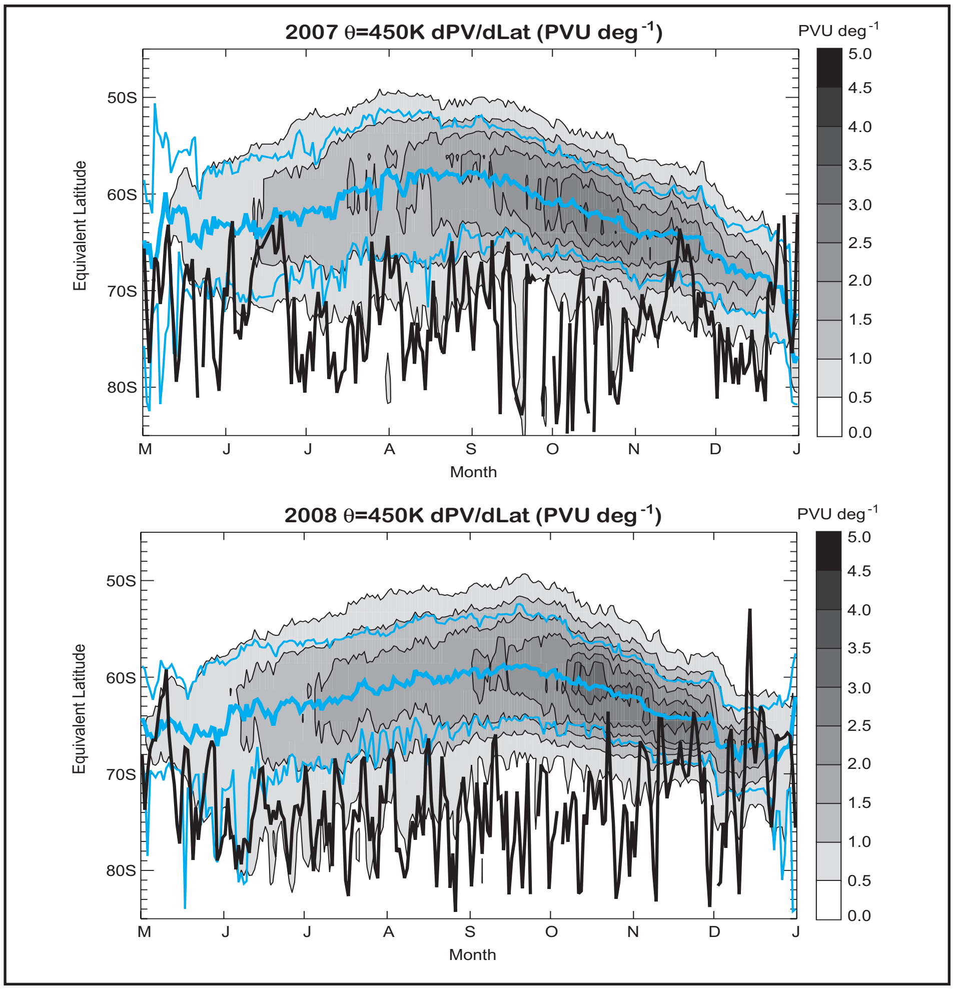

Figure 2: Potential vorticity gradient (expressed in potential vorticity units (PVU; 1 PVU = 10^{-6} K m^2 kg^{-1} s^{-1}) per degree of equivalent latitude) as a function of time and equivalent latitude for the 450 K potential temperature isentrope (near 70 hPa pressure, or 18 km altitude), derived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

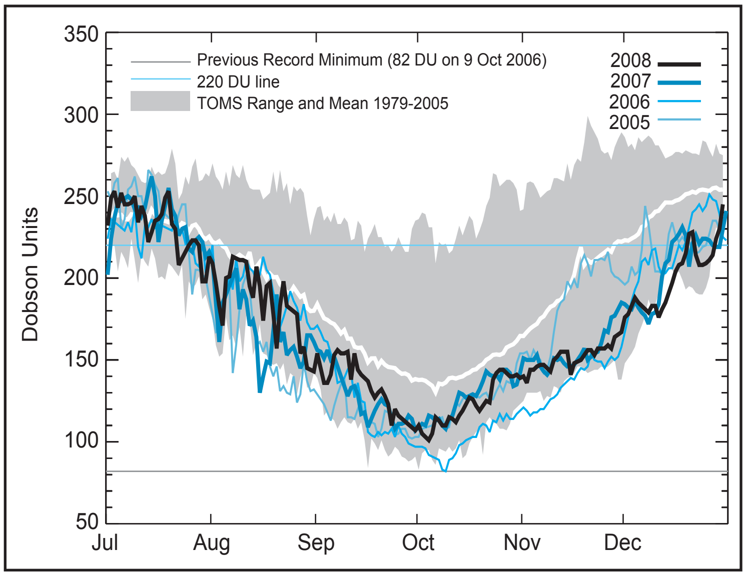

Figure 3. Daily minimum total column ozone for the Southern Hemisphere based on OMI and TOMS satellite data. The 2008 hole (OMI data) is indicated by the thick black line, the 2005, 2006 and 2007 holes (OMI data) by the light blue, cyan and thick blue lines respectively. The grey shaded area and white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

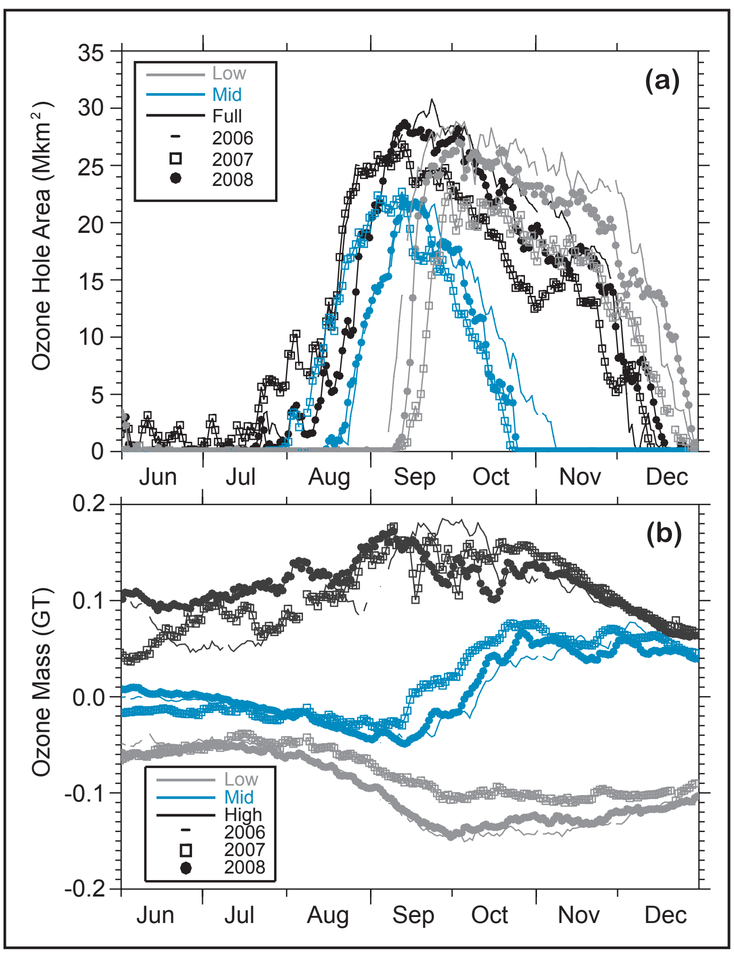

Figure 4: Analysis of gridded Aura MLS v2.2 ozone measurements south of 50°S for 2006-2008. (a) Time series of ozone hole area for three partial columns: 146-68 hPa ('low'), 46-10 hPa ('mid') and 464-0.1 hPa ('full'). Each time series represents the area where the partial column ozone amount, expressed 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.

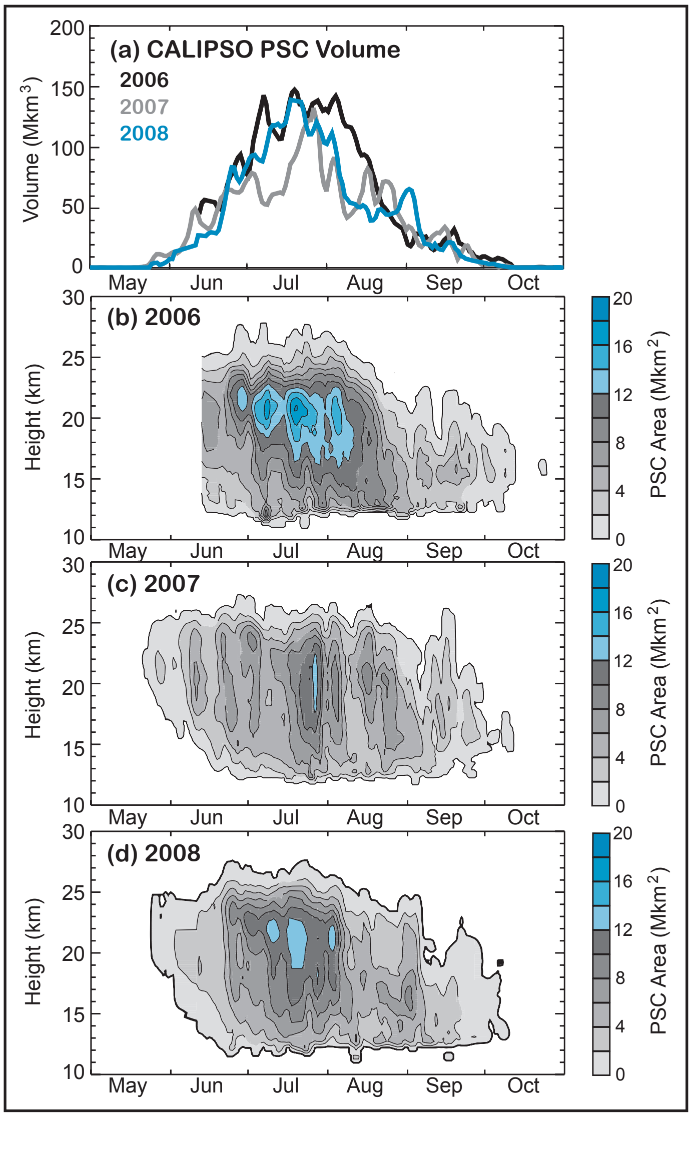

Figure 5: Daily PSC time series for Antarctica derived from the CALIPSO second generation PSC detection algorithm described by Pitts et al. (2009). (a) Time series of total PSC volume for 2006, 2007 and 2008. PSC area as a function of altitude for the (b) 2006, (c) 2007, and (d) 2008 seasons.

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.

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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

SPARC-IPY Data Archive

D. Pendlebury, SPARC IPO, University of Toronto, Canada (diane@atmosp.physics.utoronto.ca)

The goal of SPARC-IPY is to document the dynamics, chemistry and microphysical processes in the polar vortices during the IPY period, with a focus on coupling between the stratosphere and troposphere, and between the stratosphere and mesosphere. Satellite observations, aircraft and balloon campaigns and ground-based observations will all contribute to studying the state of the polar atmosphere during the IPY period. Data assimilation products can enhance this data set by filling gaps in the data during polar night, or inconsistent spatial and temporal coverage. The final product will be a data archive intensely focused on the IPY period.

Data assimilation groups participating in SPARC-IPY are the Canadian Middle Atmosphere Model - Data Assimilation System (CMAM-DAS; formerly CMAM-FDAM), the European Centre for Medium-Range Weather Forecasting (ECMWF), the Global Environmental Multi-scale – BIRA Atmospheric Chemistry module (GEM-BACH; formerly GEM-STRATO) from Environment Canada, the National Center for Environmental Prediction (NCEP), the Global Modeling and Assimilation Office (GMAO) from NASA, and the UK Met Office - Stratospheric Assimilated Data (UKMO and UKMO-UARS). Data collection is almost complete. Where possible, the analyses were collected through 31 May 2009, to ensure that the break down of the Arctic winter vortex was completely captured. We are also hoping to include BASCOE/PROMOTE (PROtocol MOniToring for the GMES Service Element), which is a project of the European Space Agency. Negotiations to add this data set to the SPARC-IPY archive are ongoing.

The data is archived for use by the community at the SPARC Data Center, located at Stonybrook University in New York. The data is publicly available for non-commercial purposes through the SPARC Data Center (**http://www.sparc.sunysb.edu/**). Please go to the registration page at **http://www.sparc.sunysb.edu/html/user_ipy.html** and fill out the online registration form. You will then be provided with a user ID for the web interface. More information about the SPARC IPY project and related IPY projects may be found on the SPARC IPY homepage at **http://www.atmosp.physics.utoronto.ca/SPARC-IPY/**.

Table 1: Summary of the SPARC-IPY Data Archive

Model	Horizontal Grid	Vertical Grid	Dynamical Fields	Chemistry and Microphysics	Time Period and Sampling
CMAM-DAS (formerly CMAM-FDAM)	3.75x3.75 97 longitudes 48 latitudes	71 model levels	Temperature, u velocity, v velocity, geopotential height, vorticity, divergence, log surface pressure	Q, specific humidity, cloud liquid water content, cloud ice water content, cloud cover, Odd oxygen, NO_x, ClO_x, BrO_x, HNO_3, H_2O, CH_4, HCl, CO, N_2O,O_3, NO_2, ClO, BrO, $ClONO_2$, NO_3, N_2O5, O3c	1 November 2005 to 31 March 2009 every 6 hours
ECMWF	0.25x0.25 1440 longitudes 721 latitudes	92 model levels	Temperature, u velocity, v velocity, geopotential height, divergence, log surface pressure	Q, specfic humidity, cloud liquid water content, cloud ice water content, cloud cover, O_3	1 June 2007 to 31 May 2009 every 6 hours
GEM-BACH (formerly GEM-STRATO)	1.5x1.5 240 longitudes 120 latitudes	80 model levels	Temperature, u velocity, v velocity, geopotential height, log surface pressure	specific humidity, CH_4, HCl, CO, N_2O, NO, N_2O_5, O_3, NO_2, ClO, NO_3, HNO_3, HOCl, HF, $ClONO_2$	1 March 2007 to 28 February 2009 every 6 hours
GMAO	0.667 x0.5 540 longitudes 361 latitudes	72 model levels	Temperature, u velocity, v velocity, geopotential height, potential, vorticity, divergence, surface pressure, pressure thickness, temperature tendency	relative humidity, cloud ice water mixing ratio, cloud liquid water mixing ratio, total cloud fraction, optical thickness of all clouds, O_3	1 March 2007 to 31 May 2009 every 6 hours
NCEP	0.313x0.313 1152 longitudes 576 latitudes	64 model levels	Temperature, u velocity, v velocity, geopotential height	specific humidity, cloud water vapour, O_3	1 March 2007 to 31 May 2009 every 6 hours
UKMO	0.5625x0.375 640 longitudes 480 latitudes	27 pressure levels	Temperature, u velocity, v velocity, geopotential height, vertical velocity		1 March 2007 to 31 May 2009 every 24 hours
UKMO-UARS	3.75x2.5 96 longitudes 73 latitudes	24 pressure levels	Temperature, u velocity, v velocity, geopotential height, vertical velocity		1 March 2007 to 31 May 2009 every 24 hours

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Network for the Detection of Atmospheric Composition Change: News and Highlights

M. Kurylo, Earth Science Division, NASA, USA (Michael.J.Kurylo@nasa.gov)
M. Chipperfield, University of Leeds, UK (martyn@env.leeds.ac.uk)

A new section entitled "News and Highlights" has been added to the website of the Network for the Detection of Atmospheric Composition Change (NDACC). This new section has been instituted to highlight significant items of interest within NDACC. We expect to provide updates at least annually following the NDACC Steering Committee meeting. However, important, newsworthy items will be added throughout the year.

Termination of NDACC Primary and Complimentary Station Designations

At the 2008 NDACC Steering Committee meeting, a decision was made to remove the "Primary" and "Complementary" designations of NDACC measurement sites/stations. This original terminology was instituted at the inception of the Network to designate a minimum of five stations with long-term measurement commitments, representing the major geographical regions of the globe (*i.e.* Arctic, Northern Hemisphere (NH) Midlatitudes, Tropics, Southern Hemisphere (SH) Midlatitudes, and Antarctic). At that time, some of these stations were instituted as a combination of several sites, each with various types of instrumentation, such that the sum of all sites comprising a Primary Station included a fairly complete suite of NDACC (then the Network for the Detection of Stratospheric Change (NDSC)) instrument types. It was anticipated that numerous Complementary stations/sites, at which a smaller number of Network-approved instruments were in operation, or at which the measurement commitment was for a shorter period of time, would augment these Primary Stations.

After nearly two decades of successful Network operations, the need for these designations no longer exists. In fact, their use now leads to some confusion and occasional misunderstanding. For example, some Complementary Sites have built up suites of instruments that are more comprehensive than those at some of the Primary Stations. And many Complementary stations/sites have measurement commitments that are just as long-tem as those at Primary stations.

Further, these designations have occasionally been misinterpreted to imply that the measurements at, and data from Complementary stations are of lesser quality than those at Primary stations, whereas the requirements to become affiliated with the NDACC are identical for both categories. There is no reduction in the expectations of instrument performance or data quality.

Lastly, some NDACC Principal Investigators felt that a Complementary designation was less advantageous than a Primary designation in justifying a long-term measurement need to their institution or funding agency.

From now on, all sites and stations will be designated simply as NDACC-approved measurement sites/stations. The NDACC Measurement and Analyses Directory is being revised to reflect this change, and measurement locations will be listed under one of the following groupings: NH High Latitudes, NH Midlatitudes, NH Subtropics and Tropics, SH Subtropics and Tropics, SH Midlatitudes, and SH High Latitudes.

Establishment of an NDACC Cooperating Network Affiliation

The NDACC recognises the importance of new measurement capabilities, and of existing capabilities whose heritage was developed external to NDACC, and has encouraged Network affiliation with such measurements. In some cases there are regional, hemispheric, or even global networks of instruments that operate independently of the NDACC, but where strong measurement and scientific collaboration would be mutually beneficial. Such networks often have set up their own quality-assurance guidelines, operational requirements, and data archiving policies, and they have national or international recognition in their own right. In such cases, bringing the network under the NDACC umbrella is neither practical nor desirable. Rather, designation of an interested external network as a "Cooperating Network" may be more appropriate, and can foster collaborative measurement and analysis activities. For such designations to occur, the relevant NDACC Working Group must assess the benefits of mutual data access. The Working Group should further ascertain whether the various protocols of the external network are compatible with those of the NDACC, and are followed consistently and effectively. A protocol detailing the specific process whereby such affiliation can occur is posted on the NDACC web site.

Two New Measurement Capabilities Designated as NDACC-Approved

Since the onset of formal operations, the NDACC has designated several specific instrument types as having official measurement capabilities. These are: Dobson/Brewer spectrometers, Fourier Transform IR spectrometers (FTIRs), Lidars (temperature, ozone and aerosol), Microwave radiometers, and UV/Visible spectrometers. Balloon sondes (ozone and aerosol) and UV spectroradiometers were added shortly after the Network became operational. The Network strives to maintain the operation of as many of these instrument types within the various latitude regions as possible.

As NDACC has matured, its measurement and analysis emphases have broadened to encompass issues such as the detection of trends in overall atmospheric composition and understanding their impacts on the stratosphere and troposphere, and establishing links between climate change and atmospheric composition. These challenges require an expansion of measurement capabilities, particularly in the area of some key climate parameters. Thus, after careful consideration and evaluation by the various NDACC Instrument Working Groups, the Steering Committee approved two new instrument types for NDACC designation: Raman Lidars for profile measurements of water vapour in the troposphere and across the tropopause, and Water Vapour Sondes (Cryogenic frostpoint hygrometers and Lyman-alpha hygrometers) for profile measurements in the troposphere and stratosphere. Data from both instrument types soon will be available in the NDACC data archives.

New Species to be Archived from FTIR Measurements

In the early days of the NDACC, the Infrared Working Group (IRWG) targeted the retrieval of total columns of several gases considered of primary importance to the original goals of the Network. These goals focused on increasing our understanding of ozone chemistry and, in the post-Montreal Protocol period, observing the accumulation (and hopefully the eventual decline) of Cl_y and F_y in the stratosphere. Consequently, the initial gases targeted were ozone, nitric acid (HNO_3), nitrous oxide (N_2O), chlorine nitrate ($ClONO_2$), hydrogen chloride (HCl), and hydrogen fluoride (HF). As the Network matured and science questions evolved to encompass the broader issue of climate change, attributing causal relationships for observed changes in atmospheric composition, and air quality, the IRWG re-evaluated the ability of high-resolution mid-IR Fourier Transform Spectrometers to contribute to and address the new scientific issues. At the 2008 IRWG meeting, the group agreed to add methane (CH_4), carbon monoxide (CO), hydrogen cyanide (HCN), and ethane (C_2H_6) to the existing suite of gases. All Principal Investigators in the IRWG maintain an archive of the recorded spectra since their observational programs began, thereby allowing a re-analysis of the spectra. Consequently, the data record for the new gases will begin from the earliest observations for each site. Some of these data already are available to the public from the NDACC Data Host Facility. Many more will be archived during 2009.

Establishment of an Ad Hoc Working Group to Assess Future NDACC Measurement Strategies and Emphases

At the 2008 NDACC Steering Committee meeting, an *ad hoc* working group was established to review existing and assess future Network measurement strategies and emphases in light of the broadening of Network goals over those established at its inception. While NDACC remains committed to monitoring changes in the stratosphere with an emphasis on the long-term evolution of the ozone layer, its priorities now encompass issues such as detecting trends in overall atmospheric composition, understanding impacts of these changes on the stratosphere and troposphere, and establishing links between climate change and atmospheric composition. The members of this *ad hoc* working group (G. Braathen, M. Chipperfield, T. Deshler, S. Godin-Beekmann, J. Hannigan, K. Kreher, J.-C. Lambert, T. McElroy, R. McKenzie, G. Nedoluha, and W. Randel) solicit your input for their consideration.

♦

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**Thank you for your attention
SPARC International Project Office**

Future SPARC and SPARC-related Meetings

2009

14-26 September	**Water Vapour in the Climate System, International Summer School,** Corsica, France http://www.lmd.ens.fr/wavacs/
19-22 October	**The Extra-tropical UTLS: observations, concepts and future directions,** Community workshop at NCAR, Boulder, CO, USA, http://www.acd.ucar.edu/utls/workshop.shtml
5-7 November	**Ocean-Atmosphere Energy Transport,** California Institute of Technology, Pasadena, CA, USA http://www.eas.caltech.edu/oaet2009
16-19 November	**5th International Atmospheric Limb Conference and Workshop,** Finnish Meteorological Institute Helsinki, Finland, http://fmilimb.fmi.fi/5thlimbmeeting/
30 November-4 December	**Vth Workshop on Lidar Measurements in Latin America,** Instituto Tecnológico de Buenos Aires (ITBA), Buenos Aires, Argentina, http://www.lidar.camaguey.cu/wlmla/5w/w5en_main.htm
14–18 December	**2009 AGU Fall Meeting,** San Francisco, CA, USA, http://www.agu.org/meetings/fm09/

2010

17–21 January	**90th Annual Meeting of AMS,** "Weather, Climate, and Society: New Demands on Science and Services," Atlanta, GA, USA, http://www.ametsoc.org/MEET/annual/

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T.G. Shepherd (Canada)

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V. Eyring (Germany)
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Detection, Attribution, and Prediction of Stratospheric Change: W. Randel (USA), T.G. Shepherd (Canada)

Gravity Waves: J. Alexander (USA)

Data Assimilation: S. Polavarapu (Canada)

CCM Validation Activity (CCMVal): V. Eyring (Germany), D. Waugh (USA), A. Gettelman (USA), S. Pawson (USA), T.G. Shepherd (Canada)

Laboratory Studies joint with IGAC: A.R. Ravishankara (USA), R. A. Cox (IGAC)

Solar Influences for SPARC (SOLARIS): K. Kodera (Japan), K. Matthes (Germany)

Dynamical Variability Activity: P. Kushner (Canada)

UTLS/SPARC Tropopause Initiative: P. H. Haynes (UK), A. Gettelman (USA), M. Geller (USA)

The Role of Halogen Chemistry in Polar Stratospheric Ozone Depletion: M.J.Kurylo (USA), B.-M. Sinnhuber (Germany)

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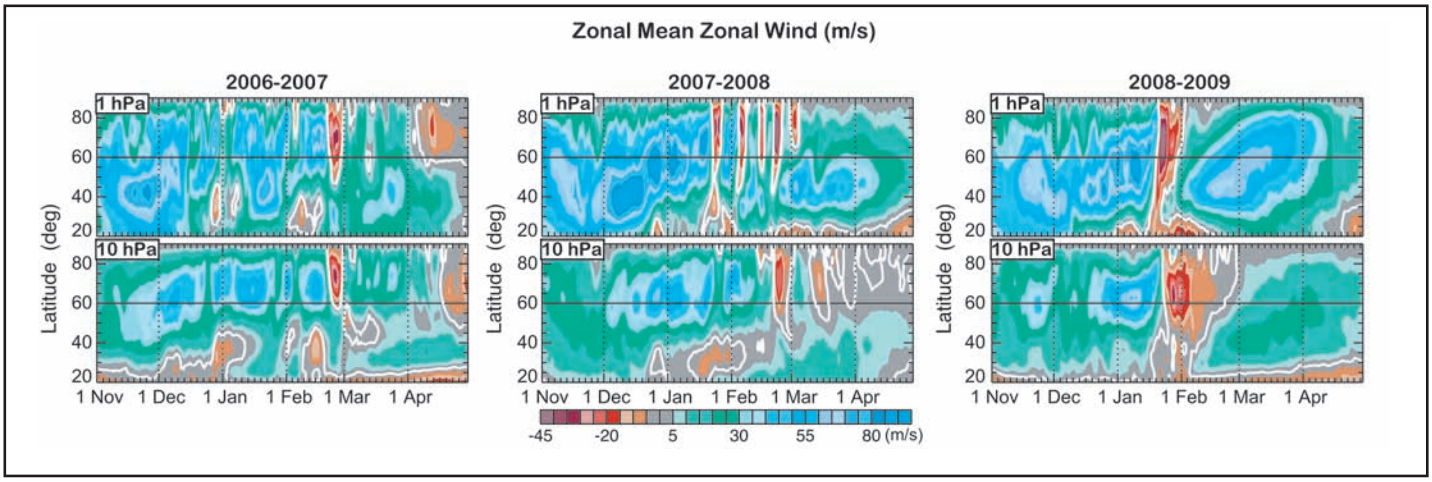
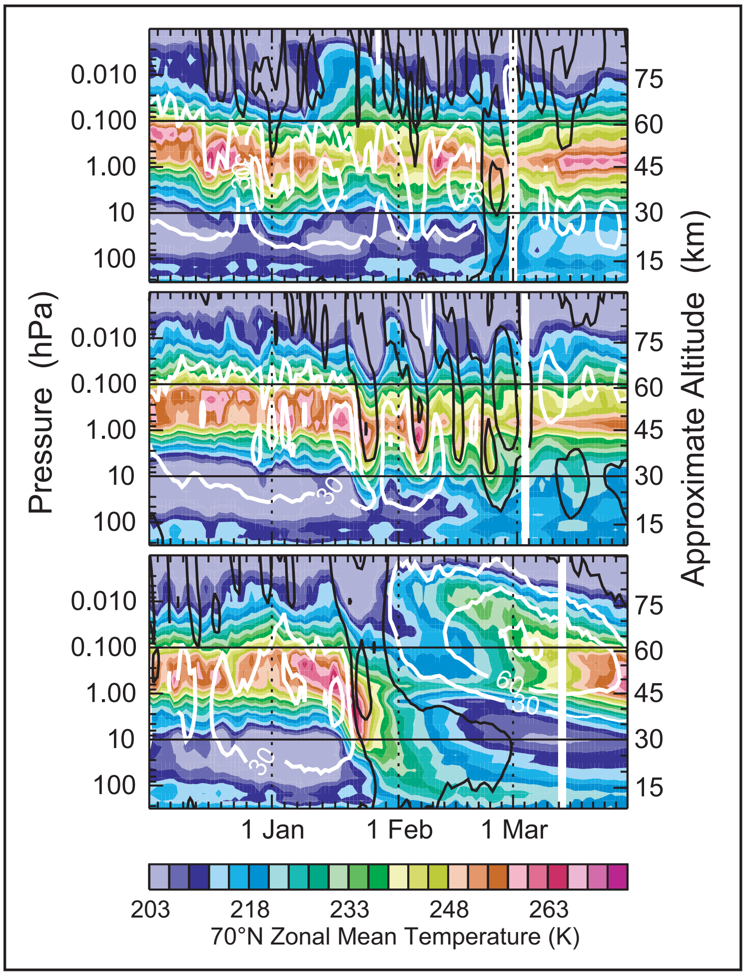
Features of the Arctic Stratosphere during IPY



^ Figure 1

GEOS-5 1 hpa (top) and 10hPa (bottom) zonal-mean zonal winds during (left to right) the 2006—2007, 2007—2008, and 2008—2009 Arctic winters. The black line is at 60°N latitude.



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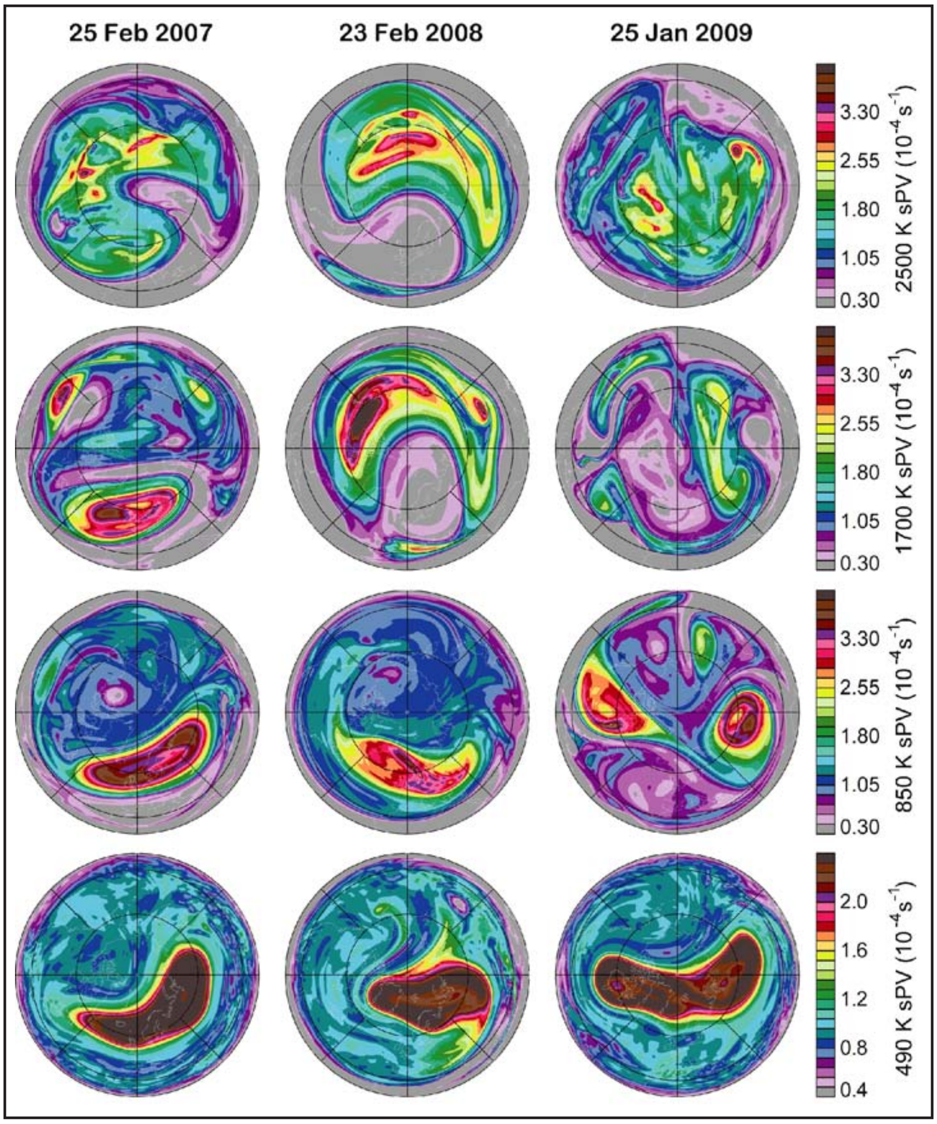
^ Figure 2

MLS zonal mean 70°N zonal-mean temperatures in (top to bottom) 2006-2007, 2007-2008, and 2008-2009. Overlaid contours are zonal mean winds of -30, 0, 30 and 60 m/s, with negative (easterly) and zero values in black, positive (westerly) values in white.

Features of the Arctic Stratosphere during IPY

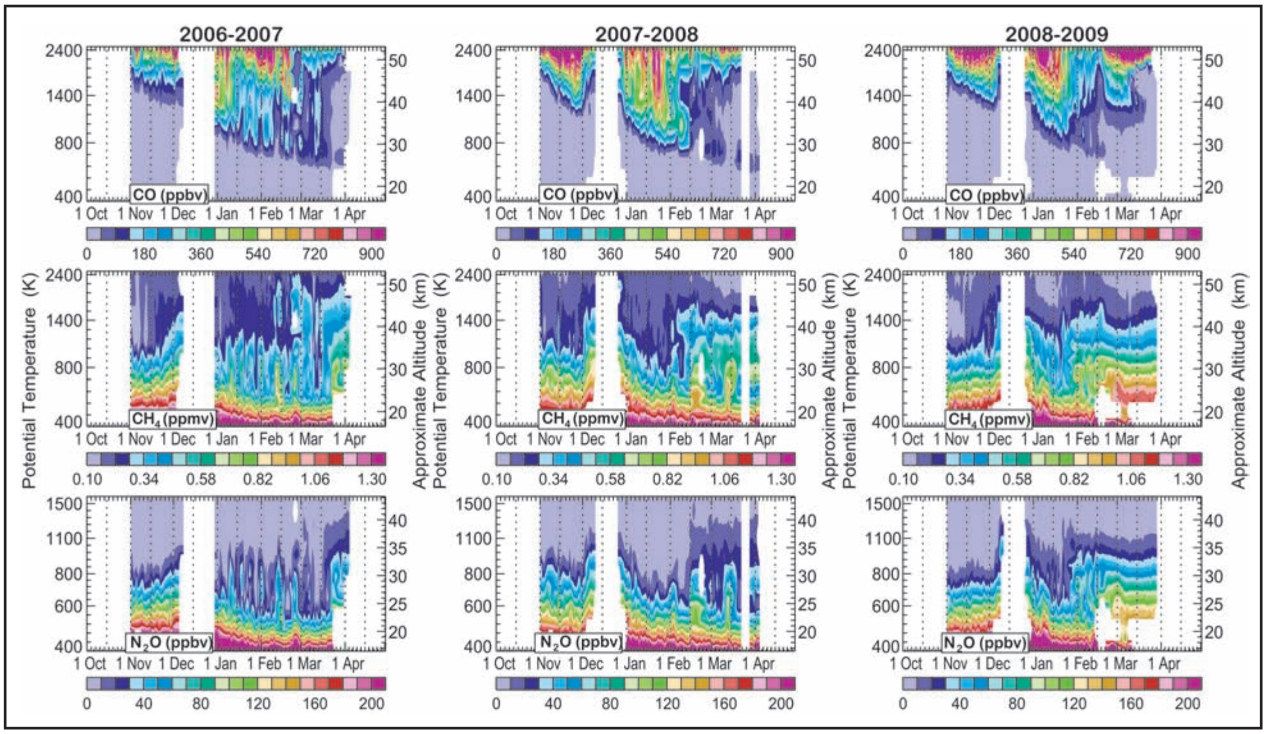


< Figure 3

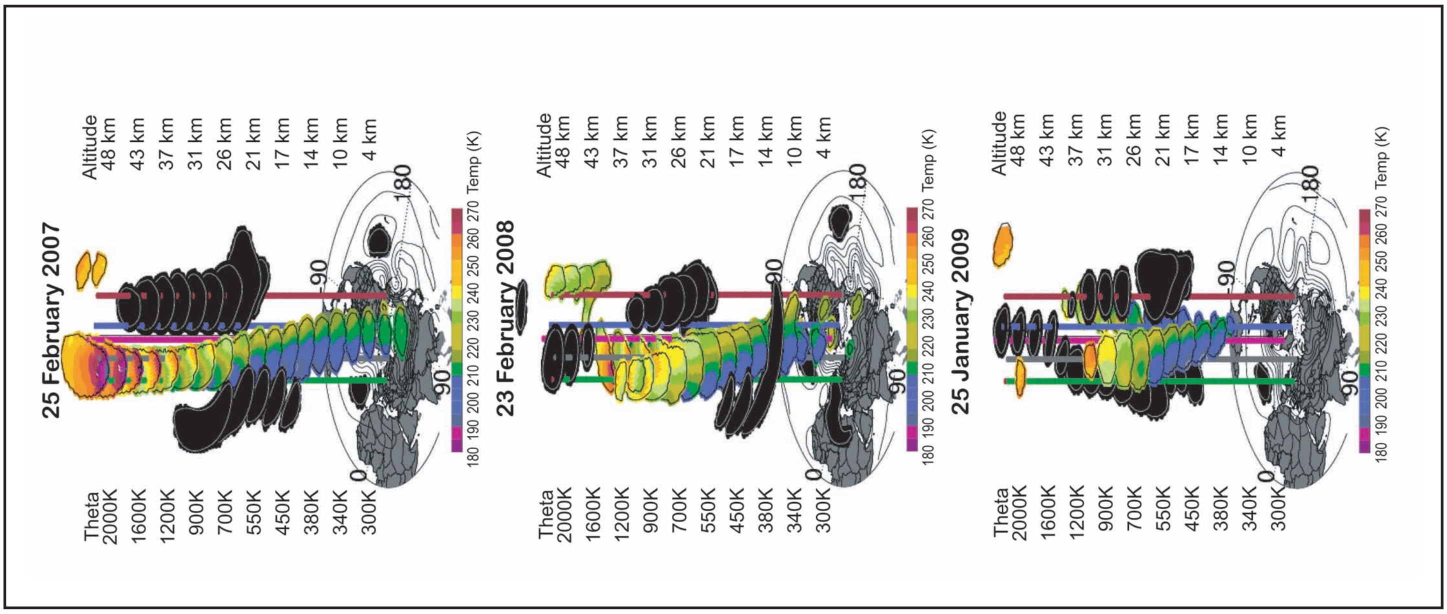
Maps of GEOS-5 scaled potential vorticity (sPV) (e.g. Manney et al., 1994) in the lower (490K), middle (850K), upper stratosphere (1700K), and in the lower mesosphere (2500K), on a date in each year 2007 through 2009 that was at the beginning of the major SSW in that year.

v Figure 4

Vortex averages (calculated as described by Manney et al., 2007) of long-lived trace gas measurements from ACE-FTS during the IPY winters. Top to bottom: CO, CH_4, and N_2O. CO and CH_4 are shown from 400 to 2500K (through the typical stratopause level); N_2O is shown from 400 to ~1600 K, into the upper stratosphere.



Features of the Arctic Stratosphere during IPY

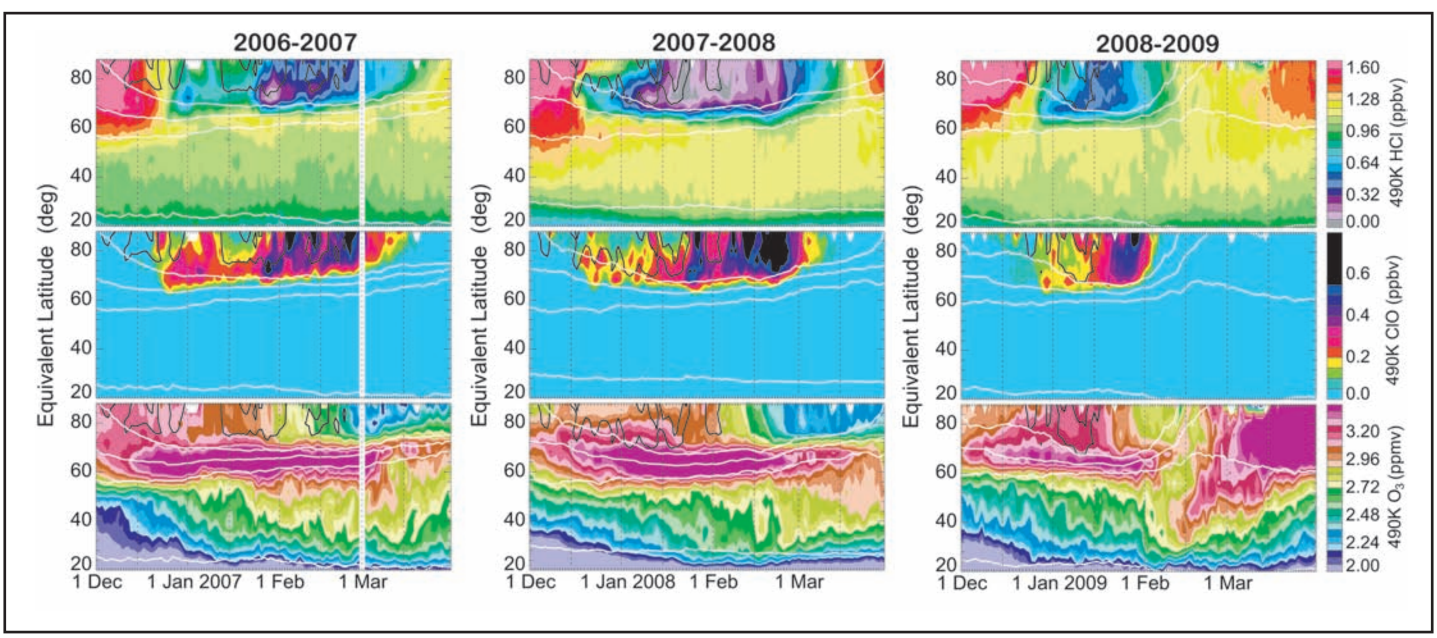


^ Figure 5

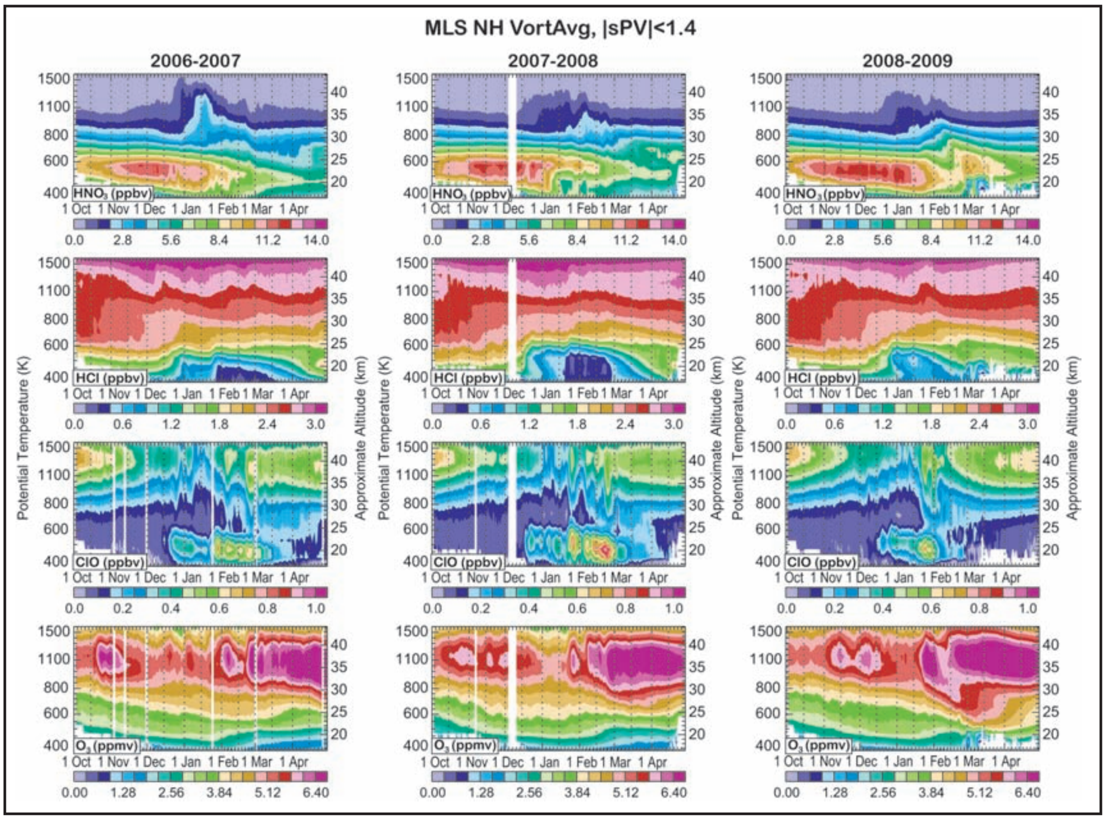
Three-dimensional representation of the Arctic vortex (coloured with temperature) and anticyclones (black) (Harvey et al., 2002) on a date in each year 2007 through 2009 that was at the beginning of the major SSW in that year.

v Figure 10

EqL-time series of MLS (top to bottom) HCl, ClO and O_3 in the (left to right) 2006-2007, 2007-2008, and 2008-2009 Arctic winters. Only data from the day (ascending) side of the orbit are shown for ClO. Overlays are PV contours in the vortex edge region.



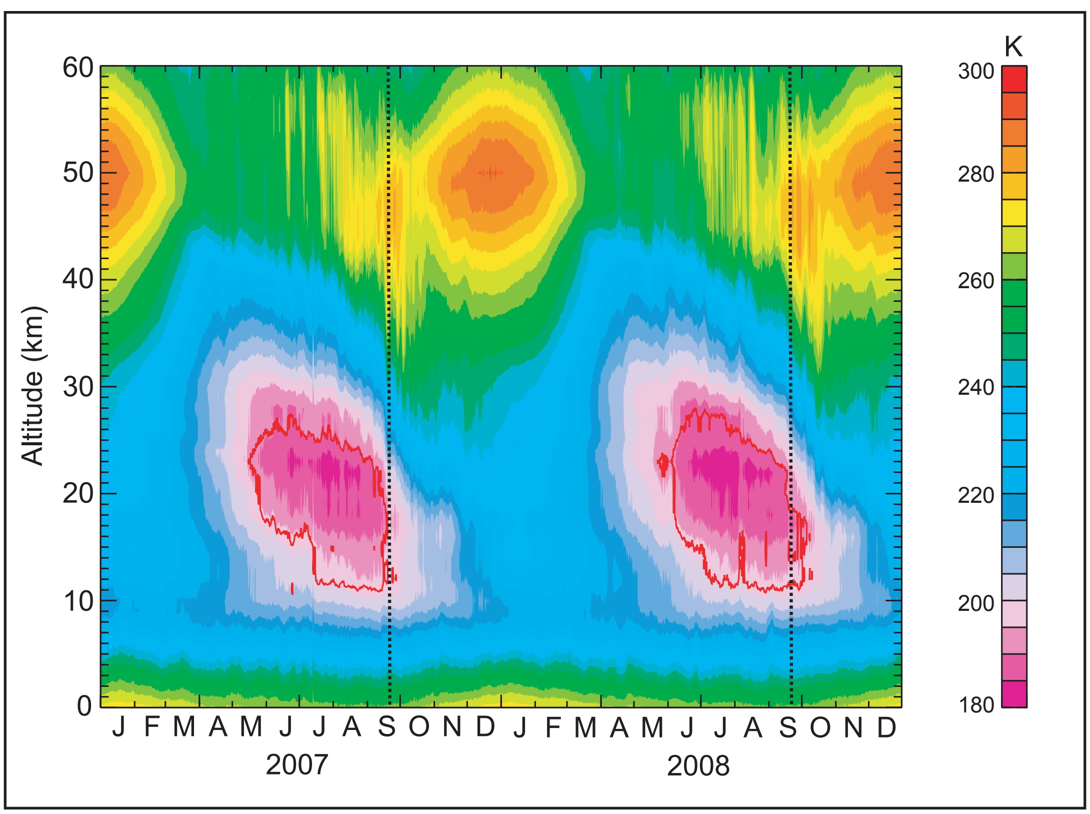
Features of the Arctic Stratosphere during IPY



< Figure 11

Vortex-averaged (within a scaled PV contour, e.g. Manney et al., 2007) MLS (top to bottom) HNO_3, HCl, ClO and O_3 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 HNO_3 and H_2O. The dashed vertical lines mark the time of the austral spring equinox.