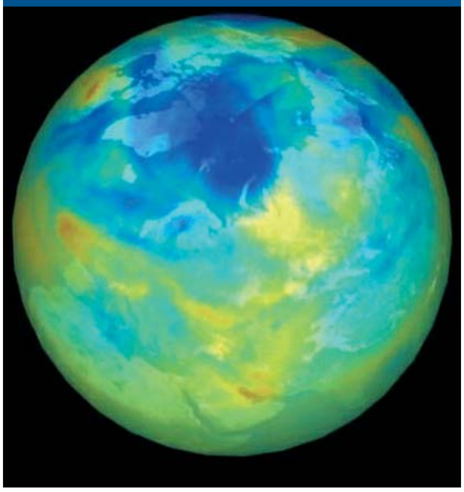
From ozone hole to chemical climate prediction



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Stratospheric Processes and their Role in Climate (SPARC) Project—a short history

The SPARC project came about over a period of years through the efforts of a community of scientists, first to formulate its central goals and then to have it accepted by the main international scientific organizations. A number of scientists were involved in the long process which led to the recognition of SPARC as a project of the World Climate Research Programme (WCRP). The major efforts of M. Geller and M.-L. Chanin, the first Co-Chairs of the SPARC Project, were critical to final success.

Although depletion of ozone in the stratosphere had been an issue of interest in research for more than a decade, discovery of the Antarctic ozone hole in 1985 added enormous impetus to this field of investigation. Understanding the chemistry and dynamics of the ozone hole, and of stratospheric ozone more generally, was recognized as a scientifically challenging issue, as well as one of great concern for human health. In his Banquet response for the Nobel Prize in Chemistry (see SPARC Newsletter No.6. on the SPARC Website (http://www.atmosp.physics.utoronto.ca/SPARC), Prof. F Sherwood Rowland drew attention to the signing of the Montreal Protocol in 1989 as recognition of the great importance to be attached to monitoring and control of gaseous emissions to the atmosphere. Many important national programmes were set up in response to this.

Although depletion of stratospheric ozone was, at first, considered as being somewhat distinct from climate-change issues, it had become increasingly clear that the future evolution of the ozone layer and its eventual recovery were part of the broader story of climate change associated with increasing concentrations of radiatively and chemically active substances in the atmosphere as a result of human activities. The critical role of such substances in the chemistry of ozone in the Antarctic stratospheric winter polar vortex, remote from their source regions, is in itself indicative of the importance of transport and exchange between the troposphere and stratosphere on time- scales ranging from weeks to years. It was becoming evident, however, that this dynamical coupling could influence the troposphere as well. In addition, recognition that the signal of climate change was sensitive to the composition and structure of the upper-troposphere/lower-stratosphere region underlined the need for a programme of research directed toward understanding the role of the stratosphere in the climate system. It was also clear that, to be successful, this programme would have to combine a wide range of disciplines and expertise and fully recognize the key role of atmospheric

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We now know that ozone is subject to transformation by long-lived chemicals, both natural and man-made, released at the Earth's surface, and substantial reductions in its concentration could have a strongly deleterious effect upon mankind and upon the rest of the biosphere.
(F. Sherwood Rowland, Nobel Prizewinner for Chemistry, 1995)

Major foci of the early SPARC Programme

Stratospheric indicators of climate change

Goal: to detect trends in stratospheric constituents, physical properties and processes, and included particular emphasis on the following topics:

- Detection of stratospheric temperature trends
- Detection of trends in the vertical distribution of ozone
- Compilation of a water-vapour climatology and detection of long-term changes
- Stratospheric aerosol climatology and trend

Stratospheric processes and their relation to climate

This initiative dealt with key physical, chemical, and dynamical processes of importance for understanding and modelling the role of the stratosphere in the climate system. These were dealt with under the following topics:

- Stratosphere-troposphere exchange and dynamics and transport in the lower stratosphere and upper troposphere
- The Quasi-biennial Oscillation and its possible role in coupling the stratosphere and troposphere
- Gravity-wave processes and their parametrization
- Chemistry and microphysics in the lower stratosphere and upper troposphere

Modelling stratospheric processes and trends and their effects on climate

This initiative emphasizes large-scale modelling and comparison of models with observations. Two components of this initiative which have produced key achievements and ongoing activities are GRIPS (GCM-Reality Intercomparison Project for SPARC) project and Compilation of a Stratospheric Reference Climatology.

chemistry in climate change. By the early 1990s, this had already received full recognition within the International Global Atmospheric Chemistry (IGAC) Project of the International Geosphere-Biosphere Programme (IGBP). The issues covered by IGAC, however, dealt exclusively with the troposphere and did not include the complex interactions of chemistry, radiation and dynamics, which characterize the tropopause region and the stratosphere.

Two main organizations prepared the way for the recognition of the role of the stratosphere in the climate. The Scientific Committee on Solar-Terrestrial Physics (SCOSTEP) included in its programme a topic entitled "Middle atmosphere response from above and below". The relevant Working Panel led by M. Geller and M.-L. Chanin had a large influence on the scientific content of SPARC. It included the issue of "Solar variability effects on the environment" under the leadership of K. Labitzke. This issue was picked up later by SPARC and has remained a theme of joint interest between SCOSTEP and SPARC.

During the same period, the role of the International Union of Geodesy and Geophysics (IUGG) in the IGBP was being discussed. As a member of the first SSC of IGBP, M.-L. Chanin undertook the task of finding a way to include the stratosphere in the IGBP Programme. Although these efforts did not succeed as planned, they were eventually rewarded with the acceptance of the SPARC project as part of the WCRP in March 1992.

The first main meeting of the SPARC Project took place in September 1992 in Carqueiranne, France, as a NATO Advanced Study Institute. It was organised by M.-L. Chanin and included a group of lecturers who played a major role in the definition of SPARC priorities (Initial Review of Objectives and Scientific Issues, 1993).

Achievements

The SPARC project has played a major role in highlighting the importance of stratospheric processes in the climate system. This has been achieved by an approach which has been: firstly, to be responsive to the need for scientific input to international scientific assessments; secondly, to identify manageable projects where coordination at international level can make a difference; and thirdly, to have clear deliverables for each project, such as scientific reviews which summarize the state of knowledge and facilitate and stimulate new directions for research.

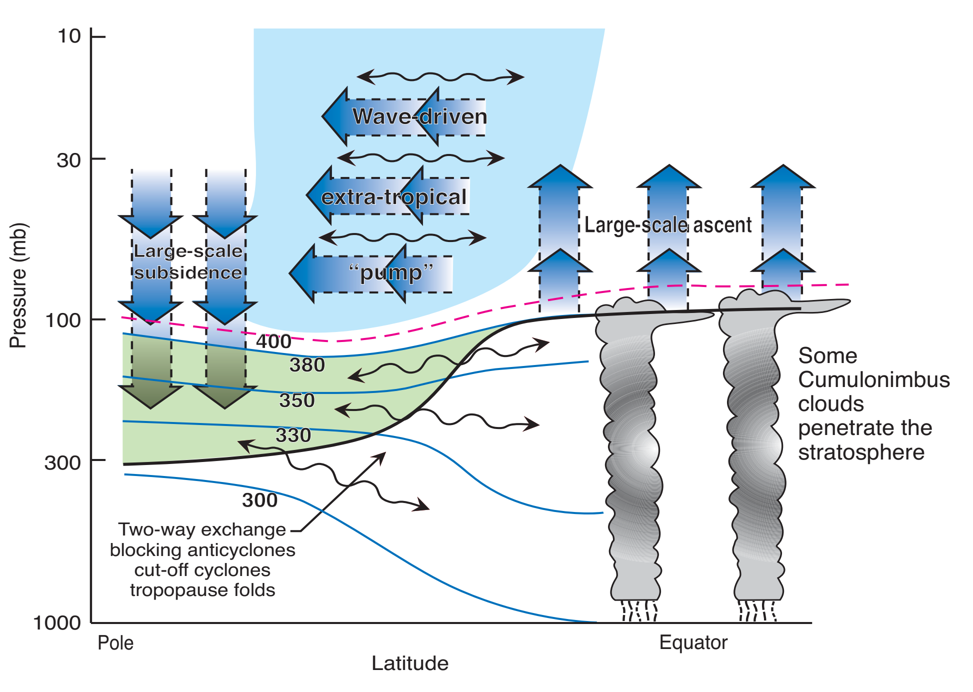


Figure 1 — The "Holton diagram" depicting the processes involved in stratosphere-troposphere exchange

Figure 1, taken from the widely cited paper of Holton et al. (1995), is an elaboration of an earlier one in the report by P. Haynes on the NATO Advanced Research Workshop on Stratosphere-Troposphere exchange (Cambridge, 6-9 September 1993) published in SPARC Newsletter No. 2. In this figure, the tropopause is shown by the thick line. Thin lines are isentropic or constant potential temperature surfaces (labelled in degrees Kelvin). The heavily shaded region is the "lowermost stratosphere" where isentropic surfaces span the tropopause and isentropic exchange by tropopause folding occurs. The region above the 380 K surface is the "overworld", in which isentropes lie entirely in the stratosphere. Light shading in the overworld denotes wave-induced forcing (the extra-tropical "pump"). The wiggly double-headed arrows denote meridional transport by eddy motions, which include tropical upper-tropospheric troughs and their cut-off cyclones as well as their mid-latitude counterparts including folds. Not all eddy transports are shown and the wiggly arrows are not meant to imply any two-way symmetry. The broad arrows show transport by the global-scale circulation, which is driven by the extra-tropical pump. This global-scale circulation is the primary contribution to exchange across isentropic surfaces (e.g. the ~380 K surface) that are entirely in the overworld.

The early SPARC programme

The early SPARC programme was organized around three major foci: stratospheric indicators of climate change; stratospheric processes and their relation to climate; and the modelling of stratospheric processes and trends and their effects on climate (see box).

Space does not permit a detailed discussion, but there have been many notable achievements within each of these foci and it is worthwhile drawing attention to some that have broadly influenced thinking and research in regard to stratospheric processes and, potentially, also public awareness and policy in important ways.

The now famous Holton diagram (Figure 1) encapsulates many of the ideas that have inspired SPARC activities and related research for the past decade. It illustrates schematically how upward propagation and dissipation of a broad spectrum of waves play a significant role in the dynamical coupling of the stratosphere and the troposphere. The Quasi-Biennial Oscillation and key features of the mean meridional circulation, transport and exchange processes in the stratosphere and upper troposphere are closely linked to upward propagation and dissipation of waves. Internal gravity waves, typically unresolved by large-scale numerical models, are an important component of the wave field. Parametrization of the effects of gravity-wave dissipation is now recognized as a key ingredient in successful modelling of the large-scale circulation of the stratosphere.

This challenging task motivated the SPARC initiative on Gravity Wave Processes and Parametrization (GWPP). A number of important activities have been organized under the

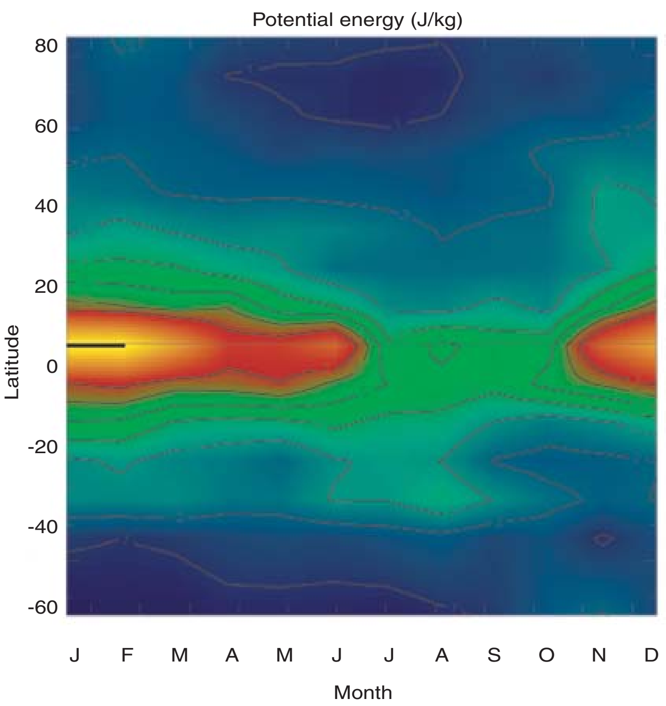


Figure 2 — Features of the gravity-wave climatology of the lower stratosphere

auspices of this initiative. These include field campaigns (e.g. the DAWEX campaign; Hamilton, 2003), workshops (e.g. the Chapman Conference on Gravity Wave Processes and Parameterization, Hamilton, 2004) and the accumulation and analysis of high-resolution radiosonde data from the Meteorological Services of several countries, under the aegis of WMO. Analysis of these data has enabled characterization of key features of the gravity-wave climatology in the lower stratosphere. Figure 2 depicts the meridional and seasonal dependence of the potential energy associated with gravity waves in the lower stratosphere, determined from the high-resolution data acquired and analysed by the scientists in the SPARC GWPP initiative. The contour labels are in J/kg.

Key findings with regard to temperature trends are illustrated in Figure 3. The first panel (Figure 3(*a*)) depicts zonal mean decadal temperature changes at three levels in the lower stratosphere, while Figure 3(*b*) illustrates the vertical profile and uncertainty (dashed lines enclose the two standard deviation range) at middle latitudes in the northern hemisphere. This figure is taken from the paper "Stratospheric temperature trends: observations and model simulations" (Ramaswamy *et al.*, 2001). A result of a SPARC collaboration, this paper was awarded WMO's Norbert Gerbier-MUMM International Award in 2003.

The increased cooling with height shown in the figure is consistent with model simulations, suggesting that changes in radiatively active trace-gas concentrations are major contributors to the observed cooling.

In addition to documented changes in the generally well-mixed gases (CO_2, CH_4, N_2O and chlorofluorocarbons), depletion of stratospheric ozone and increases in water vapour are also contributing factors. The globally averaged temperature changes observed in the lower stratosphere during the past two decades are a robust feature present in various observational datasets as is the corresponding change in the column ozone.

The vertical distribution of the trend in ozone is illustrated in Figure 4, taken from the SPARC-IOC Assessment of Trends in the Vertical Distribution of

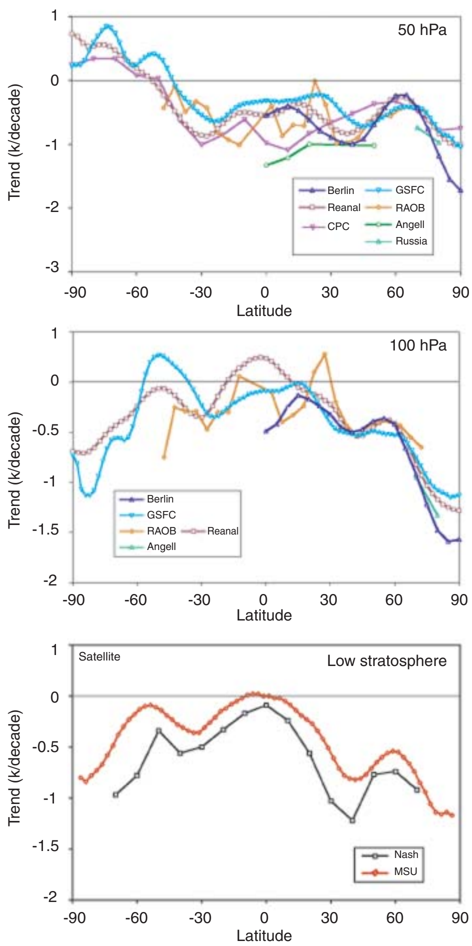


Figure 3(a) — Annual and zonal mean decadal temperature trends, 1974-1994

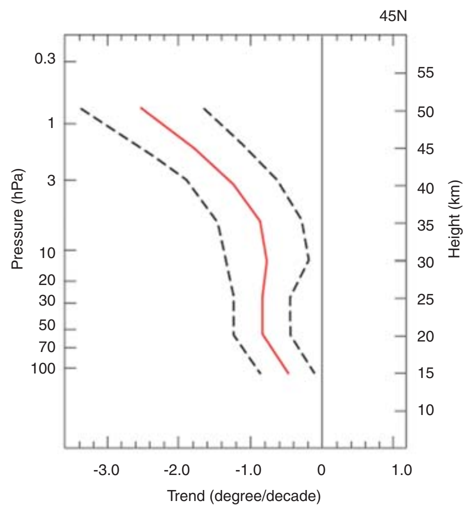


Figure 3(b) — Mean vertical profile and uncertainty of the temperature trend, 1979-1994

Ozone (SPARC Report No.1). The trends depicted in this figure were calculated using those derived from SAGE I-II, ozonesondes, SBUV and Umkehr measurements. Combined uncertainties are shown as 1σ (light solid lines) and 2σ (dashed lines). The combined trends and uncertainties are extended down to 10 km as shown by the light dotted lines but the results below 15 km should be viewed with caution.

The increasing water-vapour trend is illustrated in Figure 5 (SPARC Report No. 2) in terms of the water vapour mixing ratio linear change coefficient. Instruments, latitudes and valid time periods used are noted on the figure (error bars indicate the one standard deviation uncertainties on the coefficients from the linear regression analysis). Panel (*a*) and Panel (*b*) are identical with the exception of the HALOE time period used. Panel (*a*) shows the HALOE linear change term computed for 1993-1999, while Panel (*b*) shows the HALOE linear change term computed for 1993-1997. This water vapour trend has important radiative implications and could be contributing to warming in the troposphere and at the surface.

The Brewer-Dobson dehydration mechanism, condensation and freezing

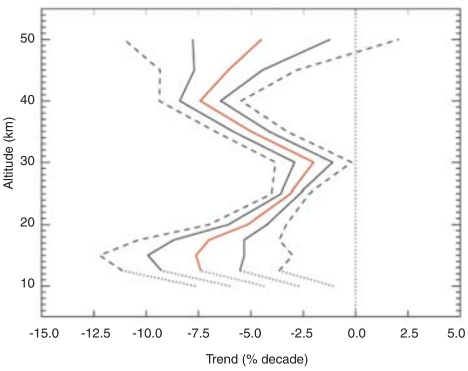


Figure 4 —Mean trends and uncertainties in the vertical distribution of ozone, northern mid-latitudes, 1980-1996

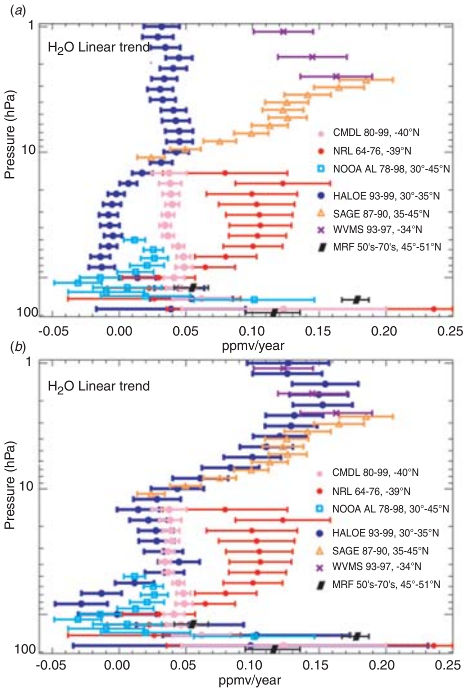


Figure 5 — Water vapour mixing ratio linear change coefficient

associated with low temperatures in the tropical upper troposphere and lower stratosphere (UT/LS), is considered to be the most important in controlling the water-vapour concentration in the lower stratosphere. This mechanism is clearly evident in the seasonal variation of water vapour in the tropical lower stratosphere derived from seasonal cycle fits of HALOE measurements (Figure 6), characterized by an elevated hygropause which ascends with time and is now widely known as the "tropical tape recorder" (Mote *et al.*, 1996).

In view of the downward temperature trend in the lower stratosphere, the increasing water-vapour trend appears to be paradoxical. However, uncertainties in measurements of water vapour are substantial, particularly in regions of low amounts, and make the trend rather uncertain. Oxidation of methane, produced at the surface and transported into the stratosphere, is one of the main sources of water vapour in the stratosphere. The observed increase in tropospheric methane over the past several decades may have contributed to the stratospheric water vapour trend but is insufficient to explain it.

SPARC has taken keen interest in the coupling processes associated with stratosphere-troposphere interactions. One of its key successes has been to bring together dynamicists, specialists in atmospheric radiative transfer, chemists and microphysicists to address key research issues. The uncertainty concerning the water-vapour trend and mechanisms determining it is one of a number of important questions that relate to our understanding of key processes in the UT/LS region. This region is where coupling between chemical, microphysical and dynamical processes is of great importance. Because of the long radiative and chemical time-scales, this region is critical for climate sensitivity and understanding.

Modelling chemical and microphysical processes is critical to success in climate prediction. This is the transition between the high ozone and low water vapour regime of the middle stratosphere and the low ozone and high water-vapour regime in the troposphere. Transport processes play a particularly strong role in determining the structure of this region and a key role in determining abundances of ozone in the troposphere. These processes are also key to cloud formation and persistence and heterogeneous and multi-phase chemical reactions. Because of the complexity and variety of chemical, physical and dynamical processes within it, the UT/LS region is of interest to both SPARC and IGAC.

In the late 1990s, therefore, as a first step, SPARC and IGAC began a joint

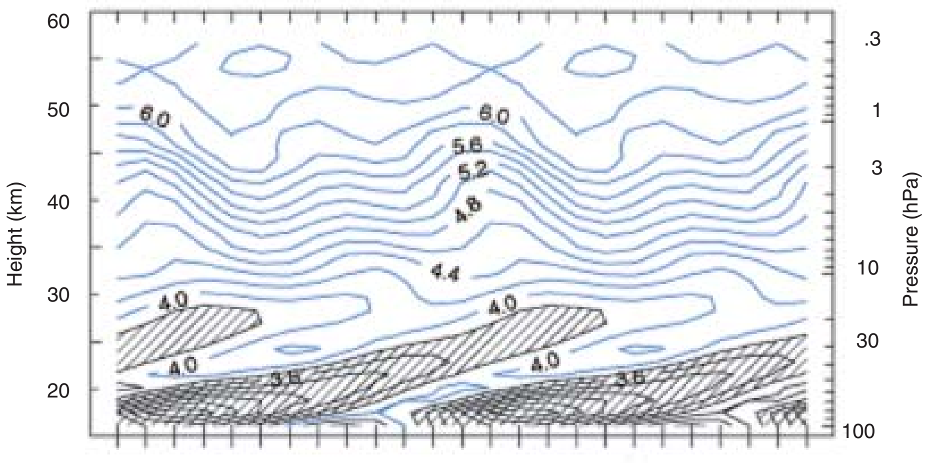


Figure 6 — Seasonal variation of the water vapour mixing ratio over the Equator

task on laboratory data of fundamental chemical processes which interested the two projects. This task produced many successful workshops that brought laboratory chemists together with the field measurement and modelling communities, and led to two successful review papers, one on the quantum yield of O(1D) in ozone photolysis (Matsumi *et al.*, 2002) and one on atmospheric chemistry of small peroxy radicals (Tyndal *et al.*, 2001). This initial collaborative task was the forerunner of the SPARC-IGAC collaborations on the Chemistry-Climate Interactions theme of SPARC (see "Future directions").

Comprehensive global climate models (GCMs) are among the most important tools for understanding the role of the stratosphere in the climate system and predicting climate change. Over the past two decades, rapid advances in computing technology and modelling expertise have resulted in the development of a number of such models, several of which include a realistic middle atmosphere.

The GRIPS project has become a focus for collaboration among major modelling groups on model development and evaluation. It has evolved through successive phases, from undertaking basic comparisons of models to studies of mechanisms. Annual workshops have served as the focus for presenting progress in the formal projects, as well as for presenting new results, as models have been developed. Key results from GRIPS collaborations have been published in journal articles. These include comparisons of simulations of key observable atmospheric variables from most of the major modelling centres (Pawson *et al.*, 2000) and documentation of other important features of model simulations such as the kinetic energy spectrum (Koshyk *et al.*, 1999) and the variability of precipitation and tropical wave activity (Horinouchi *et al.*, 2003).

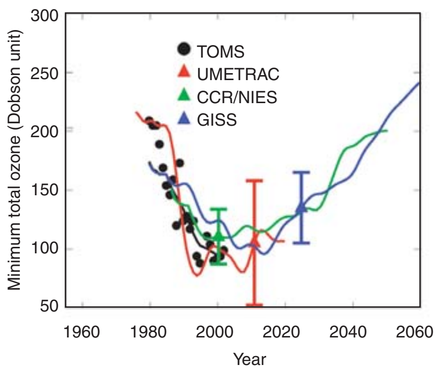


Figure 7 — Observed, simulated and predicted Antarctic total ozone

Figure 7 shows an example of chemistry-climate model predictions of Antarctic ozone changes to 2060 (from Austin *et al.*, 2003). Although the models are driven by the same imposed forcing changes, there are substantial differences in both time evolution and interannual variability among the models, and the reasons for these differences are poorly understood. Evaluating the reasons for such model sensitivities (in particular for coupled chemistry-climate models) is a crucial step forward for predicting future stratospheric change. This is but an example of intercomparisons of simulations of the current climate and of climate change that are of great value in understanding and improving the ability of models to predict future climate.

Meaningful comparison of model simulations with observations is greatly facilitated by the availability of a reference climatology which documents the observed means and variability of basic atmospheric variables that are predicted by models. The SPARC Reference Climatology Group was established to update and evaluate existing middle atmosphere (stratosphere and mesosphere) climatologies for GRIPS and other SPARC projects and activities. This led to publication of SPARC Report No. 3 (December 2002), which provides a comprehensive comparison of middle atmosphere climatologies.

Timely exchange of data between participating scientists is critical for successful collaboration. The SPARC Data Center (http://www.sparc.sunysb.edu/) was established in 1999 to facilitate collaboration and related research. Since its establishment, the number and variety of datasets in its archives and available on line have increased rapidly. These include key reference data used in SPARC assessments such as the Water Vapour

Assessment (WAVAS), as well as other data such as high-resolution temperature and wind data from radiosondes for selected years.

One of the hallmarks of SPARC has been the anticipation of the needs of international assessments such as the WMO ozone assessment and the assessments of the Intergovernmental Panel on Climate Change (IPCC). This has been done through timely workshops, development of key issues before the assessments (review articles and collaborative projects) and providing the expertise (participation of SPARC scientists as co-authors, lead-authors, contributing authors and reviewers). This service is expected to continue in the future.

Future directions

The progress of research and knowledge regarding stratospheric processes in the past decade, to a significant degree under the auspices of SPARC collaborations, has drawn attention to a number of issues that need to be addressed by collaborative research activities in the near future. In view of this, new themes and perspectives for the SPARC project have been developed and have received the support of the WCRP. Collaboration with other international projects is essential for promoting SPARC science within these themes. To this end, the Joint Scientific Committee of the WCRP has recognized that SPARC must play a leading role in achieving a number of specific objectives: (*a*) to lead a collaboration on chemistry-climate interactions with the IGAC project; (*b*) to focus on issues raised by recent studies of the Arctic Oscillation (AO); (*c*) to liaise with SCOSTEP on solar radiative forcing and temperature trends; (*d*) to work with WMO's Global Atmosphere Watch (GAW) project on the penetration of ultraviolet radiation; and (*e*) to contribute to international planning and mission planning. The above list is merely a subset of possible areas of collaboration. For instance, much stronger links with the WCRP's CLIVAR project are essential on long-term climate variability and predictability.

Recently, SPARC has organized its activities under three interlinked themes to consolidate its contributions to climate prediction and to make effective points of contact with other WCRP projects. The associated questions posed within each theme, though certainly not exhaustive, aim to identify primary foci for SPARC activities, at least in the immediate future.

Detection, attribution and prediction of stratospheric changes

- What are the past changes and variations in the stratosphere?
- How well can we explain past changes in terms of natural and anthropogenic effects?
- How do we expect the stratosphere to evolve in the future, and what confidence do we have in those predictions?

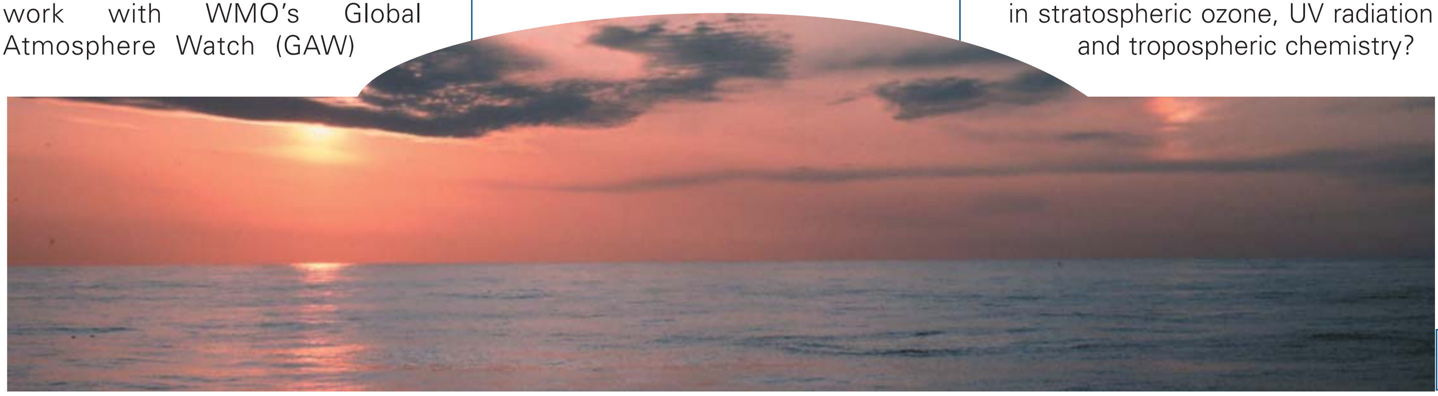
This theme is a continuation, synthesis and extension of earlier SPARC themes on long-term variability and trends in the stratosphere. Future work will emphasize attribution and prediction. This will require a concerted, collaborative research programme involving, in many instances, coupled chemistry-climate models.

Determining the magnitude of natural variability of key variables in key regions is critical to detection and attribution of long-term change. In many instances, the available observational record is not sufficiently long to evaluate the range of natural variability. For example, the major wintertime warming that occurred in the Antarctic stratosphere in 2002 (WMO, 2002) was the first recorded and abruptly reversed the trend toward a colder longer-lasting polar vortex, clearly evident in the previous 20 years of observations (Baldwin *et al.*, 2003). In contrast, wintertime warmings in the Arctic stratosphere are observed relatively frequently. The observing of this rare event in the Antarctic for the first time underlines the difficulty of evaluating the full range of natural variability from the observational record alone.

Evaluating the probability of such rare events with the aid of ensembles of long simulations using global climate models is a possibility (Taguchi and Yoden, 2002). Confidence in prediction and attribution will demand statistically significant results based on large ensembles of integrations with numerical models (or approaches that can be shown to be statistically equivalent). The experience gained within the GRIPS project is a basis for a future role of SPARC in coordinating experiments by different groups to facilitate meaningful comparison of results.

Stratospheric chemistry and climate

- How will stratospheric ozone and other constituents evolve?
- How will changes in stratospheric composition affect climate?
- What are the links between changes in stratospheric ozone, UV radiation and tropospheric chemistry?



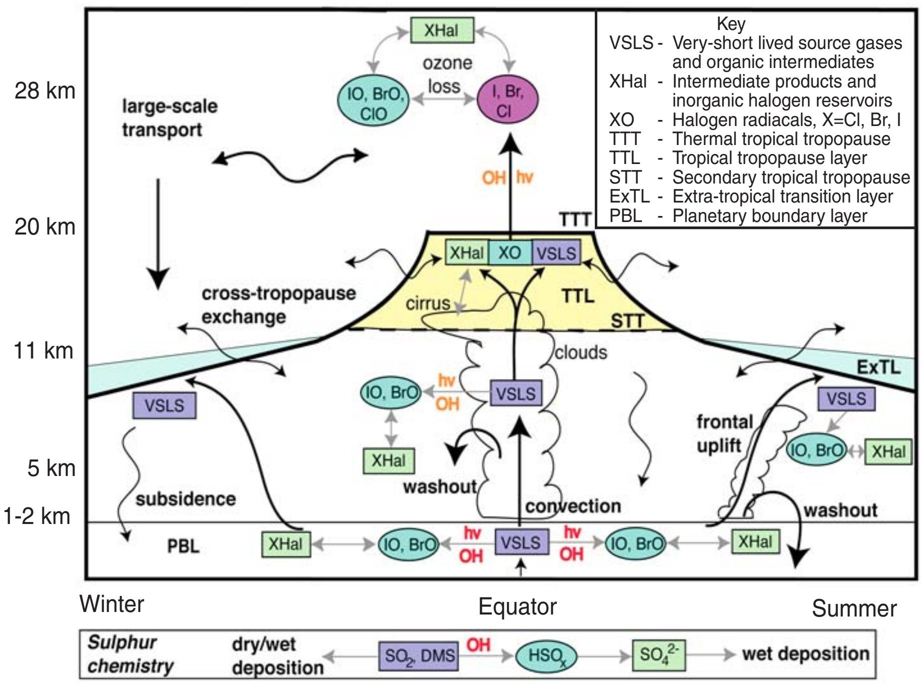


Figure 8 — Chemical and transport processes affecting very short-lived source gases and organic intermediates

The latest assessment report of the IPCC identifies insufficient knowledge of the coupling and feedbacks between atmospheric chemistry, the biosphere and the climate—and the consequent failure to represent the relevant processes adequately in climate prediction models—as serious scientific limitations. An interdisciplinary approach must be adopted, involving laboratory measurements, field campaigns and numerical modelling. Work under this theme will involve strong collaboration between the SPARC and IGAC projects. As noted above, the UT/LS region is where some of the scientific challenges are most demanding.

Clear understanding of the processes that connect emissions (source, precursors) to abundances, and the processes that connect the abundances to climate forcings are essential for an accurate prediction of the future climate and an assessment of the impact of climate change and variations on the Earth system. Studying processes involved in the chemistry and dynamics of the tropical tropopause layer (TTL) is an example of the kind of activities being undertaken in this theme. Some of these are depicted schematically in Figure 8 (Cox and Haynes, 2003; from Scientific Assessment of Ozone Depletion: 2002, WMO Global Ozone Research and Monitoring Report No. 47).

Stratosphere-troposphere coupling

- What is the role of dynamical and radiative coupling with the stratosphere in extended-range tropospheric weather forecasting and determining long-term trends in tropospheric climate?
- By what mechanisms do the stratosphere and troposphere act as a coupled system?

A strong motivation for this theme is that several recent observational studies have suggested that a so-called Arctic Oscillation (or Northern Annular Mode (NAM), with an equivalent Southern Annular Mode) is a dominant component of large-scale variability in the atmosphere. The finding that anomalies in an AO index can sometimes span the stratosphere-troposphere system has revivified the long-standing issue of stratosphere-troposphere coupling. In particular, the occasional downward propagation of anomalies from the stratosphere into the troposphere implies, with support from statistical analysis of the data, that knowledge of the state of the stratosphere can enhance our ability to predict aspects of the large-scale evolution of the troposphere, which would be of practical value for weather forecasting and climate prediction.

This is depicted in Figure 9, which shows that alterations of the tropospheric circulation down to the surface may be associated with a weakening (red) or strengthening (blue) of the stratospheric vortex. The diagrams show composites of the NAM index: (*a*) composite of 18 weak vortex events and (*b*) 30 strong vortex events (Baldwin and Dunkerton, 2001). Whether the state of the stratosphere influences the evolution of the troposphere in a causal sense (and if so, by what mechanisms and on what timescales?) are key issues demanding numerical experimentation.

As has been the case hitherto to for SPARC foci, addressing the scientific questions of the new SPARC themes will require underpinning activities within such general areas as model development, process studies and supporting data analysis and archiving. In many cases, facilitating these activities will require the setting-up (on a possibly temporary basis) of targeted working groups, some of which will

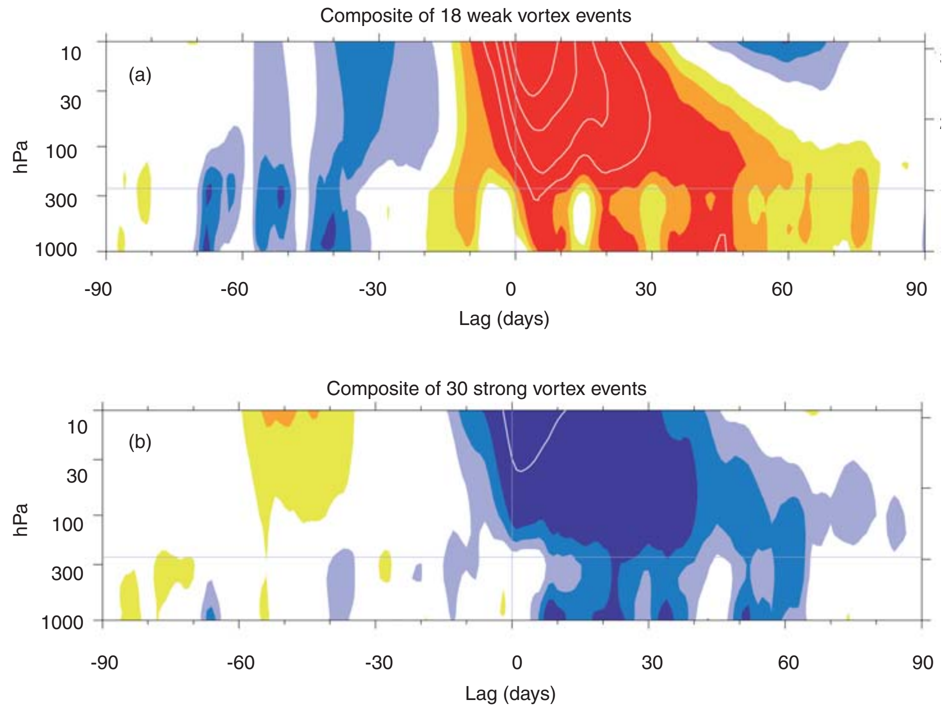


Figure 9 — Downward propagation of anomalies from the stratosphere into the troposphere

have evolved from current SPARC activities.

An example of such a new underpinning activity is the comparison of chemistry-climate models through process-oriented analysis and validation. An important component of several of the GRIPS workshops has been discussion of progress in coupled chemistry-climate models, even though no formal assessment had been organized. Climate models increasingly include chemical components and it is now well recognized that intercomparison and assessment of the performance of these components is important for improved understanding of both the chemical components and their underlying global climate models and, ultimately, for improved representations of these processes in global climate models.

Achievement of this goal as well as that of providing more scientifically useful information for upcoming assessments was the motor to include this activity as one of the supporting pillars of the SPARC programme themes. Concepts for this new activity were developed at a workshop in Grainau, Germany, in November 2003.

Targeted working groups will also be needed to resolve a variety of issues concerned with additional atmospheric processes within the context of the main scientific themes. One of many possible examples is the current uncertainty and lack of understanding of processes affecting the transport of water vapour from the troposphere to the stratosphere, which is needed to account for apparent long-term variability in water-vapour concentrations. SPARC will contribute to resolving these uncertainties through scientific assessments aimed at producing scientific review papers, and by promoting and participating in observational campaigns and associated numerical modelling. The Third SPARC General Assembly (Victoria, Canada, August 2004) highlighted the new themes and brought forward new results in a numbers of key areas that will continue to receive concerted attention from the SPARC community. (A report on the 3rd General Assembly is included in SPARC Newsletter No. 24 and expanded summary articles based on key presentations within it will appear in future newsletters). The General Assembly emphasized that, while our knowledge of the role of the stratosphere in the climate system has advanced enormously, major uncertainties remain, especially in the interaction of atmospheric chemistry and climate. Resolving these uncertainties will demand collaborative research that cuts across current WCRP projects.

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