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STRATOSPHERIC PROCESSES AND THEIR ROLE IN CLIMATE

A Project of the World Climate Research Programme

Report of the Eighth Session of the SPARC Scientific Steering Group

Buenos Aires, Argentina, November 13-16, 2000

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This Eighth Session of the SPARC Scientific Steering Group (SSG) was held in Buenos Aires during the week following the SPARC 2000 General Assembly in Mar del Plata (see the Assembly report in this issue). First the Co-Chairs of the SSG offered their warm thanks to the Foreign Minister of the Republic of Argentina and the State Secretary of Science and Technology who had provided very nice facilities for the meeting.

The session started by reviewing the main events which took place in the last year, in particular the last SSG meeting, the meeting of the WCRP Joint Scientific Committee (JSC), that took place in Tokyo in March 2000, and the SPARC 2000 General Assembly. Marvin Geller first recalled the conclusions of the SSG meeting in Paris where the future SPARC overall strategy was discussed. It had been concluded that, after 8 years of fairly

Participants in the SSG in Buenos Aires, from left to right.
First row: P. Canziani, M. Geller, M.-L. Chanin, A. O'Neill.
Second row: V. Ramaswamy, D. Kley, R. Vincent, T. Shepherd, Ph. DeCola, J. Gille, R. Newson, S. Yoden, M. Baldwin, S. Pawson.
Third row: D. Karoly, K. Hamilton, Y. Koshelkov, P. Simon, T. Peter, U. Schmidt, W. Randel, A. R. Ravishankara.

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focused initiatives, it was now timely to integrate the knowledge acquired across SPARC, in order to progress towards the goal of an overall understanding of all aspects of stratospheric variability and change, its interactions with the troposphere, and its role in climate. This was going to be a main topic of discussion during the present SSG meeting. Among the points raised at the JSC, M. Geller mentioned that the unique quality that SPARC was bringing to the WCRP, the dynamics-chemistry-radiation linkage within the stratosphere, should even be amplified by a more active role in the JSC initiative on the climate-chemistry issue led by Susan Solomon. It should become an integrated joint venture with IGAC on the troposphere-stratospheric climate problem (including S/T coupling). Other ties should be amplified with CLIVAR on the possible links between the North Atlantic Oscillation and the Arctic Oscillation, and with the newly proposed IGBP Surface Ocean and Lower-Atmosphere Study (SOLAS) on the role of the UV radiation.

Alan O'Neill, Chair of the Scientific Organising Committee of SPARC 2000, reviewed the new scientific results presented during SPARC 2000 and the conclusions, which would need to be taken into account into the future development of SPARC. He remarked that the SPARC 2000 General Assembly has started integrating the different components of SPARC and that it should help the Project to develop a more holistic approach of the issues to be solved in the future. It was recognised that, in order to understand past changes, one needs to understand and bound natural variability and its patterns and look together at the observed fields of several variables as well as their simulations.

Then the leaders of the SPARC activities provided a review of the progress in the projects and activities organised under SPARC activities.

Modelling stratospheric effects on climate

Intercomparison of stratospheric models

The "GCM Reality Intercomparison Project for SPARC" (GRIPS) has grown both in the number of research groups involved and the range of tasks being tackled. During his presentation of the GRIPS highlights of the year, Steve Pawson raised the question of what GRIPS should do and should not do. The results from the first phase of GRIPS and their scientific implications can be found in *Pawson et al.* (2000) in BAMS, *Koshyk et al.* (2000) in JGR, and *Amodei et al.* to appear in Annales Geophysicae. New data from several model groups have been collected and their analysis will focus on forcing mechanisms of stratospheric variability (wave forcing and diabatic forcing) and involve some focused model experiments (sensitivity studies for interactions between mechanisms).

The second phase of GRIPS, now in progress, involves further validation of models and carrying out controlled experiments to test parameterisation schemes, including radiation schemes, model response to the formulation of mesospheric drag, and of gravity wave (GW) parameterisation schemes (Hines' first and then McIntyre's). Models have been shown to be very sensitive to different radiation schemes, and the issue of radiation has become a major one to be solved in order for models to converge.

Goals for the third phase were defined during a very successful workshop held in 2000 in Toronto. The main goal is to explain the observed variability in the 1979-1999 period as a combination of natural variability and perturbations due to known forcing mechanisms: aerosols, solar variability, ozone change and CO2 change. As a further step, experiments will be run with imposed climate change scenarios for the period 2000-2020 (using the best possible predictions of trace gas concentrations).

A new GRIPS workshop is planned for February 26 to March 1, 2001 in Hamburg, Germany to discuss ongoing activities and plan future work. The role of GRIPS in the planned integrated SPARC activity mentioned above needs also further thought. One of the main output being the prediction of future climate/ozone interactions, it will also be discussed at the Joint SPARC/IOC ozone meeting in March 2001 to prepare for the upcoming WMO-UNEP Ozone Assessment.

Stratospheric reference climatology

It has been long recognised that a revised climatology of the averages and variances of basic stratospheric parameters was needed for GRIPS, as well as a number of other SPARC initiatives. In the last few years, a series of monthly global climatologies of temperature, zonal winds, and various atmospheric trace constituents (N_2O, O, CH_4, H_2O, O_3, NO_2, HNO_3, etc.) have been assembled from NCEP, UARS and other data. Monthly and daily stratospheric circulation statistics have been inferred from available stratospheric analyses or reanalyses. Other data compiled include upper-level radiosonde winds from Singapore (as an indicator of the phase of the QBO) and statistics on tropopause height. These data sets are now accessible from the SPARC Data Centre **(http://www.sparc.sunysb.edu/)**.

W. Randel presented a draft of the technical report to be published as a SPARC Report in 2001, describing the data sets, comparing stratospheric circulation statistics, and quantifying uncertainties and interannual variability. This report entitled "SPARC Intercomparison of Middle Atmosphere climatologies" uses 10 sets of data (some including the mesosphere) and the UARS data from 1992-1997. W. Randel indicated his plans for the near future to include the rocketsonde data in the data intercomparisons. Furthermore he intends to organise a group meeting in spring/summer 2001 to complete the report and in particular to identify the biases in each data set, to identify the quantities which have high uncertainty and to discuss the strategies for comparison with models.

Climate Forcing in the Stratosphere

Under the auspices of SPARC, a review of stratospheric aspects of climate forcing had been undertaken in order to provide, for the use of the climate modelling community, the current best estimates of the relevant parameters. The work has been completed and a report by David Karoly was included in SPARC Newsletter No. 14 (January 2000). All the relevant data are available at the SPARC Data Centre.

D. Karoly, who had chaired this activity and is a Lead Author in the current IPCC/Third Assessment Report (TAR), reported on the way detection and attribution of a Stratospheric Role in Climate Change has been taken into account in the IPCC/TAR (see the paper by David Karoly in this issue of the Newsletter).

Stratospheric data assimilation

At its meeting in Paris in 1999, the SPARC SSG agreed that it would be useful and timely to review the status of stratospheric data assimilation and specific related problems (including stratospheric data availability). A. O'Neill, who was asked to report on plans on this issue, informed the SSG that a DARC (Data Assimilation Research Centre) has been supported and set up in the UK by the Natural Environment Research Council, in view of the important role of data assimilation both for the climate studies and the numerical weather prediction (NWP). Atmospheric data assimilation will be based on the use of a general circulation model of the troposphere and stratosphere, which at this stage incorporates a parameterisation of ozone chemistry. More sophisticated chemistry is incorporated in an off-line, 4DVAR, chemical data assimilation system. The SSG supported a proposal to form a SPARC working group to focus on stratospheric data assimilation, and A. O'Neill has agreed to pursue this. Several meetings of potential European partners in the group have already taken place to make recommendations to EU towards the use of the ENVISAT data. A full meeting of all the parties is being planned to gather information on current activities and to discuss developments in stratospheric data assimilation that may be needed. This initiative will be closely co-ordinated with the Working Group on Numerical Experimentation, which has overall responsibility in the WCRP for data assimilation questions.

The data assimilation initiative is especially important in view of the new streams of stratospheric data coming on line from research satellites in the next few years (e.g., ENVISAT, HIRDLS, the NASA EOS series, etc.), as well as from operational ones.

Long-term changes in the stratosphere

Stratospheric temperature trends

The original objectives of SPARC activities in this area have been well fulfilled for the lower stratosphere. The results of the first phase of this initiative have formed the basis of the chapter 5 in the latest WMO/UNEP Ozone Assessment (1999). A summary will be published in Reviews of Geophysics in February 2001. The full account of the work is also in preparation as a SPARC Report to be edited by NOAA. The work carried out is also proving valuable input to the IPCC/TAR in particular for the discussion of radiative forcing of climate change, climate processes, and detection and attribution.

V. Ramaswamy reported that the views of the group are to pursue its activity in several directions: continuous update of the data and of model inferences, extension to the upper stratosphere and mesosphere, (this later part in liaison with ICMA and SCOSTEP), improved work on trends of quantities having high uncertainties (tropopause and stratopause temperatures). In parallel with this continuous activity, the need to have a more integrated perspective was recognised as temperature trends are closely linked with changes in other stratospheric parameters (ozone, water vapour, dynamical acti-vity, etc.), and activities will have to become increasingly integrated with other SPARC studies in these areas. A group meeting is planned for around mid-2001.

What has been strongly emphasised has been the value of the SPARC umbrella under which coherent international research into stratospheric temperature trends can be and has been carried out including the planning of future co-ordinated activities. It is viewed as important to keep together the international "expert" SPARC temperature trends group, comprising observationalists, modellers and diagnosticians.

Understanding ozone trends

After the major effort in 1998 to assess the trends in the vertical distribution of ozone (SPARC Report No. 1, 1998) and the contribution to the WMO/UNEP Ozone Assessment, 1999, thought had been given to the further development of studies in this area. Neil Harris (who sent his apologies for absence from the SSG meeting) had informed the SPARC co-chairs about a possible future workshop to be organised together by SPARC and IOC in conjunction with (and upon invitation of) the co-chairs of the Montréal Protocol Assessment Panel. This information has been confirmed since the time of the SSG meeting. The goal of this workshop is to review the scientific activity on the topic of stratospheric ozone changes and their causes. This topic will be among those addressed by the next WMO/UNEP Ozone Assessment, whose drafting will begin in the summer of 2001 and will be completed by the fall of 2002. This workshop to be held on March 7-9 at the University of Maryland, will bring together (upon invitation) leading scientists in this area of research to take stock of the current state of scientific understanding, to facilitate the formulation of common scientific viewpoints, and to encourage prompt submission of peer-reviewed publications that will form the basis of the 2002 Ozone Assessment.

In the longer term, an extension to study jointly trends in stratospheric parameters in general (including temperature, etc...) is foreseen by the ozone trends group.

Stratospheric and upper tropospheric water vapour

This SPARC initiative, originally set out to refine the water vapour climatology in the stratosphere and upper troposphere (S/UT), developed into a comprehensive Water Vapour Assessment, which investigated the concentration, distribution and variability (including the long-term changes or trends) of water vapour in this region. The processes controlling the present distribution of S/UT water vapour have also been studied. The Assessment Report is now completed and will be printed as SPARC Report No. 2, 2000 (and WCRP- 113, and WMO-TD-No. 1043). It will be available early in 2001.

The executive summary, printed in this Newsletter, gives the main conclusions as well as the recommendations for a further comprehensive and organised approach to monitoring water vapour in the S/UT. A summary of the Assessment has been provided in due time for inclusion into IPCC-TAR.

Understanding Stratospheric Climate Change

The proposal of a new integrated SPARC initiative, with a view towards "Understanding Stratospheric Climate Change (1979-1998)", was discussed at length during the SSG meeting, under the leadership of V. Ramaswamy. It was agreed that it should focus on the study of the consistency amongst the various observational data set and comparisons of model-simulated responses to well-characterised and known forcings with observations. The project should not be too ambitious to start with and should be accomplished in 3 years. Preliminary discussions about the input data and the type of models to be used took place during the meeting but should continue in the future months by email exchanges involving at least the SPARC group leaders of the trends issue and of GRIPS. This should help in preparing a workshop to be held in spring/summer 2001.

Stratospheric processes

Gravity wave processes and their parameterisation

The construction of a stratospheric gravity-wave climatology based on high-resolution radiosonde data is proceeding as planned. Following the successful Abingdon workshop in July 1999 the participants reanalysed their data to generate climatological and research products. R. Vincent presented some of the highlights of the climatologies of wave energies and propagation directions as a function of latitude. In 2001 it is planned to submit for publication a series of articles describing the research efforts that have gone into the generation of the climatologies.

Kevin Hamilton described how the planning of the international field experiment ETCE (Effects of Tropical Convection Experiment) is progressing. ETCE is designed to investigate the gravity-wave field forced by tropical convection during a six-week intensive observation period (late October-early December 2002) over the Tiwi Islands, north of Darwin, Australia. A detailed plan of the scientific objectives and instrumentation to be deployed during the field campaign may be viewed at: http://www.princeton.edu/~kph/EXP2.

K. Hamilton also described a pre-ETCE campaign called DAWEX (Darwin Area Wave Experiment). This campaign, proposed by EPIC/SCOSTEP and SPARC, is planned for the Austral spring 2001 and is aimed at characterising the wave field in the middle atmosphere over Northern Australia prior to the onset of the diurnal convection, known locally as "Hector", and during the active Hector period. As it only involves ground-based equipment, the preparation's time is much shorter than for ETCE.

Lower stratospheric/upper tropospheric processes

Transport and mixing in the UT/LS are fundamental to SPARC and hold the key to many issues, e.g., the UT/LS ozone budget, mid-latitude water vapour distribution and tropical dehydration. However, there is still no overall strategy and theoretical framework for studying stratospheric-tropospheric exchange, paradigms that can be tested, or an obvious common measurement/diagnostic approach. Thus, the role played by SPARC in this area up to now has been to keep under review the basic questions that need to be addressed and to bring the different communities involved in this subject together in various focused workshops. In view of the importance of the tropopause (where climate/ozone issues come together), consideration has been given in the last two years to planning a "tropopause workshop". This workshop, organised under the leadership of Ted Shepherd and Peter Haynes, will take place in April 17-21, 2001 in Bad Toelz, Germany. The SSG was asked to review the list of invited participants.

A.R. Ravishankara reviewed the joint SPARC-IGAC activities on chemical processes in the UT/LS. On the issue of Organic Peroxy Radicals, which was reviewed in SPARC Newsletter No. 15, a paper is now in press in JGR. The work on the quantum yield of ozone photolysis reactions was presented at the Quadrennial Ozone Symposium in 2000 and is to be submitted to JGR. Such joint SPARC-IGAC activity is judged by the SSG to be extremely beneficial to both projects and crucial in the evaluation of important UT/LS chemical reactions. It generates an important interaction between the modelling and the field laboratory communities and brings new people into the process. The question of expanding the co-operation to other issues was discussed. The topic of UT/LS water vapour and the role played by subsonic aviation in the formation of contrails/cirrus was judged to be already receiving sufficient attention by the atmospheric community.

The other issue was the Upper Tropospheric Ozone (UT O3) climatology and trends. It was thought that SPARC should undertake this task and ask IGAC to join, as the contribution of the stratosphere is important enough to be taken into consideration. A leader of this new initiative has yet to be appointed. A workshop on the role of nitrogen oxides is being organised for March 2001 in Heidelberg.

Penetration of UV radiation into the lower stratosphere and troposphere

It is essential to know the actinic flux distribution in the lower stratosphere and troposphere and to determine the climatology of photodissociation rate constants (J values) for various radicals as a function of altitude to make marked progress in model calculations. The SSG at its 1999 meeting encouraged a joint SPARC-IGAC initiative on this issue, with the objectives of evaluating existing data (including J values and actinic flux measurements), considering the requirements for new instrumentation and organising validations of computations of radiative transfer at UV wavelengths. This activity, which should well complement the joint SPARC-IGAC studies of chemical processes in the UT/LS, has not started yet. Paul Simon will contact IGAC to help identify his counterpart within IGAC. The connection with IGAC clearly needs to be strengthened on this issue.

It was noted that the workshop on UV impacts, which took place at Mar del Plata, following the SPARC 2000 General Assembly attracted about 30 participants from the SPARC community. Pablo Canziani, who was the organiser of this workshop, asked whether this issue should not become a regular part of SPARC Assemblies. The SSG hesitated to include the impact aspect of UV within its thematics at the present time.

Other scientific issues

Dynamical coupling of the stratosphere and troposphere

At the SPARC SSG Paris meeting, two (somewhat speculative) aspects of what are thought to be manifestations of the dynamical coupling of the stratosphere and troposphere were discussed, the quasi-biennial oscillation (QBO) and the Arctic Oscillation (AO). On the first topic, an extensive review of the QBO and its role in coupling the stratosphere and troposphere was published in Reviews of Geophysics in October 1999, as a consequence of the SPARC QBO Workshop of March 1998. During this SSG session, Mark Baldwin was invited to present an update on the AO and its possible link to the NAO (North Atlantic Oscillation). He noted similarities between the NAO (North Atlantic Oscillation) observed in surface pressure and features of the AO (Arctic Oscillation), which was derived as a leading "mode" of variability of the combined troposphere-stratosphere system. He proposed that the NAO and AO were, in fact, different manifestations of the same underlying dynamical phenomenon, and showed evidence for the apparent downward propagation of the AO signal. Issues raised by these ideas concern the mechanism for downward propagation of the AO signal, whether the stratosphere can influence the large-scale variability of the troposphere, and whether one can predict changes of the large-scale circulation in the troposphere from prior knowledge of the state of the stratosphere. The issue was judged still too speculative to generate any SPARC initiative, besides a continuation of the investigation. This question of joint interest for CLIVAR and SPARC should be raised at the next JSC Meeting.

A presentation was then given by Shigeo Yoden on "Intra-seasonal and interannual variations of the troposphere-stratosphere (T/S) coupled system" (see article in this issue). Results have been obtained from 1000-year runs using a hierarchy of numerical models assuming different types of linkages between the troposphere and the stratosphere. They show that the T/S system is highly non-linear and has large internal variability.

Solar forcing and climate variability

As requested by the JSC, SPARC is keeping under review research on solar forcing, its variability as a source of variations in climate and possible underlying mechanisms that could be put forward. The SPARC SSG noted last year that, although changes in the solar spectrum are known to affect ozone, temperature and the actinic flux in the middle atmosphere, there is still no consensus on whether tropospheric climate is influenced in any way by these changes. The data analysis planned in the European project SOLICE and the modelling activities in GRIPS and SOLICE, which are still at an early stage, should throw further light on this issue.

Research on links between solar forcing and climate variability is another example of a cross-cutting activity in the WCRP, where SPARC would be involved in studying the mechanisms involving the stratosphere, GEWEX on possible cloudiness variations linked to changes in solar cosmic rays, and CLIVAR in a rigorous interpretation of the observed climate signals.

Stratospheric aerosol climatology

The subject of stratospheric aerosol has attracted intense work in the past decades, but the need for an organised activity has been discussed for years without any success. The SSG decided to form a group with the mandate to look at the presently existing climatologies, identify their consistencies or inconsistencies and contribute to a better knowledge of the composition of aerosols. Two co-chairs will be named for a two-year mandate and should together with a small group prepare a report and eventually organise a workshop in this time frame.

Review of overall SPARC strategy and status of implementation

The SPARC SSG gave consideration to the overall strategy that has so far been followed and assessing whether any reorganisation of the programme is now appropriate. Hitherto, SPARC initiatives have been fairly focused and dealt with individually (by sub-project working groups). Although some of the scientific issues taken up obviously still need specific continuing efforts, it appeared that it may now be timely to integrate the knowledge acquired across SPARC in order to progress towards the goal of an overall understanding of all aspects of stratospheric variability and change, its interactions with the troposphere, and its role in climate.

In some areas, focussed efforts are still clearly needed: gravity wave climatology and understanding the role of GW in stratospheric dynamics; UT/LS chemistry and microphysics; the tropopause; solar forcing and climate variability. SPARC also saw the need to assess observations of stratospheric aerosols (jointly with IGAC). Additionally, there is a range of specific modelling questions such as the parameterisation of radiation and GW, as well as the topic of stratospheric data assimilation.

The sort of basic structure foreseen for SPARC in the future would involve integration or synthesising the understanding of stratospheric trends of temperature, ozone and water vapour, and solar effects through modelling studies. These would be particularly aimed at elucidating UT/LS variability, and its role in the overall climate system by building on the modelling work already carried out in the stratospheric trends study and GRIPS. However, additional models (e.g., two-dimensional, chemical transport) which have not so far been exploited in SPARC would also be required, as well as developing the use of data assimilation techniques. Furthermore, although the number of climate models including the stratosphere is increasing, there is currently insufficient contact between the SPARC community and tropospheric climate modelling groups. The new SPARC initiatives on stratospheric data assimilation and UV penetration could help in building bridges. Within this framework, the main priority for SPARC is to continue generally to facilitate research on stratospheric processes and their role in climate by providing a forum or umbrella for international co-operation and encouraging inter-disciplinary exchanges. SPARC will thus remain science-driven, but, at the same time, it should be in a position to provide the best available information on relevant stratospheric questions for the periodic international assessments such as those of IPCC and WMO/UNEP. This requires a forward-looking approach to identify new questions that could arise.

Interactions with other programmes and activities

As noted earlier, SPARC maintains strong links and/or interacts widely as appropriate and necessary with several other programmes. Particularly noteworthy is the co-operation with IGAC (the joint SPARC-IGAC activity on UT/LS chemical processes; the proposed joint initiatives on the penetration of UV radiation into the lower stratosphere and troposphere, the possible joint assessment of observations of stratospheric aerosols). It was unfortunate that neither Guy Brasseur nor Stuart Penkett were able to attend this SSG meeting. It was decided that in view of the increasing IGAC/SPARC interactions, an alternative method for planning is needed. In particular, it was suggested that a small IGAC/SPARC liaison-planning group be formed to plan for SPARC/IGAC programs. Of course, those plans would need ratification of the SPARC and IGAC SSGs.

Reference was also made to the planned collaboration with SCOSTEP on upper stratospheric temperature trends and on the issue of solar influence on climate. The constitution of joint SPARC/SCOSTEP working groups on these issues was discussed. Possible members for these groups were discussed. The allocation of a US$ 6,000 grant by ICSU should assist the WCRP and SCOSTEP funding of these joint activities.

The SPARC Data Centre

The SPARC Data Centre, supported by NASA, has been operated by Petra Udelhofen at the State University of New York at Stony Brook for more than a year, and a significant start has been made on assembling key stratospheric data sets in a readily accessible form. New data sets have been added to the original ones: High-resolution temperature and wind data from radiosondes, data from the GRIPS model intercomparison, the Water Vapour Assessment (WAVAS) archives. (see SPARC Newsletter No. 15 and **http://www.sparc.sunysb.edu/**).

The SPARC Office

As well as its regular responsibilities of compiling and editing SPARC Newsletters, updating the SPARC mailing list, maintaining contacts with the SPARC community of scientists, organising various SPARC meetings and periodically revising the SPARC home page, particular support has been given to the preparation of the SPARC water vapour assessment report. Substantial efforts have also been devoted to seeking sponsors for the Second SPARC General Assembly, and assisting in the arrangements for the General Assembly. The composition of the SPARC Office has been changed during the year. In June 2000 the arrival of Catherine Michaut, who has a full time position of assistant engineer at CNRS, provided an efficient manager for the Office. In November 2000 Céline Phillips decided to leave the Office for a permanent position at ADEME. A half-time position of Project scientist is opened and the SPARC Office is looking for a post-doc candidate.

Meeting of the SPARC SSG *per se*

The SSG members met twice during the 4-day meeting to discuss the partial renewal of the SSG chairs and members. This was necessary as the mandates of several members are coming to an end. Marie-Lise Chanin has expressed her intention to step down from her post as co-chair of SPARC. She proposes to stay as Director of the SPARC Office for 1-2 years, until a new offer is made to welcome the SPARC Office. The composition of the renewed SSG will be submitted for approval to the JSC in March 2001 and will be announced on the web site and in the next Newsletter.

Next SSG meeting

K. Hamilton invited the SSG to meet in Hawaii in 2001. The invitation was unanimously welcome. The exact date has now been fixed to the 3-6 of December 2001.

Reference

Pawson, S. *et al.*, The GCM-Reality Intercomparison Project for SPARC (GRIPS): Scientific Issues and Initial Results, BAMS, Vol. 81, No. 4, April 2000.

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Report on the 2nd SPARC General Assembly (SPARC 2000)

6-10 November, Mar del Plata, Argentina

Conveners: A. O'Neill (Chair), S. Diaz, R. McKenzie, V. Ramaswamy, T. Shepherd and S. Yoden
Chair of Local Organising Committee: P. Canziani

A summary of some of the scientific highlights

Since the discovery of the ozone hole in the mid 1980s, great progress has been made in understanding the dynamical, chemical and transport processes that occur in the stratosphere. At the same time, the importance of the stratosphere as an integral part of the climate system has come to be more fully appreciated. Through exchanges of mass, momentum and energy, the stratosphere is strongly coupled to the climate system as a whole. Relevant processes are commonly non-linear (for instance, the dynamical coupling between the troposphere and stratosphere), and by no means fully understood. SPARC has been instrumental in promoting the science that has led to a wider appreciation of the importance of the stratosphere in climate. It has also been active in promoting greater integration between scientific disciplines involved in the broader World Climate Research Programme.

Alan O'Neill opening the SPARC 2000 General Assembly

The Scientific Organising Committee of the 2nd SPARC General Assembly (SPARC 2000) aimed to structure the scientific meeting in a way that emphasised the importance of the stratosphere in the wider context of climate change. The five-day meeting comprised four sessions. Session 1 emphasised fundamental processes and interactions among processes. Session 2 discussed observations relevant to these processes and indicative of climate variability and trends. Session 3 focused on modelling stratospheric processes and climate variability, and was designed to present a synthesis of our current understanding. Session 4 was devoted to observations and modelling of solar ultraviolet radiation, a particularly timely topic during a year in which the Antarctic ozone hole covered the greatest area yet observed, extending for a time over the southern tip of South America. Each of these sessions was accompanied by poster sessions, the scientific quality and breadth of which were outstanding. It is clear that the convenors of future SPARC General Assemblies must be vigilant in structuring the meeting to give equal emphasis to oral and poster sessions.

SPARC 2000 was attended by over 300 scientists from more than 30 countries. All Latin American countries were represented. Attendees will remember not only the high scientific quality of the meeting, but also the warmth of the reception given by our hosts in Argentina, their hard work over many months to make the meeting very enjoyable, and the generosity of the sponsors that enabled so many young scientists to attend.

The Chair of the Scientific Organising Committee, Alan O'Neill, wishes to record here his thanks to the Scientific Conveners for their diligent work. He extends particular thanks, on their behalf, to the Chair of the Local Organising Committee, Pablo Canziani, for his unstinting efforts to ensure that the meeting was a success. A summary of some of the scientific highlights is given below.

Session 1: stratospheric processes and their role in climate

(**Convener:** T. Shepherd)

Understanding the role of the stratosphere in the climate system interpreting indicators of climate change, developing credible models, providing a framework for diagnostic studies, and quantifying and interpreting changes in UV radiation all require a fundamental understanding of the basic physical processes involved. This was the rationale for Session 1, which to some extent underpinned the following sessions. A major focal point was the Upper Troposphere/Lower Stratosphere (UT/LS), also known as the dynamical "middleworld". The UT/LS is pivotal and complex: it is the interface between the troposphere and stratosphere, so it is where exchanges of material occur; radiative and chemical time scales are relatively long, so transport is very important; low temperatures imply a role for condensed matter in the chemical balance; and there is a sensitive radiative feedback from relatively short-lived greenhouse gases (water vapour and ozone). However, the entire stratosphere affects the UT/LS region. It does so dynamically through "downward control" and the diabatic circulation, chemically through transport (the Brewer-Dobson circulation) and through filtering of actinic fluxes, and radiatively through both short wave and long-wave fluxes.

The papers in Session 1 can be grouped into five main areas: chemistry, transport, clouds and water vapour, gravity waves, and climate variability and tropical oscillations. Because of the large number of papers, only the salient themes are highlighted.

Chemistry

An invited overview talk by **A.R. Ravishankara** (NOAA Aeronomy Lab) highlighted some of the complexities of the chemistry of the UT/LS region. He noted the unique aspects of ozone: its spatial inhomogeneity, its role in both UV and IR radiation, its production within the atmosphere, and the strong role of chemistry in its abundance. The complex role of NOx in the ozone budget, still not fully understood, was discussed; it was suggested that the summer polar stratosphere, being under photochemical control, is a good place to test our chemical understanding. Finally, the UT was noted to be chemically very fertile, and the possible role of chloral was raised. The role of NOx in the UT/LS region was also discussed in the paper by **S. Meilinger** (MPI, Mainz), given by **T. Peter,** which emphasised the need to distinguish carefully between the LS and the UT; e.g. for high NOx, NMHCs can have a large effect on ozone production just below the tropopause.

The global modelling of chemical climate using general circulation models has emerged as a major evolving area of research. While several years ago only a few groups were active, now there is a wealth of activity in various countries. Results were presented on the Japanese CCSR/NIES model (**K. Sudo**), the NCAR model (**F. Sassi, D. Kinnison**), the Canadian MAM model (**A. Jonsson**), the French MOCAGE model (**H. Teyssedre**), the German KASIMA model (**T. Reddmann**), and the Utrecht model (**B. Bregman**).

Late-winter/spring polar ozone depletion continues to be a focus of investigation. **M. Rex** (Wegener Inst., Potsdam) gave an update on the latest results from the MATCH program, which identifies chemical ozone loss in the Arctic on specific air parcels through the combined use of trajectory modelling and ozonesondes. The coverage is sufficiently dense that an estimate of the net ozone loss over the Arctic can be obtained for the late-winter/spring season. Antarctic ozone loss was estimated in a paper by **B. Connor** (NIWA, Lauder). With regard to polar processes relevant to ozone depletion, the role of mesoscale processes in Arctic PSC formation was discussed by **M. Mueller** (Free Univ., Berlin) using lidar measurements, while denitrification was identified in the Arctic by **H. Oelhaf** (FZK Karlsruhe) using a combination of MIPAS-B measurements and modelling, and in the Antarctic by **R. de Zafra** (SUNY, Stony Brook) using mm-wave spectroscopic measurements of various species.

Transport

An invited talk by **P. Haynes** (Cambridge Univ.) presented the notion that the mid-latitude tropopause is a (lateral) mixing barrier, which emerges naturally in idealised studies of baroclinic instability. In this view, the extratropical tropopause is the transition level between altitudes which experience widespread mixing (the tropopause) and those which are constrained by this mixing barrier (the lowermost stratosphere). The subject of mixing and transport across the extratropical tropopause was addressed in several other papers: by **E. Shuckburgh** (Cambridge Univ.) and **R. Scott** (Laboratoire d'Aérologie, Toulouse) using analysed winds, by **A. Zahn** and **H. Fischer** (both MPI, Mainz) using measurements from the CARIBIC and STREAM aircraft campaigns, respectively, and by **Y. Rao** (IITM, Pune) and **Y. Tomikawa** (Tokyo Univ.) using radar data.

Another mixing barrier exists on either side of the tropical stratosphere, and there has been much interest in recent years in quantifying the upwelling in the "tropical pipe" and the associated mixing rates. **M. Volk** (Frankfurt Univ.) provided latest estimates of the mixing rates using Geophysica data from the APE-THESEO campaign, which were complemented by a study using both lidar measurements and modelling by **H. Bencherif** (Réunion Univ.). The representation of the tropical tape recorder in general circulation models was found to be highly sensitive to the choice of numerical advection scheme in studies by **K. Nissen** and **V. West** (both Edinburgh Univ.) and **S. J. Lin** (NASA/GSFC). In a somewhat different but related study addressing the origin of the tropical upwelling, **R. Garcia** argued that a transient calculation was required in order to account for the seasonal cycle of upwelling.

Yet another mixing barrier exists on the edge of the wintertime stratospheric polar vortex, and several studies were devoted to quantifying mixing across the vortex edge and within the neighbouring surf zone. This remains an important issue for quantifying polar ozone loss, especially in the Arctic. The papers included several studies with the French MIMOSA model by **F. Fierli**, **A. Hauchecorne** and **M. Marchand** (Service d'Aéronomie, Paris) and one by the Berlin model by **K. Krueger** (Free Univ., Berlin). A variety of measurement platforms are available in the Arctic; papers were presented using ILAS satellite data by **H. Nakajima** (NIES, Tsukuba), **L. Pan** (NCAR), and **W. Choi** (Seoul National Univ.), by **D. Gibson-Wilde** (CRA, Boulder) using ALOMAR ground-based data, and by **C. Basdevant** (LMD, Paris) using trajectory methods.

Clouds and water vapour

An invited talk by **T. Peter** (ETH, Zurich) addressed the question of the composition and origin of the subvisible cirrus clouds located at about 17.5 km altitude in the tropics. They are seen only in certain backscatter wavelengths, and sit several km above, and are apparently unconnected with, the thick cirrus associated with convection. Peter argued that it seems difficult to account for their existence unless a rather large upwelling of about 6 mm/s, which is an order of magnitude larger than the large-scale upwelling inferred on radiative ground, can be hypothesised. Some questioners wondered whether inertia-gravity waves might possibly be responsible, and this possibility was in fact discussed further in a paper by **F. Hasebe** (Ibaraki Univ.). The APE-THESEO campaign that observed these subvisible cirrus clouds was presented in a paper by **L. Stefanutti** (CNR IROE, Firenze).

The issue of tropical dehydration proved to be a lively topic. **X. Zhou** (Washington Univ.) attempted to associate variability in the cold point temperature with the QBO and ENSO. **S. Sherwood** (NASA/GSFC) examined the role of convective overshoots, noting the existence of a transition zone between the troposphere and stratosphere wherein different kinds of air coexist. **A. Gettelman** (NCAR) noted that the diurnal cycle in tropopause temperature (of about 1.5 K) over land, with a much smaller variation over the ocean, implicates the role of convection, but that convection above the tropopause is very rare, perhaps occurring less than 1% of the time across the tropics.

D. Kley (Juelich) presented the findings of the SPARC Water Vapour Assessment Report (WAVAS), which was recently completed and which focuses on the upper troposphere and lower stratosphere (see report in this newsletter). The report discusses the various measurement techniques, the data quality, limitations of data sets and advice on how to combine them (e.g. for trend studies), and the current understanding of the distribution and variability of water vapour. Copies of the report are available from the SPARC Office.

Gravity waves

An invited talk by **T. Tsuda** (RASC, Kyoto) described the new GPS/MET data set which is providing an unprecedented global view of gravity-wave activity in the lower stratosphere. The data show stronger gravity-wave activity in the tropics than in the extratropics, presumably associated with stronger convective activity, and interest naturally focuses on quantifying the connection between convection and gravity-wave excitation. This quantification is of great importance for climate modelling. Several papers investigated this connection: **T. Kerzenmacher** (Wales Univ.) using radiosonde analyses, and **Z. Eitzen** (Colorado State Univ.) and **Z. Chen** (LASG, Beijing) using idealised model simulations. **N. McFarlane** (CCCma, Victoria) reported results from the Canadian middle atmosphere GCM showing that the nature of the convective adjustment scheme had a strong effect on the gravity waves (including equatorial waves) generated in the model.

While GPS/MET is providing a global view from satellites, SPARC has been co-ordinating the development of a global gravity-wave climatology from high-resolution radiosonde data. Even though this has the obvious spatial biases, it does provide excellent vertical resolution. **R. Vincent** (Adelaide Univ.) gave an overview paper on the SPARC radiosonde initiative, while **T. Birner** (DLR, Oberpfaffenhofen) reported on German results, **M. Geller** (SUNY, SB) on US results, and **I. Son** (Yonsei Univ.) on Korean results. These studies are beginning to show links with source mechanisms. In related papers, **E. Pavelin** (Wales Univ.) studied gravity waves in a field experiment over Aberystwyth, while **K. Sato** (Kyoto Univ.) identified long-lived layered structures in radiosonde observations over Japan.

Gravity waves are important in the middle atmosphere because of their effect on mixing and momentum transport. **D. Fritts** (CRA, Boulder) reported on high-resolution numerical simulations directed at quantifying the generation of turbulence by breaking gravity waves. **J. Alexander** (also CRA, Boulder) derived constraints on the gravity-wave forcing of the atmospheric circulation based on UARS satellite observations to infer the radiative heating and cooling, while **H. Chun** (Yonsei Univ.) did a similar thing based on closing the momentum budget in the UKMO analyses. The important question of parameterising the effects of unresolved gravity waves in climate models was addressed in papers by **R. Tailleux** (LMD, Paris) and **M. Charron** (MPI, Hamburg).

Climate variability and tropical oscillations

It was at the first SPARC General Assembly in Melbourne in 1996 that the first results were announced concerning the simulation of a QBO-like oscillation in a (simplified) high-resolution GCM (by **M. Takahashi**). Since then there has been a lot of progress, with QBO-like oscillations first simulated in more realistic but still high-resolution GCMs, and most recently in coarse-resolution GCMs. The missing ingredient seems to have been momentum transport by small-scale gravity waves, which can either be resolved (at very high resolution) or parameterised. The latter possibility is crucial if GCMs are to include this most important mode of atmospheric variability, and yet run long enough to produce climate simulations. The focus now is on understanding why models produce QBO-like oscillations, and whether they do so for the right reasons. There were three papers on the presence or absence of such oscillations in coarse-resolution models: **A. Scaife** (UKMO) using the UKMO unified model, **C. McLandress** (Toronto Univ.) using the Canadian middle atmosphere model, and **M. Giorgetta** (MPI, Hamburg) using the MAECHAM model. McLandress noted that the period of the oscillation depended on the finite differencing used to determine momentum flux divergence in the parameterisation scheme, suggesting that much more work is needed to assess the reliability of these kinds of results.

A large component of climate variability in the stratosphere concerns ozone and temperature in mid-latitudes and in polar regions. Understanding this variability, and its possible link with the troposphere, is crucial for delineating anthropogenic ozone loss and climate change. There were several papers on this topic; e.g. **R. Bernardi** (Univ. Republica, Uruguay) linked changes in the SH vortex to SST anomalies, **P. Canziani** (Buenos Aires Univ.) linked total ozone anomalies (or 'mini-holes') to synoptic variability, and **L. Hingane** (IITM, Pune) linked the evolution of the mini-holes to the monsoon circulation.

Session 2 : stratospheric indicators of climate change

(**Convener:** V. Ramaswamy)

This session focussed on recent research concerning stratospheric indicators of climate change. The subjects covered included variations and changes in trace species such as methane and other well-mixed gases, ozone, water vapour, aerosols, polar stratospheric and cirrus clouds; temperature; tropopause features; stratospheric circulation; and forcing/ variability of stratospheric ozone and climate. Both the oral talks and posters on display yielded new insights besides covering a wide array of technical issues related to the above topics.

The invited presentation (**W. Randel**) pointed out the prominent as well as unusual features in the observations of the stratosphere during the 1990s, e.g., the variation in the Brewer-Dobson circulation and eddy wave fluxes, the accompanying variations in methane and water vapour, and trends in temperatures especially in the northern polar regions during springtime. Besides influences due to solar cycle and volcanoes, there is also a significant coupling with the climate of the troposphere.

The availability of long (~a decade or more) time series of several relevant stratospheric parameters, as measured by satellites and ground based instruments, have initiated analyses studies seeking to understand causes of the associated phenomena. Besides ozone which was the focus of several papers, recent observations of stratospheric water vapour have generated a lot of interest, in part because of the importance of the apparent changes for stratospheric temperature trends/climate and stratospheric chemistry, and in part because the basic causes are not well understood.

Findings of the recently completed SPARC water vapour assessment (see also Session 1 report) suggest significant increases in the lower stratospheric water vapour content over the past few decades.

Investigations of the long-term (~2 decades or more) temperature trends in the global stratosphere based on measurements from a number of platforms reveal a general cooling, but with distinct seasonal and latitudinal variations; however, there is a wide divergence in the estimates for the mesosphere. There are some problematic issues regarding the currently (and the only one) deployed AMSU satellite instruments' ability to detect climate change in the stratosphere. Stratospheric aerosol concentrations appear to be at their lowest values now compared to the late 1970s when such global observations were begun. The utility of long-term lidar measurements at a specific site to diagnose the climatology of locally present cirrus clouds was demonstrated. The tropical upper tropospheric and tropopause regions are generating substantial research interest. Radiosonde measurements indicate correlation between surface and stratospheric temperatures, with a cooling of the lower stratosphere during El Niño events, although the sonde data quality at the lower stratospheric altitudes have to be accounted for with some care. Intraseasonal and longer-term variations in the tropical tropopause are inferred from observations and analysed fields.

Diagnostic investigations, based on observations and models, have explored the possible links between stratospheric climate, ozone and tropospheric features. Solar variations and their possible modulation of the QBO could be enabling a solar component in the long-term variability of the stratosphere. The plausible connection between interannual changes in stratospheric circulation, tropospheric structure and total ozone may bear on the causes of the observed stratospheric ozone and temperature trends in the northern mid-latitudes. The modes of atmospheric variability, in particular involving planetary wave propagation, could have substantial implications for climate change and detection.

While the oral presentations exposed several important contemporary issues concerning stratospheric indicators of climate change, the poster sessions provided the setting for amplifications on several of the above issues. In addition, the poster sessions reported important outcomes or anticipated results from several campaigns or new measurement techniques or new diagnostic methods. The details showcased the in-depth scrutiny and research underlying the diagnostic analyses of observations e.g., different kinds of problems affecting interpretation of observed phenomena, sampling problems and instrument uncertainties, temporal discontinuity difficulties, inconsistencies between various observational platforms, global versus regional features, and accounting for the natural internal variability of the stratosphere.

Nonetheless, the ability to synthesise the numerous observations available now, and the resulting understanding of the variations in stratospheric features, have advanced considerably since the First SPARC General Assembly and have opened up a host of new research opportunities.

Session 3: modelling and diagnosis of stratospheric effect on climate

(**Co-conveners:** S. Yoden and V. Ramaswamy)

This session was focussed on the synthesis of stratospheric processes in the context of climate interpretation and prediction. Issues concerning stratospheric climate and effects of stratospheric processes on the lower atmosphere were discussed based on both numerical modelling and diagnostic studies involving observations. It was divided into four sub-sessions; (3-1) Climatology, (3-2) Internal variations in S-T coupled system, (3-3) Responses to forcings, and (3-4) Trends. Regular periodic annual cycle or internal variations of the stratosphere-troposphere coupled system were discussed in the first two sub-sessions, while responses to "external" forcings were discussed in the rest.

In the first sub-session of climatology, **M. Chipperfield** (Leeds Univ.) gave an invited talk on the current status of three-dimensional global chemical transport models (CTMs) and their use to understand the interaction of ozone depletion and climate. **R. Kawa** (NASA/GSFC) showed the capability of such CTMs by the comparison with atmospheric measurements on the winter of 1999-2000 in the Northern Hemisphere. We also had active discussions on the interactions between chemistry and climate in the focused discussion session in which several new results with different hierarchy of numerical models (2-D or 3-D, CTM or fully coupled chemistry-climate (dynamics) model) were presented. Several other papers in this sub-session dealt with the GRIPS(GCM Reality Intercomparison Project for SPARC) initiative. For instance, **T. Horinouchi** (Kyoto Univ., presented by **S. Pawson** of NASA/GSFC) gave a clear dependence of the generation of vertically propagating waves in the tropics on the cumulus parameterisation scheme in each GCM.

The subject of the second sub-session was the internal variations in the stratosphere-troposphere coupled system, and the hot issue was the Arctic oscillation (AO), or the annular mode. More than ten papers were submitted on this subject. **M. Baldwin** (NWRA) described the observed deep, longitudinally symmetric patterns of low-frequency variability and the downward propagation of the AO signature, while **A. O'Neill** (Reading Univ.) pointed out the importance of the three-dimensional structure in the AO. Not only observational studies but several types of numerical studies were presented on the AO-like internal variations. In the invited talk of this sub-session, **D. Shindell** (NASA/GISS) showed that the AO patterns are frequently obtained in responses to greenhouse gas, ozone, solar and volcanic forcing in climate change simulations. Other internal variations with intraseasonal and interannual time scales were also discussed intensively in this sub-session.

The third sub-session of responses to forcings were divided into three: (1) QBO and ENSO, which are, in a sense, "external forcings" to the extratropical stratosphere, (2) solar forcing with the 11-year cycle, and (3) volcanic aerosols. Some fully coupled chemistry-general circulation models were used to investigate the responses. **J. Haigh** (Imperial College) gave an invited talk on the response to solar variability, and **A. Robock** (Rutgers Univ.) summarised the impact of the 1991 Mt Pinatubo eruption based on the Pinatubo Model Intercomparison Project. On the other hand, **V. Ramaswamy** (GFDL) pointed out the difficulty of getting statistically significant results in the high-latitude winter due to large internal variability as a result of the GFDL "SKIHI" experiments.

The last sub-session on trends, which was also the last part of the assembly, had an invited talk by **D. Karoly** (Monash Univ.) who gave a perspective of the Intergovernmental Panel on Climate Change for detection and attribution of a stratospheric role in climate change. Stratospheric forcing processes include not only natural forcing variations discussed in the third sub-session but also anthropogenic variations such as in greenhouse gases or stratospheric ozone. Model studies of stratospheric trends in ozone, temperature and water vapour were reported by several authors. For example, **B. Boville** (NCAR) showed a result of climate change simulations with the NCAR Climate System Model (a coupled ocean-atmosphere general circulation model) for the period of 1870-2100 with several scenarios of trace gas changes. Importance of the modulation due to large internal dynamical variations was repeatedly pointed out during the sub-session.

Session 4: UV observations and modelling

(**Conveners:** S. Diaz and R. McKenzie)

The UV session invited papers on measurement studies as well as modelling studies of UV radiation in the troposphere and at the Earth's surface. We were particularly interested in receiving contributions that relate to changes in UV to changes in ozone, cloud, and aerosols. Particular emphasis was placed on the co-ordination of ground-based measurements of UV to assess the accuracy of the estimations of UV derived from satellites since in years to come it is expected that these will play a major role in UV radiation assessment, in the same way that satellite derived ozone has already proved crucial to our global understanding of ozone depletion.

This session attracted more interest than expected, with over 50 papers being accepted. Only 10 of these were given oral presentations, and it could be argued that greater emphasis be given to this area in future assemblies of SPARC, since changes in UV are the major driving factor for this research. There was a good mix of topics and geographical coverage: it was especially pleasing to see an excellent representation of the wide range of research into UV and its impacts that is being undertaken in South America.

The posters presented were of a very high quality and the focused discussion sessions provided an excellent forum for informal discussion with the authors, despite the inclement weather (but low UV) which prevailed most of the time at the meeting. They attracted a lot of interest among the atmospheric scientists as well as with the biological scientists who convened the associated workshop on impacts of UV radiation on terrestrial and aquatic ecosystems on the Saturday following the SPARC meeting.

Several papers (orals and posters) focused on relating ground-based measurements of UV to satellite-derived estimates of UV. Most of these compared of ground-based measurements of UV with estimates using data products from the TOMS instruments. There was a general consensus that while satellite products provide a useful global coverage of UV patterns at the surface, significant discrepancies remain. The discrepancy appears to be related to uncertainties in allowing for tropospheric extinction (e.g. from ozone and aerosols). At unpolluted sites differences between satellite-derived estimates of UV and ground-based measurements are smaller. Improvements may be achievable with a better understanding of regional scale differences in tropospheric extinction and with higher resolution topography and cloud imagery.

Several speakers (including the invited speakers to this session **Drs Bais and Seckmeyer**) discussed the present status of UV research, and the extent to which recent internationally co-ordinated activities have improved the measurement accuracy and our understanding of processes that affect UV radiation. One of these was the IPMMI (International Photolysis Frequency Measurement and Model Intercomparison) campaign, which focused primarily on actinic radiation. It was argued (**S. Madronich**) that the effects of air pollution can be larger on actinic UV fluxes than irradiances and that more emphasis should be given to measuring actinic fluxes, particularly in polluted environments.

SPARC Assessment of Upper Tropospheric and Stratospheric Water Vapour

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Introduction

An initiative to conduct an assessment of upper tropospheric and stratospheric water vapour was begun following a SPARC sponsored international workshop held at NCAR, Boulder, Colorado, USA, 26-28 August 1998. Two main goals for the assessment were identified: 1. To critically review measurements of water vapour in the stratosphere and upper troposphere in order to consolidate our knowledge and understanding of its distribution and variability and 2. To collect quality assured water vapour data, in order to make them available for independent examination of the assessment results and to preserve such data for future use.

The objectives for the assessment, the report structure and the production schedule were published as a White Paper in SPARC Newsletter No. 13 [Kley and Russell, 1999]. Drafts of three chapters of the assessment report were prepared in 1999. The first draft report was examined by an international panel of peer reviewers both by mail review and at a meeting in Paris, France in January 2000. During the Paris meeting responses to the mail review comments were proposed by the chapter authors and discussed by the participants. This rigorous evaluation greatly improved the report with the contribution of the reviewers being significant. A second draft report was evaluated by mail review in August 2000.

Following the second review, a report: "SPARC Assessment of Upper Tropospheric and Stratospheric Water Vapour" was completed and published in December 2000 [SPARC, 2000].

The success in producing the Report is the result of the intensive work and enthusiastic co-operation of a large number of scientists world-wide who have worked towards improving the quality of the measurements and our understanding of the observations. The work of the contributors and reviewers was generously supported by many organisations and agencies including WMO, WCRP, SPARC, DG Environment of the European Commission, NASA, NOAA, NCAR, CNRS, CNES, Forschungszentrum Jülich, Imperial College and other national research programmes and institutions.

We take this opportunity to express our gratitude to all the scientists (authors, contributors and reviewers) who helped in the preparation of the assessment and to the SPARC Scientific Steering Group who have been supportive since its inception. Our special gratitude is due to the lead authors of the chapters and to Petra Udelhofen at the SPARC Data Center for setting up the data archive. Particular thanks must be given to Samuel Oltmans who organised the workshop at NCAR, Boulder Colorado; Computational Physics Inc. CPI, for hosting a workshop in Washington D.C.; François Dulac from the CNES for hosting the review meeting in Paris; Céline Phillips at the SPARC Office for her co-editorship, Marie-Christine Gaucher at the SPARC office for her help in the organisation of the review meeting in Paris and in the final editing of the report, and Catherine Michaut at the SPARC Office for her help in editing the second peer-review draft and the final draft of the report.

The full report is available at **http:www.aero.jussieu.fr/~sparc/**. The Report Summary is reproduced below.

Summary

Key findings

• A significant increase in the number and quality of stratospheric water vapour measurements has occurred over the past 25 years, particularly with the advent of satellite observations. Stated accuracy of most *in situ* and remote instruments as well as direct or indirect comparisons of coincident field measurements cluster are within a ±10% range.

• The concentration of stratospheric water vapour in the "overworld" ($\Theta \geq \sim 380$ K) is determined by dry air upwelling through the tropical tropopause, methane oxidation in the stratosphere, and transport by the poleward-and-downward (Brewer-Dobson) mean circulation. At the tropical tropopause, air is dried by a complex mix of processes that act on a variety of spatial and temporal scales. Water vapour in the upper troposphere is controlled by local and regional circulations and seasonal changes of upper atmospheric temperature.

• There has been a 2 ppmv increase of stratospheric water vapour since the middle 1950s. This is substantial given typical current stratospheric values of 4-6 ppmv. Methane photochemical oxidation in the stratosphere produces approximately two molecules of water vapour per molecule of oxidised methane. The increase in the concentration of tropospheric methane since the 1950s (0.55 ppmv) is responsible for at most one half of the increase in stratospheric water vapour over this time period. It is not clear what is responsible for the remainder of the observed increase in stratospheric water vapour.

• In the upper troposphere, no major inconsistencies were found between existing satellite-based measurements that would preclude their use in describing the long-term behaviour of upper tropospheric humidity. The data are also of sufficient quality for climatological and process studies.

• Upper tropospheric relative humidity (UTH) has been monitored for about 20 years by instruments on operational satellites. Assessing long-term changes in the UTH is difficult because of high variability during ENSO events, other natural modes of variability in the large-scale circulation, and the competing effects of water vapour and temperature changes on the UTH. Although both positive and negative statistically significant long-term changes can be found in different latitudinal bands, no striking global trend emerges from preliminary analyses.

• The operational radiosonde network does not produce water vapour data that can be used for either long-term change analyses, process studies in the upper troposphere, or for validation of upper tropospheric humidity (UTH) measurements. However, emerging data sets from improved quality, quasi-operational aircraft and ground-based instrumentation show promise and should be used more extensively for UTH process studies, climate analyses and satellite data validation.

Instrumentation, precision and accuracy

Tropospheric and stratospheric water vapour has been measured over the past 50 years by a large number of individuals and institutions using a variety of *in situ* and remote measurement techniques. Measurement results are widely dispersed in the literature. Instrumentation has steadily evolved from a small number of manually operated *in situ* instruments to automatic devices deployed on balloon and aircraft platforms, and more recently to high precision sensors on satellites. Only limited measurements of relative or specific humidity using a single instrument type have records longer than 10 years.

Operating principles and measurement specifications of most *in situ* research-type instruments currently in use are presented in **Table 1** along with their estimated measurement accuracies. These instruments provide point measurements in time and space with high vertical resolution, typically in the range of a few hundred meters or better. Accuracy estimates range from 5 to 10% based on known or estimated random and systematic uncertainties inherent in the instrument system, calibration procedures and retrieval algorithms. Remote sensing instruments deployed on ground-based, balloon-borne and airborne platforms provide vertical profile measurements with stated accuracies similar to those from *in situ* instruments, although with coarser vertical resolution. Such vertical resolutions range from several hundred meters in the case of LIDAR, a few kilometres for the infrared (IR) and far infrared (FIR) spectrometers, and approximately 10 km for microwave instruments.

Satellite and shuttle based experiments for measuring stratospheric and upper tropospheric water vapour are listed in **Table 2** along with random and systematic error estimates for single profile observations (as opposed to zonal or temporal averages). Accuracy estimates can be obtained from the root-sum-square of the random and systematic error components. Error estimates are given for ranges of vertical levels. Since some systematic error components vary randomly from profile to profile, these components are less important for daily, seasonal, or zonal means. Therefore, a zonal-average stratospheric error profile is dominated by the truly systematic error components, whose signs may be unknown and offsetting. The vertical resolution of satellite instruments, also given in **Table 2**, depends on the individual measurement concept (e.g. occultation or emission) and the specific instrument implementation. Horizontal resolution is typically on the order of 50 km to 300 km depending on whether the experiment is nadir or limb viewing.

The Microwave Limb Sounder (MLS) and several generations of High Resolution Infrared Sounder (HIRS) instruments on the TIROS Operational Vertical Sounder (TOVS) suite of missions have provided measurements of upper tropospheric relative humidity (UTH) from satellites. MLS relative humidity accuracy estimates for low to mid-latitudes range from 10 to 35% at 147 hPa and 20 to 50% at higher pressures. Accuracy estimates for individual relative humidity measurements made by TOVS are difficult to obtain but several generations of TOVS instruments span a temporal range of

Technique	Range	Altitude range	Accuracy
Frost point hygrometry	10,000 – 0.5 ppmv	5 – 30 km	5 – 10%
Lyman-a fluorescence	500 – 0.2 ppmv	5 – 35 km	6 – 7%
Tuneable diode laser spectrometry	> 0.1 ppmv	0 – 30 km	5 – 10%
MOZAIC sensor	> 20 ppmv	Troposphere	5 – 7% RH
Radiosonde	100 – ª5%RH	middle and low troposphere	not assessed
Micro wave spectrometry	20 – 0.2 ppmv	20 – 80 km	0.6 – 0.2 ppmv
LIDAR	> 4 ppmv	0 – 20 km	5 – 10%
IR and FIR spectrometry	> 1 ppmv	5 – 40 km	5 – 13%

Table 1. In situ and remote sensing techniques for measurements of H_2O from ground-based, balloon-borne and airborne platforms, along with their typical measurement range and overall accuracy, i.e. the sum of systematic and random errors.

Instrument and data set	Random error	Systematic error	Vert. Res.(km)
LIMS (version 5) (Limb IR emission)	20-15% (1 – 5 hPa) 15-10% (5 – 10 hPa) 10% (10 – 50 hPa)	31-24% (1 - 5 hPa) 24-20% (5 – 10 hPa) 20-37% (10 – 50 hPa)	≈5
SAGE II (version 5.9) (IR solar occultation)	10-5% (3 – 10 hPa) 5-14% (10 – 25 hPa) 14% (25 – 300 hPa)	6-13% (3 - 7 hPa) 13% (7 - 25 hPa) 13-27% (25 – 100 hPa) 27% (100 – 300 hPa)	≈3
ATMOS (version 3) (IR solar occultation)	9-11% (1 – 300 hPa)	6% (1 – 300 hPa)	3 – 6
HALOE (version 19) (IR solar occultation)	9-7% (1 – 10 hPa) 7-13% (10 – 40 hPa) 13% (40 – 100 hPa)	10-14% (1 – 10 hPa) 14-19% (10 – 40 hPa) 19-24% (40 – 100 hPa)	2.3
MLS (version 0104) (Limb mwave emission)	4% (1 – 10 hPa) 3% (10 – 50 hPa) 3-8% (50 – 100 hPa)	6-9% (1 – 10 hPa) 9-16% (10 – 50 hPa) 16-50% (50 – 100 hPa)	≈3
MAS (Limb mwave emission)	5-10% (1 – 50 hPa)	10-15% (1 – 50 hPa)	≈5
ILAS (version 4.20) (IR Solar occultation)	More than 10% (above 2 hPa) 10-5% (2 – 300 hPa)	30% (1 - 2 hPa) 30-10% (2 - 7 hPa) 10% (7 – 300 hPa)	1 – 2
POAM III (version 2) (IR Solar occultation)	5% (3 – 100 hPa)	15% (3 – 100 hPa)	1 – 3

Table 2. Estimates of random errors, systematic errors and vertical resolution of stratospheric H_2O profiles derived from satellite instrumentation.

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The objectives for the assessment, the report structure and the production schedule were published as a White Paper in SPARC Newsletter No. 13 [Kley and Russell, 1999]. Drafts of three chapters of the assessment report were prepared in 1999. The first draft report was examined by an international panel of peer reviewers both by mail review and at a meeting in Paris, France in January 2000. During the Paris meeting responses to the mail review comments were proposed by the chapter authors and discussed by the participants. This rigorous evaluation greatly improved the report with the contribution of the reviewers being significant. A second draft report was evaluated by mail review in August 2000.

Following the second review, a report: "SPARC Assessment of Upper Tropospheric and Stratospheric Water Vapour" was completed and published in December 2000 [SPARC, 2000].

The success in producing the Report is the result of the intensive work and enthusiastic co-operation of a large number of scientists world-wide who have worked towards improving the quality of the measurements and our understanding of the observations. The work of the contributors and reviewers was generously supported by many organisations and agencies including WMO, WCRP, SPARC, DG Environment of the European Commission, NASA, NOAA, NCAR, CNRS, CNES, Forschungszentrum Jülich, Imperial College and other national research programmes and institutions.

We take this opportunity to express our gratitude to all the scientists (authors, contributors and reviewers) who helped in the preparation of the assessment and to the SPARC Scientific Steering Group who have been supportive since its inception. Our special gratitude is due to the lead authors of the chapters and to Petra Udelhofen at the SPARC Data Center for setting up the data archive. Particular thanks must be given to Samuel Oltmans who organised the workshop at NCAR, Boulder Colorado; Computational Physics Inc. CPI, for hosting a workshop in Washington D.C.; François Dulac from the CNES for hosting the review meeting in Paris; Céline Phillips at the SPARC Office for her co-editorship, Marie-Christine Gaucher at the SPARC office for her help in the organisation of the review meeting in Paris and in the final editing of the report, and Catherine Michaut at the SPARC Office for her help in editing the second peer-review draft and the final draft of the report.

The full report is available at **http:www.aero.jussieu.fr/~sparc/**. The Report Summary is reproduced below.

Summary

Key findings

• A significant increase in the number and quality of stratospheric water vapour measurements has occurred over the past 25 years, particularly with the advent of satellite observations. Stated accuracy of most *in situ* and remote instruments as well as direct or indirect comparisons of coincident field measurements cluster are within a ±10% range.

• The concentration of stratospheric water vapour in the "overworld" ($\Theta \geq \sim 380$ K) is determined by dry air upwelling through the tropical tropopause, methane oxidation in the stratosphere, and transport by the poleward-and-downward (Brewer-Dobson) mean circulation. At the tropical tropopause, air is dried by a complex mix of processes that act on a variety of spatial and temporal scales. Water vapour in the upper troposphere is controlled by local and regional circulations and seasonal changes of upper atmospheric temperature.

• There has been a 2 ppmv increase of stratospheric water vapour since the middle 1950s. This is substantial given typical current stratospheric values of 4-6 ppmv. Methane photochemical oxidation in the stratosphere produces approximately two molecules of water vapour per molecule of oxidised methane. The increase in the concentration of tropospheric methane since the 1950s (0.55 ppmv) is responsible for at most one half of the increase in stratospheric water vapour over this time period. It is not clear what is responsible for the remainder of the observed increase in stratospheric water vapour.

• In the upper troposphere, no major inconsistencies were found between existing satellite-based measurements that would preclude their use in describing the long-term behaviour of upper tropospheric humidity. The data are also of sufficient quality for climatological and process studies.

• Upper tropospheric relative humidity (UTH) has been monitored for about 20 years by instruments on operational satellites. Assessing long-term changes in the UTH is difficult because of high variability during ENSO events, other natural modes of variability in the large-scale circulation, and the competing effects of water vapour and temperature changes on the UTH. Although both positive and negative statistically significant long-term changes can be found in different satellite measurements. Judicious use of data from the MOZAIC (Measurement of Ozone and Water Vapour by Airbus In-Service Aircraft) project provided some information used in assessing the quality of the MLS and TOVS measurements. To gauge their value in future correlative efforts, DIAL and Raman LIDAR systems were compared with radiosondes and frostpoint hygrometers. The LIDAR results in the troposphere agree to within about 10% with other correlative measurements, suggesting that such systems accurately measure water vapour. If deployed in sufficient numbers, such measurements could provide profile data valuable for validation of UTH satellite measurements.

Spatial variability and seasonal changes

Stratosphere, including the tropopause

The annual zonal mean water vapour distribution in the stratosphere is depicted in **Figure 2**. Key features are sharp vertical gradients at the tropopause and in the extratropical lower stratosphere, a minimum in the tropics at or just above the tropopause, and gradual increases upward and poleward. The water vapour distribution can be understood as a balance between dry air entering via the tropical tropopause, a source of water vapour from methane oxidation in the upper stratosphere and return to the troposphere via the extratropical tropopause. The general features of the distribution are explained by Lagrangian-mean transport via the Brewer-Dobson circulation, wave-induced isentropic mixing, and upward extension of tropospheric circulations in the lowest few kilometres of the stratosphere. Nearly all air that reaches the stratosphere above 100 hPa passes through the tropical tropopause where freeze drying at low temperatures and other poorly understood processes produce annual mean mixing ratios of ~3.5-4 ppmv. Some of this dry air rises slowly in the tropics, but most spreads poleward, primarily in the lowest few kilometres of the stratosphere. In addition, water vapour concentrations increase upward and away from the equator as methane is oxidised into water vapour. Below approximately 100 hPa, the extratropical lower stratosphere is moistened by air transported from the tropical upper troposphere horizontally across the subtropical tropopause at the location of the subtropical jet.

The horizontal transport in the lower stratosphere has a strong seasonal component (**Figure 3**). An absolute minimum of the mixing ratio (~2.8 ppmv) is centred near 20°N during January-March, with the dry air propagating both poleward and into the Southern Hemisphere. Relatively high water vapour values, centred near 30°N, are observed during the Northern Hemisphere summer coincident with the convective phases of the summer monsoons. Similar to the winter poleward propagation of the dry air masses, the higher summer values also appear to spread out to the poles and into the winter hemisphere. The horizontal transport caused by the South Asian monsoon is stronger than other monsoon circulations, leading to more water vapour in the upper troposphere during boreal as opposed to austral summer.

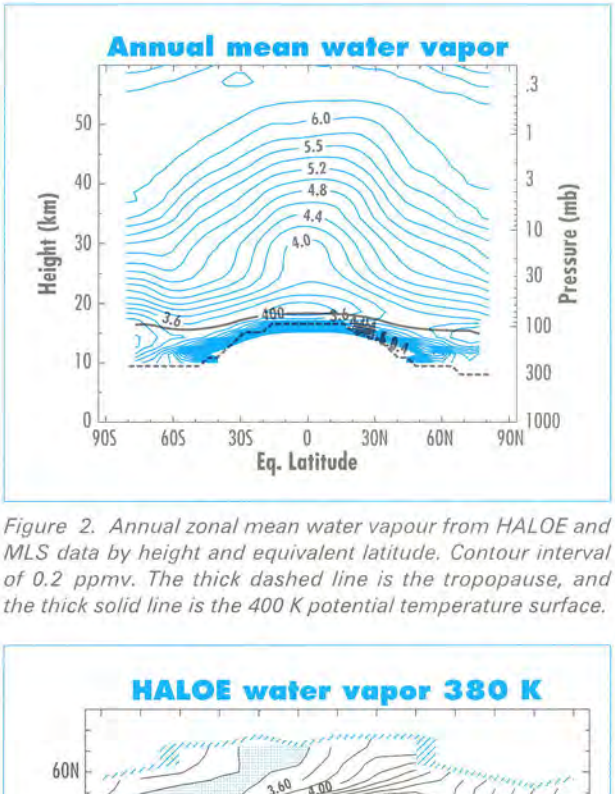


Figure 2. Annual zonal mean water vapour from HALOE and MLS data by height and equivalent latitude. Contour interval of 0.2 ppmv. The thick dashed line is the tropopause, and the thick solid line is the 400 K potential temperature surface.

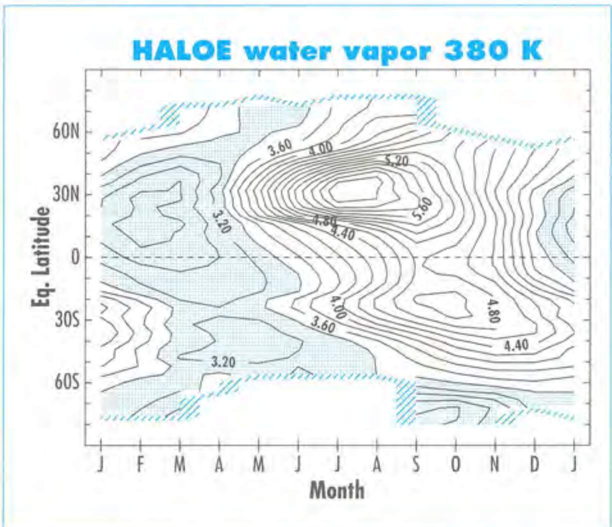


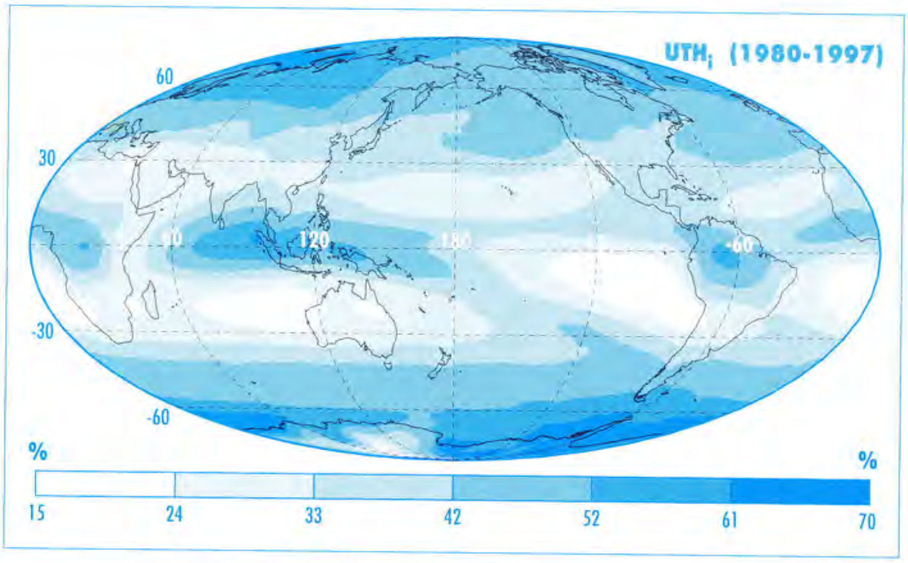
Figure 3. Latitude-time evolution of water vapour mixing ratio near 380 K derived from seasonal cycle fits of the HALOE data.

At the tropical tropopause, a complex mix of processes act to remove water vapour from air as it enters the stratosphere from the troposphere below. Within the framework of large-scale mean ascent, the dehydration processes probably include smaller-scale (convective) ascent, radiative and microphysical processes within clouds, and wave-driven fluctuations in temperature. The location, strength, and relative importance of these processes vary seasonally. However, the observed seasonal variation in tropopause-level water vapour is influenced primarily by the annual variation in tropical tropopause temperatures. Air rising through the tropopause is marked with seasonally varying mixing ratio, and retains these markings as it spreads rapidly poleward and more slowly upward into the stratosphere.

Upper troposphere

Upper tropospheric water vapour in the tropics and subtropics is strongly influenced by the Hadley Cell and the Walker Circulation. The predominant source for moisture in the tropical and subtropical upper troposphere is convection, producing, on average, moist regions in the convective areas over the western Pacific, South America and Africa (**Figure 4**). Moist areas also appear seasonally in the region of the Asian summer monsoon and along the intertropical and South Pacific convergence zones. The seasonality of surface temperature and of convection, which roughly follow the sun, as well as seasonal variations in monsoon circulation, produce concomitant seasonal changes in water vapour in the troposphere. This relationship between convection and upper tropospheric moisture changes sign near the tropical tropopause, somewhere between 150 hPa and 100 hPa, so that convection dries the tropopause region. Water vapour is also

Figure 4. Annual mean Upper Tropospheric Humidity over ice (UTHi) averaged for 1980-1997 from HIRS instruments, in percent.



influenced by fluctuations at both shorter and longer time scales, including the quasi-biennial oscillation in the stratosphere and the El Niño-Southern Oscillation and the Tropical Intraseasonal Oscillation in the troposphere.

Upper tropospheric water vapour at middle and higher latitudes is highly variable and can be supplied by transport from the tropics, by mesoscale convection, or by extratropical cyclones. Dry air can be transported from the subtropics or from the extratropical lower stratosphere. These transport phenomena tend to be episodic rather than steady.

Long-term changes

Stratosphere

There is only one nearly continuous stratospheric water vapour time series of 20 years duration, using a single instrument type, that is available for long-term change determination. Although differences between instrument systems were largely determined to fall within their stated uncertainty estimates, those differences are still too large to combine various instrument records to construct a longer time series. However, a number of data sets used in the assessment sampled the atmosphere periodically over a long period providing several time series of intermediate length (8-15 years). These were used in combination to estimate stratospheric changes. The observations are consistent in suggesting that water vapour has increased at a rate of about 1%/year over the past 45 years (**Figure 5**, p. III). The record also suggests that this increase has not been uniform but has varied over this period.

Upper troposphere

The longest data set of upper tropospheric humidity is one that is derived from the HIRS instrumentation on different TOVS satellites. The HIRS instruments cover a time period of nearly twenty years. A linear fit of relative humidity from 1979 to present is shown in **Figure 6.** The trends for different latitudinal bands, and especially in the deep tropics, are slightly positive but insignificant at the 99% confidence level.

A shorter time series of upper tropospheric relative humidity, 1992 to present, exists from the MLS instrument. **Figure 7** shows the MLS humidity for centre altitudes of 147 and 215 hPa over the latitude range 30°S-30°N. For the overlapping time period both data sets show a minimum in relative humidity that occurs in 1994 although the MLS minimum is shallower.

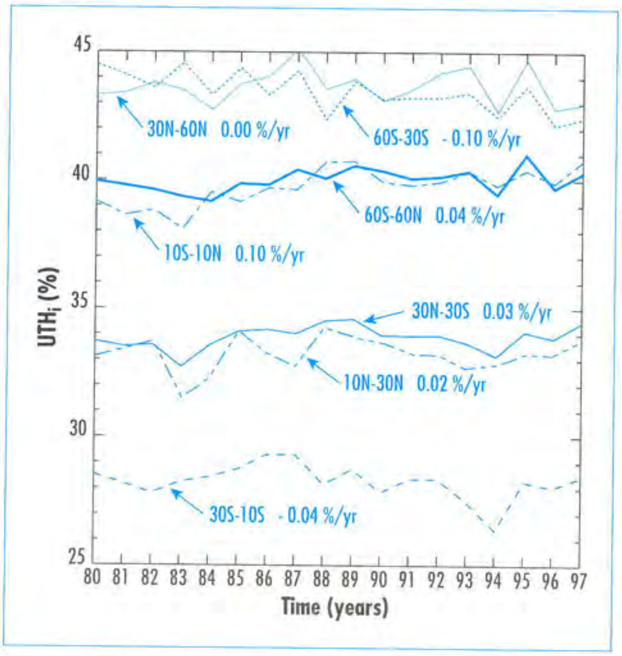


Figure 6. Annual mean upper tropospheric humidity over ice from HIRS for various latitude bands and linear fit statistics from 1980 to 1997. 60°S-60°N (solid line), 60°S-30°S (dotted line), 30°S-10°S (dashed line), 10°S-10°N (dot-dash line), 10°N-30°N (dash-3dots line) and 30°N-60°N (long dashed line).

When combined with satellite-derived upper tropospheric temperature data which also show a small positive trend since 1979, the HIRS data imply a larger positive specific humidity trend, but the combination of uncertainties in these two types of measurements means that the uncertainty in specific humidity is large enough to hide trends that are significant to climate.

Recommendations

1. Further studies, including well designed intercomparison experiments and laboratory work, are required to quantify and understand the differences between stratospheric water vapour sensors. This is particularly important for *in situ* instruments. *In situ* instruments are critical for obtaining high-resolution data for use in process studies of water vapour transport between the troposphere and stratosphere. Strong validation programs including correlative measurements need to be a part of water vapour satellite measurement efforts. In the upper troposphere, such validation has not been a part of the measurement program. Improvement of radiosonde observations of water vapour and wider use of LIDAR would aid in such validation.

2. Greater attention needs to be paid to the continuity of measurements for determination of long-term changes in both the stratosphere and upper troposphere. It is important to have

complementary observations, not relying solely on one instrument or approach. To better quantify dynamical effects that can impact long-term changes, all stratospheric measurements, whether satellite or *in situ*, should be combined with simultaneous methane measurements. Maintaining current long-term *in situ* measurement programs is necessary for any interpretation of long-term change. Stratospheric water vapour should be monitored *in situ* at various latitudes, and in particular in the presently data sparse tropics and Southern Hemisphere. Satellite sensors with a history of high quality measurements should be included in future satellite missions in order to monitor long-term changes in stratospheric and upper tropospheric water vapour. Upper tropospheric specific humidity should be monitored with a view to determining long-term trends. To determine these trends effectively, the sequence of future satellite missions should be planned to provide overlap with existing instruments in orbit.

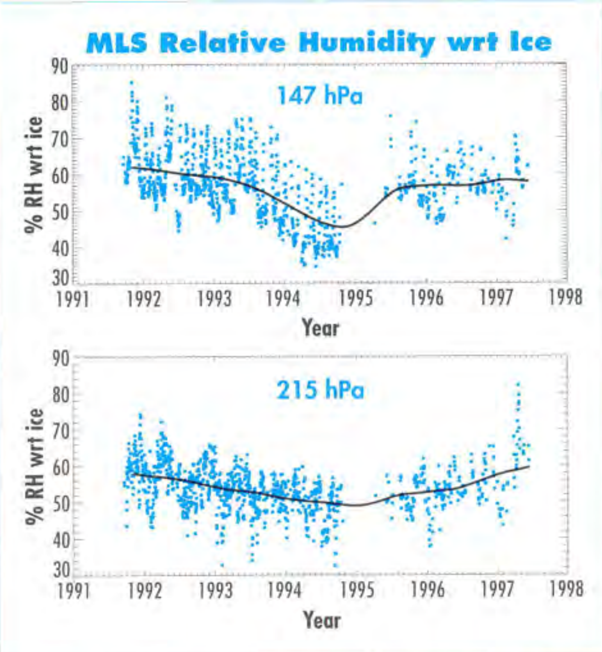


Figure 7. MLS relative humidity over ice. Data were averaged for 7 years between 30°S and 30°N. The top figure represents a 3 km layer around 147 hPa and the bottom figure a 3 km layer around 215 hPa. Dots are daily averages and the line is a 12-month running mean boxcar filter to remove the annual cycle.

3. Process studies of upper tropospheric water vapour and convection should be undertaken. These would include joint measurements of water vapour, cloud microphysical properties, and chemical species that can provide a history of the air. More observations of the tropical tropopause region (15-20 km), by both *in situ* and remote sensing methods, are needed in order to improve our understanding of stratosphere-troposphere exchange there.

4. Data sets collected in the future should be added to the SPARC Data Center at **http://www.sparc.sunysb.edu.** Valuable data from the 1940's, 1950's, and 1960's may already be lost, but some could and should be rescued.

References

Kley, D. and J.M. Russell III, Plan for the SPARC Water Vapour Assessment (WAVAS), SPARC Newsletter 13, 5-8, 1999

SPARC Assessment of Upper Tropospheric and Stratospheric Water Vapour, Dieter Kley, James M. Russell III and Céline Phillips (eds), WCRP – No. 113, WMO/TD - No. 1043, SPARC Report No.2, Paris 2000.

Detection and Attribution of a Stratospheric Role in Climate Change: An IPCC Perspective

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(Coordinating Lead Author, Detection of Climate Change and Attribution of Causes, IPCC Third Assessment Report)

Introduction

There has been increasing scientific, government and community interest over the last twenty years on the possible role of human activity in global and regional changes to climate. The Intergovernmental Panel on Climate Change (IPCC) was established by the World Meteorological Organization and the United Nations Environment Program to carry out regular assessments of climate change science, the impacts of climate change, and approaches for mitigation of and adaptation to climate change. It includes representatives of the governments of more than 120 countries and its reports are approved and accepted by consensus of all Panel members.

The main conclusions from the first volume of the IPCC Second Assessment Report "Climate Change 1995" (*Houghton et al.*, 1996) were:

- greenhouse gas concentrations have continued to increase
- climate has changed over the past century
- the balance of evidence suggests a discernible human influence on global climate
- climate is expected to continue to change in the future
- there are still many uncertainties

The third conclusion attracted considerable attention, as it suggested for the first time that there was a discernible human influence on global climate.

The IPCC Third Assessment Report is being finalised at present and will be released later in 2001. In this report, there has been a greater appreciation of the important role of the stratosphere in the climate system due to changes

Numerical Experiments on Internal Interannual Variations of the Troposphere-Stratosphere Coupled System

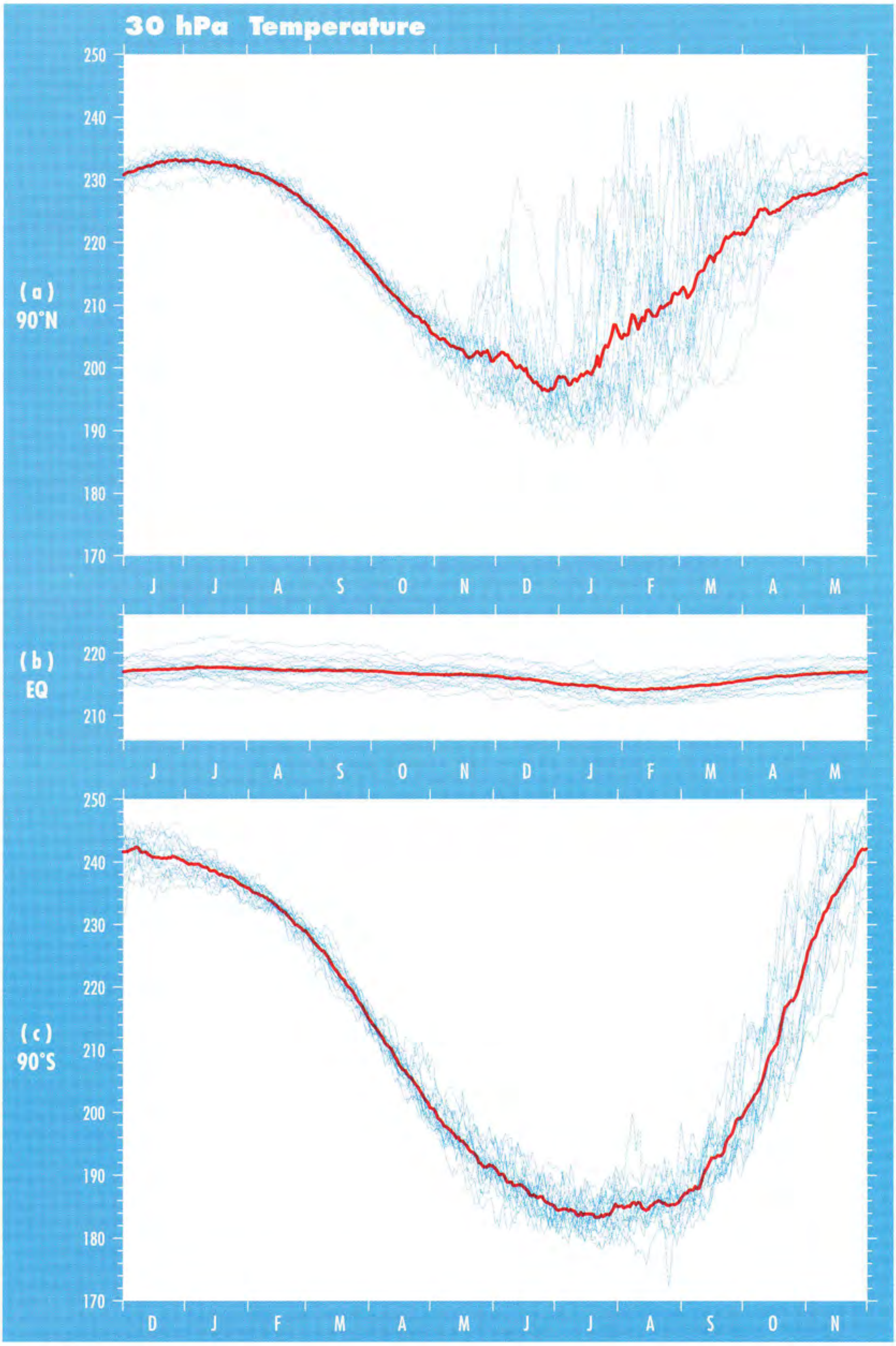


Figure 1

Seasonal variation of daily temperature at 30 hPa at the North Pole (a), the equator (b) and the South Pole (c) drawn with NCEP/NCAR re-analysis data for 1979-1997. Thick red line is the 19-year average for each calendar day.

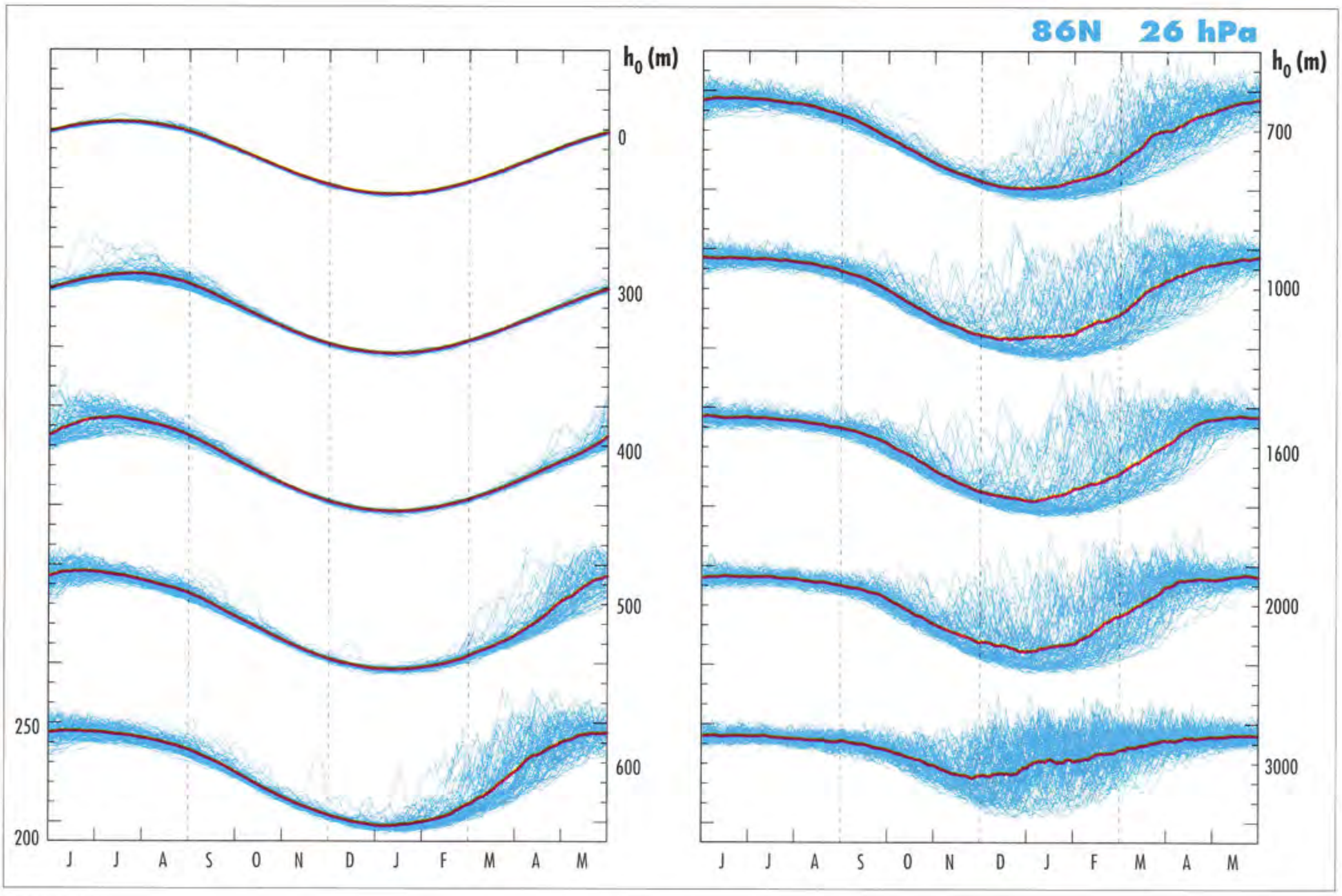
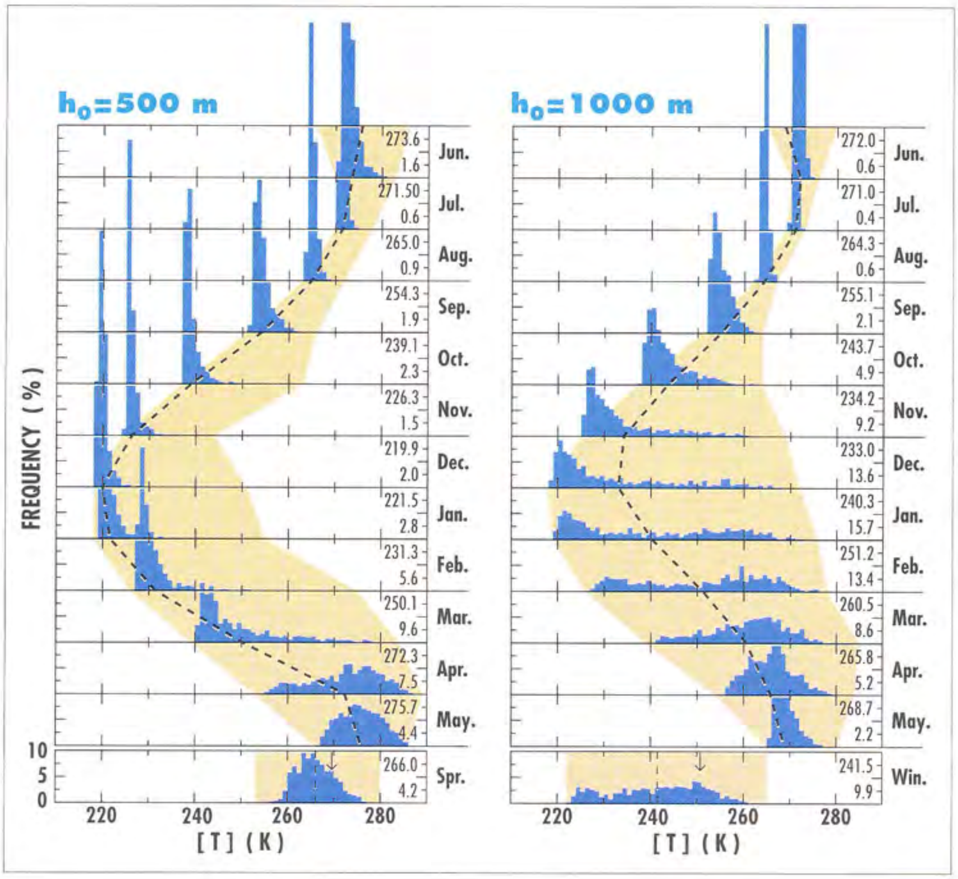


Figure 2
Seasonal variation of daily temperature at 86°N and 26 hPa for 10 runs of 100-year integrations under a purely periodic annual forcing. The topographic amplitude h_0 of zonal wavenumber 1 is changed from 0 m to 3000 m as the experimental parameter. Thick red line is the 100-year average for each calendar day.

Figure 3
Frequency distributions of the monthly mean polar temperature at p = 2.6 hPa in the two millennium integrations: h_0 = 500 m (left) and 1000 m (right). Dashed line denotes the 1000-year mean annual variation of the monthly mean temperature, and orange shade shows the variable range. Averages and standard deviations for the 1000-year data are also written on the right hand side of each panel (top and bottom numbers, respectively). Frequency distributions for a seasonal mean are also displayed in the bottom: spring mean for h_0 = 500 m and winter mean for h_0 = 1000 m. The downward arrow in the seasonal mean indicates a threshold value for the 200 years of highest temperature.



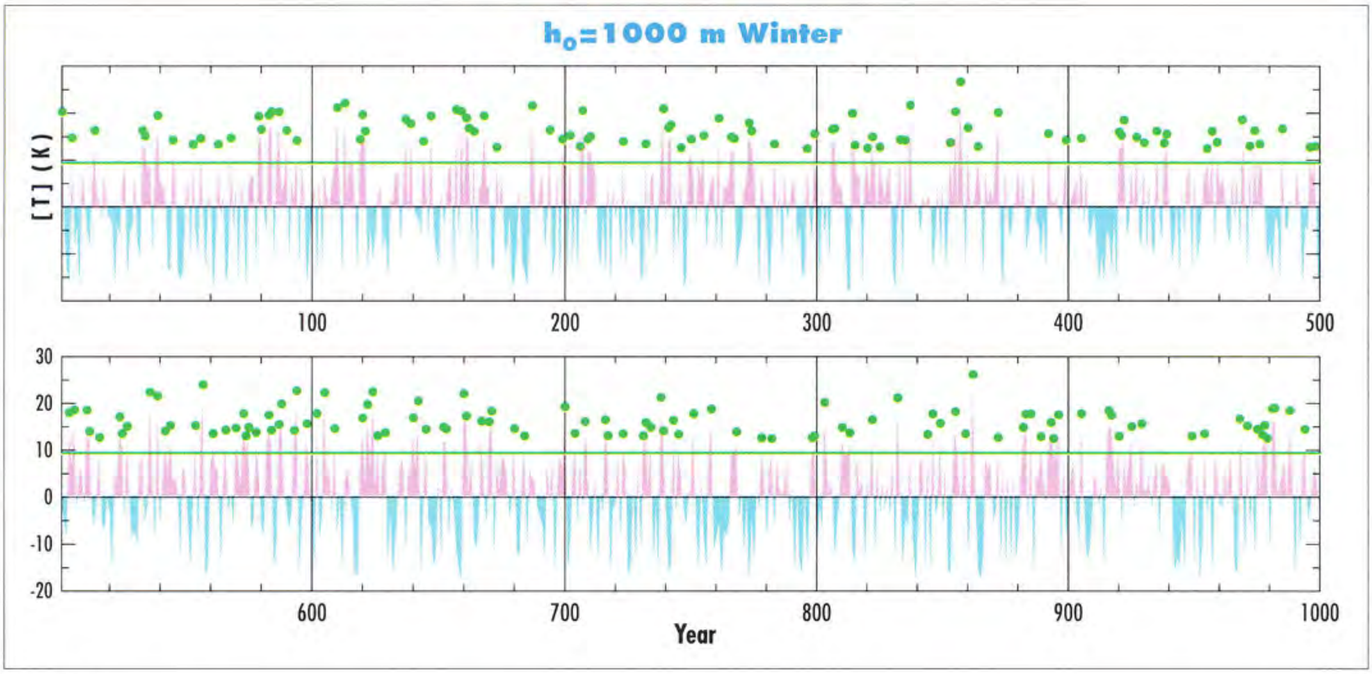


Figure 4
Time series of the deviation of winter-mean polar temperature at p = 2.6 hPa in the millennium integration for h_0 = 1000 m, which is made by connecting 10 independent 100-year integrations. The green horizontal line is the threshold value (+ 9.2 K) to select the 200 warmest winters denoted by green dots.

SPARC Assessment of Upper Tropospheric and Stratospheric Water Vapour

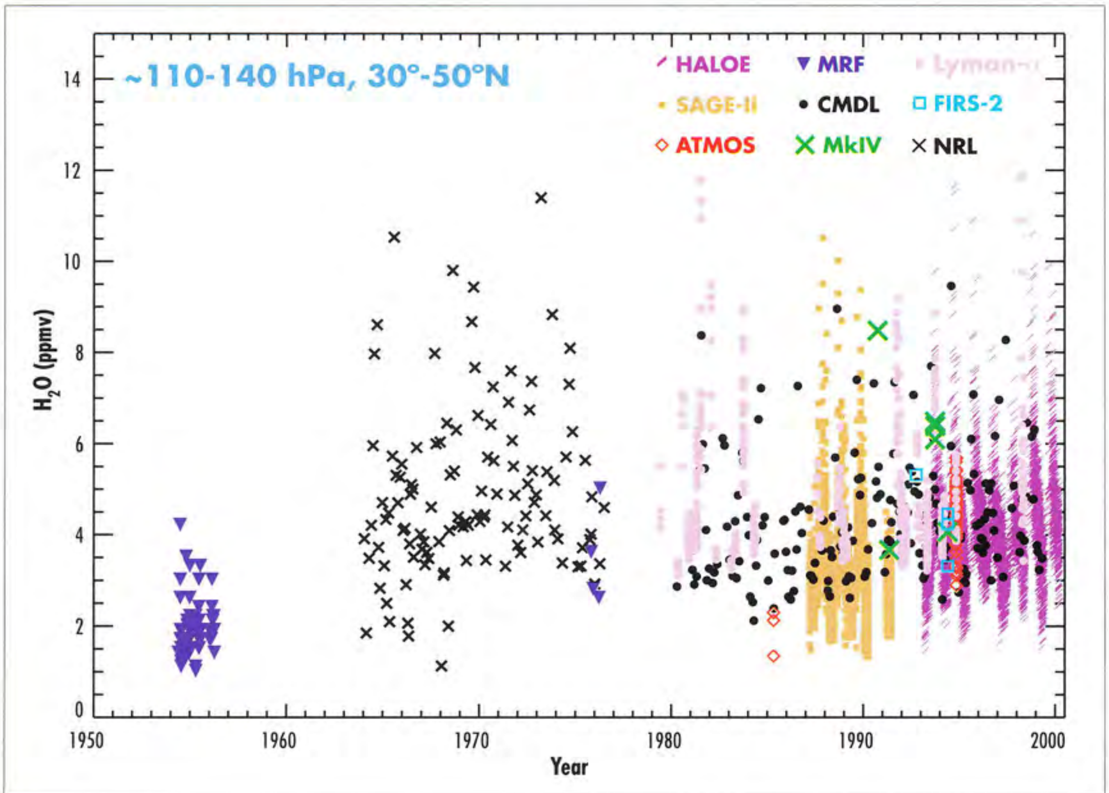


Figure 5
Water vapour time series for several instruments between 30-50°N over the pressure range 110-140 hPa. Data plotted are individual measurements with the exception of NOAA-AL Lyman-alpha (1 minute averages).

Integrated Global Observing Strategy (IGOS) for Ozone and Relevant Atmospheric Parameters

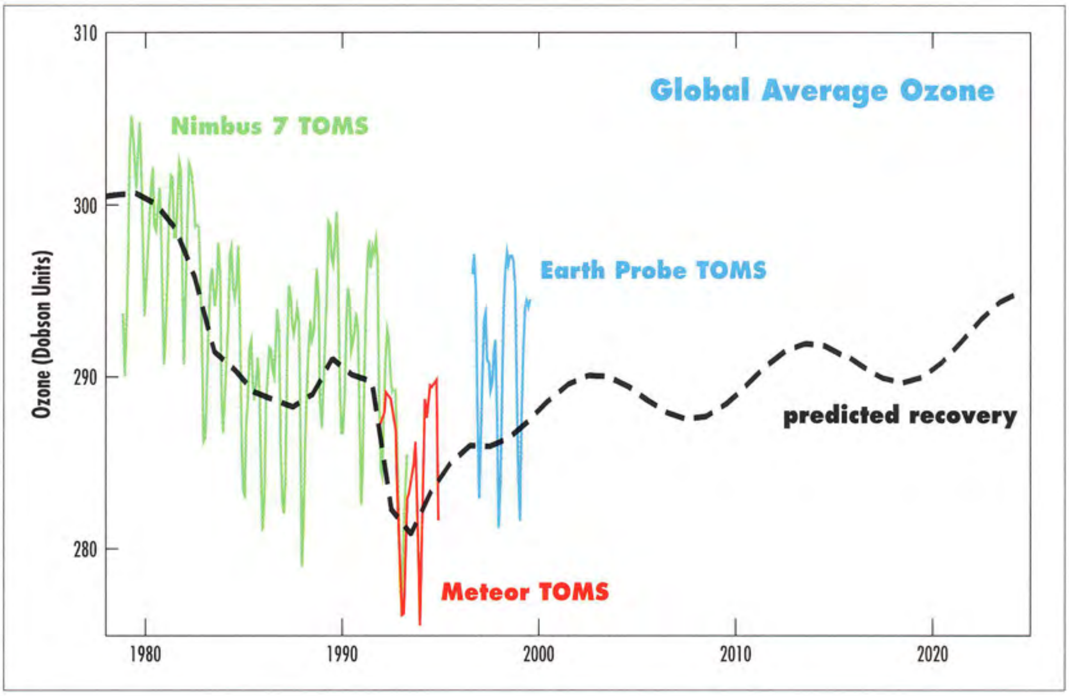


Figure 1
Observed and predicted ozone trends; TOMS (Nimbus-7, Meteor, and Earth Probe) and model predictions that include the known chemical catalytic processes and solar cycles, but not temperature trends in the lower stratosphere which could further slow ozone recovery.

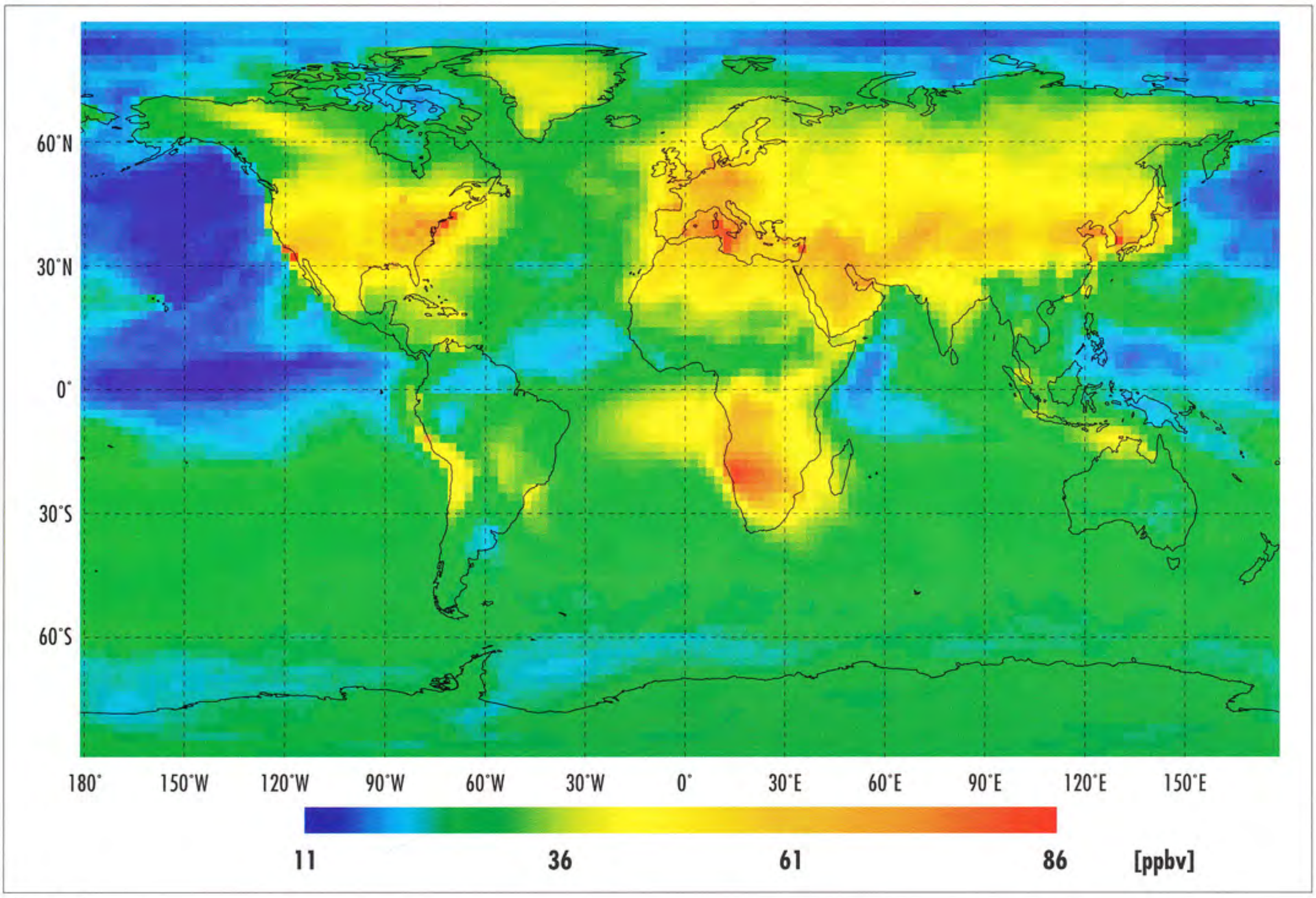


Figure 2
Monthly mean afternoon (1 to 4 pm) surface ozone concentrations calculated for July using Harvard GEOS-CHEM model.

INSTRUMENT	MISSION	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
TOMS	Earth Probe																
	Quik TOMS																
EPIC	Triana																
OMI	EOS Aura																
OMPS	NPOESS																
SBUV/2	NOAA - 11																
	NOAA -14																
	NOAA -16																
	NOAA - M																
	NOAA - N																
	NOAA - N'																
GOME	ERS - 2																
IMG	ADEOS																
ODUS	GCOM - A1																
ODUS	GCOM - A2																
SCIAMACHY	ENVISAT																
GOME - 2	METOP - 1																
	METOP - 2																
	METOP - 3																

Figure 3a
Satellite missions and instruments, which will measure total ozone, 2000 to 2015

INSTRUMENT	MISSION	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SAGE III	Meteor-3M																
	ISS																
	FOO																
SMILES	ISS																
POAM	SPOT - 4																
SBUV/2	NOAA - 11																
	NOAA -14																
	NOAA -16																
	NOAA - M																
	NOAA - N																
	NOAA - N[1]																
ILAS - 2	ADEOS - 2																
SOFIS	GCOM - A1																
SOFIS	GCOM - A2																
OSIRIS	ODIN																
Microwave	ODIN																
ACE	SciSAT																
ERS - 2	GOME																
GOMOS	ENVISAT																
SCIAMACHY	ENVISAT																
MIPAS	ENVISAT																
HIRDLS	EOS Aura																
MLS	EOS Aura																
TES	EOS Aura																
OMI	EOS Aura																
GOME-2	METOP																
OMPS	NPOESS																

Figure 3b
Satellite missions and instruments, which will measure ozone and atmospheric constituent profiles, 2000 to 2015.

Public Access to the Network for the Detection of Stratospheric Change Database

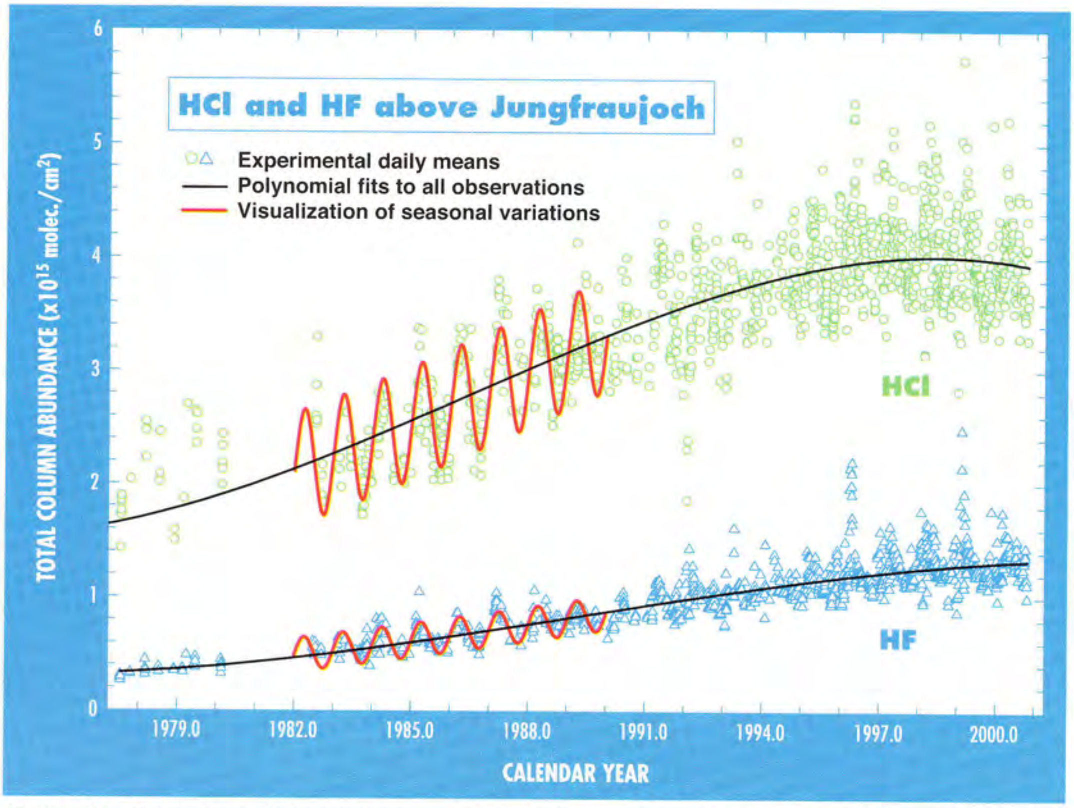


Figure 1 - Evolution of the daily mean total column abundance of hydrogen chloride and hydrogen fluoride measured above the Jungfraujoch station (47°N, 8°E) since 1977, as part of the University of Liege commitment to the NDSC. For details see European Research in the Stratosphere (1997), and *Mahieu et al.*, (2000). Figure courtesy of R. Zander.

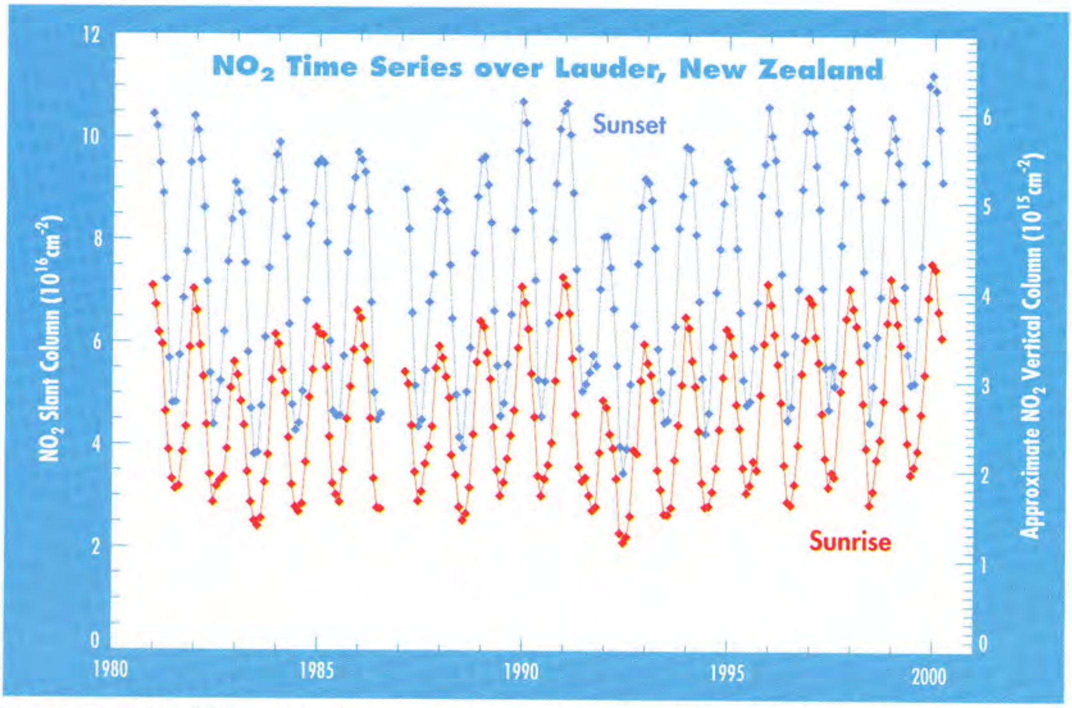


Figure 2 - Monthly means of sunset (pm, blue) and sunrise (am, red) NO_2 slant column measurements at Lauder (45°S, 170°E) as part of NIWA's commitment to the NDSC. The right-hand scale shows approximate values for vertical column NO_2 based on an air mass factor of 17.5. For details see *Liley et al.*, (2000). Figure courtesy of P. Johnston.

The Evolution of the Antarctic Ozone Hole in 2000

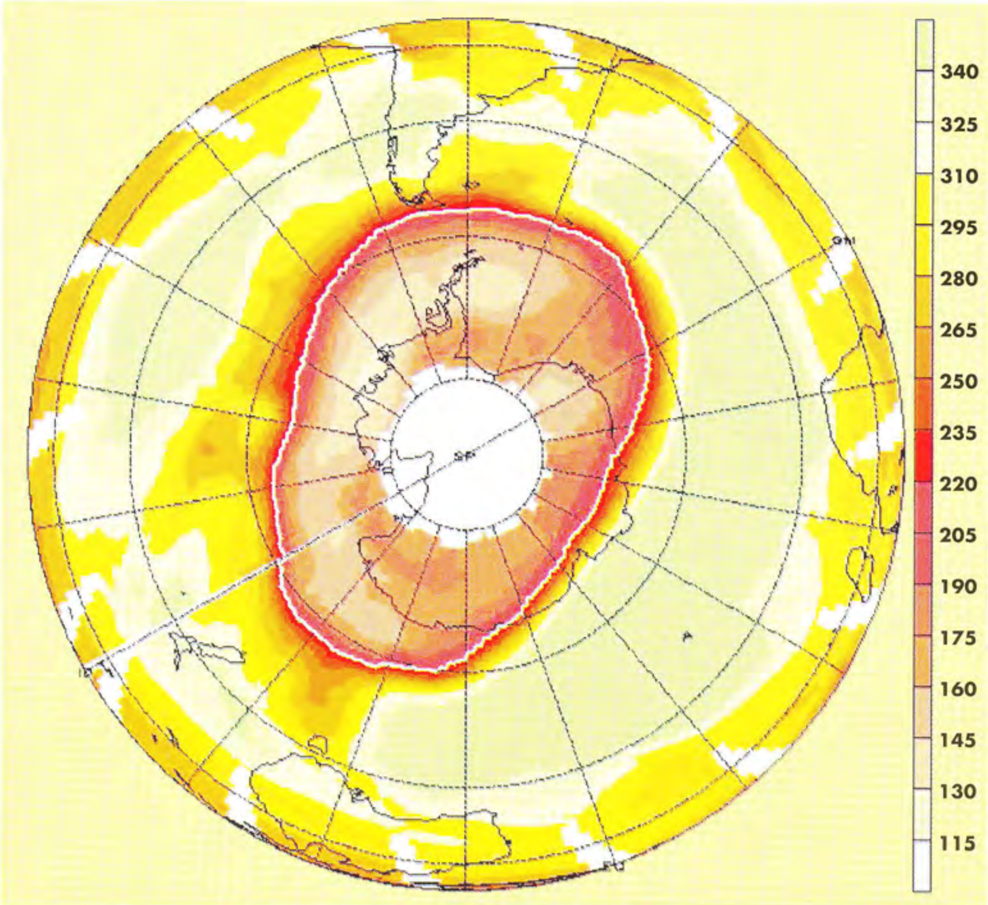


Figure 1
Map of the total ozone over the Southern Hemisphere, on September 10, 2000, as seen by EP-TOMS. On this day the ozone hole reached its largest size on record. The white line shows the 220 DU isoline. Values larger than 340 DU are not shown.

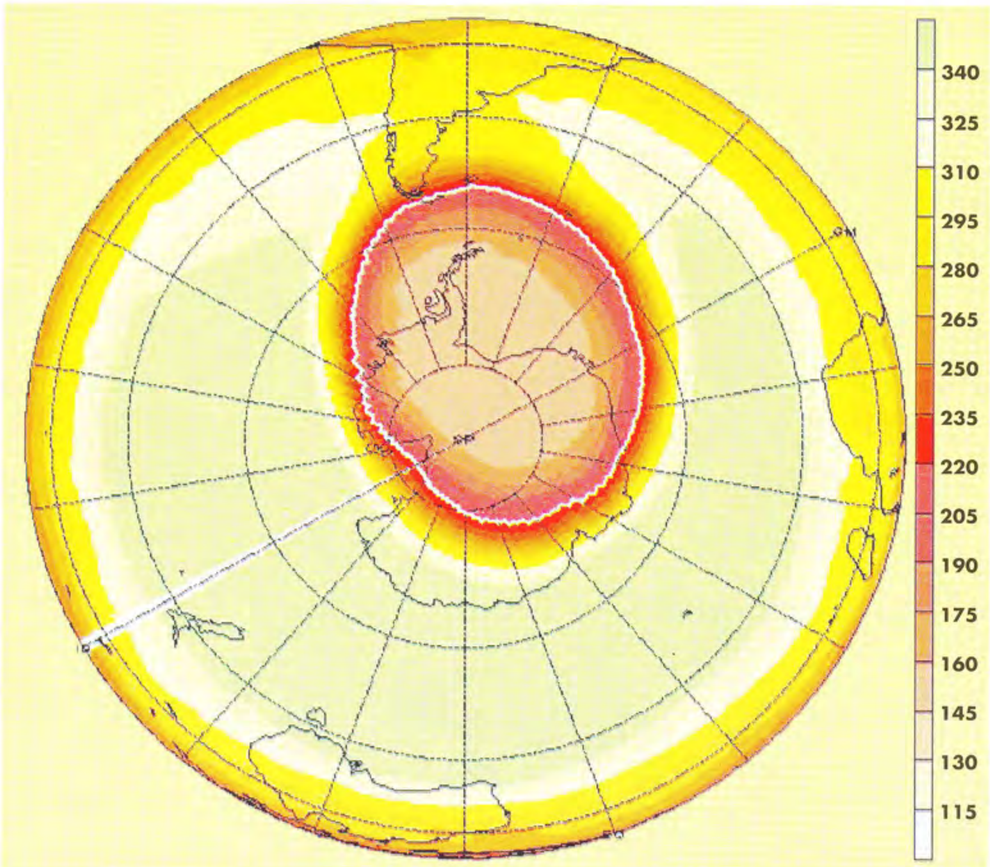


Figure 2
Mean total ozone over the Southern Hemisphere between October 6 and 20. Note the displacement of the ozone hole and how it covers at least half of Tierra del Fuego during this fortnight.

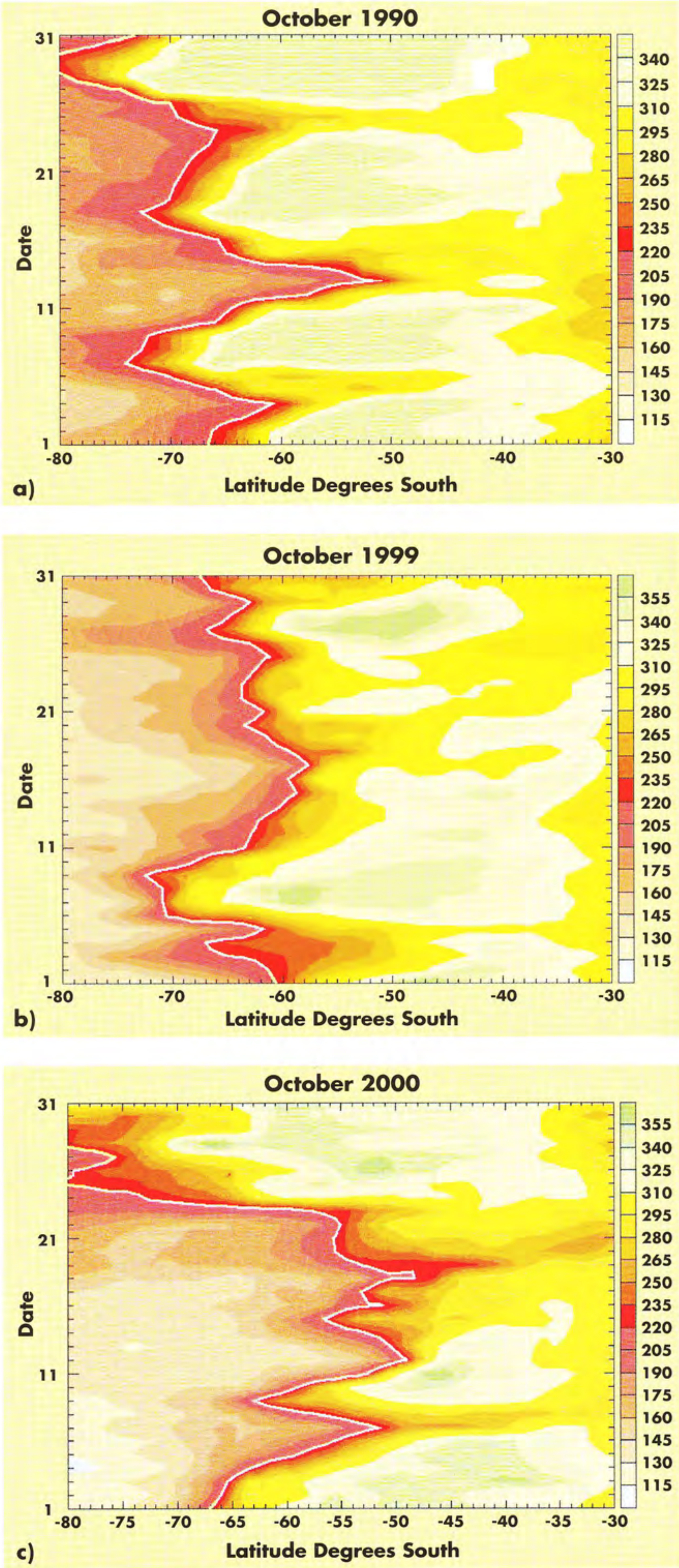


Figure 3.
Evolution of the ozone layer between 30° and 80°S during
a) October 1990,
b) October 1999,
c) October 2000,
averaged between 60° and 70°W, i.e. over Southern Chile and Argentina. The white line shows the 220 DU isoline.

in the structure of the stratosphere and recognition of its vital role for both radiative and dynamical processes in the climate system.

The elements of detection and attribution of climate change

Here, I briefly discuss the essential elements used in the detection and attribution of climate change, with an emphasis on the role of the stratosphere. Anthropogenic climate change, if and when it exists, must occur against a background of natural internal climate variability and natural forced climate variations. Detection and attribution of climate change is a statistical 'signal in noise' problem. Detection is the process of demonstrating that an observed change is significantly larger than could be explained by natural internal variability. Attribution is the process of demonstrating that the observed changes are consistent with the climate response to a specified forcing and not consistent with the response to other forcings. Hence, any detection and attribution study needs to consider observational evidence of climate change, estimates of internal climate variations, estimates of natural and anthropogenic forcing factors and the climatic response to such forcings as simulated by climate models, as well as quantitative methods to compare observed climate changes with the simulated responses to different forcings.

The longest instrumental climate records exist for surface air temperatures, with data available for some regions since about 1850 and adequate coverage to provide a reliable estimate of global-mean temperature since about 1900. These data show a warming of global-mean temperature by about 0.6±0.2°C over the last 100 years. Data for the stratosphere is available for a much shorter period, with radiosonde data available in the lower stratosphere since about 1960 and satellite data available from the 1970s (Chanin and Ramaswamy, 1999). These data show a global-mean cooling in the lower stratosphere of about 0.2°C per decade, interrupted by irregular warming period associated with major volcanic eruptions. Higher in the stratosphere, the cooling trends are even larger (Chanin and Ramaswamy, 1999)

In order to assess whether the changes in surface or lower stratospheric temperatures noted above are due to external climate forcing factors or to internal climate variability, reliable estimates of the magnitudes and patterns of internal climate variations are required. The observational data for both the surface and the lower stratosphere are too short to be used to estimate internal climate variability. In addition, they may have been affected by the response to external climate forcings, making it difficult to isolate the effects of internal variability alone. The only way to estimate internal climate variability is to use very long simulations of climate models that have no variations in external forcings. Such control simulations have been run with a number of different coupled ocean-atmosphere climate models for periods of 1000 years or longer. They show that the observed warming over the last 100 years is very unlikely to be due to internal climate variability alone.

However, such models do not provide reliable estimates of internal climate variability in the stratosphere, as they have very poor stratospheric resolution (*Gillett et al.*, 2000). Unfortunately, no climate models with adequate resolution in the stratosphere have been run out for extended periods of several hundred years, which would be needed to estimate internal climate variability on multi-decadal time scales. Simulations with some simpler stratospheric models show large multi-decadal variability in the stratosphere due to internal dynamics alone. In addition, it is likely that the coupling between atmospheric circulation and chemistry plays a role in the internal variability of the stratosphere. No long control simulations are available from climate models with adequate stratospheric resolution and interactive chemistry. Hence, estimates of internal climate variability in the stratosphere are uncertain.

If significant climate changes can be detected in the observational data, the next step is to compare them with the climate responses to different forcings to identify the possible causes, both natural and anthropogenic. Reliable estimates exist for the magnitude and patterns of changes in anthropogenic forcing due to increasing greenhouse gases, but there is some uncertainty in the forcing due to stratospheric ozone changes and greater uncertainty in the forcing due to changing tropospheric aerosols due to human activity. In addition to these anthropogenic forcings, changes in natural external climate forcings have been included in this IPCC assessment. Estimates of the climate forcing due to changing solar irradiance or due to changes in stratospheric volcanic aerosols are based on direct observations for the last two decades but are based on indirect evidence over the last 100-200 years and therefore have greater uncertainty. The response to these forcings must be estimated from simulations with climate models. The response to individual major volcanic eruptions seems to be well simulated but changes in volcanism appears to have played a small role in recent climate variations. The response to the direct effect of changes in solar irradiance has been simulated in climate models. However, those simulations used in detection and attribution studies have not included possible changes in stratospheric ozone associated with changes in solar UV irradiance. This coupling between ozone and climate is likely to be important in simulating the climate response to changes in solar irradiance. Another climate forcing in the stratosphere which has received little attention until recently is changing stratospheric water vapour. While there is some evidence of trends in water vapour in the upper troposphere and lower stratosphere (*Kley et al.*, 2000), this observational evidence is uncertain and the climate response even less certain.

A number of different approaches have been taken for the quantitative comparison of observed and modelled climate changes due to different causes. Early studies compared the magnitude of variations of global mean temperature between observations and climate models with anthropogenic forcings. Later, fingerprint studies compared the spatial patterns of observed temperature changes with those forced by natural and anthropogenic forcing factors. For example, *Tett et al.*, (1996) showed that the inclusion of increasing greenhouse gases, decreasing stratospheric ozone and increasing tropospheric sulphate aerosols were needed so that model simulations of the zonal mean temperature variations in the tropo-sphere and lower stratosphere over the last four decades compared well with observed temperature variations. Most recently, optimal fingerprint studies have compared the spatial and temporal variations of the observed climate with model simulations with different forcings. These show that the observed warming over the last 40 years cannot be explained by natural forcing factors alone, such as changes in solar irradiance or volcanic activity, as the observed changes in these forcings would be expected to lead to a cooling over this period (*Tett et al.*, 1999). It is only through the inclusion of increasing greenhouse gases, increasing tropospheric aerosols, and decreasing stratospheric ozone as forcings in climate model that they provide simulations consistent with the large-scale observed temperature changes over the last 40 years.

Summary

Some of the difficulties in assessing the role of the stratosphere in climate change arise from:

- poor stratospheric resolution in climate models used for detection and attribution;
- limitations of simulations of internal climate variability in the stratosphere;
- uncertainties in solar and volcanic forcing reconstructions and responses;
- uncertainties in trends in water vapour in the upper troposphere and lower stratosphere;
- the relatively short observational record for the stratosphere;
- the absence of adequate coupling between stratospheric chemistry and circulation in climate models;
- uncertainties about dynamical links between the stratosphere and the troposphere.

The main conclusions of the IPCC Third Assessment Report on the detection of climate change and attribution of causes include that:

- there is stronger evidence now of a human influence on global climate;
- paleoclimate data and model estimates of natural climate variations suggest that the observed warming over the last 100 years is unlikely to be solely natural in origin;
- simulations of the climate response to natural forcing alone, including volcanic eruptions and changes in solar irradiance, fail to explain the warming over the last 40 years;
- stratospheric ozone depletion has been a major contributor to the observed cooling in the lower stratosphere over the last 20 years;
- it is likely that increasing greenhouse gases have made a substantial contribution to the observed warming over the past 50 years;
- the accuracy of predictions continues to be limited by uncertainties in internal climate variability, natural and anthropogenic forcing and the climate response to external forcing.

Hence, there has been greater understanding and appreciation of the important role that stratospheric processes play in climate variability and change.

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Numerical Experiments on Internal Interannual Variations of the Troposphere-Stratosphere Coupled System

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Intraseasonal and Interannual Variations

Time variations of the atmospheric state have two periodic components known as a diurnal cycle and an annual cycle, which are responses to the periodic variations of the external forcings due to the earth's rotation and revolution, respectively. Intraseasonal and interannual variations are defined as deviations from the periodic annual response; generally the intraseasonal variation means low-frequency variation with week-to-week or month-to-month time scales, while the interannual one means year-to-year variation. Some part of these variations is a response to the time variations of the external forcings or boundary conditions of the atmospheric system, while the rest is generated internally within the system. Well known natural forcings with interannual time scales are the 11-year solar cycle, irregular and intermittent eruptions of volcanoes, and interannual variations of seasurface and land-surface conditions (e.g., temperature, roughness, snow/ice, ...), although the last ones should be considered as internal variation of the coupled system of the atmosphere, ocean and land. The Quasi-Biennial Oscillation (QBO) of the zonal mean zonal flow in the equatorial stratosphere, which is basically caused by the interaction between the mean zonal flow and equatorial waves propagated from the troposphere, could be considered as variation of a lateral boundary of the mid-latitude stratosphere. In addition to these natural forcings, there are some anthropogenic forcings such as the increases of greenhouse gases, aerosols, chemical constituents related to the stratospheric ozone decrease, or something else. Responses to these anthropogenic forcings are usually called "trends". On the other hand, external forcings are not so significant in the intraseasonal time scales; fundamentally intraseasonal variation is considered as a result of internal processes that may exist even under constant external conditions. Such variation may be a linear periodic oscillation or non-linear variation (periodic, quasi-periodic or chaotic) produced in the atmospheric system. These time variations can be classified systematically with some simple models (Yoden, 1997).

Figure 1 (p. I) shows an example of the variations in the polar stratosphere: daily temperature at the North Pole (a) has large intraseasonal and interannual variability in winter and early spring, while large variability at the South Pole is seen in spring (c). Large fluctuations at the North Pole are direct results of the occurrence of stratospheric sudden warming (SSW) event, which is associated with a rapid breakdown of the polar vortex from a cold, strong and undisturbed state to another warm, weak and disturbed one. The difference between the two hemispheres is quite noticeable. These intraseasonal and interannual variations are also seen in the monthly mean temperature data. In the equatorial lower stratosphere, the QBO signal is dominant in the original time series of temperature, but the annual component is also discernible in Figure 1 (b); the low temperature in northern winter can be understood as a result of adiabatic cooling due to the stronger upward motion associated with the wave-induced meridional circulation in the northern hemisphere (NH).

Hierarchy of Numerical Models to Understand the Stratospheric Variations

We have made some numerical experiments with a hierarchy of models over a decade, in order to understand intraseasonal and interannual variations in the polar stratosphere and their dynamical linkage to the troposphere. The importance of a balanced attack with a hierarchy of numerical models was pointed out by Hoskins (1983) a long time ago, and his advocacy has much influenced our experimentation.

Numerical models can be divided into three classes based on their complexity or degrees of freedom (number of dependent variables after spatial discretisation). In the past, only simple low-order models (LOMs) with 10^{0-2} degrees of freedom could be used in parameter sweep experiments due to the limitation of computing resources. We have to be careful with spurious results due to severe truncations in the spatial discretisation, but LOMs are still useful for conceptual description or illustration of the basic dynamics with limited components. Nowadays it becomes possible to use full dynamical models with 10^{4-6} degrees of freedom for parameter sweep experiments. We call them mechanistic circulation models (MCMs). Some idealisation of physical processes in these models helps us to understand the essential dynamics. We do not need to worry about the truncation effect. For quantitative arguments, more complex general circulation models (GCMs) with 10^{4-8} degrees of freedom are necessary, in which sophisticated physical parameterisation schemes should be adopted. However, parameter sweep experiment with full GCMs is still limited even in the most advanced computational environment.

Use of Stratosphere - Only Models

Some simplified models on the interaction between the zonal mean zonal flow and planetary waves propagated from the troposphere have been developed to study the stratospheric variations including SSW events. Yoden (1987, 1990) discussed the intraseasonal and interannual variability in the stratosphere by using LOM introduced by Holton and Mass (1976, hereafter referred to as HM). The HM model is a highly-truncated spectral model which consists of the zonal mean and a single wave components in a mid-latitude beta-channel. Important external parameters in the HM model are the intensity of the mean zonal flow forcing, dU_R/dz, and the wave amplitude at the bottom boundary placed near the tropopause level, h_B.

Yoden (1987) showed that multiple stable solutions of a cold/strong polar vortex and another warm/weak one may exist for the same external conditions in a finite range of h_B, and discussed a possible application of such concept for understanding the intraseasonal variability of the NH winter stratosphere. Some theoretical models of SSW were reinterpreted with the same framework of the HM model. The essence of Matsuno's (1971) theory is an impulsive initiation of a wave forcing in the troposphere; transient response to the increase of h_B for a short time interval may cause a rapid transition from the state of cold/strong polar vortex to the other warm/weak state. Another theory of SSW is the strato-spheric vacillation found by HM. They showed the periodic variation of the stratosphere that mimics repeated occurrence of SSW events with a period of 50-100 days may exist even for a time-constant h_B. The vacillation is a non-linear internal variation of the mid-latitude stratospheric system with fixed external conditions.

These two theories made a very opposite assumption on the dynamical linkage between the troposphere and the stratosphere. Matsuno (1971) assumed a "slave stratosphere"; the stratospheric variation is caused by the variation of its bottom boundary, that is, the troposphere, without any stratospheric influence on the troposphere. On the other hand, HM assumed an "independent stratosphere" in the time variations; the stratospheric variation is possible for a time-constant bottom boundary condition.

Seasonal and interannual variations of the stratospheric circulation have been studied theoretically with some "independent stratosphere" models. Yoden (1990) varied dU_R/dz in the HM model periodically with an annual component to investigate the response to the periodic forcing, but did not obtain any example of interannual variations (i.e., deviations from the periodic annual response). The periodic response, or the seasonal variation is qualitatively different depending on h_B, and the difference resembles that of the climatological seasonal march between NH and the Southern Hemisphere (SH); larger h_B corresponds to NH. By using similar dynamical conditions in a hemispheric primitive-equation model, Scott and Haynes (1998) found interannual variations even for a periodic annual forcing. The internal interannual variability arises owing to the longer "memory" of the stratospheric flow at low latitudes. A given wind signal at low latitudes is less affected by radiative damping, of which time scale is much shorter than a year, due to the smaller Coriolis parameter. Internal variability due to the longer memory of low latitude winds might have a role in the interannual variability in the real stratosphere.

Troposphere-Stratosphere Coupled Variation

The stratosphere-only models described in the previous section, either "slave stratosphere" models or "independent stratosphere" ones, assume no downward influence from the stratosphere to the troposphere. However, some recent studies pointed out the coupled variability of the troposphere and the stratosphere with intraseasonal and interannual time scales (see, e.g., Baldwin, 2000; *Hartmann et al.*, 2000); the Arctic Oscillation (AO) is a deep signature of zonally-symmetric seesaw patterns of geopotential height, alternating between the polar region and mid-latitudes, from the surface to the lower stratosphere. Such annular variability of the polar vortex is observed in all seasons in both hemispheres and the troposphere-stratosphere (T-S) coupling is stronger in dynamically active season, namely winter in NH and spring in SH. Downward propagation of the AO signature from the stratosphere to the troposphere was noticed in association with SSW events. It was also pointed out that the propagation route of planetary waves is very sensitive to the annular variations. These studies are indicative of the importance of two-way interactions between the troposphere and the stratosphere.

Internal Variations in a T-S Coupled Model

Recent progress in computing facilities enabled us to make some parameter sweep experiments, similar to those done with LOMs over a decade ago, with three-dimensional MCMs in order to understand the T-S coupled variability. *Taguchi et al.* (2000) modified an atmospheric GCM by making some simplifications of physical processes; all the moist processes were taken out, the radiation code was replaced by a simple Newtonian heating/cooling scheme, Rayleigh friction was used at the surface, and sinusoidal surface topography was assumed in longitudinal direction with a single zonal wavenumber $m = 1$ or 2 component. It is a spectral primitive-equation model with 42 vertical levels from the surface to the mesopause and its horizontal resolution is given by a triangular truncation at total wavenumber 21 in spherical harmonics. Thus the model has full dynamical process with 105 degrees of freedom.

Under a purely periodic external condition of annual thermal forcing, 10 runs of 100-year integration were done with different topographic amplitude of $0 \text{ m} \leq h_0 \leq 3000 \text{ m}$ (Taguchi and Yoden, 2000a). The relative importance of the planetary waves forced by the topography is studied by such parameter sweep. **Figure 2** (p. II) shows the dependence of temperature variations in the polar stratosphere on h_0; if it is equal to zero or a small value, the interannual variation is very small, particularly in winter. The variation becomes large in spring for $h_0 = 400$ - 600 m, which looks like the variation in SH as shown in Figure 1 (c). If h_0 is increased further, the variation becomes large in winter. The results for $h_0 = 700$ or 1000 m look like the variation in the NH. Note that the interannual variation in this experiment is caused only by the intraseasonal variations which have a random phase depending on each year.

Taguchi and Yoden (2000b) also made 2 runs of 1000-year integration under the same purely periodic annual forcing. In the millennium integration's, statistically reliable frequency distributions of the monthly-mean polar temperature are obtained (**Figure 3**, p. II). The internally generated interannual variation is very large during winter in the run of $h_0 = 1000$ m, while it is large in spring in the run of $h_0 = 500$ m. The distributions for $h_0 = 1000$ m are positively skewed in autumn and bimodal in winter. On the other hand, those for $h_0 = 500$ m have positive skewness for a longer period from autumn to spring and extremely large skewness is found in March. Based on these probability distributions, a question can be raised on the usefulness of ordinary statistical significance tests assuming a Gaussian distribution.

Figure 4 (p. III) shows the time series of the deviation of winter-mean polar temperature at $p = 2.6$ hPa in the millennium integration of $h_0 = 1000$ m, which is made by connecting 10 independent 100-year integration. Here a threshold value is introduced to select the 200 warmest winters denoted by red dots. The occurrence of the warm winters looks like random. In some periods there is no warm winter over decades (e.g., the period around year 410), while warm winters appear frequently in some other periods (e.g., around year 620). To test the randomness, intervals of two consecutive warm winters are examined statistically. **Figure 5** shows frequency distribution of the interval of warm winters that is longer than the interval indicated on the abscissa. The cumulated frequency is well fitted by an exponential function $A\ exp(-t/T)$ as denoted by the broken line with estimated T of 4.5 years. The exponential distribution means that the occurrence of a warm winter itself is described by a Poisson process. That is, the warm winters occur at random from year to year, and preferred periodicity does not exist in the present internal interannual variability.

The warm winters are directly related to the occurrence of SSW events. A lag-correlation (regression) analysis of such intraseasonal variations shows two-way interactions in the T-S coupled system. A typical preconditioning and "after-effect" of SSW event are identified. The after-effect is characterised by poleward and downward propagation of anomalies of the zonal mean zonal wind and planetary-wave amplitude, which continues for several months. Some signatures of the after-effect are also seen in the troposphere.

Concluding remarks

Generally, the parameter sweep experiments are important to investigate non-linear systems because of the limitation of linear interpolation in parameter space. Such experiments are useful for understanding the dynamical mechanism, and were done to study the internal variations of the T-S coupled system with a MCM. The coupling process is fundamentally a two-way interaction in which roles of the mean zonal flow and planetary waves are important, and the generation of planetary waves is a highly non-linear process in the range of realistic topographic amplitude h_0. Internal intraseasonal and interannual variations that we obtained are large in a dynamically active season, that is, spring for small h_0 while winter for large h_0. These variations have some similar characteristics of the real atmosphere, although no interannual variation of the external forcings is permitted in the model.

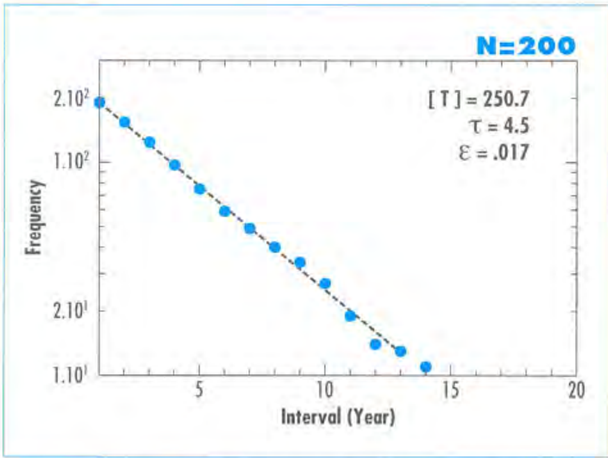

Figure 5: Frequency distribution of intervals of two consecutive warm winters in the millennium integration for h_0 = 1000 m. Blue dot shows the frequency (number) of the interval that is longer than the year indicated on the abscissa. The warm winters are defined in Figure 4 as the top 200. The broken line is the best-fit exponential function A exp(-t/T), determined by the least square method. The mean interval T is 4.5 years, and the mean error ε=0.017. The scale of ε is 1 for one order of frequency.

A large internal variability and a clear bimodality seen in the frequency distributions of the monthly-mean polar temperature in late winter (Figure 3) remind us of some non-linear dynamical perspective to appreciate the effects of small-amplitude external forcings such as the solar cycle, eruptions of volcanoes, and so on as stated in the first section. First, we should be very careful to draw any conclusion from data with a limited length, either from a numerical experiment or real observation, because the large internal variability may produce spurious "response" just due to the limited number of sampling. Longer dataset would give more statistically reliable conclusion, although it might be very difficult to get a sufficiently long dataset. Longer dataset is quite desirable, but we have no intention of insisting on the hopelessness in detecting the effects of small-amplitude external forcings. For example, the bimodality in the frequency distributions gives a hint of the possibility of stochastic resonance. *Benzi et al.* (1982) introduced a concept of stochastic resonance in a system with bimodality to explain the glacial-interglacial cycles in paleoclimatic records; if relatively short-term fluctuations (noises) in the system have enough intensity as an internal stochastic forcing, a small-amplitude periodicity in the external forcing could be greatly amplified by regular transitions between the bimodal states. If we could regard baroclinic disturbances in the troposphere as a source of stochastic forcing, small changes in a bistable energy potential that produces the bimodality might be amplified by the stochastic resonance.

Palmer (1999) gave another example that shows the importance of non-linearity of the system to appreciate the effects of small-amplitude external forcings. Again the existence of bimodality (or, multiple metastable states) is the key point. He demonstrated with LOM that the response to a small-amplitude external forcing is primarily changes in the residence frequency associated with the metastable states. The external forcing does not have much influence on the structure of metastable states. If this concept is applicable to our T-S coupled system, a perturbation run with any kind of small-amplitude external forcing would give significant changes in the frequency distributions of the monthly-mean temperature as shown in Figure 3.

Anyhow it is important to notice that the T-S coupled system is a typical non-linear system with large internal variability and non-Gaussian frequency distributions. We should be careful not to misuse linear concepts to analyse the data obtained from such system.

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Integrated Global Observing Strategy (IGOS) for Ozone and Relevant Atmospheric Parameters

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Introduction

There is an urgent need to assess the global consequences of industrialisation for which reliable global data are essential. The IGOS (an international working group linked to the Committee on Earth Observing Satellites, CEOS) proposes to integrate the major satellite and ground-based systems to provide highly accurate global environmental observations of key variables of the atmosphere, cryosphere, oceans and land in a cost effective fashion (http://www.unep.ch/earthw/igos.htm). To satisfy this objective, IGOS must provide a framework for compiling user requirements coupled with an overarching strategy for conducting global observations. This will allow data providers to tune their contributions to the requirements, make better decisions on the allocation of resources, and take advantage of better international collaboration and co-ordination.

At the present time, ground, balloon, airborne, and space observations of the atmosphere are used to verify not only that the Montreal Protocol is in fact working but also to gather vital data on the changing global atmosphere and thus help establish a solid scientific foundation for future policy debate and action. To assure the most effective use of available resources for global observations, priorities must be established for upgrading existing and/or establishing new systems. IGOS will provide a framework for decisions to ensure 1) the long-term continuity and spatial comprehensiveness of key observations and 2) the research needed to improve understanding of Earth processes so that observations can be properly interpreted. IGOS will build upon existing international global observation programs and identify deficiencies in the current and planned systems.

The Ozone Project is one of six Pilot Projects established within CEOS to assess the feasibility of achieving the objectives of IGOS in the area of ozone monitoring. Variations of ozone in the troposphere and stratosphere must be understood because of the central role it plays in several important environmental problems such as: controlling the amounts of biologically damaging ultraviolet radiation that reaches the Earth's surface, its impact on air quality as an oxidising pollutant that is harmful to biosphere, and as a "greenhouse" gas that contributes to the Earth's radiative balance. The "Project" not only deals with ozone, but also considers the long-term measurements of source and reservoir gases that control ozone chemistry throughout the atmosphere. In addition, relevant meteorological parameters and aerosols are included in the requirements.

The specific objective of this project is to document the requirements for ozone measurements and those parameters needed to accurately interpret the ozone observations. Once the requirements are established, recommendations are directed to the observing community that outlines the steps needed to meet user requirements after assessing ongoing and planned observing systems. The project recognises the need and existence of appropriate physical and assimilation chemical and transport models used to interpret the observations. An initial report, which fulfils this objective, sponsored by CEOS and the WMO, entitled the "The WMO/CEOS Report on a Strategy for Integrating Satellite and Ground Based Observations of Ozone" (Report No. 140), is now in its final stages of publication by the WMO.

Requirements

The IGOS Ozone Project solicited user requirements from the scientific (GAW, SPARC, IGAC) and application (WMO, WHO, UNEP) communities. These requirements were documented by the WMO and GCOS and then compiled in the "Ozone Project" Report. The existing measurement programs from space and ground-based (surface, balloon and aircraft) were then documented via consultation with the space agencies and the ground-based network sponsors. From an analysis of the requirements and measurements, a set of recommendations for establishing an integrated global observing system is proposed. Two levels of measurement requirements were established and defined as 1) *Target* requirements that satisfy the needs of most (if not all) of the user communities and 2) *Threshold* requirements satisfy the needs of at least one set of users. The *Target* requirements are more stringent and demanding than the *Threshold* requirements. In addition, the strategy distinguishes measurements that are needed continuously from those that are only needed occasionally. A well-supported and ongoing validation program and data quality control is also considered a requirement. As data sets are improved, planning for reprocessing and distribution of data becomes a major goal for IGOS. **Figure 1** (p. IV) (from Goddard Space Flight Center) aptly illustrates the need for continuous ozone monitoring with a long-term precision of at least 1% per decade.

As indicated above, an array of chemical species must be observed in addition to ozone. These include a limited set of long-lived source gases, reservoir species, radicals in the major catalytic cycles and several closely associated meteorological variables such as temperature and winds measured with at least the same spatial and temporal resolution as the gases. Aerosol properties are highly interactive with the chemistry and radiative properties in both the stratosphere and troposphere; therefore their characteristics must also be measured. These data are also needed for accurate trace gas retrieval algorithms. In addition, the total and spectral solar irradiances must be observed to be able to interpret climate and ozone changes. Concerns about air quality and transport of pollution and its precursors on

Parameter	Class	Surface	Total Column	Lower Trop.	Upper Trop.	Lower Strat.	Upper Strat. & Meso.
O_3	Mon./Trends	A	A	A	A	A	A
O_3	Oper. Met.		A		A	A	
O_3	Air Quality	A		N	N		
O_3	UV Forecasts	A	A				
Temp.	Met. Variable	A		A	A	A	A
Wind	Met. Variable				A	A	
Tropopause	Met. Variable				A	A	
Cloud Tops	Met. Variable			A	A	A	
H_2O	Source Gas	A	A	A	A	A	A
N_2O	Source Gas	A	A			A	
CH_4	Source Gas	A	A	N	N	A	A
CO	Source Gas	A	A	A	A		
CO_2	Source Gas	A				N	
HCl	Reservoir		A			A	A
HNO_3*	Reservoir	A				A	A
BrO	Free Radical	N				N	
ClO	Free Radical	N				A	A
NO_2*	Free Radical	A	A	N	N	A	A
NO*	Free Radical	A	A	N	N		
Aerosol Pres.	Met. Variable	A	A	A	A	A	
Aerosol Char.	Met. Variable	A		N	N	A	
PSCs	Met. Variable					A	
UV	Met. Variable	A					A

Table 1. Atmospheric parameters that must be measured regularly on a near global scale: A = available, N = needed

regional to intercontinental scales place an even more stringent demand on observations and models. **Figure 2** (p. IV) (from the Harvard University) illustrates model calculations of monthly mean afternoon surface ozone concentrations in July. Particularly noteworthy is pollution over industrial areas in the US, Europe and Asia, with enhancements in Asia due to burning.

The combined requirements for ozone depletion, air quality and climate research and monitoring are compiled in **Table 1** that lists the selected parameters that must be observed frequently. Tables that document the requirements, for each of these atmospheric parameters, including spatial and temporal resolution and range, accuracy, and precision (*Threshold and Target*) appear in more detail in the report.

Available and Planned Measurements

A broad range of operational and research observations are underway and are planned from space and ground. The space missions that will measure total and profile ozone and other atmospheric parameters are illustrated in **Figure 3a** and **b** (p. V). Data from NOAA, UARS, ERS-2, Terra, ADEOS, WMO-GAW and NDSC, and many aircraft and balloon missions have led to an understanding of atmospheric processes and provided a baseline for evaluating changes in the atmosphere. Upcoming research missions such as ENVISAT and Aura, and operational missions, such as METOP and NPOESS, will provide platforms to continue the baseline measurements, but will only partially satisfy the requirements. TOMS-type data sets are assured until NPOESS, which will continue those measurements. The next two SAGE missions are assured, beginning in 2001, except for the third platform expected later in this decade. UV-VIS-NIR backscatter measurements will continue with GOME-2 on METOP. Follow-on ADEOS and GCOM will also provide collaborative data from space. ODIN, ACE, and SABRE research missions will compliment the larger research and operational missions. To date chemistry measurements have been made from low Earth orbit, but upcoming missions will take advantage of new strategic orbits such as geostationary and Lagrangian to observe diurnal changes for air quality studies.

Ground observations (surface, balloon, and aircraft) must continue and be expanded to provide correlative and validation data for the satellite missions as well as conducting essential research observations. The networks such as NDSC and WMO-GAW (e.g. ozone sonde, Dobson/Brewer, ozone/aerosol lidars, and *in situ* source gas stations) must continue to provide data as part of IGOS. Research-driven aircraft campaigns should continue to study processes in the upper troposphere and lower stratosphere with high spatial resolution. The commercial airlines also have a role for providing a platform for collecting continuous data over a wide geographic area with high spatial resolution (e.g. MOZAIC). The operational agencies must play a major role to insure long-term sustainability of these systems

Calibration and Validation

Calibration and validation are critical to assure the scientific value of remote sensing measurements. They are essential for deriving climate quality data sets. The space faring nations have and must continue to allocate resources for calibration and validation of Earth science missions as is presently being done for ENVISAT and Aura. Both Europe and the United States are now planning operational satellite systems that will carry ozone sounders to extend the long-term record already produced by national research and operational missions. Japan is also committed to fly atmospheric chemistry missions. However, despite the fact that the major space agencies have embarked on these missions, no concurrent long-term validation program, covering the lifetime of these missions is being planned, nor is there any assurance that existing ground-based infrastructure will be in place when they are needed. Satellite systems can only meet the established requirements if they are supported by correlative data of known quality and continually challenged by reliable ground-based observations and quantitative science.

Based on the experience gained from past satellite missions, an end-to-end approach for calibration/validation, highlighting the need for a fully integrated global observing system, to include both ground and space-based measurements, must be established. For satellites this approach includes the internal calibration program, post-launch calibration employing on-board systems, external validation programs using highly controlled correlative measurements, subsequent algorithm refinements and scientific analyses of the data to ensure consistency with the best understanding of atmospheric processes and conditions.

Figure 4 illustrates how these steps are inter-connected. The figure also demonstrates that end-to-end validation program is a highly iterative process. The magnitude of the effort demands international pooling of resources and close collaboration given the existence of parallel streams of the national operational missions, e.g. the European METOP and the US NPOESS ozone instruments and corresponding research missions discussed above.

Recommendations

As discussed above, many of the identified requirements will be met by the existing and planned measurements from ground and space. However, the lack of formal co-ordination among the space faring nations to optimise the deployed systems and to assure compatibility for international users is a serious problem. In addition, there must be formal recognition and support for the international community who are providing critical data from ground-based systems for calibration and validation of the space-borne systems.

The CEOS/WMO report's recommendations emphasise the missing components of the upcoming systems as well as describe what needs to be improved in the existing systems. The specific recommendations are too detailed for this short summary but are highlighted below. (The SPARC community is encouraged to read the full report available from the WMO):

• A coordinated validation activity must be established which extends over the entire lifetime of satellite sensors and which encompasses all elements of the IGOS system taking maximum advantage of concurrent national validation activities.

• The coverage of ground-based (WMO-GAW and NDSC) systems must be extended (particularly in the tropics and the Southern Hemisphere) and a carefully selected subset thereof designated as permanent, long-term ground "truthing" facilities.

• Sustained support for the ground networks must be provided by space agencies that require validation data sets to insure data availability and quality.

• Deficiencies, revealed by the survey of existing and planned measurements,

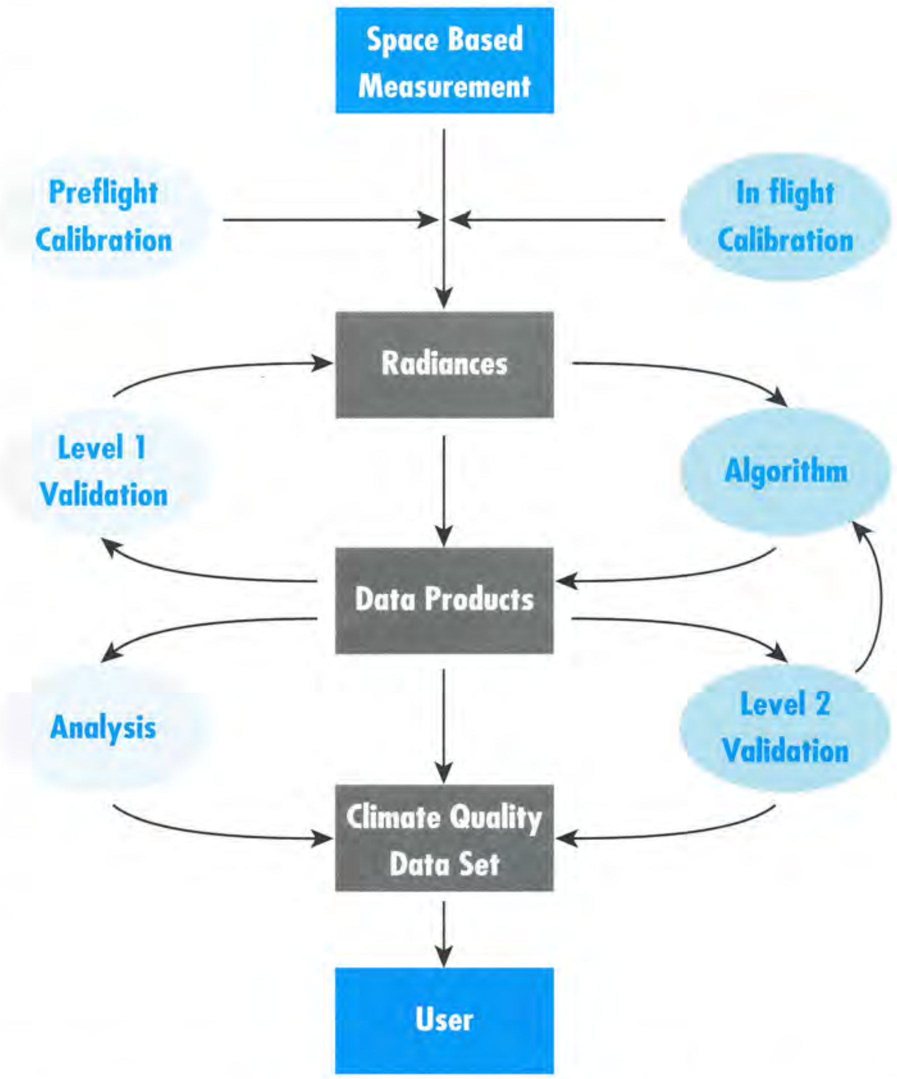

Figure 4. Steps necessary for a space-based measurement to be scientifically acceptable by the user. Steps include rigorous pre and post launch calibration, validation, algorithm and data product evaluation, and subsequent reprocessing.

must be corrected by improving and/or providing additional measurements. There is a particular need for continuous measurements in the lower stratosphere and troposphere.

• Validation is an iterative process, so resources for reprocessing data must be made available to insure that users have access to the highest quality data.

• The synergetic use of data must be encouraged by standardising data formats, by ensuring archives are easily accessible and by providing proper provision for reprocessing.

• National radiometric standards must be improved with the full involvement of the user community to advise on calibration issues.

• International co-operation must be encouraged in the development of algorithms employed by similar instruments and in the pooling of knowledge of radiative transfer physics.

• A body of scientists, engineers and managers must be established to provide technical support to funding agencies to ensure compatibility and completeness of the systems.

There is a practical incentive for swift action as an array of satellite missions with atmospheric instruments are scheduled for launch during this decade (beginning in 2001) (Figure 3). The recommendations outlined above attempt to identify those areas that remain deficient in the present and planned observing systems. Data collected following the CEOS-IGOS approach will have the necessary quality to enable the state of the atmosphere to be reliably monitored and changes understood through supporting research thereby providing a basis for formulating sound environmental policies.

Public Access to the Network for the Detection of Stratospheric Change Database

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Introduction

The Network for the Detection of Stratospheric Change (NDSC) is a set of research stations extending from 80°N to 90°S) for observing and understanding the physical and chemical state of the middle atmosphere. Since 1991 ozone and key ozone-related chemical species and parameters have been measured at this network in order to detect and understand stratospheric changes and to assess the impact of these changes on the troposphere and on global climate. In particular the NDSC aims to provide data for:

• Making the earliest, possible identification of changes in the ozone layer and to discern their causes.

• Establishing links between changes in stratospheric ozone, UV radiation at the ground, tropospheric chemistry and climate.

• Testing and improving multi-dimensional stratospheric chemical-dynamical models.

• Providing an independent calibration of satellite sensors of the atmosphere.

These aims require high quality data and, accordingly, since the inception of the NDSC, much effort has been invested into instrument inter-comparison, calibration, and software validation. The result is a self-consistent data set suitable for addressing the above aims. In order to permit the widest possible usage, all data over two years old is made publicly available. This article briefly describes the NDSC database and how to access it.

Example Data

The NDSC data base consists of ground-based and sonde observations of ozone and other key species in stratospheric chemistry and climate. Ground-based column observations are obtained with Dobson, UV-visible, microwave, and Fourier Transform infrared (FTIR) spectrometers. The list of species observed includes O_3, HCl, $ClONO_2$, ClO, NO, NO_2, HNO_3, HF and other tracers. Ozone, aerosols and temperature vertical profiles are also obtained using lidar and sondes. The NDSC database also includes UV flux at the ground and supporting meteorological data.

Examples of NDSC data are given in Figures 1 and 2. **Figure 1** (p. VI) shows observations of column HCl and HF at the NDSC Primary station of Jungfraujoch (47°N, 8°E). These observations, which include those obtained before the start of the NDSC but which have been subjected to the same NDSC validation, clearly show the increase in the stratospheric loading of halogens due to the use of CFCs which has led to stratospheric ozone depletion in both the polar regions and at mid-latitudes. Following the Montreal Protocol, and its amendments, the increase in HCl slowed and now appears to have levelled off. In the future we expect the stratospheric loading of chlorine and fluorine to decline. Continued observations are an essential component of monitoring the rate of this recovery.

Figure 2 (p. VI) shows column sunset and sunrise observations of NO_2 at Lauder (45°S, 170°E). On top of the diurnal and annual variations, this data set shows long-term variations. Relatively low NO_2 was observed around 1992, following the eruption of Mt. Pinatubo. However, after allowing for these aerosol-induced variations and the expected increase in NO_2 from increasing N_2O, the clear upward trend throughout the 1990's may be larger than current models predict. These NDSC data are therefore essential for comparison to models that test our understanding of atmospheric chemistry and transport.

Accessing the Data

NDSC data over two years old is now publicly available. Access to this data is available through anonymous ftp access to the ozone.wwb.noaa.gov server. It is expected that users of these NDSC data will consult the on-line documentation and reference articles to fully understand the scope and limitations of the instruments and resulting data. Scientific users of the data are encouraged to contact directly the appropriate NDSC Principal Investigator (listed in the data documentation on the web page) to ensure the proper use of specific data sets. The PI can also be contacted if you wish to use data less than two years old.

Further information on the NDSC can be obtained from the NDSC homepage (**www.ndsc.ws**). This web site principally provides a link to the public ftp database, but also includes maps of the NDSC sites, instrument information, available data sets, and contact information.

Acknowledgements

Because of its world-wide dimension, the NDSC has been recognised as one of major components of the international upper atmosphere research program. As such, it has been endorsed by national and international scientific agencies, including UNEP and the International Ozone Commission (IOC) of IAMAP. It has also been recognised by WMO as a major contributor to WMO's Global Ozone Observing System (GO3OS) within the frame of its Global Atmosphere Watch (GAW) Programme.

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The Evolution of the Antarctic Ozone Hole in 2000

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The year 2000 Antarctic ozone hole event had peculiar characteristics. The most outstanding are:

1. A particularly rapid growth during August

2. The largest surface area on record.

3. The longest continued period of residence over inhabited regions of southern South America.

4. The earliest break-up since 1991.

The ozone hole extent began, at a rapid growth about the middle of August, reaching an initial peak of 25 million km^2, i.e. about as large as the 1999 event, on August 20/21, followed by a sudden decrease and a another rapid growth until it reached the maximum extent, close to 30 million km^2 on September 9/10 (**Figure 1**, p. VII). It is important to remember that the 1999 event reached its maximum extent between September 14 and 16, 1999 and the TOMS climatology shows that previous events had reached their peak size during late September and early October. Hence this year's event grew beyond previous recorded extremes about three weeks earlier than in 1999 and reached its peak, also three weeks before the climatological mean timing and one week earlier than the 1999 event.

As can be seen in Figure 1, the shape of this ozone hole was significantly elliptic during most of the period. For example, during September 15, the 220 DU isoline reached 50°S, over the central south Pacific. On October 12 and 18 the 220 DU isoline reached close to 48-47°S over Southern Chile and Argentina. The dynamics of the ozone hole was significantly perturbed throughout the period of its existence. **Figure 3** (p. VIII) show the mean ozone levels between 80 and 30°S averaged for the 60-70°W longitude band, i.e. Southern Argentina and Chile, during 1990, 1999 and 2000. 1990 was chosen as an example of another dynamically perturbed ozone hole, while 1999 showed a far more stable behaviour. It is clear that the year 2000 was probably the most perturbed on record as can be seen in Figure 3 c). Normally as the ozone hole rotates, elongation towards mid-latitudes takes place, more commonly between the South Pacific and the South Atlantic. These are separated by 8 to 16 days, as can be seen in Figure 3 a). The year of 2000 however, and particularly in October, the elongations were far more frequent and did not follow the "rotation" of the ozone hole. In other words the shape of the hole was not elliptic during these events, but quasi-triangular.

Furthermore the hole was very much displaced towards South America as can be seen in **Figure 2** (p. VII), which shows the mean state of the ozone layer between October 6 and 20, 2000. On the other hand, peak values above 430 DU were observed south of Australia. In other words the ozone distribution over the hemisphere was quasi-bipolar. This implies that there was a very strong quasi-stationary wave one event. The significant eccentricity of the ozone hole behaviour coupled with important perturbations and deformations of the ozone hole resulted in a behaviour completely anomalous. Indeed in previous years the excursions of the ozone hole outside the polar region were not so prolonged in time, as can be seen in Figure 3 for 1990. It must be noted however that because of cloud cover only during a few days of this very low ozone period did the surface UV levels rise significantly above average. Observations from the Servicio Meteorológico Nacional UV network show that during clear days UV levels over Ushuaia (54.5°S) were equivalent to those observed in Buenos Aires (34.5°S) or Córdoba (32°S) during January. While such levels can be tolerated by human beings they are significantly high for the local terrestrial and marine ecosystems. It must be noted that there were reports of sunburns in Ushuaia as well as Punta Arenas from people unaccustomed to such sudden changes in UV levels.

Though the size of the hole has significantly decreased after the peak in September, after October 20 the ozone hole begun a very rapid, sustained decrease in size, closing between November 20 and 25. The size of the hole during this period was within the TOMS climatology and far smaller than the records for the '90s. This was the earliest break-up since 1991. Furthermore it took place almost a month earlier than in 1998 or 1999. The comparison of figure 3 a) b) and c) and observations of the corresponding ozone fields show that the perturbed dynamics of this year's event and the excursion to mid-latitudes with higher solar radiation levels are the probable causes of such an early break-up. The 1999 event with a more stable behaviour and fewer deformations lasted much longer. 1990 and 1991, which were also significantly perturbed, also had a relatively earlier break-up. Nevertheless it must be noted that those break-ups were not separated by so many days from those in other years as was the case this time.

The reasons for the ozone hole behaviour in 2000, in particular the early rapid growth, may be linked to the mean prevailing weather in the troposphere. The year 2000 has been the wettest in many parts of the Pampas region in Argentina since 1860. The winter 2000 was among the coldest and longest in recent years. Exactly what mechanisms led to this rapid growth and the huge size of the hole is currently under study. At this stage, the implications of the year 2000 event for the future behaviour of the ozone hole remain uncertain.

SOLVE-THESEO 2000 Science Meeting

Palermo, Italy, 25-29 September 2000

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Introduction

Between November 1999 and April 2000, two major field experiments, the European Commission-sponsored Third European Stratospheric Experiment on Ozone (THESEO 2000) and the NASA-sponsored SAGE III Ozone Loss and Validation Experiment (SOLVE), collaborated to form the largest field campaign yet mounted to study Arctic ozone loss. Briefly, the campaign involved research aircraft, balloons, ozonesondes, ground-based and satellite instruments, which were greatly augmented by meteorological and chemical models. In all more than 400 scientists from the European Union, Canada, Iceland, Japan, Norway, Poland, Russia, Switzerland and USA were involved. A description of the SOLVE-THESEO 2000 activities and the early findings was published in SPARC newsletter No. 15 (*Newman*, 2000).

The main aims of SOLVE-THESEO 2000 were to study the processes leading to ozone loss in the Arctic vortex and how the ozone amounts over northern mid-latitudes are affected. These processes occurring in the Arctic vortex have been closely studied over the past decade or so and, qualitatively, are fairly well understood. The Arctic stratosphere cools during polar night and at sufficiently low temperatures, polar stratospheric clouds (PSCs) form. Heterogeneous reactions occur on the surface of these clouds which convert relatively inactive chlorine compounds such as HCl and $ClONO_2$ into forms such as ClO which can lead to rapid chemical destruction of ozone in the presence of sunlight. This ClO then gradually revert back to the inactive forms and the ozone destruction slows down. These processes largely take place in the Arctic vortex. As the vortex breaks down, ozone-depleted air is mixed with mid-latitude air.

Given the planning involved, the campaign was fortunate, from a scientific perspective, to take place during a cold winter in the Arctic stratosphere in which there was large ozone loss. The processes involved were therefore extremely well observed, and since the end of the campaign scientists have been poring over the measurements trying to understand what happened.

The results were discussed at the joint SOLVE-THESEO science meeting held in Palermo, Italy from September 25-29 2000. Generous support for the meeting was provided by CNR, ENEA, Regione Siciliana and the city of Palermo. Over 250 scientists participated with over 50 talks and just under 200 posters. Many of these are being written up for submission for publication in two special issues of JGR or in other journals. In this article we report on some of the key findings presented at the meeting and on the summaries of the discussions of outstanding issues prepared by groups of rapporteurs. The findings presented below are only a small part of those presented at the meeting, and we apologise in advance to those whose results are not included.

Meteorology and dynamics

As discussed in SPARC newsletter No. 15, the Arctic stratosphere was cold during the 1999/2000 winter and the vortex was stable into mid-March at which time it was split with one substantial remnant present well into April. The temperatures were below

PSC existence temperatures from late November until mid-March. A number of studies of the long-lived tracer data collected during SOLVE-THESEO 2000 found that there was a relatively small amount of mixing in of mid-latitude air into the vortex, probably less than 10% of the vortex volume at around 18 km. The amount of mixing in of mid-latitude air masses is an important issue for at least three reasons. First, the chemical reaction rates governing the activation and deactivation processes and the ozone loss itself are affected if chemically distinct air is mixed in, particularly for nitrogen rich air. Second, improved quantification of the in-flow across the vortex edge is inherently valuable for understanding the mass balance of the vortex. And third, the mixing in of air across the vortex edge can cause errors in the ozone losses estimated using tracer/ozone correlations.

The long-term context of the 1999/2000 winter and the possibility of long-term changes in the Arctic vortex were discussed at some length (see also several articles in SPARC Newsletter No. 15). The past decade has certainly seen, on average, a colder, longer-lived vortex, but it is hard to define the significance of these changes. The most robust change is the longer duration of the vortex which during the 1990s broke up, on average, in March, compared to February during the 1980s and earlier. The fundamental reason for this is unclear, but it does seem related to the decreased wave driving during the January-February period.

One of the scientific foci of SOLVE-THESEO 2000 was to improve understanding of the formation, chemical impact and importance of mountain waves. A number of beautiful case studies were presented which showed that the meteorological mesoscale modelling of these events was good and, further, that the new ECMWF analyses with their improved resolution also described mountain wave events well. However in such a cold winter where PSCs were ubiquitous in the vortex, the chemical impact was probably not great although this might not be true in warmer winters where temperatures were close to the PSC existence temperatures.

Finally there was a lot of discussion of the quality of the trajectories derived from analysed wind fields. The largest errors were observed at lower pressures (the uncertainties in the analyses increased at pressures below about 30 hPa). More work is needed to quantify these uncertainties at all altitudes as trajectories are such a basic tool used in Lagrangian photochemical box models, identification of the origin of air masses and in ozone loss studies.

Stratospheric Particles

The long, cold winter combined with advances in instrumentation, particularly for the *in situ* particle measurements, has provided a wealth of data. There were two particularly notable findings: (a) the first measurements of with a chemical composition of nitric acid trihydrate (NAT) (*Voigt et al.*, Science, 290, 1756, 2000) and (b) the discovery of PSC particles with radii of 15 micron or so, much larger than previously thought (*Fahey et al.*, Science, in press).

The chemical composition measurements showed the presence of layers of NAT particles and layers of sulphate ternary solution particles. Some of the NAT particles were present near or even above their equilibrium temperature. These balloon-borne observations were made over northern Scandinavia in the presence of mountain waves. They underline the fact that the evolution of particles in rapidly changing temperature fields such as mountain waves is complex and at the same time, they show that such complex processes can be unravelled.

The large particle observations ('rocks') were made more generally within the Arctic vortex from the ER-2 aircraft. Their size, and low concentration, meant that they had previously eluded discovery as most available instruments lose sensitivity above a few microns. The particle size also causes them to fall quickly through the stratosphere, and, as they contain HNO_3 and water, their sedimentation can denitrify and, to a lesser extent, dehydrate the Arctic vortex. This was borne out by measurements showing extensive denitrification and some dehydration in the coldest regions and enhanced nitric acid and water vapour amounts lower at lower, warmer altitudes. However it is still not clear what the nucleation mechanisms are for these PSCs, and there was a great deal of debate on this subject.

Chemistry

An unprecedented set of instruments (on aircraft, balloons, satellites and the ground) observed the chemical evolution of the Arctic stratosphere from November 1999 through April 2000. In conjunction with measurements made in other winters over the past decade or so, they have allowed studies of chemistry on a whole range of temporal (minutes to years) and spatial scales (metres to 1000's of kilometres).

In situ measurements of long-lived tracers during SOLVE-THESEO 2000 showed that the total organic chlorine (that in the form of the source gases – CFCs, CH_3CCl_3, CCl_4, etc.) has now peaked in the stratosphere, some 6-7 years after it peaked in the troposphere. As in the troposphere, the early response to the Montreal Protocol is driven mainly by the steep decline in the relatively short-lived (5 years) CH_3CCl_3.

For the first time, simultaneous *in situ* measurements of all major chlorine species were made on the ER-2. Preliminary results from these were presented which showed progress toward understanding whether the chlorine budget is balanced within the estimated uncertainties. Since nearly all the major chlorine species were measured by more than one technique (*in situ* and remote), it was agreed to make sure that proper comparisons are made to achieve a consistent data set, as is already being done for the long-lived tracer data. Currently the main features of the chlorine activation and deactivation in 1999/2000 are clear, with a long activated period and slow recovery. However more detailed studies showed that a number of quantitative issues remain. For example, there were reports that comparisons of ozone loss calculated from the observed ClO and BrO amounts were less than the empirically determined ozone losses. However the ozone loss calculated by the SLIMCAT 3D chemical transport model were in good agreement with the empirically derived ozone losses in 1999-2000 (*Sinnhuber et al.*, GRL, 27, 3473, 2000), unlike some previous winters.

Bromine compounds are significant contributors to Arctic and mid-latitude ozone loss. Bromine activation is now much better understood and there is good evidence that 50-80% of inorganic bromine is in the form of BrO in most conditions (Arctic, mid-latitudes, tropics, all seasons). The overall understanding of the stratospheric bromine budget has also improved (i.e. putting the uncertainties associated with the tropospheric sinks and sources to one side). A decadal increase in BrO consistent with tropospheric increases seems to have occurred, and there is strong evidence for a source of bromine in the very low stratosphere from short-lived compounds.

Ozone Loss

Ozone loss in the 1999/2000 winter was large and extensive. At altitudes around 18km, 60-70% of the ozone was destroyed between January and mid-March, slightly larger that the previous record loss which occurred in 1995/96. The column ozone loss inside the column was 20-25% in 1999/2000, less than the previous record years largely because the vertical extent of the ozone loss was less than in those years. There was reassuringly good agreement between the estimates of ozone loss found by several techniques using measurements from a number of instruments. A number of technical issues about the various techniques used to estimate ozone were discussed. However, once the differences resulting from the different time periods considered were taken into account, it seemed as though these were not that important in the 1999/2000 winter because the ozone loss was large and because the vortex was strong and well isolated. As mentioned above, there was good agreement with the loss calculated by the SLIMCAT 3D CTM, there was poorer agreement with other models. Further work is needed to understand the causes of these differences.

A number of modelling studies investigated the ozone loss at mid-latitudes, including the impact of the polar ozone loss. The interannual variability in dynamics causes the export of air from the vortex to mid-latitude to vary greatly in amount and timing, so that even for a given chemical ozone loss inside the vortex, the effect on mid-latitudes will also vary. Modelling studies are now realistically quantifying this effect. Chemical transport model calculations also showed how polar processes vary from year to year, and they additionally showed how the importance of changes in the contributions of the different chemical loss cycles. All models showed that a strong, long-lived vortex has little effect on mid-latitudes until it starts to break up. This was true dynamically (no export of ozone-poor air) and chemically (no chemical perturbation at mid-latitudes without mixing out or activation outside the vortex).

General

A number of related issues came up several times during the meeting. Chief among these was one of the main driving forces of SOLVE-THESEO 2000 – how will climate change affect the future stratosphere? Or, more dramatically, will there be an Arctic ozone hole? The interaction of climate change with the stratosphere and with the ozone depletion processes is complex and will be a major area of research in the future. As one example, there is a clear need for a greater understanding of stratospheric water vapour for dynamic, radiative and chemical reasons. In the polar vortices, the water vapour concentration will be one of the factors which determines the temperatures at which PSCs can form, with higher water vapour levels raising the PSC existence temperatures. It may well be the radiative effect of the increased water vapour which is causing the Arctic vortex to cool. If these conditions also lead to enhanced denitrification and to more stable vortices, how much will the effect of the declining halogen levels be offset by the increased water vapour and cooling stratosphere? There are many uncertainties in such trains of thought – equally they are plausible and need to be investigated further.

Further details on the SOLVE-THESEO 2000 campaign can be found at:
http://www.nilu.no:80/projects/theseo2000/
http://cloud1.arc.nasa.gov/solve/
http://www.ozone-sec.ch.cam.ac.uk/
and on the SOLVE-THESEO 2000 science meeting, including the rapporteurs' reports at:

http://hyperion.gsfc.nasa.gov/Personnel/people/Newman,_Paul_A./speaker.html

We thank all scientists and technical support staff involved in SOLVE-THESEO 2000 for their magnificent efforts during the last year. We also thank all those who helped in organising the meeting at Palermo, including Dr Adriani's team at CNR-IFA, Rebecca Penkett, Kathy Wolfe and her team, and Georgios Amanatidis (EC Research DG) and Mike Kurylo (NASA HQ).

First S-RAMP (STEP Results, Analysis, and Modelling Phase of the Solar-Terrestrial Energy Program)

Sapporo, Japan, 2-6 October, 2000

The first international S-RAMP symposium consisted of 19 subsymposia and three workshops. The S-RAMP project has been promoted by SCOSTEP (Scientific Committee on Solar-Terrestrial Physics) in 1998-2002 in order to consolidate and integrate results from the many disparate STEP (Solar-Terrestrial Energy Program) campaigns in 1990-1997.

The SRAMP symposium was sponsored by the Ministry of Education, Science, Sports and Culture, Japan (Monbusho) and SCOSTEP ("**http://www.ngdc.noaa.gov/stp/SCOSTEP/scostep.html**").

Symposium S17: The middle atmosphere including response to forcing from above

Conveners: Marvin Geller and Toshitaka Tsuda (mgeller@notes.cc.sunysb.edu).

This symposium was devoted to the dynamics and chemistry of the middle atmosphere, with particular emphasis on wave forcing, having their sources in the troposphere and to chemical changes from natural and anthropogenic causes. Because the middle atmosphere is also subject to forcing from the variable sun and energetic particle effects, the chemistry, energetics, and dynamics of the middle atmosphere in response to these forcings were also key subjects of this symposium.

The main topics in dynamics were radar/optical/in-situ observations, modelling and theory of the general circulation, generation and propagation of various atmospheric waves, and their interactions and instabilities. Topics in chemistry included observational analyses, laboratory and modelling of gas phase and heterogeneous photochemical processes, as well as studies of transport and mixing of minor constituents. The coupling between chemistry, radiation and dynamics was also an important subject of this symposium.

A total of 41 papers were presented: 23 presentations, including seven solicited papers, were given orally in two sessions on October 3 and 5, and 18 were displayed as posters. The first oral session treated tropospheric processes, where **M. A. Geller** talked on the QBO and ENSO influences on the tropical cold point tropopause, followed by a summary report of the SPARC/SOWER campaigns in 1998-2000 by **F. Hasebe.** Then, in a session on chemistry and transport, **S. Hayashida** described the behaviour of the polar stratospheric clouds (PSCs) observed from space, and **M. Takahashi** showed the results on ozone variations seen in chemical climate models.

In session on the processes in the Mesosphere and Lower Thermosphere (MLT) region, **R. A. Goldberg** talked on a study of polar summer mesosphere with rocket, radar and lidar (DROPS program). **N. J. Mitchell** discussed the coupling of tide and planetary waves, and **J. F. Kafkalidis** described the planetary scale variations in the nightglow structures seen by UARS/HRDI satellite.

Symposium S18: Solar variability effects upon the lower atmosphere and climate

Conveners: Lon Hood and John Austin (lon@lpl.arizona.edu)

Most of the papers were observationally based, with a strong emphasis, on the interaction of solar cycle forcing with that by the equatorial wind QBO.

K. Labitzke showed updated results from the data set compiled at the Free University of Berlin, which now indicate an 11-year solar signal in lower stratospheric geopotential height extending over at least 4 solar cycles.

Additional analysis of the US National Centre for Environmental Prediction (NCEP) data set, which includes the Southern Hemisphere, was also presented. **K. Mohanakumar** reported evidence for an influence of the 11-year cycle on temperature in the mesosphere (6-8 % per 100 units of 10.7 cm solar flux) and in the troposphere (1-2% per 100 units) using a combination of radiosonde data, rocket data, and the NCEP reanalysis data. **H. Nakane** also applied the NCEP reanalysis data from 1959 to 1997 to investigate properties of the northern polar vortex. It was found that properties of the vortex, including strength, duration, radius, and stability, depended on the phase of the 11-year solar cycle as well as that of the QBO. A similar theme was pursued by **Y. Naito** who showed that the "Holton-Tan Oscillation" in which polar temperatures are forced entirely by the QBO has a different phase dependence under solar maximum conditions as compared to solar minimum conditions. **M. Salby** suggested that some aspects of the QBO itself (equatorial westerlies below 30 hPa and equatorial easterlies above 30 hPa) may vary slightly with the 11-year solar cycle.

J. Austin presented the results of general circulation modelling in which the primary forcing is variations of several percent in the UV part of the solar spectrum. Comparisons of the model response on the solar cycle time scale with satellite observations of ozone and temperature changes were presented. **M. Takahashi** presented a range of results from the CCSR/NIES climate model. These included investigations of the 11-year solar cycle, which gave very similar results to those of Austin. In particular, the model results were significant improvements over 2D models in the lower stratosphere, while a discrepancy remains in the upper stratosphere. Simulations with the Berlin climate model had not commenced by the time of the meeting but the model was outlined in a poster display.

A number of other potentially important issues were addressed. In a plenary lecture preceding the symposium, **E. Friis-Christensen** suggested that Galactic cosmic ray (GCR) fluxes, which are modulated by the 11-year solar magnetic activity cycle, may be an additional contributor to solar forcing of climate through effects on cloud nucleation processes. **K. Georgieva** pointed out that the effects of GCR's on terrestrial climate may depend on whether the northern or the southern solar hemisphere is more magnetically active. **O. Troshichev** noted that an empirical separation of energetic particle effects on the middle and lower atmosphere from those of spectral irradiance variability may be facilitated by analysing data from the polar night. He presented correlative evidence for effects of short-term (days to weeks) GCR variability on pressure in the stratosphere and troposphere at the Vostok station in Antarctica. **K. Boyarchuk** pointed out that the solar output varies on a number of time scales, including a small-amplitude periodicity near the QBO period, and that this periodicity may influence GCR access to the atmosphere on the same time scale.

D. Knipp investigated the heat budget above the stratosphere and showed that solar UV radiation accounts for 70-80 % of the heating while auroral zone currents and particle deposition account for another 15-25 %. **T. Kuznetsova** analysed terrestrial Carbon 14 data (an inverse proxy for solar activity through effects on GCR fluxes reaching the ground) for a 4500-year period and discussed two maxima, one of which coincides with the Maunder sunspot minimum. She suggested that global temperature may correlate inversely with Carbon 14 and that extrapolation of the available record using Fourier harmonics provide a forecast of climate change. **B. Zieger** investigated the behaviour of Schumann resonances (SR) in the Earth's ionosphere which are associated with lightning discharges.

Future SPARC and SPARC-related Meetings

6-8 **March 2001: Lidar Measurements in Latin America Workshop, Camagüey, Cuba** (http://climate.envsci.rutgers.edu/antuna/workshop).

19-22 **March 2001: Workshop on Nitrogen Oxides in the Lower Stratosphere and Upper Troposphere,** Heidelberg, Germany (http://www.ozone-sec.ch.cam.ac.uk).

25-30 **March 2001: EGS XXVI General Assembly, Nice, France:** (egs@copernicus.org). (http://www.mpae.gwdg.de/EGS/egsga/nice01/nice01.htm).

2-4 **April 2001: Global Atmosphere Watch, GAW 2001, WMO,** Geneva. Registration information: Liisa Jalkanen (Jalkanen_L@gateway.wmo.ch).

2-6 **July 2001: 2nd Workshop on Long-term Changes and Trends in the Atmosphere (IAGA/ICMA/SPARC),** Prague, Czech Republic: Convener: Jan Lastovicka (jla@ufa.cas.cz), http://www.ufa.cas.cz/html/climaero/Trend2001.html.

10-13 **July 2001: Global Change Open Science Conference (IGBP/WCRP/IHDP),** Amsterdam, The Netherlands (www.sciconf.igbp.kva.se). Parallel session: "The Atmosphere and Global Change". Conveners: M. Geller and G. Brasseur.

10-18 **July 2001:** IAMAS 2001, Innsbruck, Austria (http://iamas.org).

- Symposium "Middle Atmosphere Dynamics", 7 days, Lead Convener: K. Hamilton, Co-conveners: T. Hirooka, B. Lawrence, F.-J. Luebken, L. Hood (turbulence, GW, planetary waves, tides, forcing of mean circulation, long-term variability, mesospheric layered phenomena, MA aspects of climate change).
- Symposium "MA Chemistry, Transport and Radiation", 6 days, Lead Convener: A.R. Ravishankara, Co-convener: N. Harris, V. Fomichev, D.W. Waugh (observations, models, transport relevant to understanding chemistry, aerosol microphysics, MA climate-chemistry interactions, energy budget of the MLT-layer).
- Workshop "Solar Cycle Forcing of the Stratosphere and Troposphere", 1 day. Convener: L. Hood (possible mechanisms: solar UV variability, energetic particle precipitation, etc.).

18-30 **August 2001: IAGA-IASPEI 2001 Joint Scientific Assembly,** Hanoi, Vietnam: (http://www.IAGAandIASPEI.org.vn/pta.htm).

G2.04. Solar Activity Effects on the Middle and Lower Atmosphere. Convenor: E.S. Kazimirovsky, Institute of Solar Terrestrial Physics, Russian Academy of Sciences, PO BOX 4026, 664033, Irkutsk, Russia. Fax: +7 3952 462557, email: edkaz@iszf.irk.ru. Co-convenor: S. Sofia.

G2.05 Propagation of Tidal and Gravity Waves and Planetary Signature Into and their Effects on the Mesosphere, Thermosphere, and Ionosphere. Convenor: J.M. Forbes, Department of Aerospace Engineering Sciences, Campus Box 429, University of Colorado, Boulder, CO 80309-0429, USA. Fax: +1 303 492 7881, email: forbes@zeke.colorado.edu. Co-convenors: K.P. Hamilton (USA), A.D. Aylward (UK), D. Pancheva (Bulgaria).

G2.09 Long-term Trends in the Mesosphere, Thermosphere, and Ionosphere Systems. Convenor: G. Beig, Indian Institute of Tropical Meteorology, Dr. Homi Bhabba Road, Pashan, Pune-411 008, India. Fax: +91 20 5893825, email: beig@tropmet.ernet.in. Co-convenor: J. Lastovicka (Czech Republic).

19 **August-01 September 2001: Cargese International School,** Cargèse, Corse, France: (http://cargese.univ-corse.fr).

- Dynamical barriers, stirring and mixing in geophysical flows - Mathematical model and applications.
- Application deadline: March 15 (http://gershwin.ens.fr/geomix).

20-24 **August 2001: Workshop on Atmospheric Chemistry and Climate Interaction** during the Climate Conference 2001, Utretch, The Netherlands. http://www.fys.ruu.nl/~www.imau/cc2001.html

24-27 **September 2001. Network for the Detection of Stratospheric Change : NDSC 2001 Symposium** "Celebrating 10 years of Atmospheric Research" , Arcachon, France. (http://www.observ.u-bordeaux.fr/public/ndsc.symp).

25 **September-October 5, 2001. School on the Physics of the Equatorial Atmosphere,** ICTP, Trieste, Italy (http://www.ictp.trieste.it/cgi-bin/ICTPsmr/mklinks/mklist?smr1328). **Deadline for student applications: May 31, 2001.**

Network for the Detection of Stratospheric Change : NDSC 2001 Symposium "Celebrating 10 Years of Atmospheric Research"

24-27 September 2001, Arcachon, France

Goals: to emphasise scientific results from NDSC data and to generate discussions/collaborations among NDSC working groups.

Scientific Programme Committee (SPC): Chair: Prof. Gérard Mégie. Organising Committee: Chair: Jérome de la Noe, Tel: +33 557 77 61 56, Fax 61 55.

The NDSC 2001 Symposium will be structured around six oral and two poster sessions, as well as a final " Symposium Summary and Discussion session ".

Oral sessions include invited reviews and presentations of some posters selected by the SPC.

The sessions cover primarily:

a - Intra- and inter-seasonal variability and trends;
b - Validation and assimilation of ground- and space-based data;
c - NDSC data and models;
d - Stratosphere-troposphere -climate interactions;
e - Prospects: new stations, techniques, databases, network synergies.

Short abstracts (one page maximum) submission by 30 April 2001, registration fee (120 US $) by 30 June, final manuscripts by 15 December 2001.
http://www.observ.u-bordeaux.fr/public/ndsc.symp,
http://www.ndsc.ncep.noaa;gov/, http://www.nilu.no

2nd Workshop "Long-term Changes and Trends in the Atmosphere"

Prague, 2-6 July 2001

The workshop is focused on trends in the mesosphere, thermospshere and ionosphere, but includes also stratosphere and troposphere. Among the goals: to sum up current information (observations, models) for trends in various parameters; to help distinguish between trends of anthropogenic and natural origin.

For information: contact Jan Lastovicka (jila@ufa.cas.cz).
http: www.ufa.cas.cz/html/climaero/Trend2001.html

UV/VIS Spectra Data Base of Atmospheric Constituents

A new data base containing about 1200 spectra and spectra data sheets of about 120 atmospheric constituents is available free-of-charge to all interested scientists.

You will find it at **www.science-softcon.de/uv-vis.**

If you need more information or a short description of the data base, please contact:

Dr. Andreas Noelle, Science-softCon, E-mail: **andreas.noelle@science-softcon.de**, http://www.science-softcon.de

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