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STRATOSPHERIC PROCESSES AND THEIR ROLE IN CLIMATE

A Project of the World Climate Research Programme

From the Chemistry Nobel Prize Laureates

Banquet Response for the Nobel Prize in Chemistry

Dec. 10, 1995. F. Sherwood Rowland

Your Majesties, Your Royal Highnesses, Ladies and Gentlemen. My friends, Paul J. Crutzen and Mario Molina, and I are most grateful for the honours bestowed upon us today, for the Nobel Prize is the ultimate in recognition in the scientific world. It is immensely satisfying to us that our efforts to understand the chemistry of ozone in the atmosphere have been judged worthy of this honour.

The atmosphere and its manifold changes have held fascination for men and women ever since human beings have trod this Earth. Its study played an integral role in the evolution of natural philosophy from which all of our present sciences have sprung. The scientific and technological developments of the past several decades, not available to our predecessors in past millennia, have provided the theories and tools which have now permitted us to develop a significant understanding of several atmospheric processes which affect the concentration of ozone in our stratosphere.

This ozone is vital to us and to all other species living on the sunlit Earth because it both establishes the temperature structure of the atmosphere and simultaneously protects us against damage from the most energetic solar ultraviolet radiation. We now know that ozone is subject to transformation by long-lived chemicals, both natural and man-made, released at the Earth's surface, and substantial reductions in its concentration could have a strongly deleterious effect upon mankind and upon the rest of the biosphere.

Our gratitude extends well beyond our own personal satisfaction because these honours also confer high scientific approval upon the field of atmospheric chemistry and upon environmental science in general. The current understanding of the atmosphere has progressed over the past two decades through the skilful and dedicated work of many hundreds of our colleagues in the field of atmospheric chemistry. Their work has collectively evolved to the point that the nations of the world have accepted through the Montreal Protocol of the United Nations the need for careful monitoring and, in some instances, control of gaseous emissions to the atmosphere.

Once again, speaking on behalf of Paul Crutzen, Mario Molina, and myself, we thank you all for the wonderful honours given to us today.

● F. Sherwood Rowland

Paul Crutzen responds to a question at the Nobel Press Conference, Stockholm, Sweden, December 8, 1995.
From left : F.S. Rowland, M.J. Molina, P.J. Crutzen. Courtesy. S. Solomon

Letter from Paul Crutzen

Dear SPARC colleagues,

On this way I would very much like to thank you all for the many personal congratulations I received for the 1995 Nobel Prize award. Unfortunately, it is quite impossible to thank you all personally. As almost all letters emphasised, this is at the same time a Nobel Prize for the entire, international atmospheric chemistry and aeronomy community which has made and still is making such enormous contributions to resolve the issue of human interventions in the atmosphere. The Royal Swedish Academy of Sciences has set a very important sign and I am quite certain that this will not be a single event and that other Prizes including hopefully in Physics will follow. Thanks again to all of you.

● Paul Crutzen

Letter from Mario Molina

Dear SPARC colleagues,

I am deeply honoured to be recognised by my peers in the scientific community and to share the 1995 Nobel Prize in Chemistry with my good friends and colleagues Paul Crutzen and Sherry Rowland.

Although we were singled out to receive this prize, I see it really as a recognition of the joint efforts of the numerous scientists who have worked on stratospheric chemistry over the past two decades and who have contributed so much to our understanding of the ozone depletion issues.

Sincerely,

● Mario Molina

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Report from the Third SPARC SSG Session

Geneva, October 17-20, 1995

The focal point of the session was the review of the progress made within the SPARC Initiatives. Addition of specific topics has been proposed within some of the existing initiatives. They concern mostly the role of aerosols and ozone changes in the Lower Stratosphere-Upper Troposphere (LS/UT) Chemistry.

GRIPS (GCM-Reality Intercomparison Project for SPARC)

GRIPS provides a coordinated framework for : the intercomparison of Troposphere-Stratosphere General Circulation Models (TSM-GCMs) and the parameterisations included in them, the understanding of the effects of physical processes on (middle) atmospheric circulation, the studies of middle atmospheric structure and variability, including its relationships with the troposphere, the prediction and understanding of stratospheric change and its effects on climate. Also GRIPS helps to establish regular contact between members of the middle atmospheric modelling community and with the tropospheric modellers.

Tasks for Phase 1. This Preliminary Intercomparison Phase includes : documentation of the participating TSM-GCMs groups working in a common format ; validation of the TSM-GCM climatologies, including the identification of common systematic errors in the location and strength of specific climatic features and budget studies of the physical mechanisms at work ; examination of the ability of the GCMs to develop sudden warmings and the two-way interactions between the stratosphere and troposphere during these events ; examination of the modes of variability in the GCMs, including the statistical links between the stratosphere and troposphere on seasonal timescales ; assessment of the sensitivity of the TSM-GCMs to the parameterised physical processes, investigations of the accuracy of the parameterisations, especially the radiative transfer schemes.

Present status of GRIPS :

- First chance for international discussion : IUGG, MW5 meeting, 10 July 1995 (a report is published in this Newsletter)
- New letter of invitation to participate in GRIPS : October 1995. At present, 10 groups are participating, and the number may increase to about 15.
- Commencement of EuroGRIPS : January 1996. EuroGRIPS was submitted to the Framework IV (Environment and Climate Programme) of the European Community. It is now in the «negotiation phase» after successful scientific review. The participants in «EuroGRIPS» include S. Pawson (Berlin), W. Lahoz (Reading), P. Simon (Météo-France), and R. Swinbank (Bracknell).
- First GRIPS workshop : 4-7 March 1996 (tentative), Victoria, BC, Canada, with the participation of 1-3 members of each modelling group and several prominent modellers invited as observers.
- Organisation, during the SPARC Assembly in Melbourne, possibly, of another GRIPS workshop.
- Completion of the intercomparisons for phase 1 (limited intercomparisons, documentation, long-term means).
- Completion of phase 1 and definition of phase 2 : late 1996 or 1997.

Phase 2. The exact goals of Phase 2 need careful definition so that useful scientific problems are addressed and allow the participation of as many groups as possible. All participants should obtain positive feedback for their own work, in the sense of yielding useful research results, as well as contributing to the whole intercomparison.

Some of the many ideas put forward are : AMIP-type project (i.e. long integrations using identical boundary conditions and other imposed quantities) ; case studies (but the initialisation will pose problems) ; predictability studies (including sensitivity to initial

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conditions) ; perturbation studies (e.g., sensitivity to ozone distribution) ; routine swapping (e.g. compare results from one model with two different radiation or convection schemes).

The **discussion** focused on the introduction of chemistry into the models involved in GRIPS. It was stated that most groups intend to put chemistry sooner or later and the question was raised on whether SPARC has a role to play in putting together the information for chemistry. This could, in fact, be an output of the UT/LS Chemistry SPARC Project (see below).

The possibility of enlarging EuroGRIPS to non-European groups was also discussed, and a proposal could be submitted to the next EC Call of Opportunity.

SPARC Reference climatology

The **aim** of this work is to construct a comprehensive climatology of means and variabilities of observed data, primarily for comparison with TSM-GCM simulations. The overall goal is to provide the atmospheric variables of most use to the research community, in a simple to use and easily accessible format (available via anonymous ftp from NCAR).

Primary **data sources** should be the National Meteorological Center (NMC) operational stratospheric and tropospheric analyses (1000-1 hPa, October 1978 - present). **Analysis products** are temperature and geopotential height, from which balanced winds are derived. Tropical winds can also be obtained from radiosondes. The ECMWF and Berlin analyses will be useful for comparison at selected altitudes. The ECMWF extends up to 10 hPa. The Berlin analyses contain temperature and height data available over the Northern Hemisphere (100-10 hPa, 1958 - present, for some levels). Shorter data sets could also be quite useful for examining future GCM simulations of stratospheric constituents, i.e., the United Kingdom Meteorological Office (UKMO) tropospheric-stratospheric assimilation (covering 1000-0.3 hPa for October 1991 - present), which includes winds and temperatures, and Goddard STRATAN assimilation (1000-10 hPa for 1985-1993, 1979 - present, by the end of this year ; their 1000-0.4 hPa analyses span January 1991 - present).

The question of the **mesospheric** temperature/wind climatology is still unclear : Two possible data sets are the Pressure Modulated Radiometer (PMR) data (low vertical resolution, extending to 85 km, 1975-1978) and Microwave Limb Sounder (MLS) data (high vertical resolution, 20-70 km, 1992-1994). As for the HRDI stratosphere-mesosphere wind data, these are still a research topic and may not be adequate to be included in the reference climatology at this time. There were also suggestions to use lidar or rocketsonde data to get «ground truth».

The proposed **spatial sampling** is 5° x 10° on NMC 17 pressure levels (1000, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 10, 5, 2, 1 hPa).

The **quantities to be included** in this climatology are monthly means, together with daily and interannual variability estimates. Results will include :

- Zonal averaged values of temperature, zonal wind, components of the residual mean meridional circulation (derived from a thermodynamic balance - continuity equation analysis), poleward heat and momentum fluxes, Eliassen-Palm flux divergence, rms planetary wave amplitudes (stationary plus transient waves).
- Fourier analysis of observed fields and uncertainties.
- Space-time power spectra to complement the stationary wave and transient wave concept.
- Latitude-longitude fields at selected pressure levels, e. g., 500, 200, 100, 50, 10 and 1 hPa. A suggestion was also made to include extreme temperatures or temperature probabilities in the lower stratosphere (for chemistry modelling) and to include statistics on isentropic potential vorticity on a couple of standard surfaces, in the lower and middle stratosphere.
- A sample of stratospheric constituent data : zonal mean ozone, methane, and water vapour (possible from SBUV, MLS or HALOE data).

As a conclusion of the discussion, it appeared clearly that Phase 1 of the Project is well defined, but more work is needed for defining Phase 2. Cooperation with the revised CIRA activity was considered desirable.

Gravity wave processes and their parameterisation (GWPP)

Actions on the High-Resolution data Archiving Issue. The US National Weather Service started, on April 1 1995, archiving 6-second data at 95 stations in the continental US, Alaska, Caribbean and tropical Pacific. Data will be available through U.S. NODC. The Canadian Atmospheric Environment Service was also contacted as well as the German (Neisser at Observatorium Lindenberg) and the New Zealand Met. services. A larger number of countries should be contacted through the WMO. An article was prepared for EOS : Hamilton & Vincent «High Vertical Resolution Radiosonde Wind and Temperature Data : New Prospect for Widespread Availability and Some Important Research Applications».

A closely related issue has been raised during discussions at the IUGG in Boulder : the archiving of meteorological data associated with ozonesondes.

Scientific progress. Numerous results were presented during the IUGG in Boulder during the Middle Atmosphere Symposium, IAGA session on tropical aeronomy, SPARC sessions, Gravity Wave Workshop. It showed tremendous interest in the problem of GW parameterisation. Initial experience with sophisticated GW-drag schemes has been obtained by some 3D modelling groups (NCAR, MPI Hamburg, GSFC). Interesting developments in observational techniques were presented, e. g. airglow imaging (Swenson), the applications of native-resolution radiosonde data (Karoly), etc. Results from the coordinated ALOHA campaign led to a discussion on the need of a massive observational GW campaign in 1998.

A NATO Advanced Research Workshop on «Gravity Wave Processes and Their Para-

meterisation in Global Climate Models» is being organised by K. Hamilton (director), M.L. Chanin and N.A. McFarlane (April 1-5, 1996, Santa Fe, U.S.A). Funding has been approved from NATO. WCRP will also sponsor the workshop and provide support for non-NATO participants.

The ARW will be an ideal forum for debating and making decisions concerning the need of archiving high-resolution ozonesondes, the need of a large observational campaign in the line of ALOHA, and the constitution of a GW climatology.

Stratosphere-Troposphere Exchange (STE)

A SPARC Workshop on STE took place at La Pointe-du-Lac, Québec from June 13 to 15, 1995 (an extended report is given in this issue of the Newsletter). This workshop, following the NATO/ARM held in Cambridge in 1993 on the same topic, has changed our perception of the way to approach the issue (cf the review paper on STE by Holton et al. in Reviews of Geophysics, 33, 4, 403-439, 1995).

The SSG discussed at length the need to elaborate a global measurement strategy to help plan future campaigns. There seems to be an agreement on the fact that the traditional local approach is limited when trying to quantify the global STE, or, as T. Shepherd phrased it, «making spot measurements to study STE is like looking at each eddy to study turbulence». The need for chemical airmass characterisation to document the transport implies the use of chemical tracers of different lifetimes, in addition to physical quantities. Availability of global measurements of these parameters from satellite platforms is for an unforeseeable future.

It was decided by the SSG that **a small group should be appointed** to meet for a few days within the next few months with the following charge : «Proceeding from the previous international workshops that were held in Cambridge, UK, and in Québec, Canada, on this topic, the group is to work to develop **combined measurement and modelling strategies** to progress in gaining the necessary understanding of these processes that are needed for better assessments. These strategies should consider the newly developed paradigms for stratosphere-troposphere exchange and be delivered for consideration at the next SPARC SSG meeting. The group should hold a meeting at which they may invite presentation of ideas by experts in measurement, models, and theory. They should then develop «strawman» strategies. Further development of the concepts may take place though electronic communications and meetings of opportunity.»

In this context, two presentations were made on future stratospheric aircraft : D. Ehhalt presented the status of the **STRATO 2C** project. The plane in the present configuration can fly one hour at 20 km, but existing plans to modify the design could help increase the ceiling (up to 23 km) and the duration of flight. V. Khattatov presented the Airborne Polar Experiment on board the **M-55 Geophysika** Stratospheric Research Aircraft (see SPARC Newsletter N° 5) and announced the success of the proposal submitted for support to the CEE, ESF and the Italian Antarctica programme and the offer by NILU to archive the data. The use of this aircraft is open for international cooperation, and 8 countries are planned to participate so far.

Water vapour Instrumentation and Climatology

Presently there is a poor knowledge of mean distribution/variability of H_2O and of processes that maintain mean distribution ; there is also a controversy over future changes of distribution. The **main tasks** being undertaken are to review the present data base and available instrumentation, to explore plans for future measurements and suggest the monitoring programme that could lead to a climatology of LS/UT water vapour.

Local and global measuring **techniques** should be evaluated (i.e. **locally** : improved radiosondes, frost point instruments, Lyman-α hygrometers, tunable laser diode instruments, Raman lidar techniques and differential absorption lidar (dial) ; and **globally** : nadir-viewing sounders, occultation sounders : SAGE II & III, HALOE, microwave limb emission sounders and infrared limb emission sounders : LIMS, CLAES, ISAMS, HIRDLS).

The climatology requires a **global monitoring effort** with continuous validation ; it should provide the seasonal evolution of global means and the measurement of the variations with «sufficient» vertical resolution. Also, **measurement and theoretical campaigns** are required to understand the mechanisms that control water vapour and its variability, having as a goal a predictive capability to include in climate models. It will require measurements of several variables beyond water vapour.

During the GEWEX Water Vapour Project (GVaP) phase II planning meeting on 12 July 1995, the SPARC activities and goals were presented, and the plans for LS/UT water vapour measurements received a strong support. As a conclusion, the tentative plan now is to hold an international workshop to develop a Science/Implementation Plan for a **broadened water vapour project** which would be designed to meet the needs of cooperating and cosponsoring projects : GEWEX/GVaP, CLIVAR/GOALS, and SPARC. It could take place in winter 1995/early spring 1996.

The SPARC Water vapour Initiative plans are to complete the draft report and to hold a **workshop** early in 1996 in order to develop statement of measurement requirements, to review and refine the report on measurement capabilities present status, to develop plans for measurement campaigns needed for validation and climatology, and to develop a strategy of how SPARC could have best interactions with GVaP.

The SPARC SSG stressed the need of **cooperation** with GVaP. Vital interest was shown in connection with some evidence of a H_2O **trend** in the stratosphere. It was also noted that the vertical distribution of H_2O should be studied with reference to the tropopause level.

Stratospheric Temperature Trends Assessment (STTA)

Two meetings of STTA already took place : in Reading (UK.) in March 1995 and during IUGG in July 1995. The next one is planned in Berlin on 18-19 December 95. It will be concerned with the following questions : base time period for viewing anomalies ; time intervals over which trends have to be determined ; statistics regarding the time series : correlations, standard deviations, attempt to understand the differences ; how to 'weight' instrumental record vs 'analysed' field ; trend determinations ; optimal choices to account for solar cycle, QBO, ... ; merits/limitations of different data sets.

The results already obtained were presented by V. Ramaswamy, essentially the zonal mean temperature between 100 and 2 hPa from MSU, SSU (UKMO and Nash) and radiosondes (Labitzke, Angell and Oort) as well as the NMC analysis. The study of the **upper stratosphere** will need to be completed later on a more local aspect by using rocket and lidar data.

As for model predictions, in the lower stratosphere the model uncertainties are due to the incomplete knowledge of the vertical profile of the O_3 loss, the forcing of the surface-troposphere system and the role of changes of O_3 versus changes in well-mixed GHGs ; in the upper/middle stratosphere, the question is still open whether the CO_2 signal is visible or not and, if not, if the absence of signal is due to the O_3 decrease ; there is large dynamical variability on the time scale of interest, and the understanding of the sources of the variability should be done in parallel.

Lower Stratosphere-Upper Troposphere (LS/UT) Chemistry

Ivar Isaksen reported on numerous on-going activities in this field and referred to the recent Halkidiki (cf SPARC Newsletter N° 5) and Schliersee (cf this issue) meetings. Close SPARC/IGAC cooperation is needed to avoid that some key issues fall in between both programmes. This is of utmost importance as the vertical distribution of the perturbations in this altitude domain are key issues in the climate change detection.

A list of possible activities were discussed including : review of LS/UT chemistry, parameterisation of heterogeneous chemistry in the models, comparison of chemical models, the role of convective processes for the upper troposphere, modelling the impact of aircraft emissions, the use of aircraft and satellite data, modelling long term O_3 loss, parameterisation of climate-chemistry interactions, UV radiation in relation to LS/UT chemistry.

The idea of a joint workshop with IGAC/GIM/GLOCHEM (i.e. the Global Chemical Modelling Issue) was suggested and should be discussed with IGAC.

Several suggestions were made by the SPARC SSG : to organise the use of the numerous data sets recently available in the LS/UT domain, to test the sensitivity of models to perturbations in order to force models to extreme mode, set up perturbation experiments and have 5-6 or so models run, to look at the coupling between O_3, H_2O, aerosols in the LS/UT, to look at chemical-radiative-dynamical interactions at different time-scales.

The SSG recognised the need to better define the main focus of this initiative. Finally, three foci were identified : effect of perturbation, aerosol chemistry and chemistry-climate coupling. With the addition of these thematics, it was suggested, that in the title of the Study Group, the term «Chemistry» is replaced by «O_3, Aerosols and Climate» to reflect more precisely the content of its activity, and A. R. Ravishankara was invited to co-chair the group with I. Isaksen.

Ozone trends

The group met first in Halkidiki in May 1995 and in Boulder in July 1995. The next meeting is scheduled in France at the Observatory of Haute-Provence for July 1996 (together with the WMO/IOC group).

The goals of this group are mainly (cf Newsletter N° 5) : to advance understanding of the O_3 trends in the lower stratosphere, to look at the likely quality of the O_3 measurements to be made in the coming years, to help develop a validation and intercomparison programme, and to keep an eye on the developments of total O_3 data quality or trends especially in the tropics.

The available data sets are the key long-term data sets : ozonesondes, SAGE, SBUV and SBUV/2, and the Umkehr data set (as a second class product).

The work is planned to include : a comparison of O_3 profiles (SAGE, MLS, HALOE), a full description of the SAGE algorithm, a study of the August 1995 Mauna Loa/SAGE O_3 profile intercomparison, an analysis of the SME/correlative measurements with the European Brewer-Mast O_3 sondes.

Two suggestions were made by the SSG : to include the upper troposphere in the analysis (the emphasis will stay on the lower stratosphere), and to add a statistician to the group in order to improve the statistical approach.

J. Kaye presented the present schedule of space-based O_3 measuring systems from 1990 to 2002, and gave some ideas on how to deal with the large number of satellite data and in particular how to ensure that the data quality would be as high as possible. He insisted that SPARC should have an important role to play in ensuring coordination in treating this large variety of data. This issue concerns not only O_3 measurements, but also other parameters. For this reason, it was decided to create a «group of coordination of space-based observations of the stratosphere». J. Gille, at the request of the SSG, defined the charge of the group as follows :

«...Every effort should be made to ensure the highest quality of the data sets and consistency among them. This means, at least, that attention must be paid to ensuring consistent approaches to instrument calibration and characterisation, development of data reduction algorithms, and validation of the geophysical products. This group is

charged with bringing together the appropriate people responsible for various aspects of data quality, and their funding agencies, in order to foster agreement on common approaches to these problems» .

Report on the WMO/GAW UV-B programme

P. Simon as chairman of the «WMO ad hoc Scientific Steering Committee on UV monitoring» reported on the activities of this group for which the terms of reference and composition were given in the SPARC Newsletter N° 5. The plans and priorities of the different working groups were presented and the contact with SPARC identified : S. Madronich, in charge of the modelling working group will be asked to report to SPARC.

Preparation of a SPARC Implementation Plan

It was agreed that SPARC is sufficiently advanced in the definition of its scientific priorities, and has even already implemented some actions. Therefore it was thought timely to prepare an Implementation Plan. The draft of such a document was outlined and the responsibilities defined.

The EC contribution to SPARC

The EC contribution to SPARC was presented by G. Amanatidis. The point of general agreement was to increase cooperation between the EC Environment and Climate Programme and SPARC.

Organisation of the 1st SPARC General Assembly

The Organisation of the 1st SPARC General Assembly in Melbourne was discussed at length including : list of invited speakers, preparation and distribution of the Second Circular, publication of extended abstracts, list of sponsoring agencies, etc. The second Circular and Call for Papers are included in this issue.

Activities of the SPARC Office

The SPARC Office has been until now suffering from lack of permanent scientific staff. However support for a new position has now been offered by CNRS for a young scientist, and Céline Phillips, the new appointee, was warmly welcomed. Also, M-C. Torre whose contract expired was thanked by the members of the SSG for her contribution in the last three years to the success of SPARC. The part-time contribution of Yuri Koshelkov, detached from the Central Aerological Observatory of Russia, will continue in 1996. Candidates which might be assigned to the Office by their own organisation for a one-year stay should let themselves be known by writing to the SPARC Office.

The SPARC Office produces a biannual SPARC Newsletter, which is being distributed to a mailing list of 2000 persons. The SSG congratulated the Office with the high quality of the SPARC Newsletters. It was proposed to have a SPARC Web page containing up-to-date information.

One of the charges of the SPARC Office has been the organisation of SPARC meetings, whether they were closed SPARC Study group meetings or symposia and workshops in international meetings. This load should even increase in the next years.

The next meeting of the SPARC SSG will be taking place in Adelaide, Australia, on December 9-12, 1996.

SPARC Workshop on Stratosphere-Troposphere Exchange

Pointe-du-Lac, Québec, Canada, 13-15 June 1995. Convener : Ted G. Shepherd.

Background

The subject of Stratosphere-Troposphere Exchange (STE) is crucial to many areas of atmospheric science, and lies at the heart of present concerns about the impact of aircraft emissions on the ozone layer. This last issue is a prime motivation behind the considerable research funds that are currently being invested around the world (particularly in Europe and the USA) in measurement campaigns and in the development of research aircraft. In light of this activity, the SPARC SSG decided at its meeting of September 1994 that it would be useful to bring together a cross-section of experts from the various scientific communities concerned with STE, in order to provide improved coordination between the different national research activities and to work towards a comprehensive measurement and modelling strategy.

The resulting workshop was sponsored jointly by the Atmospheric Environment Service of Canada and the WCRP. Participants were invited from the following scientific communities : theory, global modelling, mesoscale modelling, airborne measurement, ground-based measurements, satellite measurements, stratospheric chemistry, diagnostics, and assessment studies. There was also representation from funding agencies. A total of 37 scientists participated, from eight different countries.

Future SPARC and related meetings

Future SPARC meetings :

17-19 December 1995 : «Stratospheric Temperature Trends» SPARC Workshop, Berlin, Germany. Convener : V. Ramaswamy (GFDL, PO Box 308, Princeton, NJ 08542, USA) .

4-7 March 1996 : GRIPS Workshop, Victoria, BC, Canada. Convener : Steve Pawson (Institut für Meteorologie, Freie Universität Berlin, Carl-Henrich-Becker-Weg 6-10, 12165 Berlin, Germany).

1-5 April 1996 : NATO ARW «Gravity Wave Climatology and Parameterization», Santa Fe, NM, USA. Convener : Kevin Hamilton (GFDL, PO Box 308, Princeton, NJ 08542, USA).

8-12 July 1996 : «Ozone Trend Assessment» SPARC/WMO Workshop, Observatoire de Haute Provence (OHP), France. Convener : Neil Harris (British Antarctic Survey, High Cross, Madingley Road, Cambridge, CB3 0ET, UK).

2-6 December 1996 : First SPARC General Assembly, Melbourne, Australia. Conveners : M. Geller (SUNY, Stony Brook, N.Y. 11794-5000, USA) and D. Karoly (CRC for SH Meteorology, Monash University, Clayton VIC. 3168, Australia).

SPARC related meetings :

6-10 May 1996 : EGS General Assembly, The Hague, Netherlands

- Session OA9/ST12 : Stratosphere-Troposphere Exchange. Convener : Dr. Volkmar Wirth (Institut für Meteorologie, Universität München, Theresientr. 37, 80333 München, Germany).
- Session OA17 : Atmospheric Chemistry and Climate. Convener : Dr Johan Feichter (Theoretische Klimaforschung, Max-Planck-Institut für Meteorologie, Bundesstr. 55, 20146 Hamburg, Germany).
- Session ST2 : Open Session on the Middle Atmosphere. Convener : Dr. Martin Dameris (Institut für Physik der Atmosphäre, DLR Oberpfaffenhofen, Postfach 11 16, 82230 Wessling, Germany).

19-20 July 1996 : COSPAR : Symposium AI-I : «Middle Atmosphere-Satellite Observations, Interpretation and Validation, Models and Processes and their Role in Global Change». Birmingham, UK. Convener : J. J. Barnett (Oxford University, Clarendon Lab., Oxford OX1 3 PU, UK).

19-24 August 1996 : IRC Symposium on «Current Problems in Atmospheric Radiation», Fairbanks, AL, USA. Convener : K. Stamnes (Geophysical Institute, University of Alaska, 99775-0800 Fairbanks, AL, USA)

12-21 September 1996 : XVIII Quadriennial Ozone Symposium-96, Rome, Italy. Conveners : G. Fiocco (Physics Department University, La Sapienza, Rome, I-00185, Italy) and G. Mégie (CNRS/SA, Université Paris VI, B. 102, 4 Place Jussieu, 75252 Paris Cedex 05, France).

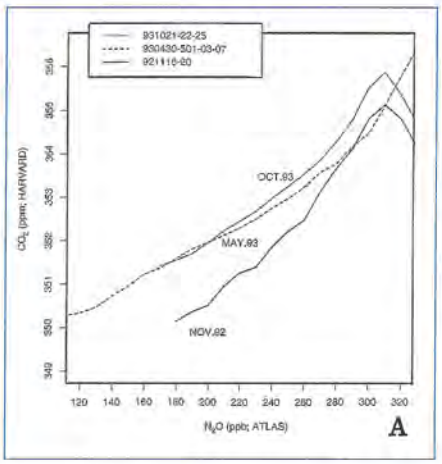
4-15 August 1997 : IAGA-ICMA General Assembly, SPARC Session, Uppsala, Sweden. Conveners : D. Fritts (LASP, University of colorado, Boulder, CO 80309-0392, USA) and S. Pawson (Institut für Meteorologie, Freie Universität Berlin, Carl-Henrich-Becker-Weg 6-10, 12165 Berlin, Germany).

4-8 August 1997 : 9th Quadriennial SCOSTEP STP Symposium, Uppsala, Sweden. (Chaiman of the Scientific Programme Committee: C. H. Liu, NCU, Chung-Li, Taiwan, Republic of China).

The workshop took as its starting point the progress reported at the highly successful NATO ARW on STE held in Cambridge in September 1993 (see report by P. Haynes in SPARC Newsletter No. 2), which led to the excellent review paper on STE by *J.R. Holton et al.* in *Reviews of Geophysics, 33, 4, 403-439, 1995.* The Cambridge workshop marked the beginning of a turning point in the subject. Previous research on STE had focused almost exclusively on the behaviour of the tropopause itself, and on the mesoscale phenomenology of strong mixing events such as midlatitude tropopause folds and deep tropical convection. At Cambridge, it was explicitly recognised that STE is but one aspect of a global picture of transport and mixing of chemical species, and one which for many purposes involves the dynamics of the entire stratosphere. In this respect it is clear that rather than focusing on STE per se, it makes more sense to consider the broader question of transport and mixing in what is now referred to as the «lowermost stratosphere» namely that part of the stratosphere whose isentropic surfaces are connected to the troposphere (it is also sometimes called the stratospheric part of the atmospheric «middleworld»). This development was consolidated, and pushed still further, by the recent SPARC workshop described herein.

Summary of presentations

The workshop began with overview presentations on the theoretical and modelling background. M. **McIntyre** (Univ. of Cambridge, UK) emphasised the connection between global and local aspects of exchange, as demonstrated so clearly by the «tropical tape recorder» which he had first proposed at the 1993 Cambridge workshop to explain certain puzzling features of observed tropical water vapour profiles. He noted the crucial distinction between the



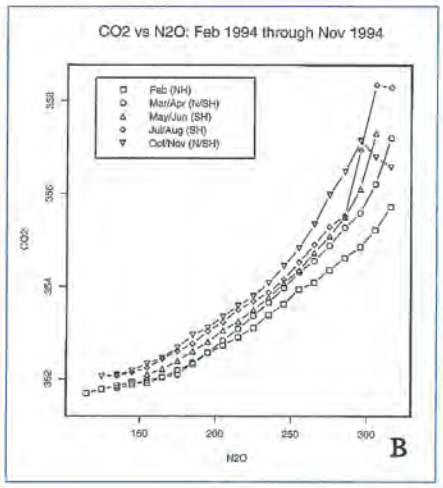


Figure 1 *- Correlation between simultaneous measurements of CO_2 and N_2O obtained from the NASA ER-2 aircraft from 1992 through 1995 place qualitative and quantitative constraints on troposphere-to-stratosphere transport into both the «overworld» and the «stratospheric middleworld» as well as on transport rates within the stratosphere. Data obtained from 15 to 60 N during the Stratospheric Photochemistry, Aerosols, and Dynamics Expedition in 1992/3* ***(Figure A)****, in which the CO_2 data have been binned and averaged as a function of N_2O) showed that seasonal oscillations in tropospheric CO_2 due to the uptake and release of carbon by the biosphere propagate into the «overworld» up to pressure-altitudes of about 19 km (approximately 280 ppb N_2O) before being completely attenuated. Note the decrease in CO_2 with increasing N_2O in both Fall 1992 and Fall 1993 but an increase in Spring 1993; these CO_2 oscillations are approximately in phase with the annual cycle of CO_2 in the upper tropical troposphere and are inconsistent with air entering the stratosphere at midlatitudes. Data obtained from 70 S to 60 N between February and November 1994 during the ASHOE/MAESA campaigns* ***(Figure B)*** *showed that the phase of the annual CO_2 cycle in the stratosphere is the same in both hemispheres, similar to the annual cycle in water vapour, suggesting that the source of air into both hemispheres is the same (data obtained at midlatitudes in the northern or southern hemispheres or both are noted as «NH»,»SH», or «N/SH», respectively). Combined with measurements in the tropics, the ASHOE/MAESA data also show that the «tropical signature» of air entering the stratosphere in the tropics reaches midlatitudes within approximately one month. In addition, correlation between CO_2, N_2O, and H_2O (not shown) obtained in the stratospheric middleworld in both the northern and southern hemispheres to date suggest that air in this region of the atmosphere is comprised of a mixture of air which has descended from the overworld and tropospheric air which originated from the tropics or subtropics but not mid- or high latitudes. Current ER-2 campaigns are focusing efforts on obtaining more data in the middleworld. (Figure and caption supplied by K. Boering, Harvard University).*

lowermost stratosphere and the «overworld» (that part of the stratosphere not connected to the troposphere along isentropic surfaces). The overworld is partitioned by a subtropical transport barrier which maintains a contrast between ascending and descending air. Exchange between the overworld and the lowermost stratosphere is dominated by the zonal mean vertical (diabatic) mass flux, which is significantly controlled by extratropical wave driving (termed the «extratropical pump»). Exchange across the tropopause itself is, in contrast, strongly affected by eddy fluxes (TUTTs, folds, monsoon circulation, Cb anvils).

P. Haynes (Univ. of Cambridge, UK) noted that although there is a general connection between tropical ascent and extratropical wave driving (as expressed by the «downward control principle»), a quantitative understanding of the details of tropical upwelling remains elusive. Another outstanding theoretical puzzle is the relation between the Transformed Eulerian Mean (TEM) circulation – which is the one connected to wave driving – and the transport (tracer-bearing) circulation ; previous work by Matsuno, and recent work by Mo, suggest there may be important differences between the two, especially within the polar vortex. On a different note, Haynes addressed the issue of stirring and mixing in the lowermost stratosphere, and suggested that this region should contain chemical filaments of smaller scale than potential vorticity (PV) filaments ; one might call such structures «fossils of exchange». Estimated horizontal scales were 2-20 km, with vertical scales of 20-200 m. The question of the sensitivity of chemical reaction rates to the spatial scale of mixing was raised.

A. Plumb (MIT, USA) also emphasised the importance of the subtropical transport barrier to STE. It is analogous to the polar-vortex transport barrier, though rather more porous ; both are, to a certain extent, a consequence of PV mixing in midlatitudes, creating edges on each side. Plumb proposed two simple models of exchange, which could be fit to chemical tracer observations. The first was a «pipe model», consisting of a tropical pipe (uniform ascent) together with a midlatitude stratospheric surf zone (horizontally sheared descent plus lateral diffusion). The second was a model of the lowermost stratosphere with a mean downward mass flux together with a «hyperventilation» coefficient representing mass-conserving exchange across the tropopause.

J. Holton (Univ. of Washington, USA) began by presenting results from a diagnostic study with Appenzeller and Rosenlof on the seasonal mass budget of the lowermost stratosphere, to assess the relative importance of variations in the amount of total mass. He then proceeded to focus on the tropical «tropopause layer» (15-18 km altitude), representing the transition region between clearly tropospheric and clearly stratospheric dynamics. (Some argued the top of this layer should be more like 20 km.) Holton highlighted

a number of critical questions concerning this region, including : What are the mechanisms for exchange between the tropics and midlatitudes ? (And, hence, how fuzzy is the tape recorder imprint ?) How can we account for the observed water vapour distribution ? What is the role of thin cirrus in this ? (It was noted that the existence of subvisible cirrus, supporting the notion of broad tropical ascent, was only recently confirmed by SAGE II and LITE observations.) What is the role of the Indian monsoon in dehydration ? How is the tropopause sharpened ? What is the longitudinal dependence of the tropopause height and temperature ?

K. Hamilton (GFDL, USA) and **B. Boville** (NCAR, USA) discussed the extent to which general circulation models (GCMs) are able to represent STE. Hamilton noted that the GFDL SKYHI model does get a reasonable diabatic circulation, with upward propagation of water vapour anomalies (consistent with the tropical tape recorder), and a vertical decay of N_2O in the tropics presumably due to lateral inmixing. Boville emphasised the extreme difficulty of getting a correct representation of the tropical troposphere-to-stratosphere water vapour transport in a GCM: water vapour mixing ratios vary by nearly four orders of magnitude over a few vertical grid points, and models don't like such large gradients. Also, the details of upper troposphere dehydration in the model depend strongly on the parameterization of small-scale processes, which are poorly understood.

J. Rodriguez (AER, USA) reviewed the present status of 2-D and 3-D assessment models. Historically, 2-D models were developed for the CFC problem, where they could be argued to be somewhat reasonable because of the long tropospheric lifetimes (and hence well-mixed nature) of CFCs and HCFCs. But current assessment questions concern the effect on chlorine and bromine chemistry from the injection of NO_x, H_2O and aerosols from subsonic (at the tropopause) and supersonic (at 50-60 mb) commercial aircraft. The shorter chemical lifetimes and the importance of lower stratospheric processes, including heterogeneous chemistry, make 2-D models more questionable in this case. For the time being, however, 2-D models remain a «necessary evil» for assessment purposes. The importance of including the effect of transport barriers in 2-D models, and the difficulty of doing so in a reasonable fashion, was emphasised, as was the need for measurement strategies specifically designed to test existing models.

The workshop then moved on to detailed presentations from the measurement community. **J. Anderson** (Harvard, USA) began with the question of how measurements of meteorological variables and trace species could be used to test theories of STE. The NO_y/O_3 ratio from ASHOE/MAESA, as a function of latitude, was one example which clearly showed isolated ascent in the tropics. Recently attention has focused on using a greater variety of tracers, with shorter lifetimes, in order to pinpoint seasonal and latitudinal dependencies (see next paragraph). Factors critical to the effectiveness of such studies include: accuracy, precision, and spatial resolution of the measurements ; good spatial and temporal coverage ; and well designed aircraft flight paths. With appropriate precision and sampling, one can infer chemical reaction rates. Anderson went on to describe the remotely piloted **PERSEUS** aircraft presently under development and the sort of measurements it would be able to make.

K. Boering (Harvard, USA) described measurements of tracer correlations obtained in the recent SPADE and ASHOE/MAESA campaigns, as well as in STRAT test flights. The strong seasonal cycle of tropospheric CO_2 means that CO_2 : N_2O correlations in the lowermost stratosphere can be used to infer constraints on tropical-to-midlatitude quasi-isentropic transport, suggesting transport timescales on the order of 1-2 months (see Figure 1). Corroborative evidence using a combination of CO_2, H_2O and N_2O measurements suggests that the principal route by which air reaches the lowermost stratosphere from the

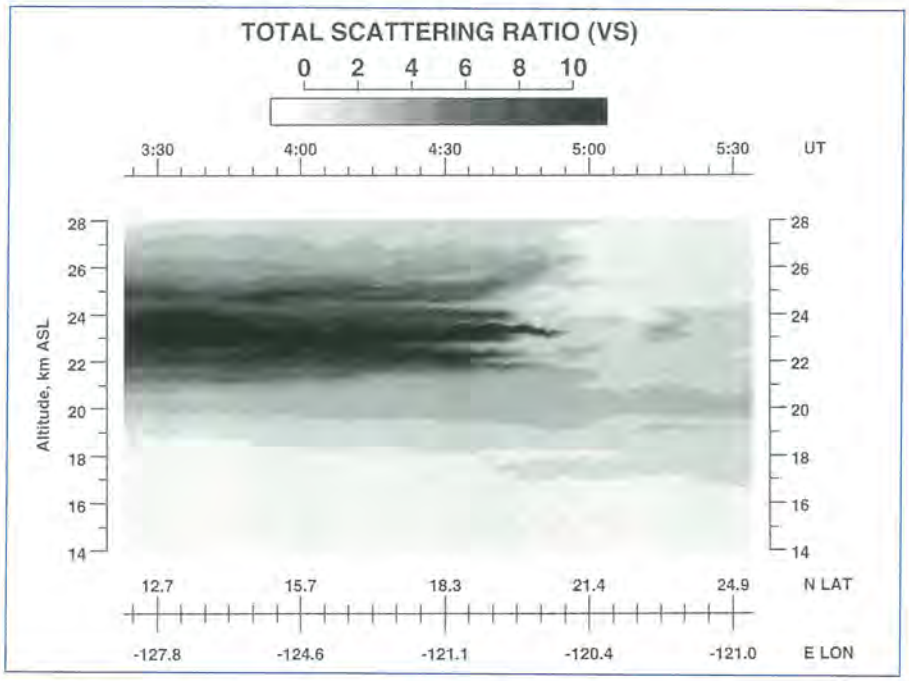


Figure 2. *Aerosol scattering ratio measured with DIAL system, in cross-section obtained from a flight during AASE 2 from Tahiti to Ames on 30 December 1992. After aerosol loading from volcanic eruptions (in this case, Mount Pinatubo), aerosol is a good indicator of airmass boundaries: here the relatively high values are indicative of air of recent tropospheric origin. The figure thus demonstrates tropical ascent, with some quasi-lateral transport into midlatitudes around 20 km, but with well-isolated ascent above that. There is evidently a subtropical transport barrier above about 22 km. (Figure supplied by E. Browell, NASA Langley, after a colour figure in Grant et al., JGR, 99, 8197 (1994)).*

troposphere is precisely this quasi-isentropic transport across the subtropical edge of the tropical tropopause layer, rather than across the midlatitude tropopause itself or «up-and-over» in the overworld via the Brewer-Dobson circulation (both of which require diabatic transport). This possible short-circuiting of the Brewer-Dobson circulation is an important effect to quantify.

S. Wofsy (Harvard, USA) described work with Plumb aimed at constructing a simple model of transport and mixing that was crudely consistent with stratospheric dynamics and could be completely constrained by observed tracer distributions. An example constraint might be lateral inmixing rates inferred from the observed decrease of N_2O with height in the tropics (also noted by Boering). A «3-pipe» model was described, with prescribed mean vertical transport (based on a radiative calculation), and with vertical diffusion and subtropical lateral exchange (leakage) parameters to be determined. Using CO_2, N_2O, and CFC_{11} measurements from ATMOS, ASHOE and SPADE, the model suggests strong lateral exchange below about 480 K (in the 15-17 km layer), and only modest exchange above that. The vertical diffusivity is only weakly constrained by the data, but appears to be much stronger in midlatitudes than in the tropics. There is a pressing need for high-resolution vertical profiles of tracers in the tropics, with seasonal coverage, at altitudes above those the ER-2 aircraft can reach.

P. Newman (NASA Goddard, USA) described the **STRAT** (Stratospheric TRacers of Atmospheric Transport) experiment which he and Wofsy are leading, including preliminary results from test flights in May 1995. Initial flights with the ER-2 were from NASA Ames, allowing access to latitudes 15N-60N. (Future flights from Hawaii will reach the equator). Contour advection was used to predict PV filaments, then the aircraft was directed to fly through them. Identification of the nature of the air (e.g. tropical or polar vortex, lowermost stratosphere or overworld) was made via tracers, corroborated by backward domain-filling trajectories. It appears that filamentary chemical features can be forecast from contour advection based on assimilated PV fields started between 5 and 15 days in advance. One problem is that in midlatitudes, the ER-2 cannot fly low enough to sample STE events ; there is a need for coordination with low-flying aircraft.

Newman went on to present (on behalf of M. Schoeberl) the upcoming NASA **TOTE/VOTE** (Tropical Ozone Transport Experiment/ Vortex Ozone Transport Experiment) campaign. The aim is to investigate exchange processes across the subtropical and polar transport barriers, focusing in particular on filamentation processes (which are argued to be insufficiently resolved in satellite measurements). The DC-8 aircraft will be flown from Hawaii, and Alaska/Norway, in winter 1995-96.

B. Vincent (Univ. of Adelaide, Australia) presented an overview of ground-based radar techniques. He noted that radar reflectivity is very sensitive to static stability and to water vapour ; thus it can be used to identify airmass boundaries such as the tropopause, and clouds. Measurements of turbulence intensity have previously been used to infer vertical diffusivity. M. McIntyre argued that these inferences are based on dubious assumptions about a «turbulent Prandtl number». However, F. Bertin argued that the estimated vertical diffusivities are consistent with the statistical models of Dewan (1979) and Woodman (1984) applied to high-resolution UHF radar observations of turbulent patches. This point remains controversial and requires further elucidation. Radar measurements of mean vertical velocities were also argued to be problematical, because of the requirement for a very narrow beam antenna which is only possible with UHF radars.

L. Gray (RAL, UK) described results from the two TOASTE (Transport of Ozone And STE) experiments. The experiments used a European network of radars, ozone lidars, temperature/water vapour lidars, aircraft, ozonesondes, and radiosondes, in combination with ECMWF analyses and modelling, to study tropopause folds and cut-off lows. Examples were found of dry, ozone-rich air, evidently of stratospheric origin, with no corresponding PV signature ; are these «fossils of exchange» (cf. Haynes presentation described above) ? The degree to which the troposphere (and, indeed, the lowermost stratosphere) is filled with such fossils is clearly worth further study. It was suggested that having tracers other than just O_3 and H_2O would be useful for discriminating more precisely between tropospheric and stratospheric air.

G. Ancellet (CNRS, France) described the **ESTIME** (Echanges Stratosphere-Troposphere, Investigations à Moyenne Echelle) experiment, which, much like TOASTE, used a network of ground-based radars, lidars, and ozonesondes (all in France) together with chemical transport modelling (CTM) from KNMI (Netherlands), to study STE in cut-off lows. Despite the obvious limitations (as for TOASTE) of a fixed spatial location of the network, the temporal continuity of the measurements allowed a characterisation of a variety of small-scale erosion processes involved in STE : turbulent mixing by shear instability, wave breaking, and diabatic effects related to convective activity. ECMWF analyses of tropopause height agreed well with the radars ; also, ozone was found to correlate well with analysed PV. It was hoped that the ozone measurements, combined with the CTM, could provide estimates of tracer transport. However, the CTM was found to be too coarse – a mesoscale model appears to be required – and the ozone profiles too few.

H. Kelder (KNMI, Netherlands) first presented results on the cross-tropopause mass flux calculated using the formulation of Wei (1987) applied to ECMWF analyses. The results were found to depend sensitively on the horizontal resolution employed. (Some noted that Wei's formulation is computationally ill-conditioned). Kelder went on to describe the recent **STREAM** (Stratosphere-TRoposphere Experiment by Aircraft Measurements) and **POLINAT** (POLlution from aircraft emissions In the North

ATlantic corridor) experiments, both of them European efforts. STREAM used a twin-engine Cessna jet aircraft to measure a number of chemical constituents, with the objective of assessing the role of NO_y in the lower stratosphere, and the impact of aircraft exhausts. POLINAT had rather similar goals, but used the DLR Falcon aircraft, and complemented the study with extensive modelling. Results focused on identifying chemical structures and relating them either to aircraft plumes or to transport from other regions of the atmosphere.

L. Pfister (NASA Ames, USA) described preliminary results using a satellite water vapour channel, in conjunction with STRAT aircraft measurements, to study processes on various scales in the vicinity of the midlatitude tropopause. He focused on identifying the mechanisms by which tropospheric air gets into the lowermost stratosphere. Pfister argued that for this purpose, H_2O provides a much better tracer than N_2O. Measurements show that midlatitude convection occurs close to the tropopause, but only just bumps into the stratosphere ; convection does not seem able to account for the relatively high H_2O values found at the top of the middleworld. Much deeper intrusions into the stratosphere are observed in conjunction with cut-off lows and anticyclones (i.e. lateral mixing), with parcel trajectories extending over tens of degrees of latitude. Breaking inertia-gravity waves were observed in many cases, and are presumably important in the final mix-down.

J.P. Cammas (Laboratoire d'Aérologie, Toulouse, France) presented a case study of a tropopause fold in the Caribbean observed during the **TROPOZ II** (TROPospheric OZone) airborne experiment. Subtropical folds appear to be commonplace, but are under-represented in standard climatologies of tropopause folds which are biased towards midlatitudes by their use of PV thresholds. The PV signatures of subtropical folds are comparatively weak, and one requires chemical signatures for their identification. The challenge remains of how to fit isolated observations such as these into a global framework of transport and mixing.

E. Browell (NASA Langley, USA) presented results from his airborne lidar systems, which measure ozone or water vapour, and aerosols and clouds. His ozone **DIAL** system, mounted on a DC-8, has been used in many campaigns since 1980. The lidar takes a vertical profile, and when employed in an aircraft flight track provides a horizontal-vertical cross-section. An example is provided by Figure 2, which suggests subtropical lateral exchange in the lower stratosphere and well-isolated tropical ascent above about 22 km (cf. presentations by Plumb, Boering, and Wofsy). The existence and detailed structure of the tropopause can be clearly identified in the ozone cross-sections and sometimes in the aerosol cross-sections. By superimposing a number of legs, a large-scale cross-section can be obtained, for example covering the sloping tropopause from equator to midlatitudes. The small scale cross-sections show plenty of fold structure, as well as more generic filamentation: the tropopause appears to be an extremely choppy (though distinct) surface. Correlations between ozone and PV have been examined in the troposphere to determine the extent of STE. Browell also described his H_2O lidar (called **LASE**) for use in high-altitude studies with the ER-2 ; this instrument can observe sub-visible cirrus and the water vapour associated with it, which have been found to be highly spatially inhomogeneous (cf. Holton presentation described above).

K. Hoinka (DLR, Germany) described the two DLR research aircraft, the **Falcon** and the **STRATO-2C**. The Falcon is presently being upgraded, which will increase its ceiling (from 38,000 to 41,000 ft), range (from 1,800 to 3,500 km), and flight time (from 3 to 5:45 hr). In addition to measuring meteorological parameters, it has optional chemical sensors as well as a DIAL (lidar) system ; the upgrade will include a dropsonde system, which is presently being developed in collaboration with NCAR and NOAA. Examples were shown of cross-sections through a B-747 wake and through an orographically induced tropopause deformation. The STRATO-2C is still under development, and the first proof-of-concept flight testing took place between the end of March and early August 1995. The aircraft was designed to have a high cruising altitude and long range ; the modified mission aircraft will be able to cruise at about 22 km for 5 hr. This falls well short of the original design specifications, however, and a decision will have to be made soon on whether to proceed with further modifications. The aircraft is now not expected to be operational before 1998. Anticipated cost of flight time is DM 10-20,000 per hour.

B. Gandrud (NCAR, USA) described NCAR's new high-altitude research aircraft, the **WB-57F**. This is a converted B-57, with a ceiling of 20-21 km and a range of 4,500 km. It is designed to provide measurements right across the upper troposphere/lower stratosphere region, which is inaccessible to both the DC-8 (which cannot get high enough) and the ER-2 (which cannot cruise low enough). This will be particularly important for in-situ water vapour measurements. The aircraft will have a dropsonde capability, and should have its first flight test in January 1996. Flight time will be available through NSF.

M. Shapiro (NOAA Boulder, USA) began by reviewing observational knowledge of tropopause folds. He emphasised the importance of turbulent exchange processes ; for example, the air in a tropopause fold is typically a 50/50 mixture of tropospheric and stratospheric air. Shapiro then proceeded to outline the proposed **FASTEX** (Fronts and Atlantic STorms EXperiment) campaign. This is an ambitious international project, designed to improve the forecasting of North Atlantic storms. It is scheduled to be carried out in January-February 1997, and will involve four ships and five aircraft, with extensive dropsonde activity. Rather unfortunately, from the perspective of STE, there are apparently no plans to include measurements of chemical tracers.

J.P. Cammas (Laboratoire d'Aérologie, Toulouse, France) described the **MOZAIC** (Measu-rement of OZone on Airbus In-service airCraft) programme. It provides measurements of H_2O, O_3, wind velocity and temperature taken during operational Airbus flights with five air-

craft, including vertical profiles during ascent and descent, and along-flight legs. A number of problems with the H_2O measurements were noted. At this point about 1000 flights are in the database, which is available for distribution by CD-ROM. A second phase of MOZAIC (proposed for 1996-97) will include measurements of NO_y and CO. A possible third phase (1998-2000) is uncertain.

F. Bertin (CETP, France) described the proposed **Airbus 340** project. The goal is to have a dedicated, or partially dedicated, A340 aircraft available for research use. The merits of this aircraft include its large payload (20-50 T), long range (15,000 km), and rapid vertical profiling (0-13.5 km in 1/2 hr). Airbus Industrie were initially supportive, but have recently cancelled funding for the required modifications. The project is now on hold, pending funding. Possible use could be in the context of ARGOS (Atmospheric Research Global Observation System), for which 15 European teams have proposed to make 30 species measurements using the A340. Another proposed use is for NEPONA (Nitrogen oxide Emission and Photochemistry Over the North Atlantic), a POLINAT-like experiment. Anticipated cost of flight time is US $ 20,000 per hour, minimum.

Discussion

R. Stolarski (NASA Goddard, USA) raised the challenge of aircraft assessment studies. These focus on the expected impact of emissions from three categories of aircraft: high-speed (supersonic) commercial transport, or HSCT, cruising at 65,000 ft ; current subsonic aircraft, cruising at 35-39,000 ft ; and possible future higher-altitude subsonic aircraft, cruising at around 45,000 ft. What we *think* we need is information on the lifetime and accumulation of pollutants, and on the extent of transport to high altitudes, together with some limits or uncertainties. This has led to a three-track approach: measurements and analysis of individual events, to quantify the degree of irreversible mixing ; global analyses and 3-D models, to quantify its frequency and intensity (and provide constraints on parameterisation) ; and 2-D or low-resolution models, to quantify the overall uncertainty. But what do we *really* need ? In particular, do we need to understand (and parameterise) irreversible mixing in detail ? For chemical reactions that are highly nonlinear, the answer could well be yes (cf. Haynes and Rodriguez presentations above).

M. Geller (SUNY Stony Brook, USA) focused on the measurement issues. Given the fact that there are some very expensive aircraft experiments, and aircraft development projects, it is imperative to ask whether there is sufficient communication between them, and whether their science plans are sufficiently coordinated. Is the community yet in a position to agree on what the most important measurement activities might be ? And how could such measurements be most effectively used to improve assessment models ?

T. Shepherd (Univ. of Toronto, Canada) highlighted some of the key outstanding issues that had arisen during the workshop. These include :

- Understanding of how the tropopause is maintained (and evolves seasonally)
- Quantitative theory of the details of tropical upwelling
- Quantitative theory of dispersive mixing, and of transport barriers
- Relation between the residual circulation and the transport circulation
- Determination of the most appropriate measures of STE
- Understanding of the tropical «tropopause layer» (roughly 360-380 K), including a quantitative determination of water vapour mixing ratios
- Observational constraints on lateral mixing in the tropical stratosphere, especially the lowest part

(Note that the last two questions are presently hampered by the lack of reliable wind measurements in the tropics ; for the time being, the only way to estimate mixing rates appears to be by inferring them from chemical tracers.)

- Determination of mix-down time of filaments in the lowermost stratosphere and midlatitude upper troposphere
- Observational constraints on midlatitude mixing
- Can radars be used to determine vertical fluxes of tracers ?
- How (if at all) is turbulent intensity related to vertical diffusivity ?

More generally, it can be said that the problem of STE is fundamentally a fluid dynamical problem of transport and mixing. A comprehensive understanding of STE therefore requires a comprehensive theoretical framework to understand transport and mixing. Traditionally this framework has consisted of mean (Lagrangian) advection plus diffusion, but this is completely inappropriate, sometimes spectacularly so, in the vicinity of sharp edges in the tracer fields – which is the essence of the STE problem. (Stirring by large eddies generates strong gradients, quite the opposite of diffusion.) New conceptual models (transport barriers, leaky pipes and so on) are beginning to emerge, but they would have to be considered quite heuristic and certainly preliminary.

Where do we go from here ?

All will agree that we need to develop well-conceived global measurement strategies, using appropriately chosen chemical tracers, in order to constrain conceptual and numerical models ; the question is, how ? In this regard, the recent use of satellite data in combination with carefully designed chemical tracer sections from airborne instruments offers an extremely promising development. Results presented at the workshop clearly demonstrated the potential for chemical measurements to provide quantitative information on critical questions such as the extent of mixing across the subtropical potential vorticity edge, as a function of altitude, and the most likely route for air to get from the troposphere into the lowermost stratosphere. To many participants, these new results offered the kind of insight long familiar to oceanographers in their ability to identify water masses by their T-S relations. It seems that we may now be in a position to achieve a similar kind of Lagrangian view of the chemical circulation of the stratosphere – which is an exciting prospect.

This raises the question of whether a global measurement strategy (akin to WOCE) might now be appro-

priate, if not required. That time has not yet come, however ; as argued above, we still lack a satisfactory theoretical framework for defining a critical measurement strategy, and for integrating those measurements in global models. In the meantime, there are a number of more sharply focused questions, including those described above, that are amenable to quantitative study. In any such study there is a pressing need for better design of complementary measurement programmes, in order to avoid the crippling limitations that are often associated with particular measurement platforms (e.g. intrinsic biases and under sampling inherent in fixed-location measurements ; inability of the ER-2 aircraft to cruise low enough to intersect the midlatitude tropopause ; lack of chemical-tracer measurements in «traditional» meteorological studies of STE ; lack of connection to the global circulation in mesoscale studies ; and so on).

●Ted G. Sheperd

NATO Advanced Study Institute : The Stratosphere and its Role in Climate

Québec, Canada, 5-15 September 1995
Director : Guy Brasseur

In early September, 1995, 85 students and approximately 15 teachers from 25 countries gathered in the middle of the Laurentides, 100 km north of Montreal to attend one of the NATO Advanced Study Institutes sponsored by SPARC, and supported by NATO, the US National Aeronautics and Space Administration (NASA), the US National Science Foundation (NSF), the European Commission (EC), several agencies from Canada and Quebec, as well as the National Center for Atmospheric Research (NCAR).

The purpose of the Advanced Study Institute was to provide a detailed view on the coupled chemical, radiative and dynamical processes in the stratosphere that affect the global climate system. Several tutorial lectures focused on fundamental and theoretical questions, while others discussed more applied topics.

The role of dynamics and transport was first emphasised. It was explained that the general circulation in the stratosphere is driven primarily from momentum deposition associated with gravity wave breaking and planetary wave absorption. The concept of the transformed Eulerian mean circulation was presented. The role of tropical waves and their relations with the observed quasi-biennial oscillation were also discussed. The fundamental equations for the dynamics of the atmosphere were established. The theoretical concepts (including that of potential vorticity) were used to analyse and interpret observed situations.

Comprehensive lectures on radiative transfer in the atmosphere were also presented. The emphasis was on the penetration of solar radiation in the stratosphere and troposphere, and specifically the role of absorption and multiple scattering. Another aspect, which received much attention, was the role of terrestrial radiation. Simple techniques to solve the radiative transfer equations were presented, including the concept of band models which are often used in practical applications. The theory used in satellite remote sensing applications was also presented and discussed in fair detail.

Several lectures were given on the chemistry and photochemistry of the middle atmosphere. The focus was on the processes that lead to the formation and destruction of ozone in the stratosphere. The specific roles of nitrogen, chlorine, and bromine compounds were discussed. Much attention was given to the importance of heterogeneous chemical reactions on the surface of aerosols and ice particles in polar stratospheric clouds. The mechanisms responsible for the formation of the Antarctic springtime ozone hole were presented. Finally, the role played by sulphate aerosols, especially after large volcanic eruptions such as that of Mt Pinatubo (1991) was discussed. The basic techniques used to probe the chemical composition of the stratosphere (in-situ and remote sensing) were intensively discussed.

In addition to tutorial lectures, several presentations focusing on specific subjects related to the physics and chemistry of the stratosphere were given. These included subjects such as the role of trace gases in radiative forcing, the potential importance of solar variability in atmospheric changes, observations of chemical constituents from space, the specific role of aerosols, the methods to develop numerical models of the atmosphere, the key findings provided by recent polar ozone campaigns, etc.

What was unique to this Advanced Study Institute was the active participation of the students in the preparation of a comprehensive textbook, which will summarise the lectures given during the school. Val Morin, the small village of the Laurentides which hosted the meeting, has offered a unique experience to an outstanding group of students and teachers. An unanimous conclusion was that other schools of that nature should be organised, especially for the 300 applicants who were not selected because of limitations in space and funding.

● Guy Brasseur

Second Circular and Call for Papers

1st SPARC General Assembly Melbourne, Australia 2-6 December 1996

The World Climate Research Programme on **Stratospheric Processes And Their Role in Climate (SPARC)** will hold its first general scientific assembly in Melbourne, Australia, during the period December 2-6, 1996. It will be hosted by the Australian Cooperative Research Centre for Southern Hemisphere Meteorology (CRC SHM), and the Australian Meteorological and Oceanographic Society (AMOS) and be co-sponsored by SCOSTEP, COSPAR, IUGG, IAMAS, NASA, CNES, CSIRO DAR and Australian Academy of Sciences. Additional cosponsorships will follow.

SPARC is an international programme with the goal of facilitating research on the relationships between stratospheric processes and their role in climate (both tropospheric and stratospheric). It is recognised that there is much national and international activity in stratospheric research, so SPARC seeks to facilitate research into areas that need additional activity and/or can benefit from more international communication among separate national programmes.

The 1st SPARC Assembly will include invited and contributed oral and poster papers on the following topics :

1 - Troposphere-stratosphere general circulation models with and without chemistry.
2 - Stratospheric climatology studies.
3 - Trends in temperature, ozone, and water vapour and the observational capabilities in these areas.
4 - Gravity wave processes and their parameterization.
5 - Stratosphere-troposphere transport and mixing.
6 - Chemistry-climate interaction in the lower stratosphere and upper troposphere.
7 - UV radiation and its impacts.
8 - Other aspects of stratospheric processes and their role in climate.

Those invited speakers who have already agreed to speak :

B. Armstrong, G. Brasseur, J. Gille, K. Hamilton, N. Harris, J. Holton, K. Kodera, A. Kricker, R. McKenzie, A. O'Neill, S. Pawson, V. Ramaswamy, W. Randel, A. R. Ravishankara, T. Shepherd, S. Solomon, D. Toohey, R. Vincent.

Submission of Abstracts

Those wishing to participate should forward brief abstracts (300 word limit) of proposed presentations for consideration by the Scientific Organising Committee. Those accepted will be reformatted by the SPARC 96 secretariat and collated for distribution to all participants at the time of registration. To assist with collation and layout, electronic mail submission is preferred. (For those without access to e-mail and for abstracts containing equations or special type, please post or fax hardcopy versions). The specifications for these brief abstracts are provided below.

Specifications for brief abstracts

Please separate each of the following items with a blank line.

1 - Title, Upper (capitals) and lower case.

2 - Author(s) Upper and lower case, with presenting author in upper case only.

3 - Author affiliations : Upper and lower case.

4 - Text (300 word limit). Simple ascii text where possible.

5 - Address (e-mail, phone, fax and postal) for correspondence.

6 - Preferred session (suggest which of the 8 SPARC topics is the most relevant to your paper).

7 - Indicate whether you prefer a poster or an oral presentation (only one oral presentation per speaker allowed).

Abstracts must be submitted by May 1, 1996 to SPARC 96 (address below)

Venue

The meeting is being held at the University of Melbourne as it offers excellent lecture theatres with state-of-the-art audiovisual facilities and is close to the Melbourne city centre with many restaurants, shops and parklands nearby.

Registration Rates

Full including Conference dinner : Aus$ 220 (After 1 October 1996 : Aus$ 280)
Student : Aus $ 110 (After 1 October 1996 : Aus $ 150) (Aus$ = 0,75 US$ on the 20 Oct 95)

Accomodation

A range of accommodation has been reserved at prices negotiated for our conference (eg. a 3 -star hotel will cost approximately Aus$ 100/night for a single room) All hotels are located close to the venue. More economical accomodation is available in Melbourne University residential colleges in single study bedrooms for about Aus$ 35/night including breakfast.

Travel

A visa is necessary for all visitors travelling to Australia. Melbourne (Tullamarine) International and domestic Airport is approximately 20 km from the central business district.

Support

Limited funds are available to support young scientists and other newcomers to the field. On the registration form please indicate whether you are applying for such support. Please indicate approximately the support needed and whether your attendance is contingent on such support.

Publications

The authors are asked to supply at the time of the meeting a camera-ready extended abstract for publication. It should be written in GRL format with no more than 4 pages.

Scientific Organising Committee : M. Geller (Chair), R. Atkinson, M.-L. Chanin, J. Pyle, S. Solomon, R. Vincent.

Local Organising Committee : D. Karoly (Chair)

Some Key Dates :

Final date to submit abstract : May 1, 1996
Notification of acceptance of abstract : July 15, 1996
Deadline for early registration : October 1, 1996
Conference : December 2-6, 1996

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SPARC activities - news from different countries

Brazil and Chile cooperate to study the Antarctic ozone hole

For many years, Brazil and Chile cooperated in maintaining a Brazilian station Commandante Ferraz (King George Island., near the Antarctic Peninsula). Also, the influence of the ozone hole on the largest population nearest to the Antarctic, the city of Punta Arenas, was found to be of mutual interest. Here the Brazilian INPE, through its ozone group, installed in 1992 a Brewer spectrophotometer to measure ozone, UV-B radiation at narrow spectral bands, column SO_2 and NO_2. Since then, a UV-Radiometer was added to measure integrated UV-B radiation, and in 1995 a comprehensive field campaign (Brewer, UV-Biometer, ozonesondes) was held from September 20 to October 30 to observe the passage of the ozone hole (which reached Punta Arenas on October 13-14). Column ozone values (DU) observed with the ECC sondes from October 6 to 16 were as follows : 348 (6 Oct.), 285 (9), 294 (10), 220 (11), 218 (12), 202 (13), 205 (14), 351 (15), 347 (16 Oct.). The vertical profile on 14 Oct. showed a large ozone destruction near 100 hPa.

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SpanishAntarctic campaign of 1994-95

During the past summer campaign at the Spanish Antarctic Base (62.7°S, 60.4°W), the Instituto Nacional de Meteorologia (Madrid) carried out 25 ozone soundings in January and February 1995. Also, during this campaign, NO_x measuring instruments developed in the Instituto Nacional de Technica Aeroespacial, were distributed to different Argentine Antarctic bases to observe continuously this trace gas in the polar stratosphere. On the basis of the accumulated ozone soundings (first initiated in 1989), interannual variations and trends can be obtained, for instance, for the height of the ozone stratospheric maxima (highest in 1993) ; some decrease in these maxima can also be detected.

Juan M. Cisneros, Inst. Nat. Meteor., Madrid. Fax : +34-1-5819-767.

1995 Ozone hole from New Zealand's perspective

In September 1995 the onset of ozone depletion occurred earlier than in previous years, resulting in ozone values as much as 10% lower than at similar times in recent years. Minimum ozone values at Arrival Heights (78S, 167E) were comparable to most recent years. This year minimum was 130 DU on October 4th, which is just slightly higher than the lowest measurements at that site of 128 DU on 7th and 12th October 1993. Since mid-November Arrival Heights ozone measurements have all been above 270 DU, and over the last few days of November have been around 350 DU. This is a result of the ozone hole being displaced away from the Ross Sea area (towards the Weddell Sea).

The ozone hole should break up within the first week of December. Measurements of trace gases containing chlorine and odd-nitrogen that are active in the chemistry of ozone depletion were also made with ground based spectrometers at Arrival Heights during the 1995 spring. These data show the change in partitioning of both the active chlorine and nitrogen species during the ozone hole period but the final results from these experiments are not yet available.

In summary the 1995 ozone hole was similar in size and depletion to most recent years - but it will be the longest-lasting one (due to the earlier onset).

Andrew Matthews, NIWA, Lauder, Central Otago, NZ. Fax : +64-3-447-3348.

Australian monitoring of 1995 Antarctic ozone depletion

This year the TOVS-depicted ozone hole evolution was monitored in real time in Australia using a global ozone analysis and prediction system developed recently by the Cooperative Research Centre for Southern Hemisphere Meteorology, in collaboration with the Bureau of Meteorology Research Centre. (This scheme is also to be used by the Bureau of Meteorology this summer as the basis for an experimental system for providing deterministic prediction of clear-sky surface UV-B irradiance over the Australian region.)

As detailed by WMO in its periodic Antarctic ozone bulletins covering this year's ozone hole development, the 1995 Antarctic ozone hole was similar to those of the last few years, as gauged by its maximum area and depth of depletion, time of onset and overall duration.

This year's ozone hole episode is now waning. The TOVS-depicted minimum total ozone levels over Antarctica had risen to about 200 DU by the end of November : the combined result of an influx of high ozone concentrations into the Antarctic middle and upper stratosphere which accompanied a period of moderate dynamical wave activity during November, and the progressive subsidence warming of the lower stratosphere triggered by this activity. Despite partial recovery of the total ozone column, however, the Antarctic lower stratospheric ozone deficit has again persisted into December. It is expected that this will as usual dissipate during December, as the lower stratospheric remnants of the polar vortex are broken up and redistributed throughout the extratropical region of the hemisphere.

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South Africa - a second DOBSON station is established

This station is located in Springbok (29,67°S, 17,9 °E) and is now fully operating within GO3OS. During February 1995 Mr A. I. Asbridge from Canada came to

South Africa to ensure that the operational status of the newly acquired Dobson spectrophotometer #132 was reached according to international standards.

High emphasis was placed on Dobson operators training, and thus the monitoring program was highly enhanced. Intensive total ozone and Umkehr observing schedule is being followed and the data are being archived in WODC, Toronto. Since March 1995 the Czech Republic's total ozone Dobson programme has been officially adopted in South Africa for calculating the measurements.

Gerrie J.R Coetzee, South African Weather Bureau. Private Bag X097, Pretoria, 0001. Fax : 27122903031. E-mail : coetzee@cirrus.sawb.gov.za.

Ozone monitoring in Korea

The Korean Meteorological Administration enhanced its stratospheric ozone monitoring by installing a vertical ozone measurement system since Jan. 12, 1995 to existing Brewer spectrophotometer and UV-Biometer at Pohang (36N, 129E). The adopted W-90000Z Vertical Ozone Measurement System is a WMO compliant synoptic meteorological processing system capable of fully automatic upper air soundings. The parameters sampled by W-90000Z are : pressure (1080 to 3 hPa, rms accuracy 0,5 hPa, resolution 0.1 hPa), temperature (+60 to -9O°C, accuracy 0.2°, resolution 0.1°), relative humidity (5 to 100%, accuracy 2%, resolution 1%), ozone partial pressure, etc. The samples are obtained within every 15 sec interval. The measurements have been done once per week, on Wednesdays. The ozone sonde data will be ready to the world within near future. There was no chance yet to compare with Brewer data.

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The Middle Atmosphere Sciences Symposium

IUGG Assembly, Boulder July 2-14, 1995. Convener : Rolando Garcia.

The Middle Atmosphere Sciences Symposium (MASS) was held in conjunction with the IUGG XXI General Assembly in Boulder, Colorado, during the first two weeks of July, 1995. Over 250 papers, invited and contributed, were presented at the Symposium. Oral and poster sessions were held throughout the first week of the Assembly, and on Monday and Tuesday of the second week. The MASS included four topical symposia : Dynamics, Chemistry, Radiation ; and Transport ; Solar-Terrestrial Interactions ; and Polar Mesosphere. Symposium participants also had the opportunity to attend a Union lecture on Ozone Depletion and Global Change, symposia on Equatorial Atmosphere-Ionosphere Interactions and Effects of the Mt. Pinatubo Eruption, and workshops on Solar Cycle Effects, Gravity Waves, and Middle Atmosphere Models. The very large number of topics covered by the MASS precludes a complete discussion of all of the sessions ; thus, this summary provides only a partial account of the many interesting papers presented at the Symposium.

Dynamics of the Middle Atmosphere

The sessions on Dynamics of the Middle Atmosphere covered many topics of current interest, including tropical dynamics, planetary and gravity waves, tides, and numerical modelling. **M. Salby** (U. of Colorado, US) showed how data from the International Satellite Cloud Climatology Project (ISCCP) can be used to infer the spectrum of equatorial wave activity that forced by deep convection in the tropics. His results suggest that a very rich spectrum is excited, with substantial power at wavenumbers and frequencies beyond the sampling capabilities of polar orbiting satellites. Studies by **F. Sassi** (NCAR, US) and **L. Pfister** (NASA/Ames Research Center, US) indicate that some of these smaller-scale, high-frequency waves may play important roles in the forcing of the tropical quasi-biennial and semiannual oscillations.

Substantial progress has also been made in observations and modelling of the small-scale gravity waves that are thought to be important in the momentum budget of the middle atmosphere. **O. Andreassen** (NDRE, Norway) and **T. Palmer** (U. of Colorado, US) presented three-dimensional simulations of gravity wave breaking. They showed that cross-stream instabilities can develop from small, random perturbations in the flow field of an initially two-dimensional gravity wave, altering its subsequent breakdown. **D. Durran** (U. of Washington, US) showed how the use of wave pseudomomentum allows a much more concise and physically meaningful description of the interaction between a breaking wave and the background flow than the conventional Eulerian zonal-mean formulation. **J. Prusa** (Iowa State U., US) discussed a set of numerical calculations illustrating how gravity wave packets forced by localised sources in the troposphere undergo substantial dispersion as they propagate to the mesosphere. As a consequence, the mesospheric wave field is dominated by monochromatic wavetrains, much as envisaged by parameterisations of gravity wave breaking.

Observational evidence of the interaction between small-scale gravity waves and the circulation of the middle atmosphere was presented by **A. Smith** (NCAR, US), who used data from the High Resolution Doppler Imager (HRDI) on UARS to illustrate how the stratospheric flow field apparently filters the spectrum of upward-propagating gravity waves to produce a mesospheric circulation which shows a strong negative correlation with stratospheric winds. UARS/HRDI observations were also employed by **R. Liebermann** (U. of Michigan, US) to deduce the mean circulation at altitudes between 70 and 90 km. Other interesting phenomena of the mesosphere/lower thermosphere region were studied by **J.A. Whiteway** (York U., Canada) and **J. Meriwether** (Clemson U., US), who documented the occurrence of mesospheric inversion layers and speculated on possible mechanisms for their formation. Numerical modelling by **T. Leblanc** (Service d'Aéronomie, CNRS, France) suggests that gravity wave breaking may be involved in the formation of the inversion layers.

A thorough review of the status of numerical modelling of the middle atmosphere was presented by **K. Hamilton** (Geophysical Fluid Dynamics Laboratory, US). He pointed out that, despite substantial advances in the field, comprehensive models of the middle atmosphere are still subject to uncertainties arising from the need to parameterise subgrid-scale processes. **J. Kinnersley** (Edingburgh U., UK) showed that it is possible to produce a realistic middle atmosphere climatology in a quasi-linear model wherein the mean state is influenced by suitably parameterised gravity and planetary wave driving. **R. Roble** (NCAR, US) reported on the use of comprehensive three-dimension models to study the behaviour of tides in the mesosphere and lower thermosphere.

Chemistry, Radiation and Transport

These sessions included the largest number of papers contributed to the Symposium, an indication of the rapid growth of the field in the years since the discovery of the Antarctic ozone hole. Advances in numerical modelling of stratospheric chemistry were highlighted in papers by **M. Chipperfield** (Cambridge U., UK), who studied the behaviour of chlorine species and their impact on polar and midlatitude ozone, and by **F. Lefevre** (Météo-France, CNRM, Toulouse), who demonstrated the ability to simulate realistically the behaviour of chemical species during Arctic and Antarctic winters.

Two full days were devoted to the presentation of observations of chemical constituents and their long-term trends. The papers by **A. Tuck** (NOAA, Aeronomy Laboratory, US), on dehydration of the polar lower stratosphere, **J. Remedios** (Oxford U., UK), on UARS/ISAMS observations of NO_2 in the upper stratosphere and mesosphere, **S. Ruth** (Rutherford-Appleton Laboratory, UK), on temporal variability of methane and nitrous oxide, and **J. Harries** (Imperial College, London, UK), on the validation of UARS/HALOE observations of water vapour, are representative of the many interesting contributions in the area of new chemical observations. The subject of long-term trends has gained importance in recent years because of the need to document changes that may be brought about by human activities and to distinguish these from natural variability. **N. Harris** (UK) reviewed global ozone trends, while **Y. Yung** (California Institute of Technology, US) discussed the decadal evolution of the Antarctic ozone hole. **J. Russell** (NASA/Langley Research Center, US) used HCl and HF observations from UARS/HALOE to provide the most convincing demonstration to date that chlorine derived from CFCs is responsible for the observed trend in the stratospheric trend of this species.

Several sessions addressed observational, laboratory and modelling studies of heterogeneous processes and their impact on stratospheric ozone. **A.R. Ravishankara** (NOAA, Aeronomy Laboratory, US) presented a review of the heterogeneous chemistry of species containing chlorine, bromine and iodine, and their possible role in the ozone budget of the lower stratosphere. **Y. Kondo** (Nagoya U., Japan) discussed measurements of nitrogen compounds and their implications for heterogeneous chemistry and ozone depletion. The effect of the eruption of Mt. Pinatubo on stratospheric ozone was reviewed by **W. Randel** (NCAR, US), while **G. Wetzel** (U. Karlsruhe, Germany) and **A. Roche** (Lockheed/Palo Alto Research Laboratory, US) presented evidence for perturbations in nitrogen chemistry attributable to the enhanced aerosol concentration produced by Mt. Pinatubo.

Radiative processes and their relation to stratospheric chemistry and climate were the subject of a review talk by **V. Ramaswamy** (GFDL, US). **M. Schwarzkopf** (GFDL, US) discussed calculations made with the GFDL «SKYHI» model, showing the impact of known and expected changes in the stratospheric concentration of N_2O, methane, CFCs, carbon dioxide and ozone. Recent observations from UARS were used by **M. Mlynczak** (NASA/Langley Research Center, US) to calculate the radiative budget of the middle atmosphere and by **M. Lopez-Puertas** (Instituto de Astrofisica de Andalucia, Spain) to study non-LTE emission from the upper stratosphere and mesosphere.

The impact of transport processes on chemical species in the middle atmosphere was the subject of several sessions (well-attended, despite being held on a Saturday !) Constituent transport by the quasi-biennial oscillation was discussed by **K.-K. Tung** (U. of Washington, US), who documented the relationship between the tropical QBO and its manifestations at higher latitudes. **J. Austin** (Meteorological Office, UK) discussed how the QBO influences the severity of the Antarctic ozone hole. The effect of planetary waves was addressed in talks by **A. Plumb**, on polar vortex dynamics, **W. Grose** (NASA/Langley Research Center, US), on tracer correlations, and **M. Hitchman** (U. of Wisconsin, US), on longitudinal variations of transport across the tropical stratosphere. **A. Plumb** (Massachusetts Institute of Technology, US) discussed the concept of the «tropical pipe», wherein tropospheric air enters the stratosphere in the tropics and remains substantially unmixed with midlati-

tude air. In the extratropical «surf-zone», on the other hand, constituents are thoroughly mixed by planetary wave breaking.

The concept of the tropical pipe was supported by the work of **Mote** and co-workers, who showed that water vapour mixing ratios in the tropical lower stratosphere bear the imprint of the seasonal cycle in upper tropospheric temperatures. This signal persists as the tropical branch of the mean meridional circulation transports nearly unmixed air to the middle stratosphere. Transport by the mean meridional circulation was also highlighted by **M. Lopez-Puertas** (Instituto de Astrofisica de Andalucia, Spain), who showed that CO mixing ratios in the high latitude stratosphere are influenced by descent of CO-rich air from the mesosphere. These results are consistent with those of **D. Siskind** (Naval Research Laboratory, US), who presented evidence for the transport of NO-rich air from the lower thermosphere to the upper stratosphere.

Solar-Terrestrial Interaction

The last two days of the Symposium were devoted to sessions on Solar-Terrestrial Interactions and the Polar Mesosphere, respectively. **T. Huang** (NCAR, US) reviewed modelling work on the response of the middle atmosphere to solar variability. **G. Rottman** (NCAR, US) presented observations of solar UV variance made during solar cycle 22 by the Solar Stellar Irradiance Comparison Experiment (SOLSTICE) on UARS. The results indicate variations of nearly 10% at 180 nm, but less than 1% longward of 300 nm. **G. Thomas** (U. of Colorado, US) used water vapour measurements from UARS/HALOE and irradiance measurements from UARS/SOLSTICE to document an inverse relationship between Lyman-alpha intensity and water vapour abundance. **L. Callis** (NASA/Langley Research Center, US) discussed the production of NO_y by relativistic electron precipitation (using data from the Solar Anomalous and Magnetospheric Particle Explorer on UARS). He showed that this source of NO_y can be significant, even with respect to oxidation of N_2O, and that large increases in NO observed by HALOE are apparently due to electron precipitation.

Polar Mesosphere

The sessions on the Polar Mesosphere focused primarily on observations of small-scale dynamical processes, and on modelling and observational studies of noctilucent clouds, and of polar mesospheric summer echoes (PMSE). However, a detailed review of the large-scale circulation and energetics of the region was presented by **R. Portmann** (NOAA, Aeronomy Laboratory, US), who also addressed the question of climate change in the middle atmosphere induced by increases in the concentration of carbon dioxide.

E. Thrane (NDRE, Norway) discussed rocketsonde, lidar and radar observations of mesospheric dynamics. He pointed out that small-scale waves appear to play a fundamental role in the formation of noctilucent clouds and of PMSE. **G. Witt** (Sweden) reviewed current knowledge of noctilucent clouds, including nucleation and growth mechanisms, influence of gravity waves, and the possible role of particle charging in the production of PMSE. **L. Thomas** (U. of Wales, UK) discussed radar observations of PMSE and noted that lidar measurements recorded the presence of ice crystals simultaneously with PMSE. **T. Blix** (NDRE, Norway) presented rocketsonde observations that document the presence of negatively charged aerosols during occurrences of PMSE, and of positively charged aerosols in connection with a noctilucent cloud layer.

● Rolando Garcia

Middle Atmosphere : Solar-Terrestrial Interactions

MJS3, IUGG Assembly, Boulder, July 10, 1995. Convener : Lon Hood

This session was part of MASS (already reported briefly by R. Garcia) ; it consisted of 4 invited talks, approximately 14 contributed talks, and 19 poster or abstract presentations. The morning session, chaired by C. Jackman and J. Laštovička, began with an invited review of two-dimensional models of the middle atmospheric response to solar radiative flux variations. The paper was presented by **G. Brasseur** of NCAR (substituting for **T. Huang**). In a contributed paper, **G. Rottman** and **T. Woods** of NCAR/HAO summarised UARS SOLSTICE measurements of solar ultraviolet flux variations during the decline of solar cycle 22. In an invited paper, **S. Chandra** of GSFC reviewed recent observations of the effects on middle atmospheric ozone and temperature of solar UV variations occurring mainly on the solar cycle time scale. In a miss-scheduled paper, **C. A. Reddy** of GSFC described rocket measurements of the zonal wind SAO in the equatorial stratosphere. **M. Kirkland** and **B. Tinsley** of the University of Texas at Dallas discussed correlative evidence linking variations in GCR flux with tropospheric dynamics in winter as represented by the 500 mb vorticity area index. **R. Donnelly** of Solar Radiation Research in Boulder applied the 10.7 cm radio flux together with satellite measurements of the Mg II core-to-wing ratio to estimate solar UV fluxes for the 1947-1978

time period. **J. McCormack** and **L. Hood** of the University of Arizona presented a study of the solar cycle variation of upper stratospheric ozone and temperature using Nimbus 7 SBUV data, NMC data, and radiative model calculations. G. Thomas of the University of Colorado (with **L. Chen**, **J. Russell**, and **G. Rottman**) described UARS HALOE measurements of mesospheric water vapour variability in the tropics and its relationship to solar Lyman-alpha variations.

The afternoon session, chaired by L. Callis and S. Chandra, began with an invited paper by **J. D. Winningham** and **R. Link** of Southwest Research Institute in Texas on middle atmospheric effects of solar particle events observed by the UARS PEM instrument. This instrument primarily measures energetic electrons over the energy range from 5 eV to 5 MeV and protons from 1 eV to 150 MeV. In an invited paper, **J. Laštovička** of the Institute of Atmospheric Physics in Prague (with **E. S. Kazimirovsky**) reviewed the influence of geomagnetic activity and energetic electrons on the dynamics, composition, and ionisation of the upper middle atmosphere. **L. Callis** of Langley Research Center (with **R. Boughner**, **D. Baker**, **R. Mewaldt**, **J. Blake**, and **M. Natarajan**) used the relativistic electron data from SAMPEX to estimate long-term changes in middle atmospheric energy deposition. They suggested that the middle atmosphere NO_y production due to precipitation of relativistic electrons can be significant compared to the oxidation of N_2O. **M. Cordescu** of the University of Colorado (with **T. Fuller-Rowell**, **R. Roble**, and **D. Evans**) discussed the effects of medium-energy (30 keV to 2.5 MeV) particles on the mesosphere and the lower thermosphere based on the model results from the NCAR TIME-GCM. W. Swider of Hanscom Air Force Base in Massachusetts suggested that D region ionisation sets limits on NO amounts in the mesosphere. He derived NO profiles from the electron density ([e]) distribution assuming $[NO] = 20\ e^2$. **E. A. Martinez** of Ciudad University in Buenos Aires (with **S. Duhau**) presented the results of cross-correlation studies of geomagnetic activity and column ozone during the 1989 solar and geomagnetic disturbances. **W. Mende** of the Free University of Berlin suggested that the northern hemisphere temperature record has a high degree of coherency with the Gleissberg cycle (88 year period) as inferred from the Carbon 14 record.

A number of related papers were presented as posters or as published abstracts. **S. Perov** of the Central Aerological Observatory, Moscow, analysed statistically the relationship between equatorial total ozone oscillations and solar activity. **G. Petrova** and colleagues of the Polar Geophysical institute, Murmansk, modelled the ion composition in the D region during solar proton events of 1989. **D. Ponyavin** of the Institute of Physics in St. Petersburg suggested evidence for a correlation between air surface temperature variations and solar and geomagnetic activity for the period since 1775. **J. Sharber** and colleagues of Southwest Research Institute in San Antonio estimated the input of magnetospheric particle energy into the middle atmosphere using UARS PEM data. **G. Teptin** of the State University of Kazan in Russia discussed a model for the non-linear interaction in the lower ionosphere between the solar daily tidal variations and seasonal atmospheric oscillations. **E. Terez** and **G. Terez** of Simferopol State University, Ukraine, discussed evidence for 27-day and solar cycle periods in ground-based ozone records in the latitude range from 43N to 60N. **W. K. Tobiska** of JPL and colleagues presented new preliminary results on the solar cycle variability of Lyman-alpha and EUV irradiance based on a series of satellite records. **T. Valchuk** of Izmiran in Russia discussed possible connections between geomagnetic activity and climate changes. **Q. Zhang** and colleagues of Lanzhou Institute in China discussed the relation between precipitation anomalies over China and solar variability as modulated by the QBO. **G. Zhrebtsov** and colleagues of the Institute of Solar-Terrestrial Physics in Irkutsk, Russia, discussed some features of long-term variations of cosmic ray intensity and atmospheric radiation monitored at stations in eastern Siberia. **B. A. de la Morena** of the Atmospheric Sounding Station in Spain and colleagues presented experimental evidence for the influence of solar activity and geomagnetic variations on lower ionospheric radio absorption. **W. Ding-Wen** of the Institute of Atmospheric Physics in Beijing analysed statistically polar ozone data sets to investigate the possible role of the charged particle deposition in producing ozone at high latitudes. **E. Kazatkina** of the High-latitude Geophysical Lab in St. Petersburg and colleagues investigated possible evidence for a stratospheric aerosol enhancement following solar proton events. **A. Krivolutsky** of the Central Aerological Observatory, Russia, and colleagues discussed the possible influence on the ionospheric D region of the solar cycle variation of ozone. **L. Makarova** and **A. Shirochkov** of the Arctic and Antarctic research institute in St. Petersburg searched for a possible influence of the solar wind kinetic pressure on the polar middle atmosphere. **M. Miah** of the University of Arkansas and colleagues investigated spatial and temporal features of energetic particle precipitation using data from the Japanese EXOS-C satellite. **M. Shaltout** of the Institute of Astronomy and Geophysics in Cairo performed a correlation analysis between solar EUV radiation, Penticton 10.7 cm radio flux, and solar X-radiation. **A. Akchurin** of Kazan University in Russia and colleagues analysed effects of the semidiurnal tide on the formation of the sporadic E layer. **J. Krzyscin** of the Institute of Geophysics in Poland presented a statistical analysis of the quasi-decadal variation in the north polar stratospheric temperature. **J. Olivero** of Embry-Riddle University in Florida and colleagues presented a preliminary analysis of polar mesospheric clouds seen in solar occultation by POAM II.

● Lon Hood

IUGG Worshops relevant of SPARC

The Solar Cycle Variation of the Stratosphere

MJS3, IUGG Assembly, Boulder, July 11, 1995 . Convener : L. Hood

This workshop began with a discussion by J. Haigh of Imperial College, London, of a modelling study of solar variability and atmospheric change. She reported results of several experiments using a 3-D model in which solar forcing was simulated by changes in both the incoming solar radiation and stratospheric ozone concentrations. A second invited paper by M. Salby of the University of Colorado addressed statistical issues that must be considered in assessing the influence of solar variability on the middle atmosphere in the presence of the QBO. A paper by L. Hood of the University of Arizona summarised evidence for a solar cycle variation of lower stratospheric ozone and temperature using satellite measurements covering > 16 years. It was concluded that the solar cycle variation of total ozone occurs in the lower stratosphere and is forced primarily by changes in dynamical transport. K. Labitzke of the Free University of Berlin and H. van Loon reviewed correlative evidence for a 10-12 year oscillation of lower stratospheric geopotential height based on Berlin analyses of radiosonde data extending over 4 decades. (Figure 3) The observed variation is largest near 30°N and is strongest in spring, summer, and autumn. D. Rind and N. Balachandran of the Goddard Institute for Space Studies in New York presented results of numerical experiments with the GISS GCM to investigate the effect of UV variability on the stratosphere and troposphere. Finally, C. Jackman of GSFC and colleagues reviewed the status of current research into the effects of energetic particle precipitation on stratospheric odd nitrogen and ozone on the solar cycle time scale.

The workshop was well attended and was marked by discussions and numerous questions and comments from the participants.

● Lon Hood

Intercomparisons of Middle Atmospheric Models

Workshop MW5, IUGG Assembly, Boulder, July 10 1995. Conveners : Steven Pawson and Richard Rood.

The workshop included eight invited papers and about 30 posters, several of which were related to the GRIPS initiative. The invited papers reviewed progress and presented new results in the areas of dynamics, radiation transfer and chemistry of the middle atmosphere.

The workshop began with four papers about the current ability of GCMs to simulate the dynamics of the middle atmosphere. U. Langematz (FU Berlin, Germany) gave a historical overview of the modelling of sudden warmings in comprehensive models, beginning with the pioneering work in the 1970s and ending with recent results from several contemporary models. Current models are capable of simulating minor and major midwinter warmings, although in the latter stages of the modelled events the polar vortex often does not break down fully and the radiative recovery back to the wintertime state is too slow. The dynamical coupling between the troposphere and stratosphere in several GCMs was discussed by K. Kodera (MRI, Tsukuba, Japan) : the results were intriguing, in that the various models showed different «coupled» modes of variability which were related to SST anomalies in rather complex ways. K. Hamilton (GFDL, USA) addressed the current status of modelling the tropical lower stratosphere, which is dominated by the quasi-biennial oscillation. This feature is absent from current GCMs, even though a realistic spectrum of tropical waves is simulated. One reason could be the need to resolve strong vertical shears but even GCMs with increased vertical resolution seem incapable of representing the oscillation. Detailed analysis of the momentum budget suggests possible reasons for the absence of the oscillation. The role of dissipative mechanisms in the GCMs needs further study, as mechanistic-type models can support QBO-like oscillations. N. McFarlane (CCC, Canada) discussed the importance of the gravity wave drag to the middle atmospheric circulation. The non-local effects of the

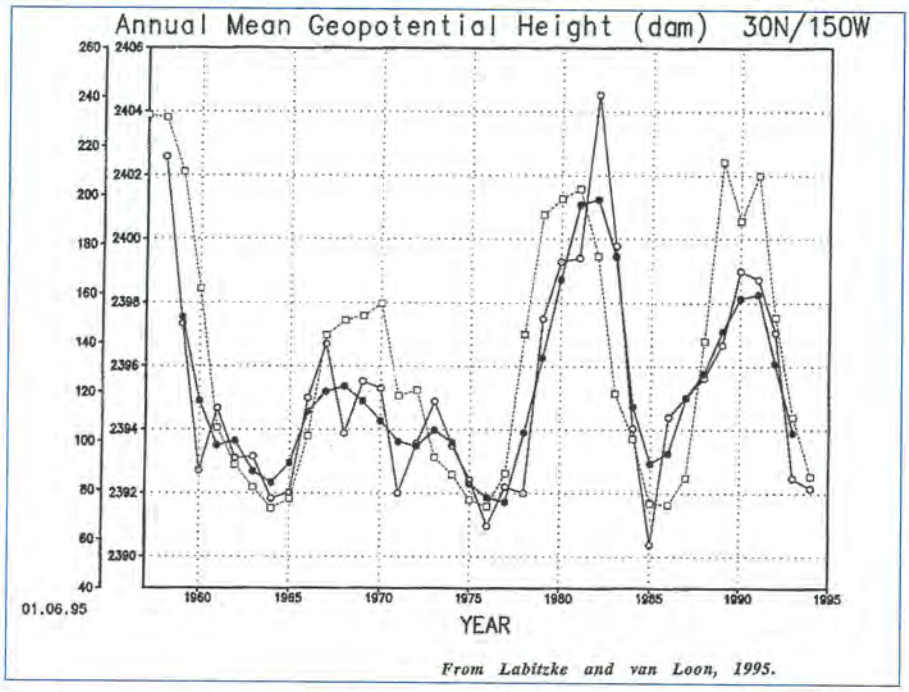

Figure 3 *- Time series of the 10.7- cm solar flux (dashed line), the annual mean 30-hPa height at 30°N, 150°W (thin line), and the three-year running mean of the 30-hPa height at this point (heavy solid line) Updated from Labitzke and van Loon, Tellus, v. 47A, p. 275, 1995 (K. Labitzke, private communication, 1995).*

drag and the problems associated with calculating the propagation of waves from their poorly-defined sources was emphasised. N. McFarlane also introduced the idea that hydraulic jumps across mountain ranges might be an important process to parameterise for surface-atmosphere interactions. While it is clear that gravity wave drag schemes have a strong positive effect on the model climate, critical tests to verify the mechanisms of the schemes do not exist.

The topic of exchange across the tropopause, which is important because of the climatological relevance of many trace gases in the lower stratosphere, was addressed by J. F. Lamarque (NCAR, USA). Since the dynamics of cross-tropopause transport cannot be captured by GCMs with limited spatial resolution, mesoscale models are often applied. Problems of exchange in both directions were discussed using state-of-the-art modelling. Topics discussed included the role of transport in the tropics and the sub-tropical barrier, the role of convection in mid-latitude stratosphere-troposphere exchange and the water vapour budget in the lower stratosphere. Stratosphere-troposphere exchange has taken on new significance because of the international assessments of the environmental impact of aircraft flying in the lower stratosphere.

Chemical and radiative effects of stratospheric trace gases were also discussed. A. Douglass (NASA GSFC, USA) discussed the current state of atmospheric chemistry models ; it was particularly clear how the use of recent satellite data has helped improve the modelling capabilities. The recent results from HALOE data that suggest that the 40 km ozone problem was solved were the subject of lively discussion that was not resolved until after the meeting. Focusing on transport-related issues, the sensitivity of chemical processes to the model's ability to represent the long-lived trace gases was discussed. For instance, the same dynamical shortcomings that lead to the «cold-pole» problem lead to inadequate wintertime descent of chlorine compounds necessary to represent polar chemistry. Furthermore, the temperature biases strongly impact the ability to simulate heterogeneous chemistry. R. Orris (GFDL, USA) presented calculations which addressed the consistency of current knowledge about middle atmospheric trace gas and temperature distributions — this is an important theme since many current GCMs use prescribed ozone distributions. This is a long-standing problem and she used several new data sets in the study. The use of a fixed dynamical heating model suggests that the middle atmospheric temperature can be modelled correctly to within +/- 5K in the middle and upper stratosphere, which is within the range of observational uncertainty. The uncertainties were slightly larger at higher levels.

The increased availability of satellite observations of middle atmospheric trace species, thermal structure, and even horizontal wind velocities has been accompanied by the development of new data analysis techniques. Data assimilation is an effective method of combining observational data sampling into numerical models, ultimately enabling more sophisticated diagnosis than by traditional methods and constraining the models to behave like the atmosphere. R. Swinbank (UKMO, UK) showed how the data assimilation has proven quite successful in providing winds to study transport and to integrate tracer measurements for chemical studies. However, significant problems remain in the representation of tropical fields where the data are not sufficient to constrain the model.

The invited papers were supplemented by the posters ; these ranged from basic descriptions of current middle atmosphere-climate models and their performance, through studies of their sensitivity as well as contributions about specific aspects of the middle atmospheric circulation, composition and chemistry. They illustrated diverse applications of current circulation models which include the middle atmosphere, as well as highlighting several improvements in recent years as well as remaining limitations of our ability to simulate the structure and composition of the middle atmosphere.

A lively discussion session ended the meeting, when several people were able to present their views and air opinions about the current state of middle atmospheric modelling.

● Steven Pawson,
Richard Rood

Gravity Wave Sources and Parameterisations

Workshop MW4. IUGG Assembly, Boulder, July 13, 1995. Convener : Dave Fritts.

This 1 1/2 day workshop during the Boulder IUGG General Assembly in July 1995 attracted approximately 40 oral and poster presentations. Much activity addressed gravity wave sources, both from observational and numerical perspectives. Modelling studies addressed convective, orographic, and shear excitation and the potential effects of such waves at greater altitudes. Observational studies examined the possible influences of various sources and their climatologies. Discussion focused on the possible viability of various sources and their contributions geographically, seasonally, and statistically. Other efforts examined the evolution of the atmospheric wave spectrum with altitude, analytically, numerically, and observationally. Discussion here concerned the importance of various wave processes and interactions in accounting for spectral evolution, wave saturation, turbulence, and diffusion.

A number of presentations also discussed gravity wave parameterisations having various emphases. Several addressed specific sources and provided comparisons with observations which were very encouraging. Others described the implementation, testing, and effects of existing schemes in large-scale models. For the most part, these showed the newer schemes to behave reasonably and to have results consistent with large-scale observations when properly tuned. Also noted, however, were areas in which present schemes remained unable to account fully for observed features of the atmospheric circulation.

Overall, workshop participants appeared pleased with the interactions and the apparent progress that was being made both in quantifying the spatial and temporal variations of the gravity wave spectrum throughout the atmosphere and in describing their effects increasingly well in large-scale models.

● Dave Fritts

The Third European Symposium on Polar Stratospheric Ozone Research

Schliersee, Bavaria, 18-22 September 1995.

The Symposium had two objectives. The first was a review of recent European research activities ; the second was to look forward by considering new directions in stratospheric research. More than 300 participants were involved in a stimulating week of discussion. DGXII of the European Com-mission and BMBF, who supported the meeting, are to be thanked.

A major component of the meeting was a discussion of the results of the SESAME (Second European Stratospheric Arctic and Mid-latitude Experiment) campaign. Eleven invited speakers covered topics ranging from a review of the stratospheric meteorology of recent Arctic winters, through measurement and interpretation related to O_3, NO_y and ClO_y species, to measurements of UV-B and laboratory studies.

One day was devoted to a session on «New Directions in Stratospheric Research». Again the format involved four invited speakers and a wide-ranging discussion session.

The names of the speakers at the symposium are : **B. Naujokat** (review of meteorology), **A. Engel** (tracer measurements in SESAME), **B. Stein** (ground-based measurements of PSCs and aerosols), **A. Adriani** (aerosols), **F. Arnold** (NO_y/NO_x measurements), **D. Toohey** (ClO_y measurements), **F. Lefevre** (NO_y/ClO_y modelling), **C. Zerefos** (total ozone), **G. Vaughan** (review of ozone measurements), **M. Chipperfield** (modelling of ozone), **B. Gardiner** (SESAME), **A. Bais** (UV-B intercomparisons), **R. A. Cox** (homogeneous chemistry), **M. Rossi** (heterogeneous chemistry), **T. Peter** (microphysics), **G. Mégie** (satellite research in atmospheric chemistry), **P. Simon** (measurements related to global change), **P. Woods** (new developments in instrumentation), **J. Pyle** (given by **N. Harris** due to absence) (new platforms for atmospheric research).

The poster sessions were a particularly important part of the meeting with more than 200 posters on display. Results from these sessions fed into a half-day open discussion on SESAME. A lot of exciting new work was presented ; here we highlight in particular three areas. The 1994/95 winter, when most of the SESAME activities took place, was very cold. As a consequence, polar stratospheric clouds were widespread and many different measurements of PSC properties were made. These provide insight into the formation of PSCs and their role in perturbing stratospheric chemistry. A number of measurements show that the vortex was denitrified : further analysis will increase our understanding of the poorly known processes by which denitrification occurs in the Arctic vortex. Last, great progress has been made in quantifying the chemical ozone loss which occurs in the Arctic vortex. Observations and models have been used to look at changes in both the column amount and in the vertical distribution of ozone. Extended abstracts (4-6 pages) of the posters are to be published in the EC Air Pollution Research Report series by DGXII.

For further information, contact Dr. G. Amanatidis, European Commission DG XII/D-1, fax : +32 2 296 30 24, or Dr. J. Pyle, European Ozone Research Coordinating Unit, fax : +44 1223 467390.

● Neil Harris

A new approach to atmospheric profiling and global change monitoring using GPS/GLONASS radio occultation technique

A good knowledge of the temperature field and its evolution in the upper troposphere-lower stratosphere (UT-LS) is needed to understand the causes of its natural variability and to estimate the anthropogenic perturbations (see in this context the efforts of the STTA/SPARC Initiative). Numerical Weather Prediction (NWP) models are also sensitive of the assimilated data in the UT-LS. Present techniques to measure the temperature field (radiosonde stations and satellite nadir-viewing radiometric sensors) suffer from limitations in terms of geographic coverage, vertical resolution and/or absolute calibration. The recent development of the Global Navigation Satellite Systems (GNSS) allows to define a new technique for atmospheric temperature profiling. GNSS consists of the U.S. Global Positioning System (GPS) of 24 satellites and the similar Russian navigation system (GLONASS).

Method

The principle of the method is to monitor phase changes in radio signals from a GNSS satellite (GHz band), when the observing low-Earth orbiting (LEO) satellite is occulted by the atmosphere. Phase changes are converted into bending angles in the atmosphere and the

latter are converted into vertical profiles of the refractivity index. The vertical resolution of the profile is limited to about 1 km by the diffraction of the radio wave by the atmosphere. The refractivity index contains information about temperature, pressure and water vapour content in the neutral atmosphere as well as electron density in the ionosphere. The ionospheric contribution is determined using two GNSS frequencies with different refractivity indices in the ionosphere ; the remaining term is due to the neutral atmosphere. Above the tropopause the water content is very low and the index of refraction is directly proportional to the neutral density. The temperature profile is deduced from the density profile assuming the hydrostatic equilibrium. This method works also in the upper troposphere where the water vapour contribution remains low. In the lower troposphere, the water vapour term is no longer negligible, and radio occultation data can be used to infer the water vapour content; in this case the dry atmospheric term has to be estimated by using an independent estimation of atmospheric density from meteorological data.

Some applications

Temperature data obtained with the GNSS radio-occultation technique have a great potential for climatology studies in the UT-LS. They have several advantages compared to other techniques :

- they are self-calibrated because the basic measurement is measurement of time which can be made with a very high accuracy ; as a consequence, the lifetime of each GNSS satellite is not a limitation, and it is possible to compare two data sets separated by many years,
- they have a global and evenly distributed coverage and high vertical resolution.

Operational Numerical Weather Prediction models now have reached a stage when major improvements in the output will be due mostly to the assimilation of more advanced observations of the key parameters of the atmosphere. On the other side, one single LEO satellite tracking both GPS and GLONASS satellites would provide around 1000 high vertical resolution temperature profiles evenly distributed over the world for a 24 hour period. It would complement and enhance the present set of radiosonde observations and would have a significant impact in the accuracy of the output of NWP models.

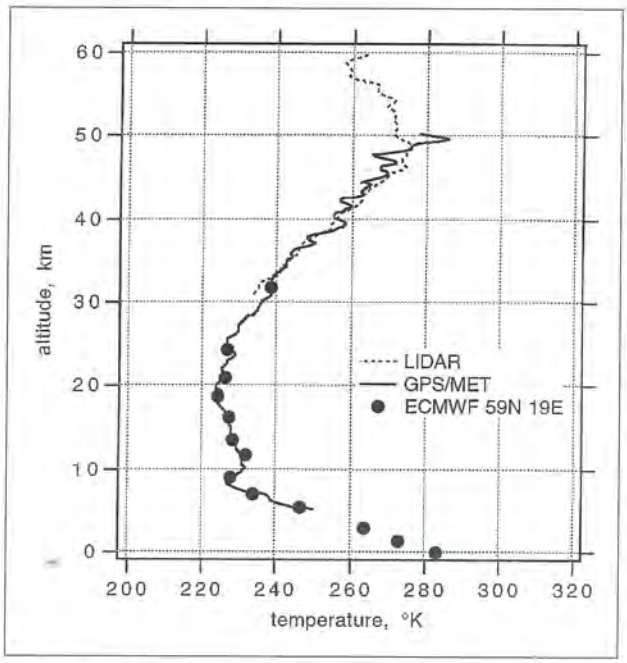

Figure 4 *- GPS/MET temperature profile obtained on July 1st, 1995 (full line) compared with profiles from the ECMWF analysis (large dots) and a nearby French Rayleigh lidar based at Juliusruh, Northern Germany (55°N, 13°E) (From B. Belloul, CNRS, France ; Private communication).*

Proof of concept

Atmospheric radio occultation observations using a GPS receiver in low earth orbit has been tested in a proof-of-concept experiment with the launch, by NASA, of the University Corporation for Atmospheric Research (UCAR) GPS-MET experiment in April 1995. This experiment had limited capacities in terms of global coverage, tracking performances and lifetime. Nevertheless it demonstrated the potential of the technique for sounding the structure of the atmosphere with high accuracy and vertical resolution. In a preliminary statistical validation exercise, 100 retrieved profiles have been compared to radiosonde data and atmospheric analyses from the ECMWF (Kurzinski et al., 1995). In the Northern Hemisphere, the GPS occultation temperature profiles between 5 and 30 km are in agreement with ECMWF to better than 1K in the mean, with a standard deviation of 1-2K, which confirms the theoretical predictions. The Figure 4 shows a comparison between a retrieved GPS temperature profile, the ECMWF analysis from 5 to 30 km, and the profile obtained by a near-by ground-based Rayleigh lidar from 30 to 50 km. The tropopause structure is very well defined in the GPS profile and a fairly satisfactory agreement with the lidar profile is obtained up to about 45 km.

Perspectives

Theoretical studies as well as the first proof of concept GPS-MET experiment have demonstrated that accurate atmospheric temperature profiles from the mid-troposphere through the lower stratosphere can be retrieved from GNSS radio occultations. With a potential of 500 to 1000 occultations per day per orbiting receiver, the GNSS technique provides a unique combination of well distributed global coverage, high vertical resolution and insensitivity to clouds. Moreover, due to the small weight of the receiver (less than 10 kg), it can be put either on a dedicated microsatellite or as an additional equipment on board of a larger satellite at a relatively low cost. Several projects for an operational radio occultation experiment are under study in Space Agencies (NASA, ESA and CNES). Some of them are likely to fly during the next decade. They should make a major contribution to global change and weather prediction programs.

Reference

E.R. Kurzinski et al., Initial results of radio occultation observations of the Earth's atmosphere using GPS, (submitted to Science, 1995).

● Alain Hauchecorne