

Report on the WCRP/JSC Meeting

Kiel, Germany, 15-20 March 1999

Marie-Lise Chanin and Marvin Geller (SPARC Co-Chairs)

The twentieth session of the Joint Scientific Committee (JSC) for the World Climate Research Programme (WCRP) was held in Kiel, Germany from 15-20 March 1999. Marvin Geller and Marie-Lise Chanin, co-chairs of the SPARC Scientific Steering Group (SSG) were invited to attend the meeting and to report on SPARC developments since March 1998.

The presentation of SPARC activities, as described in the Implementation Plan and summarised in the precedent SPARC Newsletter, was made by both Co-chairs and received wide support. Special attention was given during this session to the subject of solar forcing of climate which, even though the idea that changes in the Sun may affect the weather and climate on Earth has been considered for a very long time, is still a subject of strong controversy. At the 1998 JSC meeting, SPARC was given the responsibility to review the status of research on the subject and Marvin Geller was invited to present a critical review of its state. He pointed out some of the extreme positions recently put forward by newspapers, since they represent a real risk if the public confidence on scientists' objectivity in the subject of climate research is

being questioned so drastically. He presented the two main scientific approaches which are being followed to elucidate some suggested physical mechanisms to account for the apparent solar effects which have been shown by recent statistical studies. One interpretation by Svensmark and Friis-Christensen (1997) is based on the influence of solar modulations of cosmic rays and cloudiness based on a few years of ISCCP data sets. The other one is based on the impact of solar UV changes on ozone concentrations and their impact on the atmospheric circulation, as it has been demonstrated by two recent models (D. Shindell *et al.*, 1999, and J. Haigh, 1999). Marvin Geller raised further the question of the interplay between the solar induced changes and dynamical linkages between the stratosphere and the troposphere, through oscillations such as the QBO and AO. After quite active discussions, it was decided: 1) to ask GEWEX to assess the validity of analysis of ISCCP data in showing the linkage between cloud amounts and solar activity, 2) to ask SPARC, through its modelling project GRIPS, to encourage more modelling groups to run their models with identical changes in solar forcing and ozone changes in order to

be able to validate the above mentioned results, 3) to investigate further the eventual relationship between past climate changes and solar activity. The results of those three different activities will be presented at the next JSC in order to decide whether or not a co-ordinated WCRP activity is required in this area. In the meantime and jointly with SCOSTEP, SPARC will encourage both the identification of solar signals in the data and the runs of a larger number of models with ozone changes induced by solar forcing. A proposal has already been put forward to the European Commission with this view in mind.

A major issue raised during the JSC meeting was the requirement for WCRP to develop a closer co-operation with IGBP. The already existing co-operation of SPARC with IGAC was recognised and further encouraged and the preparation of a joint assessment of tropospheric chemistry and its relation to climate change was discussed. Susan Solomon has been charged to lead this activity which should involve some key people within SPARC.

SPARC, as all the other WCRP projects, was again encouraged to contribute to the GCOS



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initiative in preparing guidelines on the development of national plans on climate observations.

The membership of the SPARC SSG was discussed and the extension of the terms of appointment of the Co-chairs and three members, K. Hamilton, V. Khattatov and T. Shepherd, which were due to expire on 31 December 1998, was proposed and accepted. They were extended until the end of 2000. Two new members were named to replace D. Hofmann and H. Tanaka:

P. McCormick from Hampton University and S. Yoden from University of Tokyo. We welcome them to the SPARC SSG.

References

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The 1999 GRIPS Workshop

Reading, UK, 22-25 March 1999

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The fourth GRIPS workshop was held from March 22-25 at the Centre for Global Atmospheric Modelling, University of Reading, UK. Staff members, particularly Anne Pinnock, organised excellent facilities and accommodation.

The workshop had three main objectives: to review progress since the 1998 workshop, to plan the future, with attention to the needs of SPARC, and to discuss recent activities of the modelling groups. There were three special themes, each with overview presentation: transport (T. Hall), the relationship between ozone and climate (P. Forster), and solar variability effects on the atmosphere (J. Haigh). An afternoon was set aside for working groups which reported back to the entire meeting: (1) A group exploring European funding (led by J. Austin); (2) Participants in the "Mesospheric Drag" experiments (S. Beagley); (3) Transport evaluations (T. Hall); (4) Solar forcing (K. Kodera).

March 22, Rapporteur: A. Gregory

After introductions by the convenors (W. Lahoz, CGAM, Univ. of Reading, and S. Pawson, USRA/NASA DAO), A. O'Neill (CGAM) and T. Shepherd (Univ. of Toronto), gave opinions about GRIPS. A. O'Neill noted recent interest in the middle atmosphere amongst modelling groups such as ECMWF and the UKMO-Hadley Centre. He discussed the roles the middle atmosphere can play in short-term and seasonal forecasting, in forcing patterns of climate change, and in atmospheric chemistry. He also thought that GRIPS should go beyond model intercomparisons, taking an approach based on identifying the key scientific issues and trying to understand

the chemical and dynamical processes. T. Shepherd argued that efforts should be made to develop confidence in the models and that GRIPS should tackle problems relevant to the next ozone and IPCC climate-change assessments. To obtain better confidence in models, he pointed out the need for more analysis of models abilities to satisfy "first principles" (such as conservation of momentum). He asked whether the performance of models is converging and whether there are clear physical explanations for their strengths and weaknesses. He also emphasised the importance of using the models to address questions being examined by other SPARC working groups (such as trends, or the UT-LS ozone budget).

J. Haigh (Imperial College) investigated the climate response to the 11-year solar cycle. The modelled circulation at solar minimum was compared to that with increased solar UV irradiance (representing solar maximum), with and without changes of the prescribed stratospheric ozone. In all cases at solar maximum the stratosphere was warmer and the troposphere showed bands of warming and cooling associated with a weaker, broader Hadley circulation and a poleward shift of the subtropical jets, particularly in the summer hemisphere. The results, including correlations of solar activity with 30hPa heights, were realistic. It was concluded that further experiments and better observations are needed to further assess the importance of the solar variability on the climate system.

Four presentations examined tracer transport. T. Hall (NASA GISS) summarised the results of the M&M2 intercomparison of tracer transport, describing two experiments: an SF₆ type "age-of-air" simulation and "tape recorder" (CH₄+2H₂O) study. Most

models underestimate the mean age compared with observations and many have unrealistic features in their mean-age isopleth shape. Most models overestimate the tape recorder phase speed. These inaccuracies are a major source of uncertainty for trace gas simulations. W. Norton (Univ. of Oxford) showed similar results from the European TOPOZII project; he showed that isentropic models generally have better tape-recorder propagation speeds but have an old mean age. L. Coy (GSC/NASA GSFC) presented results of the GMI comparison of the stratosphere in three meteorological input fields (two GCM's: NCAR CCM2 and GISS2, and the DAO GEOS assimilations). The quantities evaluated included lower stratospheric temperatures and the distributions of N₂O, CO₂ and H₂O+2CH₄ from a CTM. A novel feature was the grading of the data sets, based on several criteria. The NCAR CCM2 was rated best overall, so it will be used for an extended integration with full chemistry. M. Schlesinger (UIUC) proposed a new GRIPS intercomparison, whereby various model winds would be used to simulate the CH₄ distribution using the UIUC 3D ACTM. He gave examples of how his research group has used the ACTM in parallel with their GCM. The approach he suggested would allow the evaluation of the stratospheric circulation in the GRIPS models.

R. Rood (NASA DAO) described the joint development at NASA and NCAR of a new GCM with a next-generation dynamical core. A 5-year simulation shows favourable results and the first forecasts look promising, with sharp fronts and self-spawning hurricanes. There are also assuringly small differences between simulations at 2- and 1-degree resolution. The new dynamical core is a viable candidate for the CCM4.

March 23,

Rapporteur: R. Bannister

S. Beagley (York Univ.) summarised progress in the mesospheric drag project, in which a specified force/unit mass is imposed in the mesosphere. The four models which have done the proposed runs show very different mesospheric responses (some models show a wind reversal, others do not). It is important to isolate the reasons for this and to determine whether the experiment needs re-formulating. The issues were deferred to the discussion groups.

P. Forster (Univ. of Reading) gave an overview of the ozone-climate issue, with discussion on other greenhouse gases and aerosols. He raised questions associated with the recent observed cooling of the lower stratosphere: (1) Are the observations robust? (2) Is the ozone change known? (3) Is it anthropogenic? (4) Is the model response to these changes correct? (5) Could anything else have contributed to stratospheric cooling? There is strong evidence of an ozone decrease, but its magnitude is uncertain, especially in the tropics (points 1 and 2); other factors are known to impact LS temperatures (point 5). Experiments using a GCM of intermediate complexity reveal that (a) CO₂ increases warm the troposphere, (b) ozone depletion causes cooling in the 100–10hPa layer in the polar regions and (c) the thermal response to water vapour increase resembles that of ozone decrease. He concluded that there is strong evidence that the observed ozone decreases cause LS cooling, but that other factors can have an impact.

D. Fairlie (NASA LaRC) presented results from an improved coupled climate-chemistry model. A more accurate vertical advection scheme has led to more realistic water vapour distributions. The surface area densities of sulphate aerosols are now included, which enables volcanic aerosol perturbations to be studied. Total ozone abundancies show that the model can well simulate tropical ozone, the springtime ozone hole and its recovery. Volcanic aerosols warm the LS and enhance the concentrations of NO_x and nitric acid, leading to LS ozone loss, in broad agreement with observations.

J. Austin (UKMO) gave some plans for a Framework V application, a collaboration between UKMO and CGAM (UK), CNRS/SA and LMD (France), the Free Univ. of Berlin (FUB, Germany) and the Finnish Met. Inst. A combination of data analysis and model studies was planned, with estimates of observed trends being supplemented by model simulations with realistic trace gas perturbations. In accord with the aims of GRIPS, this would ask whether the models can successfully replicate the observed changes over the past two decades and address the confidence of predictions of future change.

March 24,

Rapporteur: S. Rosier and V. West

T. Hall summarised the discussions of the "transport" working group. Two different approaches were adopted. First, simulations of SF₆ (a "mean-age" tracer) will be made using a simple specified surface source and passive advection in integrations of at least 10 years (which are needed to determine the mean age of air). T. Hall will write specifications for this experiment. The second experiment would follow the UIUC proposal using simulated winds to drive an off-line CTM which transports CH₄. Eugene Rozanov, who showed two posters about the CTM, would co-ordinate the experiment from UIUC. The initial plan is to recycle one year of GCM output for multi-year CTM runs. These two transport experiments should offer contrasting views of the problem, each approach having advantages and disadvantages.

The existing GRIPS comparison exercises were presented. S. Pawson updated on the model documentation and the intercomparison. Most groups have provided AMIP-style documentation, as requested at the 1998 workshop. The GISS group have now joined GRIPS, but the UGAMP model has been withdrawn since CGAM are now collaborating on the UKMO Unified Model. Several groups have replaced their data with longer integrations. The UIUC and new NASA/NCAR models plan to join in. A paper documenting the initial (monthly mean) model intercomparison is now submitted to the BAMS. It shows that while most models can simulate the major climatic features there are some deficiencies, such as the differing skill at simulating the quasi-stationary wave fields. These limitations might impact our ability to accurately predict future climate changes.

T. Shepherd showed results from J. Koshyk, who has completed an assessment of the kinetic energy spectra (as a function of spatial wavenumber). The spectrum shows a -5/3 slope in the mesosphere, where there is strong divergent component to the kinetic energy field, consistent with a resolved spectrum of inertio-gravity waves. The spectral amplitudes and growth rates of the spectrum differ considerably between models; this is thought to arise from the horizontal diffusion schemes. The results from four models have been submitted to the JGR.

M. Amodei (CNRM) examined tropical waves in four European models and UKMO assimilations. All models show Kelvin waves, with possibly too much activity in the upper stratosphere. No model simulated a QBO and the SAO strengths differed considerably. It is apparent that models with a parameterisation of convectively forced gravity waves tend to produce a SAO where both phases propagate downwards, whereas in reality only the westerly phase

of the SAO is wave forced. M. Giorgetta (MPI Hamburg) compared results from an 88-level version of the ECHAM4 model to the standard 39-level model (with an upper boundary in the mesosphere). Increasing vertical resolution led to some westerly winds near 30hPa, but the model still did not simulate a QBO. Additionally, the ascent rate of water vapour in the tropical lower stratosphere was more realistic (slower) with higher vertical resolution. A. Untch (ECMWF) also addressed tropical oscillations; at the 1998 workshop she showed that the free-running version of the ECMWF model sometimes produced a QBO-like oscillation. Notably, with 50 levels a QBO was only obtained with a semi-Lagrangian advection scheme and not with an Eulerian scheme. This year she showed that with 72 levels there were more similarities between the two advection schemes. Generally, increasing the vertical resolution leads to a more robust QBO-like oscillation in the model, but it remains weaker than that observed. Neither T. Horinouchi nor J. Wilson, who are co-ordinating a comprehensive comparison of tropical waves and their excitation mechanisms, could attend the workshop; it was noted that they have defined a data set needed for a comprehensive intercomparison of tropical wave spectra.

W. Lahoz (CGAM) examined sudden warmings in four models. In reality, several winters without major mid-winter warmings were followed in 1998/1999 by a winter with two: in December and in February. The FUB model simulates too many warmings, the CNRM model has too many early winter warmings, and two versions of the UKMO model behaved reasonably, despite a reduction from 10K to 5K of a cold-pole bias between the two versions. He also showed the first results of the PRO-VOST project, in which an ensemble of seasonal prediction experiments has been performed. A 58-level version of the Unified Model has been integrated for nine realisations of four months for 19 northern winters. Preliminary results suggest that this is a good way of producing robust statistics about the variability of the model.

K. Kodera (MRI) reported on statistical troposphere-stratosphere connections. The background is an attempt to account for impacts of stratospheric variability on the troposphere, especially in the context of global warming. The issue has become topical because of current interest in the "Arctic Oscillation" and its possible importance to climate change. It was felt that the emphasis of the project should change in the light of the topical nature of the Arctic Oscillation. The major conclusion is that ten years of data, as provided by most models, is insufficient to obtain a robust signal in the troposphere-stratosphere connection.

Y. Kuroda (MRI) compared the downward-propagating mode in the Antarctic stratosphere. In observations he showed a strong anomaly in September-October-November from year to year related to the timing of the vortex breakdown. This mode is not present in the MRI model, it has an overly short lifetime in the FUB and SKYHI models, and was too weak in the MPI and CNRM models. G. Roff (BMRC) also reported on the Southern hemisphere polar vortex. He used "elliptical" diagnostics to characterise the evolution of the new BMRC middle atmosphere-climate model, showing that this technique provides a concise way of describing the polar vortex and its evolution. He proposed this technique to be used to characterise the vortices in all GRIPS models.

K. Shibata (MRI) showed that changing physical processes in the JMA model can lead to a PNA-like response. The pattern appeared when the Kuo and Arakawa-Schubert convection schemes were interchanged and when the horizontal diffusion scheme was changed. The latter change also led to a response in the stratospheric vortex.

U. Langematz (FUB) reported on the radiation intercomparison. The input data sets have now been compiled. The most troublesome field was water vapour, for which a combination of tropospheric data from the NCEP/NCAR reanalyses has been combined with HALOE stratospheric data. Limited results available from the MRI and FUB radiation schemes showed differences in the solar heating rates near the stratopause. The longwave cooling rates also showed differences especially pronounced when isothermal (240K) temperature profiles were used.

W. Lahoz reported on the interactions with AMIP-2. A 58-level version of the UKMO Unified Model shows some biases, many of which (such as a tropospheric cold bias) also appeared in a low-top 30-level model version. He summarised some preliminary results from AMIP; so far three models have

seasonal runs with different upper boundary heights. The tropospheric climatology is sensitive to the upper boundary height, but the results could be model dependent; other GRIPS models ought to be examined.

In a further presentation, W. Lahoz showed results of some predictability studies. The main issues were whether an accurate representation of the stratosphere is necessary for climate modelling and whether changes in the stratosphere impact the tropospheric climate. There was some evidence that the seasonal forecast skill was improved when the stratosphere was included and that there is likely a benefit resolving the stratosphere in climate models.

J. Austin reported on his working group. The planned work could be used in an application to the European Union. The observational data sets are probably adequate for their purposes. The model experiments would need greenhouse gases (IPCC scenarios), CFCs (possibly from WMO assessments) and sea surface temperatures and sea-ice data. A number of quantities will be evaluated, including meteorological fields and forcing terms.

March 25, Rapporteur: V. West

S. Beagley reported on the Mesospheric Drag working group. He outlined four possible experiments. The first is a continuation/revision of the original plan, designed to examine the residual circulation and downward control of imposed and model-resolved drag. All models will be run for JJA for a "no-drag" and a "specified-drag" scenario; a 2-year ensemble should be sufficient. The other three experiments outlined for the future are: to repeat the first experiment for the NH winter (DJF), when a 5-year ensemble may be needed to account for the larger inter-annual variability; to compare the GW drag schemes off-line using an observed wind data set; to investigate the effects of the same GW drag scheme in different models.

K. Kodera reported on the solar-forcing working group. Two 10-year model runs will be carried out, for solar minimum and maximum conditions, using the same spectral irradiance and ozone distributions. The analysis will first focus on the stratospheric impacts. K. Kodera agreed to coordinate the experiment design, but it is unclear who will perform the analysis. He will also examine the robustness of the proposed perturbation data sets.

T. Shepherd spoke about defining a framework for future climate experiments which could be carried out by all interested groups. These experiments are aimed at interpreting recent temperature changes or determining how much of the stratospheric cooling is due to radiation. The plan was to divide the experiments into three groups; first, looking at recent ozone change by imposing the observed change in radiative gases; second, predicting the future ozone changes; finally, looking at the effect of the stratosphere on tropospheric climate. For the first two cases, the advantages and disadvantages of transient runs from 1975 to 2000 or equilibrium runs in the 1970s and 1990s were discussed. For the third section discussion involved whether or not we should attempt to do runs of the GRIPS models with high and low "lids" to see the effect on the tropospheric climate of including a high resolution model stratosphere. T. Shepherd will formulate and circulate a more formal framework to all groups.

The meeting ended very positively, with a feeling that much had been discussed. It was agreed to hold the next annual GRIPS workshop in Toronto in the week beginning 13 March 2000.

Brewer-Dobson Workshop

Oxford, UK, 13-15 December 1999

The workshop will be to mark 50 years since Brewer's 1949 paper on water vapour and 70 years since Dobson's 1929 paper on ozone. It will examine our current understanding of the Brewer-Dobson circulation, including: ♦ the dynamics of how it is driven, ♦ its effect on tracers (e.g. water vapour, ozone) and chemistry, ♦ how accurately we can model it with GCMs, ♦ and future changes in the Brewer Dobson circulation from changing levels of greenhouse gases and ozone.

The organising committee is W. Norton (Oxford, UK), A. Plumb (MIT, USA), A. O'Neill (Reading, UK). Around 40 participants will be invited.

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Plan for the SPARC Water Vapour ASsessment (WAVAS)

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Introduction

Water vapour plays a fundamental role for chemistry, dynamics and the radiation budget of the atmosphere. Water vapour in conjunction with UV-B photolysis of ozone is the precursor for the hydroxyl radical which controls the oxidative capacity of the atmosphere. Transport and release of latent heat provides a major contribution to the energy budget of the global and regional atmosphere.

The importance of water vapour reaches through all atmospheric regions: troposphere, stratosphere and mesosphere. Yet the distribution of water vapour, its climatology and the short and long-term variability of its concentration in the Upper Troposphere (UT) and stratosphere are not well enough known, particularly in the altitude region just below and above the tropopause. To single out climate change: Harries (1997) presented evidence from sensitivity studies that the concentration of humidity in the UT may need to be known with an accuracy in the range of 3-10% in order to keep calculated radiative balance uncertainties on the same order as the radiative effect of doubling the CO₂ concentration.

Considering the fundamental role of water vapour in climate and the scarcity of information concerning its evolution, the SPARC SSG decided at its last meeting in Nagoya, Japan, to undertake an assessment of our knowledge on water vapour in the UT-LS region. This note provides some arguments in the context of climate studies as to why UT-LS water vapour was chosen for an assessment and gives an outline of the planned assessment.

Water Vapour and Climate

Water vapour is the strongest contributor to the atmospheric greenhouse effect even more so than carbon dioxide. Contrary to CO₂, which contributes to the anthropogenic forcing of the greenhouse effect, the action of water vapour is considered as a feedback rather than a forcing. The simple reason for this is the fact that, in a static system, thermodynamic arguments dictate that a temperature increase of a water body causes an increase of the water vapour partial pressure above that body. The Clausius-Clapeyron equation gives the exact value for the

increase of water vapour partial pressure per degree of temperature change. However, the earth-atmosphere system is not static and it is by no means clear if evaporation to the air above a water body is governed by thermodynamics or by dynamics. Manabe and Wetherald (1967), using a radiative-convective climate model showed that the sensitivity of their modelled climate to perturbations of greenhouse gases was increased if the water vapour was allowed to change according to a constant relative humidity. This assumption, borne out by the bulk of the then available observations in the lower troposphere (LT), provides a strong positive feedback because of the exponential increase of the absolute humidity with increasing sea surface temperature (SST). The results from complex GCMs are generally consistent with Manabe's assumption, leading to similarly large positive feedbacks.

Ellsaesser (1984) argued that an increase of convection in the tropics causes an increase of the strength of the Hadley Cell circulation and a clear air return circulation which would cause a drying of the atmosphere.

Lindzen (1990) asserted that increased convection in a warmer climate will lead to a drying rather than a moistening of the UT. Lindzen's cumulus drying hypothesis is equivalent to a strong negative feedback by water vapour in the enhancement of the greenhouse effect caused by increasing CO₂.

Del Genio *et al.* (1991) simulated the effect of a warmer climate on atmospheric humidity using two versions of a climate model, one of which included a GCM with a cumulus convection that was constrained by mass flux balance between convective scale and large scale motions using the method of Arakawa and Schubert (1974). Simulations of runs in which the global mean SST was increased and decreased, respectively, by 2K showed only marginal differences of specific humidity and relative humidity between both model runs. The comparison of model runs (2K warmer-2K cooler) revealed a peak increase of the fractional specific humidity ($\Delta q/q$) of 80%, at 200hPa and a 30% increase near the surface. So, the absolute change was greatest near the surface but the largest relative change occurred at 200hPa. There was also a slight positive change of relative humidity

with values increasing from zero near the surface to 6% at 200hPa. It should be noted that, with regard to an experimental verification of changes of UT specific and relative humidity, it seems more promising to compare observed seasonal changes of UT humidity to those of seasonal model predictions. Apart from such questions, there are also uncertainties in the spectroscopy of water vapour and, consequently, in the interaction of water vapour with the radiation field which manifests itself in a preponderance of UT versus LT water vapour and vice versa.

Shine and Sinha (1991) considered the relative importance of the different spectral regions in the water vapour absorption spectrum on the radiative balance. They pointed out that the continuum absorption at wave numbers between 800 and 1200cm⁻¹ is most important for water vapour residing in the LT around 800hPa and that the far infrared spectrum at wave numbers <600cm⁻¹ is important for water vapour residing near 500hPa. They argued that, contrary to Lindzen's results, perturbations of water vapour in the LT would indeed exhibit a substantial influence on climate. Their line of reasoning did not consider the fact that an optically thick atmosphere in the continuum absorption spectral band stays optically thick when the total amount of water in a vertical column increases but that, as far as absorption at higher altitudes in the rotational bands of water vapour is concerned, an increase or decrease in the water content of the column would nevertheless have an effect on the radiative balance.

Such considerations were reinforced by Clough *et al.*, (1992) who presented line-by-line calculations of the water vapour absorption line strengths in the far infrared. Harries (1996) reviewed the complete absorption spectrum of the water vapour molecule and concluded that the UT humidity controls cooling to space via the strong rotational bands below 600cm⁻¹. He pointed out (1997) that, because the effects of water vapour on the radiative balance of the earth are very large, small errors in the spectroscopic parameters and in the radiative-dynamical models that are used to model the energy balance of the atmosphere produce potentially large uncertainties in the prediction of climatic change.

The various IPCC reports (1990, 1992, 1995) have been slow to acknowledge these and other difficulties that arise from the uncertainties that surround the quantification of the water vapour feedback (see the citations in the insert below). Taking into account Lindzen's arguments, even the sign of the water vapour feedback is not known. There are plenty of spectroscopic questions which add to the basic uncertainty of quantifying the feedback. One cannot be sure if the Manabe and Wetherald assertion of nearly constant humidity for the current atmosphere is correct. The fact that 3D climate models have produced refined answers to this elementary question does not help because there is still a dearth of data on water vapour concentration and relative humidity in the UT and LS. It seems fair to say that the UT-LS water vapour results from 3D models have not yet been objectively validated against observations in the UT; that is, it is not known if model results on UT water vapour and observational data agree or disagree within the total uncertainty of the combined model and observational data sets.

Citation from IPCC 1991. The IPCC Scientific Assessment. Report prepared by the working group 1. Chapter 3.2.2: "...The best understood feedback mechanism is water vapour feedback, and this is intuitively easy to understand".

Citation from IPCC 1993. The Supplementary Report to the IPCC Assessment Report prepared for IPCC by working group 1. Chapter 3.3.2: "...There is no compelling evidence that water vapour feedback is anything other than the positive feedback it has generally been considered, although there may be difficulties with the treatment of upper level water vapour in current models.

Citation from IPCC 1995. The Science of Climate Change. Contribution of working group 1 to the second assessment report of the Intergovernmental Panel on Climate Change. Chapter D.2: "...An increase in the temperature of the atmosphere increases its water holding capacity and is expected to be accompanied by an increase in the amount of water vapour. Since water vapour is a powerful greenhouse gas, the increased water vapour would in turn lead to a further enhancement of the greenhouse effect (a positive feedback). About half of this feedback depends on water vapour in the upper troposphere, whose origin and response to surface temperature increase is not well understood. Feedback by water vapour in the lower troposphere is unquestionably positive and the preponderance of evidence points to the same conclusion for upper tropospheric water vapour. Feedbacks resulting from changes in the decrease of temperature with height can partially compensate the water vapour feedback.

On the other hand, the uncertainties in the various observational data sets (in-situ operational, in-situ research, operational and research satellite) and those of 3D modelled water vapour fields and seasonal changes have not been assessed individually. Currently therefore, a coherent picture of the global UT-LS water vapour distribution does not exist with sufficient accuracy to quantify the water vapour feedback relative to the effects on the radiative forcing from a doubling of CO₂. As far as the observational data base is concerned, it is certainly difficult to analyse the data for the presence and establishment of trends of relative or specific humidity or to use these data sets for 3D model validation because the data quality of combined observational data sets has not been assessed. However, shorter-term observational data might exist which could allow discrimination between positive (Manabe and Wetherald) and negative (Lindzen) feedback. In this regard, we note that in the global mean, there is a large seasonal swing (>5K) of SST and that, consequently, the effects of the oscillatory temperature change on the horizontal and vertical water vapour distribution should be measurable over the course of a single season. This is perhaps difficult to achieve in the LT because of the extreme variability of water vapour which is partly due to the non-conservative nature of water. However, in the UT, the variability is much damped and, furthermore, there are large regions of clear air in which the non-conservative nature of water vapour would not matter very much.

Toward this end, Ramanathan and Inamdar (1999) have used a tropical set of surface, satellite and in-situ radiosonde data to show, for the zone between 10°S and 10°N that: a) the middle troposphere responds to increased convection by moistening; b) the Hadley cell response to the equatorial convection causes drying in the subtropics, which partially compensates for the moistening in the tropics; and c) on the tropical scale, including the subtropics, there is a net moistening effect. This is a valuable study but it must be stressed that the extratropics and the combination of sub- and extratropics were not investigated.

Since the seasonal swing of UT temperature over a large region (e.g. North Atlantic) is large, the investigation of the seasonal change of water vapour over such regions seems promising. MOZAIC data (Kley *et al.*, 1998) show that, although there is a strong positive correlation of specific humidity with UT temperature over the course of a season, there is actually a negative correlation of relative humidity with UT temperature in summer. This result points to a feedback which is not as strong as it would be at constant relative humidity.

SPARC Workshop UT-LS Water Vapour

A SPARC workshop on UT-LS water vapour was organised by J. Gille (NCAR), S. Oltmans (NOAA, CMDL) and D. Hofmann (NOAA, CMDL) on 26-28 August 1998 in Boulder, USA. Its purposes were to review our knowledge of the distribution and variability of UT-LS water vapour and the processes that maintain it. Also reviewed were the present capabilities to model the UT-LS water vapour distribution and future changes. An important question addressed was the observational capabilities needed to determine long-term changes in the water vapour concentration in the context of its important role as a greenhouse gas and a major precursor for hydroxyl radicals.

The workshop was organised into three sessions. The theme of session 1 was: What do we need to know about water vapour in the UT-LS?. Session 2 was concerned with our present day knowledge on UT-LS water vapour. The view from various measurement platforms formed the first part of session 2. The emphasis was on the distribution, comparison of measurement systems and trends. The second part was concerned with process studies, e.g. transport of water vapour through the tropopause and with transport and control of water vapour in the UT. In session 3: "Where do we go from here?", the participants discussed developments in modelling water vapour behaviour, observational needs and measurement programs.

SPARC Water Vapour Assessment (WAVAS)

The Boulder workshop re-emphasised the fact that the global, regional and seasonal distributions of water vapour, its climatologies and its variability in the UT-LS are not known with sufficient accuracy to allow climate models to be validated. It was stressed that it is important to compile UT-LS water vapour trends. A prerequisite for this would be to look at the various data sources in existence (e.g. in-situ operational, in-situ research, observations from satellites and aircraft) from a common vantage point. The data quality of a combined selected data set would need to be established. As far as tropical tropospheric-stratospheric exchange is concerned, a high absolute accuracy on the entry level of water vapour concentration or equivalent tropopause temperature is required before it can be decided if broad scale ascent through the tropical tropopause or overshooting deep convection controls the transfer of water vapour to the stratosphere.

One of the primary outcomes of the workshop was the recognition that UT-LS water vapour state of knowledge has never been

critically reviewed. As a result, a group was formed under the auspices of the SPARC SSG and chartered to plan an assessment of the available information on the UT-LS water vapour distribution, its seasonal variability and short and long-term concentration changes. Furthermore, it was noted that, although the IPCC has stressed the role of water vapour as a powerful greenhouse gas in each of its reports, this may become more explicit in future reports with the acknowledgement that it is the water vapour question that represents perhaps the single largest uncertainty in the prediction of global and regional warming caused by the increase of CO₂ concentration. It was also agreed that completion of a water vapour assessment in time for making its findings available for the Third IPCC Assessment Report (TAR) would be desirable.

At the SPARC SSG meeting in Nagoya, Japan, on October 26-29, 1998, it was resolved that an assessment of our knowledge on UT-LS water vapour distribution and variability should be conducted and that the results should be published as a SPARC report (WAVAS). The fact that the assessment results should be made available for TAR was strongly emphasised by the SSG.

The goal of WAVAS is to critically review available information on the concentration, distribution and variability (trends) of UT and stratospheric water vapour, the latter with emphasis on the LS. A wealth of UT-LS observational results have been published but the data themselves are often not easily accessible. Also, of the various data repositories only a small fraction of the data have been used in open literature publications. Another problem is the large differences which exist among different in-situ measurements and between in-situ and satellite observations. These differences exceed the estimated error bars of individual measurements. Such differences

make it difficult to specify important parameters like the entry level value of water vapour entering the stratosphere from the troposphere or to determine if there are regional or global trends in water vapour mixing ratio. It is still unclear for example, whether the entry of water occurs by overshooting deep convection or by broad scale diabatic ascent through the tropical tropopause. These, and other issues, necessitate a water vapour assessment in which our knowledge of the distribution and variability of UT-LS water vapour is judged on the basis of extensive and intensive comparisons of existing data sets and analysis of these data sets independent of historic and current theories of the UT-LS hydrological cycle. WAVAS is undertaking a study to address these issues. The work is divided into three chapters:

- **Chapter 1** provides the techniques, measurement system descriptions and the error bars for the individual measurement systems. This chapter is also responsible for making the latest, best data sets available to the assessment team.

- **Chapter 2**, using the output from chapter 1, will provide the definitive statement of data quality. This will be done by critically assessing the data limitations, precision and accuracy and by performing comparison studies of the various data sets. Chapter 2 makes statements to chapter 3 on what can and cannot be believed in the distributions and trends that will be studied.

- **Chapter 3** will provide the description of the H₂O distribution and variability in the context of Chapters 1 and 2 findings.

The SPARC community has tried to enlist as many investigators as possible with an interest in the experimental and interpretative aspects of UT-LS water vapour. A preliminary table of contents of the chapters is given in the insert below, including the authors of each section.

WAVAS Assessment Schedule

It is planned to have the Report peer reviewed in January 2000, to print the Report in February and make it available to IPCC by the end of March.

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1.1.2. Lyman- α instruments (E. Hintsa, K. Kelly, C. Schiller, E. Weinstock)

1.1.3. Tunable Diode Laser (R. May, G. Sachse)

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1.2.3. IR and far-IR (H. Fischer, H. Oelhaf, G. Toon, D. Johnston, K. Chance, W. Traub)

1.3. Spaceborne sensors (E. Remsberg)

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- 3.4.2. Stratospheric changes (G. Nedoluha, S. Oltmans, U. Schumann, R. Toumi, X. Zhou)

News on the planned Darwin field campaign (ETCE)

Kevin Hamilton (kph@gfdl.gov)

At the December 1996 SPARC Scientific Steering Group meeting, planning was initiated for a major international field experiment to examine deep tropical convection and its effects in the Darwin Australia region (see Newsletter #9, page 5). Further planning meetings have been held in Victoria, Canada (June 1997) and in Boulder (June 1998 and December 1998). The original plans for an experiment focussed on convective gravity wave generation have been expanded to include such issues as convective transport and chemical transformation in the troposphere,

stratosphere-troposphere exchange and anvil-cirrus dynamics and microphysics. The expanded aims are reflected in the new name "Effects of Tropical Convection Experiment" and acronym (ETCE). Detailed plans are presented in the current draft of the ETCE White Paper which is available at <http://www.princeton.edu/~kph/EXP2>. At present the experiment is planned for November through mid-December 2001. Some concrete steps to secure funding have also been taken. Several groups in Australia are preparing or have submitted proposals to fund measurements during

ETCE. A European consortium is preparing a Framework 5 proposal to the European Union to fund aircraft deployments. In the US some preliminary contact has been made with funding agencies which should result in firm proposals to fund both aircraft and ground-based radar deployments for ETCE.

Evaluation of the Atmospheric Chemistry of Small Organic Peroxy Radicals

Geoffrey S. Tyndall (tyndall@ncar.ucar.edu), A.R. Ravishankara, and R.A. Cox

A Workshop took place at the CNRS/Service d'Aéronomie laboratory in University Paris VI, Jussieu, from 7th to 9th December, 1998 to discuss the reactions of small organic peroxy radicals in the clean atmosphere. Participants were G.S. Tyndall (NCAR), R.A. Cox (Cambridge), R. Lesclaux (Bordeaux), G.K. Moortgat (Mainz), M.J. Pilling (Leeds), A.R. Ravishankara (NOAA) and T.J. Wallington (Ford Motor Co). The group was assembled under the initiative of the IGAC and SPARC Activities on Laboratory Processes. The chemistry of peroxy radicals is tied very closely to the production and destruction of ozone in many regions of the atmosphere. Recent measurements of OH and

HO₂ from aircraft, along with theories linking acetone and organic hydroperoxides in the upper troposphere to HO_x chemistry, have provided an extra incentive to understand the chemistry of peroxy radicals. In the relatively clean upper troposphere, where levels of nitrogen oxides can be quite low, reactions between the various peroxy radicals can dominate the chemistry. The measurement of such radical-radical reactions in the laboratory is very difficult, since it requires the simultaneous quantification of two reactive species, often on a submillisecond timescale. The members of the working group have all had extensive experience with peroxy radical chemistry and met to quantitatively evaluate the

available data. The group hopes to provide recommendations for future use in the laboratory and in global models. The group will meet again at NCAR in Boulder at the end of April 1999, to finalise their evaluation. The data will be made available in a peer-reviewed publication later in the year, which will also include the results of a 3D model of the free troposphere (C. Granier) using the evaluated data.

Chapman Conference on Water Vapor in the Climate System

Maryland, USA. 12-15 October 1999

Conveners: Dian Gaffen (NOAA Air Resources Laboratory), John Gille (NCAR), Rebecca Ross (NOAA Air Resources Laboratory).

Topics: ♦ Radiative role of water vapor and associated feedback mechanisms; ♦ Stratosphere/troposphere exchange of water vapor; ♦ The hydrological cycle and its potential intensification; ♦ The role of water vapor in stratospheric chemistry; ♦ Water vapor in climate models and comparisons with observations; ♦ Water vapor as a tracer of stratospheric flow; ♦ Water vapor/cloud interactions; ♦ Climatology and trends of water vapor and its fluxes in the troposphere and stratosphere; ♦ Water vapor observations applicable to climate studies.

For further information, contact the conveners or: AGU Meetings Department (meetinginfo@agu.org). AGU web site: <http://www.agu.org/meetings/cc99bcall.html>.

Impact Of Stratospheric Ozone Changes on the Distribution of Tropospheric Species

Claire Granier, Service d'Aéronomie du CNRS, France (clg@aero.jussieu.fr) and CIRES/NOAA Aeronomy Laboratory, USA (cgranier@al.noaa.gov)

Solar ultraviolet radiation (UV-B), defined as the part of the solar spectrum within the 280 to 315nm wavelength range, is one of the key environmental factors controlling the chemistry of the troposphere. The amount of UV-B reaching the troposphere is to a large extent determined by the thickness of the ozone column in the stratosphere, and many observations (as reported in Chapter 9 of the 1998 WMO Scientific Assessment of Ozone Depletion (WMO, 1999) have shown that the UV-B flux reaching the troposphere and the Earth's surface has increased significantly over the last two decades. As a result, as enhanced UV-B radiation in the troposphere increases the photodissociation of some key chemical species, stratospheric ozone loss is expected to lead to perturbations of the chemical composition of

the troposphere. This paper reviews the different studies performed during the past few years, that have quantified the impact of stratospheric ozone changes on photodissociation rates in the troposphere and on the associated perturbations in tropospheric species distributions. These studies have also been discussed in Chapter 10 of WMO (1999), together with the climatic impact of stratospheric ozone depletion.

Sensitivity of photodissociation rates to stratospheric ozone changes

Ultraviolet radiation penetrates into the troposphere, and it is sufficiently energetic to photolyse atmospheric chemical species, leading to the formation of highly reactive radicals. For ultraviolet radiation at wavelengths greater than about 320nm, in the UV-A domain, the absorption by ozone becomes weak, and the intensity of the solar flux is almost entirely determined by atmospheric scattering. Therefore, changes in total column ozone affect mainly chemical species which photolyse mostly in the UV-B. An example of the calculated change in the photodissociation rate of ozone ($O_3 + h\nu \rightarrow O(^1D) + O_2$) for the 1979-1992 period is given in Figure 1: the photodissociation rate global average has increased

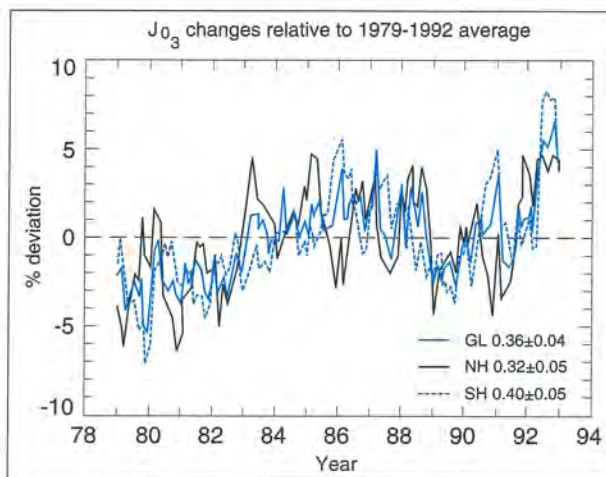


Figure 1. Changes in mid-tropospheric photodissociation rate for the $O_3 + h\nu \rightarrow O(^1D) + O_2$ reaction, computed using ozone column measurements from the Nimbus 7 satellite. Values are given as monthly deviations from the corresponding 1979-1992 averages. GL corresponds to the area-weighted global average, NH and SH correspond to the northern and southern hemispheres, respectively (From Madronich and Granier, 1994).

sed by about 0.36% per year, with slightly higher values in the Northern Hemisphere (NH) than in the Southern Hemisphere (SH).

A measure of the sensitivity of photolytic processes to total column ozone is provided by the sensitivity factor S , which is defined as the percentage change ΔJ in a photodissociation rate J for a percentage change in total column ozone Ω :

$$\frac{\Delta J}{J} = -S \frac{\Delta \Omega}{\Omega} \quad (1)$$

The sensitivity factor S depends on total column ozone, as well as on the altitude of the ozone perturbation and on the solar zenith angle. Examples of sensitivity factors for several photolysis processes and for different conditions are given in Table 1. The photodissociation of ozone is the most sensitive to changes in total column ozone, a 1% decrease in total

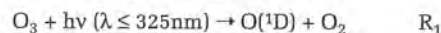
column ozone resulting in a 1.4 to 2.3% increase in the photodissociation rate in the troposphere, depending on location, time, spatial and temporal averaging.

Effects of photodissociation rates on tropospheric chemistry

UV-B is one of the key environmental factors controlling tropospheric chemistry, as the distribution of the most efficient oxidising compound, the OH radical, strongly depends on the available ultraviolet radiation in the troposphere. The abundance of the OH radical is important for evaluations of the evolution of climate forcing, as it regulates the lifetimes of greenhouse gases such

as methane, hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs), and of other species which act as ozone precursors such as carbon monoxide and hydrocarbons. In addition, OH plays an important role in tropospheric chemistry as its abundance plays a large role in the determination of the chemical production of tropospheric ozone, which is itself a greenhouse gas.

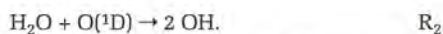
The production of the OH radical in the troposphere occurs through the photodissociation of O_3 yielding ($O(^1D)$):



Most of the electronically excited oxygen atoms produced through this process are de-activated to produce $O(^3P)$ atoms, which recombine with O_2 to reproduce ozone molecules. However, a few percent of the $O(^1D)$ atoms react with water vapour to produce OH radicals:

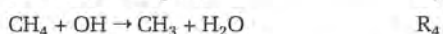
	Photodissociation rate					
	O_3	NO_2	H_2O_2	HNO_3	$CH_2O(1)$	$CH_2O(2)$
Krol and van Weele, 1997(1)	2.3	0	0.4	1.1	0.5	0.2
Madronich and Granier, 1994(2)	1.83	0.02	0.36	1.08	0.45	0.15
Fuglestad et al., 1994(3)	1.4	0.04	0.35	0.89	0.47	0.16

Table 1. Sensitivity factors for key photolytic processes in the troposphere. The values in the table correspond to near-surface conditions and (1) a total column ozone of 324 DU and a zenith angle of 46° , (2) a diurnal average for $20^\circ N$, May 15, and a total column ozone of 280 DU and (3) global annual tropospheric mean value. $CH_2O(1)$ and $CH_2O(2)$ correspond to reactions ($CH_2O + h\nu \rightarrow H + HCO$) and ($CH_2O + h\nu \rightarrow H_2 + CO$), respectively.



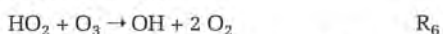
Reaction R_1 , as seen in the previous section, is very sensitive to changes in overhead O_3 column. OH is therefore expected to have increased as a result of the observed depletion in total column ozone over the last decades, if all other factors, such as emissions of CH_4 , CO or nitrogen oxides, have remained unchanged. The magnitude of the change in OH distribution as a response to changes in $\text{O}(^1\text{D})$ is also determined by other chemical processes that could affect OH.

OH radicals react with several chemical species:

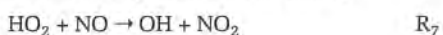


and with many other gases through analogous reactions.

Rapid cycling is maintained between OH and HO_2 through:

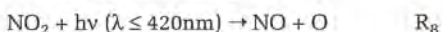


in remote unpolluted areas, and by:



when the concentration of nitrogen oxides is larger than about 50pptv.

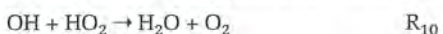
Reactions (R_1+R_2), together with R_5 and R_6 , represent the major loss process of odd oxygen compounds in the troposphere, while R_7 is the rate limiting process that leads to the production of ozone, as NO_2 is a source of oxygen atoms through:



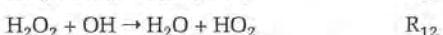
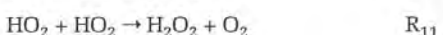
followed by



The strong coupling between hydrogen radicals OH and HO_2 is of great importance for the evaluation of perturbations of the OH distribution, since a major part of the loss of odd hydrogen in the free troposphere proceeds via reactions involving both radicals. In regions of low nitrogen oxides, the loss of odd hydrogen radicals results from reactions:

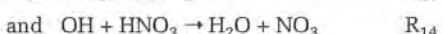


or from the sequence:



H_2O_2 being also removed through wet scavenging or dry deposition.

When the concentrations of nitrogen oxides are sufficiently high, loss of odd hydrogen results from reactions:



The chemical processes described above are responsible for the strong dependence of OH and other radicals concentrations on CH_4 , CO and NO_x levels.

Impact of stratospheric ozone changes on the distribution of the hydroxyl radical

Different types of photochemical and chemical-transport models have been used to assess the impact of the observed total column ozone changes on tropospheric composition at the global scale (WMO, 1999 and references therein). These models have been used to calculate the sensitivity α of the distribution of tropospheric OH and other chemical species to total column ozone changes, defined as:

$$\alpha(X) = - \frac{\left(\frac{\Delta X}{X} \right)}{\left(\frac{\Delta \Omega}{\Omega} \right)} \quad (2)$$

where X represents the global tropospheric annual average level of $\text{J}(\text{O}_3 \rightarrow \text{O}(^1\text{D}))$, or the tropospheric average concentration of chemical species like OH and O_3 , and Ω is the total column ozone. Ω and X represent the reference level, while $\Delta\Omega$ and ΔX represent the difference between the perturbed level and the reference level. The values of the sensitivities α obtained by the different 2D and 3D models, calculated for total column ozone changes observed during the 1979-1994 period are reported in Table 2.

	X= $\text{J}(\text{O}_3)$	X=OH
Bekki <i>et al.</i> , 1994 (2D)	N/A	0.86
Fuglestad <i>et al.</i> , 1994 (2D)	1.38	0.99
Van Dop and Krol, 1996 (1D)	N/A	$0.45 \cdot X(\text{J}(\text{O}_3))$
Granier <i>et al.</i> , 1996 (3D)	1.57	0.82

Table 2. Sensitivity of the ozone photodissociation rates and of tropospheric chemical species to stratospheric ozone changes for the period 1979-1994. The assumed scenarios are discussed in the different publications. The type of model used is indicated in parentheses.

The fact that $\alpha(\text{OH})$ is lower than $\alpha(\text{J}(\text{O}_3))$ indicates that mechanisms exist that damp the perturbations. The response of chemical species distributions to total column ozone changes is not uniform in space, and depends significantly on the distribution of nitrogen oxides (NO_x). An example of changes in surface OH density resulting from stratospheric ozone depletion between 1979 and 1994 is shown in Figure 2 (plate I). In this simulation performed with the IMAGES 3D model, the total ozone change applied to the model, which is shown on the left panel of Figure 2, is a zonal average. Differences in the OH concentration as a function of latitude are observed, which reflect the impact of the nitrogen oxides levels on the concentration of OH and on OH changes.

Averaged results from simulations performed with different models are shown in Figure 3 for the full 1979-1994 period. In the simulations, zonally averaged total column ozone from TOMS measurements was used as an input for calculations of the photodissociation rates. A rather similar increase in the average photodissociation rate of ozone is obtained in the three model studies for the period considered. 2D model calculations have shown an increase in global tropospheric OH of 0.3% per year between 1979 and 1990, followed by a maximum increase of 6% from mid-1991 to Spring 1993, similar to values obtained with the 3D model.

Evaluations of trends in the global OH distribution using surface observations of methyl chloroform (CH_3CCl_3) have been reported by Prinn *et al.* (1995) and Krol *et al.* (1998). Two different statistical methods were used by the authors, who evaluated the OH trend to be close to zero (Prinn *et al.*, 1995) and $0.46 \pm 0.6\%$ per year (Krol *et al.*, 1998), for the 1979-1993 period. The trend in OH computed by the global models is consistent with the evaluation of Krol *et al.* (1998), but more studies are needed before a definite quantitative conclusion about the magnitude and origin of an OH trend since 1979 can be drawn.

Another species which could be affected by the stratospheric ozone decrease is hydrogen peroxide (H_2O_2), which acts as another important oxidant in the troposphere. Increased UV-B in the troposphere should result in a slight increase in its loss from photodissociation, as shown in Table 1; however, the increase in OH and HO_2 due to ozone

depletion leads to a larger production of H_2O_2 , which eventually results in an increase in H_2O_2 concentrations, especially in areas with low nitrogen oxides concentrations, where the predominant removal mechanism of odd hydrogen radicals is the formation and wet scavenging of peroxides. An overall increase of 60% in H_2O_2 during the last 150 years from the analysis of firn/ice core records in Greenland has been observed by Anklin and Bales (1997) and Sigg and Neftel (1991). Most of this increase occurred in the past 20 years, at a rate of 1.6 to 4% per year since 1970. A larger increase was reported by Anklin and Bales for the 1988 to 1993 period, and they proposed that this increase could be due in part to increasing UV-B radiation, and to a combination of changes in tropospheric chemistry.

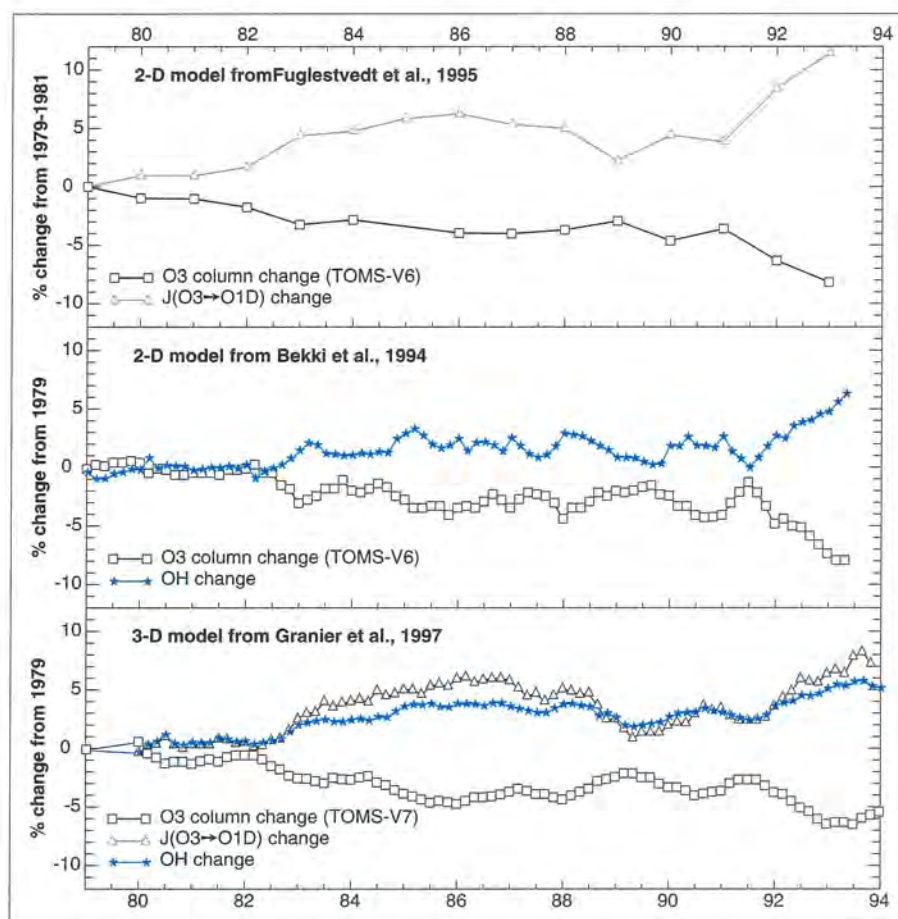


Figure 3. Relative change in total column ozone and calculated associated change in $J(\text{O}_3 \rightarrow \text{O}(^1\text{D}))$ rate from Fuglestad et al. (1994), global tropospheric OH (from Bekki et al., 1994) and $J(\text{O}_3 \rightarrow \text{O}(^1\text{D}))$ rate and global tropospheric OH (Granier et al., 1997; updated version from Granier et al., 1996).

Impact of stratospheric ozone changes on distributions of ozone precursors

The removal of most tropospheric trace gases, including gases like CO, methane or the non-methane hydrocarbons is dominated by the reaction with OH. Therefore, any changes in tropospheric OH resulting from stratospheric ozone changes should be accompanied by changes in the growth rates of these trace gases. Furthermore, the atmospheric levels of CO and CH_4 are closely linked to their interaction with OH, as changes in the emissions of CO may affect the levels of CH_4 , or vice-versa, through induced changes in the global OH distribution.

Concentrations of CO, after showing a positive trend at most observing surface stations until the late 1980s, were characterised by a significant decrease from 1990 to 1993; a decrease of 7ppbv per year in the NH and 4ppbv per year in the SH was observed by Novelli et al. (1994). Calculations performed with 2D models and a 3D model have shown that trends in surface CO appear to be affected by stratospheric ozone changes, with for example a decrease of 5-6ppbv in surface CO from Spring 1991 to Spring 1993 and a decrease in

CO concentrations reaching 2-4ppbv late 1992-early 1993. This significant change calculated after 1991 represents up to about 25-40% of the observed CO trend, which suggests that increases in UV radiation resulting from stratospheric ozone depletion is likely to have contributed to the observed changes in CH_4 and CO trends, though they cannot explain entirely these changes.

Impact of ozone changes on lifetimes and trends of methane, ozone and other greenhouse gases

Recent surface measurements from global networks have revealed a decline in the growth rate of CH_4 during the last decades, from 17-21ppbv per year in the early 1980s to 12-14ppbv per year at the end of the 1980s. Measurements performed over the last few years indicate a growth rate of about 6ppbv per year in 1995-1996. Most of this reduction has been occurring in the NH. The methane growth rate slowed down even more during the 1991-1993 period, and showed a value between 0 and 5ppbv per year at the end of 1992 (Dlugokencky et al., 1994).

The response in CH_4 due to the increase in OH follows rather well the long-term variation of global ozone: the simulation results show a CH_4 growth rate decrease reaching 2-4ppbv per year in the mid 1980s, with a maximum decrease of 7ppbv per year in the NH in 1992-1993. This value, coincident with the record-low total column ozone value observed during this last period, accounts for about 20 to 40% of the observed decrease in the methane trend. The reaction rate constant for the methane oxidation by OH (reaction R_4) increases with temperature. Therefore, the chemical loss of methane is larger in the LT at low-latitudes than in the regions where the relative OH changes are largest, i.e. at high latitudes in the spring months. The low correlation between the changes in OH and the rate of CH_4 oxidation explains this moderate response in methane calculated by the models.

Furthermore, due to the differences in lifetimes of CH_4 (8 years) and of CO and O_3 (2 to 3 months), large differences in the timing of the responses to changes in total column ozone are expected. Global levels of ozone and OH respond in the same years as changes in total column ozone, with a maximum delay of a few weeks, while, due to its longer lifetime, the maximum response of CH_4 occurs with a delay of a few years.

Higher levels of OH lead also to enhancements of HO_2 concentrations, which lead to a further decrease in tropospheric ozone through reactions R_5 and R_6 . In regions where low levels of nitrogen oxides are found, the loss of ozone through R_1 and R_2 will also contribute to the reduction of ozone concentrations. The 2D and 3D models calculate a global decrease in tropospheric ozone as a result of decreasing stratospheric ozone, as shown on Table 3, which gives the sensitivity of the global ozone concentration in the troposphere to stratospheric ozone changes for the period 1979-1994. This table shows that, globally, a 1% decrease in stratospheric ozone leads to a 0.3% decrease in tropospheric ozone.

There are significant differences between the models on the seasonal variation of the tropospheric ozone response to stratospheric ozone depletion. While the 3D model (Granier et al., 1996) calculates a decrease in ozone at all latitudes and time of year, as shown for example in Figure 4 (plate I) for

	$X = \text{O}_3$
Fuglestad et al. 1994 (2D)	-0.29
Granier et al. 1996 (3D)	-0.32

Table 3. Sensitivity of the average tropospheric ozone concentration to stratospheric ozone changes for the period 1979-1994. The models used in these calculations are the same as the ones used for calculations shown in Table 2.

December, the 2D model of Fuglestad *et al.* (1994) calculates a global ozone decrease, except for spring at mid- and high latitudes of the NH, where an ozone increase is calculated. The difference between these results obtained by a 2D and a 3D model could be due to different spatial resolution, different parameterisation of the chemical scheme involving non-methane hydrocarbons, or lower global nitrogen oxides concentration calculated by the IMAGES model.

Observations at the South Pole indicate a 17% reduction in surface ozone from December to January over the 1976-1990 period (Schnell *et al.*, 1991). Several explanations were proposed by the authors, who suggested that enhanced net destruction of ozone resulting from the large stratospheric ozone losses in that region is probably the principal mechanism. Calculations give reductions in Antarctic tropospheric ozone of the same magnitude between 1979 and 1993. However, due to the high variability of tropospheric ozone, and the sparsity of trend data, especially in the SH, comparisons between the calculated impact of stratospheric ozone depletion on tropospheric ozone and observed trends cannot yet be performed with confidence.

The trends of several other source gases which are mainly destroyed through reaction with OH could also be affected. For example, simulation results show that the growth rate of CH_3CCl_3 should have decreased by 1pptv per year from spring 1991 to autumn 1992 as a result of stratospheric ozone depletion. This feedback between stratospheric ozone and halocarbon lifetimes may need to be taken into account when assessing ozone depletion and global warming potentials of species destroyed by OH in the troposphere. Toumi *et al.* (1994) also discussed the impact of stratospheric ozone and OH changes on aerosol formation. OH oxidises sulphur dioxide to gaseous sulphuric acid, which is a source of new sulphate particles via homogeneous nucleation. Changes in the production of sulphuric acid might affect not only the number of sulphate particles but also the number of particles that can act as condensation nuclei. The calculations reported in

these papers suggest that the mean gaseous sulphuric acid production might have increased by about 2% from 1980 to 1990, which may have increased cloud condensation nuclei and cloud droplets number.

In summary, the decrease in total column ozone observed over the last two decades resulted in an increase in the UV-B fluxes to the troposphere followed by an increase in the tropospheric concentration of the OH radical. This process is probably responsible for perturbations of the tropospheric distributions and lifetimes of chemical species such as CO, O_3 , CH_4 , H_2O_2 , HCFCs and HFCs. From currently available model results, 25 to 40% of the decrease in the CO mixing ratio and 20 to 40% of the decrease in the methane trend observed more particularly during the 2 years following the Mount Pinatubo eruption could be attributed to the significant stratospheric ozone depletion observed over this period.

Some critical uncertainties remain in the model calculations discussed in the previous paragraphs, such as the impact of cloudiness and aerosols on the calculation of photodissociation rates, uncertainties related to the transport of chemical species, as well as in the distribution of key chemical species such as nitrogen oxides or water vapour. This review has shown the significant impact of stratospheric ozone changes on the distribution of chemical species in the troposphere. This impact has to be taken into account in studies of the evolution of the oxidising capacity of the troposphere and of the long-term evolution of several greenhouse gases. It should also be noted that, for a complete description of the impact of stratospheric ozone changes on the troposphere, changes resulting from UV increase have to be superimposed to changes resulting from other processes, such as changes in surface emissions or in STE.

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An Estimate of the Trend of the Stratospheric Chlorine Loading Based on In-situ Balloon-borne Observations

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Introduction

Since the first observations of the Antarctic Ozone hole (Farman *et al.*, 1985) numerous investigations of the changing abundance of total organic chlorine (CCl_y) in the troposphere (see e.g. Cunnold *et al.*, 1994, Elkins *et al.*, 1993, Montzka *et al.*, 1996, Montzka *et al.*, 1999) and of the respective global trend of stratospheric ozone that is expected as a result of this increase (SPARC, 1998) have been carried out. However, the increasing chlorine loading of the stratosphere has not been investigated to the same extent although this is the region where the source gases for reactive chlorine, the chlorofluorocarbons (CFCs), have (next to climate effects) the strongest environmental impact.

Most of the tropospheric organic chlorine containing compounds have large chemical lifetimes and, therefore, can get mixed into the middle stratosphere where they are eventually photolysed and release inorganic chlorine (Cl_y). In the stratosphere inorganic chlorine exists either in forms which can react directly with ozone or which can be activated into forms capable of reacting with ozone on rather short time scales. Inorganic chlorine is, therefore, often also referred to as available reactive chlorine. The sum of total inorganic available chlorine (Cl_y) and total organic chlorine (CCl_y) is total chlorine (Cl_{total}). So far no observational method to directly determine the abundance of Cl_y is available and, therefore, it must be inferred from the difference of total chlorine (Cl_{total}) and CCl_y .

For assessing the effect of the chlorine loading in the stratosphere, information about the past trend (and the possible temporal evolution) of Cl_y is of prime interest. Unfortunately this is also the quantity that is most difficult to derive because its determination requires knowledge of the abundance of both Cl_{total} and CCl_y .

In-situ observation of long-lived trace gases in the stratosphere

Although global data on the distribution of long lived trace gases have become available after the launch of satellite instruments (e.g. UARS), these data do not provide long term coverage. The most complete information about the long-term temporal evolution of the stratospheric distribution of CFCs can be derived from the results of balloon-borne

in-situ observations. These observation provide spot measurements only but have been performed since the 1970s. In fact, the longest series of CFC observations became available from the analyses of whole air samples collected by means of cryogenic whole air samplers (Figure 1, plate II) during a programme of regular balloon flights that has been performed by the stratospheric research group at the Research Centre (KFA) Jülich, Germany, from 1982 until 1995 and is now continued by our group. The whole air samplers consist of 15 internally electropolished stainless steel sample flasks which are immersed in a liquid Neon cooled dewar. The sample flasks are baked and evacuated prior to each flight. They are opened at different altitudes of the strato-

NASA, 1994). In addition to these CFC compounds, nitrous oxide (N_2O), methane (CH_4), sulfurhexafluoride (SF_6), and several other halogenated hydrocarbons are measured in the samples. Stratospheric data of some of these gases have been obtained since 1977.

The total chlorine loading in the stratosphere in 1997 and 1999

The most recent profile measurements of CFCs were performed by our group inside the Arctic polar vortex in February 1999. At the time of writing the results for the most important chlorine species are already available. A full set of measurements of chlorine

source gases and related species is available for two profile observations in 1997. The fraction of Cl_y relative to total chlorine, Cl_{total} , as derived for both years is shown in Figure 2 as a function of the N_2O mixing ratio. N_2O was chosen as a vertical scale in order to compare mid- and high latitude observations. The right hand vertical axis shows approximate altitude for a typical mid-latitude distribution of N_2O . While in the lowermost stratosphere most of the total chlorine still resides in the organic source gases, more than 80% of the chlorine is released from the source

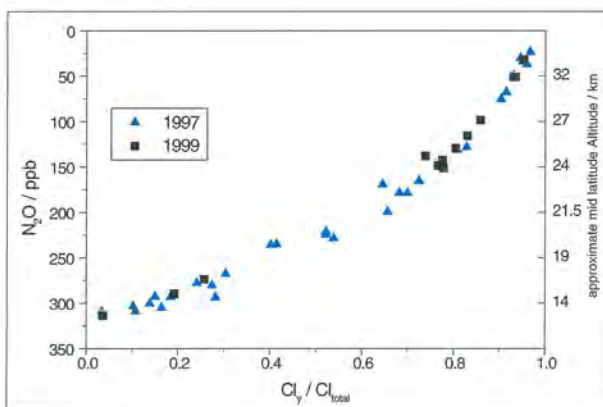


Figure 2. The amount of available chlorine, Cl_y , relative to total chlorine, Cl_{total} , as a function of the N_2O mixing ratio, as derived from mid- and high-latitude observations in 1997 and 1999. The right hand axis is an approximate altitude scale for mid-latitudes. At an N_2O level of 100ppb about 80% of the chlorine has been released from its source gases. This N_2O level corresponds to an altitude of about 25km at mid-latitudes.

sphere by remote control during a valve controlled slow descent of the balloon from altitudes of about 35km down to about 10km. The samples collected during each flight are subsequently analysed in the laboratory employing gas chromatography with electron capture detection (GC/ECD). It should be noted that the calibration of the data relies on long term standards which have been related to a single calibration scale (NOAA/CMDL). The chlorine compounds which are regularly measured include the major three CFCs (CFC-12, CFC-11, CFC-113), HCFC-22, CCl_4 , CH_3CCl_3 and CH_3Cl . These seven compounds contribute about 98% of the total organic chlorine loading, CCl_y , in the stratosphere (see e.g.

gases at an N_2O level of 100ppb, corresponding to an altitude of about 25km at mid-latitudes. At high latitudes inside the polar winter vortex these conditions are observed already at lower altitudes (about 22km or lower), due to the effect of subsidence.

The temporal trend of CFC-12 (CF_2Cl_2) in the stratosphere

Balloon-borne observations of CFCs are only spot measurements and, therefore, strongly influenced by spatial and temporal variations of the main patterns of the stratospheric circulation, e.g. by the subsidence

inside the polar vortices during winter. However, the effect of such dynamical processes on the vertical distribution of a specific CFC compound can be partly compensated by referring the mixing ratio observed at various altitudes to the abundance of another simultaneously observed long-lived trace gas which has no (or only a very small) temporal trend.

Nitrous oxide, N_2O , is a trace gas suitable for this purpose, because its mixing ratio in the troposphere is increasing by only 0.2 to 0.3% per year, whereas the temporal trend of most CFCs is of the order of several %. Based on the simultaneous balloon-borne observations of N_2O and CFC-12 the temporal trend of CFC-12 over the period from 1978 until 1997 was derived by Engel *et al.* (1998) for three different N_2O mixing ratios, corresponding to three altitude regions (the altitude given is based on a typical mid-latitude distribution of N_2O). The results are plotted in Figure 3 (plate II) (updated for the two lowest levels for 1999). The small tropospheric trend of the N_2O mixing ratio has been corrected for.

In principle, the trend of other CFC compounds could be derived in a similar manner. However, the results become less significant when the difference between the stratospheric lifetime of N_2O (about 110 years) and that of the respective compound is large, because the slope of the correlation function becomes very steep. Consequently, small experimental uncertainties in the observational data of the longer-lived compound (here N_2O) will transform into relatively large errors in the mixing ratios derived for the shorter lived compound (CFC).

While the decrease in the growth rate for CFC-12 observed in the troposphere since about 1990 (Elkins *et al.*, 1993) is also visible in the lowermost stratosphere (tropospheric mixing ratios of N_2O), and around 19km, a statistically significant decrease in the annual growth rate cannot yet be derived for the 200ppb N_2O level. This is due to the fact that the increase in the stratosphere is delayed by the time needed to mix tropospheric air that has entered the stratosphere in the tropics to higher latitudes and altitudes. This delay time is generally referred to as the "age" of stratospheric air (see e.g. Kida *et al.*, 1983, Schmidt and Khedim, 1991)

The trend of total stratospheric chlorine

The trend of total chlorine, Cl_{total} , at various altitudes in the stratosphere can be derived from the observed tropospheric trends of the major source gases by considering the temporal delay due to the age of the air with which these propagate into the stratosphere. The age can be derived from stratospheric observations of long-lived trace gases whose mixing ratios increase in the troposphere and that have no

chemical sinks in the stratosphere, such as CO_2 and SF_6 . Tropospheric trends of CFCs can be derived from the data obtained at the tropospheric monitoring network stations (e.g. Elkins *et al.*, 1993, Cunnold *et al.*, 1994). The propagation of these trends into the stratosphere can be estimated if some assumptions are made. For example, it is assumed that the CFC mixing ratio in the air masses entering the stratosphere are well represented by the global mean tropospheric mixing ratio derived from the network data. Further, because the transport patterns of the stratospheric circulation are quite complex, an air mass probed at a certain location will be composed of a mixture of air parcels that have reached this location via different transport pathways and correspondingly after different periods of time. The value of the mean age, Γ , determined for an air mass should, therefore, be rather interpreted as the mean of an age-spectrum (see e.g. Kida 1983, Hall and Plumb, 1994). However, this spectrum cannot be measured directly.

Consequently, the assumption of a mean age will result in an error in the calculation of the propagating trends if these are non-linear. According to Hall and Plumb (1994), the width of the age spectrum, Δ , is related to the value of the mean age, Γ , in such a way that the ratio Δ^2/Γ is rather constant throughout the stratosphere.

We calculated the propagation of tropospheric mixing ratios into the stratosphere according to Volk *et al.* (1997) and adopted their relation $\Delta^2 = 1.25 \Gamma$, which is based on the results of two different chemical transport models. A typical vertical profile distribution of the mean age for the mid-latitude stratosphere derived from SF_6 measurements is reported by Strunk (1999). The tropospheric trends of the major CFCs were taken from Elkins *et al.* (1993) and Montzka *et al.* (1996). The calculated trend of total chlorine in the stratosphere for mid-latitudes is shown in Figure 4 (plate III). The total chlorine loading of the lowermost stratosphere (around 13 to 14km) reached a maximum of about 3.6ppb already in 1995. It is now declining at a rate of about 90ppt per year. About half of this decrease is caused by the fast decrease of the global mixing ratio of CH_3CCl_3 , the chlorine source gas with the shortest atmospheric lifetime (about 5 years). The rate of decrease will slow down in the near future when most of the CH_3CCl_3 in the atmosphere has been removed (Montzka *et al.*, 1999).

A scenario for the future evolution of total chlorine loading

In order to assess future trends in stratospheric total chlorine, Cl_{total} we have used the emissions of the major CFCs reported by AFEAS (Alternative Fluorocarbons Environmental Acceptability Study) (1998)

and their atmospheric lifetimes to estimate the future tropospheric trends of CFCs. We have assumed that the emissions reported by AFEAS fully represent the real global emissions for HCFC-22 but account only for about 50% of the total global CFC emissions (P. Midgley, private communication). We have further assumed that the emissions will remain constant at the 1996 levels until 1998 and decrease thereafter, with an exponential time scale of 10 years. The future chlorine loading of the stratosphere derived in this way is shown in Figure 5 (plate III).

Several interesting aspects should be noted. First, the maximum of total chlorine loading is reached later at higher altitudes. Second, the value of the maximum at higher altitudes is smaller than that expected in the lower stratosphere. This is due to the applied spectrum of the age which tends to smear out the peak in the tropospheric chlorine loading when propagating higher up. As the age spectrum is broader in the middle and upper stratosphere this effect is more pronounced at higher altitudes. Third, this estimate suggests that it will take about 60 years until the present level of total chlorine will have dropped again to values around 1500ppt, i.e. to the level observed in the lower stratosphere during the late 1970s before the onset of the Antarctic ozone hole. If future emissions of chlorine containing species were negligible, this value would be reached about 10 years earlier. On the other hand, in the case of prolonged emissions, it will obviously take longer for stratospheric chlorine levels to drop.

It should be emphasised at this point that, due to the declining temperatures in the stratosphere and also due to changes in the bromine loading of the stratosphere, this will not necessarily mean that stratospheric ozone values will recover by that time to pre-ozone hole values (e.g. Shindell *et al.* 1998, Waibel *et al.* 1999). The emissions of other chlorine and bromine gases such as HCFCs and Halons which are not considered in this study, will further retard the recovery of stratospheric ozone, too.

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Third European Stratospheric Experiment on Ozone: second year of activities

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The Third European Stratospheric Experiment on Ozone (THESEO) is taking place in 1998 and 1999. The general motivation of this campaign is the understanding of the stratospheric ozone decline at mid-latitudes through the investigation of the relevant chemical and dynamical processes, and the links between the mid-latitudes and the other nearby regions, the upper troposphere and the Arctic and subtropical regions. The THESEO research campaign is composed of 15 research projects funded by the Environment and Climate programme of the European Commission and there is substantial additional funding from national agencies. Measurements are being made by instruments on balloons, aircraft and from the ground, from the Arctic to the Tropics. Numerical modelling played a central role during the active phase of THESEO and will continue to do so during the interpretation of results. Satellite data are also being used in the analysis of the measurements. A special session on the results from the first year of activities of THESEO was held during the XXIV EGS General Assembly at The Hague, April 23, 1999.

The most intensive Arctic phase of THESEO took place at SSC Esrange, Kiruna (67.9°N, 21.1°E), Sweden, between

15/01/99 and 23/02/99. During this period, 7 large balloons, 4 small balloons and 5 long duration balloons carrying scientific payloads were launched successfully, and have provided preliminary measurements. Aircraft measurements (on board the DLR Falcon, the CNRS ARAT and the Swiss Air Force Learjet) and simultaneous ground-based activities provided complementary measurements in the general Scandinavian region (ALOMAR, Kiruna, Ny-Ålesund, Sodankylä) often along the balloon flight path. On-site meteorological support was provided by the FU-Berlin. The DLR MM5 mesoscale model was used to forecast lee-waves, and the results were used to help balloon and aircraft measurement planning and to trigger additional radiosondes. Chemical transport modelling (University of Cambridge) for support and comparison with the balloon and other measurements was done at Esrange during the whole period of activities. Supplementary measurements were made available through GOME and POAM data.

This combination of measurements and other studies provided a sharp survey of the Arctic stratosphere and its characteristics during the winter of 1998/99. Over North Scandinavia, two periods of temperatures low enough for PSCs to be able to

form were detected, the first one in early December with PSCs observed over Kiruna for a few days. The second period of cold temperatures occurred in mid-February but with no PSCs undoubtedly detected, either by ground-based or satellite measurements. Several experiments dedicated to the measurements of chlorine and bromine species should provide more information on the partitioning of those chemical families and the speed of the deactivation in the Arctic during this winter. The associated ozone loss was assessed from ozonesondes, from ozone and tracers balloon measurements, satellite measurements, and modelling simulations. The estimation derived for the Arctic ozone loss appears to be small.

The very disturbed vortex during this winter has provided a good opportunity for the investigation of transport from high latitudes to mid-latitudes. Several polar filaments were sampled by the ALTO ozone lidar on board the French Mystère 20 and by ground-based measurements in February and March 1999. The results are being interpreted with the aid of a number of modelling approaches including high resolution contour advection calculations.

Investigation of the ozone loss at mid-latitudes and of coupled processes is a chief component of THESEO. This involved

ground-based, aircraft, and ozonesonde measurements including a coordinated Mach campaign. A second balloon campaign dedicated to study spring conditions at mid-latitudes took place in April and May 1999 at the CNES base in Aire-sur-l'Adour, France. Three small and four large balloon flights were performed. One of the large balloon flights was coordinated with the DLR Falcon measurements. The analysis of those measurements will provide information on the partitioning of chlorine and bromine species (including the photochemical changes at sunrise) and possible ozone reduction at mid-latitudes. The next phase of the balloon activities at mid-latitudes for THESEO will be performed in June 1999 from Gap, France.

Tropical activities are also a large component of THESEO. Intensive aircraft measurements were made in February-March 1999 in the Seychelles to investigate microphysical processes in tropical cirrus and transport of tracers across the tropical tropopause and in the tropical lower stratosphere using the Russian M-55 Geophysica and the German Falcon aircraft in the APE-THESEO project. The lidar measurements made by ALTO on board the French Mystère 20 aircraft in March and April 1999, together with ozonesondes and

MOZAIC flights, characterised the ozone distribution near the subtropical jet in the 5°W-15°W and 20°E-30°E longitude bands. The same lidar experiment on board the Mystère 20 was used to investigate transport from low latitudes to mid-latitudes by sampling subtropical intrusions in February and March 1999, complementing the longer time series of ground-based measurements.

The chief phase of THESEO activities on the field is now almost over, and the post-

campaign analysis is ongoing. The main forum for discussion of results from THESEO will be the Fifth European Workshop on Stratospheric Ozone to be held at Saint-Jean-de-Luz, France between September 27 and October 1, 1999. All aspects of the European research on stratospheric ozone will be discussed at this workshop, and the interpretation of the results gained in THESEO will be one of the main themes.

For further information on THESEO and the THESEO projects:

European Ozone Coordinating Unit: <http://www.ozone-sec.ch.cam.ac.uk>

European Commission: <http://europa.eu.int/comm/dg12/envsc/theseo-pro.html>

Individual project sites:

APE-THESEO: <http://ape.iroo.fi.cnr.it>

COSE: <http://www.nilu.no/projects/nadir/cose/cose.html>

HALOMAX: <http://www.rz.uni-frankfurt.de/IMGF/meteor/halomax/halomax.html>

HIMSPEC: <http://www-imk.fzk.de:8080/imk2/mipas-b/himspec.htm>

Lagrangian: <http://www.aero.jussieu.fr/experience/THESEO/Lagrangian.html>

METRO: <http://www.aero.jussieu.fr/experience/THESEO/METRO.html>

O3-Loss: <http://www.aero.jussieu.fr/experience/THESEO/O3Loss.html>

TOPOZ-II: <http://www.atm.ox.ac.uk/TOPOZII>

NILU's Atmospheric Database: <http://www.nilu.no/projects/nadir/index.html>

WMO Ozone Mapping Centre: <http://lap.physics.auth.gr/ozonemaps>

Reports on the Northern Hemisphere Stratosphere in the winter of 97/98 and 98/99 are available on the Coordinating Unit web site.

SAGE III Ozone Loss and Validation Experiment, SOLVE

A NASA DC-8, ER-2 and High Altitude Balloon Mission

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During the Arctic winter of 1999-2000, NASA is sponsoring the SAGE III Ozone Loss and Validation Experiment (SOLVE). This mission is designed to both investigate the processes that control polar and mid-latitude winter and spring ozone levels, and to validate measurements from the Stratospheric Aerosol and Gas Experiment (SAGE) instrument. SAGE III is scheduled to be launched aboard a Russian Meteor-3 platform in late 1999.

Since the discovery of the Antarctic ozone hole in 1985, concern over the possible appearance of similar Arctic losses has led to a series of American and European field campaigns in the Arctic region. In fact, during the 1995-96 and 1996-97 winters, large losses were observed over the Arctic as a direct result of the cold and persistent stratospheric winter conditions. While measurement campaigns during the last decade have greatly increased our understanding of polar processes and the reasons behind these low ozone winters, a number of key questions remain unanswered and

certain observed aspects of the polar stratospheric winter remain unresolved. The science goal of SOLVE is to acquire a complete body of information that will allow us to understand the detailed mechanisms that lead to these large losses, their possible bearing on mid-latitude ozone decline, and to sufficiently validate the SAGE III satellite instrument ozone observations for estimating long-term trends in the polar regions.

The SOLVE campaign combines aircraft, ground, balloon, satellite, and theoretical investigations for a comprehensive measurement campaign over the course of the 1999-2000 Arctic winter. The principal measurement platforms will be the NASA ER-2 high-altitude aircraft, the NASA DC-8 long-range aircraft, and stratospheric balloons. Additional measurements will be provided by ground-based instruments, sondes, and satellites. A substantial collaboration with the European community is currently under review, and will also involve aircraft, ground, satellite, and theoretical

investigations. The SOLVE observations will include ozone, meteorological variables, particles, long-lived chemicals, and short-lived radicals. During the field deployments, several modelling and theoretical groups will participate in flight planning and data evaluation activities.

SOLVE will be staged from Kiruna, Sweden, and will occur in three phases:

- 1 - early winter (15 Nov. to 15 Dec. 1999),
- 2 - mid-winter (12 Jan. to 5 Feb. 2000),
- 3 - late-winter (24 Feb. to 14 Mar. 2000).

The first phase is timed to see the early winter conditions both prior to and during the appearance of polar stratospheric clouds (PSCs). The second phase is timed to the peak period of PSC activity and chlorine activation. The third and final phase is timed to the period of large ozone loss.

Additional details on SOLVE can be found via the world wide web at <http://cloud1.arc.nasa.gov/solve/>.



Increased Stratospheric Resolution in the ECMWF Forecasting System

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Introduction

The European Centre for Medium-Range Weather Forecasts (ECMWF) has developed versions of its model and data assimilation system with finer and more extensive vertical resolution in both the stratosphere and the planetary boundary layer. 50- and 60-level versions (differing primarily in their boundary-layer resolution) have been extensively tested in data assimilation, forecasting and multi-year simulations. The 50-level version was implemented operationally on 9 March 1999, and the 60-level version is expected to replace it within a few months. Indications of some of the substantial improvements found in stratospheric analyses and forecasts are given here. We describe the simple parameterisation of upper-stratospheric moistening by methane oxidation used in the new model versions, and discuss the overall simulation of stratospheric humidity, which is strongly dependent on the accuracy of the thermal and dynamical representation of the stratosphere.

The revised versions of the forecasting system

The ECMWF model uses a hybrid vertical coordinate that reduces smoothly from a terrain-following coordinate in the lower troposphere to a pressure coordinate in the stratosphere (Simmons and Burridge, 1981; Simmons and Strüfing, 1983). A 31-level resolution was used operationally from September 1991 until March 1999, with levels distributed as shown in the left-hand portion of Figure 1 (plate IV) (Ritchie *et al.*, 1995). The top four levels were located at pressures of exactly 10, 30, 50 and 70hPa, and the pressures at the next two levels were very close to 90 and 110hPa.

The 50-level version of the model used operationally since March is illustrated in the right-hand portion of Figure 1. The distribution of levels is the same as in the 31-level version below 150hPa, and levels between 60 and 5hPa are almost equally distributed in height, with a spacing of 1.5km. The spacing increases above the 5hPa level and the top level is at 0.1hPa.

While this 50-level version of the model was being developed, an independent study of increased vertical resolution in the planetary boundary layer and lower troposphere was yielding promising results (Teixeira, 1999). This led to construction of the 60-level version of the model, which has much finer resolution in the planetary

boundary layer and immediately above, but also a minor rearrangement of stratospheric levels, including an extra level above 10hPa. The 60-level version is providing the basis for further developments, as summarised in the concluding section of this article.

A number of problems had to be addressed in developing the versions of the forecasting system with improved stratospheric resolution, and this led to operational changes already in the 31-level version. These included revisions of the radiative parameterisation, the two-time-level semi-Lagrangian advection scheme, the calculation of saturation specific humidity at low temperatures, the analysis of humidity and the specification of the ozone climatology.

Several other changes were introduced specifically in the 50- and 60-level systems. Rayleigh friction was applied at the uppermost few model levels to ensure a broadly realistic simulation of the mean circulation close to the stratopause. Changes were made to parameters in the semi-implicit scheme to remove noise arising from weak computational instabilities. Non-linear normal-mode initialisation was suppressed in the incremental 4D-Var data assimilation (Rabier *et al.*, 1999) to avoid large initialisation changes resulting from large normal-mode amplitudes at low pressures. In addition, the model was enhanced by introducing the parameterisation of methane oxidation specified later in this article.

New balance operators and background error covariances (Bouttier *et al.*, 1997) were needed for the data assimilation with increased stratospheric resolution, and were based on sets of differences between two- and one-day forecasts verifying at the same time. The first set of 50-level forecasts used for these calculations was made from initial conditions formed by merging 31-level ECMWF analyses with UKMO stratospheric analyses (Swinbank and O'Neill, 1994). Implied upper-level errors were reduced to counter effects of incompatibilities between the ECMWF model and the UKMO analyses. These background statistics were used for two periods of data assimilation and forecasts. A revised set of statistics was then computed from these 50-level forecasts.

General performance of 50-level system

A data assimilation trial using one form or other of the 50-level system was carried out without break from May 1998 until operational implementation, and 50-level assimilations were also run for December 1997

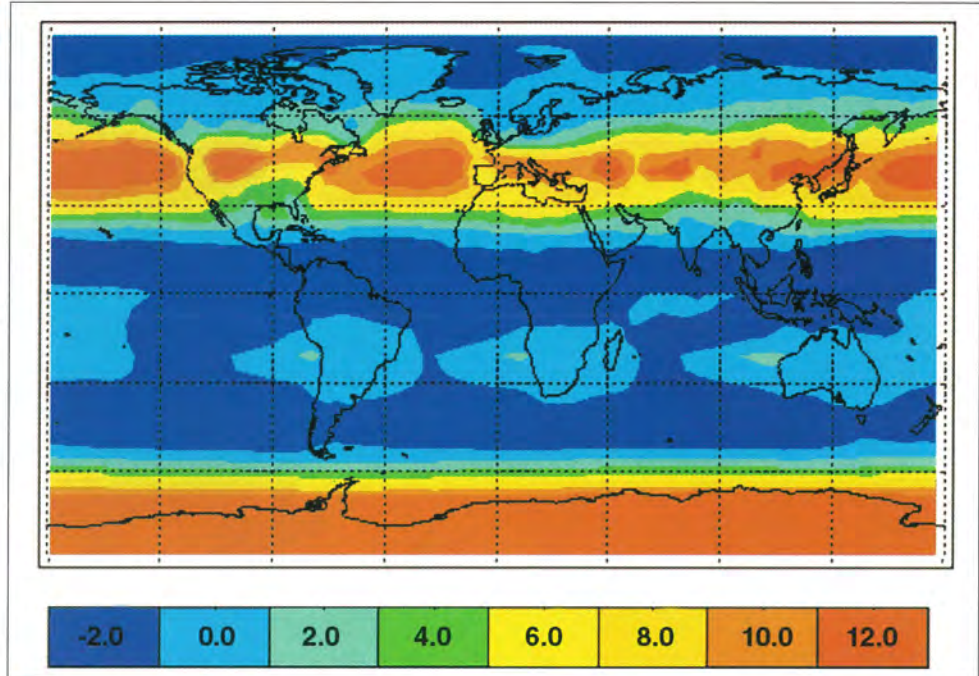
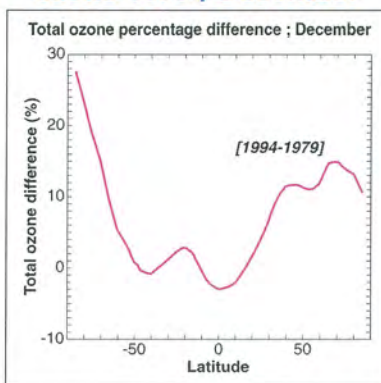
and most of January 1998. Objective verification showed that the enhanced resolution provided substantially better stratospheric analyses and forecasts at the levels up to 10hPa where comparison could be made with results from the standard 31-level system. Verifications of 30hPa temperatures and winds against radiosonde measurements over the northern hemisphere are presented in Figure 2 (plate IV). They are averaged over 165 forecasts from assimilations completed using the original background statistics; 50-level experiments for shorter periods using the revised background statistics gave slightly better results still. The 50-level analyses (day 0) and forecasts (out to day 10) can be clearly seen in Figure 2 to be closer to the verifying radiosonde data than the 31-level analyses and forecasts. Similar plots for other areas and stratospheric levels, and for verification against analyses, confirmed the superior performance of the 50-level system. The only notable exception was in the tropical lower stratosphere, where the 50-level forecasts developed a larger temperature bias, although temperature analyses (and wind analyses and forecasts) were nevertheless better from the 50-level system.

Synoptic study of wintertime stratospheric forecasts also clearly demonstrated that the 50-level system performed better than the 31-level system. This was seen in particular for the two major stratospheric warmings that occurred in the northern winter of 1998/99. The upper panel of Figure 3 (plate V) shows analyses of 10hPa height from the 50-level system for 13, 17 and 20 December, the first period of rapid polar warming. The analyses benefited in this example from assimilation of level-1c radiances from the new AMSU-A instrument on the NOAA-15 satellite (McNally, 1999), which was under separate test at the time. Maps of the height analyses from the 31-level system (not shown) are, however, largely similar. The seven-day forecasts for 20 December from the 31-level system and from the 50-level system without and with the 1c-radiance assimilation are shown in the lower panels. The superior performance of the 50-level versions in capturing the circulation change is evident, with improvement coming directly from the increased vertical resolution but also from the improved radiance assimilation. This is an extreme case, but the stratospheric forecasts from the 50-level version were almost invariably better synoptically than those from the 31-level version in depicting features such as the strength and position of the Aleutian high or the shape and orientation of the polar vortex.

Impact Of Stratospheric Ozone Changes on the Distribution of Tropospheric Species

Simulated OH surface mixing ratio difference (%)

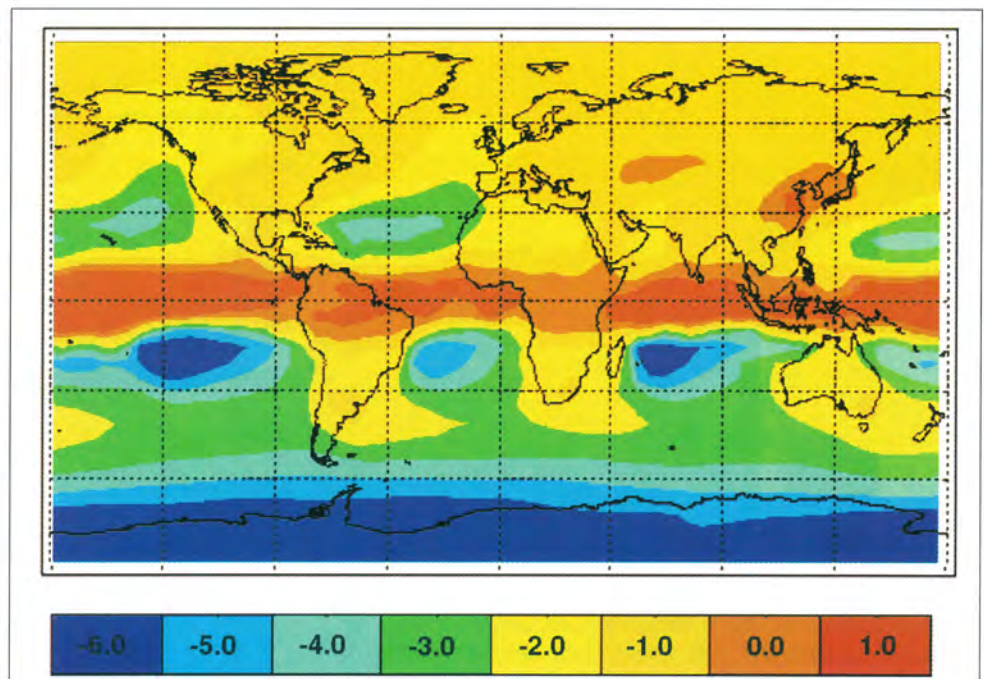
Total ozone 1994 – total ozone 1979 ; December



▲ Figure 2

Percentage change in surface OH distribution (right panel) resulting from stratospheric ozone changes between 1979 and 1994, as shown in the left panel.

Simulated O3 surface mixing ratio difference (%)



▲ Figure 4

Percentage change in surface ozone resulting from stratospheric ozone changes shown in the left panel of Figure 2, from December 1979 to 1994.

An Estimate of the Trend of Stratospheric Chlorine Loading Based on In-situ Balloon-borne Observations

Figure 1

Schematic drawing of the cryogenic whole air sampler. The sampler is designed for operation under stratospheric balloons at ambient pressures down to 5 hPa. In order to prevent contamination by the balloon, the samples are only collected during a valve controlled descent.

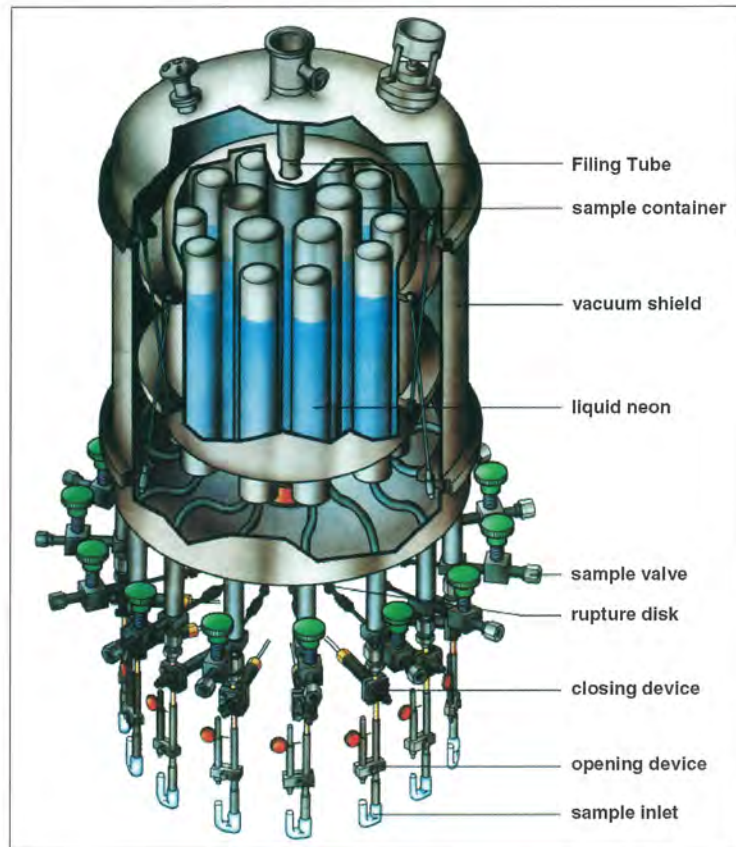
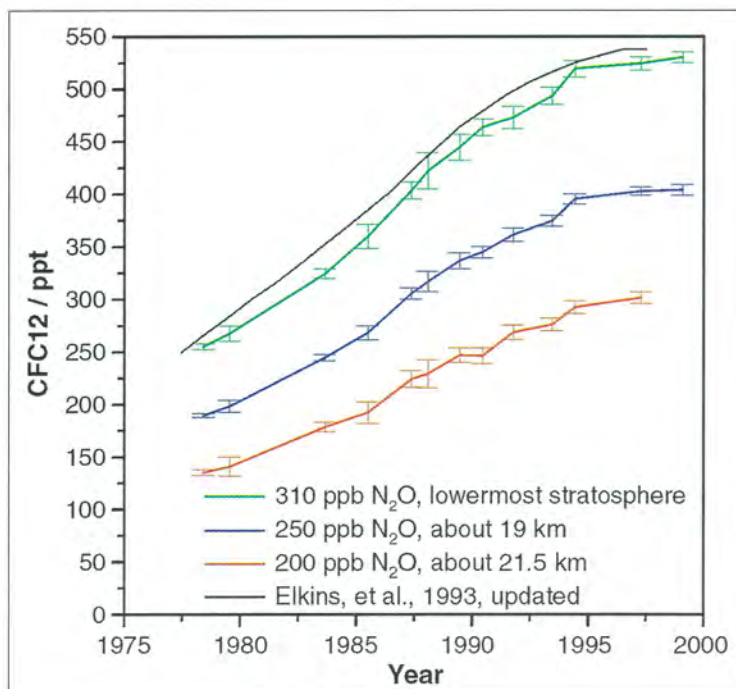


Figure 3

Temporal trend of the mixing ratio of CFC-12 interpolated to 3 different N_2O levels. Data are from both mid- and high-latitudes, the altitudes given are typical for mid-latitudes. A slowing of the increase rate is statistically significant in the lower part of the stratosphere (green and blue line).



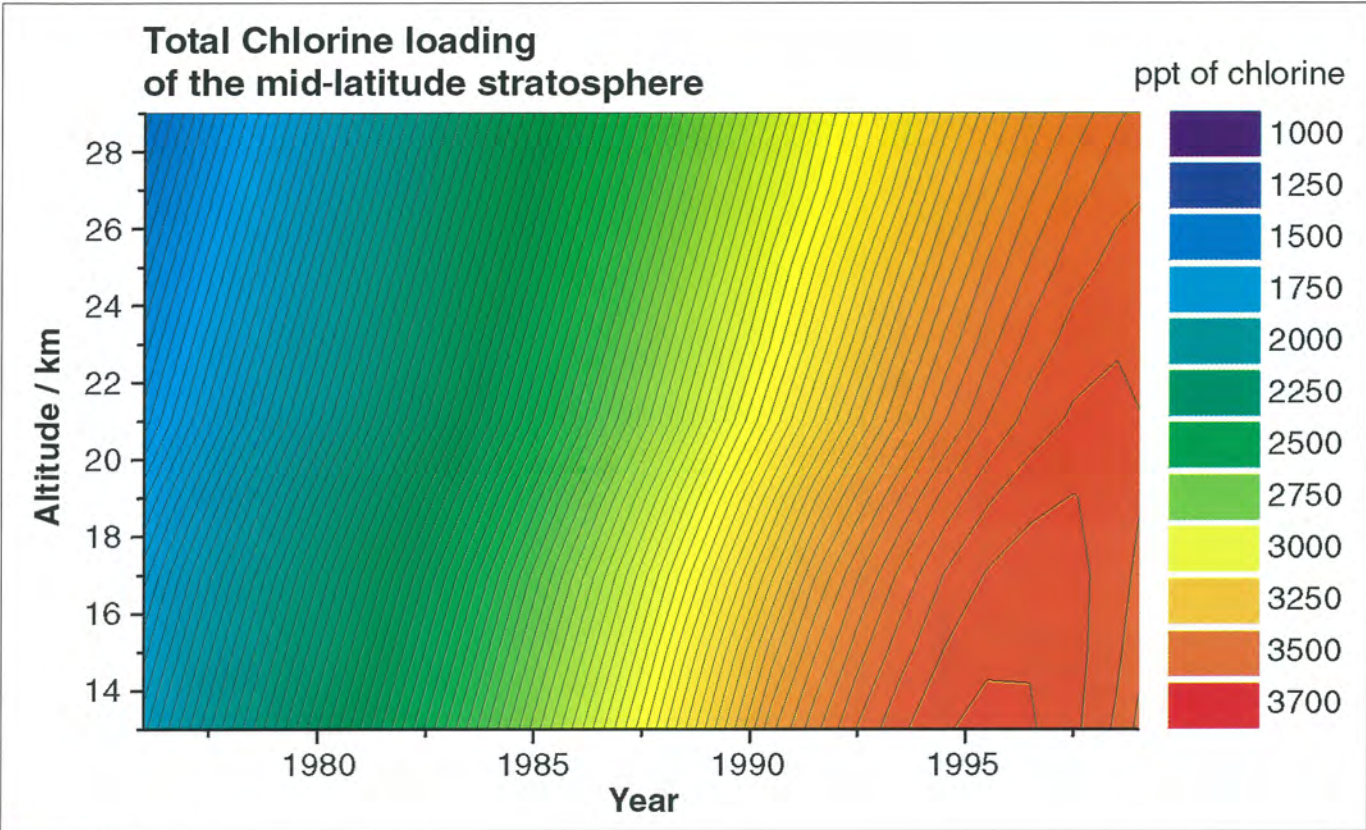


Figure 4 Reconstructed trend of Cl_{total} , derived from the tropospheric trend of the mixing ratios of the 7 most important chlorine source gases (see text for detail). The calculation of the vertical propagation is based on the age profile determined from SF_6 measurements.

III

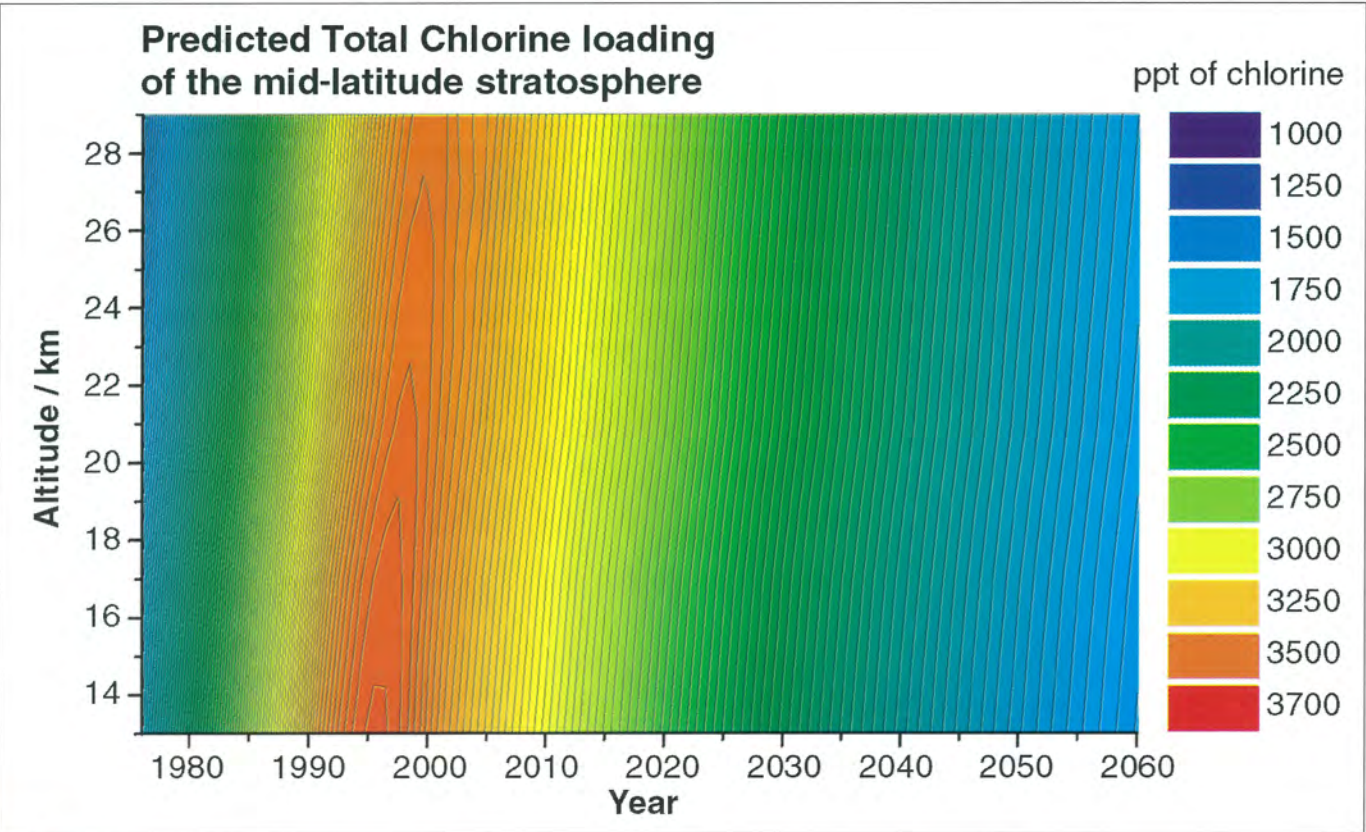


Figure 5 Same as Figure 4 extended into the future based on the lifetimes of the chlorine compounds and assumptions about future emissions (see text). Pre-ozone hole values are expected to be reached again in about 60 years.

Increased Stratospheric Resolution in the ECMWF Forecasting System

Figure 1 ▶

The distribution of the full model levels at which wind, temperature and humidity are represented, for 31-level (left) and 50-level (right) vertical resolutions, plotted for surface pressures which vary from 1013.25 hPa to 500 hPa.

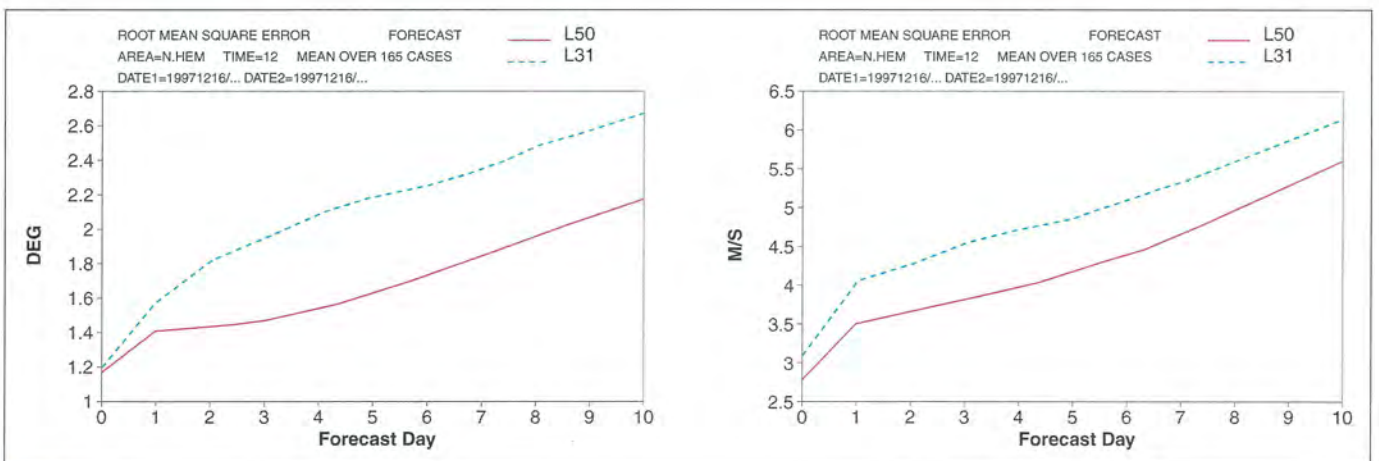
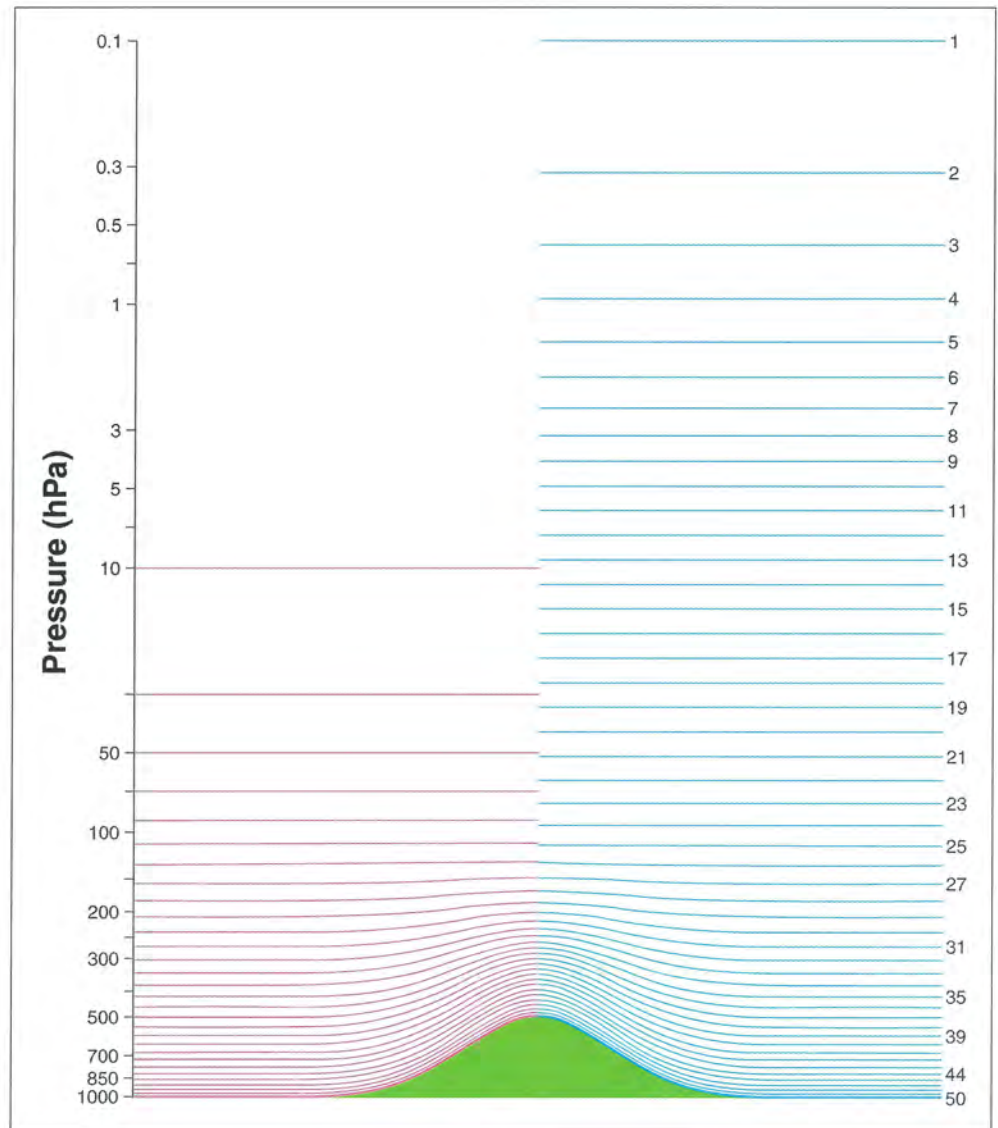
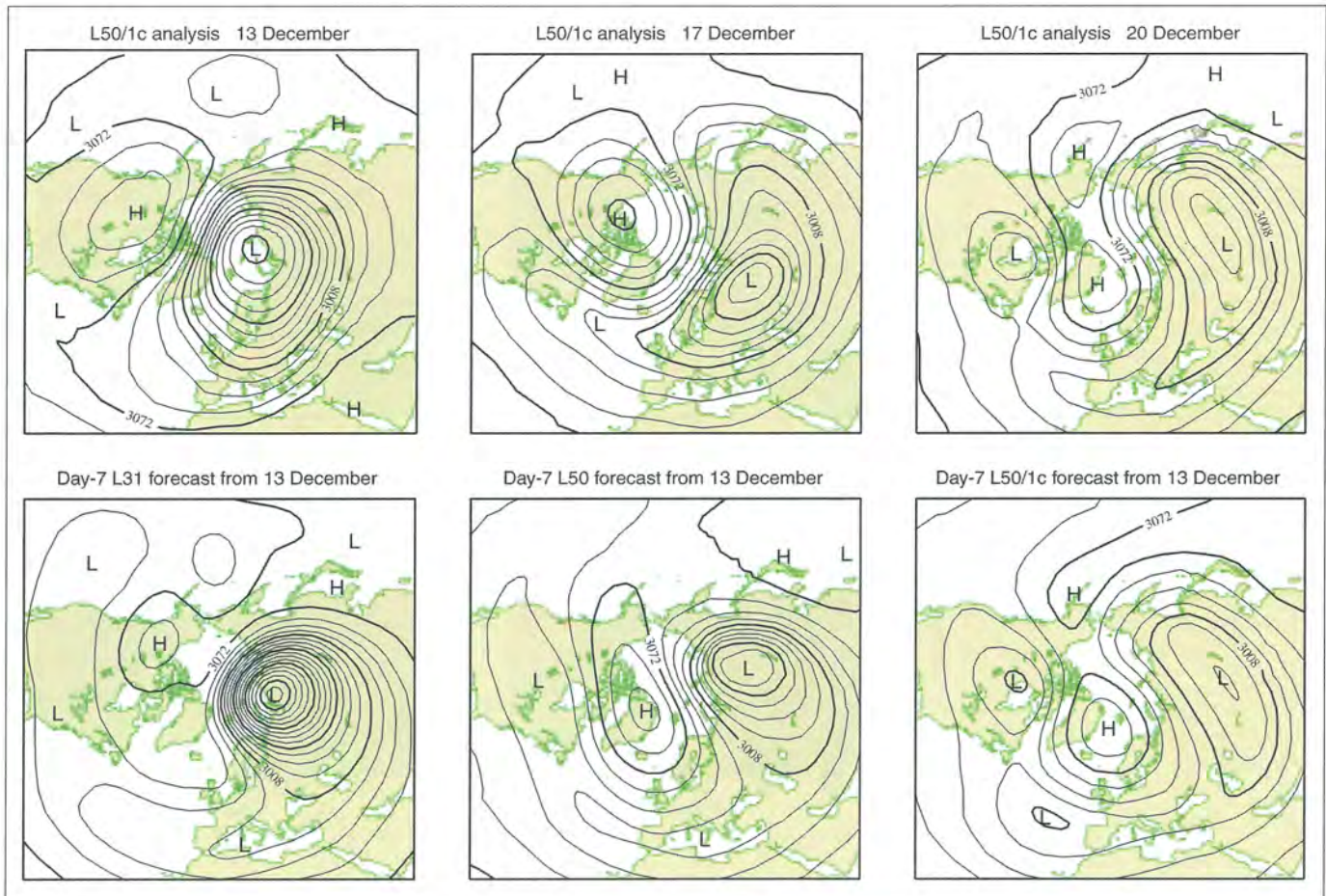


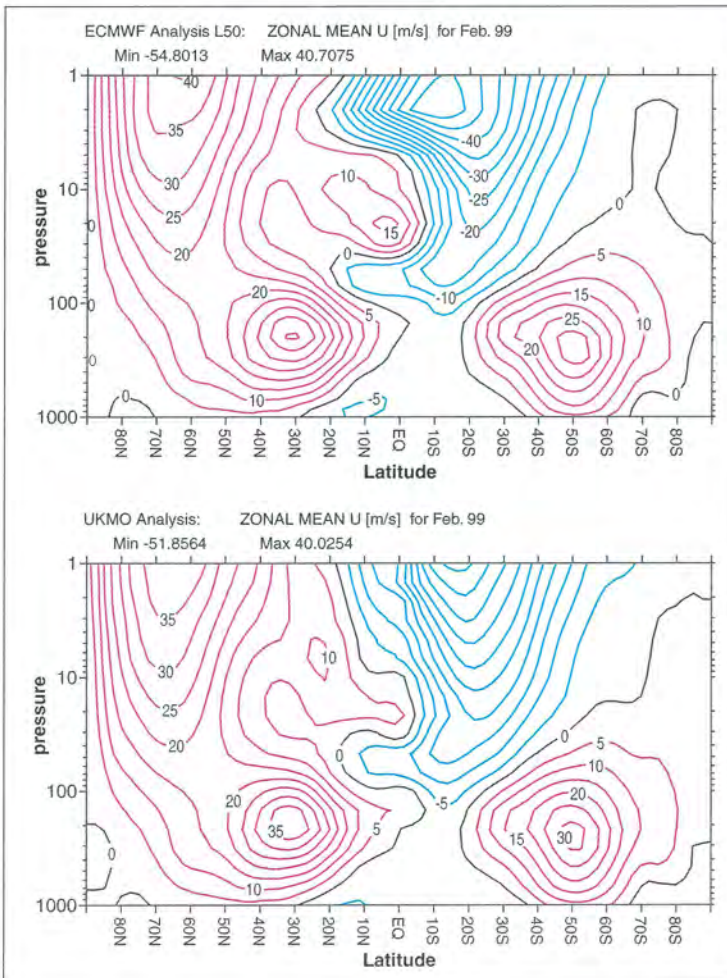
Figure 2 ▲

Root-mean-square errors of 30 hPa temperature (left) and vector-wind (right) analyses (day 0) and forecasts (days 1 to 10) verified against radiosonde measurements over the extra-tropical northern hemisphere, averaged over a set of 165 cases run with 50-level (red, solid) and 31-level (blue, dotted) vertical resolutions.



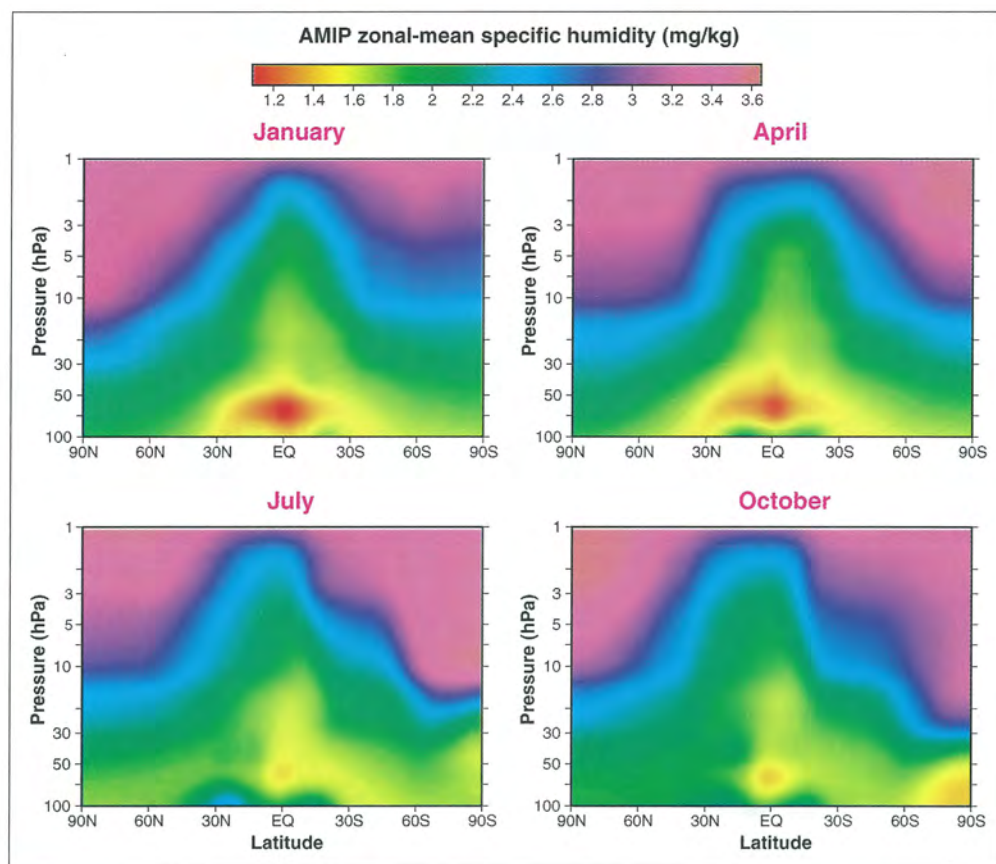
▲ **Figure 3**

10 hPa height analyses for 12UTC 13, 17 and 20 December 1998 from a 50-level assimilation including level-1c radiance data from AMSU-A on NOAA-15 (upper), and seven-day forecasts for 20 December from the standard 31-level (lower left) and 50-level (lower centre) systems, and from the 50-level system with 1c-radiance assimilation (lower right). The contour interval is 16dam.



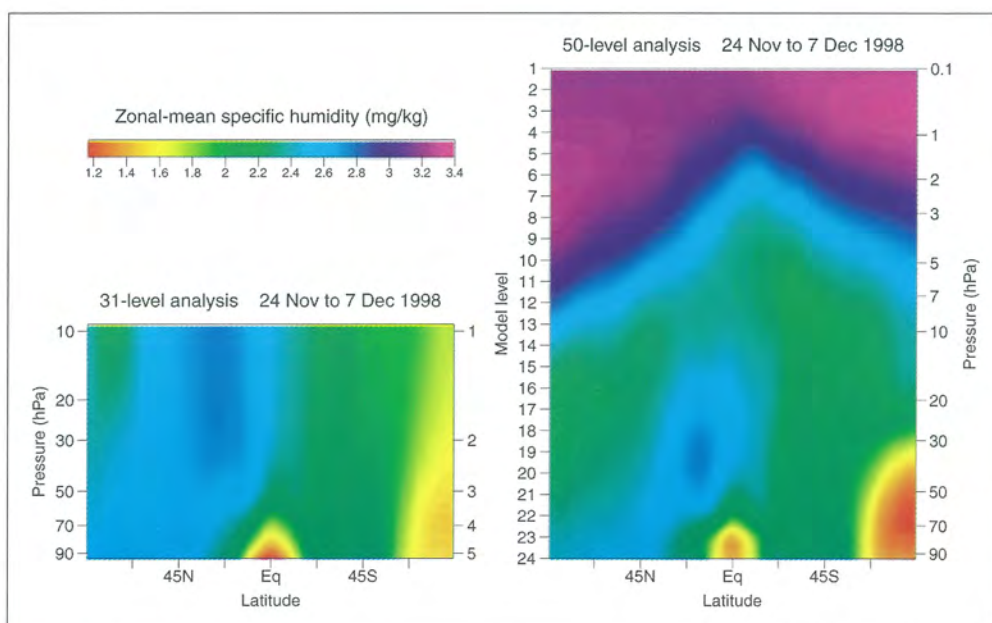
◀ **Figure 4**

Meridional cross-sections of zonal-mean wind averaged for the month of February 1999 from pre-operational 50-level ECMWF analyses (upper) and from the stratospheric analysis system of UKMO (lower). Red contours denote westerlies, blue contours easterlies, and the contour interval is 5ms⁻¹.



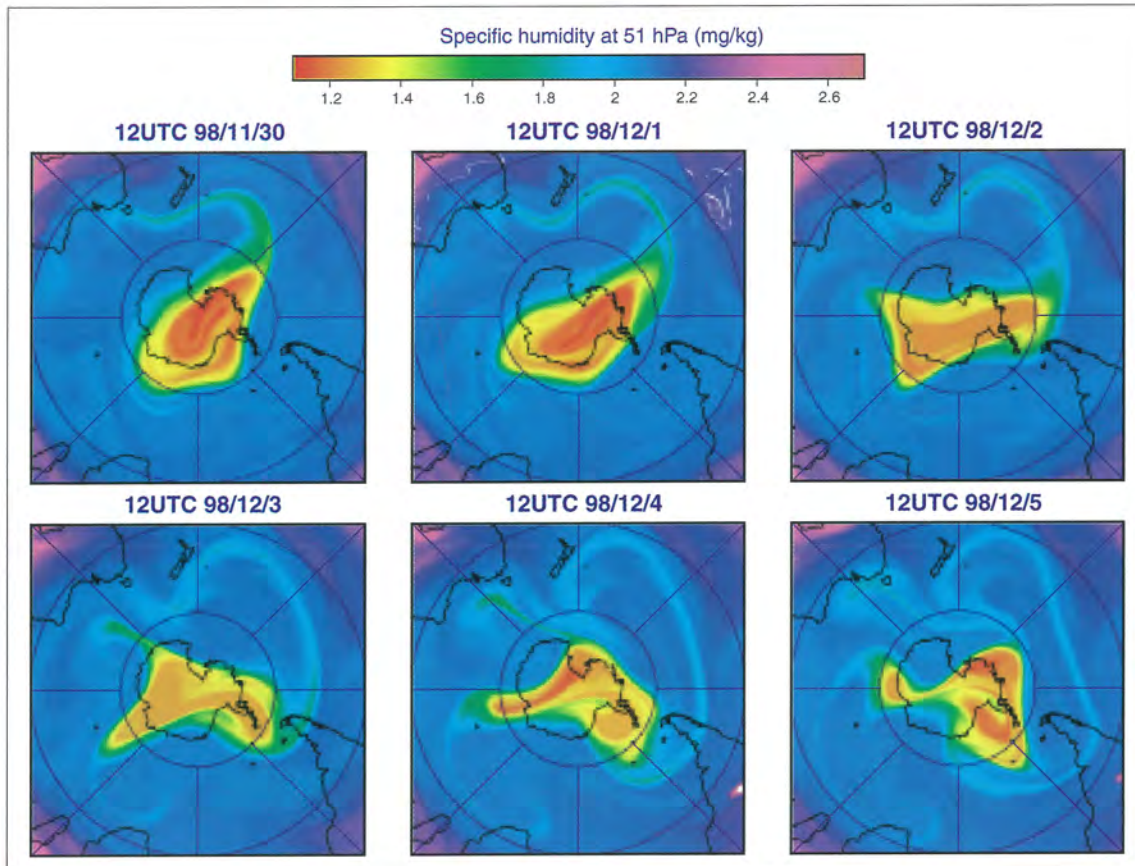
▲ Figure 7

Meridional cross-sections of zonal-mean specific humidity for January, April, July and October from a 60-level AMIP simulation. Each section is a 16-year average for 1983-1998.



▲ Figure 8

Meridional cross-sections of zonal- and time-mean specific humidity from 31- and 50-level analyses.

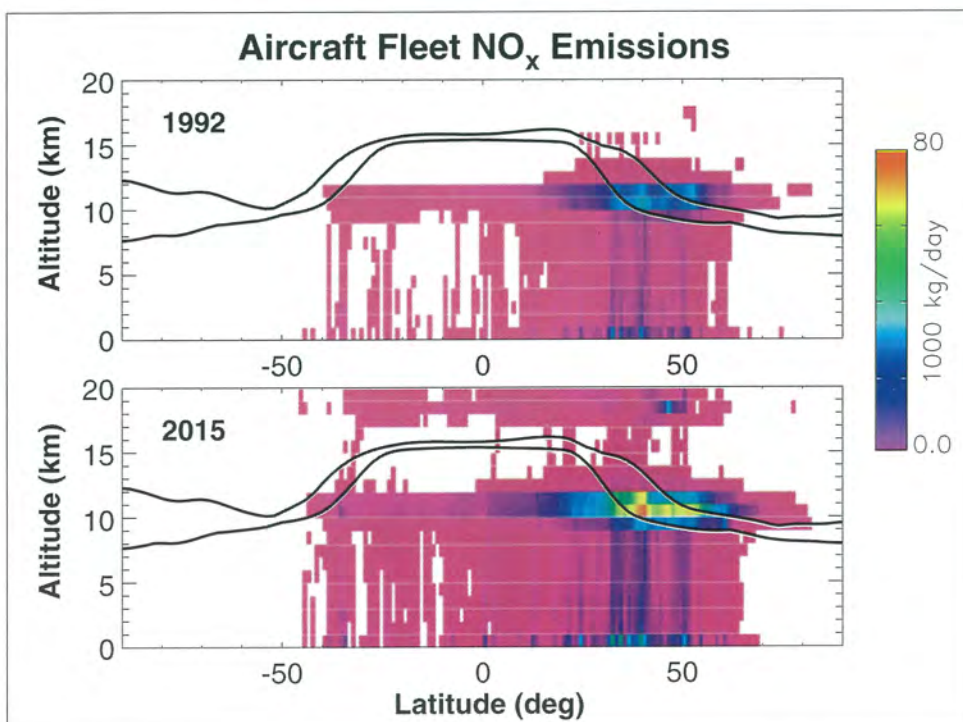


▲ Figure 9

Specific humidity at close to 51 hPa from 50-level analyses for consecutive days from 30 November to 5 December 1998.

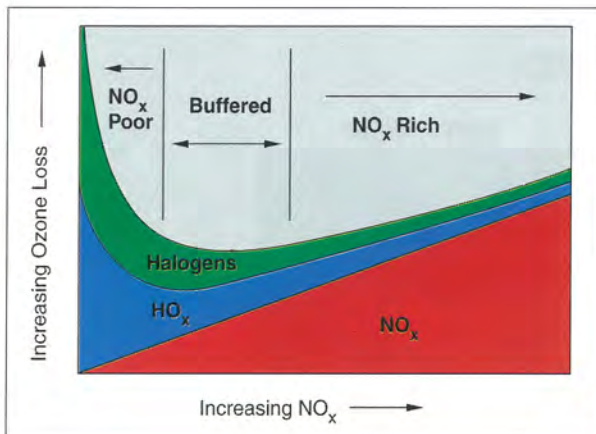
VII

Assessing the Impact of Aircraft Emissions on the Stratosphere



◀ Figure 1

Annual average aircraft NO_x emissions as a function of altitude and latitude for 1992 and 2015 from the NASA AEAP data base. The emissions for 2015 assume a fleet of 500 HSCTs operating at $\text{EI}(\text{NO}_x) = 5\text{g}(\text{NO}_2)/\text{kg}(\text{fuel})$. The range of monthly zonal mean tropopause heights for 1993 are superimposed as solid black lines (from National Centers for Environmental Prediction data).

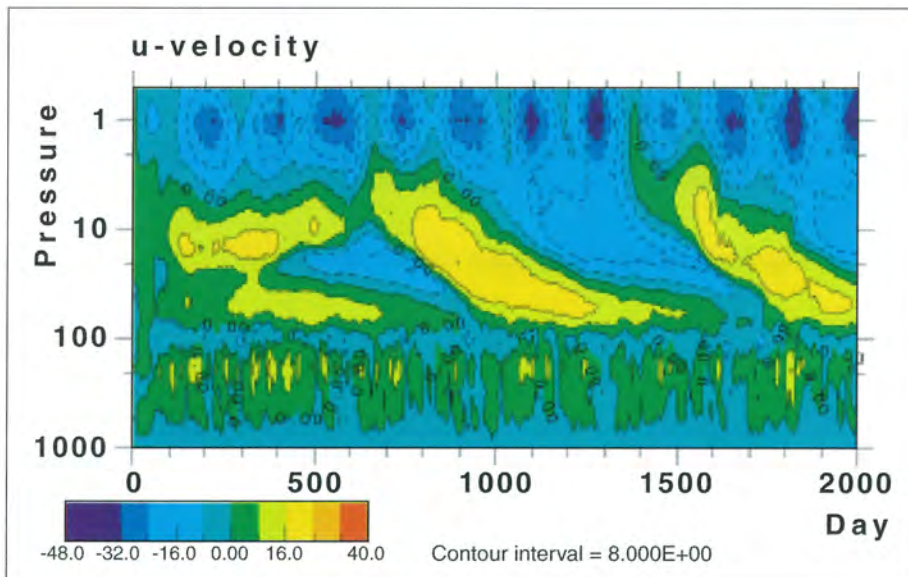


◀ **Figure 4**

Schematic representation of the response of stratospheric ozone loss to changing NO_x , assuming fixed Br_y , Cl_y , and OH (adapted from Wennberg *et al.*, 1994).

Japanese contributions to SPARC research presented at the 1998 SSG meeting in Nagoya

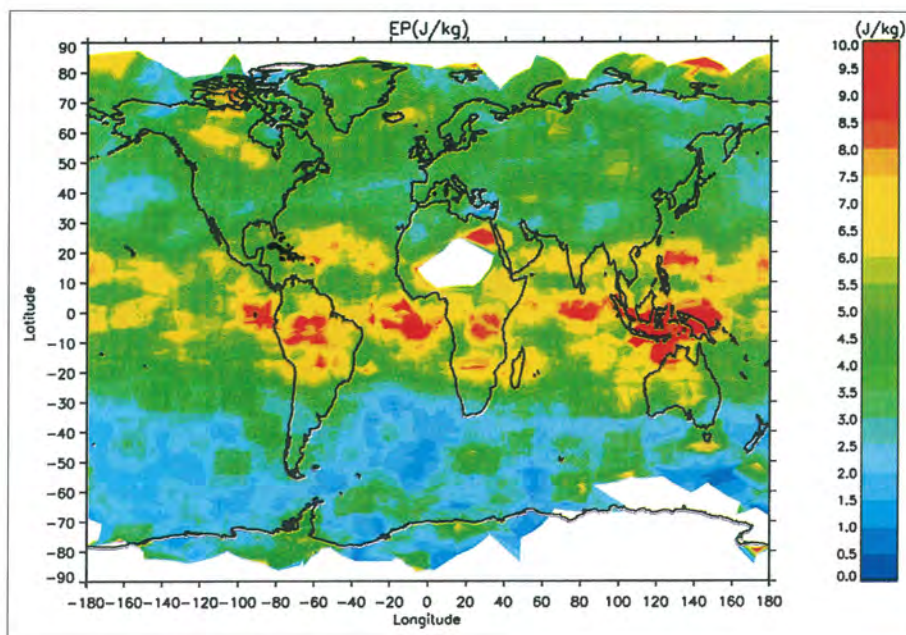
Simulation of the QBO in a General Circulation Model



◀ **Figure 1**

Time-height section of the simulated zonal-mean wind over the equator. The time coordinate ranges from day 0 to day 2000. The contour interval is 8ms^{-1} . The solid lines represent westerlies and the dashed lines easterlies.

A Global Distribution of Gravity Activity in the Stratosphere



◀ **Figure 1**

Global distribution of E_p from the GPS/MET data at 20–30 km in November–February. The E_p value is averaged in an area extending 10° and 20° in latitude and longitude, and the centre co-ordinates are shifted every 1° and 2° , respectively.

Figure 4 (plate V) shows the zonal-mean zonal flow for February 1999 from the 50-level analyses and from the UKMO stratospheric analyses. There is a reassuring agreement between the two analyses everywhere except in the tropical middle and upper stratosphere. The westerly tropical maximum at 20hPa is about 10ms^{-1} stronger in the ECMWF analysis, which also has much stronger easterlies higher up. It is not surprising that differences are large in the tropical stratosphere, because of difficulty in modelling the quasi-biennial oscillation (QBO) and because of the paucity of wind observations and the limited extent to which tropical wind analyses can be controlled by assimilating satellite radiance measurements. There is evidently a need for further study of the realism of the tropical stratospheric wind analyses from the new system, particularly to examine performance over a complete cycle of the QBO.

Figure 5 presents sample objective verifications of tropospheric forecasts from the 50- and 31-level systems. It is based on the extensive sets of forecasts available with the original background statistics, and scores are averaged over the 154 forecasts that can be verified against analyses produced by the assimilation that provided the initial conditions. The 50-level version gives small but significant improvements in such mean tropospheric verifications throughout the medium range.

A subset of the forecasts included in Figure 5 has been repeated starting from analyses produced using the revised background statistics. Hemispheric verification scores were similar to those from the original 50-level system, but there were some marked regional differences. In particular, much less improvement was found over Europe with the revised background statistics, whereas the converse was the case for North America. Further study of the specification of the background statistics is in progress.

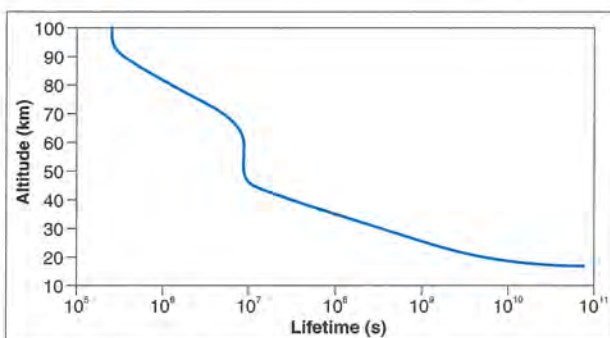


Figure 6. Combined photochemical lifetime $(k_1 + k_2)^{-1}$.

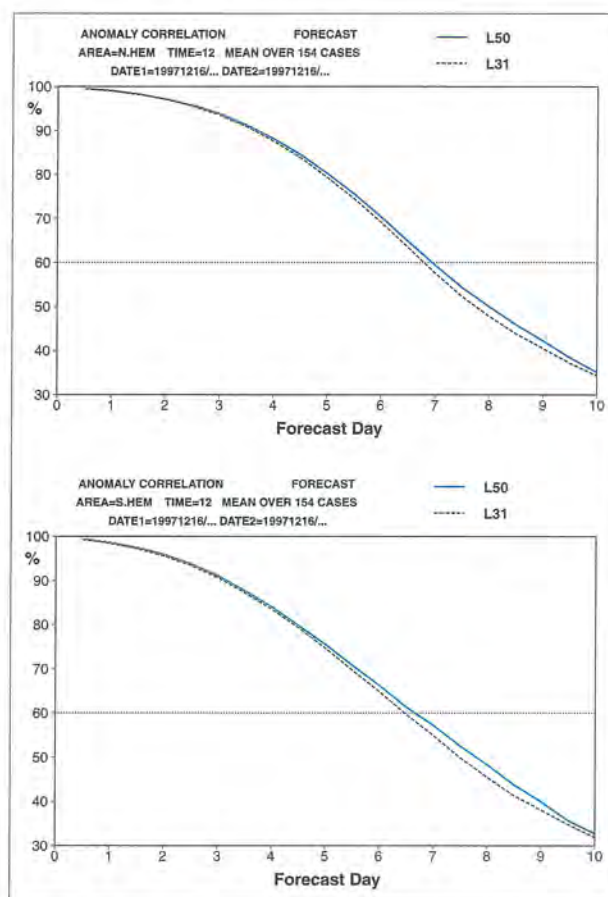


Figure 5. Anomaly correlations of 500hPa height averaged over 154 cases run with 50-level (blue) and 31-level (black) vertical resolutions, for the extra-tropical northern (top) and southern (bottom) hemispheres.

The treatment of methane oxidation

ECMWF analyses and simulations have typically been too dry in the stratosphere, because of the absence of a representation of the high-level source of water vapour due to the oxidation of methane (Simmons *et al.*, 1999). For example, in a 19-year simulation using observed sea-surface temperatures carried out as a contribution to the Atmospheric Model Inter-comparison Project (AMIP; Gates, 1992), a 50-level T63 version of the model dried gradually over the first decade of integration. Upper stratospheric specific humidities fell to around 1.75mg/kg , and were then maintained at about this value over the second half of the integration period. The equivalent mixing ratio is 2.8ppmv . This is not unreasonable in the absence of methane oxidation. Photochemical calculations and observations (e.g. Brasseur and Solomon, 1984; Bithell *et al.*, 1994) indicate that the sum of the mixing ratio of water vapour and twice that of

methane is approximately constant over much of the stratosphere, with a value close to or a little above 6ppmv . Adding twice the tropospheric methane mixing ratio of 1.7ppmv to the model water-vapour value of 2.8ppmv gives 6.2ppmv .

A simple parameterisation of the moistening by methane oxidation has thus been developed. The basic assumptions are that the volume mixing ratio of water vapour $[\text{H}_2\text{O}]$ increases at rate $2k_1[\text{CH}_4]$ and that there is a steady balance between the mixing ratios of methane and water vapour:

$$2[\text{CH}_4] + [\text{H}_2\text{O}] = 6\text{ppmv}$$

The rate of increase of water vapour (in ppmv) is then

$$k_2(6 - [\text{H}_2\text{O}])$$

In terms of specific humidity, q , the source is

$$k_1(Q - q)$$

where Q has the value 3.75mg/kg .

For completeness, an extra photolysis term $-k_2 q$ is included in the mesosphere, although it has little effect for the 50- and 60-level resolutions discussed here.

k_1 and k_2 are specified as functions of pressure, with k_1 equal to $(100\text{ days})^{-1}$ at pressures less than 1hPa . The vertical profiles of k_1

and k_2 are chosen such that the dependence on altitude of the combined photochemical lifetime, $(k_1 + k_2)^{-1}$, shown in Figure 6, is similar to that presented by Brasseur and Solomon (1984). The slow time scale of the process in the stratosphere enables latitudinal and temporal variations in relaxation rate to be neglected in the first instance.

Stratospheric humidity in simulations and analyses

A new 20-year AMIP simulation including the parameterisation of methane oxidation has been run using the 60-level vertical resolution, and T159 horizontal resolution. After an initial adjustment period of a few years, the stratospheric humidity exhibits a fairly regular annual cycle, in reasonable qualitative agreement with processed data from the UARS satellite (Randel *et al.*, 1998). Latitude/pressure sections showing 16-year simulated means for January, April, July and October are presented in Figure 7 (plate VI). The consequences of general ascent of relatively dry air throughout the tropical stratosphere, and high-latitude wintertime descent (and summertime ascent) of air moistened by methane oxidation can be clearly seen. In the upper stratosphere

the model underestimates the relative dryness of winter polar regions, which may arise both from an excessive source in these regions and from a deficient wintertime descent of dry air from the poorly-resolved mesosphere. The dryness of air in the cold Antarctic (but not Arctic) lower stratosphere in winter and spring is quite well represented, a sign of realistic simulated temperatures in the polar winter stratosphere. The model reproduces the upward tropical transfer of the annual cycle in water vapour (the "tape-recorder" effect discussed by Mote *et al.*, 1996), but is too diffusive in its representation of this feature. The simulation is drier in the tropical lower and middle stratosphere by some 30% compared with UARS data (and drier than earlier simulations), temperatures at the tropical tropopause being about 2K too cold in this version of the model.

No observations of stratospheric humidity are used in the ECMWF analysis system. Humidity simply evolves during the assimilation according to the model's dynamical and parameterised physical processes, with winds, temperatures and tropospheric humidity constrained by the analysis process. The parameterisation of methane oxidation was activated on 17 June 1998 in the pre-operational data assimilation cycles using the 50-level version of the model. The time scales of methane oxidation and vertical transport in the stratosphere are such that it requires several seasons for the stratospheric analyses to adapt fully to the change in resolution and parameterisation. It has nevertheless been instructive to compare 31- and 50-level analyses. Meridional cross-sections of zonal-mean specific humidity averaged over the last week of November and the first week of December 1998 are shown in Figure 8 as an example.

The parameterisation of methane oxidation has had little obvious effect below 10hPa by the time shown in Figure 8. Lower stratospheric differences have arisen instead mostly from the resolution difference. The 31-level analyses generally exhibited a too rapid upward transfer of relatively moist or dry air introduced at the tropical tropopause (Simmons *et al.*, 1999). 50-level simulations were much more realistic in this respect, although upward transfer in the deep tropics was still faster than observed, as in the 60-level AMIP simulation discussed above. Figure 8 shows that the benefit seen in the high-resolution simulations carries over into the 50-level analyses. Relatively moist air was introduced into the stratospheric analyses in the boreal subtropics over the summer of 1998, and by December the maximum in humidity had reached 10hPa in the 31-level analyses, but was still below 30hPa in the 50-level analyses. The maximum was located further

north in the 31-level system, and much more moistening of the northern extratropics occurred in this system. In high southern latitudes, the 31-level system was moister than the 50-level system in the lower stratosphere at this time, but was drier at 10hPa. The latter was due partly to colder 10hPa temperatures (and more condensation) in winter and early spring in the 31-level system and partly to descent of moister air from the upper stratosphere in the 50-level system. By December, however, there was mean ascent at high southern latitudes, drying the middle stratosphere.

Daily analyses of humidity over the southern hemisphere from 30 November to 5 December 1998 are presented in Figure 9, for the model level close to 51hPa from the 50-level system. The driest air is located in the decaying, highly-perturbed westerly vortex, where dehydration by the parameterised condensation process occurred earlier when temperatures were sufficiently cold. The maps show evolving filamentary structure in the humidity field, and indications of mixing. Observations of quantities that behave largely as passive tracers can be used effectively to extract information on the wind field in a 4D-Var assimilation system. This is a prime motivation for ongoing work to include stratospheric ozone as a variable of the ECMWF system.

Further developments

The operational implementation of the 50-level version of the forecasting system in March 1999 was accompanied by introduction of a new fast radiative transfer calculation for the assimilation of radiance data from satellites (Saunders *et al.*, 1999). The new calculation and availability of model background fields that cover the whole of the stratosphere as well as the troposphere have been utilised in a new scheme for the assimilation of level-1c radiances, including data from the new AMSU-A instrument (McNally, 1999). Substantial beneficial impact in a sudden-warming case has been shown in Figure 3, and extensive pre-operational trials demonstrated an overall improvement in stratospheric forecasts due to this change. Operational implementation took place in May 1999. Further improvement is expected to follow the launch of additional satellites carrying AMSU-A.

Other work has been concentrated on the 60-level system. Improved treatments of cloud and convection (reducing tropical lower stratospheric temperature biases) and a new specification of background error statistics are under test, and ozone will be included as a model variable. Operational implementation is expected within a few months.

Work is also in hand to use the 60-level system for the new ECMWF re-analysis,

ERA-40, covering the period from mid-1957 to the present day. Preparatory one-year test assimilations have already shown that the 60-level system is better than the 31-level system in analysing a descending westerly phase of the QBO. ERA-40 will include an analysis of ozone based on HIRS radiances and SBUV, SBUV/2 and TOMS products. Ozone analysis will also be carried out operationally, for which use of GOME data from ERS-2 and later the METOP satellite is a further possibility. Operational fields including ozone will be supplied to the European Space Agency in support of the generation of near-real-time products from ENVISAT. ECMWF will also carry out validation and monitoring of products from the ENVISAT ozone-measuring instruments GOMOS, MPAS and SCIAMACHY.

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Assessing the Impact of Aircraft Emissions on the Stratosphere

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Background

Research into the impacts of aircraft exhaust on stratospheric chemistry and climate began with the Climate Impact Assessment Program (CIAP) in the 1970s, well before chlorofluorocarbons and CO₂ climate warming became prominent. The scientific issues associated with assessing the impact of aircraft are central to understanding stratospheric chemical, dynamical, radiative, and microphysical processes. For the past decade, the NASA Atmospheric Effects of Aviation Project (AEAP) has been the U.S. focal point for research on aircraft effects. In conjunction with U.S. basic research programs, AEAP and concurrent European research programs have driven remarkable progress in understanding the atmospheric effects of aviation, culminating in two major assessment reports released in 1999 (IPCC, 1999; Kawa *et al.*, 1999). The former report primarily focuses on aircraft effects in the upper troposphere, with some discussion on stratospheric impacts. The latter report focuses entirely on the stratosphere. The current status of research regarding aviation effects on stratospheric ozone and climate, as embodied by the findings of these reports, is reviewed here.

Two main classes of aircraft are important to consider for the current and future stratosphere. The first is the existing commercial fleet that flies at subsonic speeds in the altitude region around 11km. These flights take place in the lower stratosphere about 20% of the time. The commercial fleet is projected to grow by approximately a factor of 4 in the next 50 years. The second class of aircraft is the proposed, hypothetical fleet of high-speed civil transport (HSCT) aircraft that would cruise at supersonic speeds (Mach 2.4, 2600km/h) near 19km

altitude, the middle of the stratospheric ozone layer. The HSCT follows on the supersonic transport (SST) aircraft first discussed in the 1970s (Johnston, 1971). Recently the HSCT development effort, supported by NASA and the aerospace industry (Wilhite and Shaw, 1997), has been suspended. Thus the deployment of a substantial HSCT fleet will probably not occur in the next 20 to 30 years. The method, problems, and findings of the HSCT assessment, however, are relevant to numerous fundamental and applied problems in stratospheric research.

The aircraft emissions of primary concern for stratospheric ozone and climate are oxides of nitrogen (NO_x), water (H₂O), and aerosol particles and particle precursor gases. Unburned hydrocarbons, carbon monoxide, and soot emissions are also considered but their impact in the stratosphere is generally considered negligible and will not be further discussed.

Nitrogen oxides are involved in the principal loss process for ozone in the middle and upper stratosphere, and thus, exhaust that is transported to these regions will reduce ozone. In the lower stratosphere, NO_x radicals moderate ozone loss due to other radical species (hydrogen oxides (HO_x), chlorine oxides (ClO_x), bromine oxides (BrO_x)); thus addition of NO_x from aircraft exhaust can either increase or decrease ozone in this region depending on the relative balance among the radicals. Increasing NO_x in the upper troposphere leads to increased ozone. In the polar winter stratosphere, nitrogen oxides participate in formation of polar stratospheric clouds (PSCs), which lead to large seasonal ozone loss, e.g., the Antarctic ozone "hole". The net effect of increasing NO_x depends on interactions between transport, heteroge-

neous chemistry, homogeneous chemistry, and the composition of the unperturbed atmosphere.

Future HSCT emissions could increase lower stratospheric water vapour by about 0.5ppmv (10 to 15% for a fleet of 500 aircraft) affecting climate, aerosol processes, and rates for chemical reactions. Warming of the lower atmosphere as a result of increased stratospheric water is predicted to be the main climatic effect of HSCTs. Since water is the source of HO_x radicals, increased water leads directly to higher concentrations of HO_x. The composition and growth of aerosol particles, including PSCs, is influenced because increased water vapour raises the condensation temperature. Over most of the stratosphere, however, the temperature is too warm and humidity too dry for the emission of water from aircraft to produce persistent clouds. Increased water also increases the reactivity of aerosol toward gases, such as HCl and ClONO₂, thus influencing the relative concentrations of radical species. Model calculations suggest that the associated increase in HO_x is as important as changing NO_x in determining ozone change.

Repeated observations since 1994 consistently show that a large number of ultrafine (<20nm diameter) aerosol particles exist in jet engine exhaust plumes, and that particle production increases as the sulphur content of fuel increases. Emission of small particles and sulphur dioxide (SO₂) can potentially increase aerosol surface area throughout the stratosphere, which suppresses NO_x and enhances ozone loss by ClO_x and HO_x. Proposed mechanisms for small particle formation are still controversial, and the effects on particle abundance throughout the stratosphere are uncertain, but atmospheric ozone is definitely sensitive

to changing aerosol conditions (WMO, 1999). In the upper troposphere aircraft particle production is a major concern because it may lead to changes in cirrus cloud properties and associated cloud radiative forcing (see IPCC, 1999).

The key factors that determine the atmospheric impacts of aircraft emissions are:

- The quantity of exhaust deposited (water, NO_x , particle mass and surface area) and its location in altitude and latitude;
- Atmospheric transport, especially the eventual accumulation of exhaust products in various parts of the stratosphere;
- Chemical reactions of the exhaust products with aerosols, atmospheric radicals, and ozone;
- Microphysics (formation, growth, coagulation, and settling) of aerosol particles in the atmosphere; and
- The background state (meteorology and composition) of the atmosphere onto which the aircraft perturbation is superimposed.

Because the impact of the current fleet is not discernible from other sources of variability in the stratosphere and the future fleet does not exist yet, we must simulate these processes and estimate the impacts in numerical models. Much of the uncertainty in the results derives from uncertainty in atmospheric modelling. Progress and uncertainties associated with key issues in calculating the impact of aircraft in the stratosphere are discussed below. Most of the discussion pertains to the effect of emission by HSCTs directly into the stratosphere. The impacts of subsonic aircraft in the stratosphere are also briefly discussed.

Aircraft Emissions

The three dimensional (3D) deposition of aircraft exhaust into the atmosphere is known to relatively good accuracy, within about 20% (IPCC, 1999). Projections of future fuel use and exhaust deposition are more uncertain, and the impact of varying assumptions for the future (e.g., number of aircraft deployed and timing of introduction into service) is tested parametrically by running the models with a variety of different scenarios (e.g., Figure 1) (plate VII). The specific exhaust emissions are expressed as an emission index (EI) in grams of emitted species per kilogram of fuel used. Current engine EIs are well known, and the gas-phase chemistry taking place in the aircraft near-field plume are generally confirmed by in-situ measurements with one notable exception.

More small volatile particles are formed in jet aircraft exhaust than previously expected, and the mechanism and control of this production are currently not well understood. Important progress has been made

with new direct measurements for existing aircraft that show formation of volatile ultra-fine aerosol particles in exhaust plumes from all aircraft sampled. In-flight measurements indicate that the number of particles is dependent on fuel sulphur content, while altitude chamber measurements show that sulphur emissions at the engine exit plane are primarily SO_2 . These observations support earlier inferences of a composition of sulphuric acid (H_2SO_4)/ H_2O for the volatile particles detected in the plume, but the particle emission yield for the HSCT is still very uncertain. The atmospheric effect depends on the fraction of the emitted sulphur that is in particle phase versus gas since the SO_2 gas is oxidised after mixing with ambient air and deposited on existing particles giving a smaller increment to total sulphate particle surface area. Model calculations testing the atmospheric sensitivity to a range of particle emissions under differing atmospheric aerosol loading, which are mainly controlled by volcanic eruptions, result in a range of impacts larger than that attributed to nitrogen oxides or water.

Transport

The effect of aircraft exhaust depends strongly on its accumulation and dispersion within the stratosphere. The exhaust distribution depends on the aggregate over many different transport processes; in particular, transport from mid-latitude flight corridors into the tropics, strength of meridional circulation, and transport out of the stratosphere into the troposphere. These same processes also determine the distribution of source gases in the background atmosphere. Concern about transport arises from simulations of the current atmosphere. To the extent that the model distributions of tracers and ozone do not match reality, the aircraft perturbation will be superimposed on an incorrect background atmosphere. Moreover, the transported distribution of the aircraft exhaust may not be correct. Models used in the HSCT assessments show a large range (greater than a factor of two) in the peak accumulation and dispersion of the HSCT exhaust (Figure 2). An even greater difference among models is seen for the distribution of subsonic exhaust in the stratosphere (below).

Observations have begun to constrain several key components of transport necessary to predicting the distribution of aircraft exhaust. In-situ measurements of chemical tracers have been obtained within the previously data-sparse tropics. These observations permit quantitative diagnosis of key pathways for dispersal of HSCT exhaust into the upper stratosphere where chemical sensitivity to NO_x is high. Measurements of CO_2 , SF_6 , and HF over a range of latitude

and altitude have enabled mean ages of air in the stratosphere to be determined. Age of air is a directly measured diagnostic related to stratospheric residence time and hence to the potential accumulation of HSCT exhaust in the stratosphere. The quantitative analysis of tropical transport and mean age provides stringent new tests of transport within numerical models. Figure 3 shows that models significantly underestimate mean age in the lower stratosphere, suggesting that their stratospheric residence time is too short. On the other hand, model comparisons with measured NO_y (a long-lived tracer in the lower stratosphere) profiles are distributed both higher and lower than the observations, although both background and aircraft delta- NO_y amounts are correlated among models with their calculated age as generally expected. Thus it remains difficult to determine which model transport and aircraft exhaust accumulation is most accurate.

One approach to resolving these uncertainties has been use of 3D atmospheric models for the first time in the HSCT assessment. Three-dimensional models incorporate a more physically realistic representation of the atmosphere than 2D models. The modular design of the AEAP Global Modelling Initiative 3D model has made it possible to test the different components of the model (e.g., the numerical transport algorithm and the source of the wind and temperature fields). Objective criteria for performance with respect to data have been applied. Thus, we discern differences among models in their response to the HSCT perturbation and begin to weigh their results. A major model-measurement comparison and model intercomparison (M&M II) has been conducted (Park *et al.*, 1999), and all models in the AEAP assessment have been tested in comparison to a standard set of performance benchmarks. Also, the 2D models have incorporated more complete process representations including those for aircraft aerosol exhaust, PSCs, heterogeneous reaction rates, and wave-driven mixing. These model developments give us more confidence in our physical representation of the stratospheric system.

Chemistry

The local response of ozone to changes in NO_x , H_2O , and aerosol is becoming increasingly well understood. Through a combination of laboratory experiments, observations of atmospheric radicals and reservoir species (including the first in summer polar regions), and improved approaches to interpreting these observations, uncertainties in chemistry have been reduced. This establishes confidence that we are not missing significant reactions or unknown species that would alter the

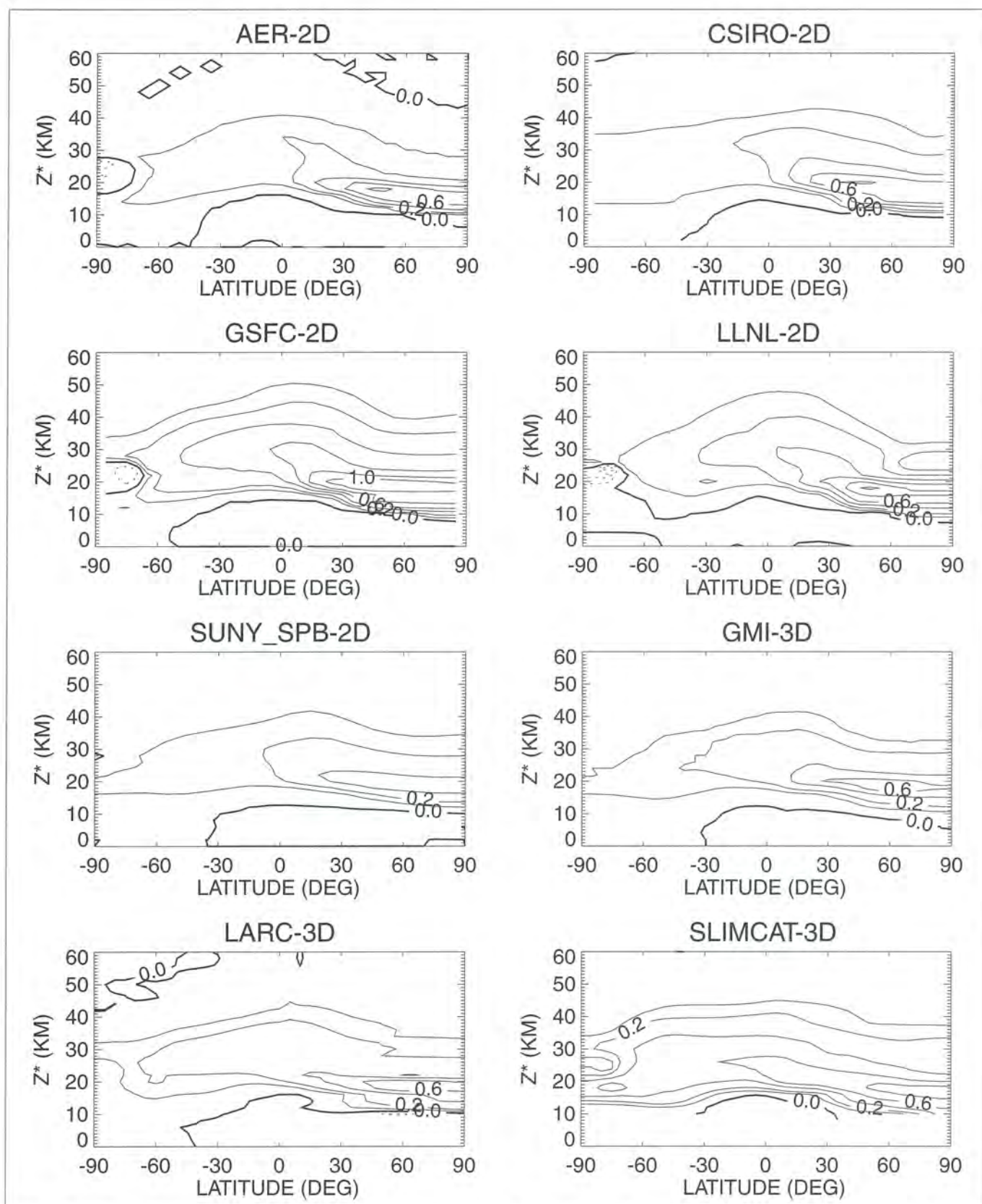


Figure 2. Calculated HSCT-induced change in NO_y (ppbv) during June from the models participating in the AEAP assessment. Results are shown for the scenario with $\text{EI}(\text{NO}_x) = 5$, and with 500 aircraft, relative to the subsonic only condition. Contours are drawn for 0.0, 0.1, and 0.2ppbv, and in increments of 0.2ppbv thereafter.

calculated response of the chemical system to the aircraft perturbation. Kinetic parameters controlling radical abundances have been constrained from simultaneous observations of radicals from all three major chemical families. For current atmospheric

conditions, increases in NO_x will decrease local ozone in the mid- to upper stratosphere. However, in the lower stratosphere due to the buffering effect of competing catalytic chemical cycles, the ozone response is only weakly coupled to NO_x over the range (factor

of 2) of NO_x concentrations currently present in lower stratosphere (Figure 4, plate VIII). Variations in the background stratospheric aerosol, NO_x , HO_x , halocarbons, and temperature resulting from natural processes (e.g., volcanic eruptions), changes in industrial

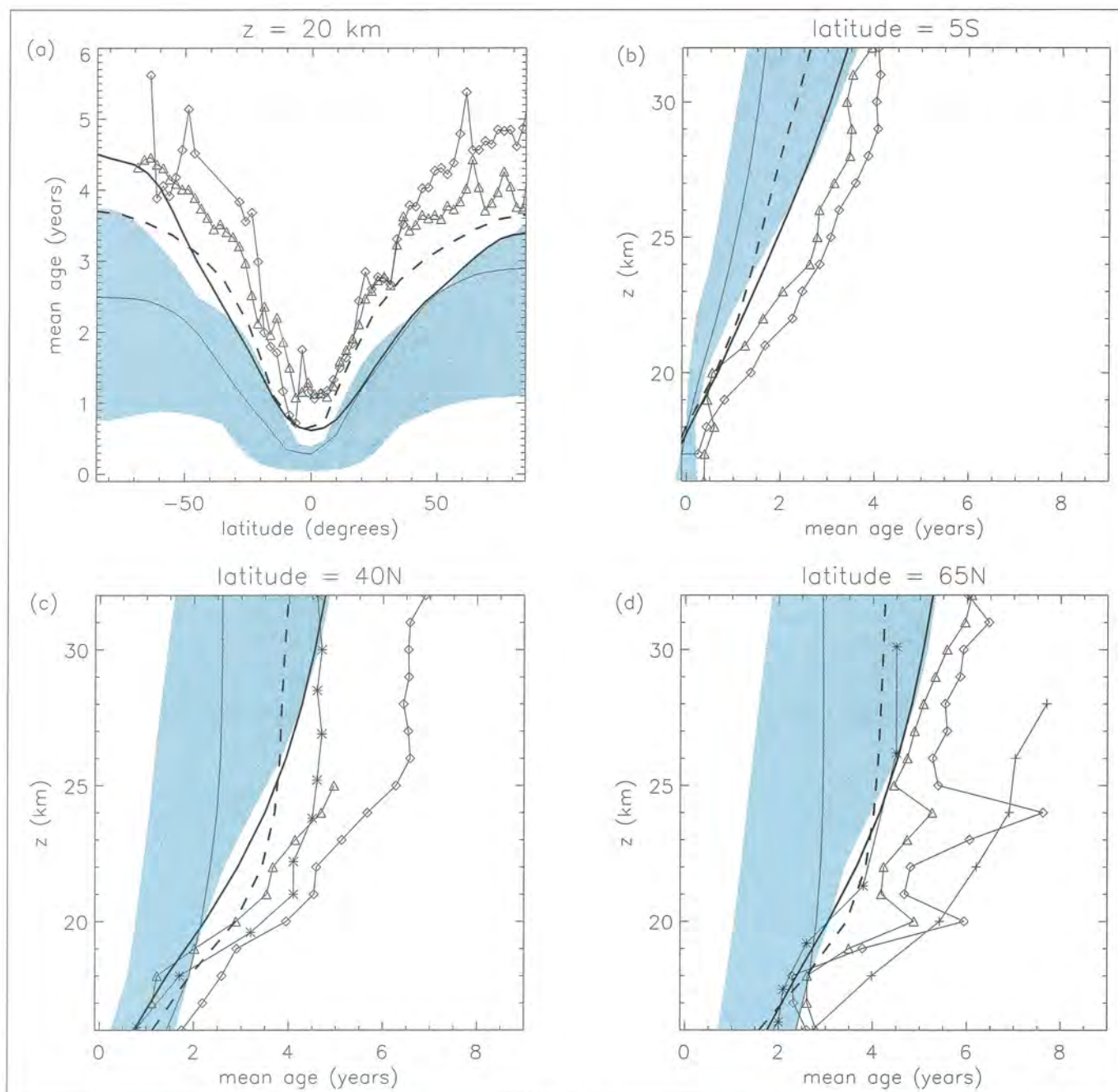


Figure 3. Comparison of mean ages of air from observations and models for a latitude profile at 20km and vertical profiles in the tropics, mid-latitudes, and high latitudes. The shaded region indicates the range of mean ages from a majority of models in the M&M II comparison (Park et al., 1999) while the curves (without symbols) correspond to mean age profiles from the GSFC (dashed) and Monash1 (solid) models. The symbols correspond to mean age inferred from observations: in-situ CO_2 (triangles), in-situ SF_6 (diamonds), and whole-air samples of SF_6 (asterisk, pluses). Adapted from Hall et al. (1999).

activity (e.g., N_2O emissions from fertiliser use), and from changes to climate will affect the response of ozone to aircraft exhaust. Predictions of the effects of HSCT exhaust are particularly sensitive to the abundance of NO_x in the lower stratosphere.

Although improved, the ozone loss chemistry is still not completely resolved in models. Recent measurements suggest inaccuracies in the chemical kinetic rates used in current model calculations of the partitioning of reactive nitrogen between NO_x radical and non-radical species (Gao et al., 1999). In general, models using current rates predict

lower concentrations of radicals than observed, a tendency that would underestimate reductions in ozone; the calculated difference for HSCTs using updated rates is small however. Also, changes in the total ozone column due to HSCT exhaust result from a balance between ozone increases in the aerosol-rich lower stratosphere and ozone losses in the NO_x -rich middle and upper stratosphere. Models differ in the magnitude of the vertical and latitudinal contributions to this critical balance. Continued observations are needed to better resolve chemical processes in the stratosphere.

Polar Processes

Properly predicting the interaction of aircraft exhaust species with cold polar processes is an important component of the aircraft assessment. The heterogeneous processes that take place in the cold temperatures of polar winter are highly non-linear in their dependence on aircraft emitted species, NO_y , H_2O , and sulphate, making this a highly sensitive regime. As a result of a combination of non-linear reaction processes, phase change transitions, and exponential dependence on the particle size distribution, ozone loss can be

highly leveraged by relatively small changes in condensibles at temperatures near those commonly observed in the polar stratosphere. This raises the possibility that synergistic effects may occur among the emitted species increasing the likelihood of severe ozone depletion in the northern hemisphere polar region. Strong local effects at high latitudes are possible and the impact may be felt at mid-latitudes. Model column ozone losses due to HSCTs are largest at high latitudes in almost all cases. For some models the maximum HSCT ozone loss occurs in polar winter/spring, but the difference among models is large lending little confidence to the quantitative estimates.

Fundamental questions about the microphysics and composition of PSCs limit our ability to parameterise key processes such as sedimentation and heterogeneous chlorine activation, which control winter/spring polar ozone loss. The representation of these processes in assessment models is highly simplified and very model-dependent. Furthermore, the 2D models used in the aircraft assessment do not properly isolate the winter polar vortex air mass. Lack of isolation of the vortex may lead to too much of the exhaust being transported into the vortex and too much of the processed air being transported out of the vortex. Uncertainties in the microphysics of PSCs, winter polar transport, reactive chlorine activation, and chemical ozone loss will all be addressed directly in the upcoming SAGE III Ozone Loss and Validation Experiment (SOLVE) scheduled for northern hemisphere winter, 1999-2000 (see <http://cloud1.arc.nasa.gov/solve/>, and P. Newman's paper in this newsletter, p. 17).

Climate Impacts of Supersonic Aircraft

The climate forcing attributable to an HSCT fleet in the year 2050 is predicted to result in a warming which is small relative to that expected from other anthropogenic sources. The total radiative forcing from 1000 HSCTs is estimated to be $+0.1 \text{ Wm}^{-2}$ in 2050, mostly resulting from increased water in the lower stratosphere. Heating from increased water is offset slightly by cooling from decreased ozone. This HSCT number is a concern because the radiative forcing is disproportionately large for the amount of fuel used and equivalent to about 50% of the forcing from the entire projected subsonic fleet. Climate forcing is sensitive to HSCT emissions because the H_2O accumulation is localised in the lower stratosphere. The uncertainty in the HSCT climate forcing is estimated to be about a factor of 3 due to uncertainty in the exhaust accumulation and uncertainty in the temperature adjustment to a non-uniform perturbation of radiatively active gases in the stratosphere (IPCC, 1999).

Subsonic Aircraft Effect on the Stratosphere

Subsonic aircraft in the altitude range 9-13km fly about 80% and 20% of the time in the troposphere and stratosphere, respectively (Gettelman and Baughcum, 1999). However, on some routes aircraft spend considerably more time in the stratosphere. For example, in the North Atlantic flight corridor in winter, as much as 65% of flights occur in the stratosphere. Virtually all of the emissions into the troposphere react locally and/or are scavenged from the troposphere to the surface on time scales of a few days. The emissions into the stratosphere occur predominantly at northern mid- to high latitudes with a greater amount of deposition during the winter. The portion of the stratosphere accessible to subsonic aircraft is a region where mixing between the troposphere and stratosphere may occur along isentropic surfaces, the stratospheric "middle world" (Holton *et al.*, 1995). In this region, emissions deposited into the stratosphere have a relatively high probability of mixing into the troposphere. Recently Danilin *et al.* (1998) studied the potential effects of subsonic aircraft on stratospheric ozone and the residence time of emitted species in the stratosphere. Results from 2D and 3D global models varied in their prediction of stratospheric residence time from about 20 to 60 days. They concluded that individual model treatment of numerical diffusion was a likely source of differences. Schoeberl and Morris (1999) have studied transport of aircraft emissions utilising a parcel trajectory model to estimate residence time of subsonic aircraft emissions in the stratosphere. They conclude that subsonic emissions have a residence time of less than three months. Because of the diabatic downward motion in the stratosphere at mid- to high latitudes, very little subsonic exhaust emissions persist in the stratosphere and the impact on ozone loss is small. Emissions from HSCT aircraft, which are deposited at higher altitudes (see Figure 1), have residence times in excess of a year. Testing the validity of these models is difficult, however, and the IPCC (1999) report concludes that uncertainties are still large, due to the lack of model resolution near the tropopause and the related issue of proper depiction of stratosphere-troposphere exchange.

Calculations of the Supersonic Impact on Ozone

Based on a combination of model calculations and expert judgement, the estimated column ozone change in the northern hemisphere is -0.4% for a fleet of 500 HSCTs flying Mach 2.4 with an $\text{EI}(\text{NO}_x)$ of

5g/kg, $\text{EI}(\text{SO}_2)$ of 0.4g/kg, and 10% of fuel sulphur converted to particles. Including the uncertainty in component processes, the hemispheric ozone response is estimated to be in the range of -2.5 to +0.5% and -3.5 to +1.0%, respectively, in the AEAP and IPCC reports. We note that the maximum seasonal and latitudinal ozone changes will be greater than the hemispheric annual mean. Calculations indicate that these ozone changes will lead to increases in exposure to ultraviolet irradiance at the ground in mid-latitudes of approximately 0.5%.

Sensitivity to Input Conditions

The sensitivity of the aircraft impact to varying assumptions about emissions (e.g., fleet size, EI, altitude of emissions) and the future atmosphere has been tested in parametric model studies over a range of scenarios. Several findings relevant to HSCT design issues come out of the atmospheric assessment.

The HSCT impact on ozone depends directly on total emissions, i.e., fleet size and fuel use.

Water vapour, which is inherent to jet fuel combustion, accounts for a major part of the calculated stratospheric ozone impact. Increased water vapour in the stratosphere may also contribute to global climate warming.

NO_x emissions are important. Although current atmospheric models do not show much relative sensitivity to very low ($\text{EI}(\text{NO}_x) = 5$ to 10) emissions, higher NO_x emissions clearly increase the impact, especially for larger fleet sizes.

Production of sulphate aerosol particles makes a significant contribution to the calculated ozone impact. This implies that low-sulphur fuel options and methods to control production of particle precursors should be explored.

Flying the HSCT at lower altitudes reduces stratospheric impacts. The atmospheric residence time of the exhaust is decreased and the chemical sensitivity is reduced.

Special issues are associated with exhaust build-up in polar regions, both winter and summer. Under current HSCT route scenarios, direct emissions into the polar vortex are minimal.

Aircraft in the future would operate in a stratosphere that will likely have different trace constituent mixing ratios and aerosol abundances. Climate change from increasing CO_2 will also change stratospheric temperatures and winds. Future changes in these and related quantities cannot be predicted with high accuracy. Assessment calculations using a range of input future

conditions have not identified any particular sensitivities different from the standard projections (Kawa *et al.*, 1999), but the applicability to future conditions is less certain. Calculations with varying aerosol background show a decreased sensitivity to aircraft in volcanically enhanced conditions.

Summary

The assessment results provide guidance for informed decisions on environmental policy and aviation technology development, and they provide direction for future stratospheric research. Great progress in stratospheric science in the last decade has been spurred by the focus on assessing aviation impacts. The pathway to future progress in understanding stratospheric processes and their role in climate lies closely in line with that for reducing the uncertainty of aircraft impacts on the stratosphere. This progress will be achieved through continued investment in observations coupled with advances in modelling the stratosphere/troposphere system.

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Fifth European Workshop on Stratospheric Ozone

St Jean de Luz, France. 27 September-1 October 1999

This workshop is being organised by the European Commission, CNRS and CNES. The results of recent research on stratospheric ozone carried out in Europe will be presented, in particular:

- ♦ the findings of the THESEO campaign,
- ♦ the ozone decline over middle latitudes,
- ♦ chemistry and dynamics of the mid-latitude stratosphere,
- ♦ the links with processes occurring in the tropics,
- ♦ the Arctic and the upper troposphere,
- ♦ observed and modelled ozone loss,
- ♦ microphysical processes and heterogeneous chemistry.

Poster sessions will be a major component. The oral plenary sessions will be a mixture of invited and selected presentations. Extended abstracts will be published by the European Commission.

For further information, please contact:

Dr. Georgios T. Amanatidis, European Commission, DG XII-E-1, (georgios.amanatidis@dg12.cec.be)

Dr. Neil Harris, European Ozone Research Coordinating Unit, UK (general@ozone-sec.ch.cam.ac.uk.)

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Information including registration materials and abstract submission will be posted on the web site:

<http://www.ozone-sec.ch.cam.ac.uk/eorcu/>.

Simulation of the QBO in a General Circulation Model

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Introduction

The quasi-biennial oscillation (QBO) in the equatorial lower stratosphere is an interesting phenomenon. The oscillation has been dynamically explained by wave-mean flow interaction theory as discussed in Lindzen and Holton (1968). Eastward and westward propagating gravity waves, which propagate upward in the lower stratosphere, are dissipated to produce the westerly and easterly phases of the QBO, respectively. Later, Holton and Lindzen (1972) assumed eastward and westward propagating waves as the Kelvin wave consisting of zonal wave number 1 and period of approximately 15 days and the Rossby-gravity wave of zonal wavenumber 4 and period of about 4.5 days which had been found in observations (Wallace and Kousky, 1968; Yanai and Maruyama, 1966). But, observational findings suggested that the Kelvin and Rossby-gravity waves might not be of sufficient strength to produce the westerly and easterly phases of the QBO (cf. Sato and Dunkerton, 1997).

Takahashi (1996) reported that a QBO-like oscillation was simulated in the equatorial middle stratosphere using a T21 60-layer general circulation model (GCM) with moist convective adjustment (referred to as the T21 simulation). The model is the first version of the GCM, developed at the Center for Climate System Research/National Institute for Environmental Studies (CCSR/NIES). The damping time for the maximum wavenumber in the fourth-order horizontal diffusion was 20 days, which is about one-order of magnitude longer than that used in standard GCMs. The period of the oscillation, however, was about 1.5 years, being shorter than that of the observed QBO. Furthermore, the height of the simulated oscillation was somewhat higher than that of the observed QBO, and the easterly phase of the QBO was weak.

Simulation

Recently, the simulation is extended to a horizontal resolution of T42, that is, a grid spacing of about 300km (Takahashi, 1999). A 1-day damping time for the maximum wavenumber in the 4th order horizontal diffusion was first used. With this damping time, however, the simulation did not produce a QBO signal in the equatorial stratosphere, but rather an almost steady state (see the left part of figure 1). After 570 days of the simulation,

the weaker 4-day damping of the maximum wavenumber was used. Reducing horizontal diffusion provides more gravity waves, which are related to noisier precipitation than that in GCMs, to produce the QBO successfully.

Figure 1 (plate VIII) shows a time-height section of the simulated mean zonal wind over the equator. In Figure 1, after 570 days of weak damping, a QBO-like oscillation in the equatorial middle and lower stratosphere can be clearly seen. The maximum westerly of about 20ms^{-1} and maximum easterly of about -18ms^{-1} are comparable to those observed. The westerly phase of the oscillation, however, is still stronger than the easterly phase in the model simulation. This is the reverse of that observed, namely easterlies of -30ms^{-1} and westerlies of 15ms^{-1} . The oscillation occurs in the middle and lower stratosphere, being slightly higher than that observed. The period of the simulated QBO is 800 days (27 months), which is almost the same as that observed. The easterlies of the simulated QBO are much stronger than those (-10ms^{-1}) in the T21 simulation.

There is no realistic semi-annual oscillation in the model. The model has no westerly phase of the semi-annual oscillation. This is probably due to the coarse vertical resolution in the model upper stratosphere.

The weaker damping generally has stronger kinetic energy around higher zonal wavenumbers. The higher wavenumbers of the weaker damping at 200hPa over the equator have slightly stronger kinetic energy than that of the stronger damping, corresponding to precipitation. Noisy higher frequency and wavenumber gravity waves with weaker diffusion amplified in the stratosphere are produced by slightly stronger precipitation. In this simulation, gravity waves play a very important role in the simulation of the QBO, as was discussed in Horinouchi and Yoden (1998).

The magnitude of the easterly acceleration by gravity waves in the middle stratosphere is $-5 \times 10^{-6}\text{ms}^{-2}$, which is much larger than that in the T21 simulation. Correspondingly, the easterly phase of the presently simulated QBO is stronger. From this result, it can be concluded that the period of the QBO in the present simulation has a reasonable value.

The QBO forcing is mainly due to gravity waves. The horizontal momentum flux convergence by planetary waves from mid-latitudes over the period of days 1110-1140

(northern hemisphere winter) is on the order of $-1 \times 10^{-6}\text{ms}^{-1}$, which is the same order of magnitude as in the T21 case. The horizontal momentum flux is not dominant, but reveals a weak contribution of easterly momentum to the QBO in this simulation.

The present simulation shows that unrealistically noisy rainfall may produce more gravity waves to produce the QBO. Now higher horizontal resolution simulation can get a realistic QBO in the ECMWF-GCM.

The QBO has important contributions to middle atmosphere dynamics and chemistry. We are now able to extend to the studies of QBO effect to mid-latitude winter circulation and ozone-QBO using the GCM (cf. Niwano and Takahashi, 1998; Nagashima *et al.*, 1998).

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A Global Distribution of Gravity Wave Activity in the Stratosphere

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Using the temperature profiles obtained with the GPS occultation technique during April 1995 and February 1997, we have analysed mesoscale temperature fluctuations in the stratosphere, and studied the global distribution of atmospheric GW activity. This study has clarified that the GPS occultation technique provides one of the most important and unique data sets to study the global distribution of atmospheric GW.

Our knowledge of the behaviour of GW has greatly advanced in the last decades, owing to intensive observational and theoretical studies. However, little is known about a global morphology of GW activity in the stratosphere, which is very important to fully understand and model wave effects according to geographic and seasonal conditions.

New satellite-borne remote-sensing measurements provide excellent global information on the background dynamical structure, planetary scale fluctuations, and even mesoscale disturbances. From high-resolution radiance measurements with the Microwave Limb Sounder (MLS) on board the UARS, Wu and Waters (1996a,b) extracted temperature fluctuations with horizontal scales less than 100km, and studied a global distribution of GW activity in the stratosphere and mesosphere (30-80km). At 30-50km altitudes the temperature variance was enhanced in high latitude region during winter. Above about 60km large variance was detected at middle and high latitudes during summer, which was interpreted as the result of a selective filtering of upward propagating GW affected by the jet stream in the stratosphere (Alexander, 1998).

The GPS/MET (Global Positioning System/Meteorology) experiment has been recently initiated by UCAR, successfully providing the international scientific community with a new global high resolution data set of temperature, pressure and refractivity profiles in the 1-60km height range. These profiles are obtained from the active limb sounding occultation technique as described by Ware *et al.* (1996) and Rocken *et al.* (1997). In this experiment, a GPS receiver aboard Microlab-1 was launched on April 3, 1995, into a low earth orbit (LEO) to observe occulted radio signals from the GPS satellites. Height profiles of atmospheric refractive index were

derived from these observations. By assuming the hydrostatic relation for a dry atmosphere, temperature profiles can further be inferred. Rocken *et al.* (1997) showed 1°C mean temperature agreement with the best correlative data between 5-40km.

In this study we have defined the potential energy E_p , from all published GPS/MET temperature profiles between April 1995 and February 1997, and analysed the energy distribution of GW in the stratosphere as a function of latitude, longitude, season and altitude (Tsuda *et al.*, 1999).

From each GPS/MET temperature profile we have extracted mesoscale temperature perturbations, with a vertical scale ranging from 2 to 10km, which are presumably caused by GW, as well as the background Brunt-Väisälä frequency squared, N^2 . Then, we have defined the potential energy, $E_p = 1/2(g/N)^2 T/T^2$ from the temperature variance. We have determined monthly mean values of E_p at 15-20km altitude around Japan 24°-46°N, 126°-146°E and found a seasonal variation with an enhancement during the winter months. This seasonal variation is consistent with the climatological behaviour of the kinetic energy of GW, E_k , observed with the MU (middle and upper atmosphere) radar at Shigaraki (34.9°N, 136.0°E) from 1985 to 1989. Thus, the utilisation of the GPS/MET profiles in the study of stratospheric GW activity has been verified at this specified radar site.

Taking advantage of the global coverage of the GPS/MET data, we have analysed the distribution of GW activity as function of latitude, longitude, altitude and season. First, we present in Figure 1 (plate VIII) the latitude-longitude distribution of E_p in the 20-30km height region during northern hemisphere winter (from November to February), when the largest number of GPS/MET data was collected (a total of 4,569 data out of 10,853). The largest E_p values are generally centred on the equator between 25°N and 25°S, and they are particularly enhanced over the Indonesian archipelago, the Indian Ocean, Africa and the Atlantic Ocean to its west, and South America. This result strongly suggests that atmospheric GW are generated by convection in the tropical region. However, it is difficult to clearly determine to what extent Kelvin waves and other equatorially trapped waves contribute to the large values at

low latitudes. Therefore, the E_p values at low latitudes could partially be contributed by equatorial waves that add a zonally symmetric bias.

We have determined latitudinal variations of E_p in the five altitude ranges between 15km and 45km, where individual E_p values are averaged every 10° in 18 latitude bands. It is noteworthy that the noise on the L2 band of GPS signals considerably increased when anti-spoofing (A/S) encryption of the GPS signals was turned on (Rocken *et al.*, 1997). Then, effects of ionospheric correction produce artificial fluctuations in the GPS/MET temperature profiles, which could be recognised down to about 30km. Therefore, we use only data during prime times under A/S-off conditions for a study of the height variations of E_p distributions, as shown in Figure 2. Note that the results in March-April are not shown here, because the number of the GPS/MET profiles under A/S-off conditions was considered insufficient (430), while 1608, 1430 and 1836 profiles were used in May-August, September-October and November-February, respectively.

In the lowest two layers below 30km (15-25km and 20-30km) in Figure 2, we have detected the largest value of E_p in the low latitudes, where the latitude range of the enhanced E_p is wider in November-February than in other seasons. In the 20-30km layer the E_p values at mid-latitudes are larger in the winter hemisphere, which is more evident in May-August, while in equinox (September-October) E_p in the mid-latitudes was nearly the same between the northern and southern hemispheres. In the overlying altitude regions, the enhanced peak of E_p near the equator tends to disappear, but the E_p at higher latitudes becomes larger, which is consistent with the shuttle experiment of stratospheric GW activity (Preusse *et al.*, 1998).

It is remarkable that in September-October the latitudinal distribution of E_p is symmetric between the northern and southern hemispheres in the entire height ranges. However, near solstices the E_p distribution involves a large hemispheric asymmetry at middle and high latitudes, which is more pronounced in May-August. Differences in the E_p distribution between the June and December solstices are also detected,

suggesting that the latitudinal distribution of the GW activity in the stratosphere depends on hemisphere as well as on season.

Both the hemispheric asymmetry and differences between the June and December conditions were also reported by Wu and

Waters (1996a, b), based on GW analysis from the UARS-MLS measurements. However, a direct comparison with our results is not discussed here, because the height and latitude ranges of the major variations do not overlap.

Acknowledgements

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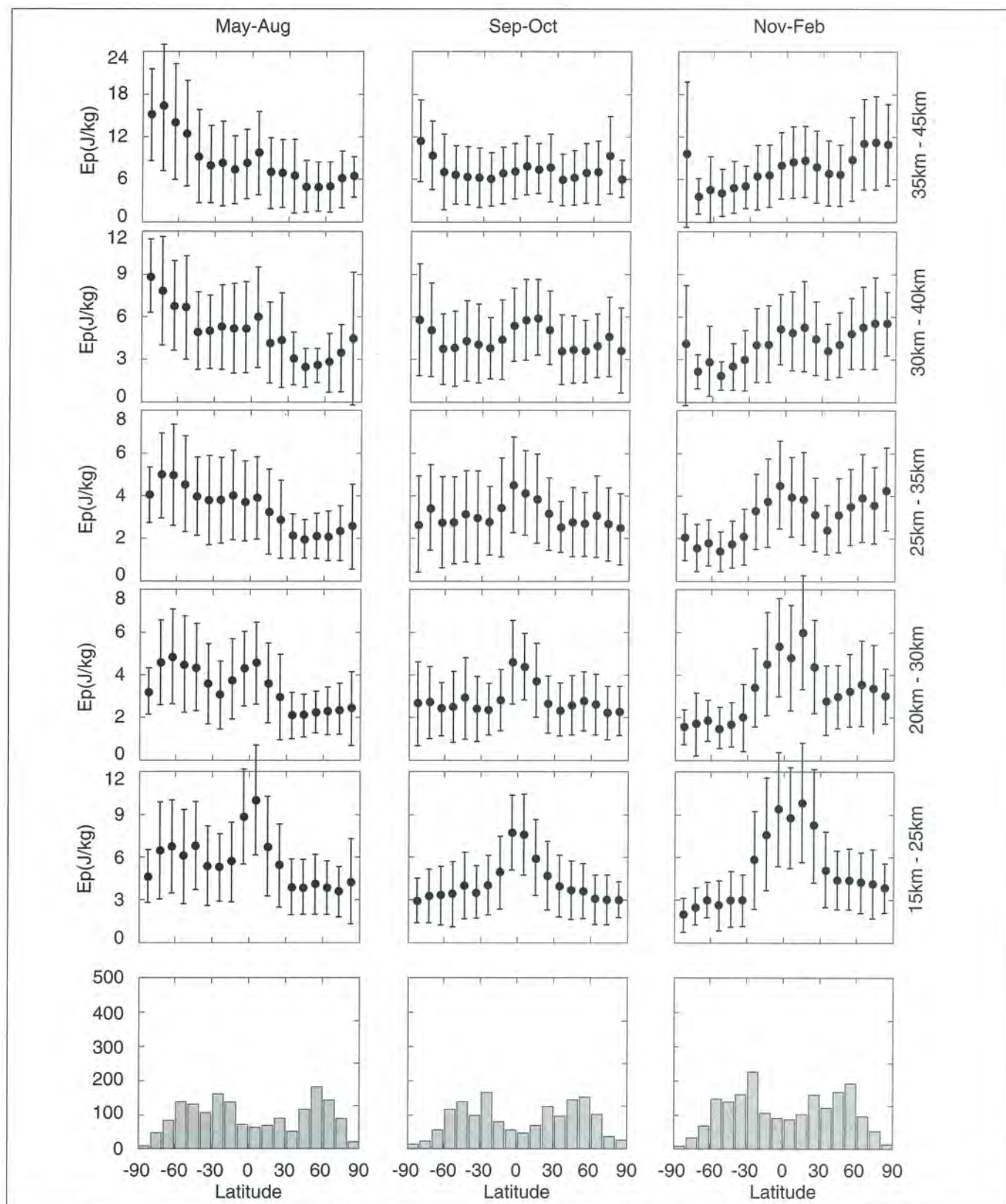


Figure 2. Latitudinal variations of the zonally averaged E_p and standard deviation in five altitude regions in November-February (left), September-October (centre) and May-August (right). Number of GPS/Met data is shown in a histogram.

UCAR GPS/MET office. This study is supported by the Japanese GPS-Meteorology project of Science and Technology Agency (STA), Japan.

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First International Workshop on Long-term Changes and Trends in the Atmosphere (LT-ACT'99)

IITM, Pune, India, 16-19 February 1999

30

Gufran Beig, IITM, India (beig@tropmet.ernet.in)

Convener: G. Beig. **Scientific Programme Committee:** J. Lastovicka, G. E. Thomas, M.-L. Chanin, V. Ramaswamy, G. Brasseur, A. P. Mitra, A. Ebel, A. D. Danilov, K. Labitzke, T. Tsuda, L. Hood, E. S. Kazimirovsky.

This workshop was sponsored and hosted by the Indian Institute of Tropical Meteorology, Pune, India. The leading international co-sponsors were SPARC, IAGA, SCOSTEP and ASICTP. National co-sponsors were DST, CSIR and ISRO.

The workshop covered the entire atmosphere from the surface to 120 km (with a special thrust on the middle atmosphere).

In total, 97 scientists from 20 countries attended the workshop. There was 1 plenary session, 4 plenary review talks, 22 invited talks, 3 special contributed talks, 16 contributed oral papers and 35 contributed posters.

Chaired by A. P. Mitra, a panel discussion session on a general topic "Human Impact on Global Atmosphere" was also arranged.

Workshop objectives

- What long-term changes have been observed and will we be able to study in the near future?
- What are the explanations of the variability and trends in terms of known physical, chemical and dynamical processes?
- Which tropospheric processes can be identified as causes for middle atmospheric

long-term changes and which middle atmospheric phenomena or observations can be used to identify/monitor long-term changes in the lower atmosphere?

- Can we identify the role of natural (solar, volcanic, meteorological) origin versus Anthropogenic changes?

Scientific proceedings

The workshop started by the inaugural keynote talk delivered by G. Brasseur entitled "Global Changes in the Atmosphere". He reviewed the major long-term changes in key atmospheric parameters based on available observational and model studies. Achievements in the last 50 years on understanding the changing chemical composition of the atmosphere were highlighted. It was mentioned that potential future changes are likely to be maximum in the tropics as per the model predictions.

Plenary reviews

The review talk of M.-L. Chanin (delivered by V. Ramaswamy in her absence) presented the main thematic developed by SPARC: ♦ stratospheric indicators of climate change, ♦ stratospheric processes and their relation to climate, and ♦ modelling stratospheric effects on climate. The need for monitoring long-term change in climate and for understanding stratospheric processes

which may be influencing them was discussed. Results on stratospheric temperature trends were highlighted.

G. E. Thomas talked about Global Change in the Mesosphere. It was mentioned that water vapour is increasing in the lower mesosphere at a higher rate than expected from methane oxidation, while in the upper mesosphere, its long-term variations may be attributed to 11-year solar cycle variability in the photodissociation rate by solar lyman-alpha irradiance. The causes of the long-term cooling, the effects of episodic volcanic warming and the water vapour increase in the lower mesosphere are unknown.

J. Lastovicka reported on trends in atmospheric waves and dynamical structure. Long-term data on winds show that the amplitudes of prevailing as well as tidal components markedly reduced during the last 30 years. He mentioned that almost no information about trends in gravity wave activity in the lower mesosphere is available. In the stratosphere, he reported strengthening of the westerly polar night jet and perhaps a tendency to more zonal circulation.

A. P. Mitra overviewed base line data in South Asia (ozone content, methane emissions from paddy fields, aerosol related parameters, meteorological parameters, upper atmospheric ionisation, etc...). However most of the data remain concentrated in certain regions and are not inter-calibrated.

Sessions

Session 1. Role of Natural versus Anthropogenic Changes, Models and Observations

This session consisted of discussions of the relative importance of various climate forcings (greenhouse gases, ozone depletion, solar variability, and aerosol changes). One of the main recommendations was that more attention be paid to dynamical changes. D. Shindell showed from the GISS model that the dynamical coupling between the stratosphere and the troposphere allows solar induced variations in the stratosphere to affect the lower atmosphere. In addition, modelled changes in stratospheric winds and in the strength of the Arctic polar vortex are able to influence surface climate by projecting onto a naturally occurring internal mode of variability. A. K. Smith reported that at NH mid-latitudes, ozone trends are heavily influenced by dynamical changes, while chemistry is the dominant forcing at high-latitudes.

Session 2. Trends in Stratospheric Minor Constituents and Aerosol

R. W. Portmann reported that the rapid deepening of the ozone hole in the early eighties was likely caused by accelerated heterogeneous chemistry associated with an increase in aerosol surface area due to volcanic injection combined with the anthropogenic perturbation of stratospheric chlorine. L. Poole discussed the primary sources of stratospheric aerosols and the roles that they play in atmospheric processes. The data records indicate that there was no trend from 1974-1998 in 0.6943-micron stratospheric aerosol backscatter at northern mid-latitudes, and also no trend from 1979-1998 in 1-micron aerosol extinction from 60°S-60°N. It appears that aerosol levels may still be decreasing at present.

Session 3. Global Change and Changing Chemistry

This session was mainly devoted to changes due to man-made activities. G. Beig addressed some anthropogenic signals in the stratospheric and mesospheric thermal structure, neutrals and ionisation based on observations and model simulations. Rocket data of electron density for the past 3 decades at Thumba (8°N) were used as a basis for simulating the future projections which shows a decrease by -80% (near mesopause) in NO, -50% in NO⁺ ions and an increase by 25% in O₂⁺ ion for a double CO₂ scenario. U. Berger addressed some problems in predicting temperature changes of the upper middle atmosphere and presented some results based on GCM simulations. A. Ebel pointed out that it is highly probable that future growth of air traffic will significantly modify the composition of the tropopause region. Impacts of increasing carbon dioxide, ozone and cirrus cloud cover on the atmospheric radiation

fluxes and consequences for climate forcing may be expected. H. Graf mentioned that a great deal of the observed changes in stratospheric climate in winter and spring of the NH is due to the exaggeration of the positive phase of the first coupled mode of tropospheric-stratospheric circulation.

Session 4. Trend in Middle Atmospheric Thermal Structure

V. Ramaswamy reviewed both observations and model calculations of stratospheric temperature trends carried out as part of SPARC activity. Radiosonde and satellite observations indicate a cooling trend of about 0.5K/decade in the LS since about 1980, with more substantial cooling in the polar LS in late winter and springtime in both hemispheres. Model simulations indicate that the depletion of lower stratospheric ozone is the dominant radiative factor in accounting for the cooling trend of ~0.75K/decade in the global-mean LS after 1979. Two papers presented the temperature trend observations at 80-95km as evidenced by the hydroxyl airglow. G. Golitsyn (paper presented by G. Beig) combined the results from different mid-latitude observatories (43°N-54°N) in the NH over a period of over 4 decades. A strong cooling trend of 9.2K/decade was found for the winter months but there was no discernible trend during the summer. In contrast, R. Lowe presented hydroxyl rotational temperature data at two mid-latitude stations at 43°N and 47°N. During the period 1990 to 1998 there is no significant trend observed. A combination of these results with observations from the period 1965-1967 leads to a trend of less than 0.1K/decade with 95% confidence limits of ±1.5K/decade. This result is consistent with model calculations for the trend at 85km of less than 0.5K/decade and inconsistent with the strong negative trend found by G. Golitsyn.

There remains a need to resolve outstanding questions of the temperature trend in the upper atmosphere. The increase in the frequency of occurrence of noctilucent clouds may be the result of a decreasing trend in the temperature of this region, but may also result from increasing amounts of water vapour.

Session 5. Baseline observations and data capabilities in South Asia

Scientists from the South Asian region presented the scientific status and data capabilities as well as major results. It is likely to provide the opportunity to local scientists to establish long-term links and collaboration with other fellow scientists around the globe.

Session 6. Trends in Upper Atmospheric Composition and Changing Ionosphere

Papers have been presented concerning trend observations in the meso- and thermosphere. A. D. Danilov described the indications of trends mainly in 3 ionospheric

parameters (ion composition in the E-region, f_oE , and electron concentration in the D-region). He proposed a scheme to explain all these trends, which assumes a change of the vertical transport of NO. From mass spectrometer, measurements in the E-region negative trends of the ion ratio NO⁺/O₂⁺ were detected. Turunen *et al.*, using ionosonde observations (mainly values of the height of the F2 layer maximum, hmF2), found a strong negative trend at Sodankyla. Bremer and U. Berger discussed trends observed in LF phase height measurements in the D-region and of different wind data in the meso- and lower thermosphere. The negative LF phase height trend is caused by an atmospheric cooling below the reflection height near 82km. As shown by model calculations this cooling can be explained by the increase of CO₂ and the ozone decrease.

Session 7. Assimilation of Data for Determining Trends

E. Weatherhead examined ozone, UV radiation and temperature for sensitivity to modern influences. Further work has combined model estimates of ozone recovery rates and temperature to determine where the expected trends will be detected earliest. The results show that the ozone recovery is likely to be detected earliest in the southern mid-latitudes because of the large signal to noise ratio expected during the next 20 years.

Session 8. Trends in Atmospheric Waves and Dynamical Structure

K. Kodera reported on the studies of trends in dynamical activity of the stratosphere for understanding spatial and seasonal characteristics of trends in atmospheric parameters. In the SH, recent mid-winter circulation change is characterised by a decrease in the speed of the upper stratospheric low latitude westerly jet, which is associated with an increase in stratospheric wave activity. NH stratospheric changes have a more complicated structure. H. Chandra presented trends from the ionospheric data in India.

Session 9. Concluding Session and Workshop Recommendations

This session was chaired by Dr. H. Grassl, Executive Director of WCRP. The concluding session panel members were: H. Grassl, G. Beig, A. P. Mitra, G. B. Pant, J. Lastovicka.

A few observations and recommendations about the future planning in development of long-term trend research were made. The major recommendations are:

Stronger co-operation: The interaction between the stratosphere and the mesosphere should get more attention. This implies the continuation of satellite measurements like those from UARS, e.g., looking at the middle atmosphere as an entity. The scientific steering group of SPARC as well as IUGG,

COSPAR and SCOSTEP should stimulate this co-operative mode and expand their respective interest.

A working group on stratosphere-mesosphere/lower thermosphere interaction could be formed. It is suggested that IAGA, SCOSTEP and ICMA (IAMAS), in consultation with SPARC, may take the lead.

Trends in the middle atmosphere: Anthropogenic effects are large and measurable now in the stratosphere and mesosphere. Hence, the workshop strongly recommends to SPARC to include or expand activities into the mesosphere. The public should be made aware of the man-made perturbations affecting the middle atmosphere and the resulting impact on human beings. The understanding of solar forcing (in the middle atmosphere) may help to understand the forcing in the lower atmosphere. The middle atmosphere is a region where both the solar and anthropogenic impacts are large. They have to be detected, modelled and separated. In this respect, SCOSTEP and SPARC may jointly play a major role. The reported SPARC initiative of inviting SCOSTEP on the solar issue is a good step forward in this direction.

Detection and attribution: Detection of climate change and the attribution of its causes seem easier in the middle atmosphere. We must form panels for new parameters beyond temperature, ozone concentration and water vapour in the stratosphere for which an assessment of changes seems promising in the middle atmosphere.

The parameters put forward at the workshop are:

- ♦ Polar Stratospheric Clouds,
- ♦ Polar Mesospheric Clouds,
- ♦ Temperature of the Mesosphere,
- ♦ Tropopause Height and Temperature,
- ♦ Geopotential Height and Derived Zonal Winds.

SPARC intends to take up the first and last two parameters.

Joint Assessment Panel: Long-term trend analysis in the middle atmosphere is a difficult task and needs scientific Assessment Groups from WCRP, IUGG and SCOSTEP, as such a framework is necessary for appropriate funding and scientific oversight.

Regional data sets: The data existing in South Asian countries (especially in India) and the

trends in this region (as presented in a special session on South Asia during the workshop) will be important in determining the long-term atmospheric composition change or climate change on a global scale. Hence, the scientific activities on this topic in this region should be enhanced. It has been strongly recommended to form a regional Assessment Panel (viz. atmospheric chemistry panel) under an existing international scientific umbrella (viz. WCRP, IGBP, ICSU). IITM, Pune, could be a focal point for such activity. SCOSTEP is asked to endorse and to include this point under its Programme EPIC.

Next workshop

This workshop was initiated by Indian scientists, and was a great success. Moreover, this series "Long-term Change and Trends in the Middle Atmosphere" should be continued. J. Lastovicka has made a proposal to hold a second workshop at IAP, Czech Republic, in the year 2001/2002. Support of all the sponsoring scientific organisations of LT-ACT'99 should also be sought for the future.



XXIV Assembly of the European Geophysical Society

The Hague, The Netherlands, 19-23 April 1999
Session reports

OA19. Solar Ultraviolet Radiation

Conveners: A. F. Bais (bais@olymp.ccf.auth.gr) and P. Koepke.

The Solar UV Radiation session covered a full day schedule with 23 oral and 22 poster presentations. The lectures and posters attracted the interest of the audience and stimulated important discussions.

The modification of solar UV radiation received at the ground due to clouds was the most favourable topic in this session. The results presented for cloud influence were obtained either by the analysis of measurements or in combination with model calculations. They were related to the attenuation but also to the enhancement of UV radiation from clouds (V. Weele *et al.*) as well as to the wavelength dependence of these processes (Seckmeyer *et al.*). Schwander *et al.* presented UV modelling results in the presence of clouds using the Neural Network technique. With their technique 90% of the simulated spectra agreed with the measured ones from $\pm 30\%$ down to $\pm 15\%$ depending on the quality of the cloud description. The determination of cloud effects with the help of satellite data was shown in an oral presentation

(Matthijsen *et al.*) and on different posters. Results of the influence of ground albedo (especially in the presence of snow), of ozone, aerosols and air pollution on UV radiation were also presented. Blumthaler *et al.* reported on measurements at the Swiss Alps which showed a wavelength dependent increase of UV irradiance by 7-12% as a result of the change in the ground albedo from 0.45 to 0.75. Weihs *et al.* presented simulations of albedo variations due to mountain shadows with the use of a 3D model. Several oral and poster presentations were devoted to UV monitoring issues, in particular to measuring methodologies (both physical and biological) and calibration and testing techniques (also supported by modelling). Bais *et al.* showed error estimates in determining the spectral response of erythral broadband detectors with the use of "broad-band" monochromatic radiation (e.g. FWHM = 4.5nm). Results from the application of a methodology to derive complete spectra of the direct sun from narrow-band filter radiometer measurements were presented by Philipona *et al.* and an improved monochromator instrument by Bernhard *et al.* Several presentations were devoted to monitoring results, from a wide range of different places between Chile and Spitzbergen,

between lowland in Finland and high mountain stations in the Alps. Webb *et al.* presented results on the differences of UV irradiances received by surfaces with different inclinations, and Groebner reported on the determination of extraterrestrial UV flux from ground measurements conducted for several months in Mauna Loa. De Backer *et al.* presented UV Index comparisons derived from model calculations and measurements at different environments in Europe, stressing the importance of the quality of the model input parameters and of the measurements. WMO UV activities and real time UV data exchange were presented as well as UV photochemistry relations and their consequences to future tropospheric air quality. In total the session covered the whole range of relevant scientific questions.

ST2. Open Session on the Middle Atmosphere

Convenor: M. Dameris (martin.dameris@dlr.de). **Co-Convenor:** B. Krueger.

During this one-day session, several exciting and interesting contributions were given.

First of all, an invited talk presented by P. Zink (Peter.Zink@mpi-hd.mpg.de) described in detail the new AIDA aerosol chamber

at the Forschungszentrum Karlsruhe. This 7m high cylinder with a diameter of 4m provides the opportunity to observe for days particle changes related to cooling, warming or through the addition of gases. PSC-like particles can be created by injecting aqueous sulphuric acid aerosols in the submicron size range into the chamber where water and nitric acid has been taken up from the gas phase. Experiments were performed in the temperature range from 195K to 215K. Effects of lee-waves can be simulated by altering quickly the pressure in the chamber. The results of such laboratory studies should enhance particularly our understanding of the chemical composition and the behaviour of atmospheric particles as well as of heterogeneous processes themselves.

The data collected during the two CRISTA-flights (Cryogenic Infrared Spectrometers and Telescopes for the Atmosphere; Nov. 1994 and Aug. 1997) onboard the Space Shuttle has been employed for 4D-VAR assimilation. Q. Errera (Quentin.Errera@bira-iasb.oma.be) presented some of the first results to describe the chemical composition of the atmosphere during the two episodes. The dynamics of the atmosphere have been prescribed using ECMWF analysed meteorological fields. A comparison of model results and observations showed the current abilities and future potential of this assimilation system. Due to the exceptional spatial coverage of the CRISTA data, a lot of detailed information regarding the interaction of dynamics and chemistry can be provided. Additionally, V. Küll (kuell@wpos2.physik.uni-wuppertal.de) showed some results of the NCAR-ROSE model related to the high spatial resolution CRISTA measurements of NO_y. The model system is quite able to reproduce the detailed structure of the trace gas distributions.

B. Steil (steil@mpch-mainz.mpg.de) introduced the interactively coupled dynamic-chemistry model ECHAM4-MA/CHEM (model top near 85km) which has treated dynamics, chemistry and radiation in a fully coupled mode, i.e. the calculated chemical species affect the radiative forcing of the dynamic fields. First results of a multi-year model simulation (16 years already finished) were presented and compared with data from the UARS satellite. It was demonstrated that the model system is able to reproduce realistically the stratospheric distributions of important compounds, e.g. ozone and methane. The differences were about 10 to 15% depending on height and latitude. A similar model system ECHAM4.L39(DLR)/CHEM has been employed by M. Dameris and others (martin.dameris@dlr.de). This model version has its upper boundary at 10hPa, but the tropopause region is resolved much higher (approx. 700m instead of 2km). This model version showed a very good reproduction of the seasonal and inter-annual variation of the

dynamics and also of the chemistry of the upper troposphere/lower stratosphere region which are in agreement with observations. Despite the upper boundary near 30km, ECHAM4.L39(DLR)/CHEM is also quite able to reproduce the high dynamical variability of the northern hemisphere winter and spring time and therefore the high variability of the northern spring time ozone distribution.

Ch. Jacobi (jacobi@rz.uni-leipzig.de) presented an actual climatology of the semi-diurnal tide at 52-56°N from ground based radar wind measurements in the mesopause region for the time period 1985-1995. Six northern mid-latitude sites (Saskatoon, Sheffield, Juliusruh, Collm, Obninsk and Kazan) provided the data. The intercomparison of amplitudes and phases showed some good agreement of the results obtained by measuring systems. It turns out that the variation of the semi-diurnal tide is smaller in summer than in winter. Based on CRISTA temperature data taken during the first mission, J. Oberheide (jens@wpos2.physik.uni-wuppertal.de) showed strong tidal structures from high southern to northern latitudes and from the lower stratosphere up to the upper mesosphere. Zonal mean temperatures were analysed with regards to migrating diurnal tides in terms of equivalent displacement heights assuming that tidal motions are adiabatic. For most part of the atmosphere, the observations were in good agreement with the results of the Global Scale Wave Model (GSWM). Zonal temperature variations in the equatorial region indicated that the tidal amplitude is not uniform at all longitudes. It was shown that this variation could be associated with a non-migrating wavenumber 2 diurnal tide.

During the XXV EGS Assembly (Nice, France; 24-29 April 2000), in addition to the "Open Session on the Middle Atmosphere", sessions on the "Impact of Air-Traffic on the Atmosphere", "Stratosphere-Troposphere Exchange" and "Atmospheric Chemistry-Climate Interaction" will be held.

ST17. New Chemistry in the Middle Atmosphere

Convener: S. S. Prasad (ssp@CreativeResearch.org).

This symposium dealt with the middle atmosphere which uniquely mediates the effects of the lower atmosphere on the upper atmosphere, and the solar-terrestrial effects on the lower atmosphere. 23 papers were presented.

The important message for SPARC was in the discussions of the emerging new chemistry of both nitric and nitrous oxide that was presented by Prasad and Zipf. Until now the reaction of nitrous oxide with the excited O atoms (in the singlet D state) has been the only significant source of nitric oxide in the stratosphere. It was pointed out that electronically excited molecular oxygen (in the B triplet sigma state)

reacting with molecular nitrogen may produce nitric oxide in the stratosphere at a rate comparable to (or even exceeding) the production from the oxidation of nitrous oxide. This new development provides a new way of coupling the solar UV variability to the atmospheric ozone (and through it to climate as well) via the direct modulation of stratospheric nitric oxide through the solar optical pumping of the excited molecular oxygen. Equally significant is the emergence of excited ozone as a source of nitrous oxide (Prasad and Zipf), since it broadens the coupling between ozone and odd nitrogen which has been until now limited to the ozone derived excited O atoms reacting with nitrous oxide. The new broadening is due to the fact that now ozone may become an important source of nitrous oxide. The new source of odd-nitrogen requires new sinks of NO_x. It was pointed out that the potential reaction $\text{NO} + \text{NO}_2 \rightarrow \text{N}_2\text{O} + \text{O}_2$ might be the answer but the required conditions are very stringent. A case was made (Aikin) for including ion-chemistry in chemical-dynamical models of the middle atmosphere, especially when dealing with the solar-terrestrial effects on the atmosphere via solar proton events and relativistic electron precipitation events.

Apart from the above mentioned matters directly relevant to SPARC, the symposium had highlighted many other topics of indirect (but still considerable) relevance. These included the important roles of isotopomers as tools to identify the sources and sinks of key atmospheric species (Thiemens), overtone induced dissociation of species like HNO₃ and HNO₄ (Donaldson and Vaida), the hydrophobic to hydrophilic transformation of organic aerosols (Rudich), and changes in the reactivity of various species when it complexes with water (Francisco). It is hoped that there will be a special issue of the EGS Journal "Physics and Chemistry of the Earth" where one can get a full view of the important new ideas discussed in this session.

OA24. Tropospheric Aerosols: Formation and Heterogeneous Chemistry

Conveners: Ch. George (george@illite.unstrasbg.fr), M. Ammann, H. Berresheim, J. Crowley, T. Hoffmann

This session attracted about 70 presentations focussed on the heterogeneous or multiphase processes on solids or in liquid aerosols that are potentially important in determining the composition of the troposphere. Especially four main topics were chosen which are: organic aerosols (formation from hydrocarbon oxidation, natural and anthropogenic HCs), sulphate aerosols (formation from sulphur oxidation), heterogeneous

chemistry on sea salt aerosols and heterogeneous chemistry on carbonaceous aerosols.

The session started with an interesting overview by D.J. Lary showing that soot is an important constituent of the atmosphere which may affect globally its composition if it is reactive. However from the different presentations, it was underlined that the reactivity of soot is an ongoing debate. In fact, chemical analysis showed large differences between different soot types and also evidence for reactivity toward NO_y. However, the latter is limited to the surface of the particles which strongly reduce its reactive potential in the atmosphere. Chamber studies clearly elucidate that long-term experiments under simulated atmospheric conditions are needed to assess the implications of soot in the key issues of atmospheric chemistry. It was shown that the primary soot particles do not have an impact on HO_x, NO_x, O₃ in the boundary layer according to current knowledge. The identified research needs are linked to the ageing of organic soot components in air, photochemistry of condensed organic species, adsorption of secondary organic material on soot and their reactivity towards other trace constituents.

The second topic was about atmospheric organic aerosol. The excellent overview presentation by S. Pandis summarised the corresponding current state of the knowledge: primary and secondary sources, modelling activities and possible impacts on tropospheric processes, such as their role as CCNs. The following presentations (orals and posters) demonstrated that the scientific community begins to meet the challenge to understand tropospheric organic aerosols by realising laboratory studies on biogenic and anthropogenic aerosol precursors, developing analytical techniques for field measurements and implementing organic aerosol formation in regional aerosol modelling. Therefore, the session showed that the first steps have been undertaken in the direction of a dynamic aerosol climatology, which also includes emission, chemical transformation and removal of organic components.

The third topic was introduced by M. Kulmala who presented a great introductory lecture on the potential atmospheric nucleation pathways for the formation of new sulphate aerosols which are supported by both field experiments and theory. From the different presentations, it

appeared that particle formation through nucleation is responsible for so called "particle bursts" observations. Both field and laboratory experiments are needed to understand the rate and mechanisms triggering such events.

Finally, R. Sander highlighted in his excellent presentation the different chemical mechanisms occurring on sea-salt that are at the origin of the formation of halogenated radicals in the marine environment. Several presentations showed the importance and consequences of such formation through modelling studies which also showed the lack of knowledge of several processes occurring at the air/water interface. This subject was discussed in other presentations dealing more specifically with laboratory measurements of uptake and adsorption processes.

It was decided to hold a similar session at the EGS in Nice next year.



NATO ASI on "Chemistry & Radiation Changes in the Ozone Layer"

Kolympari, Crete, 15-24 May 1999

Christos Zerefos (zerefos@ccf.auth.gr)

Organiser: C. Zerefos

This NATO ASI brought together key scientists and young researchers in atmospheric chemistry and radiation. The key speakers gave lectures on the variable ozone layer and the interplay of long and short wave radiative interactions that link ozone, climate and UV issues. The students were able to present their recent research work and to visit the observational sites of a large measurement campaign (held also in May 1999 in Crete) and interact with the scientists involved.

The presentations were devoted not only to laboratory studies, atmospheric observations and theoretical and modelling studies over the past decade, but also to natural variations and man-induced chemical changes in the atmosphere. These were discussed in connection to the stratospheric ozone layer reductions, including recent findings of significant ozone reductions in the LS at northern latitudes during the 1990s. Observations show that ozone

levels increased in the upper troposphere during the 1970s and the first half of the 1980s. However, during the last decade these increases have levelled off, indicating possible changes in the man-made impact on tropospheric ozone on a large scale.

Measurements of UV radiation under clear sky conditions show that low overhead ozone yields high UV radiation at the surface which alters in turn atmospheric composition through OH reactions. Model studies of the radiative forcing caused by changes in ozone give reduced radiative forcing due to ozone loss in the LS and increased radiative forcing from tropospheric increases. These recent studies demonstrate the link between ozone changes caused by man's activities and changing UV levels at the Earth's surface, as well as the link to climate changes through changes in radiative forcing.

The lectures were grouped into the following three areas: Laboratory studies, atmospheric observations, and modelling.

Laboratory studies demonstrated the importance of heterogeneous reactions in the ozone loss process. Recent observations during European and US campaigns have strongly increased our understanding of the ozone loss in the Antarctic and Arctic regions. The set-up of international UV networks improved our understanding of the level of UV radiation reaching the Earth's surface. Lectures on modelling 3D CTMs (Chemical Tracer Models) with extensive chemistry have been presented to describe global ozone chemistry and to demonstrate stratospheric ozone depletion from CFCs and the impact of aircraft on ozone at the tropopause region. Other models were presented, showing the radiative forcing caused by ozone changes. Also, models used to study ozone climate interaction have been described. Finally, UV radiative transfer calculations have been shown to be in good agreement with observations.

Seminar on Stratosphere-Troposphere Interactions

Cochin, India, 24-26 November 1998.

K. Mohanakumar, Cochin University of Science and Technology, India (atmos@md2.vsnl.net.in)

Convener: Dr. K. Mohanakumar

The seminar was held at the Cochin University of Science and Technology, India. 10 invited lectures and 46 contributed papers were presented in 8 sessions. About 150 delegates from 27 institutes and universities of India attended the seminar.

In his inaugural speech, Dr. Kelkar, Director General of India Meteorological Department in New Delhi, pointed out that thrust should be given to research on those aspects of the stratosphere, which have a direct bearing on the changes in the troposphere. He remarked that cyclones and monsoon are still the primary concerns of the people of India. Studies on stratosphere-troposphere interactions can prove useful for prediction of cyclones and for understanding of the characteristics of monsoon.

K Labitzke, Freie University, Germany, gave the keynote address on Stratosphere-Troposphere Interactions. She stressed the role of the QBO of zonal wind and its possible dynamical connection with the tropospheric circulation and weather systems. She cautioned the scientific community that the studies of trends in the stratosphere and mesosphere should be made based on sufficiently long-term and consistent data sets.

Session 1. Stratosphere-Troposphere Exchange (STE)

G. C. Asnani gave a new insight into the micro-structure of atmospheric layers near the tropopause and on stratosphere-troposphere interaction processes. This part of the atmosphere has low humidity and aerosol content and has high reflectivity with respect to MST Radar beam. The importance of this layer in the radiation balance of the atmosphere needs to be appreciated and incorporated in radiation models of the atmosphere. K.S. Appu stressed the association between polar stratospheric warming and cooling in the tropical Indian surface region (considerable surface cooling in most parts of India for a few days following the peak phase of the polar stratospheric warming).

Session 2. Stratospheric Variability and Monitoring

S. Lal (PRL, Ahmedabad) showed that the vertical distribution of trace gases exhibit constant mixing ratio in the troposphere and a sharp decrease in the stratosphere. A comparison of the tropical and mid-latitudinal data showed a strong upwelling in the tropics. A decline in the growth rates of several CFCs was noted. But new substitutes are being introduced into the atmosphere and many of these can alter the temperature of the

troposphere and stratosphere, perturbing the dynamics of the atmosphere.

Session 3. Stratospheric Dynamics

S. C. Chakravarty (ISRO, Bangalore) discussed the main STE processes such as seasonal adjustments in the altitude of the mean tropopause level, organised large-scale quasi-horizontal and vertical motions expressed by the mean meridional circulation, large scale eddy transports mainly in the jet streams and meso- and small scale eddy transport across the tropopause. It was suggested that tropical convection transports lower atmospheric constituents to altitudes close to the tropical tropopause and from there the weak upward motion of the mean circulation performs the cross-tropopause transport into the stratosphere. Systematic measurements of vertical wind fluctuations on different time-scales in the tropics will be necessary to understand transport of trace constituents.

Session 4. Solar Forcing of the Atmosphere

K. Labitzke summarised the work on an apparent signal of the 11-year sunspot cycle in the UT-LS. There was a consistent pattern in correlation between heights of stratospheric constant pressure levels as high as 25km, with the highest association found in the subtropics. The correlation between total column ozone and the solar cycle was shown to be lowest in the equatorial regions and in the subpolar regions.

S. R. Prabhakaran Nayar, University of Kerala, mainly discussed the topic of solar variability and its effect on earth's atmosphere. The global mean surface temperature increased by about 0.2°C from 1986 to 1996. In contrast, the annual mean values of composite total irradiance taken from the records of 5 satellites indicate that 1986 and 1996 solar minimum years show the same level of irradiance.

Session 5. Ozone, Aerosol and Climate

B. V. Krishna Murthy, former Director of Space Physics Laboratory VSSC in Trivandrum, gave a lecture on aerosols and their climatic effects. Increase in aerosol loading results in effective cooling of earth-atmosphere system, which opposes the effects due to the increase in greenhouse gases.

K. N. Iyer, Saurashtra University, stressed that waves and tides dynamically couple the troposphere and stratosphere. Using the Indian MST Radar at Gadanki, Kelvin and Mixed Rossby Gravity waves were detected, and upward transport of zonal momentum was estimated. Tidal oscillations

driven by heat sources in the troposphere and the stratosphere were identified.

Session 6. Physical Processes in the Atmosphere

P. Balarama Rao, former Director of National MST Radar at Gadanki, gave a talk on Radar interferometric techniques for atmospheric studies, including statistical signal processing and data analysis methods used in MST radar experiments. The effectiveness of coherent integration in reducing high data rates was discussed. For detecting weak Doppler shifted returns, spectral analysis of radar signals with the use of average periodogram was suggested.

A. R. Jain, Director of National MST Radar Facility, presented some evidence of STE during tropical convection events.

Session 7. Stratospheric Variability and Climate

Y. Ramanathan, Indian Institute of Technology in Kanpur, mentioned that the interannual monsoon variability is correlated with that of lower stratospheric circulation but the dynamics of the linkage is not yet clear. Another stratospheric effect on the troposphere may be mature thunderstorms towering to the lower stratosphere and the rising air currents causing disturbances in this region.

Session 8. Recommendations of the Panel Committee

- A full-fledged Meteorological Data Bank should be started in the Department of Atmospheric Sciences, Cochin University of Science and Technology for meeting the data requirements for research work.
- India may take active part in the SPARC programme.
- Theoretical and modelling studies should be carried out on stratosphere-troposphere coupling
- A Working Group may be established for the study of the 1999 Total Solar Eclipse in relation to stratosphere-troposphere interaction.
- Extensive studies should be carried out utilising the MST Radar data collected.
- Training courses and workshops for college teachers and students may be conducted to attract talented persons for research in Atmospheric Sciences.

Publication

The papers presented in the seminar will be published as a Special Issue of the Journal of Atmospheric and Marine Research, after peer review.

Future SPARC and SPARC-Related Meetings

27 September-1 October 1999: 5th European Workshop on Stratospheric Ozone, St. Jean de Luz, France. (<http://www.ozone-sec.ch.cam.ac.uk>).

12-15 October 1999: Chapman Conference on Water Vapor in the Climate System, Potomac, MD, USA (<http://www.agu.org/meetings/cc99bcall.html>).

21-22 October 1999, International Ozone Symposium, Basel, Switzerland (<http://www.ozone.ethz.ch/>).

13-15 December 1999: Brewer-Dobson Workshop, Oxford, UK. Contact: Warwick Norton (wan@atm.ox.ac.uk).

13-17 December 1999: AGU Fall Meeting, San Francisco, USA. (<http://www.agu.org/meetings/fm99top.html>).

25-29 April 2000: EGS General Assembly, Nice, France. (<http://www.copernicus.org/EGS/egsga/nice00/nice00.htm>).

13-17 March 2000: GRIPS Workshop, Toronto, Canada. Steve Pawson (pawson@polska.gsfc.nasa.gov).

3-8 July 2000: Quadriennial Ozone Symposium "Sapporo 2000", Hokkaido University, Sapporo, Japan. (<http://www.eorc.nasda.go.jp/AtmChem/O3symp/>).

16-23 July 2000: 33rd COSPAR Scientific Assembly, Warsaw, Poland, including a SPARC Symposium: Convener J. Gille (gille@ncar.ucar.edu).

2-6 October 2000: First S-Ramp Conference (STEP-Results, Applications and Modelling Phase), Sapporo, Japan (<http://www.kurasc.kyoto-u.ac.jp/s-ramp>).

6-10 November 2000: 2nd SPARC General Assembly "SPARC 2000", Mar del Plata, Argentina. <http://www.sparc2000.at.fcen.uba.ar/>.
Chair of the SOC: Alan O'Neill (alan@met.reading.ac.uk).

Chair of the LOC: Pablo Canziani (osvaldo@santamaria.at.fcen.uba.ar).

Opening of the SPARC Data Center: Call for Data

The SPARC Data Center has opened its web site (<http://www.sparc.sunysb.edu>). Proposed by Marvin Geller, William Randel, and Kevin Hamilton with the aim to facilitate exchange of data sets relevant to SPARC projects, the Data Center receives funding from NASA. The goal is to provide a useful resource to SPARC researchers by collecting project relevant data at a central location. The SPARC Data Center presents a platform for compiling and collecting data from different sources. For example, researchers working on the water vapour assessment report (WAVAS) might want to access different data sources through the SPARC Data Center; members of the GRIPS initiative might want to exchange model output data. All currently known SPARC related web sites are linked through the Data Center web page. However, it is important that researchers of all SPARC activities (GRIPS, WAVAS, gravity waves, etc.) contact the Data Center and share information of available data holdings.

Petra Udelhofen was appointed Project Scientist in May 1999. She is responsible for the development and operation of the SPARC Data Center. The stratospheric reference climatology data set provided by W. Randel and the high resolution radiosonde data set obtained from NOAA/NCDC for 74 stations in 1998 will be available online by the end of July. Within the following months, the Data Center will be able to provide simple computational analyses, such as plotting of reference data sets, calculating difference maps, or other analyses as requested. A more detailed plan will be worked out by September, to be discussed at the SSG meeting in November 1999 in Paris. It is essential that SPARC scientists communicate with the Data Center and provide web and ftp addresses useful for SPARC projects. Please contact Petra Udelhofen (e-mail: pudelhofen@notes.cc.sunysb.edu).

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