ECMWF WORKSHOP ON THE STRATOSPHERE AND NUMERICAL WEATHER PREDICTION

INTRODUCTION

The representation of the stratosphere in numerical weather prediction systems is a subject of increasing interest. There are growing demands for analyses and forecasts of the stratospheric circulation. Systematic model errors can be quite substantial in the lower stratosphere, and the impact of limited stratospheric resolution and a reflective upper boundary condition on the treatment of upward propagating wave motion has long been a matter for concern. The quality of the stratospheric first-guess influences the assimilation of observations, and variational assimilation methods offer the promise of using observations of trace species to improve stratospheric analyses of conventional meteorological fields. The workshop thus addressed issues of stratospheric modelling, stratospheric aspects of data assimilation, and the diagnosis and use of ECMWF's stratospheric forecasts.

The first part of the workshop comprised invited lectures, written versions of which comprise the bulk of this report. This was followed by a series of short presentations by a number of other external participants in the meeting. Three working groups then met to discuss modelling, assimilation and diagnosis.

A number of issues pertinent to the stratosphere and NWP were considered by the working groups. Among the questions addressed were the following:

Where should the top level of the model be located?
How should the model levels be distributed?
Are better numerical schemes needed?
What are the specific issues concerning the parametrizations of radiative transfer and gravity-wave drag?
What do we need to consider with regards to water vapour, ozone and other trace constituents?
What are the particular problems of data availability and quality control?
Do we need to revise the structure functions used for stratospheric analysis?
Can we exploit new observations?
What can we learn from systematic errors and to what extent are these in common with other centres?
What is the requirement for forecasts for the stratosphere itself?

Implicit in the above questions is the overall question as to how much is to be gained from a further investment in better stratospheric analysis and modelling, particularly in respect of tropospheric predictability. It was not expected that the workshop would provide a definitive answer to this question, but there was agreement that ECMWF should explore the potential benefits of raising the topmost full level of the model above 10 hPa and increasing the number of stratospheric levels. This could improve the use of satellite radiance measurements in data assimilation, and improve model performance in the later medium range and beyond. The potential for better lower stratospheric wind analyses from use of information on ozone should also be explored. Generally, the workshop provided an informative review of progress in a number of relevant areas and recommendations for future studies aimed at improving the representation of the stratosphere in NWP systems.

The discussions of the working groups are summarized in the following three reports.

1. WORKING GROUP 1: MODELLING

1.1 STRATOSPHERIC RESOLUTION

A basic choice that has to be made in constructing a numerical weather prediction model is the extent to which the stratosphere will be resolved. This involves both decisions as to where to place the uppermost full model level at which primary variables are represented and the level at which the upper boundary condition is applied (often, but not always p=0), and decisions as to the number and position of other model levels within the stratosphere.

The trend among NWP groups has been towards higher model levels. ECMWF raised the top full level of its operational model from 25 to 10 hPa in 1986, and has recently begun consideration of a further increase. Amongst other centres, the UK Meteorological Office raised the top level from about 7 to 2 hPa when the Unified Model was introduced operationally in 1991; Canada moved from a 50 hPa to a 10 hPa top in the same year, and NMC Washington raised the top level of its model from 50 to 2.7 hPa in August 1993. Climate modelling groups have quite considerable experience of running models (including derivatives of the ECMWF model) with significantly higher tops, around 0.1 hPa in the case of MPI, Hamburg and NCAR, and 0.01 hPa at GFDL and UGAMP.

There is no clear evidence as to the optimal location of the top level for NWP, although there are indications from experiments such as presented by Simmons at this workshop and from work such as that of *Boville and Baumhefner* (1990). If the prime interest is in the tropospheric forecast for a time period of a week or so ahead then results suggest that the top level needs be located no higher than 1 hPa, and not below about 10 hPa. Simulations using the GFDL SKYHI model reported at the workshop by Hamilton show that Eliassen-Palm fluxes in the winter stratosphere are typically about half as small at 10 hPa as at 50 hPa, but an order of magnitude smaller at 1 hPa. Consideration of the timescale for vertical propagation also points to a top between about 10 and 1 hPa as being adequate at present. A higher top level may be needed in models used for prediction over time ranges of several weeks or longer, particularly if skill in the wintertime tropospheric forecast at these ranges is in part dependent on accurate representation of stratospheric warming events. There may however be practical reasons for locating the top level somewhat lower or higher than 1 hPa, as polar-night jet speeds are largest close to 1 hPa in the winter hemisphere, and placing the top level there may give particular problems of computational instability. A further problem arises with the specification of a computational reference profile (e.g. in semi-implicit schemes) which needs to be more stable than the actual atmospheric profile. Above about 10 hPa the static stability increases on average towards the stratopause, and the computational reference profile may need to be modified at these levels. The top level of the UK Meteorological Office model was lowered from 2 to 5 hPa in autumn 1992 to enhance the computational stability of the model.

There is similarly no general agreement as to how levels should be distributed within the resolved model stratosphere. For example, although the UK Meteorological Office model has a higher top level than ECMWF, its vertical resolution is coarser below 10 hPa. Experiments carried out within UGAMP indicate more benefit to the lower stratospheric forecast from increasing vertical resolution within the lower stratosphere itself than from adding more layers at the top of the model. Arguments have been advanced as to the desirability of maintaining an approximately uniform resolution in height for the accurate representation of wave propagation, but we are unaware of demonstrations of practical benefit in comprehensive NWP experiments. It does seem desirable that layer thicknesses should be smoothly varying in some sense, which for example precludes the bunching of levels around the jets.

In view of the above, two main recommendations emerge:

(i) The performance of operational forecast models in the stratosphere should be compared, since sensitivity to different choices of model top and resolution may become evident. Two types of comparison are considered desirable:
   (a) Routine comparison of verification scores and systematic errors at 50 hPa at least, either through exchange of scores and error maps, or through exchange of basic fields. This would be an extension of the existing practice for tropospheric forecasts.
   (b) More detailed comparison for specific cases. Proposed WGNE activities could provide the basis for this.

(ii) Experimentation with alternative distributions and numbers of levels in the model stratosphere should be continued, for both medium-range forecasts and longer-range simulations. Testing of promising model versions in data assimilation should be an important component of this work.

1.2. THE UPPER BOUNDARY CONDITION

The upper boundary condition that is almost universally applied in NWP models is one of vanishing vertical velocity, $\dot{\eta} = 0$, where η is the model vertical coordinate, typically pressure (near the top of the model) or sigma (pressure normalized by its surface value). This condition is applied either formally at $\eta = 0$ or at some small finite value of η. It is well known, following the work of *Lindzen et al* (1968) and others (see for example the review by *Clark*, 1991) that this boundary condition results in the reflection of incident upward propagating wave motion. It is common in general circulation models applied to the stratosphere and mesosphere, and in regional mesoscale models used for process studies, to include a number of "sponge" layers near the top of the model in which substantial damping is applied to remove upward propagating waves (although this can itself cause some wave reflection). Some increased upper-level damping may also be used in operational forecasting models, but, for global models at least, the rather small number of model levels in the middle stratosphere and intrinsic interest in forecast fields at these levels limits the scope for application of sponge layers. There is some experience of applying radiating upper boundary conditions for gravity waves in mesoscale models (*Bougeault*, 1983; *Klemp and Durran*, 1983), and an approach has been proposed for Rossby-wave motion (*Rasch*, 1986). At present, however, the consensus appears to be that if the upper boundary condition poses a serious problem for forecast performance, then the problem is best addressed by an increase in stratospheric resolution and a raising of the uppermost full level. If work is needed on the upper boundary condition, it may be appropriate to consider first the representation of the mean meridional circulation rather than upward wave propagation.

1.3 NUMERICAL SCHEMES, MODEL VARIABLES, AND VERTICAL COORDINATE

Atmospheric simulations are sensitive to the vertical aspects of numerical discretizations, especially in regions of sharp vertical gradients, particularly near the tropopause and, presumably, the stratopause.
One area of concern that emerged during this workshop is the treatment of vertical advection. The T213/L31 ECMWF model was implemented operationally in September 1991 using the "fully interpolating" version of the semi-Lagrangian scheme. This higher resolution version immediately demonstrated clear improvements in the forecasts in the first few days of the 10-day forecast period. However, during the subsequent months it was found that, relative to the former operational version, there was increased day-to-day variability in the forecasts in the medium range. The levels of eddy kinetic energy were typically higher with this version, too. Following several studies it was found that the "vertically non-interpolating" scheme had a positive impact on the day-to-day variability, the objective measures of skill, and the levels of eddy activity. This version was implemented operationally in August 1992. However, the reason for the improvement is not fully understood. *Ritchie* (1991) originally attributed it to an excessive smoothing in the fully interpolating version due to vertical interpolation through the tropopause where all the dynamical fields vary abruptly in the vertical. This was based on 5-day experiments with a baroclinic model that included only very simple parametrizations. More recently *Williamson and Olsen* (1994) have examined climate simulations using a semi-Lagrangian version of the NCAR CCM2 which includes sophisticated physical parameterizations, and concluded that the fully interpolating version actually reduces deficiencies that the Eulerian version had in the vicinity of the tropopause.

The centred finite differences traditionally used in the Eulerian treatment of advection are prone to spurious short-scale oscillations. During this workshop Thuburn demonstrated improvements obtained by converting the vertical advection in an earlier Eulerian cycle of the ECMWF dynamics to a flux-limited form. It is likely that a similar improvement could be made in the vertically non-interpolating version by converting the residual vertical advection to a flux-limited form. We recommend that this possibility be examined. Use of a fully interpolating semi-Lagrangian scheme with shape-preserving interpolation is another promising approach.

In a preliminary study presented by Ritchie during this workshop, it was also suggested that the quality of stratospheric modelling might be improved by modifying the vertical operators in NWP/GCM models to explicitly remove a singular dependence in the dependent dynamical variables at high altitude that arises due to the reduced density. Early results with the vertical structure operator and the hydrostatic operator are very promising, and we recommend that this research be continued.

Quasi-horizontal coordinate surfaces (e.g. pressure or height) have been preferred to sigma coordinates for stratospheric modelling. However, the theta coordinate also has certain theoretical advantages. A hybrid sigma-theta-pressure vertical coordinate has been tested in the UGAMP GCM. In idealized baroclinic wave life-cycle experiments there is some suggestion that spurious amplification of potential vorticity maxima may be reduced compared to a sigma coordinate case. In a tropospheric climate simulation the hybrid theta-coordinate model was particularly sensitive to short comings of certain schemes in that version of the model, namely, radiation and vertical advection of temperature. We recommend that ECMWF encourage and monitor further testing of the hybrid-theta coordinate model (a) with improved radiation and vertical advection schemes and (b) in the stratosphere where its advantages might be more conspicuous.

1.4 HORIZONTAL DIFFUSION

A characteristic feature of ECMWF forecasts at stratospheric levels is their smoothness when compared with either analyses (which themselves tend to appear rough), or with corresponding forecasts from the UK Meteorological Office. This is particularly noticeable when viewing PV maps but is also detectable in height maps. The enhanced horizontal diffusion employed at these levels in the ECMWF model reduces fine-scale structure of the type simulated in contour advection experiments and indicated by aircraft measurements. The necessity of using such a general enhancement of diffusion should be reassessed. If extra diffusion is required to remove noise inserted by the analysis or arising from a local model problem, a more selective application in time or space should be sought.

1.5 GRAVITY WAVE DRAG

The comparisons discussed above also suggest sensitivity to the implementation of the parametrization of gravity wave drag. A marked reduction in the amplitude of stratospheric PV anomalies has been found in ECMWF forecasts since modification of the gravity wave drag parametrization and the increase in horizontal resolution, as illustrated by Simmons at this workshop. There is a possibility that the ECMWF model may now have too little drag in the lower stratosphere. Experience at the UK Meteorological Office suggests that too much drag may be deposited at the uppermost levels of the Unified Model.

Throughout the workshop, it has been shown that gravity wave drag parameterization remains an essential ingredient of Middle Atmosphere Circulation Models. Introduction of non-orographic gravity waves with non-zero horizontal phase velocity in the UGAMP model (Thuburn, in these proceedings), in addition to the more conventional subgrid scale orographic gravity wave drag schemes (such as *Palmer et al*, 1986), clearly has a positive impact on the model zonal mean circulation. Certain features, such as the mesospheric temperature minimum in the summer hemisphere, as well as the stratopause temperature become comparable to the climatology. Furthermore, some forecast-sensitivity experiments presented at this workshop by W Norton show a slight impact of the gravity wave drag on the dynamics of the stratospheric polar vortex. It has, however, been noted above how gravity wave drag schemes can induce features such as local anomalies in the potential vorticity fields. Also, numerical experiments done with the SKYHI GFDL model (K Hamilton), which does not have any gravity wave drag, show that in the stratosphere, the drag provided by the subgrid scale waves, can be partly provided by the model resolved waves, when these are suitably dissipated.

Although these results show that the proper representation of upward propagating waves remains a crucial ingredient in the modelling of the middle atmosphere dynamics, no clear suggestion has emerged to introduce substantial modification in the present ECMWF gravity wave drag scheme. Nevertheless, recommendations are made to revise the present scheme to improve the fit with observations, and to develop again, in the new IFS version of the model, the momentum budget diagnostics.

1.6 VERTICAL SUBGRID-SCALE MIXING

Outside of moist convective regions, the vertical subgrid scale mixing in the current ECMWF model occurs only through a Richardson-number (Ri) dependent diffusion that acts on potential temperature, horizontal momentum and water vapour. The present formulation of this mixing is such that the resolved scale Ri has to drop near 0.25 for significant diffusion to occur. One interesting feature observed in the stratosphere is the tendency for turbulence to occur in rather thin horizontal layers. The vertical extent of these turbulent layers is generally an order of magnitude smaller than the ~2 km level spacing typical for GCMs or NWP models in the stratosphere. This suggests that "subgrid scale" velocity fluctuations can be important in initiating KH instability in the stratosphere, and that this needs to be accounted for in model parameterizations based on resolved Ri. The approach adopted in the GFDL "SKYHI" troposphere-stratosphere-mesosphere GCM is described in *Levy, Mahlman and Moxim* (1982). The practical effect of their formulation is the initiation of significant vertical mixing at resolved Ri~3 for a 2 km level spacing. Experience with the SKYHI model suggests that this parameterized mixing can be very important in damping vertically propagating waves of all scales in the middle atmosphere. This approach should be considered for use at ECMWF.

1.7 RADIATIVE TRANSFER

Radiative transfer (RT) in the stratosphere above about 10 hPa must include the absorption effect arising from Doppler broadening at low pressures. Given observed distributions of water vapour and ozone, the 3-D distribution of radiative heating rate in the stratosphere can be computed with a reasonable degree of accuracy (~10 %). In the longwave range, this is achieved using RT parameterizations either derived from line-by-line RT calculations (e.g., GFDL SKYHI), specifically designed for the stratosphere (e.g., UGAMP), or based on tropospheric-type RT schemes modified to account for the Voigt line profile predominant in the stratosphere (e.g., MPI). In the shortwave range, the main problem is to ensure the proper vertical distribution of the solar absorption from UV to visible to near-IR radiation. In this respect, most of the present RT parametrizations use old spectroscopic data for the UV (*Inn et al*, 1953; *Vigroux and Tanaka*, 1953; *Howard et al*, 1961) and their explicitly resolved spectral range (0.25 - 4 μm) make them applicable to RT calculations at most up to roughly 60 km.

In the application of an emissivity-type RT scheme to the stratosphere, the introduction of a simplified energy exchange calculation may be desirable to save computer time. Speed-up of the RT computations is achieved at ECMWF using a time-space interpolation procedure. Thuburn has shown at this workshop how this procedure leads to problems in the stratosphere, and has suggested improvements.

During the ECMWF analysis, the stratospheric water vapour is given a background value of 2.5 ppm and is then allowed to adjust during the forecast. However, the long timescale of the stratospheric water vapour cycle (e-folding time ~ 5 years) prevents any adjustment on the forecast timescale and therefore can produce systematic errors in the radiative forcing. The background value could be more realistically defined from a climatology (e.g. SAGE, UARS). No allowance has been made for setting the stratospheric humidity in the 3D variational analysis system to be implemented soon at ECMWF. It may be necessary to relax to climatology in at least the uppermost layer of the assimilating model in this case, to prevent slow desiccation of the stratosphere due to neglect of methane oxidization.

Another source of systematic errors in the stratosphere could be associated with the use of the present ozone climatology (*London et al*, 1976). This climatology is not applicable to a model extending above 10 hPa. Moreover, there are suggestions that its seasonal evolution around 10 hPa disagrees with more recent climatologies (e.g. CIRAS) or chemical model simulations. Use of a new ozone climatology in the model should thus be considered. Alternatively, the model could use a diagnostic ozone algorithm of the type presented by Allaart at the workshop to give a good representation of the total ozone column. Another possibility is use of a prognostic ozone variable if this is introduced either for use in 4D variational assimilation to improve wind analyses or for UV forecasting.

2. WORKING GROUP 2: DATA ASSIMILATION

2.1 PERCEIVED PROBLEMS IN ECMWF'S OPERATIONAL STRATOSPHERIC ANALYSES

Users of ECMWF's operational products had noted the following problems with stratospheric analyses which merit further investigation:

(i) The Berlin group had noted a bias between ECMWF and radiosonde temperatures in the Arctic in winter.

(ii) UK Met Office had noted occasional anomalies in the PV field derived from analyses at the S pole.

(iii) NOAA/ERL had identified a number of problems in connection with Arctic and Antarctic stratosphere experiments and the analysis of HALOE/UARS data:

- In 1987 over Antarctica at 200-300 hPa, trough-ridge systems in the 30-90°W sector were consistently analyzed and forecast to be cresting at 60-72°S latitude with temperatures too warm and wind speeds too low, with directional errors of up to 180°. Aircraft observations showed the ridge cresting at 85-90°S, with winds of 50 ms^{-1} and temperatures down to 193 K at 250 hPa.
- At high latitudes in winter in both hemispheres, minimum temperatures observed by radiosondes and aircraft are often very much lower than the analyzed values. Some of these problems are attributable to bias in NESDIS retrievals at the times of the experiments (S Hemisphere, 1987; N Hemisphere, Jan-Feb 1989).
- Analyzed temperatures at 10 hPa are 5-10 K above those necessary to produce ice-saturation (as estimated from Smithsonian tables), and this is inconsistent with dehydration signatures inferred from HALOE water vapour and methane data.
- Tropical tropopause temperatures appear to be systematically warm, particularly over the western Pacific.

(iv) KNMI had noticed problems with the vertical motion field in the analysis and, to a lesser extent, in the 6 h forecast. Not only is it noisy but its amplitude exceeds expected values by a factor of about 10.

(v) It was noted that analyses (from ECMWF and other centres) contained "blobs" in the PV field which were not realistic in structure and did not resemble structures in subsequent forecast fields or in contour advection experiments. It was agreed that such "blobs" were to be expected as a weakness in current analysis methods. 4DVAR would result in a different treatment of the problem but would not necessarily remove it. No obvious solution to the problem was identified.

2.2 PROBLEMS WITH PRESENT OBSERVATIONS

Observations currently available operationally for stratospheric analysis are:

(i) radiosonde measurements of temperature and wind profile,

(ii) TOVS radiances measurement from the NOAA polar orbiting satellites, from which temperature information (at coarse vertical resolution) can be derived.

It was noted that the number of radiosondes which reach the stratosphere is decreasing as many countries seek economies in observing system costs. The number of sondes reaching 10 hPa is very poor. This has adverse consequences for analysis and forecast systems both directly, through the loss of these observations, and indirectly, through problems in the calibration/validation of satellite sounders. It was also noted that the move to replace radiosondes with profilers adds to this problem. With regard to the stratosphere, profilers are not an adequate replacement for radiosondes.

The working group agreed that it was essential to retain a basic network of well-distributed, high-quality radiosonde observations reaching 10 hPa. Priority should be given to:

(i) preserving the current network of observing stations and improving their quality, for temperature and wind,

(ii) making wind observations which are likely to have the largest impact on the quality of the analysis, namely in mid/high latitudes in winter and in the tropics.

Quality control techniques used in the stratosphere do not differ, in general, from those used elsewhere. However, stratospheric analyses are particularly susceptible to poor quality-control because of the paucity of data, particularly for wind. A specific problem was noted with some radiosonde profiles; an otherwise accurate profile had a clearly erroneous value at the uppermost level of the report. This problem merits further investigation.

Bias corrections for radiosonde temperatures are particularly important in the stratosphere. ECMWF had recently introduced a new scheme to address this problem. It was noted that relative biases between different radiosondes leads to particular problems when satellite data are introduced into the analysis.

2.3 MODEL REQUIREMENTS FOR DATA ASSIMILATION

At present the use of satellite sounding radiances is complicated by the fact that the weighting functions of several channels extend above the top of the present ECMWF operational model. An extension of the model to about 1 hPa would ease this problem. Use of auxiliary analyses or climatologies for the upper stratosphere and lower mesosphere would also be of help.

Analysis accuracy is limited in some situations (e.g. QBO, polar vortex) by the model's vertical resolution. More levels are required between 100 and 5 hPa to improve the description of these phenomena and thus to assist the data assimilation.

Successful 4DVAR for the stratosphere may require the (simplified) treatment of important aspects of model physics.

It emerged from discussions that the mechanisms controlling present analyses of the tropical stratosphere are not well understood; the extent to which the wind analysis, for features such as the QBO, is driven by the small amount of available wind data or is influenced by temperature data merits further investigation.

2.4 SPECIFIC PROBLEMS FOR STRATOSPHERIC DATA ASSIMILATION

Horizontal structure functions used in the present OI analysis scheme are tuned to the mid-troposphere and so are not well suited to the stratosphere. With the introduction of 3D/4DVAR, this constraint will be relaxed and more appropriate structure functions will be used in the stratosphere.

Vertical structure functions used in the stratosphere are currently tuned to be best suited to mid-latitudes and are not sharp enough for the tropical stratosphere. Further work is required to address this problem.

The current OI analysis scheme rejects tropical data for certain values of local absolute vorticity in order to avoid incorrect balance between height and wind increments. The treatment of this problem in 3D/4DVAR requires attention.

The mixing of different data types presents general problems for data assimilation. A particularly acute problem has been noted at ECMWF with the combination of satellite sounding information and radiosonde data in the tropical stratosphere, and the problem is not at present well understood.

2.5 STRATOSPHERE/MESOSPHERE CLIMATOLOGIES

Daily stratospheric analyses have been produced by both the USA's Climate Analysis Center NMC and the UK Met Office since October 1978, using observations from the TOVS instruments. The NMC analyses are readily available as monthly-mean fields of geopotential heights and temperatures for the entire period. Comparisons with meteorological rocketsonde data and lidar temperatures have allowed assessment of systematic biases at each level. These bias adjustments have been applied to the calculated monthly-mean fields. These data are produced on the NMC 65 x 65 polar stereographic grid for each hemisphere at 70, 50, 30, 10, 5, 2, 1 and 0.4 hPa.

At higher levels, a climatology compiled by *Labitzke et al* (1985) is available, but this is in some cases based on short periods (and so may not be representative). Since September 1991 additional data have become available from instruments flown on the UARS satellite. These data are now starting to be released for public access. Temperature data are available from the MLS, CLAES and ISAMS instruments. Comparisons between UARS data and NMC analyses in the stratosphere suggest near zero bias and RMS differences of 3-6K. The UARS data extend above the domain of the TOVS observations. To supplement the currently available climatologies, the best data to use would be the MLS data, which are currently available up to approximately 0.1 hPa for a 2-year period.

Since the launch of UARS, the UK Met Office has been running a stratosphere data assimilation system largely using TOVS data. These data are available on a monthly-mean basis at UARS standard pressure levels and could be used to supplement the NMC data.

2.6 ASSIMILATION OF OZONE INFORMATION

Ozone information is currently available operationally on a global basis through HIRS channel 9, which senses a radiance related to the ozone and temperature profiles. Cloud contamination is an important problem. Within ECMWF's 3D/4DVAR framework, clear-column radiances could be assimilated directly. WMO ozone sondes are the best description of the vertical structure of the ozone profile and they are an invaluable source of information. It is recommended that the quality and real time availability of these sondes be investigated. For research purposes, total ozone from TOMS is also available. Ozone information is also available from limb sounders (such as MLS on UARS) and nadir sounders (such as SBUV2 on NOAA satellites). The value of these research data would be considerably enhanced if they could be made available in real time to NWP centres.

As seen from the workshop presentations, total ozone observations may contain information on the wind field since there is a strong statistical link with vertically integrated potential vorticity. Furthermore tracking of small scale ozone structures can also provide wind information. In the 3DVAR framework, the first relationship may be used to build an observation operator although further work is required to establish how successful this might be. In 4DVAR, ozone being a passive tracer of the model, wind information would be derived directly. To what extent it is important to account for the statistical relationship in the background term of 4DVAR remains an open question. Météo-France and DMI are pursuing an active collaboration on ozone assimilation within the ARPEGE/IFS framework. It is recommended that ECMWF follow closely this activity and provide support with data assimilation expertise.

2.7 FUTURE OBSERVATIONS

The Working Group reviewed some of the observations which might become available to improve operational stratospheric analyses over the next 7-10 years.

With the transition from TOVS to ATOVS on the NOAA satellites planned for 1995/6, the introduction of AMSU-A will lead to improved accuracy and vertical resolution in the analysis of stratospheric temperature. The uppermost channel of AMSU-A will peak around 2-3 hPa (cf. 1.5 hPa for the SSU, at present) and will have a sharper weighting function. Thus there will be some loss of information on temperature above 2 hPa.

A microwave instrument, originally proposed as "AMSU-C" to complement AMSU-A above 2 hPa, is now planned for DMSP satellites from about 1998. Data from this instrument should be available in near real-time.

The next enhancement to the polar system will come with the deployment of high spectral resolution infra-red sounders (AIRS and IASI) from about 2000. They will improve substantially the infra-red information on stratospheric temperature, thus significantly complementing AMSU-A. They will also improve the information on the ozone profile — from one piece of information (as at present from TOVS) to 2 or 3 — and on the upper tropospheric water vapour profile.

For geostationary satellites, the inclusion of an ozone-sensitive channel in SEVIRI on Meteosat Second Generation (from about 2000) was noted. Tracking features in these images should provide information on winds around the tropopause and lower stratosphere.

Information on total column ozone and on the upper parts of its profile is available from SBUV/2 on the NOAA satellites, but at present the data are not processed in real-time. ERS/2 (to be launched in 1995) will carry an ozone-sensing instrument GOME. The potential use of these data in operational data assimilation should be investigated.

It was noted that one of the main interests in ozone-sensitive measurements for operational meteorology was its treatment as a quasi-passive tracer to infer information on the wind field. Similarly, measurements of other long-lived minor constituents and trace species could potentially be exploited in the same way. For this reason, measurements of these species from UARS and from follow-on instruments in the EOS era were of interest.

Concerning direct observations of stratospheric wind, little improvement was expected in the next decade. The HRDI instrument on UARS should be able to provide line-of-sight wind information in the 20-65 hPa region. However, usable products were not yet available and, as far as was known, there were no plans to continue flying instruments of this type within the next decade.

A number of present and planned experimental instruments should yield useful information on water vapour in the stratosphere and around the tropopause.

As a general remark concerning experimental instruments, the Working Group noted that the value of their data was considerably enhanced if they could be made available in real-time. Not only were such data capable of enhancing the observational data base used in operational NWP, but also data assimilation systems were able to feed back information to assist the calibration and validation of these instruments and thus improve their utility for other scientific and research applications.

2.8 RECOMMENDATIONS

The Working Group made the following recommendations:

(i) that ECMWF should investigate further the perceived analysis and quality control problems reported in 2.1 and 2.2

(ii) that WMO should be advised of the comments relating to radiosonde measurements in the stratosphere reported in 2.2

(iii) that ECMWF should investigate the role of observations in determining the analysis of the tropical stratosphere (see 2.3) and specific data assimilation problems affecting this region of the atmosphere (see 2.4)

(iv) that ECMWF should follow and encourage research on the use of ozone information in variational data assimilation as proposed in 2.6

(v) that agencies responsible for experimental instruments which provide information capable of exploitation in NWP data assimilation systems should be encouraged to make such data available in real-time (i.e. within about 3 hours of measurement time).

3. WORKING GROUP 3: DIAGNOSIS AND NUMERICAL EXPERIMENTATION

3.1 INTRODUCTION

Study of the representation of the stratosphere in the ECMWF forecasting system is evidently justified insofar as there is either an operational requirement for medium-range forecasts in the stratosphere itself or a significant benefit for tropospheric forecasts from a better treatment of the stratosphere. There are, however, other ways in which benefit might be gained from examing the performance of the system in the stratosphere. Firstly, the stratospheric structure and circulation can be significantly affected by the troposphere, so the stratosphere can be a sensitive detector of some tropospheric errors. Secondly, the behaviour of the stratosphere may highlight deficiencies in specific model processes which are masked in the troposphere where there are generally more varied and intense diabatic processes.

In recent years, there has been a number of campaigns making detailed stratospheric measurements using satellites, aircraft and balloons. The success of these campaigns, which have been aimed principally at increasing our understanding of ozone depletion, has owed much to the provision of operational analyses and forecasts from the major NWP centres, including ECMWF. The NWP products have been used both for detailed real-time planning of the experiments and for the subsequent interpretation of results. The weather prediction centres have, in turn, benefited from the close examination of their products, from the availability of accurate, high-resolution data, and from the resulting better understanding of stratospheric processes. It is strongly recommended that such operational data as can be provided at reasonable cost be made available in support of future campaigns.

3.2 SOME SUGGESTIONS FOR DIAGNOSIS AND EXPERIMENTATION IN THE STRATOSPHERE OF THE ECMWF MODEL

(i) ER2 and HALOE observations of water vapour suggest that the stratosphere has two sources of dryness: the tropical tropopause over Micronesia during northern winter, and the Antarctic vortex during southern winter. The relevance of these two sources at various times is currently controversial and many new observational data continue to become available and generate interest in the stratospheric community. A series of numerical forecast experiments on timescales of a month, a season or more, with the T213 L38 model would be very interesting as regards the simulation of the stratospheric water vapour field. The vertical gradients at the tropopause and the horizontal gradients near the vortex edge constitute a severe test of the advection and transport in the model.

(ii) There is evidence from the Atlas of Objectively Analyzed Cross-Sections (Danielsen, Gaines and Hipskind, 1985) that the Antarctic vortex expanded considerably in 1976 (July-August-September) compared to previous years (1973-1975) and maintained this behaviour for the remainder of the record covered to 1983. During the last two years, 1992 and 1993, the ozone hole was 15-25% larger in September and October, after having been of constant area since 1979, the period of the TOMS record. It would be of great interest to diagnose this behaviour with PV analyses from the ECMWF, particularly since unpublished work (Austin, Jones, Palmer and Tuck) has shown strong correlations of ozone hole area with sea surface temperature, pack ice area and the distribution of the vertically integrated (surface to 100 mb) angular momentum in the Southern Hemisphere.

(iii) Diagnose the effects of high cold cloud decks on the overlying lower stratosphere, from a radiative point of view. This has implications both in the tropics, where a stratospheric mirror image of the tropospheric Walker circulation is implied, and at polar latitudes, where diabatic subsidence could be of central importance to the residence time of air in the winter vortex.

(iv) During the period 1978-1991, there was a loss of ~8% in the total ozone column over northern mid-latitudes in winter, mostly occurring below 20 km altitude. This loss increased by a further ~10% in 1992, and a still further ~10% in 1993. It is of great interest to diagnose what effects, if any, this has had on temperatures and winds in the lower stratosphere and below.

(v) Volcanic eruptions like those of El Chichón and Pinatubo need to be studied both for radiative impact on model behaviour and on satellite radiance assimilation.

3.3 OZONE AS AN ASSIMILATION AND FORECAST VARIABLE

We believe it is reasonable to expect that carrying stratospheric ozone as a predicted variable and assimilating ozone information from satellites or in situ sources will be useful for improving forecasts. Other lower stratospheric trace constituents, such as water, would also be useful if data were available. We can think of a number of arguments in support of this belief.

(i) Total ozone is sensitively dependent on potential vorticity in the upper troposphere and lower stratosphere, tropopause height and vertical displacement of isentropic surfaces in the lower stratosphere. It is also to a good approximation a good tracer in the lower stratosphere.It may therefore provide information for forecast initialization and validation that is not present in other data sources.

(ii) Carrying ozone as a predicted rather than climatologically-specified variable may provide an improvement in calculations of radiative heating in the forecast model.

(iii) The ozone forecasts themselves may eventually prove practically useful. For example, they may be useful for surface uv flux forecasts, aircraft flight level ozone amounts, or for ozone field programmes of the international research community.

(iv) Ozone depletion is a critical research and policy issue and the research community would benefit from this effort to assimilate ozone data, and from the resulting improvements in analysis and forecast products near the tropopause and above.

3.4 INFLUENCE OF THE STRATOSPHERE ON TROPOSPHERIC PLANETARY-SCALE STRUCTURES

There is evidence to suggest that the planetary-scale influence of the stratosphere on the troposphere is sometimes greater than usual. Cases include the stratospheric warmings of

(i) January 1979 (*Madden and Labitzke*, 1981)
(ii) January/February 1984
(iii) January/February 1989.

It is hypothesised that the mechanism is a weak but significant planetary-scale Rossby-wave resonance. This is consistent with the observed slowing of the zonal phase speed of travelling zonal harmonic wave 1 structures that extend from the earth's surface upward to the middle stratosphere at least. These structures resemble theoretical travelling Rossby normal mode structures that have zonal wavenumber 1 and zonal phase speeds in the right range.

It would be of interest to carry out special forecast experiments and diagnoses in which conditions in the middle and upper stratosphere (such as gravity-wave drag) are varied to see if there is an unusual impact on forecasts of tropospheric planetary-scale patterns.

3.5 TRANSPORT CALCULATIONS

Several key areas of research into stratospheric ozone depletion have come to depend heavily on computation of Lagrangian parcel trajectories or contour advection (which isolates the purely advective effects in unprecedented detail.) These are important e.g. in calculation of chemical budgets along parcel trajectories, and of mass exchange rates across the edge of the polar vortex and across the subtropics. The calculations require wind information from lower stratospheric analyses or (for observational mission planning purposes) forecasts, and place severe demands on the quality of these products. Experience suggests that such calculations can be made with useful accuracy in the Northern Hemisphere but probably not in the Southern Hemisphere (where use of products from different weather prediction centres can lead to very different results). Improvement of Southern Hemisphere analyses is thus of key importance to the stratospheric research effort, though it remains to be seen how far such analyses could be improved without better data coverage.

One problem that particularly affects ECMWF products is the apparent noisiness of stratospheric potential vorticity analyses. This makes it difficult to use this information to monitor the polar vortices or as a basis for transport calculations, and the problem needs to be addressed. This is critical both for observational campaign support and for research studies.

3.6 UPPER TROPOSPHERIC RIDGES

In the Southern Hemisphere during August and September 1987, there was a systematic failure to forecast and analyze the amplitude of upper tropospheric ridges extending poleward over west Antarctica. Typically, research aircraft observation showed ridges extending to the pole, with 100+ knot winds northerly or even north-easterly at 250hPa and temperature as low as -80° C. The forecast and analysis would show the ridge crest ~65° S-75° S, with north-westerly winds of ~50 knots and temperatures ~5° C too warm. It is recommended to investigate whether the re-analysis produces a better description of these stratospheric features.

In the Northern Hemisphere during January and February 1989 such ridges were over-forecast in the T+120 and longer prognoses at 50 mb, producing 5-6 "false alarms" in the first six weeks of 1989: the vortex was forecast to split into two, a process which did not actually occur until late February. There was also a failure to forecast and analyze a major lower stratospheric cooling above a poleward-extending upper tropospheric ridge near the Greenwich meridian during the period 890131 to 890202. This may be related to the possibility of resonance together with the artificial upper boundary condition of the model.

It has been conjectured from time to time that orographic gravity-wave drag associated with the Antarctic Peninsula (or Palmer Peninsula as it is known in the USA) might be one factor in producing departures from zonality. More likely still is that Antarctic orography in general might directly induce Rossby-wave disturbances. It would be worth including experiments on sensitivity to the representation of orography in any special numerical experiments concerning the Antarctic.

3.7 DIABATIC COOLING RATES

Three-dimensional air parcel trajectories (u,v,w) calculated from operational analyses using the code of *Källberg* (1984) in and near the Arctic vortex during February 1989 showed, in many cases, time-averaged values of diabatic Lagrangian tendencies of potential temperature $\dot{\theta}$ over, the 10 day parcel histories of

~ -K/day (in potential temperature, equivalent to ~ -2 K/day in temperature). Such values are an order of magnitude greater than those calculated in the 30 to 70hPa pressure range by radiative calculations. Studies carried out at UGAMP (J Thuburn, personal communication) get smaller values of diabatic cooling, which agree well with concurrent trajectory calculations.

3.8 PV-TRACER CORRELATIONS

Scatter-plots of PV versus aircraft and HALOE measurements of tracers in and near the vortex edge were not compact. However, the analyzed wind fields in and near the vortex did correlate very well with the HALOE tracer fields throughout the entire depth of the analyzed stratosphere.

3.9 APPLICATION OF SINGULAR VECTOR AND SENSITIVITY ANALYSES FOR STRATOSPHERIC STUDIES

Recently linear theoretic tools have been developed to calculate the fastest growing small perturbations relative to arbitrary time-evolving solutions of the primitive equations, as represented by the ECMWF model. These perturbations are referred to as "singular vectors". Below are outlined possible applications of this technique and the closely related "sensitivity analysis" for stratospheric studies.

Singular vector analysis can be used to determine perturbations whose final energy is maximized either over the whole globe, or over a specified part of the atmosphere. (The latter is achieved by applying a local projection operator to perturbations at the end of the time interval over which energy growth is calculated.) Suppose, for example, this specified region is the whole of the stratosphere; then the calculations determine those regions of the stratosphere where small perturbations will grow rapidly (as well as determining the perturbations themselves). One can also look for perturbations initially in the stratosphere that finally impact the troposphere (see below).

These types of calculation are of interest from a purely fluid dynamical point of view. Instability analysis of the disturbed polar vortex using normal modes poses theoretical difficulties that singular vector analysis can overcome. Further restriction of the predefined region, e.g. to the tongue of an observed breaking Rossby wave, would allow quantitative analysis of the initial phase of rollup in regions of reversed potential vorticity gradient. Cases of hypothesized sensitivity of forecasts to local variations in initial PV distributions could be efficiently tested this way.

From a practical point of view, the technique allows an estimation of the predictability of an NWP forecast in the short range when error growth is linear (typically within the first three days of the forecast). With the specified region (for singular vector calculations) applied to the Antarctic stratosphere, estimates of the reliability of short range forecasts of the polar vortex could be made to help flight planning for polar ozone campaigns. Medium-range forecast predictability could be assessed by running ensembles with these stratospheric singular vectors.

Previous results have suggested that improvements to tropospheric forecasts from having a well-resolved stratosphere have mainly been associated with improvements to the initial conditions, through a better fit to data. Stratospheric singular vectors could be a useful way of determining the sensitivity of tropospheric forecasts to stratospheric initial conditions. Some development of the singular vector calculation technique is desirable, so that two different local projection operators can be applied: one at initial time (ie., a restriction to the stratosphere), and one at final time (ie a restriction to the troposphere). In this way the singular vectors calculated will have maximum energy in the troposphere at final time, consistent with being purely stratospheric at initial time. Of particular interest will be the case studies of stratospheric warmings identified above (see section 3.4).

Also of some interest would be studies of sensitivity of forecast errors to initial conditions by the direct use of the tangent linear model. Such techniques could usefully be applied, also, to cases where forecasts might be sensitive to PV-theta details near the tropopause.

3.10 SUMMARY OF RECOMMENDED DIAGNOSTICS

Special interest was shown in the following types of diagnostics, in addition to the standard diagnostics, such as zonal-mean temperatures and zonal winds, monthly mean height maps, maps of standard deviation of heights, etc.

(i) Contour advection and other Lagrangian diagnostics (programme package should be considered for inclusion in the suite of diagnostic tools at the Centre). Most such diagnostics will require 3D velocity fields to be archived at time intervals of 6 hours or better. Spatial resolutions of T213 or better would be desirable.

(ii) Isentropic distributions of potential vorticity should also be archived routinely. If possible, methods of improving their quality by incorporating advective information (e.g. following the work of Fisher and O'Neill in preparation) should be considered. Such methods have proved powerful for automatically eliminating many of the spurious features in present-day PV maps. They rely on having Lagrangian information; see item (i).

(ii) Tendency diagnostics (*Klinker and Sardeshmukh*, 1992)

(iv) Gravity wave drag force fields, as force per unit mass.

(v) Radiative heating and cooling. For the stratosphere, it is valuable to express these as Lagrangian tendencies of potential temperature.

(vi) Lagrangian tendency of PV.

(vii) Eliassen-Palm fluxes and possibly in a few years time other more sophisticated wave activity diagnostics as the theory develops (Haynes and Magnusdottir, in preparation).

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