ECMWF products in the European Arctic Stratospheric Ozone Experiment

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Summary: ECMWF products were used during the European Arctic Stratospheric Ozone Experiment (EASOE) during the winter of 1991/2 for a variety of purposes which are described in detail in this paper.

1. INTRODUCTION

The discovery of the ozone hole by Farman et al. (1985) is one of the most dramatic discoveries in atmospheric science. The loss of more than 50% of the ozone column[1] above Antarctica in springtime has far reaching human and political consequences, and has generated a large research effort to understand the processes at work. It is now known that ozone loss is not confined to Antarctica; springtime losses in the northern hemisphere middle latitudes of approaching 10% have been reported. In this paper we review the dynamical circumstances and chemical processes responsible for the ozone loss. The main aim of this paper is to describe the recent observational campaign, the European Arctic Stratospheric Ozone Experiment (EASOE), undertaken to further our understanding of observed northern hemisphere ozone depletion, and the use of ECMWF products in that campaign.

1.1 Polar ozone loss

Observations of the ozone column amount by Joe Farman and colleagues at Halley Bay, produced the first published evidence that large decreases in ozone were occurring in Antarctica during the southern hemisphere spring. Fig. 1 shows the reduction in ozone that occurs in a layer been 14km and 22km. The decrease in ozone begins in August, reaching its lowest value in early October but recovering in November and December. Fig. 2 shows a graph of the mean October value of column ozone above Halley Bay for nearly 30 years. The strong gradient of minimum ozone with time showed conclusively that something dramatic was occurring. TOMS satellite data subsequently confirmed that the loss is occurring over the whole of the Antarctic continent.

Fig. 3 shows the ozone column trend against latitude and time of year. The large southern hemisphere polar loss in September to December is clearly visible, extending to about 50°S. However, a northern hemisphere

1. Column amount is the thickness of the layer which the gas occupies at standard temperature and pressure. This is about 3mm for a column containing the global mean amount of ozone. A Dobson Unit (DU) is 10^{-5}m, thus the global mean amount of total ozone is about 300DU.

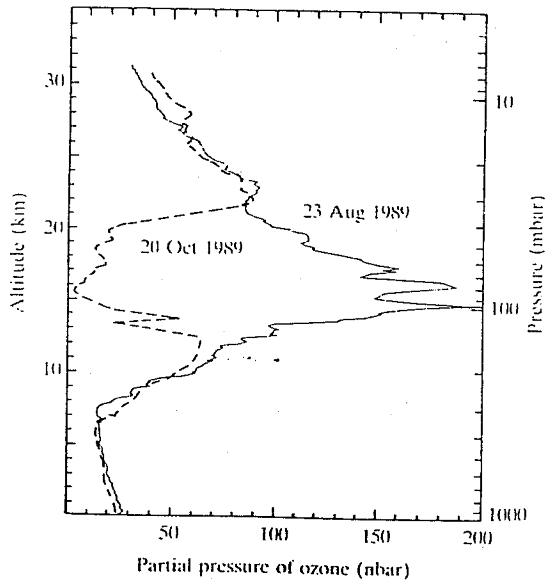


Fig. 1 Ozone concentrations over McMurdo Station in August and in October, 1989. These altitude profiles show that the concentrations dropped drastically in the layer between 14 and 22km, the reduction being 98% at 15km. Taken from Wayne (1991).

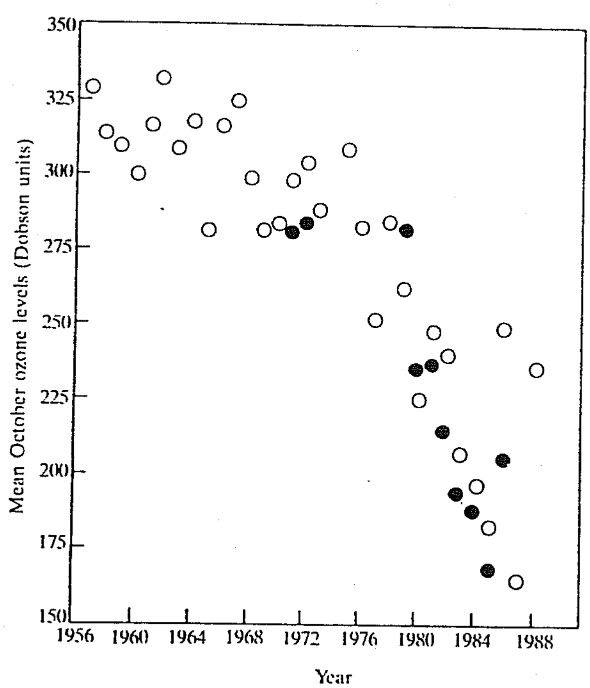


Fig. 2 Time series of minimum ozone for October above Halley Bay showing the decline in ozone concentrations during the period 1956-1988. The open circles are results from ground-based measurements using Dobson spectrophotometers, while the closed circles show TOMS measurements where they are available. Taken from Wayne (1991).

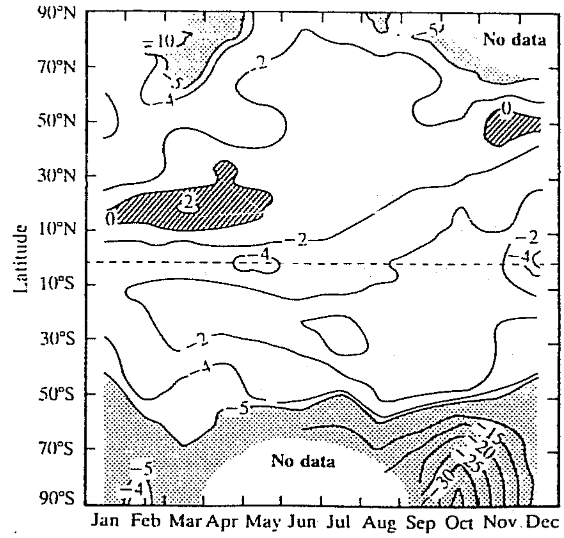


Fig. 3 The percentage difference in two-year averages of column ozone (1986/7 minus 1979/80), derived from corrected TOMS data. The dotted areas represent regions suffering losses of more than 5%, while the shaded areas show slight gains in ozone over the period. Taken from: Stratospheric Ozone 1988, U.K. Stratospheric Ozone Review Group (Her Majesty's Stationery Office, London, 1988).

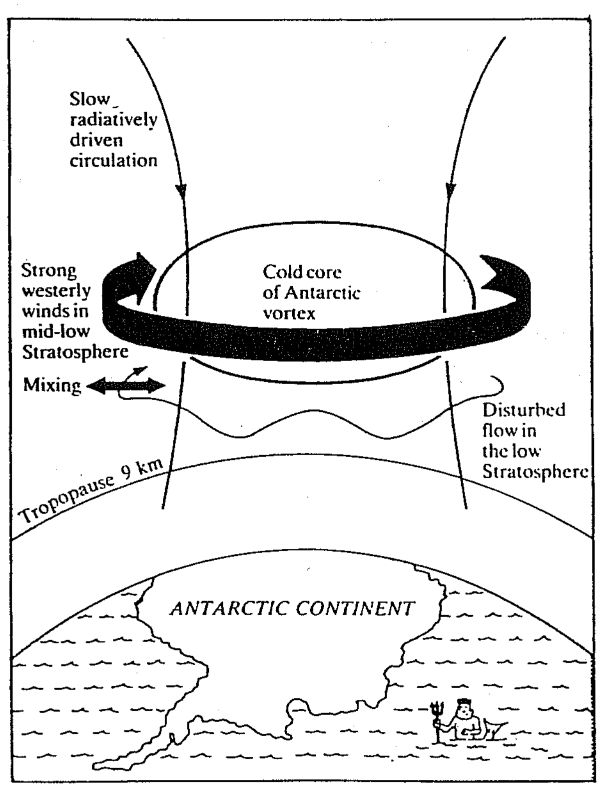


Fig. 4 Schematic of the winter vortex over Antarctica. Taken from Wayne (1991).

polar loss is also visible although to a lesser extent; at most about 10% per annum. The northern hemisphere loss also extends to middle latitudes, peaks in the spring, but is evident throughout the year.

It was the possibility of a northern hemisphere polar 'ozone hole' that prompted the NASA led AASE campaign in 1988/9 (Geophysical Research Letters, 17, 1990) to investigate whether the processes responsible for ozone loss in the southern hemisphere were being repeated in the northern hemisphere. The EASOE campaign in the winter of 1991/2 was a European venture also to make detailed and intensive observations of the northern hemisphere stratosphere.

1.2 The role of dynamics

It is believed that the cause of the ozone destruction in the southern hemisphere is fairly well understood, being an interaction between chemistry and dynamics. Before describing the chemical processes at work we describe the role of the stratospheric dynamics in priming the stratosphere for chemical destruction.

Fig. 4 is a schematic of the southern hemisphere stratosphere during winter. Central for ozone destruction is the formation of a polar vortex. Lack of sunlight during the polar night results in cold temperature over the pole as the air cools radiatively. A strong circumpolar jet develops, which acts to isolate the cold air over the pole, reducing mixing of this air with mid-latitude air. This is important because chemical changes in the vortex air are then not diluted. As the air inside the vortex cools it also descends, bringing high stratospheric air to the low stratosphere. Isentropic potential vorticity (PV) maps of the southern hemisphere show strong latitudinal gradients around the cold region with high values of PV inside the vortex. The strong gradients of PV represent, in some sense, a barrier to mixing across the vortex edge although this idea is currently controversial. The schematic in Fig. 5 represents the situation over the southern hemisphere pole.

The situation in the northern hemisphere however differs somewhat. As most of the landmasses are in the northern hemisphere, its polar vortex can be much more disturbed. Tropospheric forcing can distort the northern hemisphere vortex much more than its southern hemisphere counterpart. Descent inside the vortex still occurs and cold temperatures still arise. However, cold regions are not always within the vortex itself but can, for example, lie within the jet. Fig. 6 illustrates this schematically. Thus, it seems highly likely that the interaction between dynamics and chemistry and its relationship to ozone loss will be different in the two hemispheres.

1.3 The chemistry of the polar vortex

The existence of ozone in the stratosphere is a balance between its production by photolysis of molecular oxygen by solar ultraviolet radiation and its destruction by a number of catalytic cycles involving: (i) O and O_3, (ii) HO_2 and OH, (iii) NO and NO_2, (iv) Cl and ClO and (v) Br and BrO. Fig. 7 shows the concentrations of some of these chemical species as a latitudinal section, going into the southern hemisphere polar vortex. It is seen that a very well defined transition region exists between the cold polar vortex and the relatively well mixed air outside. Fig. 8 shows actual measurements of ozone and ClO across this transition giving a strong indication that chlorine chemistry is responsible for the destruction.

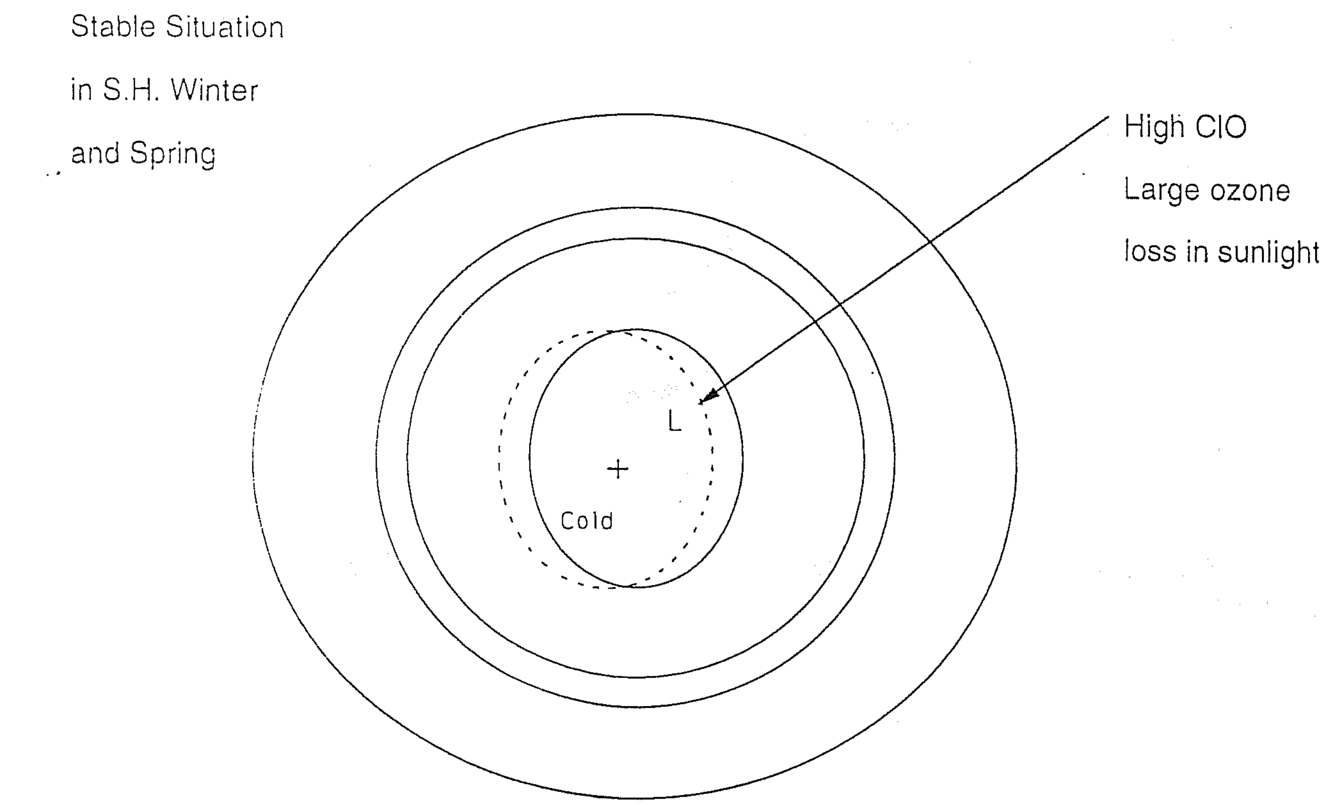


Fig. 5 Schematic (plan view) of southern hemisphere vortex, showing the strong gradient in potential vorticity around the edge of the vortex with the coldest temperatures in the centre.

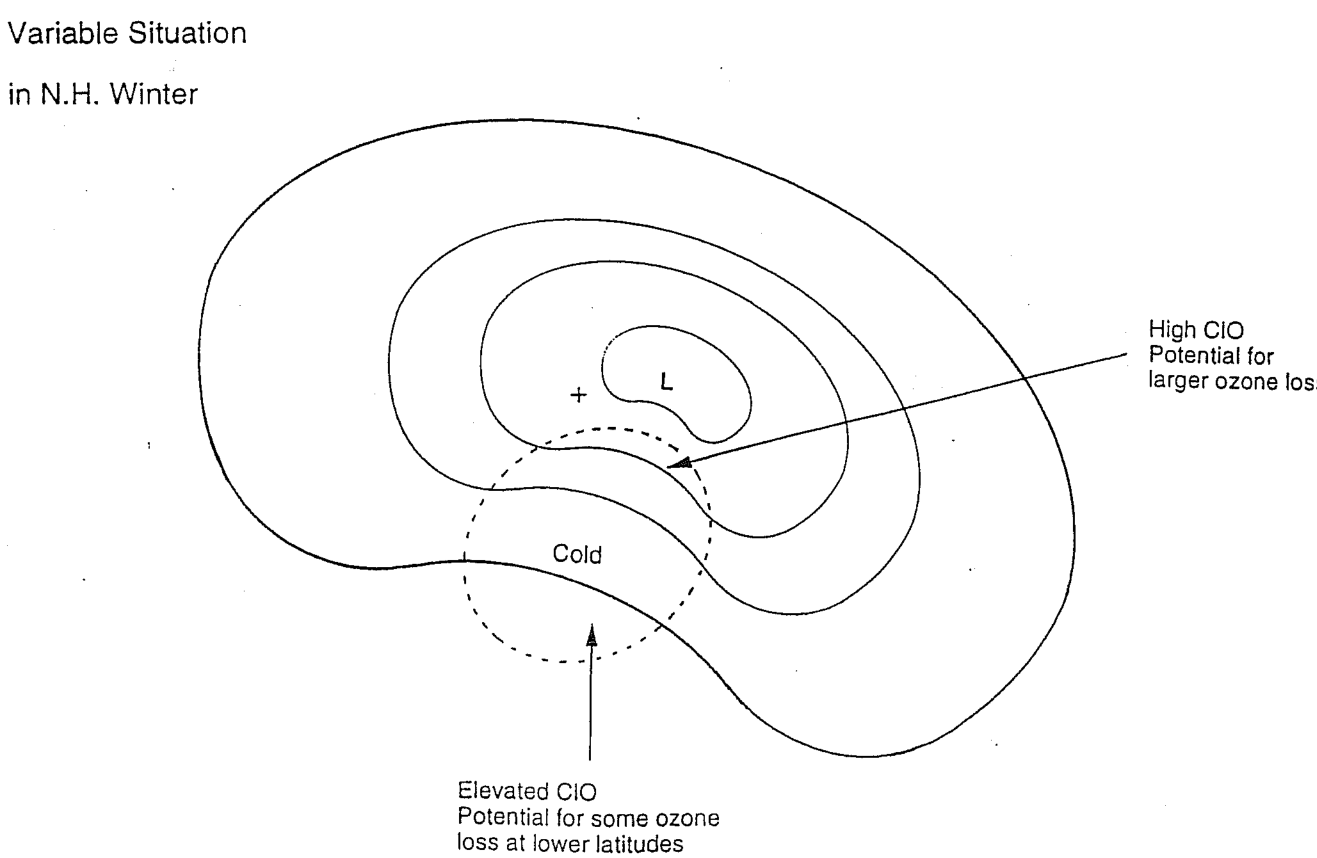


Fig. 6 Schematic (plan view) of northern hemisphere vortex. Unlike Fig. 5, the vortex is now more distorted and the coldest temperatures can often be displaced from the centre.

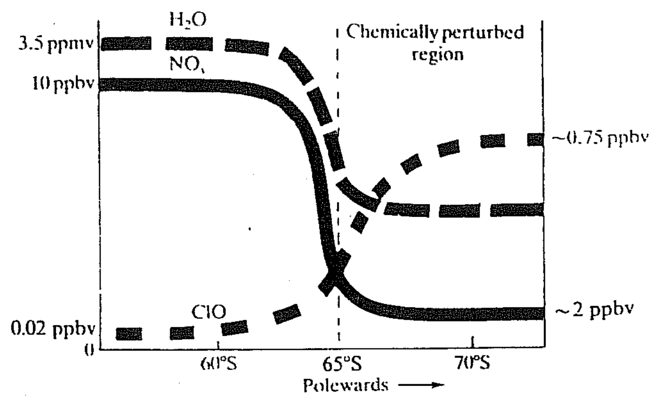


Fig. 7 Schematic representation of the latitudinal variation of some species approaching the south pole and the chemically perturbed region. Taken from Wayne (1991).

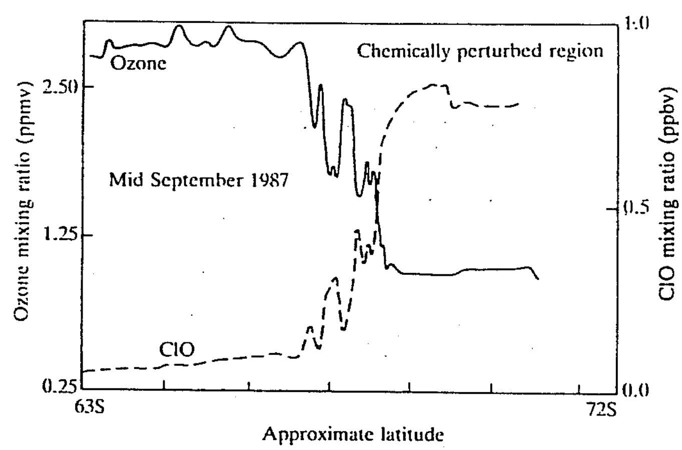


Fig. 8 Latitude variation of ozone and ClO in mid-September. Taken from Wayne (1991).

The curves in Fig. 7 are a result of an anomalous chemical environment set up by the presence of polar stratospheric clouds (PSCs) within the vortex. These clouds form at temperatures below about -80^{0}C, hence the importance of the cold vortex. Reactions, unknown before the discovery of the ozone hole, occur on the surface of the PSCs to release chlorine in its active form from its inactive reservoir species, $ClONO_2$ and HCl. PSCs are believed to be composed of a mixture of water and nitric acid. If cold temperatures are maintained these PSCs can grow and sediment and hence remove both water and active nitrogen compounds. It is this process of dehydration and denitrification that accounts for the sudden decrease in H_2O and NO_y within the vortex in Fig. 7.

A critical feature of the perturbation is the conversion of the reservoir compounds of chlorine, HCl and $ClONO_2$ to active forms of chlorine by reactions including

$$ClONO_2 + HCl \rightarrow Cl_2 + HNO_3$$

$$ClONO_2 + H_2O \rightarrow HOCl + HNO_3$$

$$N_2O_5 + HCl \rightarrow ClNO_2 + HNO_3$$

which all take place on the surface of the PSCs. The gas products Cl_2, HOCl and $ClNO_2$ photolyse to yield 'active' chlorine, Cl and ClO. Thus the PSCs perturb the chemistry by providing a surface for these unusual reactions to take place and also by removing nitrogen oxides from the vortex, thereby preventing the return of the active chlorine to $ClONO_2$, its inactive reservoir.

Once formed, the chlorine monoxide, ClO, can destroy ozone by a catalytic cycle involving the ClO dimer, $(ClO)_2$:

$$ClO + ClO + M \rightarrow (ClO)_2 + M$$

$$(ClO)_2 + h\upsilon \rightarrow Cl + ClOO$$

$$ClOO + M \rightarrow Cl + O_2 + M$$

$$2\,(Cl + O_3 \rightarrow ClO + O_2)$$

$$\text{NET:} \ldots\ (2O_3 + h\upsilon \rightarrow 3O_2) \qquad \text{(EQ 1)}$$

This cycle is thought to account for most of the ozone destruction. A further cycle involving BrO may account for 5-10% of the depletion in the south and a somewhat larger fraction in the north.

The sources of the reservoir species, $ClONO_2$ and HCl, themselves the source of the active chlorine, are the CFCs or chlorofluorocarbons. CFCs, entirely man-made, are released from the ground, mainly in the northern hemisphere, and enter the stratosphere through the tropical tropopause. Once in the stratosphere ultraviolet radiation breaks down the CFCs, releasing reactive chlorine compounds which subsequently form the stable products of HCl and $ClONO_2$. To a good approximation the amount of chlorine contained in the CFCs and in HCl and $ClONO_2$ will be constant in the stratosphere. If, as is observed, the CFCs are in low concentrations in the upper stratosphere or inside the polar vortex, the concentrations of HCl and $ClONO_2$ will be correspondingly high. In these circumstances, high levels of active chlorine can be produced on PSCs.

1.4 Polar ozone loss

The presence of solar radiation is crucial for the destruction of ozone, see (EQ 1). A key point therefore is that, although large concentrations of active chlorine may form, ozone depletion will not occur unless in the presence of sunlight. It is partly for this reason that we do not see the same levels of ozone depletion occurring in the northern hemisphere as in the southern hemisphere. In the southern hemisphere as shown in Fig. 9, the temperature stays low enough, maintaining the PSCs and hence high concentrations of active chlorine, until the sunlight returns in September and ozone depletion results (Fig. 1). In the northern hemisphere, however, although elevated levels of ClO may be present, the temperature does not always remain sufficiently cold (Fig. 9) to maintain the PSCs and hence these high levels of active chlorine until the return of sunlight.

Evidence for denitrification is difficult to obtain for the northern hemisphere vortex but it is generally agreed that it is much less than in the southern hemisphere. This allows a more rapid recovery of the active chlorine back to its reservoir forms, reducing the likelihood of ozone depletion when the sunlight returns in the northern hemisphere spring.

1.5 The European Arctic Stratospheric Ozone Experiment (EASOE)

It is clear that northern hemisphere ozone depletion does occur (Fig. 3). Several mechanisms have been proposed for the ozone losses observed in the northern hemisphere, particularly at mid-latitudes:

1. Dilution. Assuming ozone loss does occur at high latitudes, this process is the mixing of ozone-depleted air with mid-latitude air. The amount of mixing that occurs is still the subject of scientific debate.
2. Processing. This may take place in two ways; both involve air with high levels of active chlorine being produced at high latitudes and transported south.

   (i) The air separates from the vortex and mixes with mid-latitude air.

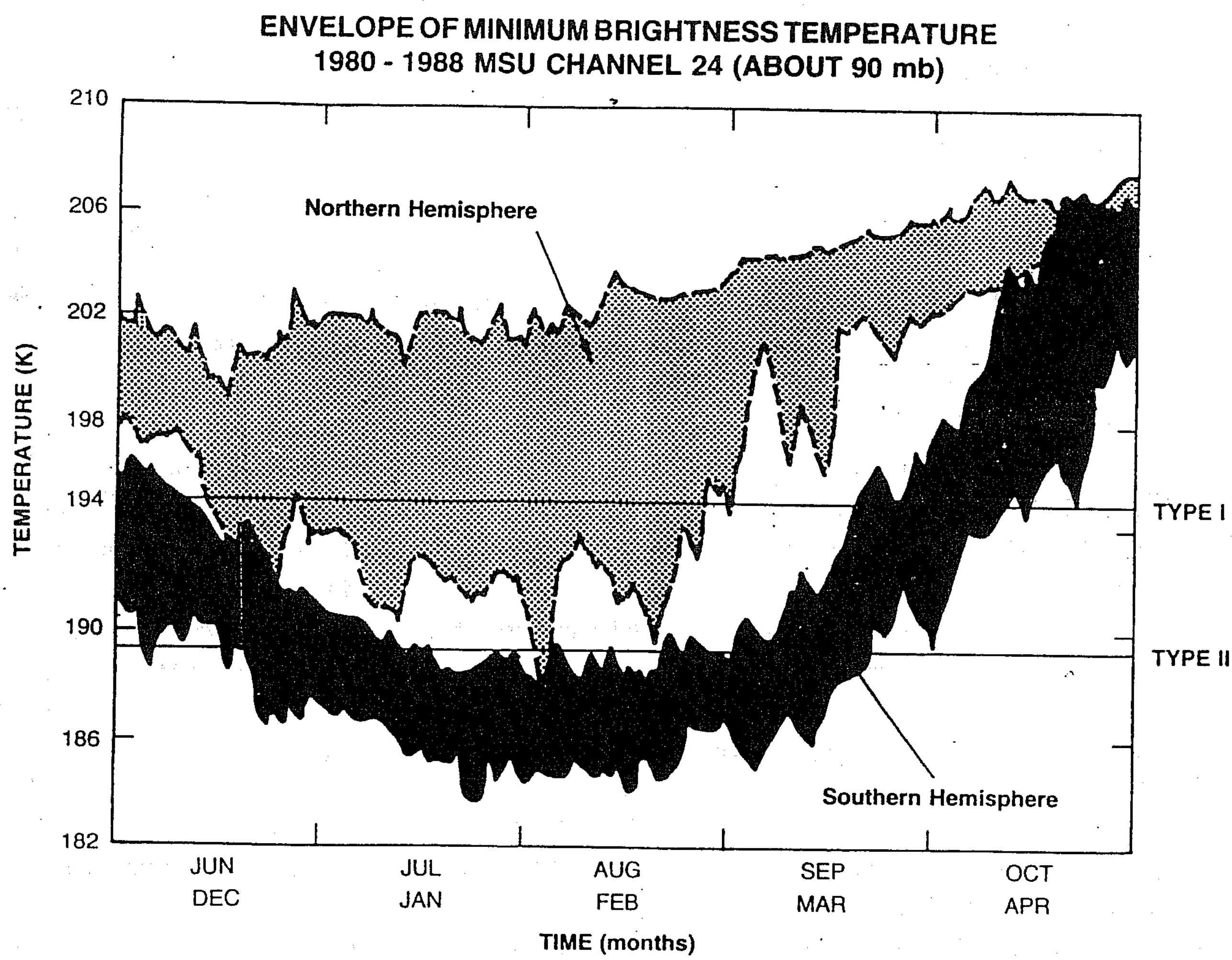
   (ii) The air stays within the vortex but the vortex distorts sufficiently to reach latitudes where sunlight is present.

   Although the amount of mixing outside the vortex is still under debate, the latter process is now receiving some attention (Pyle et al. 1993). In either case, the time period for ozone depletion depends on the recovery time for the chlorine to return to its reservoir forms, roughly two weeks.
3. In situ. All the surface chemical processes are deemed to occur *in situ* in middle latitudes, possibly on sulphate aerosol.

It was in an attempt to observe more closely the chemistry of the Arctic stratosphere and to try to understand the relative importance of these processes that EASOE was set up.

The strategy of EASOE was to make measurements over a wide area of the northern hemisphere and over a long period so that both the buildup and decay of the polar vortex could be observed. Additionally, measurements specific to various of the relevant processes, e.g. the formation of the PSCs, were included. A variety of types of measurement were made. These were then to be combined with ECMWF data and

Fig. 9 Brightness temperatures 1980-88 for northern hemisphere and southern hemisphere. Also shown are the temperatures at which Type I and Type II PSCs form.



theoretical studies to understand both polar and middle latitude behaviour. Measurements began in November 1991 and ended in April 1992.

The areal extent of the measurements was provided by a network of groundbased stations using lidars and infrared, ultraviolet, visible and microwave spectrometers. These provided information on chemical composition and the distribution of polar stratospheric clouds and sulphate aerosol. Three aircraft also provided important aerosol coverage using many of the same instrumental techniques employed by the groundbased network. Additionally, aircraft can be deployed in the most interesting locations. For example, flights both along and across the vortex edge were frequently made. Measurements upwind and downwind of the Norwegian mountains gave information on the formation of lee wave PSCs.

The aircraft were mainly confined to the troposphere. Large stratospheric balloons could, on the other hand, carry complex instruments weighing several hundred kilograms into the perturbed polar vortex. A large number of balloons flights was made from ESRANGE near Kiruna in northern Sweden. Again the measurements included many chemical species as well as cloud and aerosol properties.

A large network of ozone sonde sites was established for EASOE, with about 1000 soundings from approximately 20 locations. Ozone sondes, launched on small balloons, provide measurements of the ozone profile with high vertical resolution up to about 30km.

Finally, the EASOE measurements were complemented by a significant theoretical effort including trajectory and three-dimensional modelling. Both of these relied on ECMWF data, as did the operational planning of EASOE. The ECMWF products used are discussed next.

1.6 ECMWF products

During EASOE, many ECMWF products were used. Isobaric analyses of geopotential and temperature at 30mb, 50mb and 100mb were received routinely. There were available as standard products. In addition, isentropic analyses and forecasts were transmitted to the EASOE campaign. These data were produced by Bjorn Knudsen of the Danish Meteorological Institute with the assistance of Terry Davies at the ECMWF. Isentropic analyses, on the 350K, 380K, 400K, 475K, 550K and 700K isentropic surfaces, of both temperature and potential vorticity were obtained, as well as 1 to 5 day forecasts on the 350K, 475K, 550K and 700K surfaces. Backward, isentropic trajectories were calculated from the ECMWF analyses for the EASOE observing sites plus a number of other northern hemisphere locations. These were made extensive use of during the campaign and are now proving vital in understanding some of the observations. Lastly, ECMWF upper air and surface fields at 6 hourly intervals were used by the Cambridge Centre for Atmospheric Science, Chemistry Department, to run the general circulation model (GCM) of the UK Universities Global Atmospheric Modelling Programme (UGAMP) for chemical simulations during the 1991/92 winter.

There are two distinct ways in which the ECMWF data was used. First, the forecast data was used in mission planning to forecast the presence of PSCs and to forecast the position of the vortex. For example, certain types of measurement were best made if PSCs were likely to be present. Other measurements were required deep inside the vortex. Both balloon and aircraft planning relied heavily on the ECMWF forecasts. The second way in which the data is being used is for interpretation of the observations. For example, gradients of many chemical species can be understood more clearly within a potential vorticity framework. The CFCs, for instance, decrease rapidly on an isentropic surface, as the PV increases (see later). Also chemical models integrated along the air parcel trajectories are being used to study the chemistry processes occurring during the winter.

2. FORECASTS

In this section, we describe the ECMWF forecasts in more detail, concentrating particularly on their accuracy and usefulness during the campaign. Overall, the forecasts were found to be very accurate, enabling operational decisions during EASOE to be made with a high degree of confidence.

2.1 Temperature

We begin by examining the forecasts of temperature on the 475K isentropic surface. Fig. 10 shows the ECMWF analysis of temperature on the 475K isentropic surface for the 9th January 1992. A large region of cold temperatures, less than required for formation of PSCs, has formed north of the UK, over Iceland and Scandinavia. Fig. 11 shows the corresponding 24hr forecast for the same day. The forecast is very good; the minimum temperatures have been accurately forecast as has the location of the cold air. Fig. 12 shows the 72hr forecast for the 9th January 1992. Now the model has produced colder temperatures than the verifying analysis (Fig. 10), covering a larger area. However, one would still consider this a very good forecast.

As so much of the chemistry of the polar vortex depends critically on the formation of PSCs leading to production of active chlorine, the forecasting of minimum temperatures is of prime importance. There were instances during EASOE when the ECMWF forecasts indicated the possibility of PSC formation but the analyses did not (or indicated activation over a smaller area). For example, Fig. 13 shows the temperature analysis for the 11th January. Compared to Fig. 10, the region of coldest temperatures is now much smaller and only a small region where temperatures are less than 193K can be seen. Fig. 14 and Fig. 15 show the 3 and 5 day forecasts for the 11th January respectively. Both are significantly colder than the analysis, the 5 day forecast showing the largest region of temperatures likely to result in the formation of PSCs. In contrast, the analysis would suggest that only a small region of PSCs might form. Of course, forecasting PSCs is a particularly critical test of the model. A very small error in temperature can make a major difference to correctly forecasting a phase transition. A complicating factor is that lee waves generated by the high orography of Scandinavia could often produce localised regions of cold temperatures. The scale of these features meant that they did not show up on the ECMWF forecasts.

2.2 PV

In the previous section we described why it was important to determine the position of the vortex during EASOE. We now examine the forecasts of PV during the campaign.

Fig. 16 shows the ECMWF analysis of PV on the 475K isentropic surface for the 11th January 1992. The vortex is often characterized by its 'edge', taken to be the region of steepest gradient in PV. We somewhat arbitrarily choose a PV range of 36-42 PV units to define the edge. One of the first points to note about the

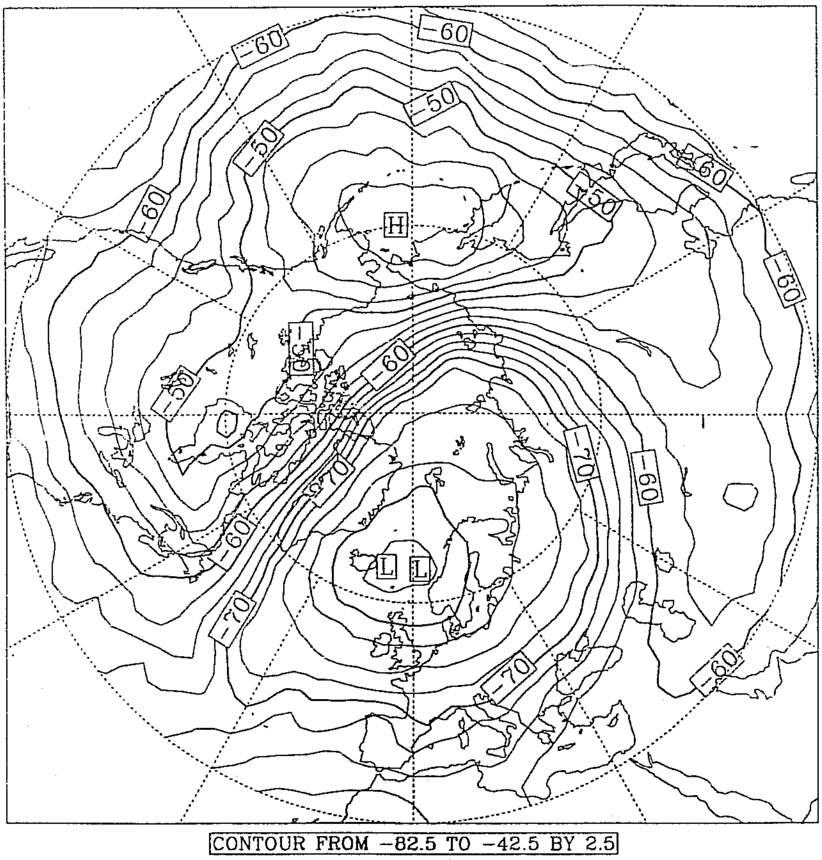


Fig. 10 ECMWF temperature analysis for 12GMT, 9th January 1992 on the 475K isentropic surface.

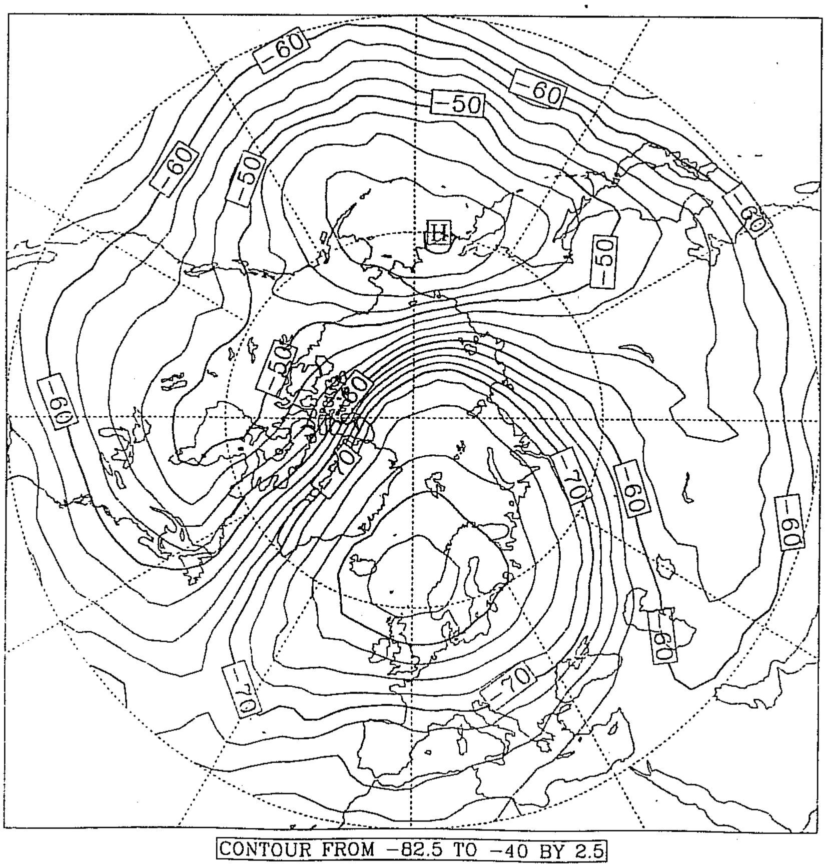


Fig. 11 24hr ECMWF forecast of temperature for 12GMT, 9th January 1992 on the 475K isentropic surface.

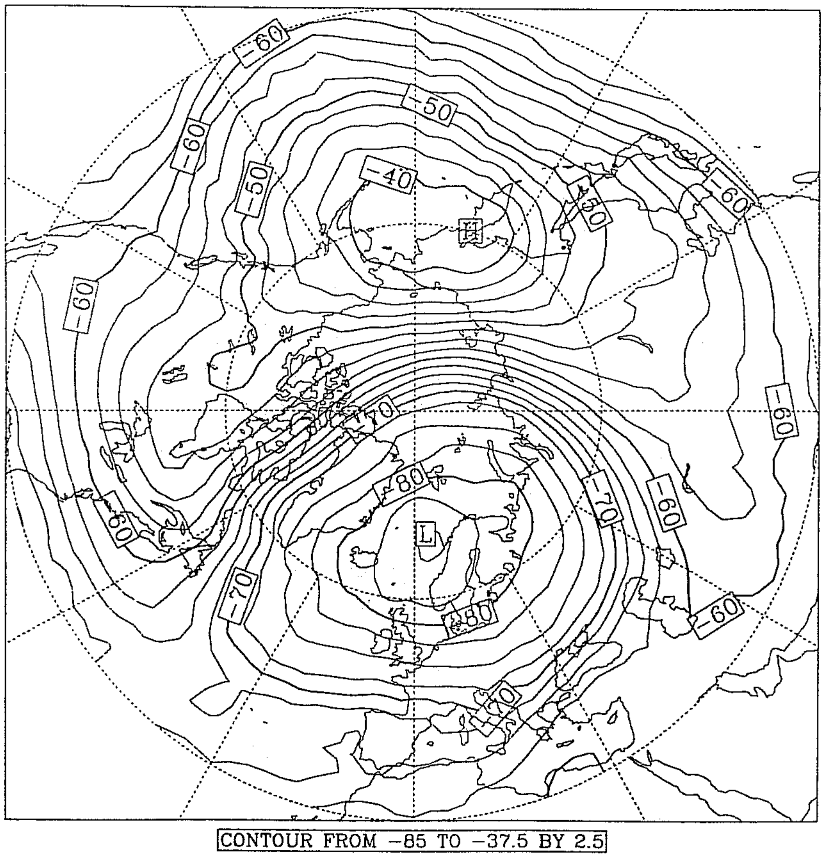


Fig. 12 72hr ECMWF forecast of temperature for 12GMT, 9th January 1992 on the 475K isentropic surface.

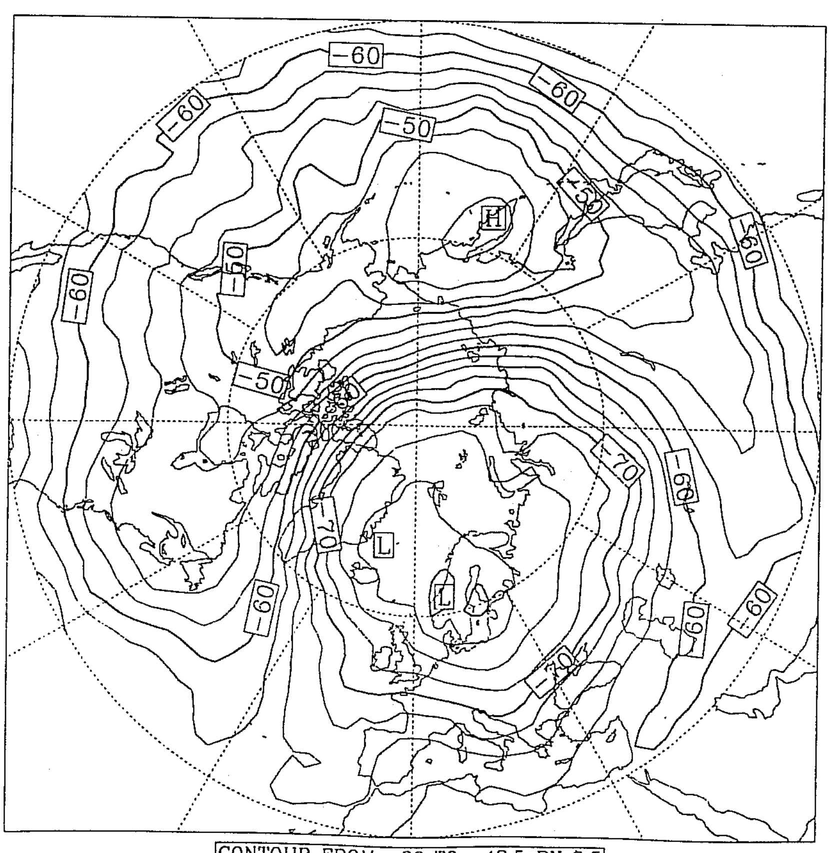


Fig. 13 ECMWF temperature analysis for 12GMT, 11th January 1992 on the 475K isentropic surface.

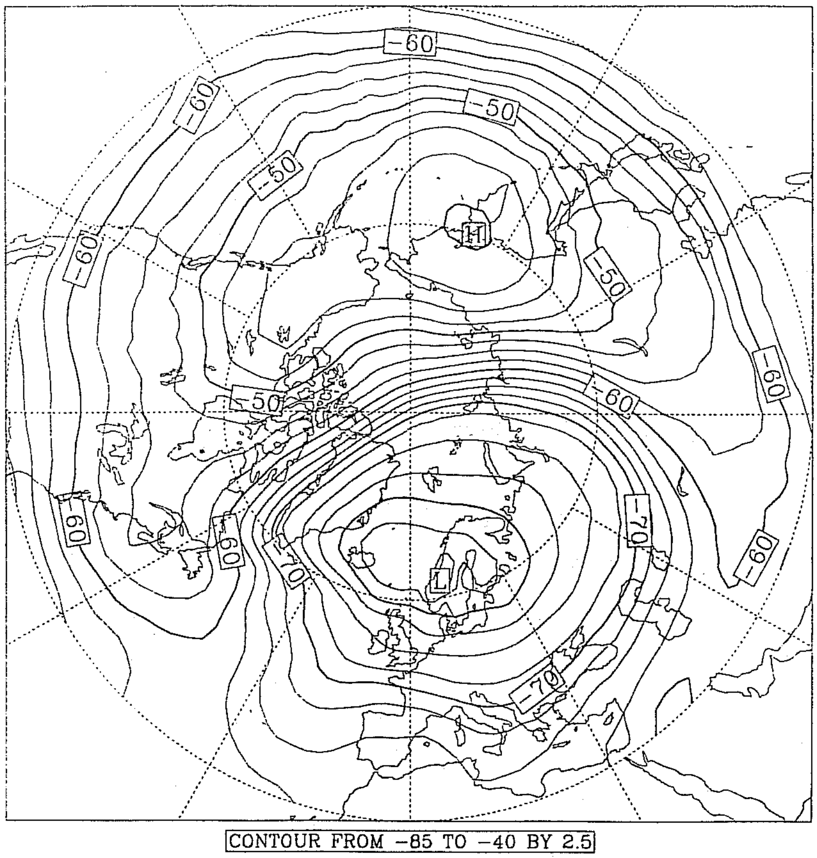


Fig. 14 72hr ECMWF forecast of temperature for 12GMT, 11th January 1992 on the 475K isentropic surface.

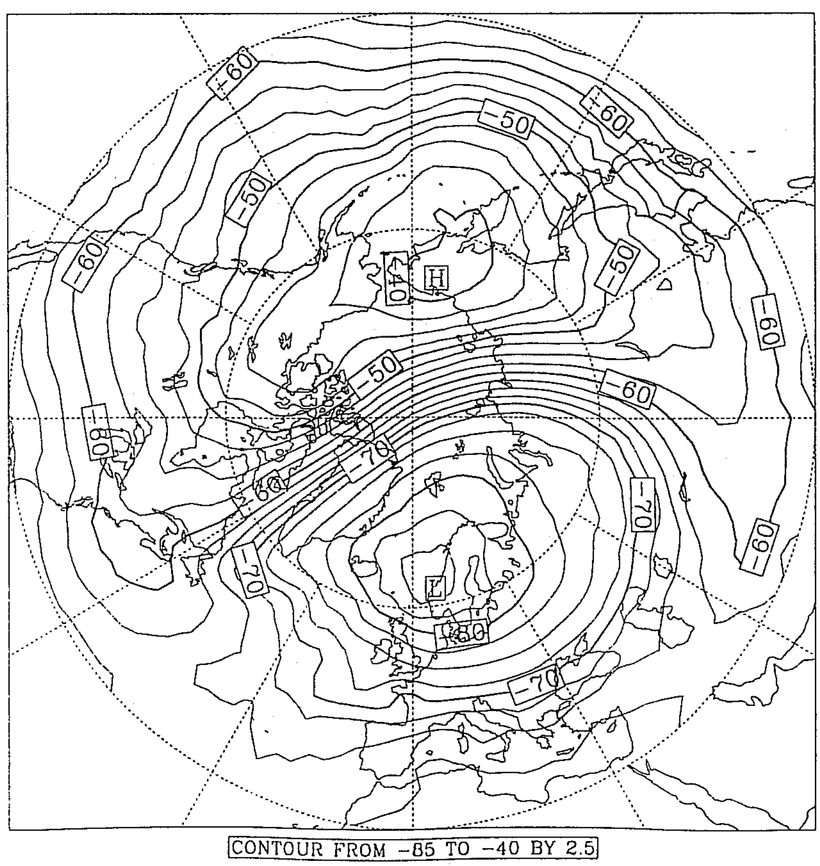


Fig. 15 120hr ECMWF forecast of temperature for 12GMT, 11th January 1992 on the 475K isentropic surface.

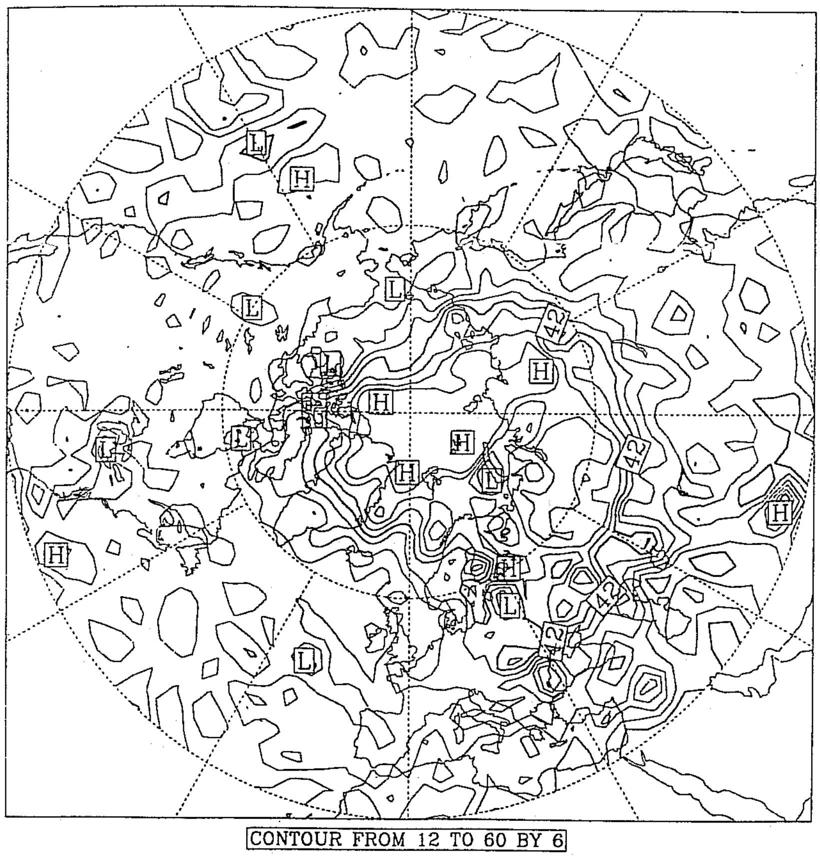


Fig. 16 ECMWF analysis of potential vorticity for 12GMT, 11th January 1992 on the 475K isentropic surface.

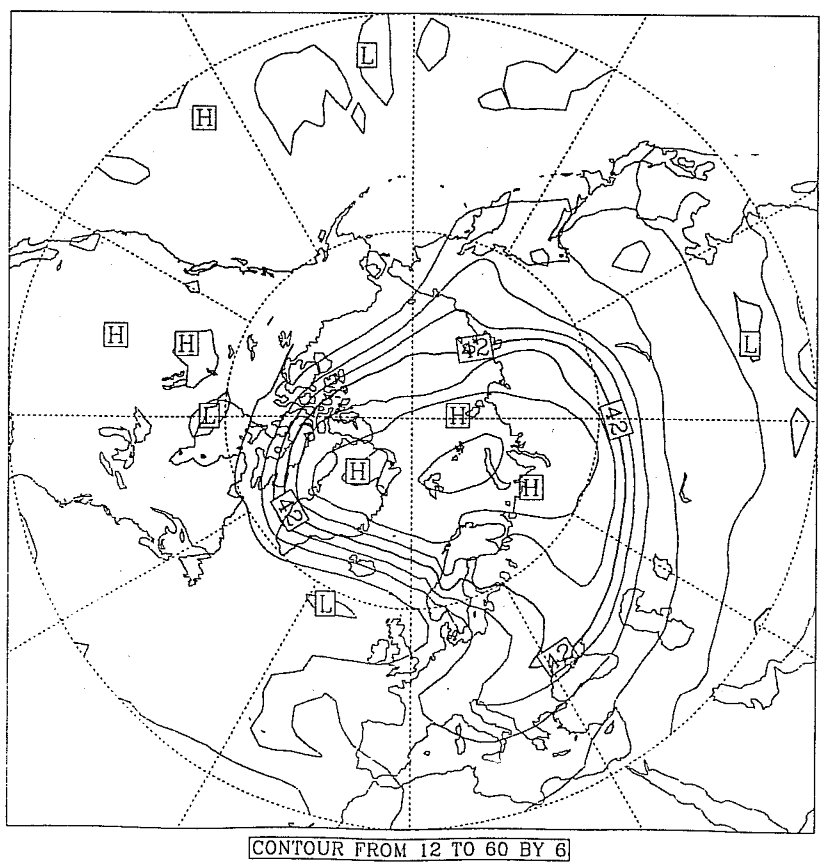


Fig. 17 72hr ECMWF forecast of potential vorticity for 12GMT, 11th January 1992 on the 475K isentropic surface.

analysis is that it is quite noisy, with a lot of structure both around the edge of the vortex and outside the vortex. Note also the appearance of regions of low PV inside the vortex and correspondingly small regions of high PV outside the vortex. Whether such features are real or not is difficult to say. Undoubtedly some features are real and small regions of high PV outside the vortex can have perturbed chemistry associated with them (Tuck et al. 1992). At the same time, some are undoubtedly an artifact of the analysis procedure.

Fig. 17 shows that many of these features are quickly removed in the ECMWF forecasts. The model has smoothed the PV gradient defining the edge of the vortex quite considerably, as well as reducing the area of maximum PV (although the total area of the vortex is about the same). Both these features are a result of the very strong horizontal diffusion present in the stratospheric layers in the ECMWF model. However, as far as the position of the vortex is concerned, the forecast is very good. Over Europe, where the edge is ill-defined in the analysis (Fig. 16), the agreement is very good, apart from a small westward extension towards Italy in the forecast. The forecast has also moved the vortex further south over Greenland.

Fig. 18 shows the 5 day forecast in PV for the 11th January. The agreement with the analysis is still very good over Europe but the vortex has now extended too far south over Greenland. We also note that the total area of the vortex has increased. For the EASOE area the 5 day forecast in this case is good, as was generally the case.

In late January, a large dynamical disturbance took place in which the vortex distorted several times and, on one occasion, a region of air appeared to separate from the high PV air within the main vortex. This distortion of the vortex was caused by an anomalously high blocking event in the tropopause over the north Atlantic that persisted for some time. Fig. 19 shows the analysis for the 22nd January, with a large extension of the vortex present over Europe, almost as far as the Mediterranean. There is a large area of low PV air that is almost as far north as the pole and appears to be being drawn inside the main vortex. This is a particularly interesting case from a chemical point of view. The main vortex (high PV air) is most probably full of activated chlorine (Bell et al. 1993, Kettleborough et al. 1993) and primed for ozone destruction. On the other hand, the low PV air may have normal mid latitude concentrations of NO_2 and the mixing of such air masses could result in the reformation of the inactive reservoir $ClONO_2$, reducing the levels of active chlorine in the vortex (Pyle et al. 1993). One must be careful however, not to imply that this low PV air is low latitude air. The so-called edge of the PV vortex can often lie *poleward* of the jet axis (O'Neill and Farman 1993). Thus the low PV air is most likely to have been circulating in the jet rather than being drawn up from lower latitudes.

Fig. 20 shows the 24hr forecast for the same day. As seen in the analysis there is clear evidence of low PV air having been drawn into the main vortex. Another interesting feature in the forecast is the intrusion of low PV air at about 225°E. It is hard to see this feature in the analysis for the same day. We also note that the high PV air (>48 PV units) has separated at about this longitude. This is just about visible in the data. Fig. 21 shows the 3 day forecast for the same date. This forecast is now beginning to show some slight phase errors. The vortex extension is now not as far east as in the analysis. Also, the main vortex, as we found for the 11th January, has moved too far south down the east coast of the USA. Even more pronounced in this forecast is the drawing of the low PV air into the main vortex. It is also interesting to see that the characteristics of the second intrusion have changed. Instead of an intrusion in the 36-42 contour we see a separation at the 54 PV units contour.

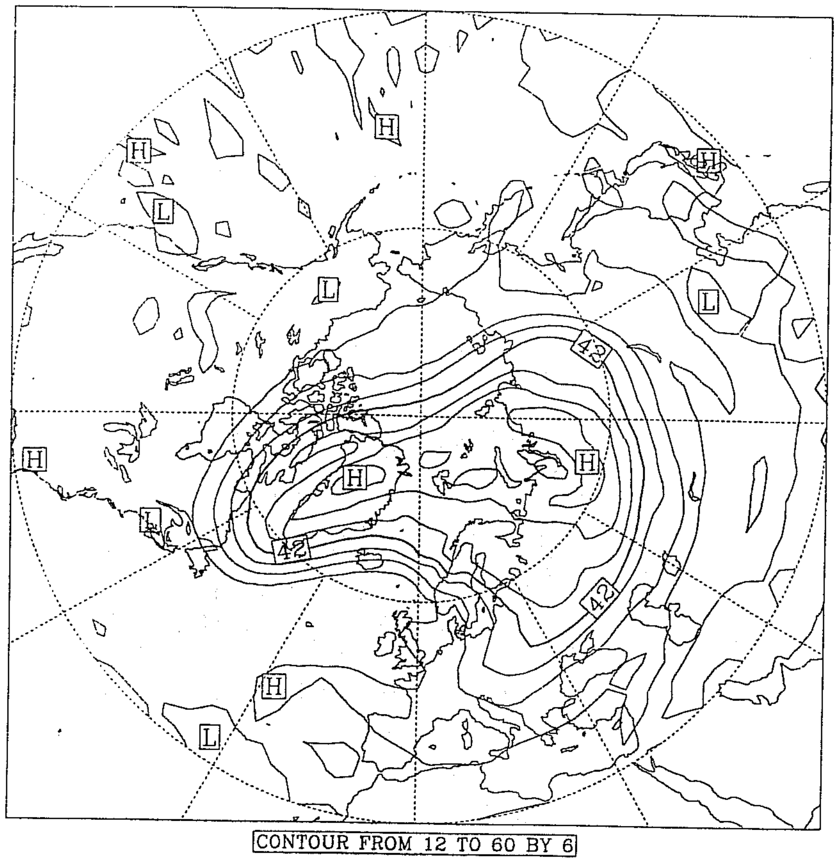


Fig. 18 120hr ECWMF forecast of potential vorticity for 12GMT, 11th January 1992 on the 475K isentropic surface.

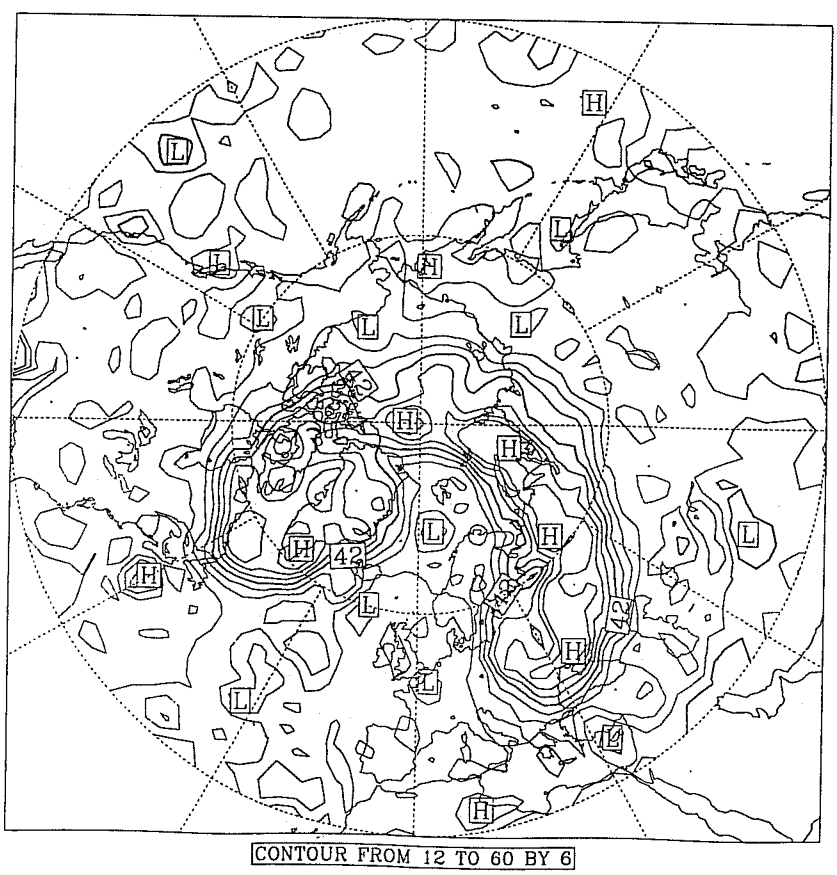


Fig. 19 ECMWF analysis of potential vorticity for 12GMT, 22nd January 1992 on the 475K isentropic surface.

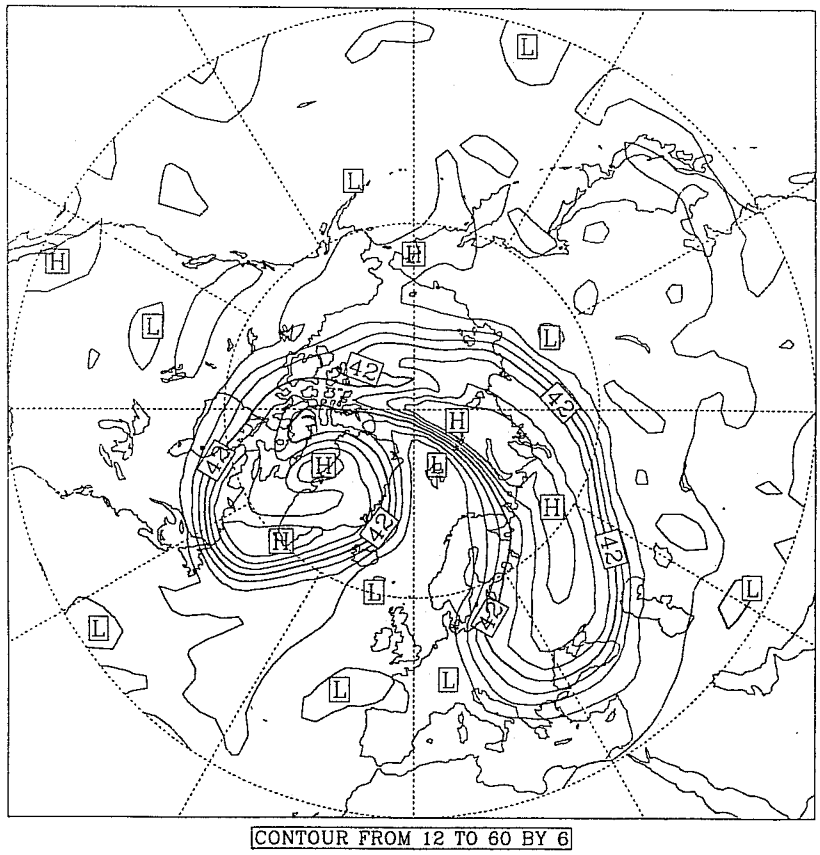


Fig. 20 24hr ECMWF forecast of potential vorticity for 12GMT, 22nd January 1992 on the 475K isentropic surface.

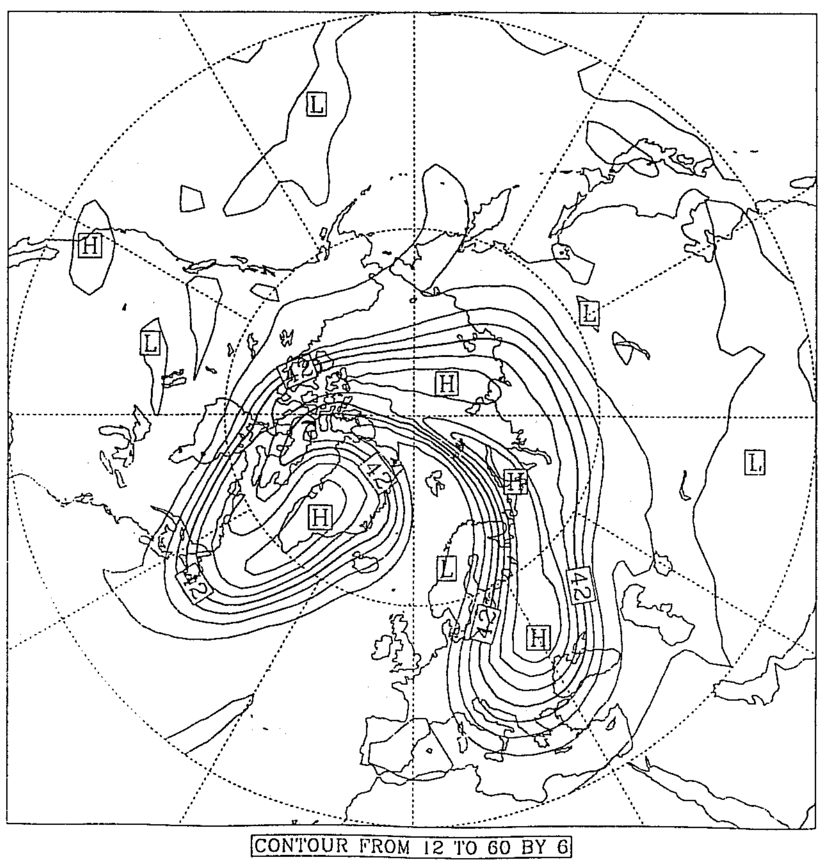


Fig. 21 72hr ECWMF forecast of potential vorticity for 12GMT, 22nd January 1992 on the 475K isentropic surface.

2.3 Forecast sensitivity

Being primarily a tropospheric forecast model, the ECMWF model has relatively coarse resolution in the stratosphere. Carver et al. (1993) carried out a study to investigate the sensitivity of the forecast to the vertical resolution in the model stratosphere. They used the general circulation model (GCM) of the UK Universities Global Atmospheric Modelling Programme (UGAMP), derived from an earlier version (cycle 27; 1987) of the ECMWF model.

In the first run, the UGCM was run with 19 levels, using the same stratospheric levels as in the current ECMWF model. This was done to give an indication of the forecast quality beyond the day 5 forecast used by EASOE. Fig. 22 shows the analysed PV on the 475K isentropic surface for the 24th January. The vortex extension has now moved east and thinned considerably. Regions of PV of values greater than 42 PV units have clearly separated from the main vortex. There is also a thin intrusion of low PV air between the vortex extension and the main vortex between longitudes 90°E and 180°E at about 85°N. Fig. 23 shows the 7 day forecast of the 19 level model. There are now some serious forecast errors. The main vortex has moved too far east over Scandinavia. The tip of the vortex extension has also moved too far east. The arm of the vortex extension has distorted considerably at about 135°E, but high PV (> 42 PV units) has separated from the main vortex. There is also low PV air wrapping around the main vortex as in the analysis but it is out of position. There are also very strong gradients in this region which are not present in the analysis. The day 7 forecast therefore did not forecast the position of the vortex edge well.

To test the sensitivity of the forecast to the stratospheric resolution, the UGCM was run with 23 levels instead of the default 19. The new stratospheric levels were chosen so as not to alter the model's troposphere. The new top level was at 5mb with a constant spacing of 10mb until 65mb, with new hybrid levels at approximately 79.5mb and 104.5mb. Other model levels were the same as in the default 19 level UGCM. Fig. 24 shows the 7 day forecast from the 23 level model. There has been a considerable improvement in the quality of the forecast compared to Fig. 23. The main vortex does not extend so far east in this forecast. Also, the low PV air is now shown well inside the main vortex. This had not appeared in the 19 level case. The vortex extension is much better represented in this run. The tip of the extension has not been advected so far east of its position in the analysis. The structure of the extension is more coherent, the large distortion of the arm of the extension seen in Fig. 23 has now gone. However, the arm is still extending too far south, particularly at about 135°E.

3. SOME INTERPRETIVE STUDIES

One of the aims of EASOE was the study of the role of polar processes in producing the observed middle latitude ozone decline. In this section we use chemical constituents data from the EASOE campaign to examine some aspects of the production of active chlorine in high latitudes. Two cases are examined. In the first, cold temperatures are found within the vortex; in the other, the coldest temperatures are found on the vortex edge (outside the sharpest PV gradients). Using ECMWF analyses we examine the implication of these two situations.

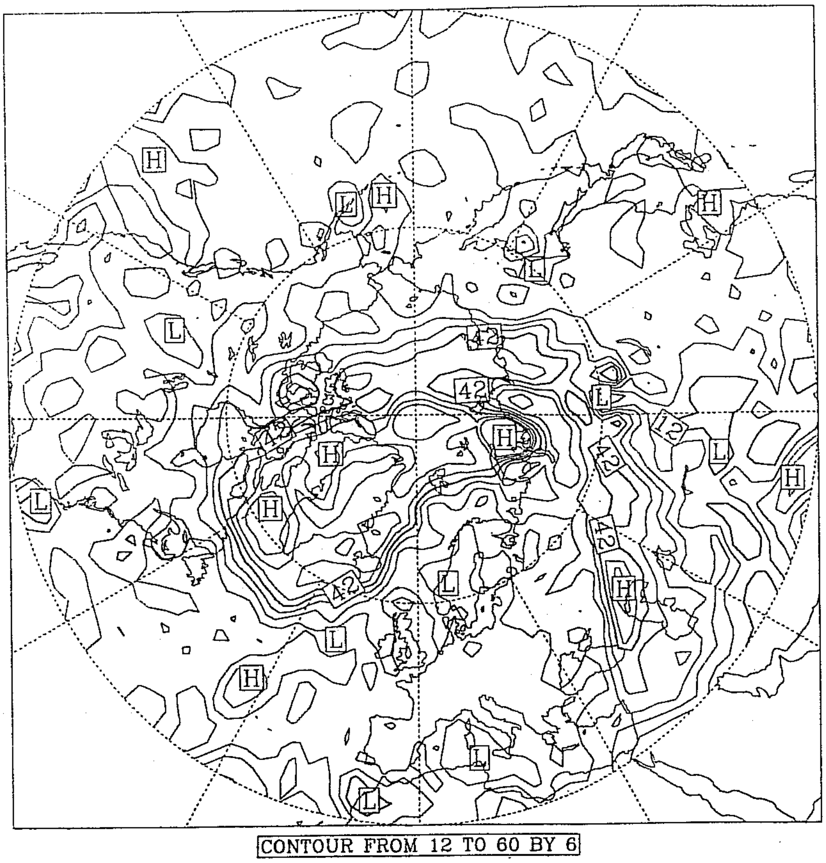


Fig. 22 ECMWF analysis of potential vorticity for 12GMT, 24th January 1992 on the 475K isentropic surface.

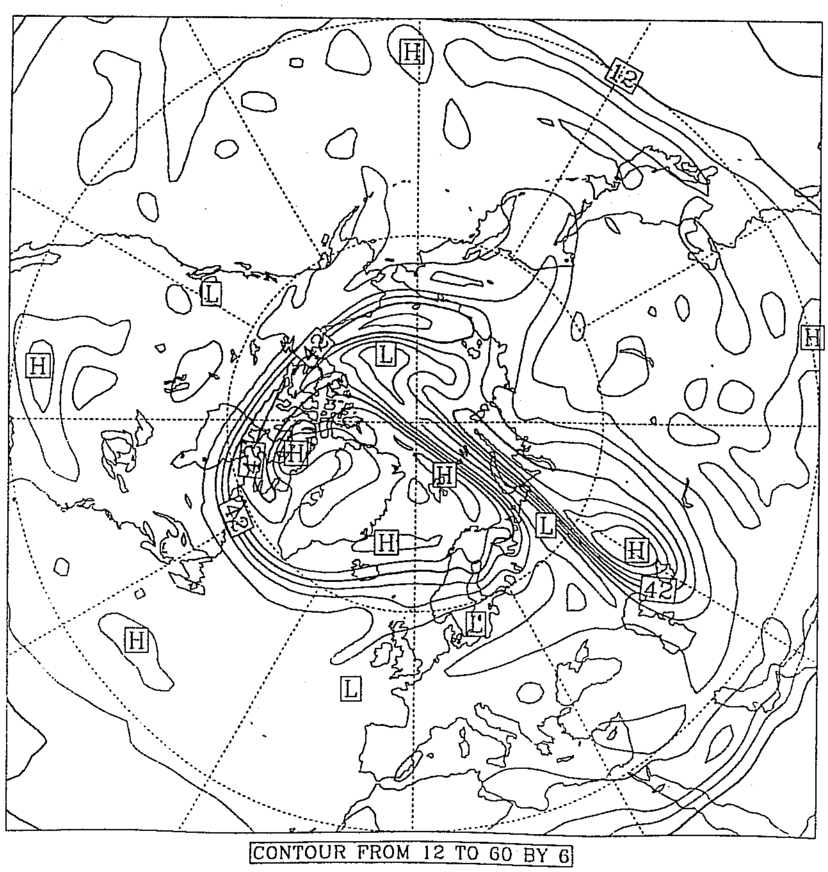


Fig. 23 7 day forecast of potential vorticity on the 475K isentropic surface from the 19 level UGAMP GCM, starting from 12GMT, 17th January 1992.

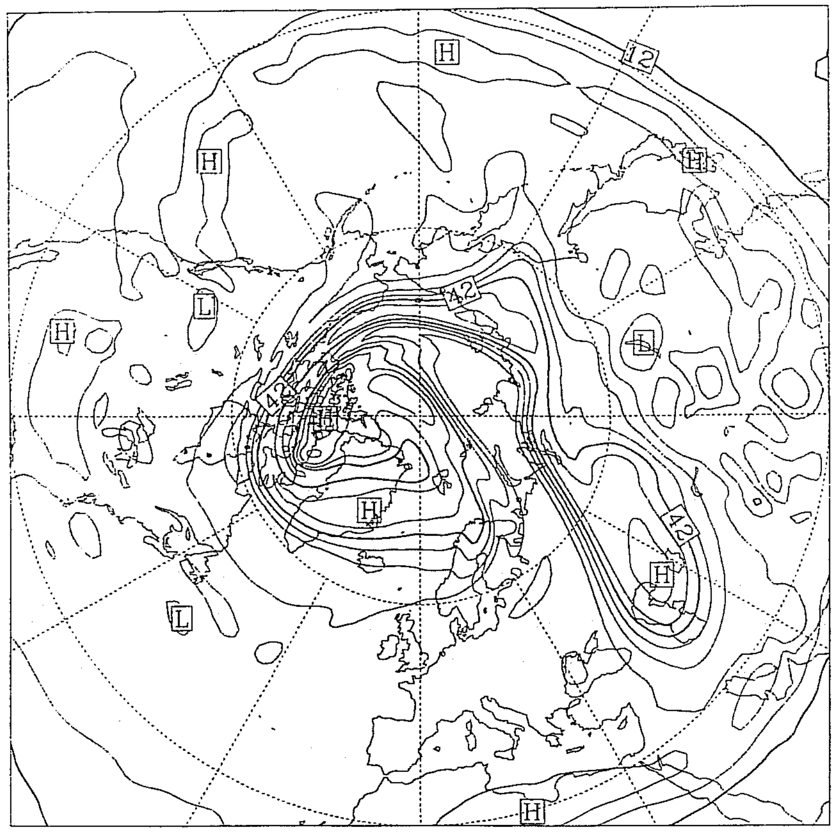


Fig. 24 7 day forecast of potential vorticity on the 475K isentropic surface from the 23 level UGAMP GCM, starting from 12GMT, 17th January 1992.

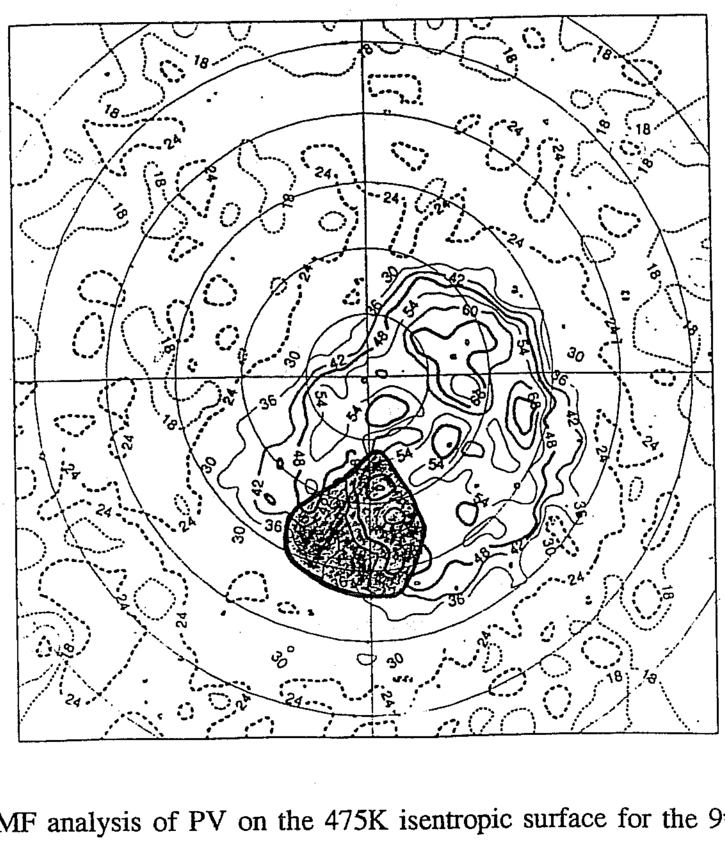


Fig. 25 ECWMF analysis of PV on the 475K isentropic surface for the 9th January 1992. The region of temperatures below 193K is shaded.

Fig. 25 shows the ECMWF analysis of PV on the 475K surface for the 9th January 1992. The vortex lies over northern Europe and Russia. We use a temperature of 193K to indicate PSC activity; the cold temperature region is also indicated in Fig. 25. Temperatures low enough for PSC formation cover a large area over the North Sea and North Atlantic. In this example, the coldest temperatures are found predominantly within the 36 PV units contour.

Fig. 26 shows measurements of CF_2Cl_2 made using ASTRID, the KFA grabsampler. The instrument was flown from Kiruna, well inside both the vortex and the region of coldest temperatures on the 9th January 1992 (see Schmidt et al. 1993 for more details of these measurements). At 475K very low concentrations of CFCs were measured indicating that the air within the vortex had previously been at much higher altitudes where the CFCs had been broken down. The available chlorine at 475K on the 9th January can be calculated by taking the difference between the tropospheric value and the 475K value. This assumes that all air parcels entering through the tropical tropopause have the same concentration of CFCs (the tropopause value in Fig. 26) and ignores the increase in tropospheric values during the several years since the parcel sampled at 475K entered the stratosphere. With these assumptions the available chlorine from CF_2Cl_2 is 2x(418-92)pptv=652pptv; from $CFCl_3$ (measured but not shown in Fig. 26) the available chlorine is 3x(223-0)pptv=669pptv. Adding these two values together and allowing for the available chlorine coming from the other halocarbons (using 2D photochemical model calculations) we arrive at a total value for available chlorine of about 2.6ppbv, in good agreement with the values derived independently by Schmidt et al. (1993). Note that only half the available chlorine derives from CF_2Cl_2 and $CFCl_3$.

The temperatures on the 9th January (Fig. 10) imply that PSC processing was operating over a wide area. In this region, including Kiruna, most of the available chlorine should therefore have been converted to active chlorine. This is supported by observations (Bell et al. 1993) and by model calculations (Kettleborough et al. 1993), both of which show massive processing within the whole of the polar vortex.

Fig. 27 shows the PV and the region of temperatures below 193K during a different meteorological situation on the 18th January 1992. In this case, the very cold temperatures are on the edge, or outside, the vortex, a situation forced by the upward extension of a tropospheric anticyclone. The cold temperatures arise from strong adiabatic ascent over the anticyclone (discussed in more detail above).

We would like to calculate the available chlorine which could be turned into active forms in the cold region in Fig. 27. There were measurements at Kiruna on this day but, as can be seen from the figure, Kiruna (68°N, 20°E) was in a region of much higher PV at some distance from the cold area. Since available chlorine varies so much with PV, or position relative to the vortex (Schmidt et al. 1993), it would not be appropriate to use the Kiruna measurements on the 18th to estimate the available chlorine in the cold region. A much better proxy dataset is provided by the CFC measurements at Kiruna on the 22nd January. On that day, the 475K PV value at Kiruna, about 30 PV units, compares well with the PV in the cold region on the 18th and it is expected that very similar CFC concentrations would have been present in the two locations. Thus, we take the 22nd January data from Kiruna as representative of the concentrations of CFCs which would have been measured in the cold region, outside the 36 PV contour, just to the east of Iceland on the 18th January.

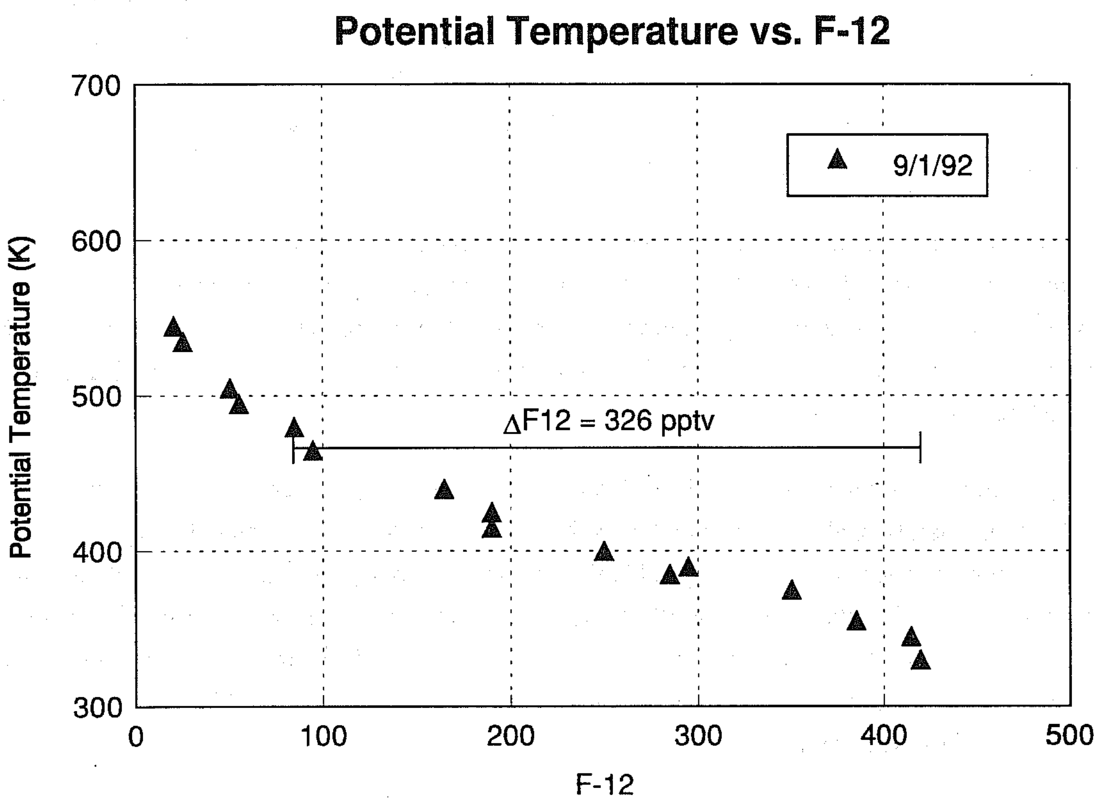


Fig. 26 CF_2Cl_2 mixing ratio versus potential temperatures from Schmidt et al. (1993) measured at Kiruna on the 9th January 1992.

Fig. 27 ECMWF analysis of PV on the 475K isentropic surface for the 18th January 1992. The region of temperatures below 193K is shaded.

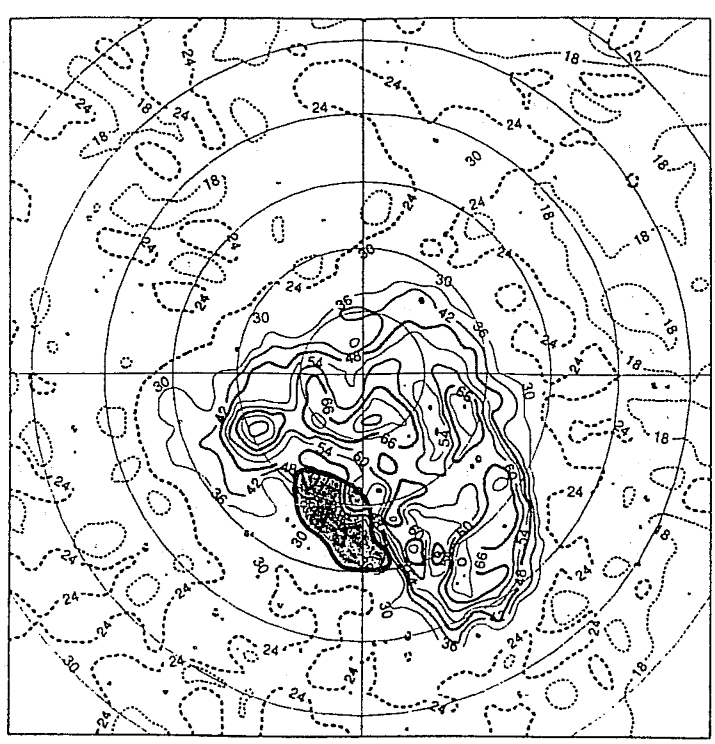


Fig. 28 shows the CF_2Cl_2 data for the 22nd January. The available chlorine is now 2x(424-244)pptv=360pptv from CF_2Cl_2 and 3x(243-70)pptv=519pptv from $CFCl_3$ (not shown). When allowance is made, through our 2D photochemical model, for the other halocarbons, the total available chlorine is approximately 1.7ppbv, about two thirds of that available on the 9th January. Given the cold temperatures on 18th January, much of this available chlorine would have been activated.

It is clear from the comparison of these two situations that in the northern hemisphere the precise location of the cold temperature pool relative to the vortex, and hence relative to the horizontal gradient of available chlorine, will be critical in determining the amount of active chlorine produced and therefore the amount of ozone depletion occurring (note that the rate of ozone destruction in the ClO dimer cycle (EQ 1) goes with the square of the ClO concentration).

Although the chlorine activated on the 18th January is not so large as earlier in the month, it is still considerably larger than typical mid-latitude values. Note also that this air is outside the highest PV gradients and hence, possibly, outside the vortex edge. If this air could be transported to middle latitudes, significant ozone loss could occur. To check this hypothesis forward trajectories were run, starting from nearly 1300 locations, at $1^o x 1^o$ resolution, from within the 195K contour on 18th January. The three-dimensional trajectories were calculated in a forecast run of the 23 level T106 version of the UGCM initialised with the ECMWF analysis of the 18th January.

The calculated trajectories are shown in Fig. 29. Fig. 29a shows the initial location of points on the 50mb pressure surface. A number of very interesting features are evident in Fig. 29b which shows 25th January, day 7 of the model run. Firstly, the majority of the trajectory endpoints in Fig. 29b define the edge of the vortex. There is no evidence at this stage of mixing into or out of the vortex. Secondly, at around 180^oE the trajectory endpoints lie along two separate paths separated by air of lower PV. This feature was discussed in section 2. It is expected that mixing of these two air masses with different PV values will occur subsequently. Thirdly, a number of trajectory endpoints are found in a tongue extending across northern Scandinavia. This feature is not evident in the analysis for the 25th January, but is seen on subsequent days. The forecast has reproduced this feature, but too early. Finally, Fig. 29b shows another very interesting feature near the Caspian Sea at 60^oE, 40^o-50^oN. A group of endpoints, well separated from the vortex edge, can be seen there, coinciding with the high PV feature seen in Fig. 22, a day earlier. The feature is evident for a number of days in both the trajectory calculations and the analyses and is reminiscent of similar features discussed by Tuck et al. (1992). This processed air, formerly at the vortex edge, could clearly have an important chemical impact at the lower latitudes.

Fig. 29c shows the endpoints on the 28th January. Many of the points are now in the arm of the vortex which extends to 40^oN. However, by day 10, the forecast position of the vortex would have significant errors compared to the analysed position (Carver et al. 1993) and therefore the position of these points may also have significant errors.

While Fig. 29 shows no evidence of large scale mixing of vortex air into middle latitudes, there is evidence of some degree of mixing which could be important chemically. Furthermore, it is clear that, with the highly disturbed vortex, some air in which chlorine has been activated does spend significant periods of time at lower

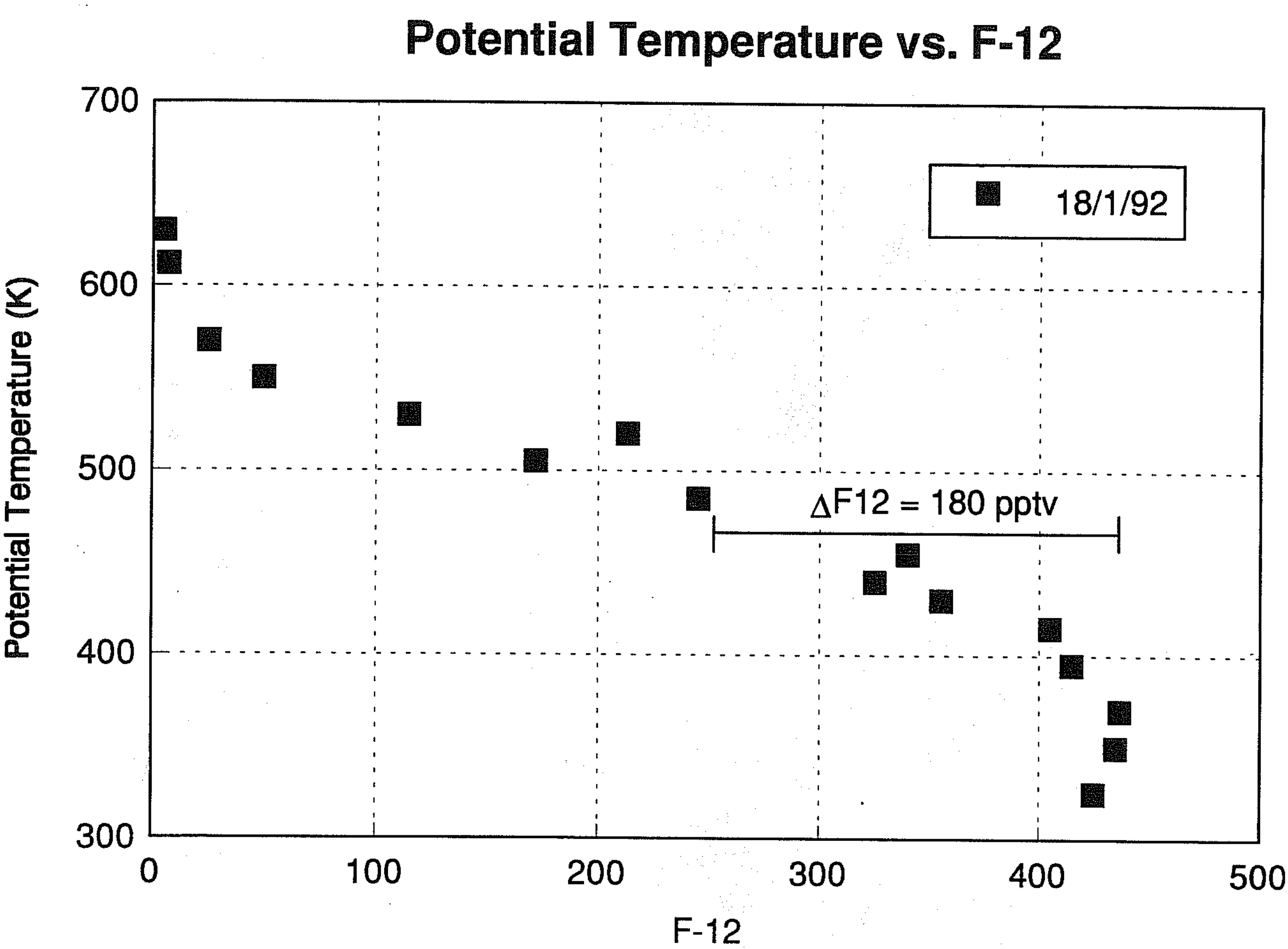


Fig. 28 CF_2Cl_2 mixing ratio versus potential temperatures from Schmidt et al. (1993) measured at Kiruna on the 22nd January 1992.

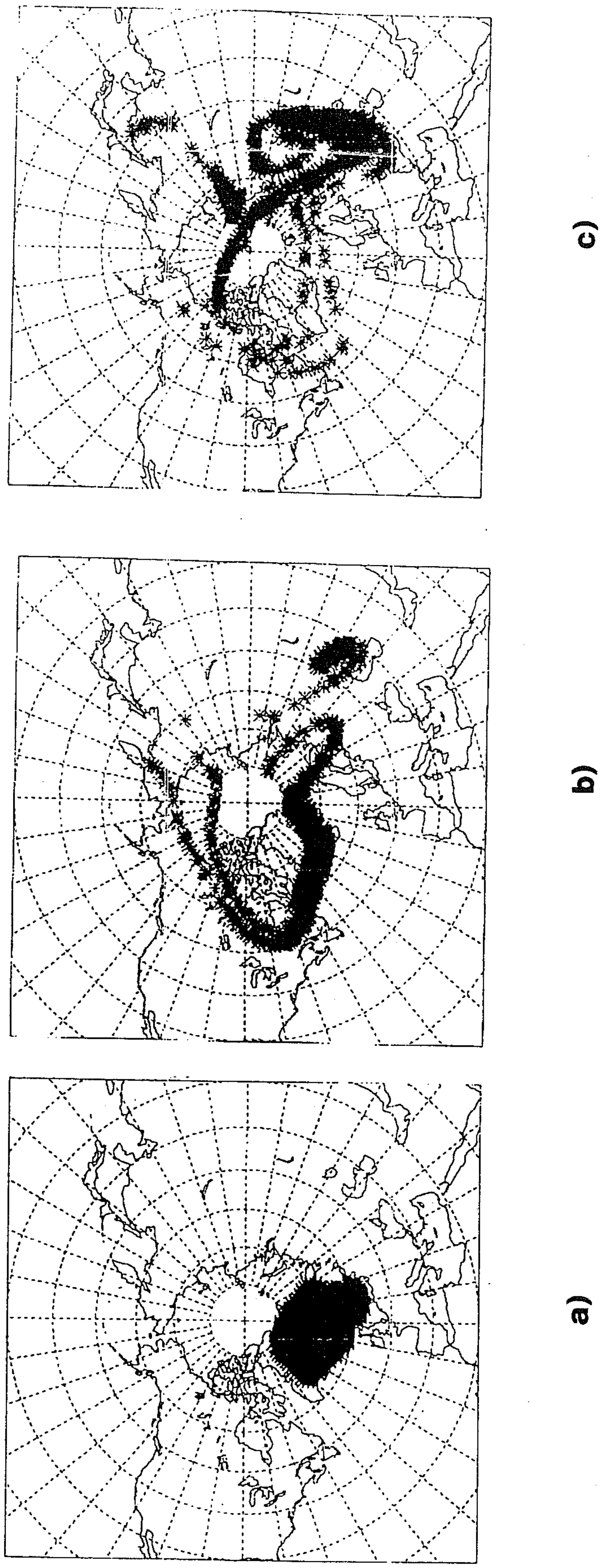


Fig. 29 The cluster of trajectory endpoints calculated from a forecast run of the UGAMP model initialized with the ECMWF analysis for 18th January 1992. All trajectories start at 50mb with a temperature less than 195K. a) shows the initial position of the trajectories, b) the position at day 7, 25th January, c) the position at day 10, 28th January.

latitudes where the increased solar insolation favours ozone depletion. However, it remains to be seen how representative this particular case is for other northern hemisphere winters. It seems possible that a significant part of the middle latitude ozone loss could be due to depletion around the polar vortex, which can be displaced southwards, a conclusion supported by a statistical treatment of trajectories during the AASE I and EASOE campaigns (MacKenzie et al. 1993).

4. CONCLUSIONS

The forecasts of PV provided by ECMWF during EASOE were extremely useful during the campaign. The quality of the 5 day forecasts were shown to be very good. The 5 day forecasts of the UGCM were also shown to be very good. However, in the case studied by Carver et al. (1993), the 7 day forecast showed significant errors. These errors were reduced quite considerably by doubling the stratospheric resolution in the UGCM. The high quality of the forecasts and especially the forecasting of the position of the polar vortex was a substantial benefit in the operational planning of EASOE.

We discussed examples of how ECMWF data products were being used in interpreting some of the results from EASOE. Two cases during January 1992 are considered when temperatures cold enough to form PSCs were present in the Arctic lower stratosphere. On the 9th January, the cold region fell well inside the vortex, CFC concentrations were low and all the available evidence points to a very high degree of chlorine activation. In mid January the cold region was around the edge of the vortex where the CFC concentrations are higher and hence the degree of chlorine activation is lower. Part of the reported middle latitude ozone loss could also arise from the movement of the disturbed vortex over middle latitudes. A case was also found where low PV air was mixed into the vortex. This could have played a role in reducing active chlorine from the very high levels seen in early January.

5. ACKNOWLEDGEMENTS

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