STRATOSPHERIC PV DISTRIBUTIONS IN NWP MODELS

T. Davies
Meteorological Office
Bracknell, UK

1. INTRODUCTION

The use of potential vorticity (PV) maps as a means of understanding atmospheric behaviour is becoming more widespread. For a review see Hoskins et al (1985). Certain aspects have also been discussed in recent ECMWF seminars (McIntyre, 1987 and Davies, 1992). Atmospheric values of potential vorticity increase significantly at the tropopause and within the middle-atmosphere stratospheric vortex. These regions, when viewed in terms of PV on a suitably chosen isentropic or pressure surface are revealed as distinct regions of high magnitude PV (PV is negative in the Southern hemisphere), bounded by a sharp gradient and surrounded by relatively low magnitude PV. Disturbances in the region of the high PV gradient may result in tongues of high PV extending into low PV areas or vice versa. The distribution of PV has dynamical implications insofar that a knowledge of the PV implies a particular distribution of wind and temperature (invertibility principle). The PV of a particle also implies something about a parcel's history which in some cases has implications on the chemistry.

Researchers, particularly those involved in stratospheric studies are using products from different centres. Unlike meteorological fields such as height, PV maps have more detail (being a differentiated rather than integrated quantity) so that comparison between different centres' products is not always straightforward. Experience has shown a sensitivity to the scale of structures analysed and modelled by different centres.

The aim of this paper is to show the kinds of differences and problems in using and comparing PV maps produced from ECMWF data and the Unified Model (UM) of the UK Meteorological Office. Firstly, some remarks on the calculation of PV are made. Secondly, typical examples are shown of PV maps for the middle atmosphere in the region of both 475K and 600K (around 50hPa or 20km and 20hPa or 25km respectively) in the winter hemisphere, at a time when the stratospheric polar vortex is developed. The region around the tropopause or lower stratosphere is examined in section 4. Finally, an example of the sensitivity of a forecast to tropopause PV anomalies is illustrated using a recent operational case from the UM limited-area model (LAM).

2. CALCULATION OF PV.

The usual expression for PV on an isentropic surface is

$$q=-g(\zeta_\theta+f)\frac{\partial\theta}{\partial p}$$

The relative vorticity ζ_θ is calculated from the horizontal winds on the isentropic surface. Care is required in calculating the static stability $\frac{\partial\theta}{\partial p}$. Since the potential temperature increases rapidly in the stratosphere errors in the vertical differencing, vertical interpolation or errors due to too coarse a vertical resolution each can have a significant impact upon the value of the static stability obtained and accuracy tends to be lower with higher altitudes. Different models have different systematic errors and temperature biases which will obviously lead to differences in the static stability or to differences in the altitude of a particular isentrope.

At the top of the model or data source, different choices are made when either the calculation is terminated at some upper level or if extrapolating information above the top level. It is possible for example to assume either an isothermal profile or a constant lapse rate above the top data level. For the wind field the top level wind is sometimes considered representative of conditions above. Thus, PV calculated near or above the top level of a model or data source is often more of an approximation than at lower levels. When comparing PV maps between different models these factors may account for significant differences additional to those resulting from wind and temperature differences.

3. UM AND ECMWF STRATOSPHERIC PV MAPS

Figure 1 shows 475K PV analyses of the Southern hemisphere (Greenwich meridian upper vertical) from the UK Meteorological Office Unified Model (UM) (top) and ECMWF (bottom) for 12UTC 4/10/93. Contour interval is 5 pv units (1 pv unit is 10^{-6} MKS). Colour maps greatly help in visualising PV maps in practice because of the extra structure in comparison with height fields but here we will make do with contour charts. The larger scale features such as the major troughs match reasonably well although those centred near 30° West and 120°W appear more prominent in the UM analysis because of more ridgeing near the Antarctic peninsula. The strong PV gradient defining the edge of the polar vortex is tighter in the ECMWF analysis. This is due mainly to the greater resolution of the ECMWF model (horizontal spectral T213 triangular truncation, physics (Gaussian) grid of around 50km and 31 hybrid sigma-pressure levels) than that employed by the UM (approximately 100km latitude-longitude grid and 19 hybrid sigma-pressure levels). Comparisons between ECMWF data produced at lower resolution (T106, 19 levels) and the present resolution show similar differences in the sharpness of gradients. Outside the vortex ECMWF appears noisier than the UM. In both cases the vortex edge appears to be defined by PV values of between -25 and -30 pv units. Outside the vortex there are only isolated blobs of less than -25 units in the UM analysis but a few more blobs with values lower

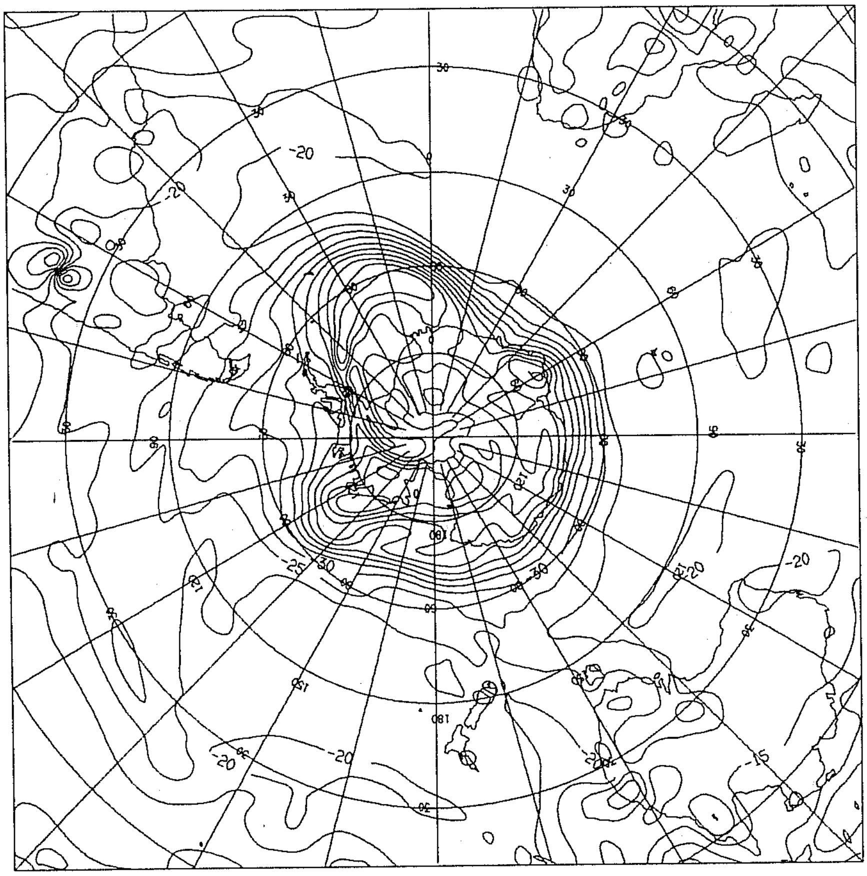

Fig 1(a) Potential Vorticity on 475K surface from UM Global Analysis. Valid 12UTC 4/10/93 Southern Hemisphere. 0° upper vertical. Contour interval every 5 pvu.

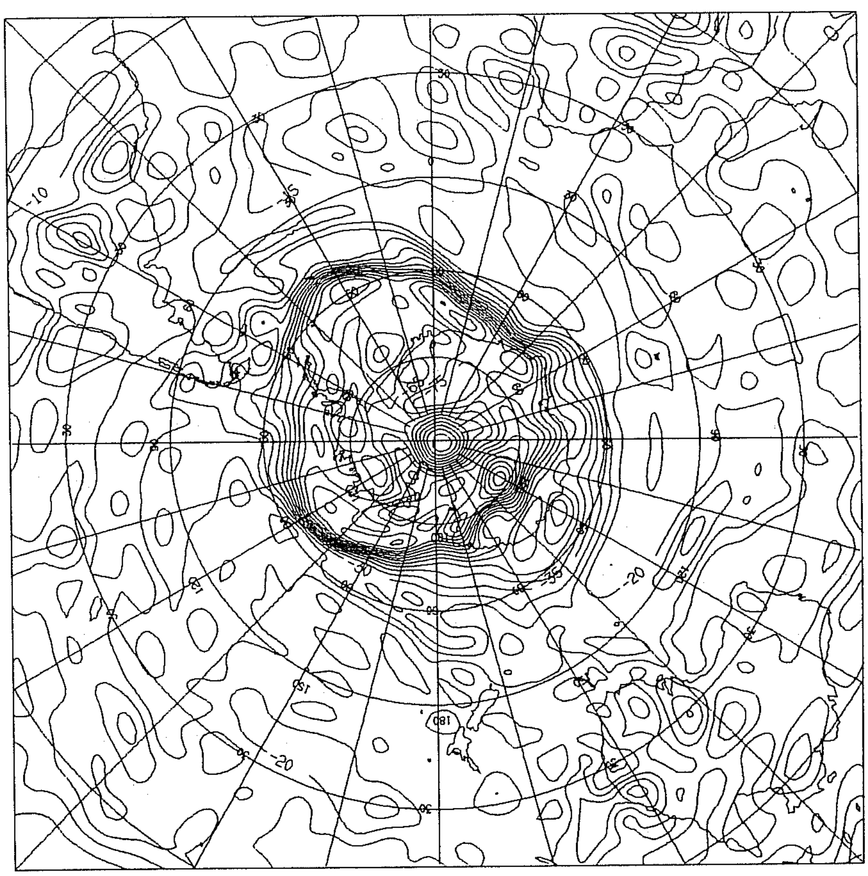

Fig 1(b) Potential Vorticity on 475K surface from ECMWF Analysis. Valid 12UTC 4/10/93 Southern Hemisphere. 0° upper vertical. Contour interval every 5 pvu.

than -30 in the ECMWF analysis. It is evident that there are quite detailed differences between the analyses even around the vortex edge. Just inside the vortex at around 120° W near the edge of Antarctica the UM has a PV value of just under -70 pv units with two other regions of similar value just to the south and upstream at around 150° E. The ECMWF analysis has lower values (< -80) just to the northwest of the first UM minimum and a minimum of less than -105 pv units near 80° S 120°E. At the pole the ECMWF analysis is greater than -35 whereas the UM is around -55 pv units.

Similar remarks apply to comparisons at 600K (figure 2, contour interval 20 pv units). PV values of around -80 units appear to define the vortex edge with very few blobs with this value outside the vortex in the UM analysis but more than twenty in the ECMWF analysis. Minimum values in the UM are below -220 with values of between -100 and -120 near the pole. The ECMWF analysis has minimum values below -260 and near the pole between -120 and -140.

Figure 3 shows the 475K PV fields from the 24 hour forecasts from 12UTC 4/10/93. The ECMWF forecast (figure 3(b)) has a tighter gradient around the vortex and a more intense trough approaching 90°W. Again it would seem that the vortex edge could be defined by values of between -25 and -30. The forecasts have fewer blobs of larger magnitude PV outside the vortex region than in the analyses 24 hours earlier. This is particularly true of the ECMWF forecast where there are now no blobs with values below -30. As a consequence, the forecast in figure 3(b) is somewhat smoother than the analysis 24 hours before shown in figure 1(b). This smoothing increases during the forecast (no figure shown) and will be commented upon later. The minimum value of PV in the ECMWF forecast is near the dateline; below -90 compared with less than -105 in the analysis 24 hours before (figure 1(b)). Near to this minimum there is an intense low magnitude PV anomaly of around -35. In contrast, the UM forecast (figure 3(a)) has a minimum below -70 near to 120°E and 30°W and PV values of around -50 near the pole. The larger-scale troughs correspond reasonably well and the filament of high magnitude PV extending northwestwards towards South America from the major trough near 30°W is of particular note. Conservation of PV between the analyses and forecasts is rather mixed and of course should not necessarily be expected because of diabatic effects.

Figure 4 shows the 600K PV maps from the 24 hour forecasts from 4/10/93. As in the analyses 24 hours earlier (figure 2) values of around -80 appear to define the the vortex edge. The UM forecast has minimum values below -220 as in the analysis 24 hours before (figure 2(a)) but there is now a region of relatively low magnitude PV (up to -60 pv units) over the Antarctic peninsula and extending towards the pole. The ECMWF forecast has one region of less than -260 near 90°E compared with three such regions in the analysis 24 hours earlier (figure2(b)). The ECMWF vortex is generally more uniform than that of the UM forecast but there is still a polar maximum within the vortex of around -150. Outside the vortex the ECMWF forecast has large areas of between -60 and -80 with eight small blobs below -80 whereas the UM forcast has just four small blobs of less than -60.

Figure 5 shows 475K PV analyses of the Northern hemisphere (Greenwich meridian lower vertical) for 12 UTC 1/2/93. Both model analyses now appear much noisier than their Southern hemisphere counterparts

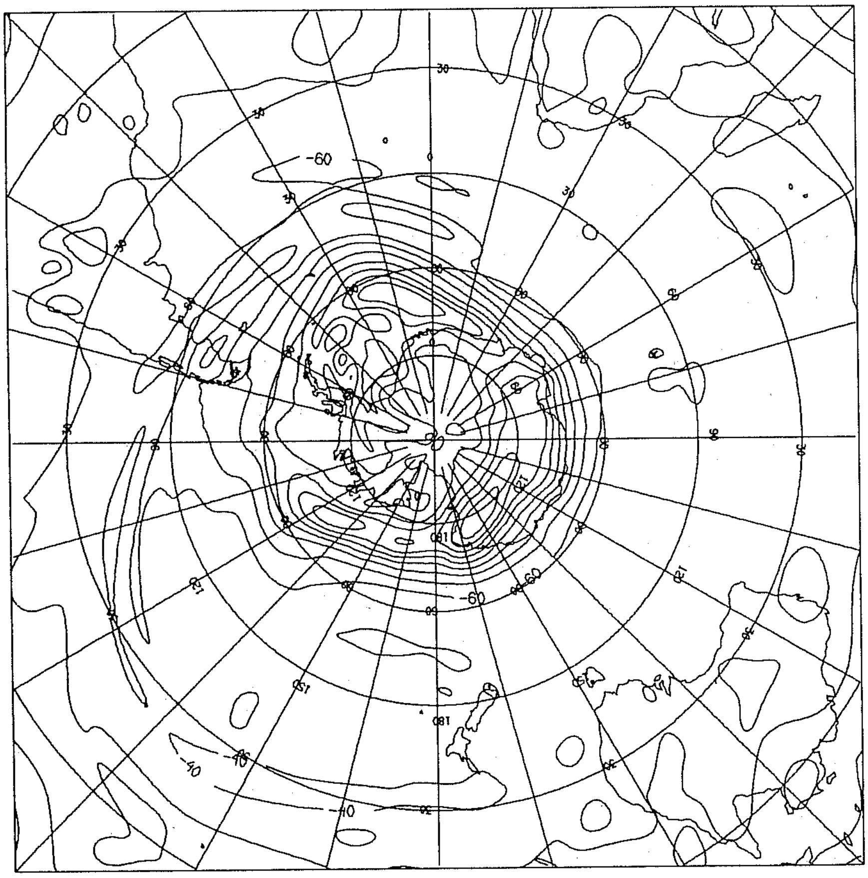

Fig 2(a) Potential Vorticity on 600K surface from UM Global Analysis. Valid 12UTC 4/10/93 Southern Hemisphere. 0° upper vertical. Contour interval every 20 pvu.

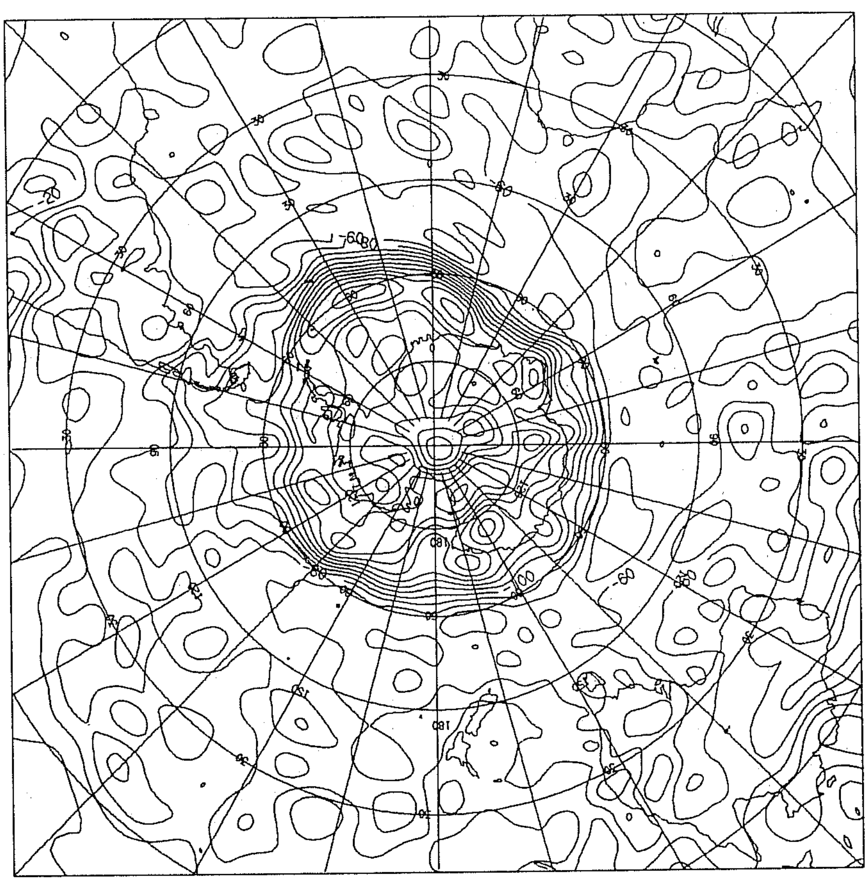

Fig 2(b) Potential Vorticity on 600K surface from ECMWF Analysis. Valid 12UTC 4/10/93 Southern Hemisphere. 0° upper vertical. Contour interval every 20 pvu.

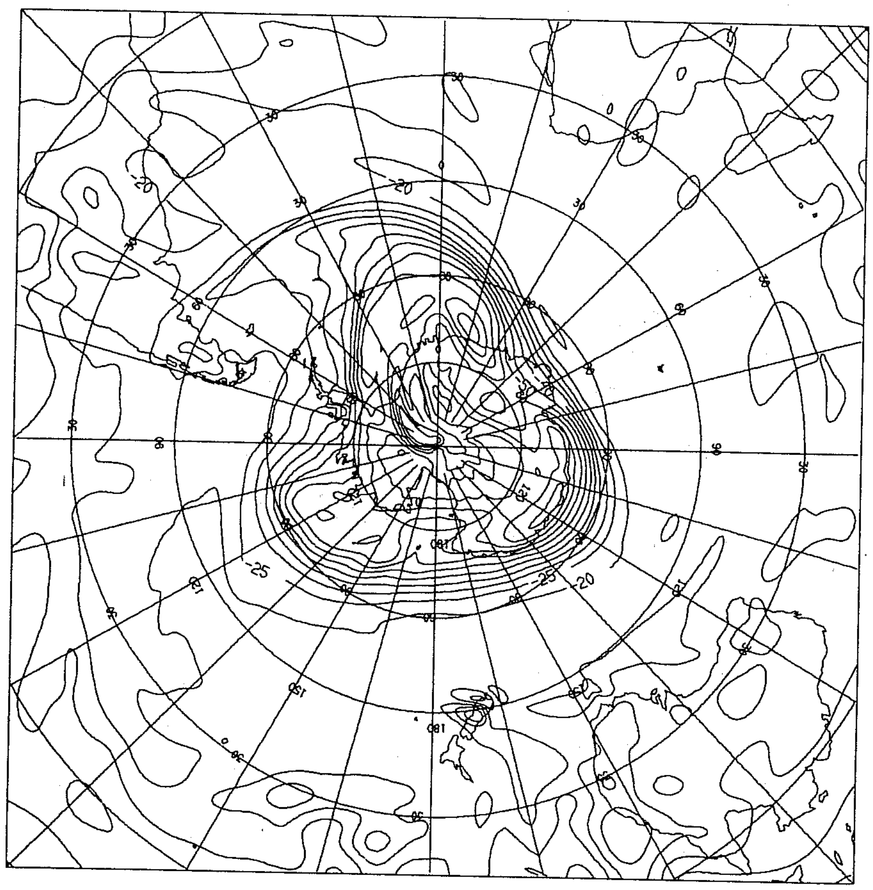

Fig 3(a) Potential Vorticity on 475K surface from UM Global T+24 forecast. Valid 12UTC 5/10/93 Southern Hemisphere. 0° upper vertical. Contour interval every 5 pvu.

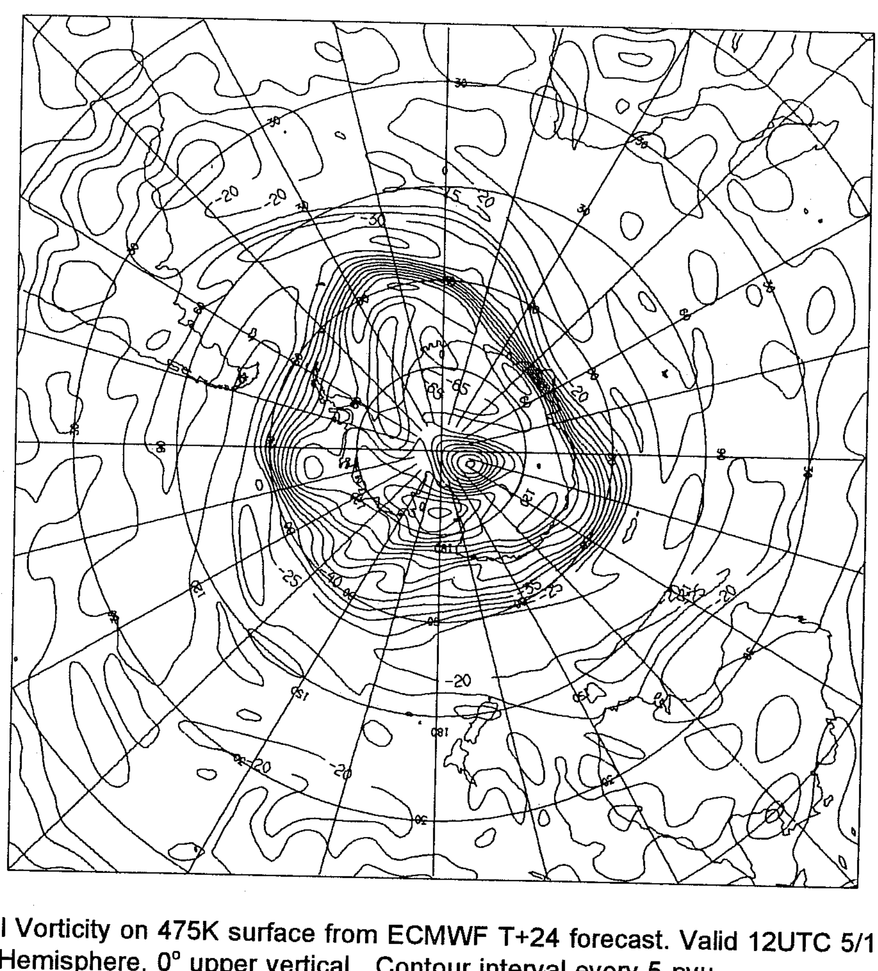

Fig 3(b) Potential Vorticity on 475K surface from ECMWF T+24 forecast. Valid 12UTC 5/10/93 Southern Hemisphere. 0° upper vertical. Contour interval every 5 pvu.

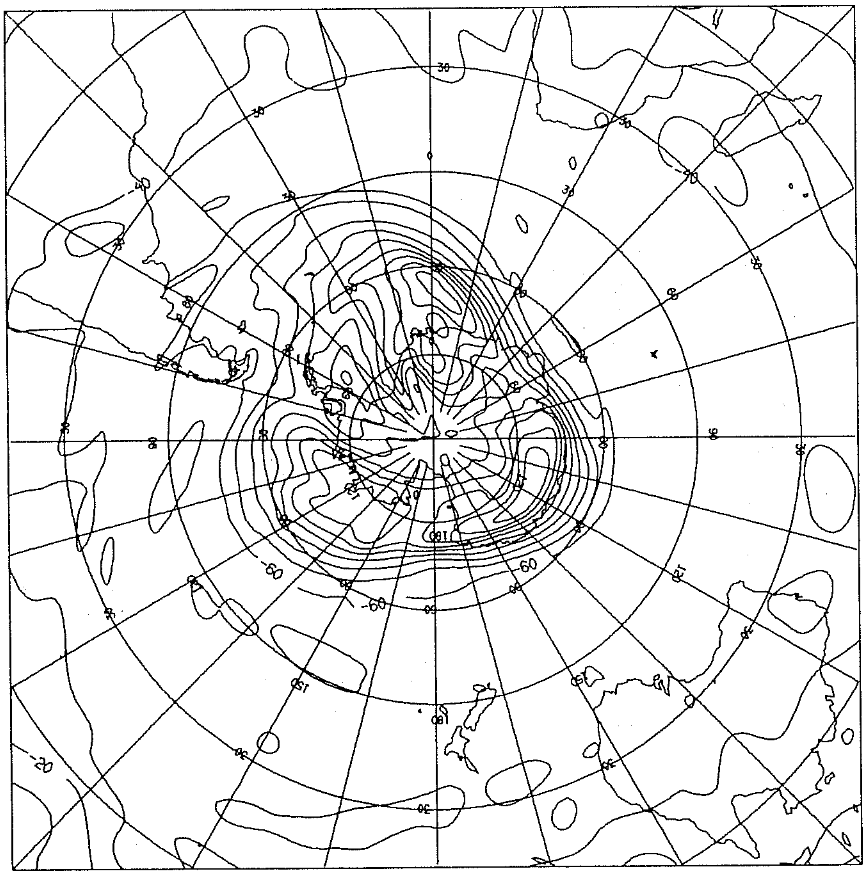

Fig 4(a) Potential Vorticity on 600K surface from UM Global T+24 forecast. Valid 12UTC 5/10/93 Southern Hemisphere. 0° upper vertical. Contour interval every 20 pvu.

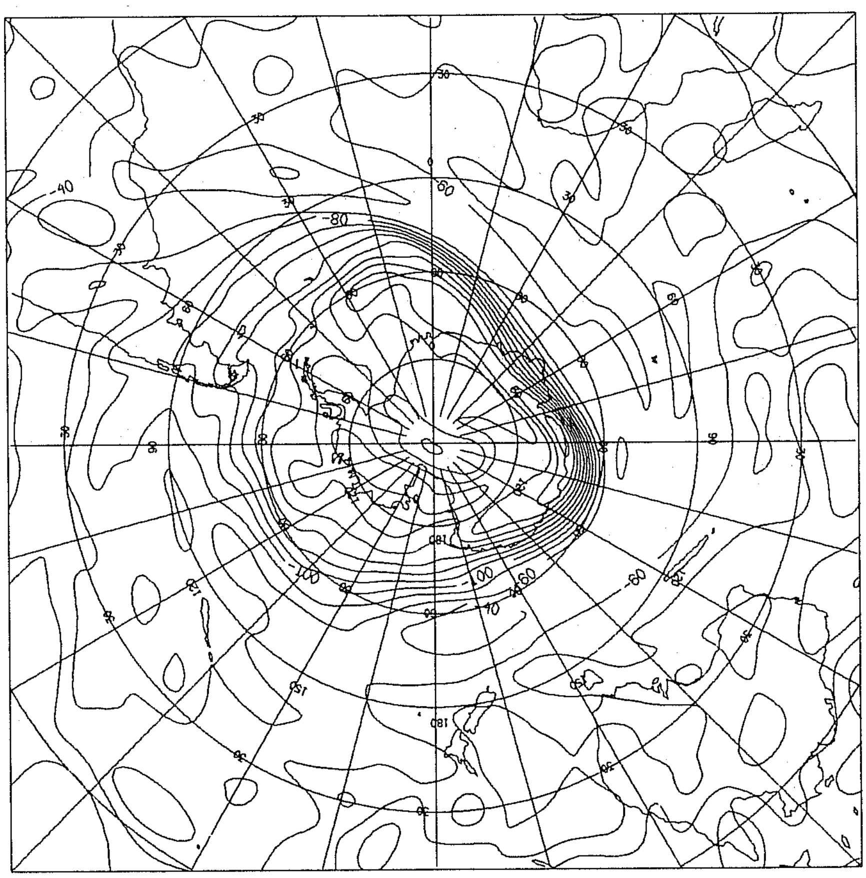

Fig 4(b) Potential Vorticity on 600K surface from ECMWF T+24 forecast. Valid 12UTC 5/10/93 Southern Hemisphere. 0° upper vertical. Contour interval every 20 pvu.

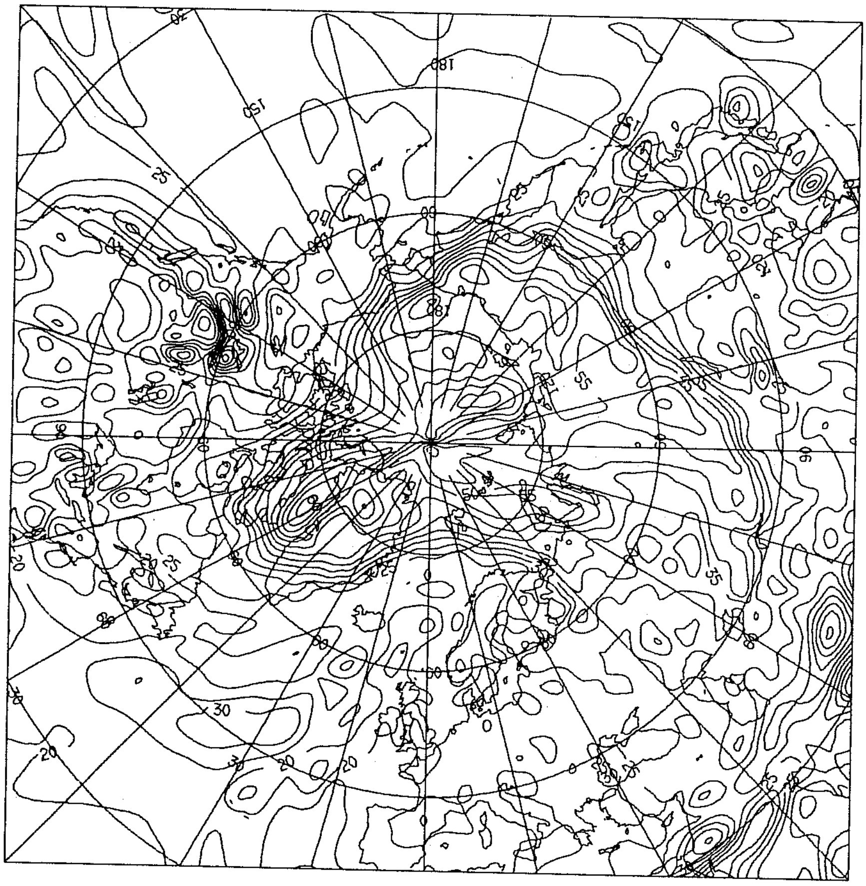

Fig 5(a) Potential Vorticity on 475K surface from UM Global Analysis. Valid 12UTC 1/2/93 Northern Hemisphere. 0° lower vertical. Contour interval every 5 pvu.

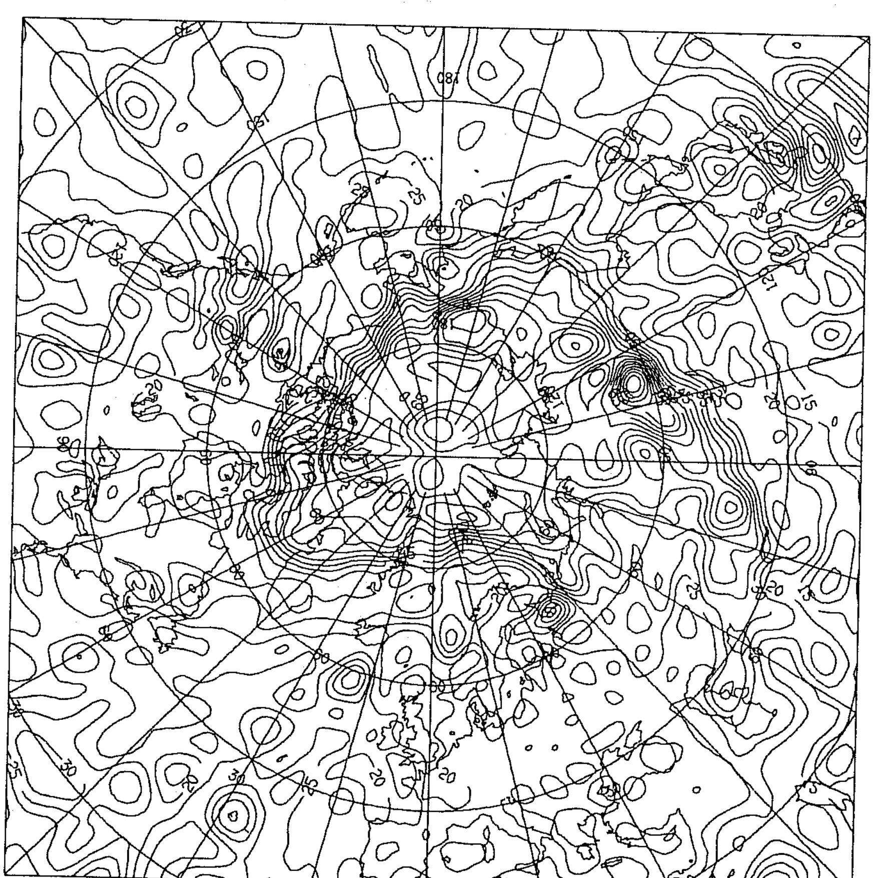

Fig 5(b) Potential Vorticity on 475K surface from ECMWF Analysis. Valid 12UTC 1/2/93 Northern Hemisphere. 0° lower vertical. Contour interval every 5 pvu.

in figure 1. In the UM analysis most of the noise appears to be over the land masses whereas the ECMWF analysis is noisier than the UM analysis over the oceans. The strong PV gradient at the edge of the polar vortex is evident in both analyses although the gradient weakens over Russia at around 60° East. PV values of around 30 pv units defines the edge of the vortex quite well. In both cases there are no values of less than 30 units within the vortex but there are a number of blobs of PV of more than 30 pv units scattered around outside the vortex. Occasionally, low PV air can be advected into the vortex region and become isolated from its source region. The UM analysis has a maximum of more than 80 near Baffin Island whereas the ECMWF maximum is around 95 units near 100°E.

475K PV charts from the 24 hour forecast from 12UTC 1/2/93 are shown in figure 6. The ECMWF chart is much smoother when compared with the analysis from the previous day in figure 5. The UM forecast is only a little smoother than its own analysis and the noise over the land masses has remained, albeit slightly cleaned up. The strong PV gradient at the vortex edge is more prominent in these less noisy T+24 charts. Again PV values of around 30 pv units appears to define a vortex edge with generally fewer blobs of more than 30 scattered outside the vortex region than in the analyses for 24 hours before, particularly in the ECMWF forecast. The UM forecast has a maximum of around 80 near 150°E whereas the high PV region over Greenland has a maximum of more than 75. The ECMWF forecast has a maximum of more than 75 near the dateline and a region of more than 70 in the trough over Greenland. The major trough extending southwards over Greenland can be followed in both sequences.

The two main components of the potential vorticity calculation , the absolute vorticity $\zeta_\theta + f$ and the static stability $\frac{\partial\theta}{\partial p}$ for the ECMWF analysis of 12UTC 1/2/93 are plotted in figure 7. Comparing with the PV analysis in figure 5(b) shows that most of the noise in the ECMWF results from the vorticity i.e. the wind field, figure 7(a).

The apparent noisiness of the ECMWF analysis PV may be due to the much higher horizontal and vertical resolutionl than that employed by the UM mentioned above. Figure 8 shows ECMWF analysis and 24 hour forecast 475K PV charts from 12UTC 1/2/89 when the ECMWF model was run at T106 and with 19 levels in the vertical. The analysis PV is still noisy although the distribution has changed somewhat with the noise now more evident over the land masses and the analysis smoother over the oceans. A breakdown between absolute vorticity and static stability in figure 9 again shows that the noise is mainly associated with the vorticity field, figure 9(a).

The difference in the amount of noise in the PV maps from the different hemispheres suggests that data coverage may be a factor. Simmons (1993) in these proceedings shows that some of the noise in the PV analyses can result from bad wind data from radiosondes but this does not explain all the noise. It appears that from the presence of the noise mainly in the vorticity field, then it is wind information that is mainly responsible, either from fitting the wind directly or from adding (balanced or geostrophic) wind increments

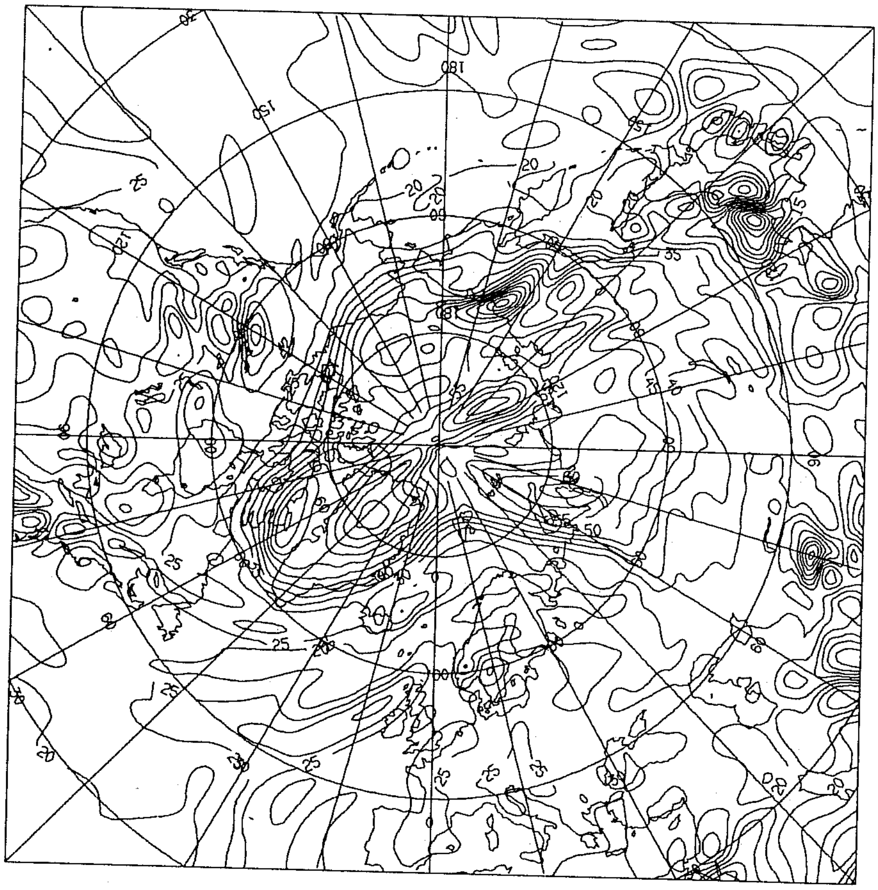

Fig 6(a) Potential Vorticity on 475K surface from UM Global T+24 forecast. Valid 12UTC 2/2/93 Northern Hemisphere. 0° lower vertical. Contour interval every 5 pvu.

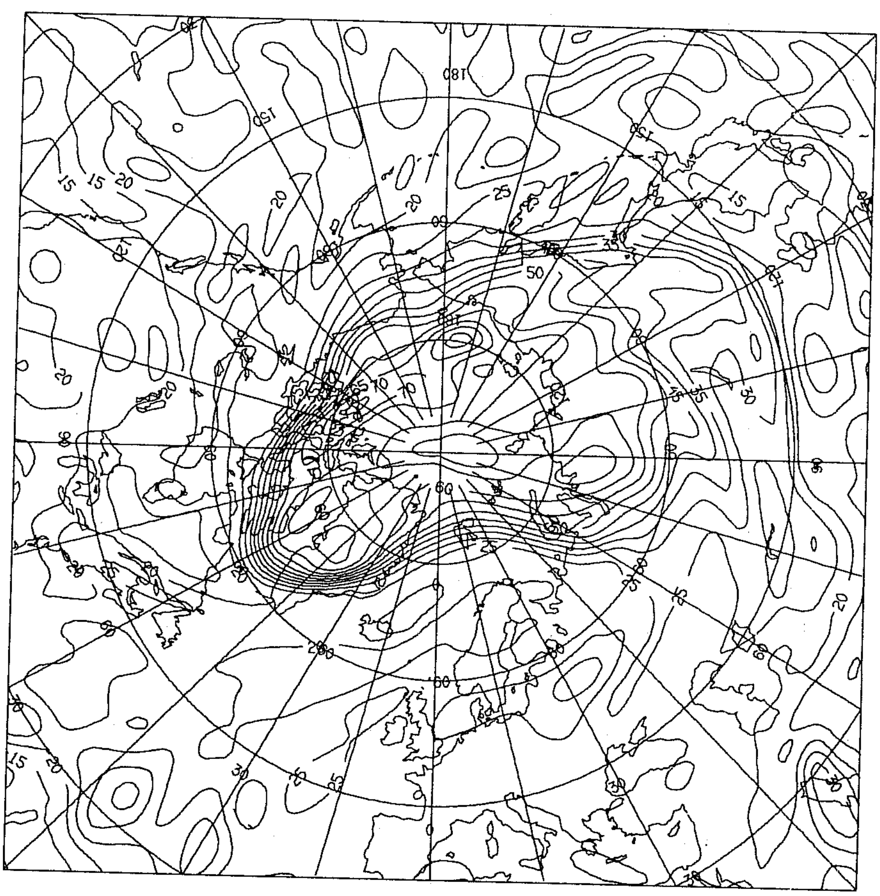

Fig 6(b) Potential Vorticity on 475K surface from ECMWF T+24 forecast. Valid 12UTC 2/2/93 Northern Hemisphere. 0° lower vertical. Contour interval every 5 pvu.

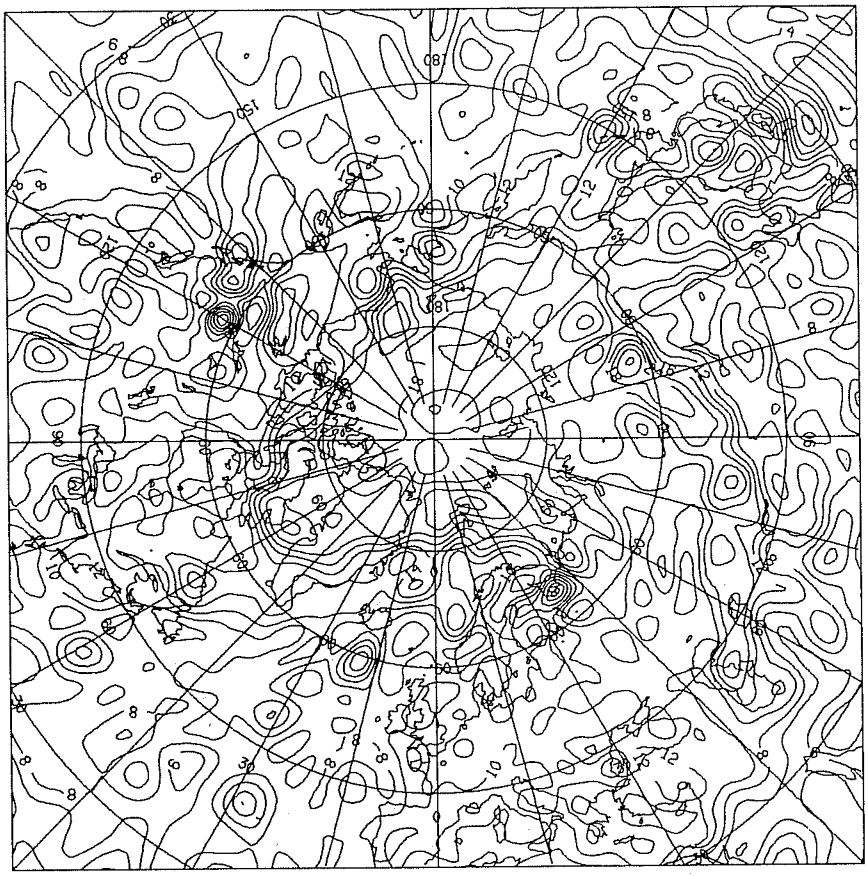

Fig 7(a) Absolute Vorticity on 475K surface from ECMWF Analysis. Valid 12UTC 1/2/93 Northern Hemisphere. 0° lower vertical. Contour interval every $2.10^{-5}s^{-1}$

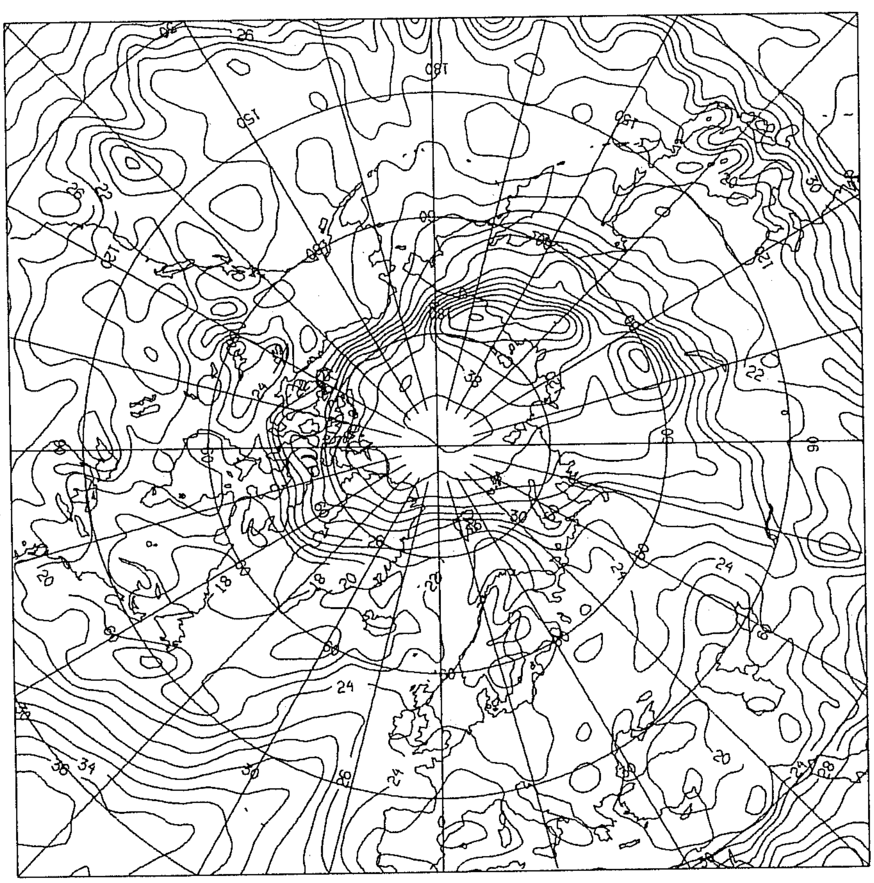

Fig 7(b) Static stability on 475K surface from ECMWF Analysis. Valid 12UTC 1/2/93 Northern Hemisphere. 0° lower vertical. Contour interval every $2.10^{-3}mKkg^{-1}s^{2}$

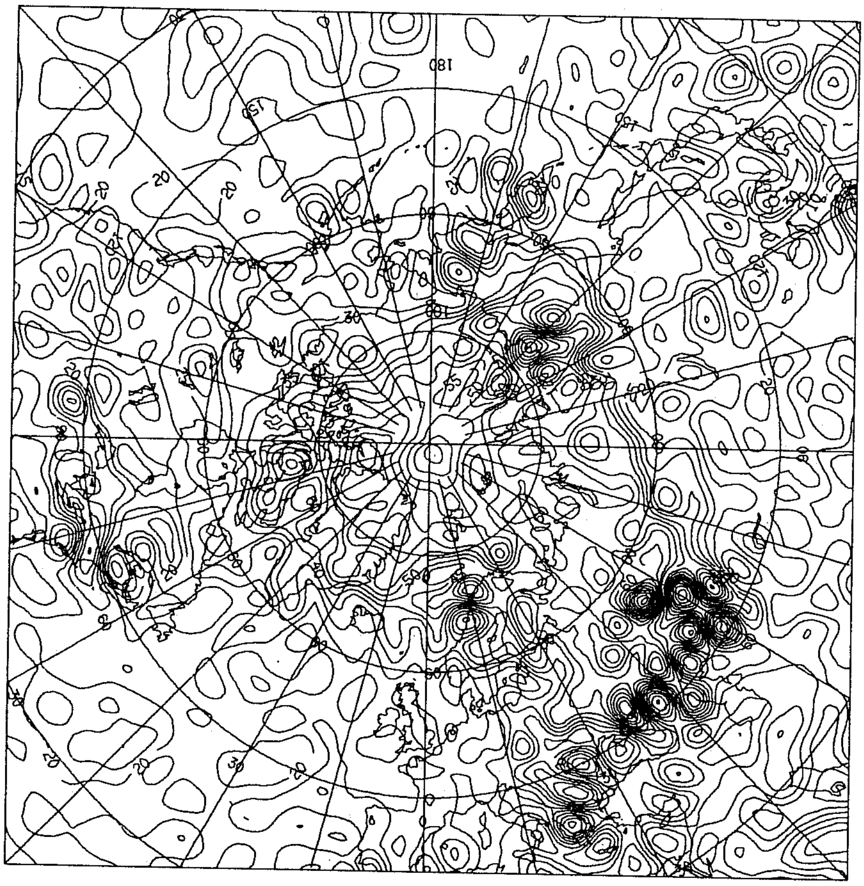

Fig 8(a) Potential Vorticity on 475K surface from ECMWF Analysis. Valid 12UTC 1/2/89 Northern Hemisphere. 0° lower vertical. Contour interval every 5 pvu.

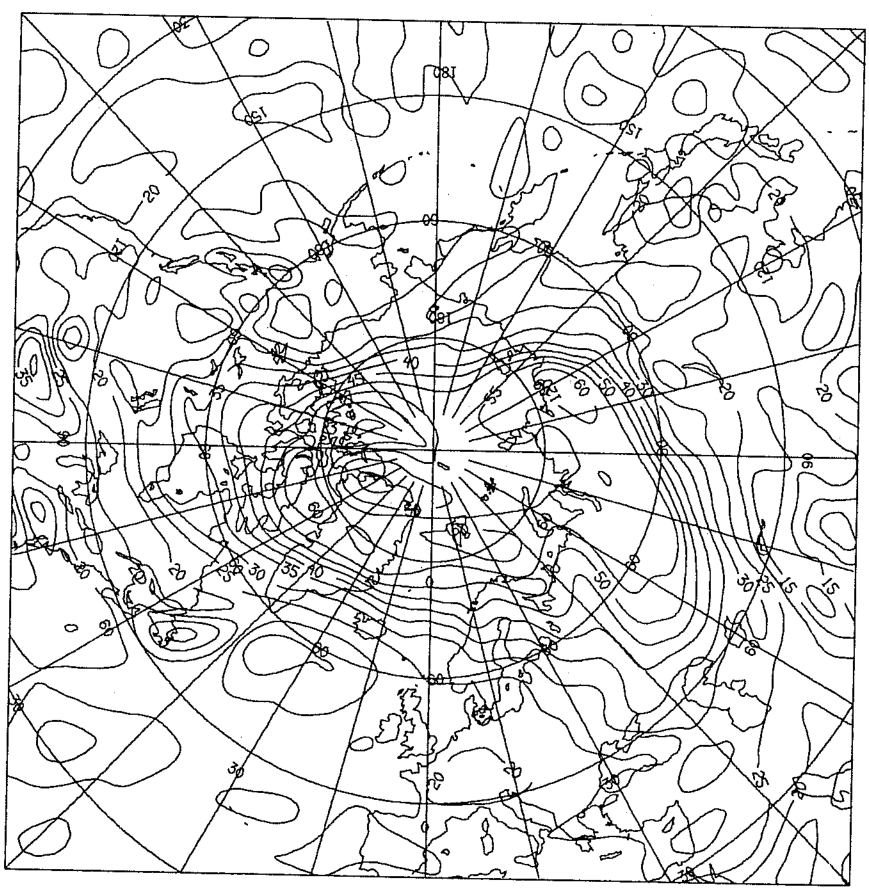

Fig 8(b) Potential Vorticity on 475K surface from ECMWF T+24 forecast. Valid 12UTC 2/2/89 Northern Hemisphere. 0° lower vertical. Contour interval every 5 pvu.

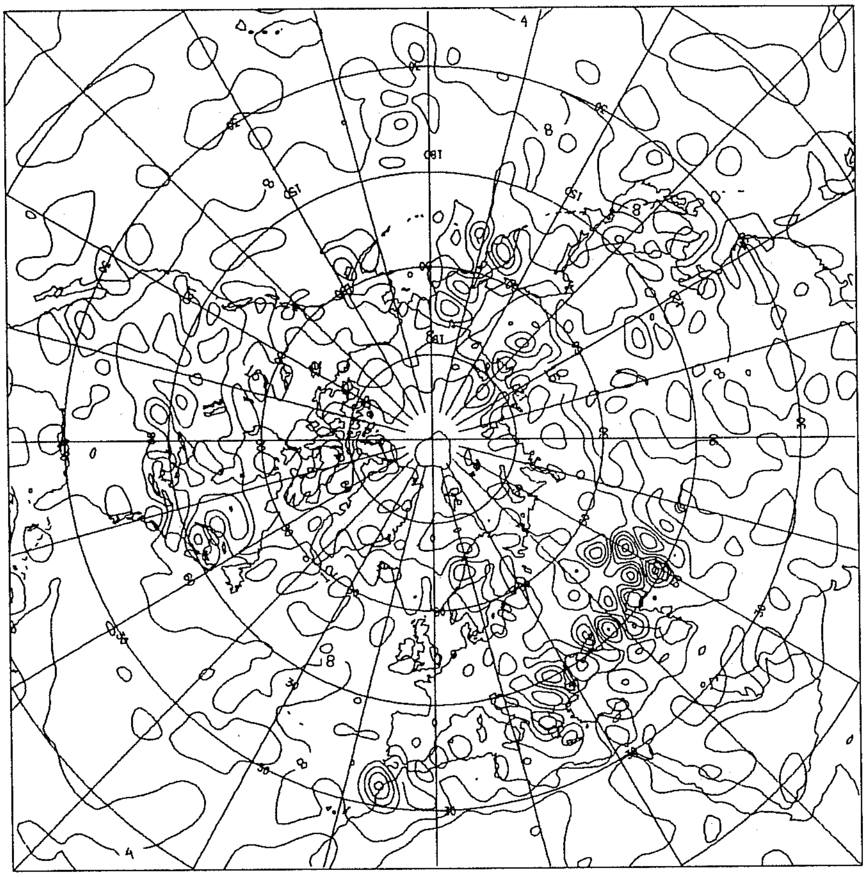

Fig 9(a) Absolute Vorticity on 475K surface from ECMWF Analysis. Valid 12UTC 1/2/89 Northern Hemisphere. 0° lower vertical. Contour interval every $2.10^{-5}s^{-1}$

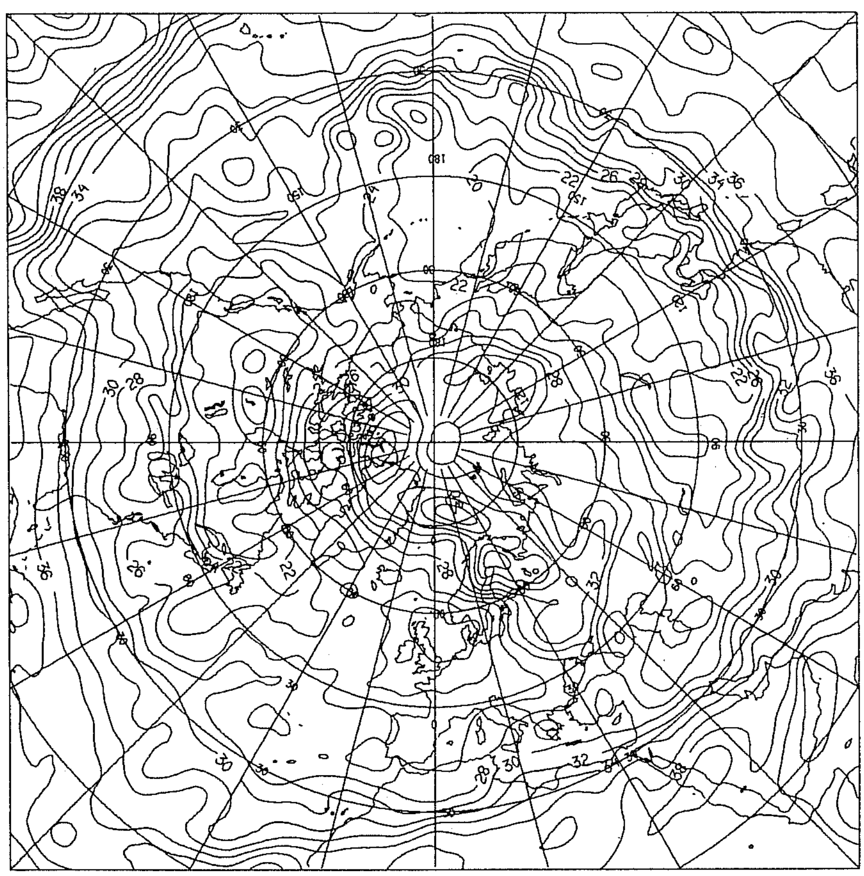

Fig 9(b) Static stability on 475K surface from ECMWF Analysis. Valid 12UTC 1/2/89 Northern Hemisphere. 0° lower vertical. Contour interval every $2.10^{-3}mKkg^{-1}s^{2}$

derived from the height or temperature information. It would appear that there is an incorrect scale in the analysis structure functions being used in the stratosphere.

The noise apparent over continental areas in the UM analyses and those from ECMWF in 1989 may be due to gravity-wave breaking or momentum deposition. The ECMWF drag has been reformulated since 1989 so that less drag is imposed at higher levels. This could account for the fact that the PV is now relatively less noisy over continental areas and during the forecast than prior to the wave-drag reformulation.

ECMWF forecast PV maps appear to be smoother than those from the UM after a couple of days and there appears to be a greater smoothing between the analyses and 24 hour forecasts in the ECMWF model. This suggests that the effective horizontal diffusion in the stratosphere is greater in the ECMWF model. It is perhaps a subjective assessment as to whether ECMWF is too smooth or the UM not smooth enough.

4. COMPARISON OF TROPOPAUSE PV ANOMALIES.

Figure 10 shows PV analysis maps for the 315K surface at 12UTC 7/1/93 (top set) and 12UTC 8/1/93 (bottom set); UM on the left and ECMWF on the right. The PV is contoured every 1 pv unit. Comparing first the analyses for 7/1/93 we see that the large-scale trough ridge pattern matches reasonably well but there are noticeable differences in the smaller-scale detail such as the regions of high PV near 60°N 30°W and in bottom left corner of the ECMWF analysis. Small differences in the size of the PV may be due to whether one model is warmer and cooler than the other which implies a difference in altitude of the isentrope and thus a sampling of air that possesses a different background PV value which is significant within the stratosphere where vertical PV gradients are large. Also note that in both analyses there are zero contours showing regions of negative PV. In the analyses for one day later (figure 10, bottom panels) , the major trough has moved to Scandinavia and there is low PV air over much of the Southern halves of the frames. Again the larger-scale features match reasonably well but differences in detail are apparent in the higher PV air. In the UM analysis there is a region of negative PV over and to the west of Ireland with spot values below -3 pv units.

Corresponding fields of absolute vorticity are shown in figure 11 and static stability are shown in figure 12. On the whole, the large-scale contrast between the low PV mainly tropospheric air (PV<1) and the higher PV mainly lower stratospheric air (PV>1) is more noticeable in the static stability as we would expect from the change in static stability at the tropopause. Differences in the PV detail do not appear to be due to either the absolute vorticity or static stability differences alone but rather a combination of the two fields in general. However, the region of negative PV in the UM appears to be due to negative absolute vorticity rather than a statically unstable atmosphere.

A more disturbing example of differences in PV between the UM and ECMWF is shown in figure 13. PV on the 330K surface is plotted at 1 pv unit intervals. The top panels are valid at 00UTC 14/6/93 and the bottom panels for 12 hours later. This time the data on the left from the UM is from the limited-area (LAM) configuration (horizontal resolution approximately 50km) with an analysis on the top and a 12 hour forecast on the bottom. The ECMWF plots on the right are both analyses valid at the same time. Comparing the

Fig 10(a) Potential Vorticity on 315K surface.
UK LAM Analysis valid at 12UTC 7/1/93.
Contour interval every 1 pvu.

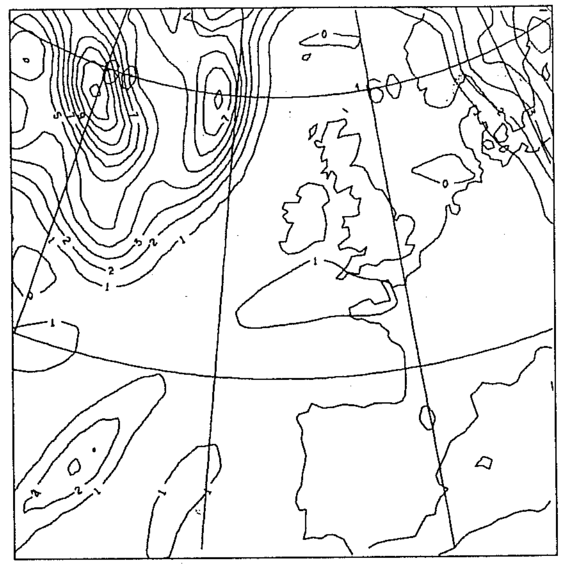

Fig 10(b) Potential Vorticity on 315K surface
ECMWF analysis valid at 12UTC 7/1/93.
Contour interval every 1 pvu.

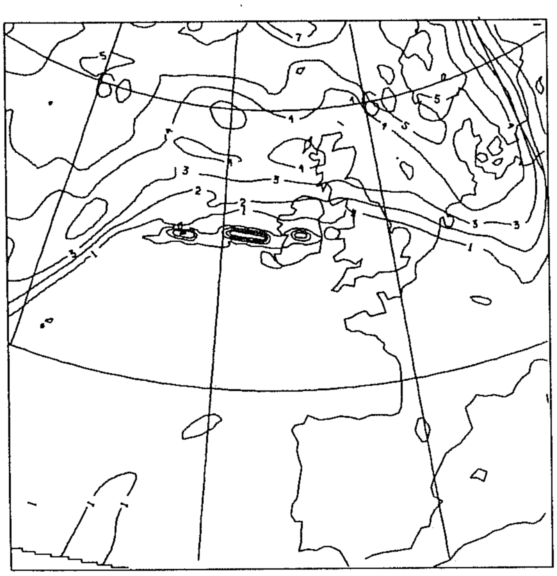

Fig 10(c) Potential Vorticity on 315K surface.
UK LAM Analysis valid at 12UTC 8/1/93.
Contour interval every 1 pvu.

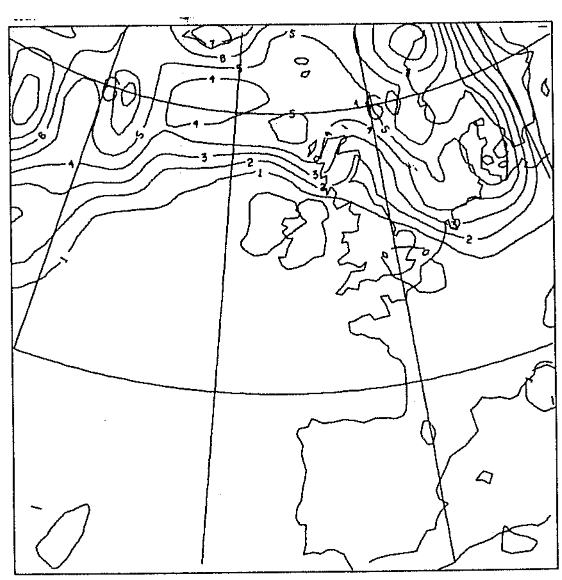

Fig 10(d) Potential Vorticity on 315K surface
ECMWF analysis valid at 12UTC 8/1/93.
Contour interval every 1 pvu.

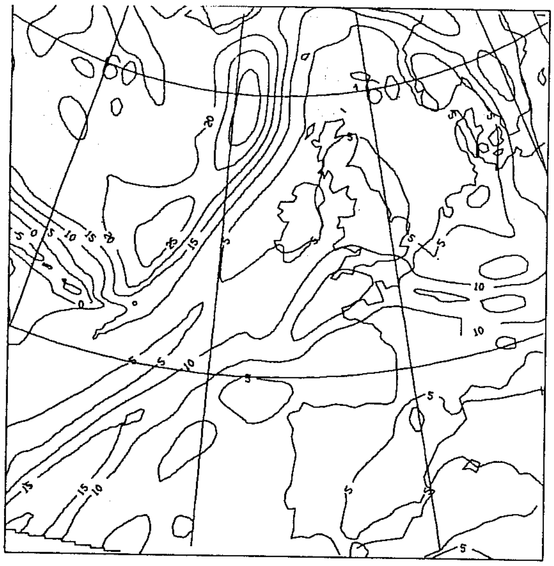

Fig 11(a) Absolute Vorticity on 315K surface. UK LAM Analysis valid at 12UTC 7/1/93. Contour interval every $5.10^{-5}s^{-1}$

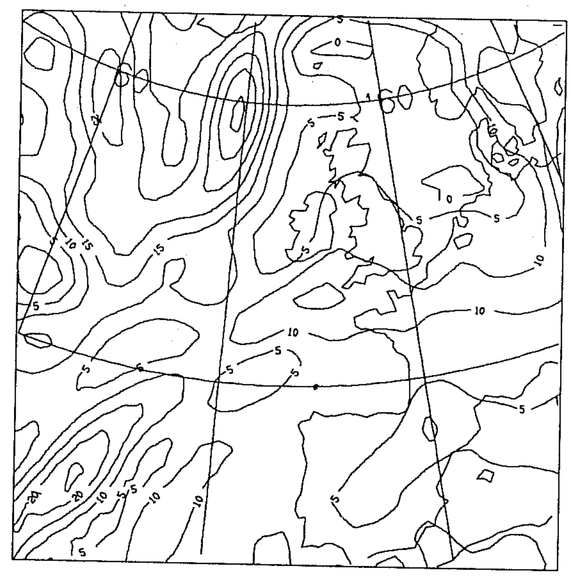

Fig 11(b) Absolute Vorticity on 315K surface ECMWF analysis valid at 12UTC 7/1/93. Contour interval every $5.10^{-5}s^{-1}$

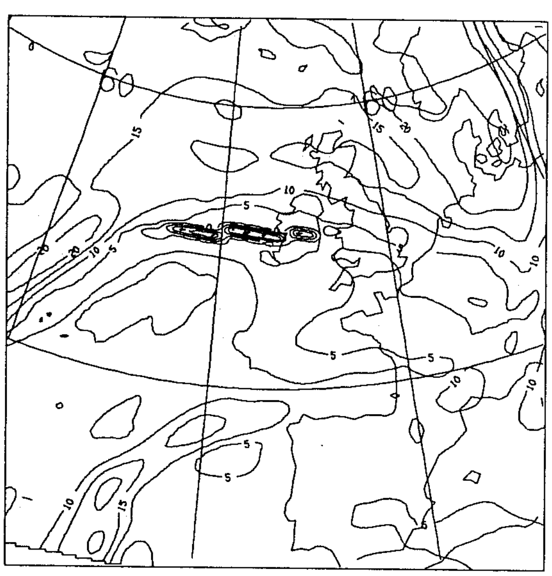

Fig 11(c) Absolute Vorticity on 315K surface. UK LAM Analysis valid at 12UTC 8/1/93. Contour interval every $5.10^{-5}s^{-1}$

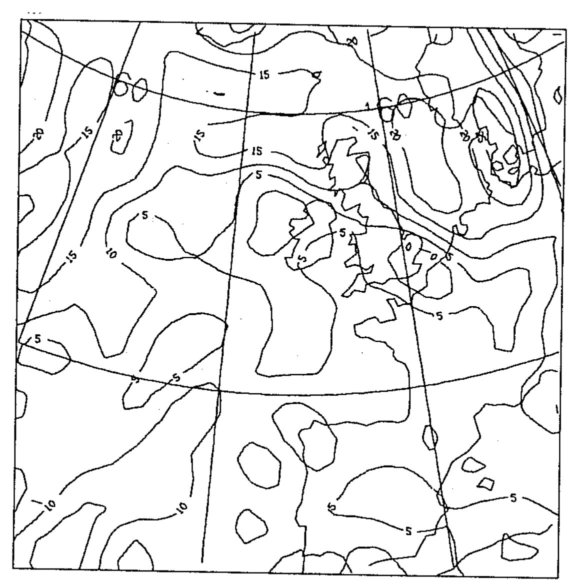

Fig 11(d) Absolute Vorticity on 315K surface ECMWF analysis valid at 12UTC 8/1/93. Contour interval every $5.10^{-5}s^{-1}$

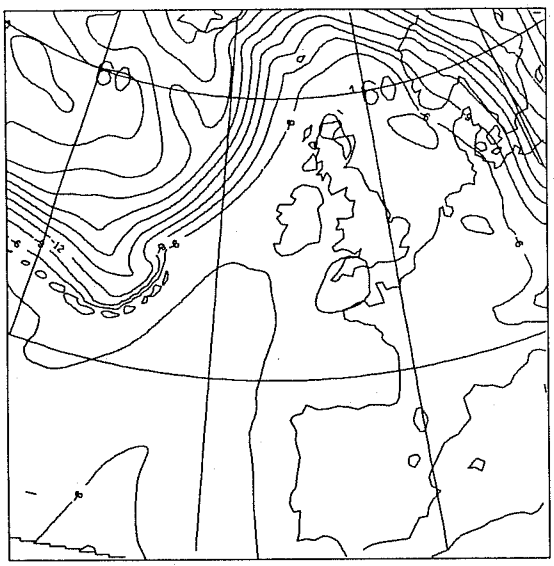

Fig 12(a) Static stability on 315K surface.
UK LAM Analysis valid at 12UTC 7/1/93.
Contour interval every $3.10^{-3} mKkg^{-1}s^{-2}$

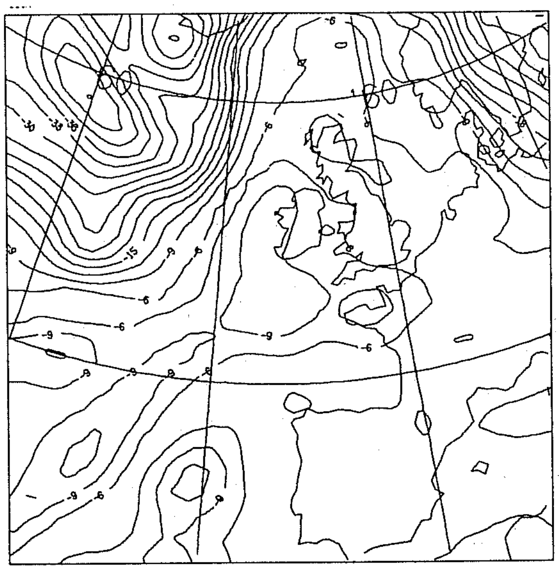

Fig 12(b) Static stability on 315K surface
ECMWF analysis valid at 12UTC 7/1/93.
Contour interval every $3.10^{-3} mKkg^{-1}s^{-2}$

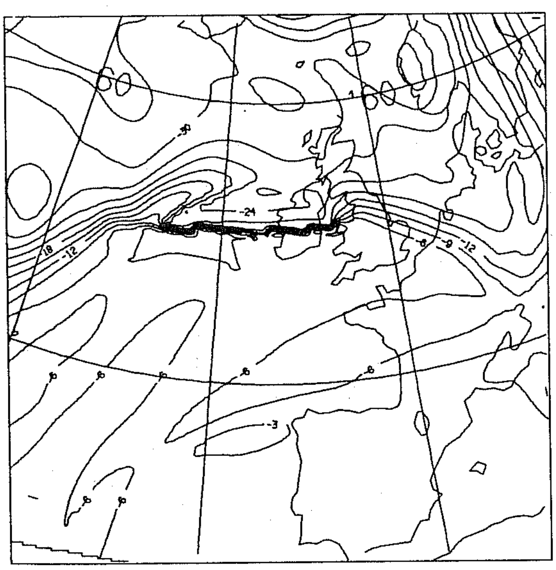

Fig 12(c) Static stability on 315K surface.
UK LAM Analysis valid at 12UTC 8/1/93.
Contour interval every $3.10^{-3} mKkg^{-1}s^{-2}$

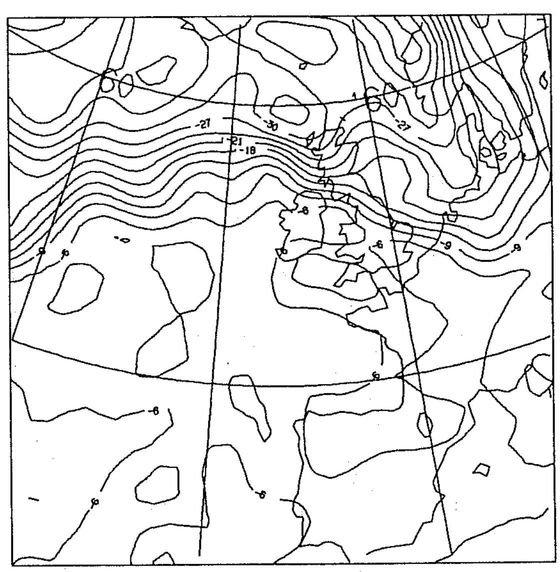

Fig 12(d) Static stability on 315K surface
ECMWF analysis valid at 12UTC 8/1/93.
Contour interval every $3.10^{-3} mKkg^{-1}s^{-2-}$

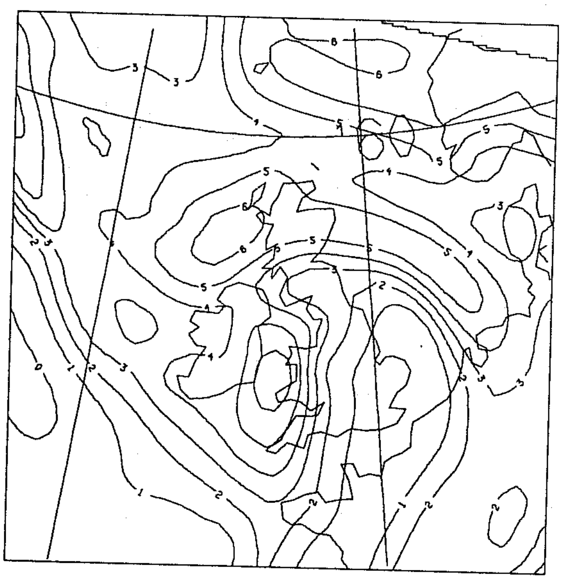

Fig 13(a) Potential Vorticity on 330K surface.
UK LAM Analysis valid at 00UTC 14/6/93.
Contour interval every 1 pvu.

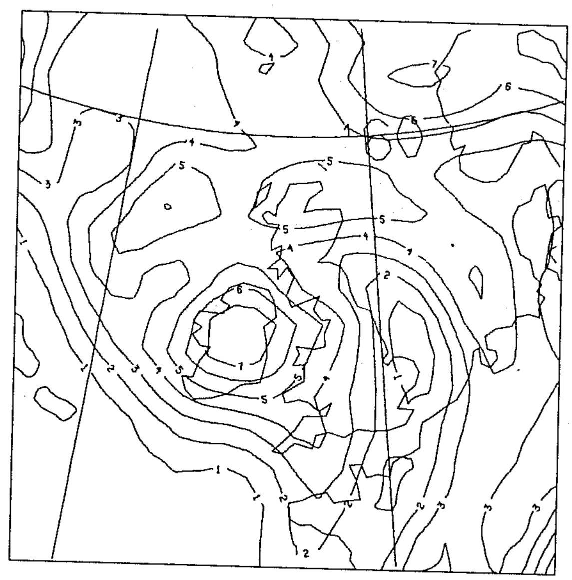

Fig 13(b) Potential Vorticity on 330K surface
ECMWF analysis valid at 00UTC 14/6/93.
Contour interval every 1 pvu.

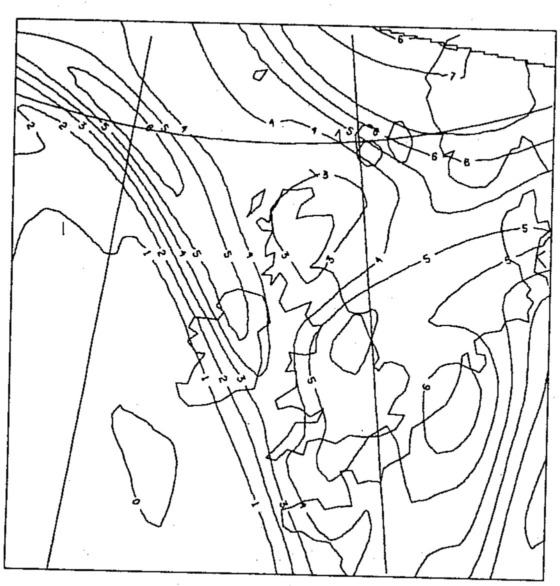

Fig 13(c) Potential Vorticity on 330K surface.
UK LAM T+12 forecast valid at 12UTC 14/6/93.
Contour interval every 1 pvu.

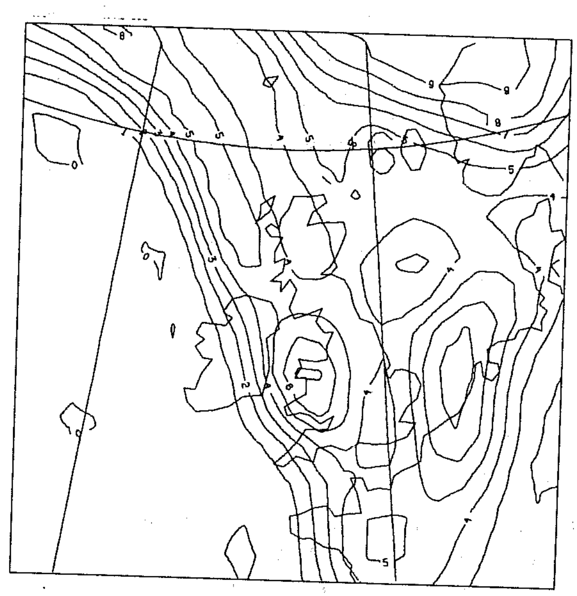

Fig 13(d) Potential Vorticity on 330K surface
ECMWF analysis valid at 12UTC 14/6/93.
Contour interval every 1 pvu.

analyses valid at 00UTC (top panels) we can see there is a significant difference in the position of the main anomaly centre which is centred over Ireland in the ECMWF analysis but over the Irish Sea in the LAM analysis. There are differences in detail all around the anomaly which are apparent as differences in where the PV gradients are situated. These differences are crucial in the implied structures and tropospheric forcings induced by the anomalies and we would expect significant differences in where and when rainfall occurs for example. The main PV anomaly crosses the UK during the next 12 hours and in the ECMWF analysis for 12UTC it is situated over the Southern North Sea. The UM LAM forecast also has the anomaly centred in the same region but as not such an intense feature. Again, to the west over the UK there are significant changes in the PV structures between the LAM forecast and the ECMWF analysis. The differences in the analyses appear to be due to differences in the wind (and hence vorticity) structures. Figure 14 shows plots of the 300hPa wind analyses with scaled wind arrows and isotachs for 00UTC 14/6/93. The ECMWF analysis has stronger winds extending towards and over Southern Ireland, the LAM has stronger winds over and to the North of Ireland. These differences are rather worrying since they reflect more of a difference in the use of (wind) data rather than say differences over a data-sparse region. As already mentioned, differences of this size would be expected to lead to significant differences in weather elements produced by the models.

5. FORECAST SENSITIVITY TO TROPOPAUSE PV ANOMALIES

An example of the sensitivity of model forecasts to differences in wind data (and thus differences in the structure and position of tropopause PV anomalies) is illustrated by the following case of UM LAM forecasts for 14/10/93. The runs considered are the 00UTC and 12UTC runs from 13/10/93. Winds at 250hPa are shown in figure 15 and PV on the 315K surface are shown in figure 16. In both figures the 12 hour forecast valid at 12 UTC 13/10/93 is shown on the top and the validating analyses are on the bottom. It is apparent that there is more of a contrast in the 12 hour forecast between the light winds in the trough axis and the strong southerly winds over Spain. This is reflected in the more intense (greater than 4 pv units) and northward extending PV anomaly in the forecast (figure 16(a)). The significance of these differences was reflected in the development of the system ahead of the anomaly (upper trough) which in the forecast from 00UTC was slightly more intense and resulted in heavier rain (wrongly) forecast over Southern England. Of course, the PV anomaly for the 00UTC analysis was situated over the relatively data-sparse region to the west of Portugal.

The importance of the upper-level (above 700hPa) structure for this particular case was confirmed by running forecasts from 12UTC 13/10/93 with either the upper or lower levels replaced with data from the T+12 forecast from 00UTC 13/10/93 (a form of transplant experiment). The forecast from 12UTC starting with the 00UTC T+12 upper air was almost identical to the full 00UTC forecast whereas the forecast starting with the 00UTC lower levels was much closer to the original forecast from 12UTC.

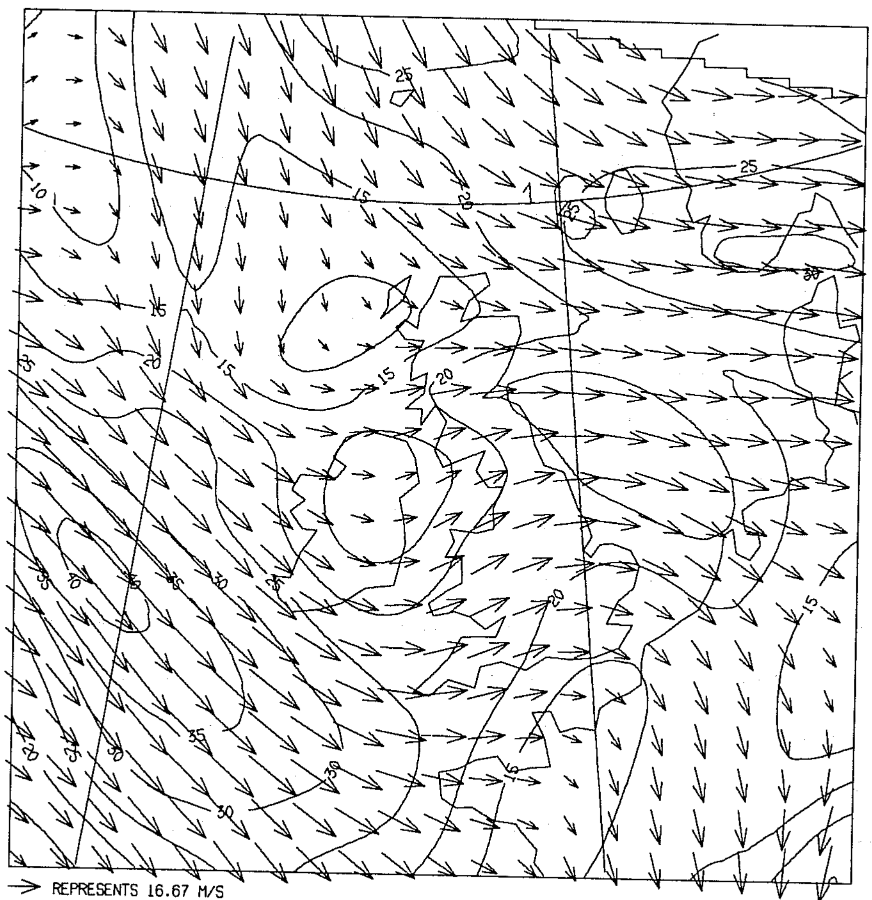

Fig 14(a) 300hPa wind arrows and isotachs from UK LAM Analysis valid 00UTC 14/6/93
Contour interval every $5ms^{-1}$

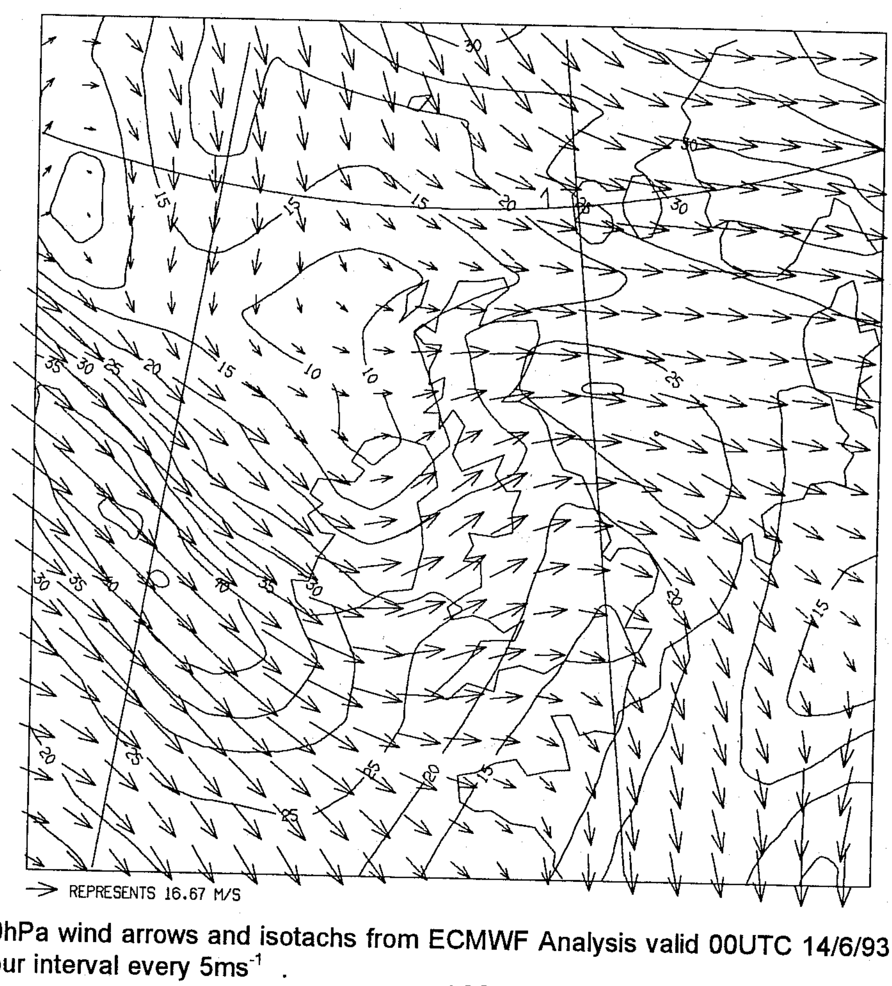

Fig 14(b) 300hPa wind arrows and isotachs from ECMWF Analysis valid 00UTC 14/6/93
Contour interval every $5ms^{-1}$.

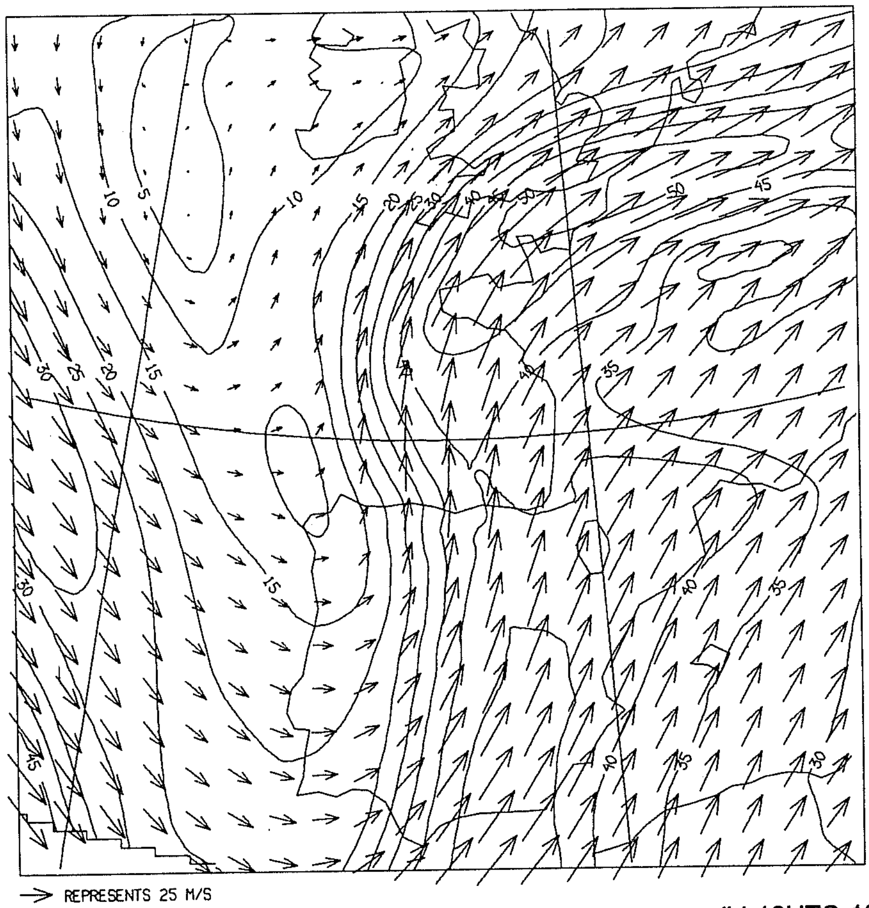

Fig 15(a) 250hPa wind arrows and isotachs from UK LAM T+12 forecast valid 12UTC 13/10/93
Contour interval every $5 ms^{-1}$

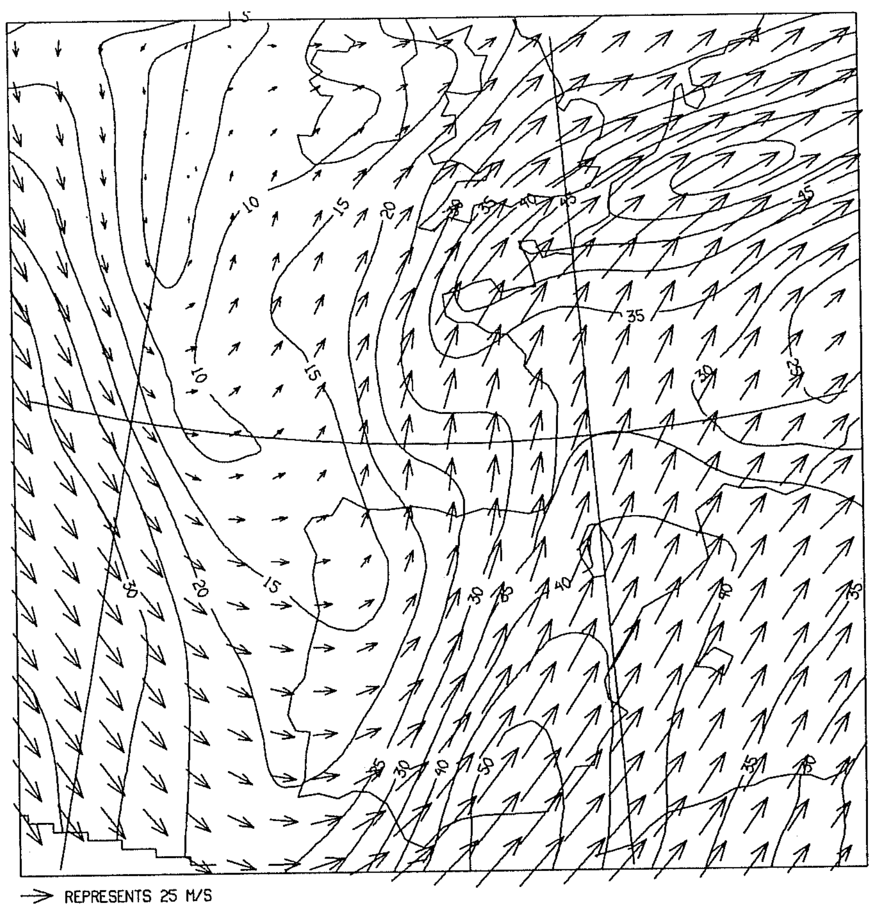

Fig 15(b) 250hPa wind arrows and isotachs from UK LAM Analysis valid 12UTC 13/10/93
Contour interval every $5 ms^{-1}$

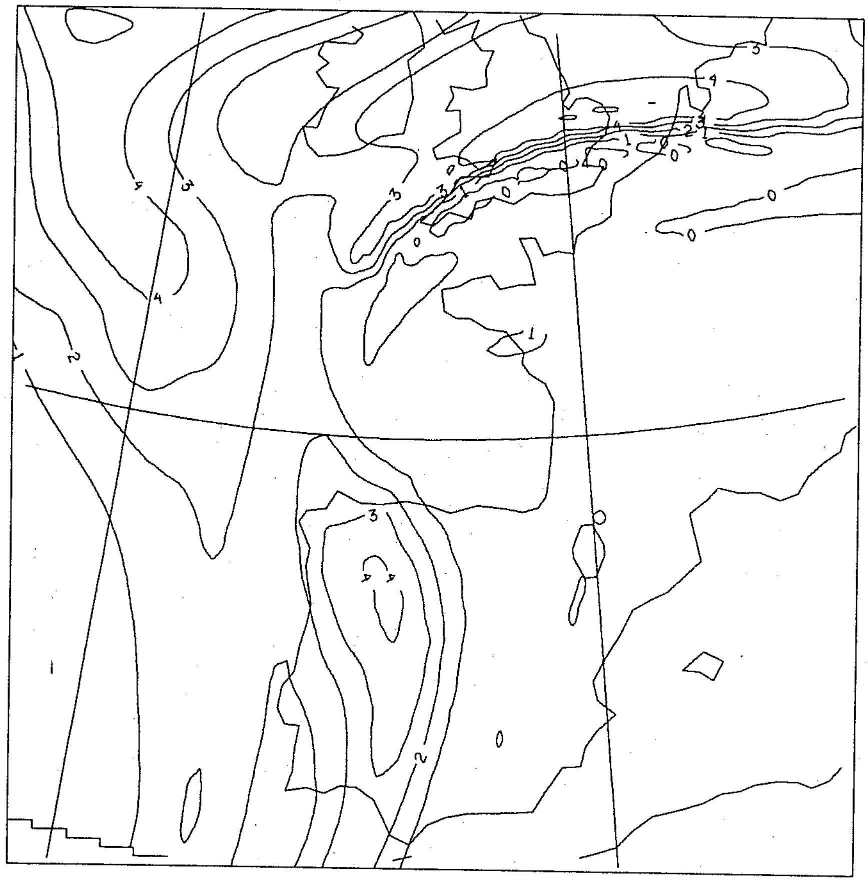

Fig 16(a) Potential Vorticity on 315K surface from UK LAM T+12 forecast valid 12UTC 13/10/93
Contour interval every 1pvu

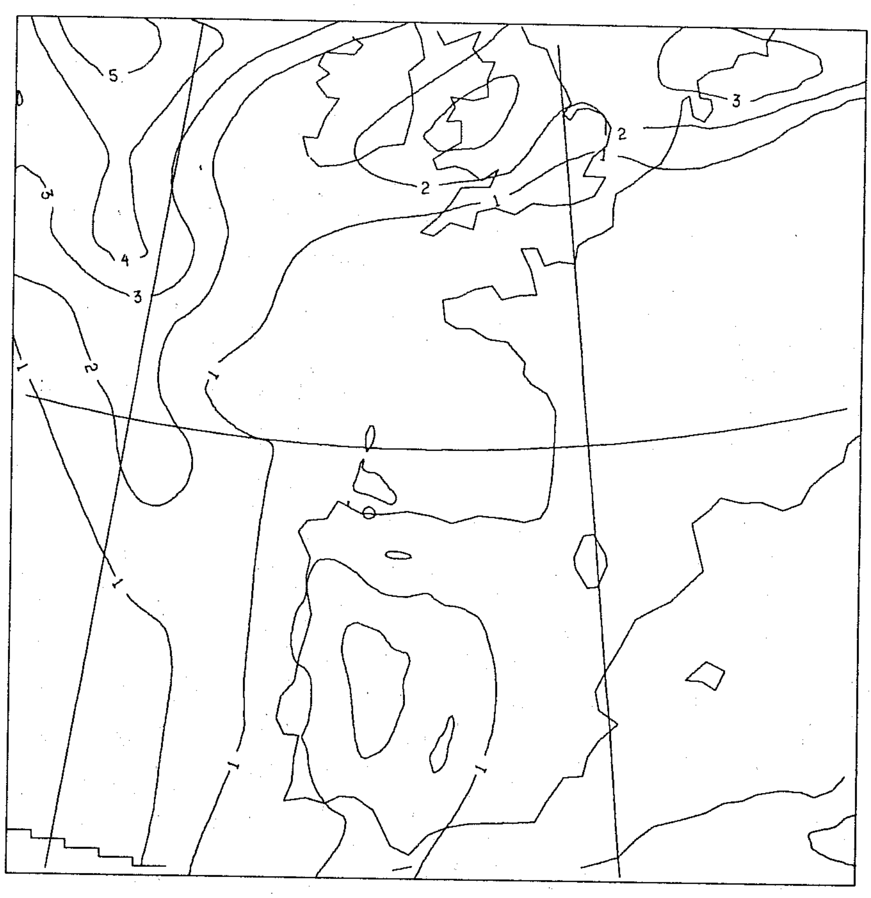

Fig 16(b) Potential Vorticity on 315K surface from UK LAM Analysis valid 12UTC 13/10/93
Contour interval every 1pvu

6. CONCLUSIONS

Some of the differences observed when comparing PV charts produced from ECMWF and UK UM model data have been identified and possible explanations for these differences have been put forward. It is worthy of note that in the middle atmosphere, these differences may be an effective indicator of the signal produced from particular aspects of the model design or formulation. In the examples described here there appears to be sensitivity to the gravity-wave drag and to the horizontal diffusion.

Near the tropopause, PV anommalies have a significant impact upon tropospheric development. An accurate description of the PV is important and is sensitive to the way in which wind data in particular is used or is available.

REFERENCES

Davies, T. 1992: Potential Vorticity perspective of model validation. ECMWF Seminar on Validation of Models over Europe, 7-11 September 1992, Vol 1, 117-151.

Hoskins, B. J., M. E. McIntyre and A. W. Robinson, 1985: On the use and significance of isentropic potential vorticity maps. Q. J.Roy.Meteor.Soc., 111, 877-946.

McIntyre, M. E. 1987: The dynamical significance of isentropic distributions of potential vorticity and low-level distributions of potential temperature. ECMWF Seminar on the Nature and Prediction of Extra-Tropical Weather Forecasts, 7-11 September 1987, Vol 1, 237-259.

McIntyre, M. E. 1987: The use of potential vorticity and low-level temperature/moisture to understand extra-tropical cyclogenesis. ECMWF Seminar on the Nature and Prediction of Extra-Tropical Weather Forecasts, 7-11 September 1987, Vol 1, 261-280.

Simmons, A.J. 1993: Some stratospheric aspects of model development at ECMWF.
ECMWF Workshop on the Stratosphere and Numerical Weather Prediction, 15-17 November 1993.