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N.W.P. Research at the Meteorological Office - Analysis Aspects

by

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This paper was prepared for a workshop on Numerical Weather Prediction at the US Air Force Geophysics Laboratory, Boston. October 1983.

N.W.P Research at the UK Meteorological Office - Analysis aspects

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Summary

The NWP system which has recently been introduced into operational use at the UK Met Office is briefly described. It consists of a global 15 layer 150 km resolution forecast model with a 4D data assimilation scheme. A limited area 75 km version of the forecast model is also used. Planned developments are outlined; these include a limited area 75 km analysis, using high resolution temperature retrievals from the TIROS-N operational vertical sounder, and a mesoscale 10 km resolution analysis and forecast for the British Isles.

Some examples are presented demonstrating the importance of the analysis for forecast accuracy. The principles behind the Met Office's analysis method, 4-dimensional data-assimilation by repeated insertion of observations into a forecast model, are discussed.

1. Introduction

This note, while attempting to review many aspects of Numerical Weather Prediction research at the Meteorological Office, places most emphasis on those subjects in which the author is personally interested, and is not a balanced survey. In this opening section research into NWP modelling is briefly covered, in section 2 some evidence is presented demonstrating the importance of good analyses for accurate NWP, and in section 3 the analysis techniques being developed at the Meteorological Office are described.

NWP research at the Meteorological Office has for the last few years had as its first objective the design, implementation and tuning of a new operational suite to run on our recently enhanced computer system (a Cyber 205, with IBM 370/3081 and 158 front ends). The new forecast system has recently been described by Cullen (1983), Bell (1983) and Foreman (1983). The new model was designed after a series of intercomparison experiments (eg Cullen et al 1981). It was developed and tested in a series of comparisons with the ECMWF forecast model (Higgins 1983). The global version runs on a 15 sigma layer 1.5 x 1.875 latitude-longitude grid. It uses a computationally efficient split-explicit time integration scheme (Gadd 1980), and parametrizations of sub-grid-scale processes largely derived from those developed for the Met Office's General Circulation Models. Details are given by Foreman (1983). A limited area fine-mesh version of this model, covering the Atlantic and western Europe with half the grid length of the global model (ie 75 km), provides the basic numerical guidance for forecast up to 30 hours for the UK, particularly for rainfall and surface wind.

A mesoscale model covering the British Isles with a 10 km grid is also under development. This is a non-hydrostatic model (Tapp and White 1976) designed to run for periods up to about 12 or 24 hours with detailed initial conditions and surface forcing, and lateral boundary conditions taken from the fine mesh model. Since the examples described by Carpenter (1979) and Bailey et al (1981), the model has been extended to predict humidity and cloud liquid water. Parametrizations of convection, turbulence, and the radiative effects of cloud are under development. The model should be ready for operational use in about 1985.

2. The effect of analysis accuracy on forecasts

In this section I attempt to demonstrate what is perhaps self evident; that good initial analyses are necessary for numerical forecasts. However study is still warranted into which parameters, observations and aspects of analysis methodology are most important. In section 3 I go on to outline the analysis methods being developed at the Meteorological Office.

The examples presented here are simplifications of detailed studies of complex situations, selected to emphasize the points I wish to make. A fuller picture may be obtained from the references given. The first two examples are for synoptic scale forecasts of one or two days. The analysis problems for this sort of case are reasonably well understood (although finding practical solutions to them is not easy). Further cases and discussion deal with longer and then with shorter periods. Both of these illustrate that different aspects of analysis quality are important for these timescales and are less well understood.

The first three cases are taken from an intercomparison study between analyses of FGGE data by UKMO, ECMWF and NMC analysis systems (Hollingsworth et al 1983). (The analysis systems were research versions differing significantly from current operational ones).

In example 1 the analysis differences are largely due to the handling of contradictory data. Figure 1 shows the observations near 300mb over the Mediterranean. Within each observation type there is quite good consistency, however between different observation types there is less good agreement. The cloud motion winds give generally lower speeds than other types; they are occasionally extremely low. The cloud wind directions over the Mediterranean and North Africa in the lower centre of figure 1 are southerly, in agreement with the Brindisi radiosonde in the centre of the figure, but in disagreement with the aircraft reports between.

The EC analysis (Fig 2) attempted to compromise between the observations and produce smooth balanced fields. The US analysis (Fig 3) rejected the cloud winds and draw a smooth field with a greater southern extent of the jet. The UK analysis (Fig 4) fitted the data more closely by drawing rougher less balanced fields. Differences between these analyses caused large differences in the one day forecast of the surface developments. Forecasts from the UK analysis failed to predict the movement of a surface low and front, forecasts from the EC analysis moved them too slowly.

In example 2 the analyses differ in their treatment of incomplete data. The major source of data over the southern Indian Ocean near Marion Island (47S 38E) was temperatures from the TIROS N satellite sounder. These, the Marion Island radiosonde, a few cloud winds, and a few ships and buoys, showed a developing wave depression. The EC and US analyses (Figs 5 and 6) give this a baroclinic wave structure, the UK analysis a much more frontal structure (Fig 7). This affects the forecasts from these analysis; those from the EC and US analyses overdeepen the low slightly, those from the UK analysis seriously underestimate its deepening (Fig 8).

In example 3 the analyses differ in the relative weight given to OWS Papa and SATEM data over the Pacific. However the example is shown here because it demonstrates a clear relationship between these differences and a 4-6 day forecast of a different weather system over the Atlantic. Figure 9 (top) shows difference maps between forecasts with the EC model from EC and US analyses. In the difference map at day 4 we see what appears to be a well organised wave-train over the central and eastern part of North America. This wavetrain can be traced both forwards and backwards in time, and its amplitude grows in time, leading to large differences in the forecast for a surface low over the Atlantic at day 5. Traced back to day 0 it seems to originate in the Pacific. To prove this, an additional forecast was run from initial conditions which were made by merging the EC analysis for most of the globe with the US analysis in the apparent Pacific source region. As expected, this forecast deviated from the pure EC forecast in the same way. Figure 9 (bottom) shows these difference fields; the same wavetrain across N America can be seen at day 4 and the Atlantic differences at day 6 are also similar. Thus in this case the impact of an analysis difference on a medium range forecast is clearly demonstrated. Without this kind of study however the importance of the Pacific for this depression might not have been suspected. The depression originated over the Caribean and its early development was governed by a trough over the Mid-west at day 0.

Example 4 is taken from Dickinson (1983). It shows an intriging but not yet fully understood impact of the analysis on a 5 day forecast of a block over the UK. The case was chosen because the operational UK MO forecast was inferior on that occasion to the operational ECMWF forecast; it is not necessarily typical. The evolution of the large scale pattern is shown in figure 10. The ECMWF and UKMO forecasts of this are shown in the top left and bottom right of figures 11 and 12. The UKMO forecast failed to predict the rebuilding of the blocking high at day 5. To study the causes of this the UKMO model was run from the ECMWF analysis (top right, labelled EC/UK), and the ECMWF model was run from the UKMO analysis (bottom left, labelled UK/EC). These runs seem to indicate that more of the difference is due to the analysis than to the forecast model.

Examples 3 and 4 thus show clear impact of analysis differences on medium-range forecasts, but in both cases the crucial differences are not those that one might have a priori expected to be important. Indeed in example 4 the cause has yet to be isolated; studies of individual systems in the four forecasts do not show clearly any differences attributable to analysis differences which might cause the large scale forecast differences.

Let us move now to the other extreme, of short range meso-scale prediction. At the limit, "nowcasting" (Browning 1982), forecasts are made by such simple techniques as persistence and advection, and the analysis is all important. Analyses of "weather" variables such as rainfall rate, cloud and surface temperature have also been shown to be important for the meso-scale forecast model. Carpenter and Lowther (1982) showed that surface temperature analyses were vital to a sea-breeze forecast, and Golding (personal communication) has shown that initial cloud amounts affect rainfall forecasts. However it is also clear that if the dynamic forcing of the mesoscale model from the boundaries (imposed from a fine-mesh forecast) and initial conditions are incorrect, then correct cloud analyses are scarcely relevant. If the dynamical initial conditions are obtained by data assimilation into a sophisticated NWP model, which include representations of processes affecting the "weather" parameters, then as a by-product realistic looking analyses of these are obtained. (Lorenc and Tibaldi 1980, Fugard 1983). Examples of this are shown in figures 13, 14, 15, which show cross sections across the cold front in example 2. The UK and EC systems which have reasonable parametrizations of moist processes, have a realistic looking humidity cross section. The US system, which had in this version cruder parametrizations, has not got the sloping frontal band. It is worth emphasising that in synoptic scale forecasts these humidity analysis differences seemed insignificant compared to those in the dynamic fields.

The need to retain the "weather" information induced from dynamic data assimilation, the need to make initial conditions consistent with the model's parametrization schemes (Krishnamurti 1982), even if these are sometimes somewhat biased, and yet the clear benefit of high resolution data on rainfall and cloud in the nowcasting limit, make the problems of analysing for a mesoscale model rather complex.

3. The Met Office's Operational Data Assimilation System

3.1 Basic Principles

The starting point of any analysis must be the observations, and the first principle is thus clear:-

The analysis must fit the observations to within their estimated observational error.

Note the qualification admitting the existance of observational error; in the modern observing network there is a large variety of observation types, some of which are less accurate than others, and this needs to be taken into account in the analysis system. Unfortunately in practice we do not usually have enough observations to define the atmospheric state uniquely via simple interpolation, and our experience of atmospheric structures must be used. This has long been recognised, as can be seen in this quote from Bjerknes (1904):-

> "Our direct observations of the higher layers of air will always be very limited. One must therefore use each observation from the higher levels to the utmost. From the directly observable quantities one has to compute to the greatest extent all accessible data about the non-observable ones. In doing this, one has to utilize the physical relationships between the quantities. Even to construct a coherent picture of the total state of the atmosphere out of scattered observations, one has to use, to a large extent, dynamical-physical methods".

This gives us our second principle:-

<u>The analysis must be internally consistent, fitting our knowledge of the likely structure and scale of atmospheric motions.</u>

This information is often incorporated implicitly into analysis schemes without being clearly stated or quantified. Other knowledge is expressed as relationships which the atmosphere (approximately) obeys, and which are used as either weak or strong constraints on the analysis. The following statements have all been used in analysis schemes.

a. atmospheric fields are smooth and continuous. All schemes I know of assume this, despite the existence of fronts;

b. the value being analysed (usually the first-guess error) is most likely to have a certain scale. Thus a single isolated observation will cause the analysis to be a feature of this most likely scale, and dense inaccurate observations will be averaged over this scale in an ideal analysis scheme.

c. the atmosphere is in hydrostatic balance;

d. the atmosphere is in geostrophic balance;

e. the horizontal wind is non-divergent;

f. the atmosphere is in a state which satisfied the balance equation;

g. the atmosphere is convectively stable;

h. the atmosphere is not super-saturated.

Note however that there are still some properties of the atmosphere which it is possible to explain, and use in a subjective analysis, but which are difficult to use in a numerical scheme:

i. mid-latitude systems often have the characteristic shape of a warm sector depression;

j. certain regions are preferred for the development of new, initially small scale, depressions;

k. developing systems usually have a vertical phase change (tilt).

Rather than attempting to implement all these, the Met Office system goes back to a more basic statement, from which many of the others can be derived mathematically:-

l. the atmosphere is always in or near a state which varies slowly in time.

Unfortunately even these two basic principles are not enough to define the atmospheric state, particularly in data gaps. Operational forecasting systems have long been organized to use information from earlier times to fill these gaps. Thus we have our third basic principle:-

Unless current observations indicate otherwise, the analysis must be near the forecast based on earlier observations.

Analysis methods based on this principle are called four-dimensional data assimiation methods.

3.2 The Operational Met Office Global Analysis System

The most difficult of these three basic principles to implement in an automatic system is the second, and it is in the approach to this that the Met Office system differs from most other operational systems.

The Met Office approach is to assume that the complete operational forecast model is the best available numerical representation of atmospheric behaviour, and to say that slowly varying states which it permits to exist are possible atmospheric states. The model is forced to a slowly varying state which fits the observations by repeatedly inserting these over a 6 hour forecast period, starting from the previous analysis. Thus all three basic principles are satisfied.

The normal prognostic equations of the model, represented schematically by

$$\Psi_{t+\Delta t} = M(\Psi_t)$$

are modified to give

$$\Psi^*_{t+\Delta t} = M'(\Psi_t)$$

and $$\Psi_{t+\Delta t} = \Psi^*_{t+\Delta t} + \lambda \sum_{i=1}^{N_{obs}} W_i \left(\Psi_i^{obs} - \Psi_{i,t+\Delta t}\right).$$

The weights given to nearby observations at each grid-point, represented schematically by W_i in the above equation, are calculated by univariate optimal interpolation. This is a statistical method designed to minimize the expected analysis error, taking into account the assumed observational errors of the data and the accuracy of the model background field. Rather than make the changes required by this immediately, which would "shock" the model and produce rapid oscillations, the factor λ is introduced. This is initially small, increasing towards 1 during the 6 hour assimilation period.

Refinements to System

The simple insertion of data described above is not the most efficient way of bringing the model to a reasonable atmospheric state. For instance an atmospheric surface low is caused by upper level divergence, yet the first effect of simply reducing the surface pressure in the model is to induce convergence in all the layers above. So various modifications to the basic method are added to speed up the assimilation of the data into a balanced state.

a. From the changes to the surface pressure field, changes are calculated to the temperature field using the hydrostatic equation such that the height field near the tropopause is unaltered.

b. From the changes to the pressure and temperature fields, changes are calculated to the wind field using the geostrophic equation.

c. Additional terms are added to the model's equations to damp divergent motions.

Quality Control

Example 1 illustrates the importance and difficulty of quality control of data. In another case studied the US system rejected data which was in fact correct, and gave a worse forecast. If incorrect data are to be detected, we must have otherwise redundant information. Yet often data are not even sufficient, let alone redundant, necessitating my second and third basic principles. Thus for efficient quality control we need to use techniques taking all three principles into account.

In the Met Office system this is impracticable, as the second principle is embodied in an expensive data-assimilation, and it is not possible to repeat this if some data are subequently found to be inconsistent and rejected. So human intervention and quality control of data remains an important part of the Met Office system.

3.3 Fine Mesh Analyses

The operational fine-mesh model is at present run from initial condition interpolated from the twice as coarse 150 km grid. It is expected that implementation of the techniques just described on the 75 km grid will result in improved forecasts, particularly of frontal rainfall in the first 6 hours. It was with this prospect in mind that the data assimilation method was designed; other methods with explicit imposition of balance constraints can lead to the forecast taking this long to spin-up the model's rain-making processes. However improvements due to a fine mesh assimilation have yet to be demonstrated. Because of the rather small difference between the resolutions (remembering also the inaccuracy of some finite difference approximations at scales close to a grid length), and the lack of data on this scale, I do not expect a consistent significant positive impact. One potential source of high resolution data is a system for direct reception and processing of soundings from TIROS-N. The Met Office has set up such a system, called HERMES, (Eyre and Jerrett 1982), and research into the best method of assimilating these data is under way.

3.4 Mesoscale Analysis

It is difficult to express, let alone to automate, relationships describing the structure of mesoscale phenomena. So design of a fully automatic analysis procedure following my three basic principles is not easy. Furthermore, many of the data on these scales, from weather radar, cloud pictures etc, are currently best presented and interpreted in pictorial form, and automatic pattern recognition techniques are insufficiently advanced to analyse them. For these reasons the planned analysis system for the mesoscale model relies heavily on an interactive man-machine system. The fine-mesh assimilation will provide a first-guess for the larger scale dynamic features, a simple univariate analysis program (Purser and McQuigg 1982) will analyse the available observations putting in mesoscale detail, and a human will monitor and compare the fields produced, modifying them if necessary to ensure a consistent picture of mesoscale phenomena.

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AIRCRAFT(A) & CLOUD TRACK(C) WINDS 250-350MB.   EACH FULL FEATHER= 5M/S.
RADIOSONDE(U) 300MB WINDS & HEIGHTS(DAM).   EACH TRIANGLE=25M/S.
VALID AT OZ ON 17/2/79 DAY 48
LEVEL: 300 MB

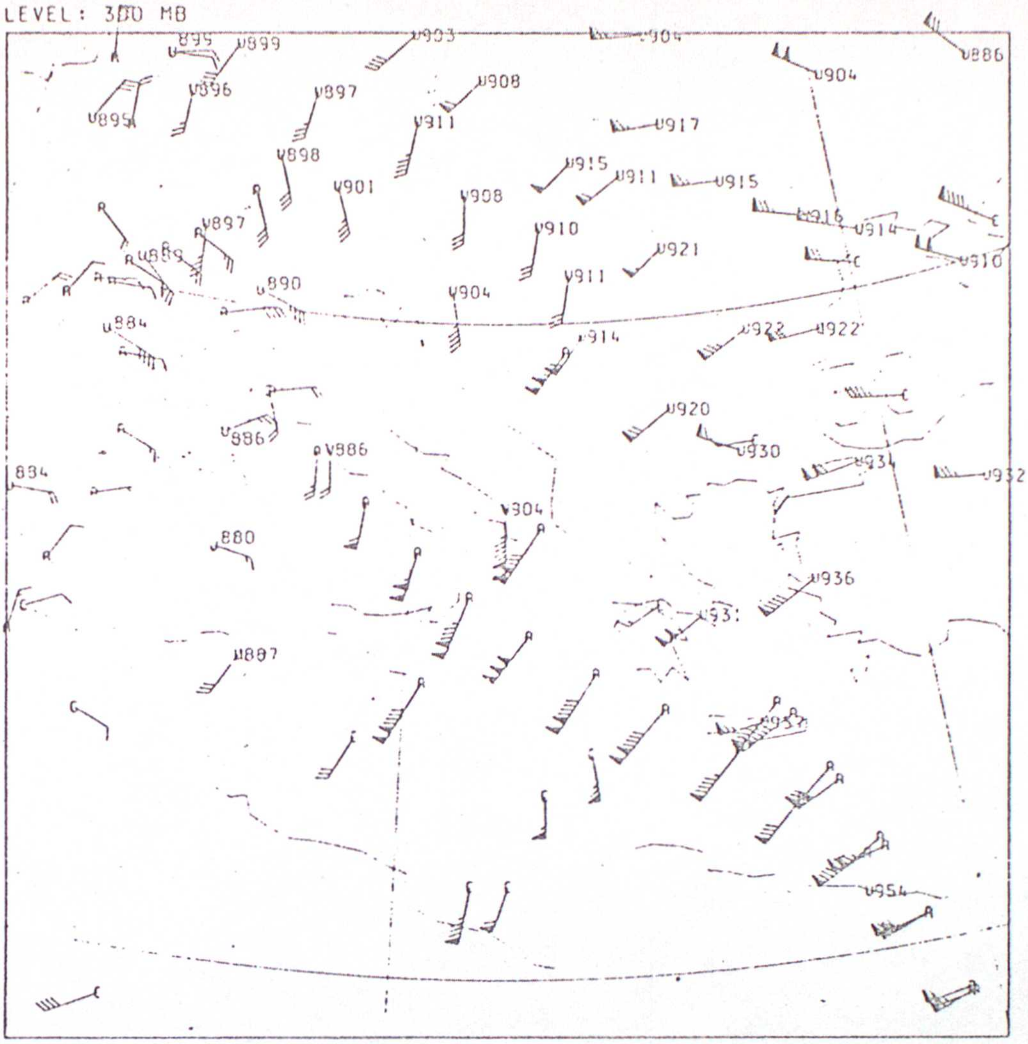
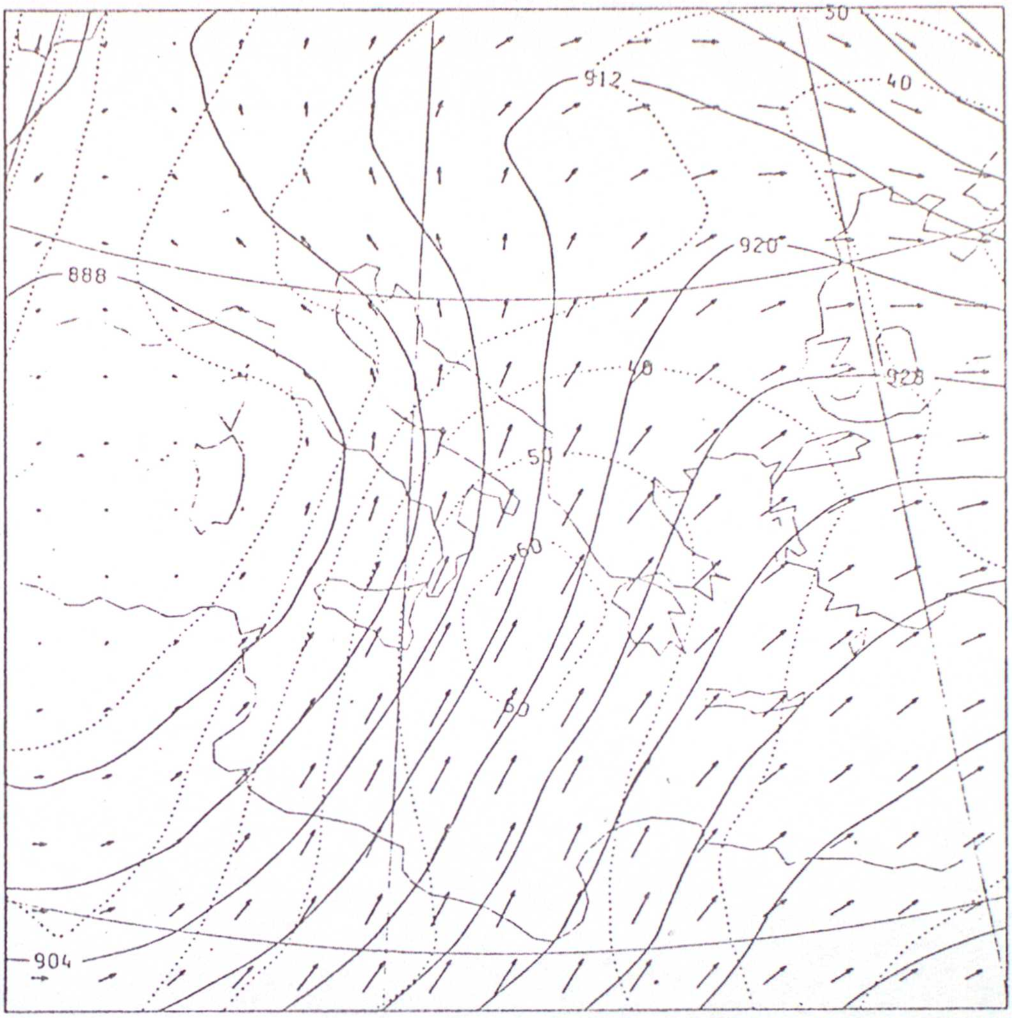


Fig 1.

EC: ECMWF IIIB ANALYSIS

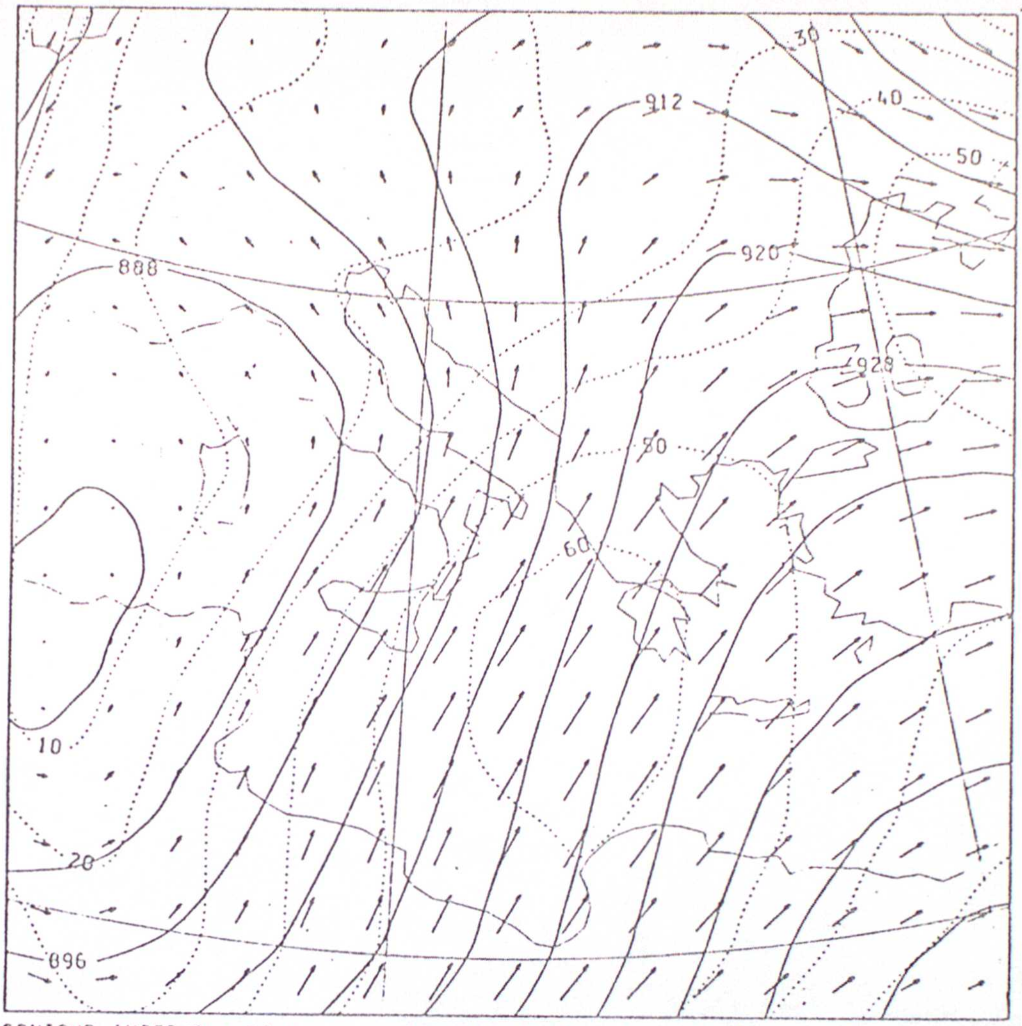
300MB HEIGHT(DAM) & WIND(M/S) 00GMT 17FEB 1979



CONTOUR INTERVAL: 80 M —→ REPRESENTS 50 M/S CONTOUR INTERVAL: 10 M/S

Fig 2.

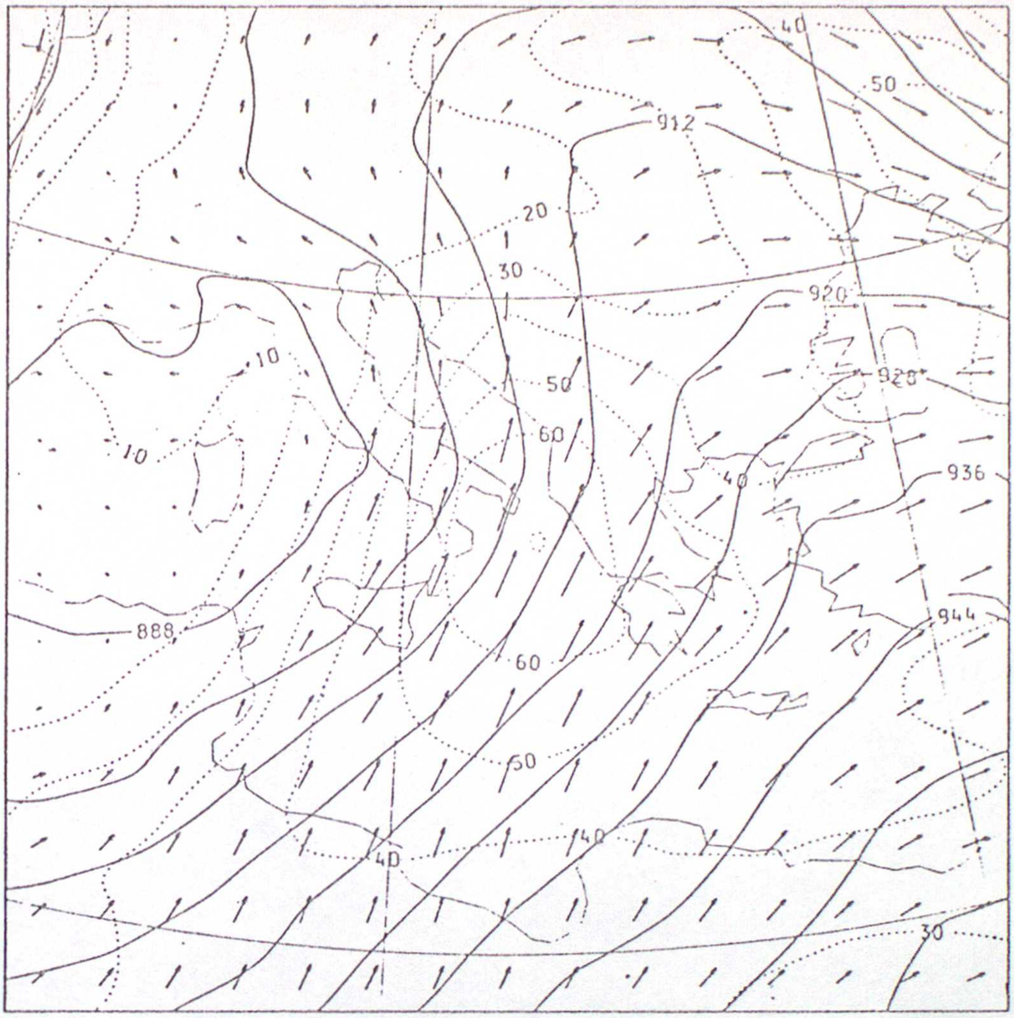
US: USNMC IIIB ANALYSIS
300MB HEIGHT(DAM) & WIND(M/S) 00GMT 17FEB 1979



CONTOUR INTERVAL: 80 M ⟶ REPRESENTS 50 M/S CONTOUR INTERVAL: 10 M/S

Fig 3.

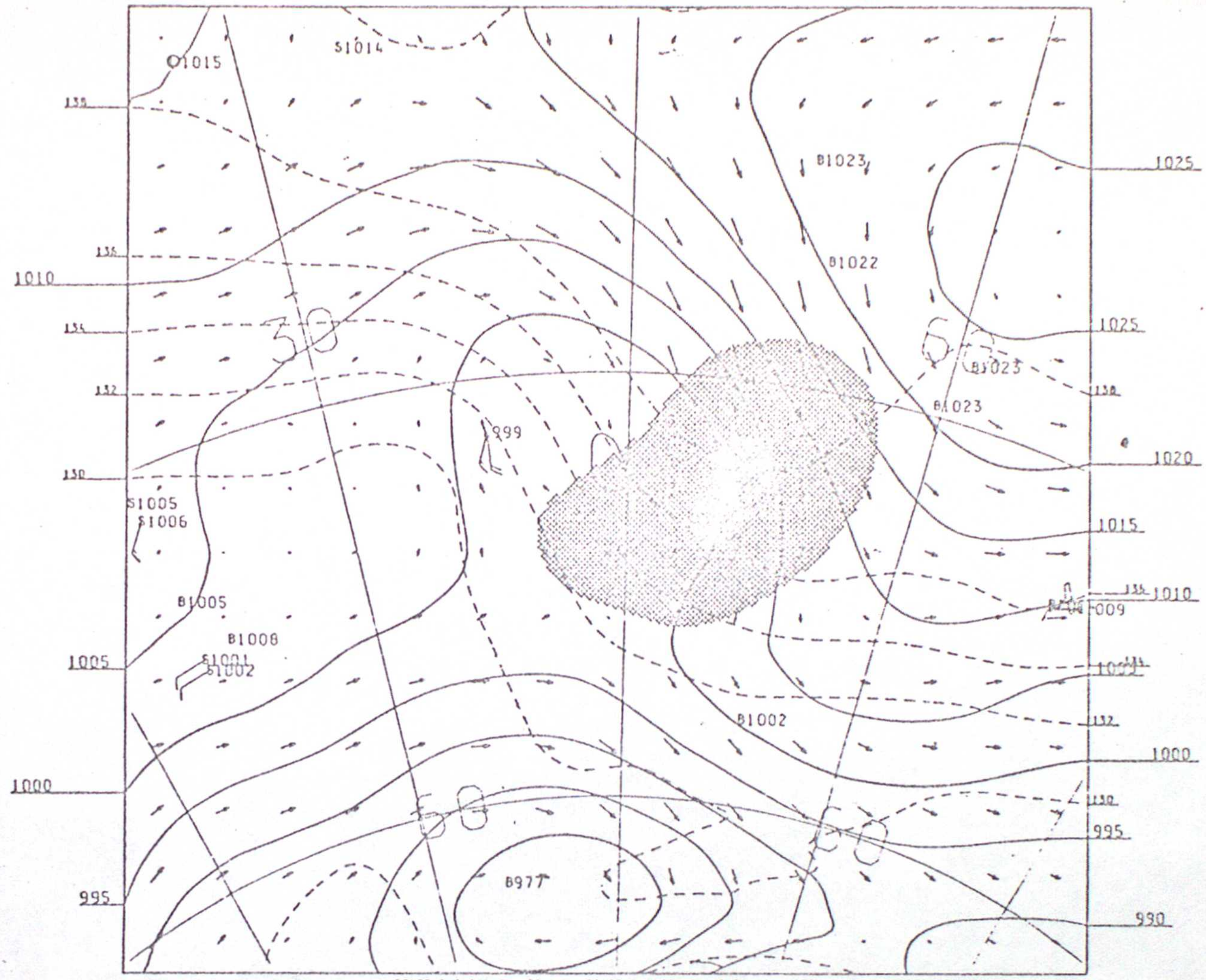
UK: UKMO IIIB ANALYSIS
300MB HEIGHT(DAM) & WIND(M/S) 00GMT 17FEB 1979



CONTOUR INTERVAL: 80 M —→ REPRESENTS 50 M/S CONTOUR INTERVAL: 10 M/S

Fig 4.

EC: SEA-LEVEL PRESSURE. 1000-850MB THICKNESS. 700MB OMEGA. 1000MB WIND.
SOLID LINES DASHED LINES UP SHADED ARROWS



CONTOUR INTERVAL: 5 MB CONTOUR INTERVAL: 20 M CONTOUR INTERVAL: 0.2 MKS UNITS → REPRESENTS 25 M/S

Fig 5

US: SEA-LEVEL PRESSURE. 1000-850MB THICKNESS. 700MB OMEGA. 1000MB WIND.
SOLID LINES DASHED LINES UP SHADED ARROWS

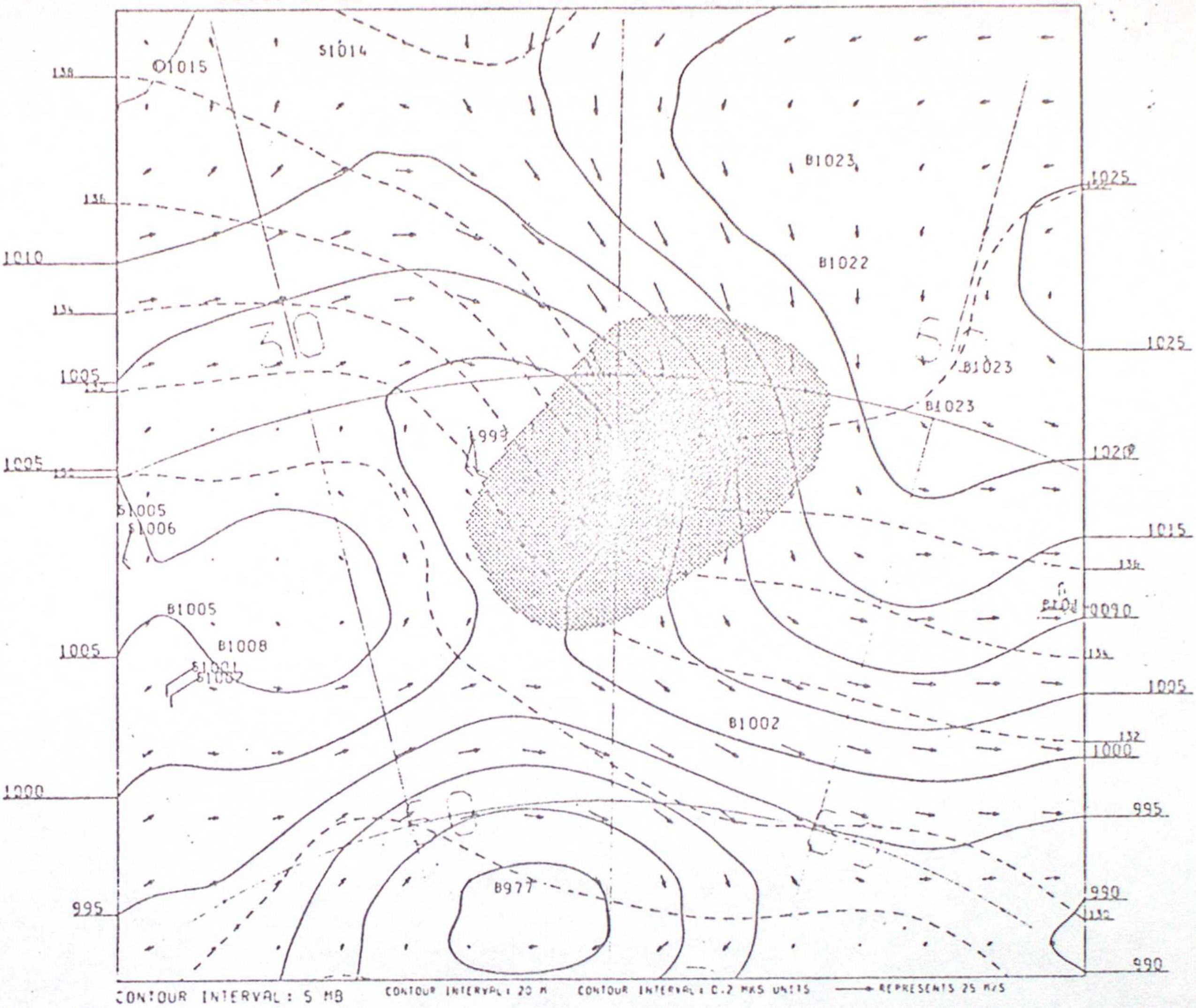
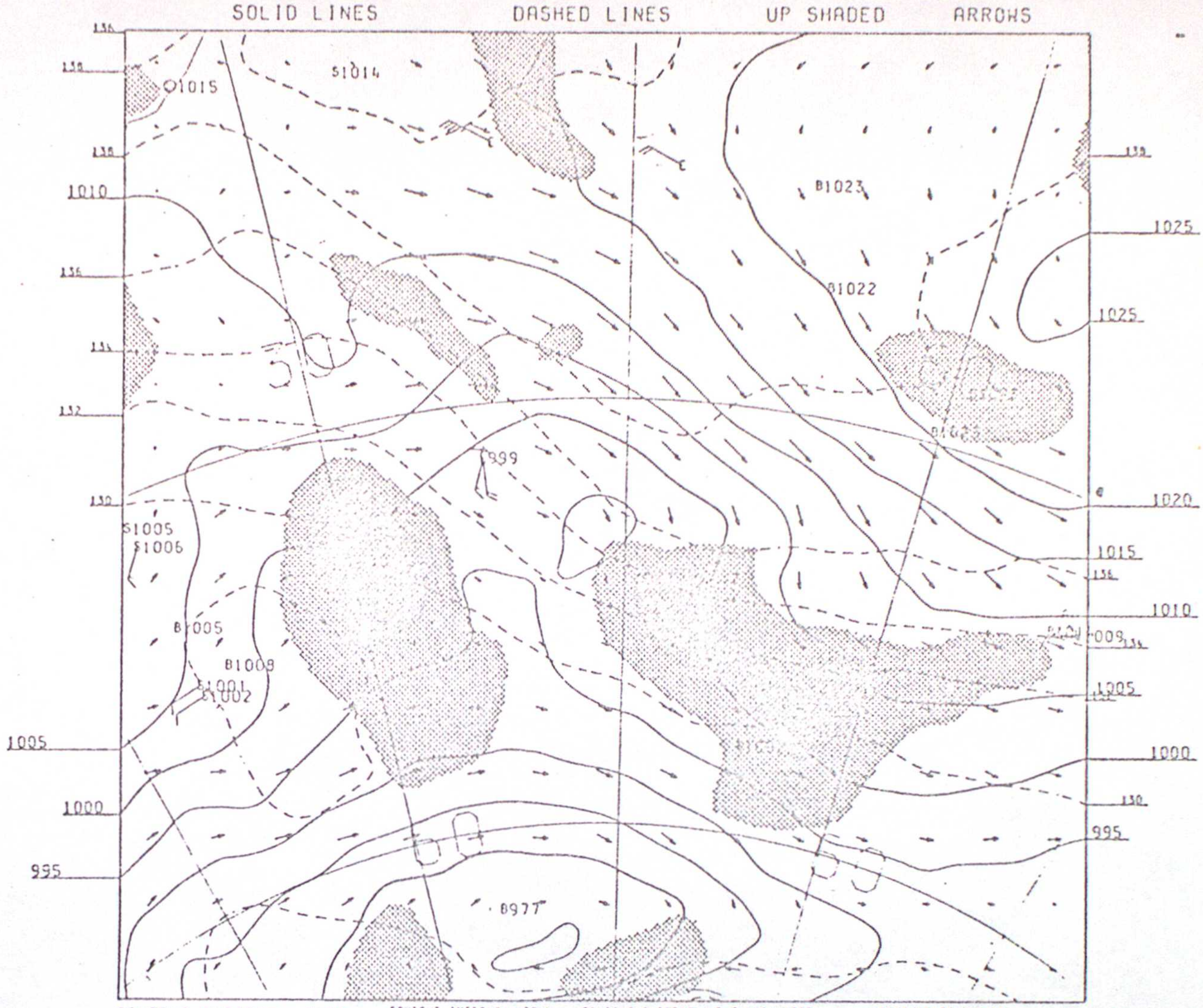


Fig 6

UK: SEA-LEVEL PRESSURE. 1000-850MB THICKNESS. 700MB OMEGA. 1000MB WIND.
SOLID LINES DASHED LINES UP SHADED ARROWS



CONTOUR INTERVAL: 5 MB CONTOUR INTERVAL: 20 M CONTOUR INTERVAL: 0.2 MKS UNITS → REPRESENTS 25 M/S

Fig 7

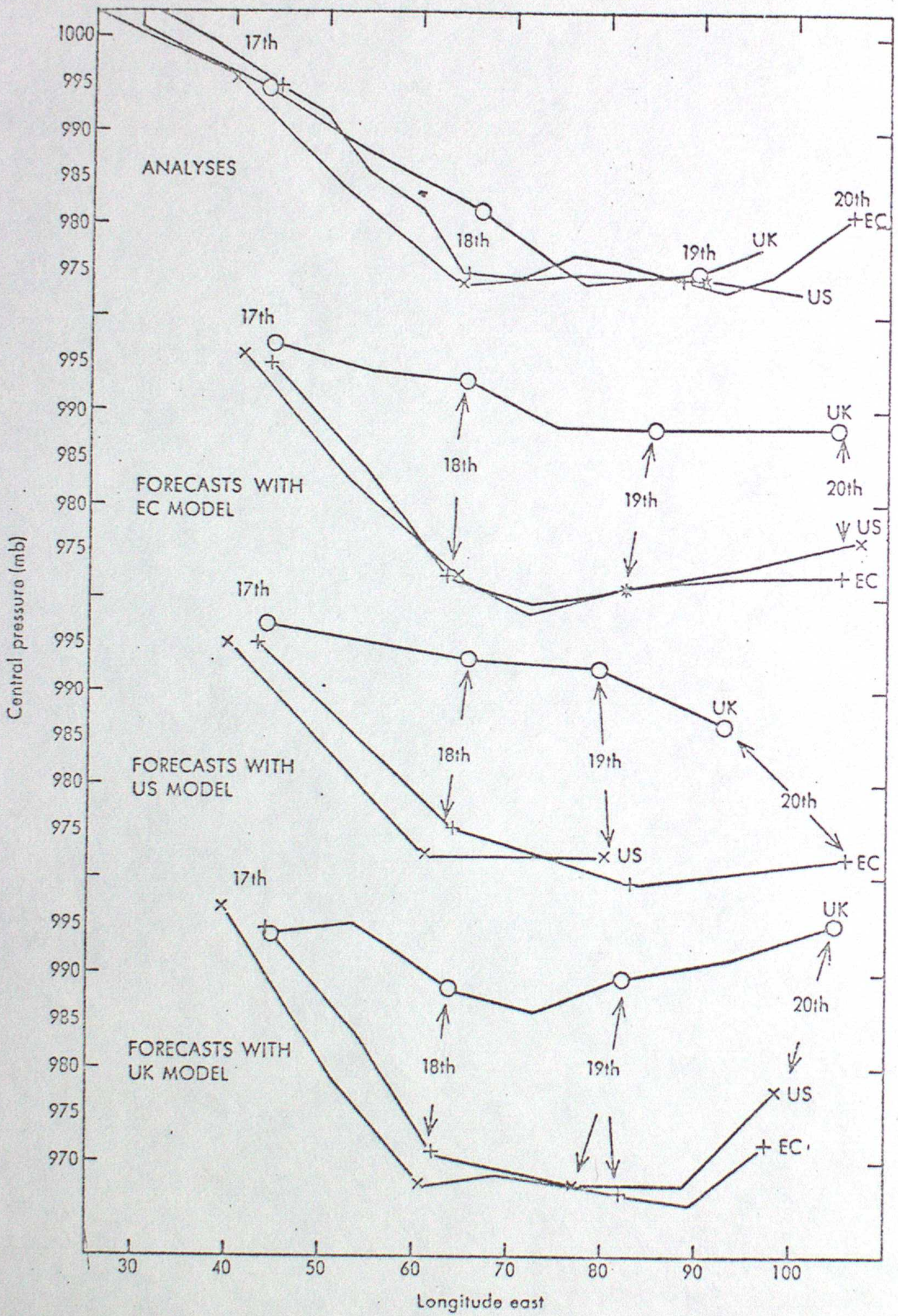
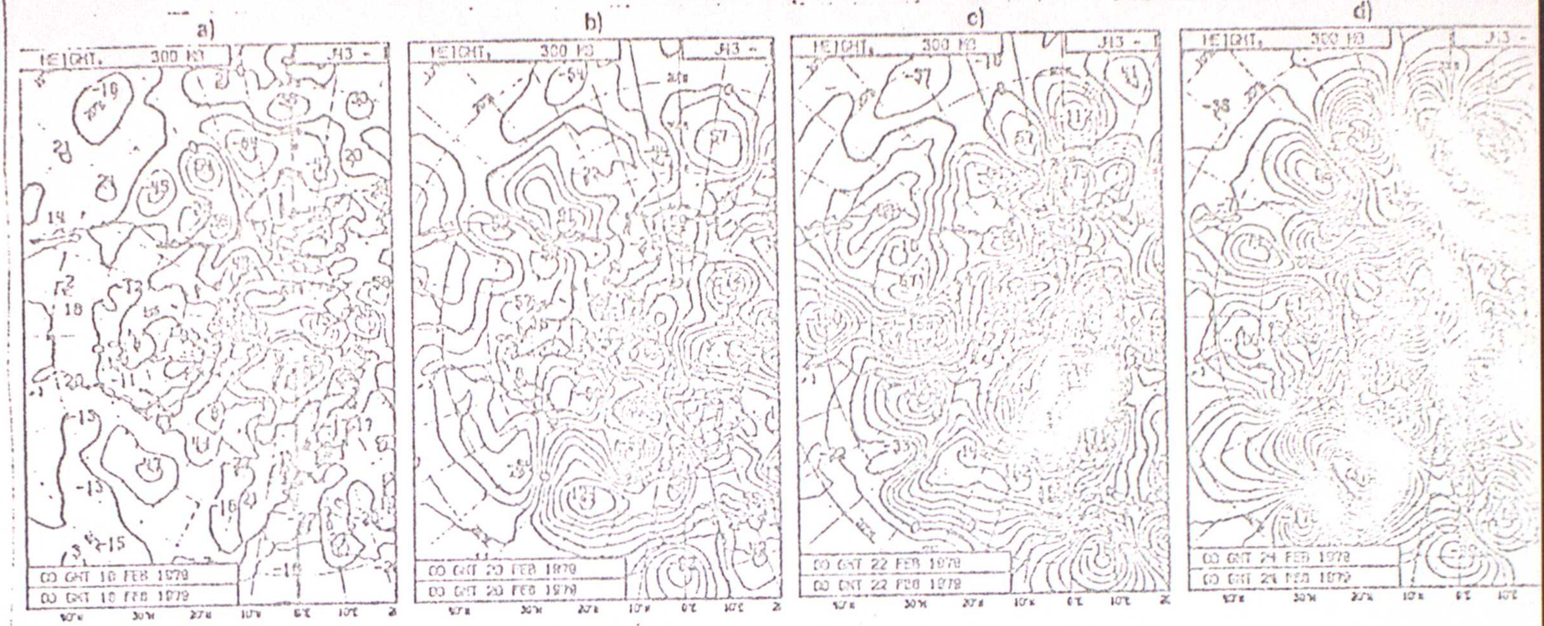
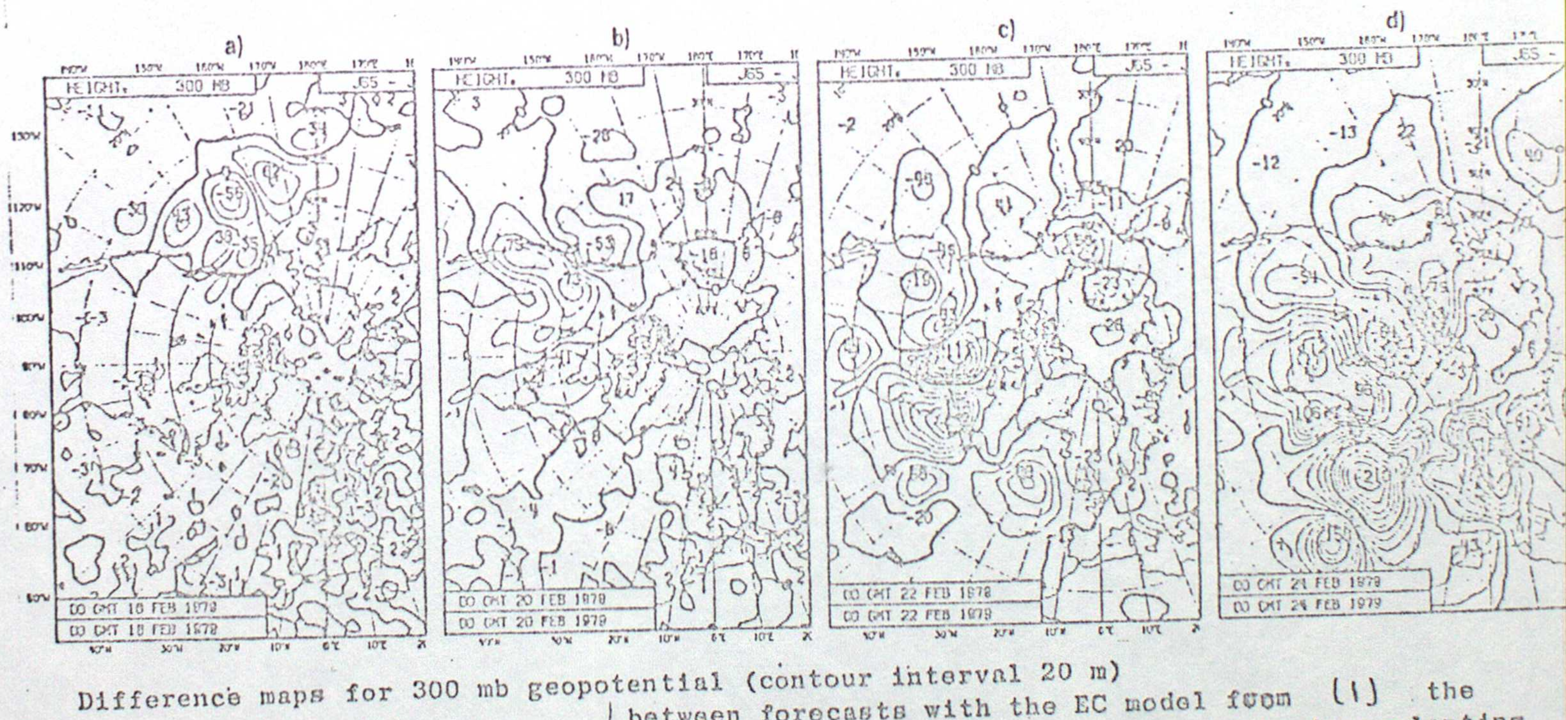


Fig 8. The evolution with time of the central pressure and longitude of the depression of example 2.

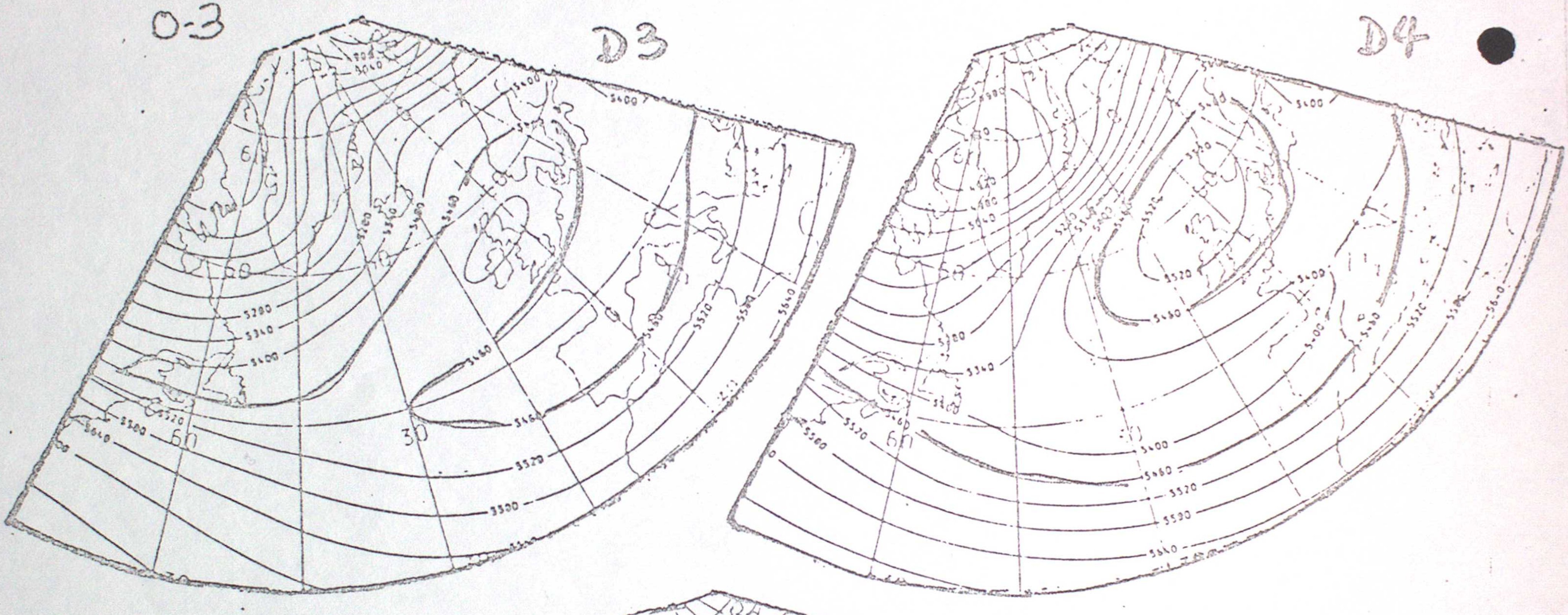


Difference maps for 300 mb geopotential. (contour interval 20 m) between forecasts with the EC model from the EC and US analyses valid at 00Z February 18, 1979. The difference fields are shown for the initial data a), and day 2 b), day 4 c), and day 6 d). These are referred to in the text as the control differences.



Difference maps for 300 mb geopotential (contour interval 20 m) between forecasts with the EC model from (1) the EC analysis valid at 00Z February 18, 1979, and (2) the data set formed by transplanting the US analysis over the North East Pacific into the EC analysis.

Fig 9.



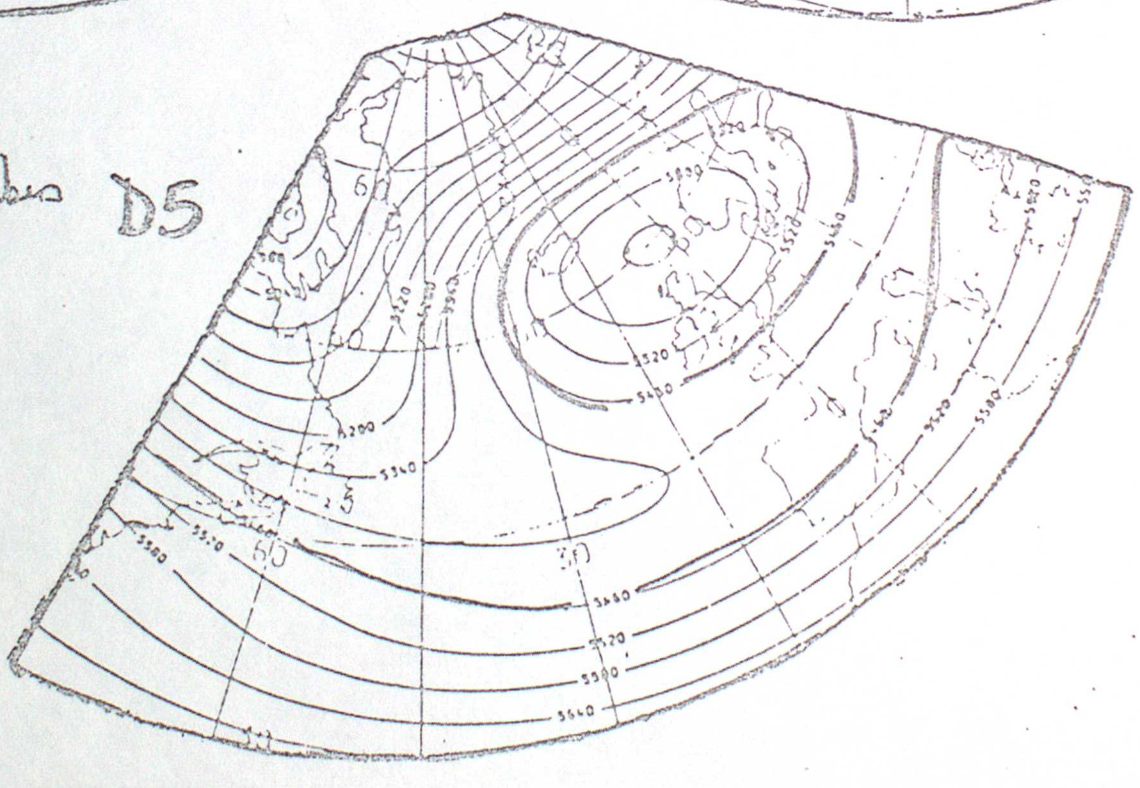
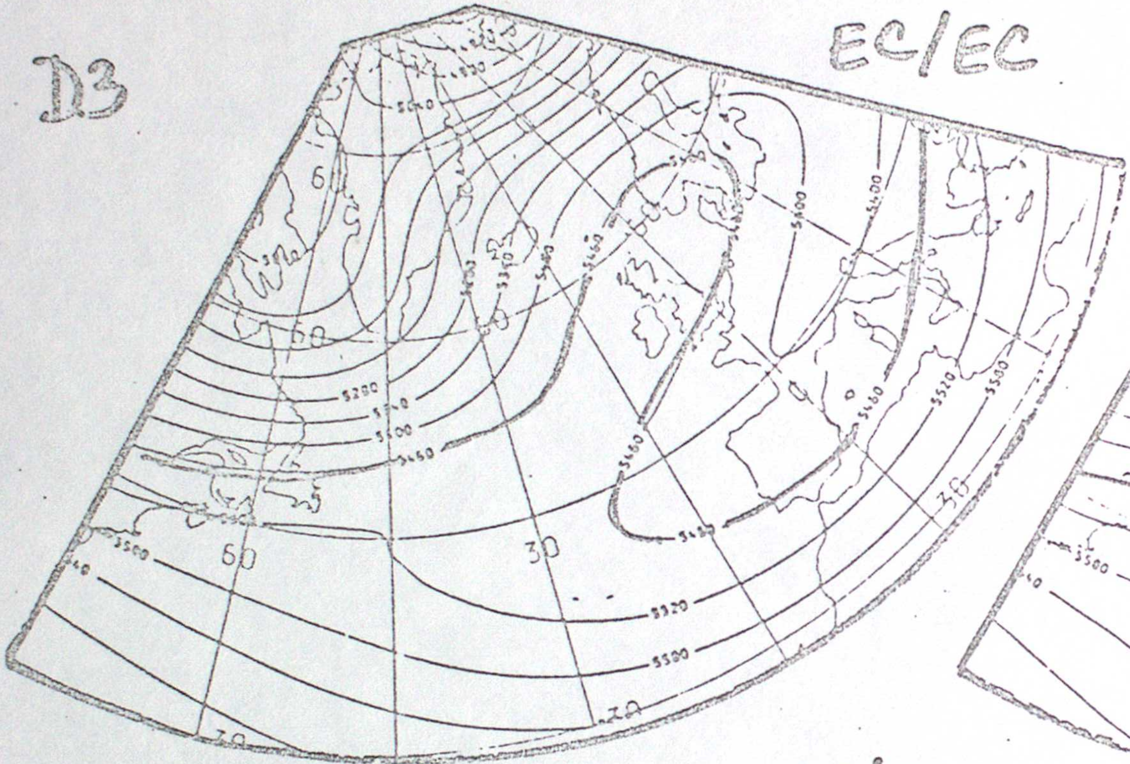


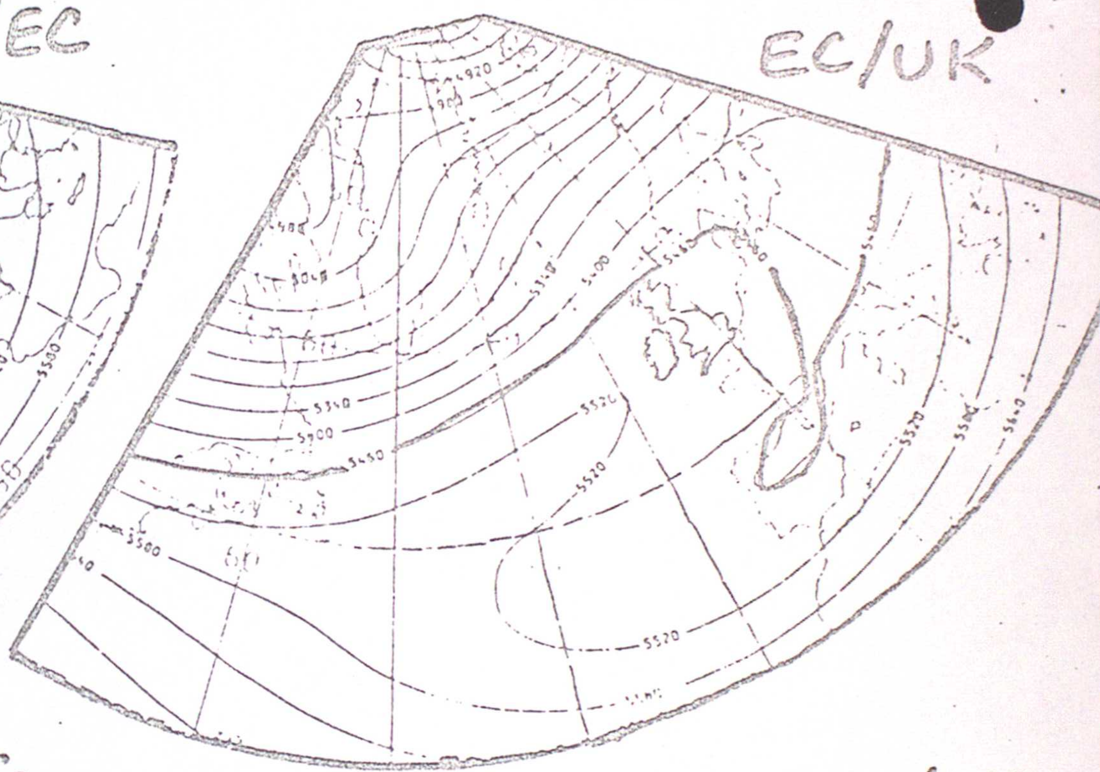
Fig 10. Zonal wave numbers 0-3 of the analyses for 13, 14, 15 Feb 1983.

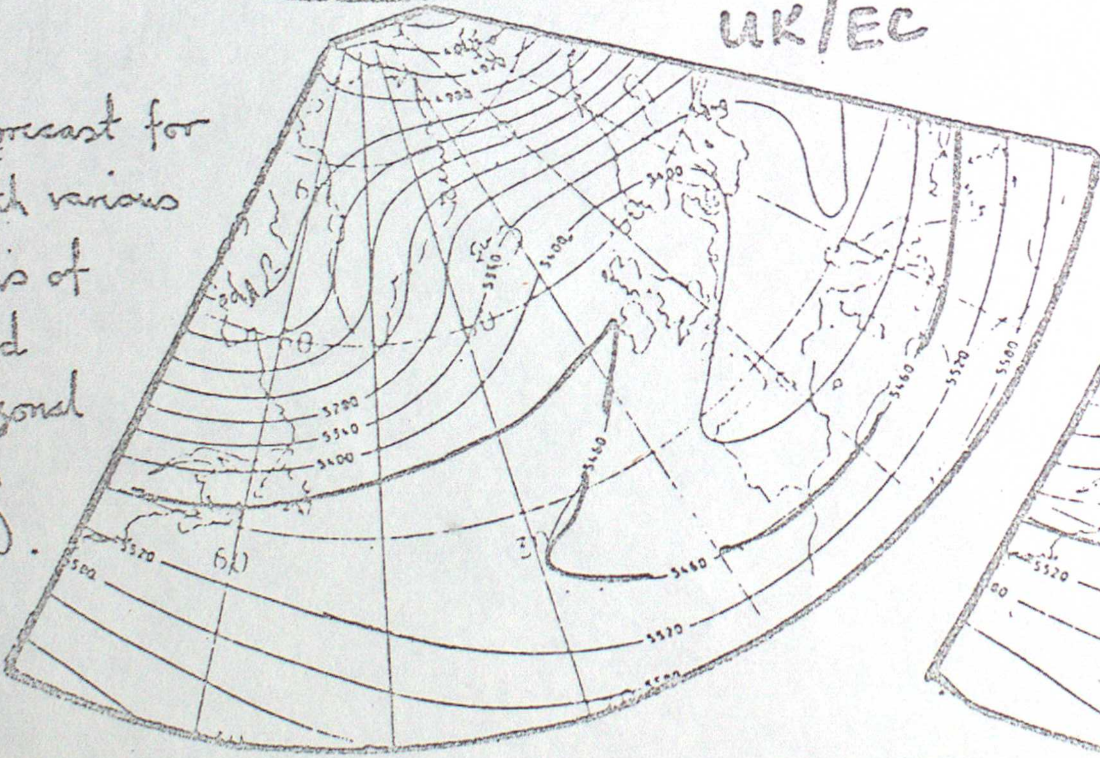
500 mb Analysis

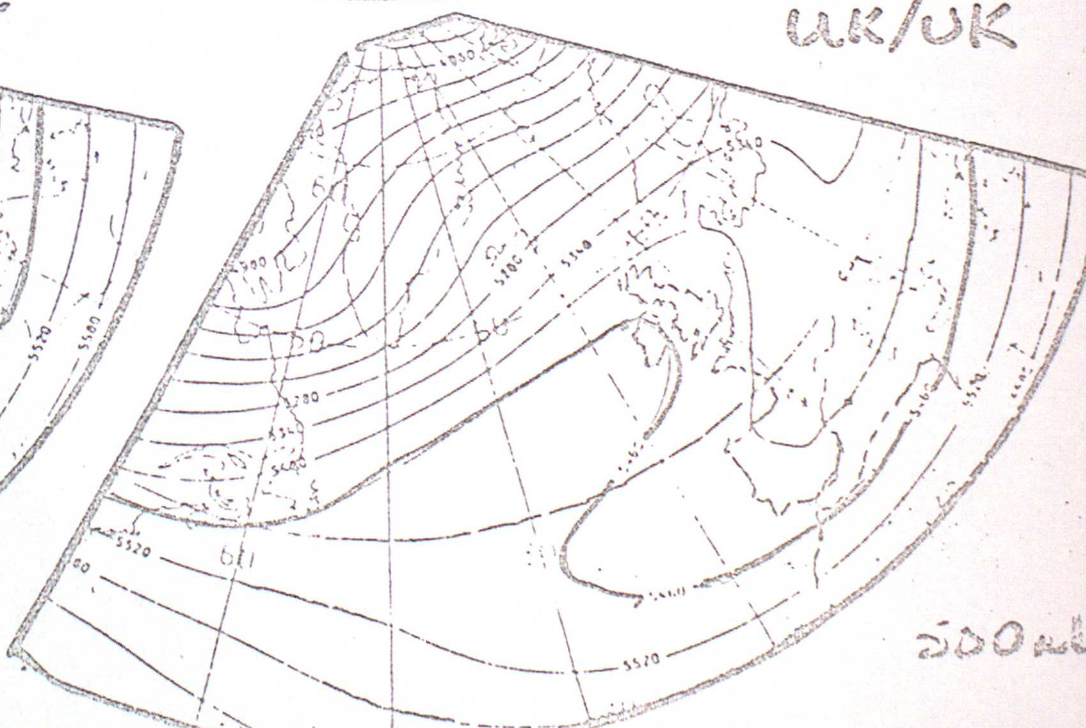
D3

0-3









500 mb

Fig 11. Forecast for day 3 with various combinations of analysis and model. (zonal wavenumbers 0-3 only).

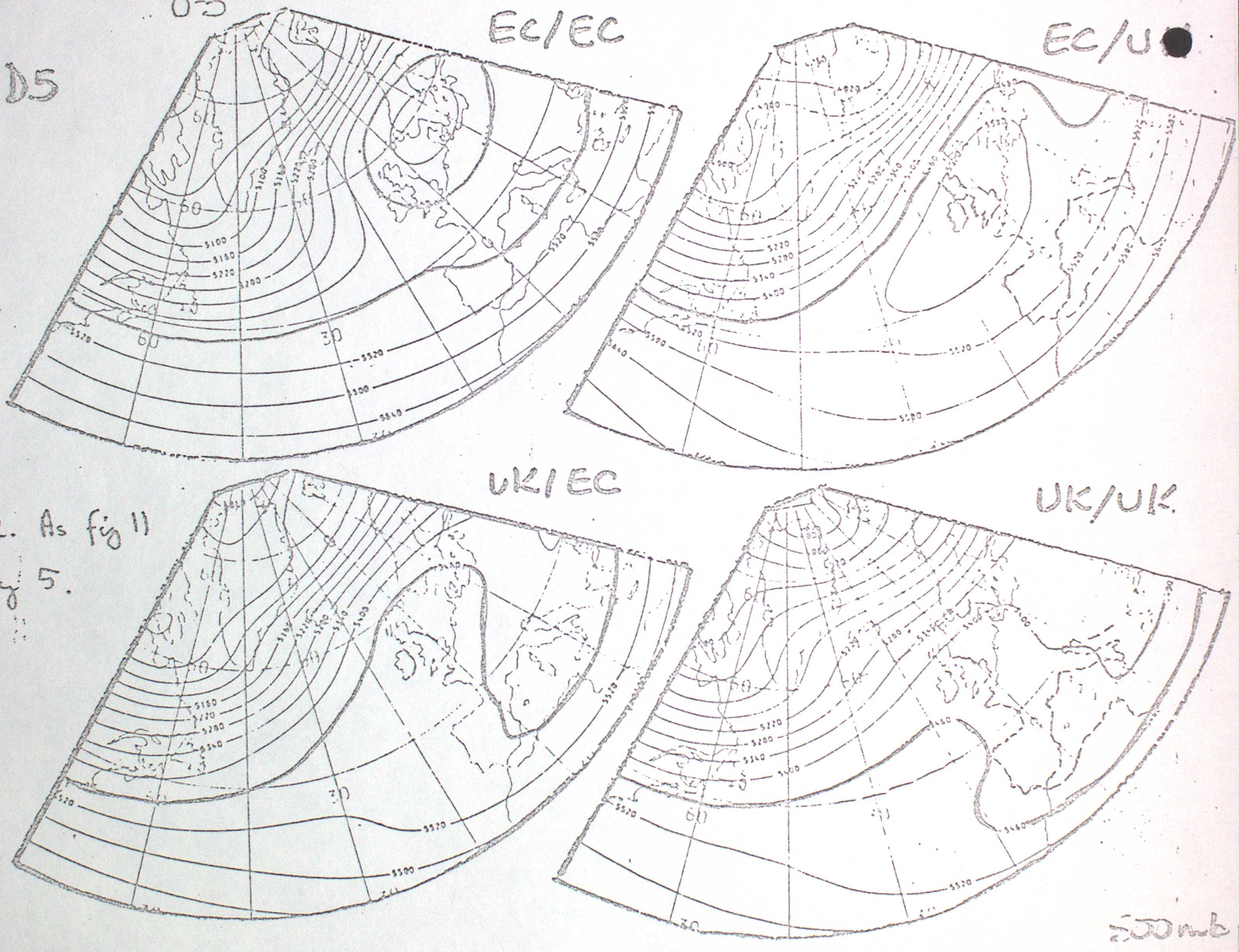
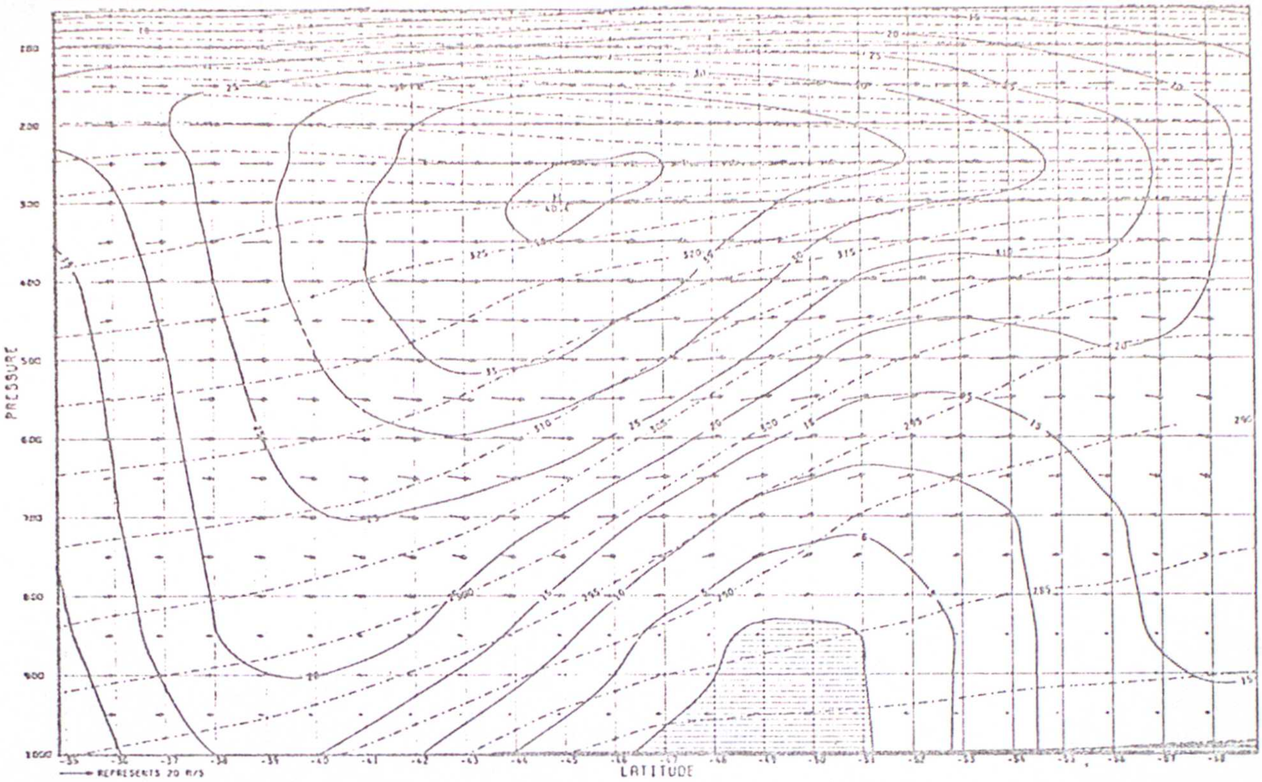


Fig 12. As fig 11 for day 5.

ECMWF FGGE IIIB ANALYSIS.
N-S X-SECTION. U=SOLID CONTOURS -VE SHADED. V&W=ARROWS. POT.TEMP=PECKED CONTOURS
VALID AT 0Z ON 17/2/79 DAY 48
LONGITUDE: 38.



ECMWF FGGE IIIB ANALYSIS.
N-S X-SECTION. RELATIVE HUMIDITY=SOLID CONTOURS. TEMPERATURE=PECKED CONTOURS.
VALID AT 0Z ON 17/2/79 DAY 48
LONGITUDE: 38.

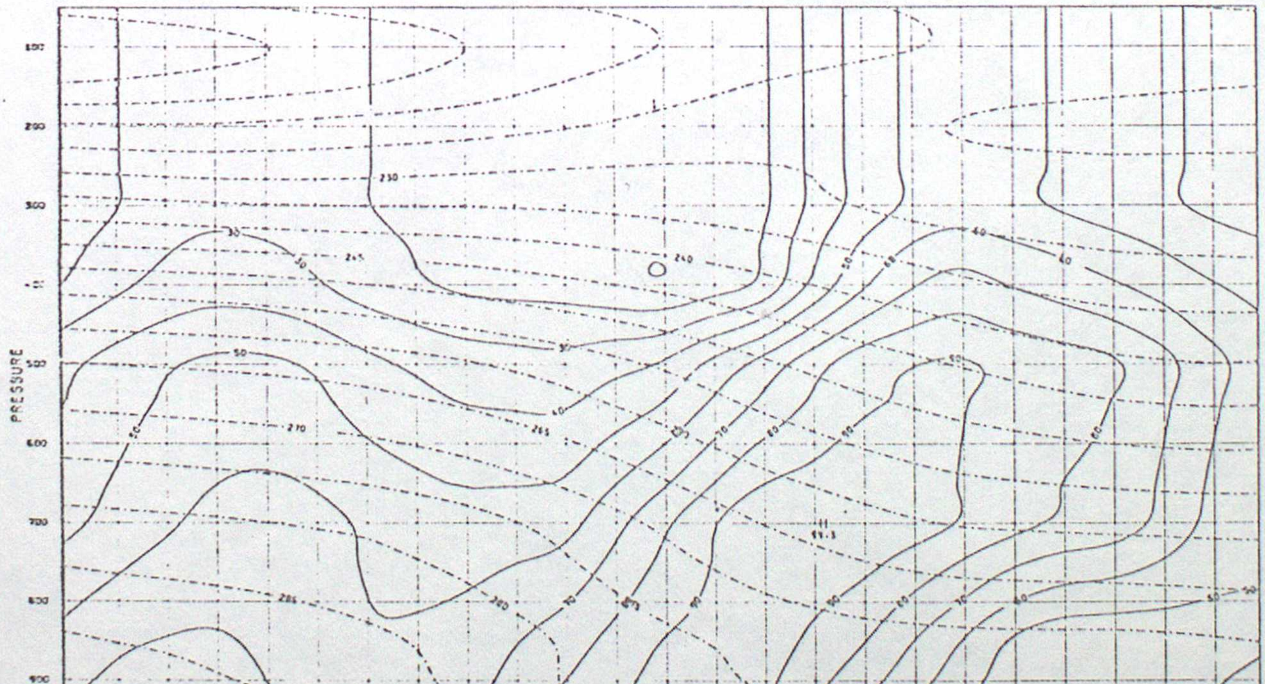
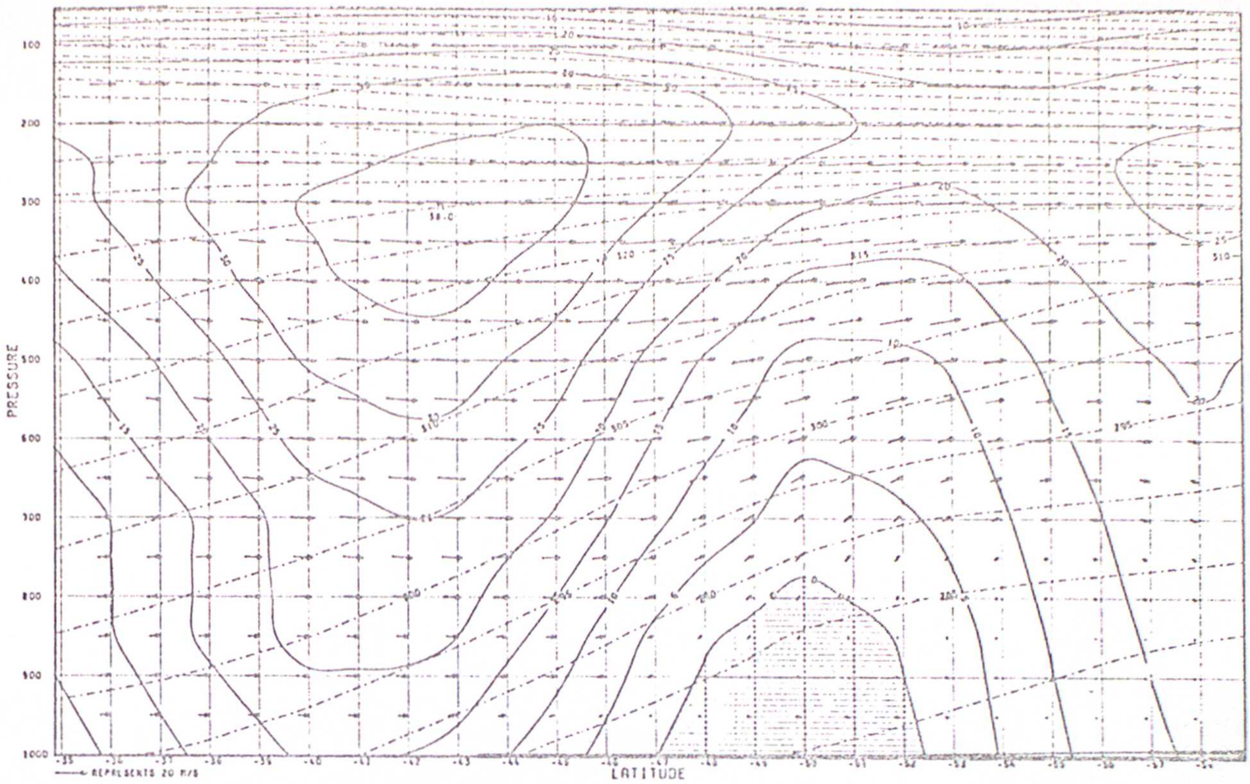


Fig 13. North-South cross-section through fig 5

USNMC FGGE IIIB ANALYSIS.
N-S X-SECTION. U=SOLID CONTOURS -VE SHADED. V&W=ARROWS. POT.TEMP=PECKED CONTOURS
VALID AT 0Z ON 17/2/79 DAY 48
LONGITUDE: 38.



USNMC FGGE IIIB ANALYSIS.
N-S X-SECTION. RELATIVE HUMIDITY=SOLID CONTOURS. TEMPERATURE=PECKED CONTOURS.
VALID AT 0Z ON 17/2/79 DAY 48
LONGITUDE: 38.

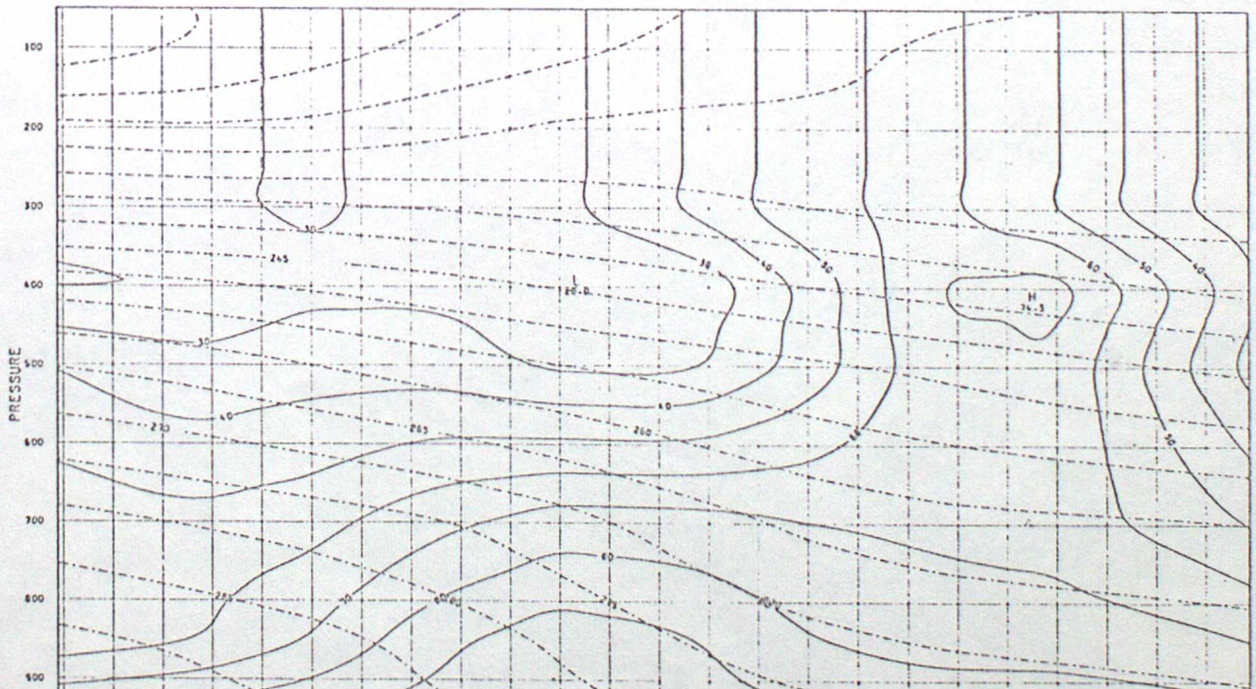
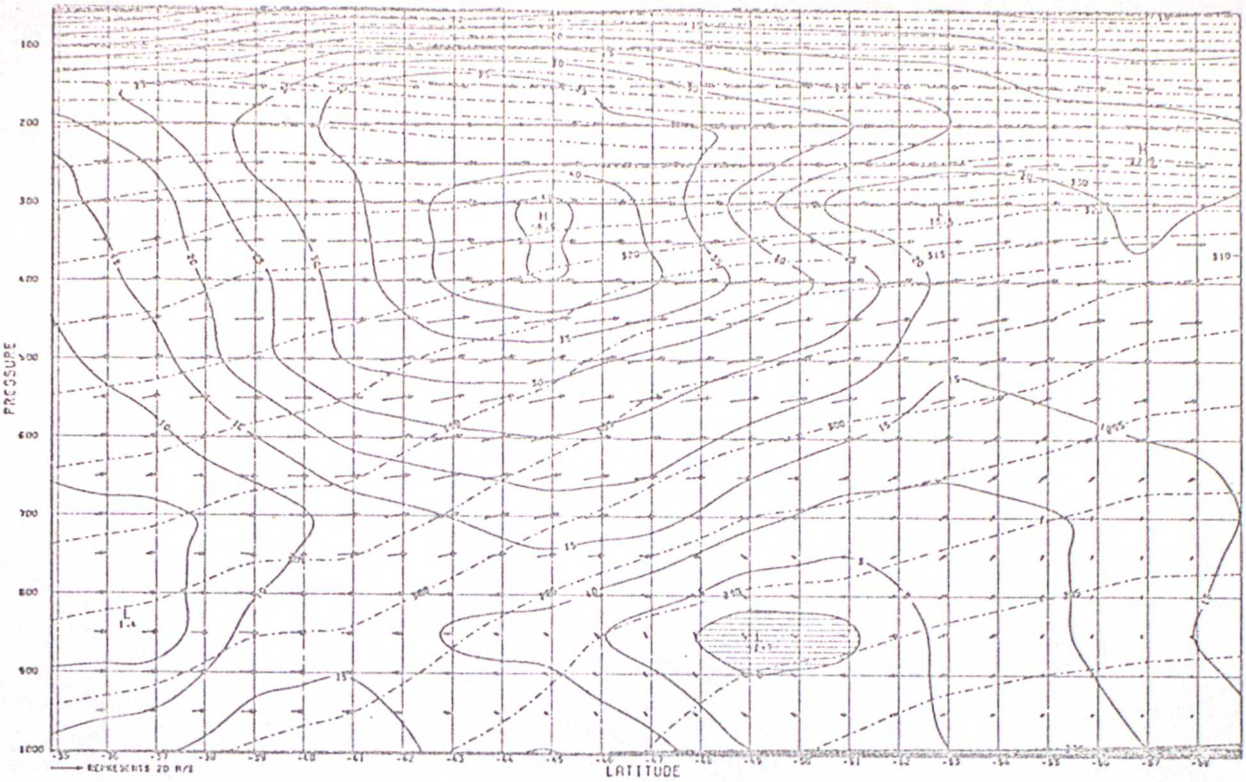


Fig 14. North-South cross-section through fig 6.

UKMO FGGE IIIB ANALYSIS.
N-S X-SECTION. U=SOLID CONTOURS -VE SHADED. V&W=ARROWS. POT.TEMP=PECKED CONTOURS
VALID AT 0Z ON 17/2/79 DAY 48
LONGITUDE: 38. EXPERIMENT NO.: 208



UKMO FGGE IIIB ANALYSIS.
N-S X-SECTION. RELATIVE HUMIDITY=SOLID CONTOURS. TEMPERATURE=PECKED CONTOURS.
VALID AT 0Z ON 17/2/79 DAY 48
LONGITUDE: 38. EXPERIMENT NO.: 208

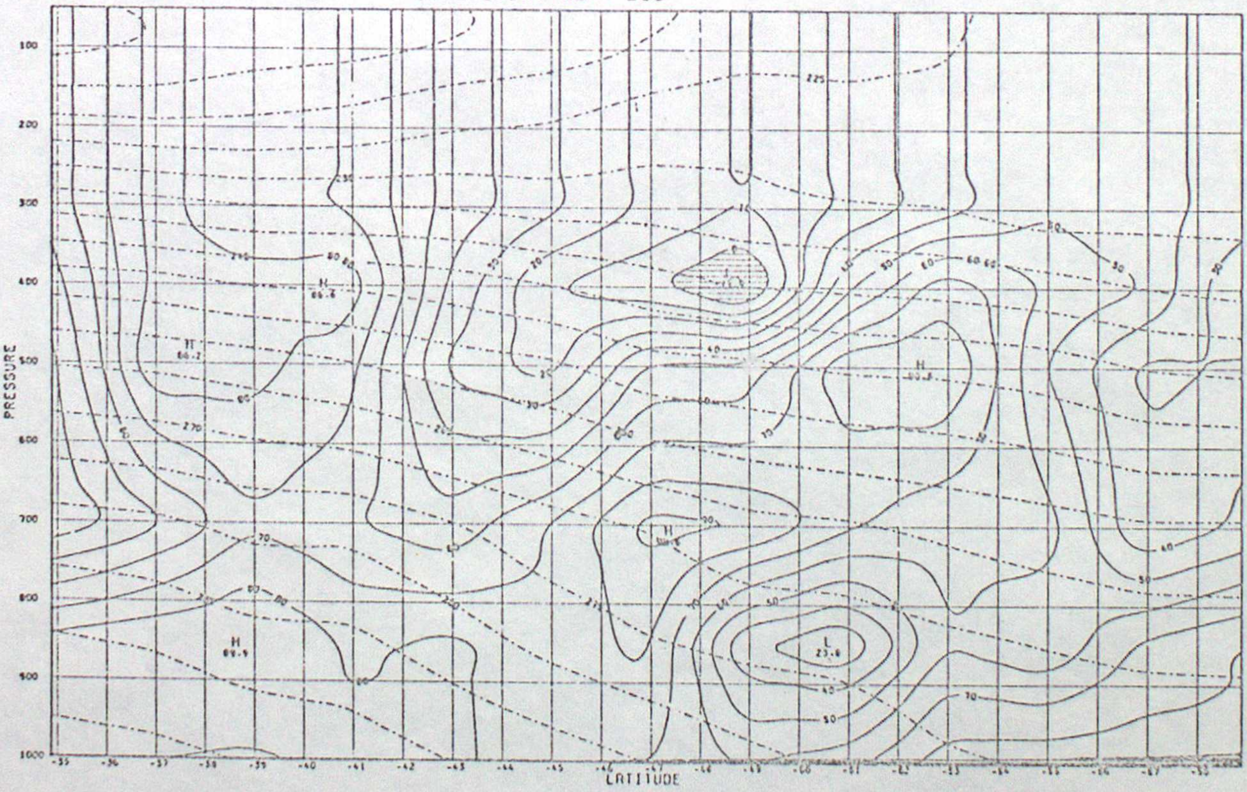


Fig 15. North-South cross-section through fig 7.