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ON THE IMPORTANCE OF PARAMETERIZED PROCESSES IN THE 10-LEVEL MODEL

by

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ABSTRACT

A number of versions of the quasi-hemispheric 10-level model, in which the parameterized processes have been successively removed, have been run on a sample data set, with the object of assessing the hypothesis that long wave errors are due to inadequate formulations of the effect of topography and of other parameterized processes.

It is found that the large scale dynamics of the model are but little altered by the parameterized processes, and that such changes as were seen can be largely ascribed to the effect of topography. It is concluded that it is unlikely that long-wave errors can be ascribed to the various parameterizations included in the model.

1. INTRODUCTION

Previous studies (James 1975), involving the statistical analysis of over 300 operational forecasts by the quasi-hemispheric version of the 10-level model, have shown that there are anomalously large errors associated with the forecasts of the largest scales of motion, particularly for wave numbers 2 and 3. I have discussed elsewhere (James 1976) some of the hypotheses regarding the source of these errors. This paper is devoted to an investigation of one of the more obvious hypotheses regarding the long wave errors, namely, that it can be ascribed to inadequacies in the formulation of the effects of topography and of surface exchanges of heat and moisture. It has long been assumed that by forcing ascent in the zonal flow, these mechanisms are largely responsible for generating the largest scale planetary waves.

In James (1976) I disputed the likelihood of the "forcing hypothesis" on two counts. First, it seemed unlikely to me that they could affect some of the massive (and erroneous) energy transfers on the very short time scales (less than 2-3 days) which were frequently observed in the model. Secondly, it has become increasingly apparent that an important source of energy in the large scales is the non-linear interaction between smaller scales. In a barotropic fluid, this result is known as Fjortoft's theorem. It may be generalized to the case of a baroclinic fluid under a wide range of conditions. In particular, Hide, Mason and Plumb (1976) describe a "side band instability" whereby the interactions between baroclinic waves of similar wavenumber can force long waves. Mechanisms such as these can, if the system is sufficiently non-linear, effect major changes on rather short time scales, and so may lie at the heart of the long wave error problem.

Nonetheless, this view is controversial, and it is widely assumed that the long wave errors must be due to the topographic and surface flux formulations. This paper describes a series of experiments whereby the influence of the representation of topography and physical processes in the model has been studied . The experiments take the form of a detailed case study of the six-day forecast on data for 12Z, 18 January 1976. This was chosen at random from the dates available, but in fact is of some local significance. During the period of the forecast, a strong mid-Atlantic ridge developed, bringing northerly winds and cold, wintry weather to the

United Kingdom. This development was entirely missed from the operational model. At the time, some suggestions were passed to the effect that the ridge may have formed as a downstream effect of the Rocky Mountains.

Two points must be emphasized. Firstly, this is a case study, and is intended merely to indicate the relative importance of some of the parameterized processes included in the model. To establish firm causal relationships would require many more examples to be considered. Secondly, my assessment will be concerned with the effect of various processes on the largest scale dynamics. I shall not consider many predictions of great importance to local, short range forecasting, which often depend crucially on the parameterized processes (eg rainfall, development of small synoptic systems, etc).

The experiments which have been undertaken are described in Section 2. The results are presented in Sections 3, 4 and 5 and are discussed in Section 6.

2. THE EXPERIMENTS

All the runs described in this paper were carried out using the semi-implicit formulation of the quasi-hemispheric version of the 10-level model, described by Burridge (1975). The arrangement of grid points is shown in Fig. 1. The grid length is 300 km at 60°N, the northern hemisphere being projected onto a polar stereographic map, with an octagonal southern boundary close to 17°N. In the vertical, pressure co-ordinates are employed, the ten levels being spaced at 100 mb intervals from 1000 mb to 100 mb.

The lower boundary condition is:

$$W_{1000} = \underset{\sim}{U}_{1000} \cdot \underset{\sim}{\nabla} H$$

where W_{1000} and U_{1000} refer to the vertical and horizontal velocities respectively at 1000 mb. H is the topography height. The invariable application of this condition at 1000 mb may lead to significant errors near high topography, where the 1000 mb variables are fictitious. On the Tibetan plateau, for example, the topography reaches to pressures of less than 600 mb, while the Rocky Mountains and the Greenland plateau are also very significant features. Over lower topography, where the actual surface is not far from the 1000 mb level, the conceptual difficulties of the pressure co-ordinate formulation are not so severe.

The topography itself is based on the mean height within each 300 km grid square, which is then smoothed considerably. Such a process causes a particularly marked attenuation of narrow, linear mountain chains, such as the Rocky Mountains of North America.

The remaining parameterized processes include surface fluxes of heat and moisture, and the release of latent heat by evaporation. I consider all these processes together for the purposes of this paper. The details of their formulation are complex, and are described by Gadd and Burridge (1975).

In each of the experiments to be described, the model was run to 6 days, and diagnostic information was acquired at 1 day intervals. This information consisted of:

(1) Analysis of amplitude and position of the large scale atmospheric waves on the 500 mb geopotential surfaces at $50^{o}N$. If $h_5(\lambda)$ represents this quantity as it varies with longitude λ, then the Fourier analysis calculates the coefficients in the series:

$$h_5(\lambda) = a_0 + \sum_{m=1}^{\infty} a_m \cos(m\lambda + \phi_m)$$

where a_m and ϕ_m are the amplitude and phase respectively of the wave with wavenumber m. Details of the analysis procedure are given by James (1975).

(2) Root mean square deviations of the 500 mb geopotential height field from the verifying analysis. RMS errors form but a very crude assessment of the success of a forecast, but are nonetheless easily obtained, and do yield useful information if taken in conjunction with the other diagnostics.

(3) Geopotential height charts at 100 mb, 300 mb and 500 mb and the surface pressure charts. Surface pressure is not a variable in the model, but is estimated from the 1000 mb height and the 950 mb thickness (that is, the temperature of the lowest layer).

In the following discussion, I shall place more weight on items (1) and (2) above, as forming a more objective analysis of the fields than is possible from a visual examination of the charts themselves. The human eye invariably picks out small scale differences between two charts and is unable to see the larger scale similarities. Furthermore, the eye places greatest weight on the pattern of particular contours, patterns which are difficult to define objectively and which may be of rather slight dynamic consequence.

In addition to the verifying sequence of data, which will be referred to as sequence V, data sequences for five experiments have been obtained. They may be grouped as follows:

(1) Sequences A and D are taken from the control experiments. Experiment A was simply the 6 day run of the normal full operational model. At the other extreme, sequence D is a run in which all parameterized processes are suppressed, except for a constant surface drag, and internal diffusion near the boundaries. This latter is simply a device to ensure numerical stability.

(2) Sequence B retains all non-dynamic processes included in the operational model, including surface fluxes of heat and moisture (which implies a land/sea distribution), and latent heat release, but has all topography removed.

(3) Sequences C and E both retain topography but omit all other parameterized processes. Topography is included in the model in two ways; firstly, it provides uplift at the 1000 mb level, and secondly, surface drag and internal diffusion both have a linear dependence on topography height. Indeed, in the current operational version, there is no internal diffusion over areas at sea-level. The two sequences were intended to distinguish between these two effects of the model topography. Sequence C includes all topographic effects while E retains only the effect of uplift at 1000 mb.

The characteristics of the various sequences are summarized in table 1 for reference.

3. THE VERIFICATIONS AND CONTROL EXPERIMENTS

In this section I shall discuss the changes in the real atmosphere during the period 18th to 24th January 1976, as revealed by the verifying analyses, and then consider the crudest experiment in this series - that is, I shall describe the effect on the operational run of removing both topography and all parameterized processes.

Since I am primarily concerned with the dynamics of the largest scale waves, I first consider the wave-data, obtained by Fourier analysis of the 500 mb height field at 50°N. Fig (2) shows the variation of amplitude for m = 1–4. All these waves were more or less fixed in position during the duration of the experiment. Wavenumbers 1 and 2 lost amplitude, wavenumber 3 gained amplitude, while wavenumber 4 varied rather widely about a constant amplitude. The operational forecast (sequence A) was generally reasonably good up to 2–3 days. Wavenumbers 1 and 2 remain acceptable up to 4–5 days, but serious errors subsequently appear in the forecasts for wavenumbers 3 and 4.

The effect of removing the topography and physical processes is remarkably slight. In particular, there is no evidence that such processes are responsible for locking features to the earth's surface on a timescale of up to 6 days. Indeed for part of the forecast at least, wavenumbers 3 and 4 are actually steadier in Sequence D than in Sequence A, and show as good an agreement with the verifying series. It might be argued that amplitude fluctuations are rather larger on the D run. The amplitude of wavenumber 2 has evidently been affected very adversely by removal of parameterized processes and topography though it is noteworthy that the phases are little changed. Large errors are also noted for the amplitude of wavenumber 4, but as there are large errors in both the A and D sequence amplitudes for this case, it is of less interest. The abrupt variation of amplitude in the V series for this wavenumber suggests that there may be a larger data error than at other scales.

Some measure of the similarity of the 500 mb geopotential height fields is provided by the root mean square deviations from the verifying field. The results are shown in fig (3), where the r.m.s. errors are plotted against time. The curves in fig (3a) relate to a square of 20x20 gridpoints centred on Europe. As it lies in the track of the main baroclinic disturbances, the fields have a large variation and the errors tend to be large. Fig (3b) is based on the whole octagon, and contains a large contribution from the flat fields in subtropical regions. The error is less because the fields have less variability, but since the subtropical regions are affected by boundary effects and are unreliably analysed, this curve is of less interest.

The curve marked p in both diagrams provides a standard for assessing the seriousness of the rms errors. It denotes the errors arising from a persistence forecast. It will be noted that the forecast curves cross the persistence curve at 4 days (for the European area) or 3 days (for the whole area of integration). Removing parameterized processes and topography does not significantly alter this predictability time. Indeed, for the European area, the D sequence is slightly less in error than is the A sequence by 6 days.

In examining the waveplots I selected only certain scales of motion; similarly the rms errors are dominated by those scales whose amplitude is large, which in practice are the atmospheric waves up to wavenumber 10 or so. In examining the charts themselves it must be borne in mind that the human eye will tend to concentrate upon certain small scale features at the expense of the larger scale features of comparable amplitude. Small scale features in the forecast can be considerably modified by very small changes to any aspect of the forecasting system, and in any case are not within the terms of reference for this particular investigation. Nonetheless, for the sake of completeness, figs (4) and (5) show the 500 mb and surface pressure charts respectively for the V, A and D sequences at 0, 3 and 6 days.

The analyses show a major trough near the east coast of North America which sharpened and intensified during the period of interest. At day 5 a strong ridge suddenly appeared ahead of the trough in the mid-Atlantic. High pressure built over the North Pole throughout the period.

The mid-Atlantic ridge was not predicted by either the A or the D forecast. The polar high is less well developed in the D sequence than in the A, while the American trough is handled similarly and incorrectly by both models. The trough axis is in the wrong position and is sloping incorrectly - this may be an effect of the lateral boundaries. The main differences between the A & D models lies in the flow in SE Asia where the effect of the Tibetan plateau and the associated topography is felt strongly.

Similar remarks also apply to the surface pressure fields shown in fig (5). In this case there is a considerable increase of surface pressure over much of the area of integration in the D sequence, especially in the sub-tropical regions.

No such effect is to be seen at 500 mb, and so it must be concluded that this is to be interpreted as a drop in temperature of the lower layers (probably the lowest layer) compared to the A-sequence.

4. EXPERIMENTS RETAINING TOPOGRAPHY

I now turn to a consideration of runs C and E, which retain topography but not parameterized processes. These experiments have two aims:-

a. To examine the effect of removing parameterized processes other than topographic effects on the motion and development of the longest waves.

b. To determine whether the uplift at the 1000 mb level or the enhanced diffusion and drag is the more important effect of topography.

In the following presentation of the analysis of sequences C and E I find it convenient to take sequence A (the usual operational forecast) as the control run.

The wave plots for wave numbers 1-4 are shown in Fig.(6). First it is evident that the A, C and E sequences are all very similar, and deviate from the verifications by a similar amount. The most noticeable exception is wavenumber 2 (especially the amplitude plot) whose behaviour is apparently very sensitive to the precise formulation employed. I shall return to this point in section 6.

The differences between sequences C and E are extremely small, and are generally less than the difference between sequence C and A up to day 4 or 5. By the end of the forecast the initially small errors have amplified considerably, as might be expected, and so there are then exceptions to the rule.

The differences between sequence A and C are slight, compared to those between A and V. While the sequence C is generally a poorer forecast than is sequence A, the degradation is small and there is certainly no evidence that the waves in the C sequence are either more mobile or of smaller amplitude. It must therefore be regarded as unlikely that surface exchanges, etc, play any major role in forcing the long waves on a timescale of 6 days.

These results are confirmed by a consideration of the root mean square errors at 500 mb. Their growth in the European area is shown in Fig.(7). It is apparent that sequences C and E are virtually indistinguishable, and that sequences A and C have very similar errors. Both cross the persistance curve at about 4 days.

Fig.(8) shows the actual 500 mb geopotential height fields at 6 days for the sequences V, A, C and E. The C and E fields are very similar, except in the region of the Himalaya and S.E.Asia. Here, note the greater development of the trough at 110°E in the E sequence, and the slight noisiness over the Himalaya itself. Similarly, the C and A sequences show only minor differences. These are mainly over the North Pacific and North Atlantic, where low pressure centres are rather less deep in the sequence A. This presumably reflects the operation of the surface exchange processes in the operational model.

Surface pressure charts will not be presented here in the interests of brevity, but lead to similar conclusions. The C and E sequences are very similar except for the development of an intense vortex pair over the S.E.Himalaya in Sequence E. Both show a rather general raising of pressure compared to the A sequence which must again be attributed to excessive cooling of the lowest layers in the absence of surface exchanges.

5. EXPERIMENTS RETAINING OTHER PARAMETERED PROCESSES

The final experiment is based on run B which included the full range of parameterized processes but for which the topographic height was set to zero. It might be argued that in its present form, the experiment is not well planned, since the surface exchange subroutines make use of a "climatic type" marker, which is defined for each gridpoint. The nature of the topography is one determinant of the climatic type, so that some effects of topography are still indirectly included. However, in view of the close similarity between sequences A and C, I do not consider this effect to be very large. It is evident from the results of section 4 that uplift at 1000 mb provides much the biggest effect of topography on the model

The purpose of this experiment is to determine to what extent the motion and development of long waves in the 10-level model can be attributed to the operation of parameterized processes and latent heat release. As control runs I have taken the operational model (sequence A) and sequence D, which retains only dynamic processes.

The usual plots of waves at 500 mb and 50°N are given in Fig.(9). In general it is seen that sequence B is rather similar to sequence D, the run excluding both parameterized processes and topography. This confirms earlier suggestions that topography is much the most significant effect after those of basic dynamics, and its absence is the most important characteristic of sequence B. Exceptions to this generalization will be noted for wavenumbers 2 and 4, although sequence B still has more in common with sequence D than with any other run.

Similar conclusions are reached on the basis of the r.m.s. errors in the 500 mb height fields. These are given in Fig.(10). Once more, upto day 4 or so, the B and D runs are very similar, and thereafter not widely different. It is interesting to note that run B has the largest r.m.s. errors of any of the sequences discussed in this paper; thus, acting in isolation at least, the parameterized processes are having what is in some senses a deleterious effect on the forecast.

For the sake of completeness, the 500 mb height fields at 6 days are presented in Fig.(11). There are certain similarities between the B and D fields, though the fields are showing some major differences at this stage. The excessive depth of the cold pool over N.E.Canada is interesting in view of the recurrent problems with this type of feature.

6. CONCLUSIONS

It is perhaps timely to re-emphasize the limited objectives I have had before me in presenting the results of this experiment. I have been concerned with the influence of various mechanisms on the overall dynamics of the model, in particular, on the long upper-air waves. I am not concerned with very local synoptic features nor with the production of rainfall or other weather types. Thus when I describe a certain process as being unimportant, I mean that it does not affect the large scale flow. It may nonetheless have an important part to play in enabling a practical forecast to be derived from the model.

As an example of this, I would cite the enhanced drag and diffusion over high topography. The most noticeable effect this had was to suppress the formation of a curious double-vortex feature in the surface pressure field in the region of the Tibetan plateau. It has no significant effect on large scale dynamics, and its main role appears to be that of ensuring that a field which is fictitious in the region of high topography is not marred by unrealistic looking features. This may be defensible but I shall not pursue the matter in this paper.

The most important conclusion to be drawn for these experiments is that the total removal of topography and parameterized processes, while it certainly degraded the forecast in some areas, had remarkable little effect, and certainly did not appear to change the fundamental character of the flow drastically. In particular, the long waves showed very little evidence of either increased mobility or decreased amplitude when these processes were removed. This implies that very little energy was exchanged between the zonal flow and the long waves during the period of the forecast.

If it is assumed that the topography and parameterized processes in the model have at least some qualitative resemblence to the same processes in the real atmosphere, than these experiments imply, not that the current formulations of these processes are so poor as to make no contribution to improving the forecast, but that such processes are not significant in the real atmosphere on the timescale under discussion. Changes in amplitude and position of the long waves must be attributed to basic dynamic processes, to the interactions between different scales of motion and to the propagation of various wave motions in the atmosphere.

In greater detail, it is apparent that of the non-dynamic processes included in the model, the action of topography is very much the most important. Furthermore the effect of topography is dominated by the lower boundary condition. Surface exchanges and moist processes have very little influence on the large scales.

However, the major effects seem to be confined to the neighbourhood of high topography and in other areas (especially, for our purposes, the "European" area of Fig.1) are only rather slight. Some of the most major sources of error (the mishandling of the N American trough, for example) remain similar in all the experiments considered.

The implication for future work is that the long wave errors are unlikely to be improved by further "tuning" of parameterized processes, or by the inclusion of hitherto neglected processes (there are sound arguments indicating that most of these are of less importance than processes already included). While such matters as surface exchanges (especially heating by the sea) and radiative transfers through the atmosphere are undoubtedly of great importance in determining climatic change and changes of weather patterns on seasonal timescales, this has perhaps led to undue emphasis being placed on these matters in short to medium term forecasting. Here, the urgent priorities must be the improvement of analyses on a hemispheric scale (including the use of novel and unconventional data sources in data-sparse regions), and the improvement of the basic dynamic processes in the model. Included in the latter must be an improved understanding of the processes which we intend the models to reproduce.

In this connection, the behaviour of wavenumber 2 would appear to merit close study. In these experiments, as in earlier work, wavenumber 2 is found to behave anomalously. It is the only wave whose behaviour was at all sensitive to the details of the formulation used and indeed shows a wide variation, particularly in amplitude, after 2 days. Upto this point, the forecasts were all similar. The deviation is not simply between the forecasts and verifications (as is the case with wavenumber 4, which also has rather large errors), but between the forecasts themselves. The implication must be that this is not a data problem, but that the amplitude of wavenumber 2 is a highly sensitive variable in the model, whether topography and surface heat sources are present or not.

To sum up: as far at least as the long waves are concerned, the model predictions up to 6 days ahead are not greatly affected by the presence of topography and various parameterized processes. Of these various processes, the effect of uplift over topography at the lowest level is by far the most significant, and its proper inclusion should perhaps be studied further. But the main contribution to long wave errors seems to come from dynamic effects and possibly data analysis errors. A first priority must be to understand these effects.

Sequence	Physical Processes	Topographic Uplift	Topographic Diffusion	Remarks
V				Verifying analyses
A	✓	✓	✓	normal operational run (control experiment)
B	✓			
C		✓	✓	
D				dynamic processes only (control experiment)
E		✓		

Table 1: Summary of the experiments carried out.

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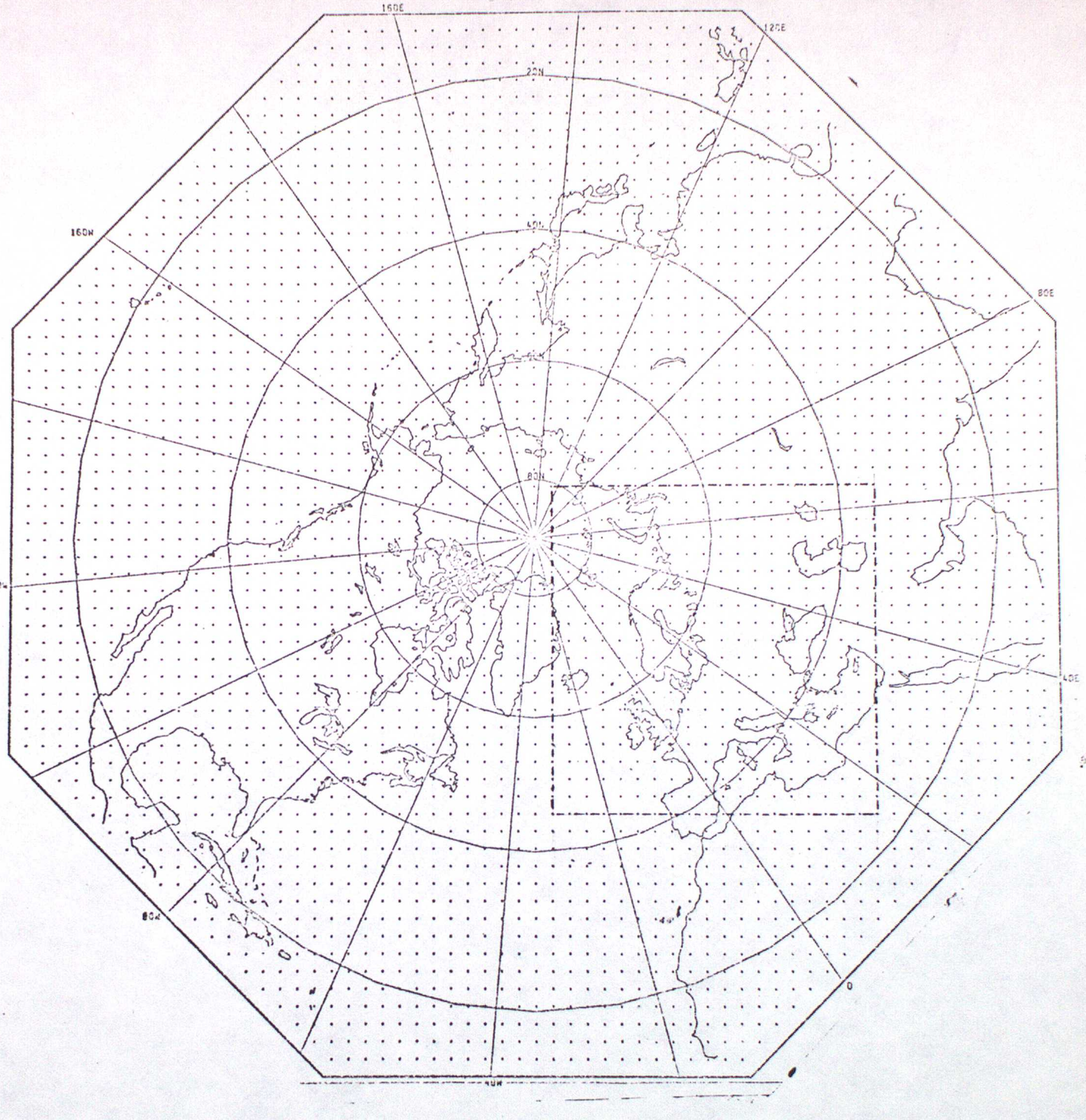

Fig.(1): The disposition of grid points in the quasi-hemispheric version of the 10-level model. The dotted rectangle delineates the "European" area used in calculating root mean square errors.

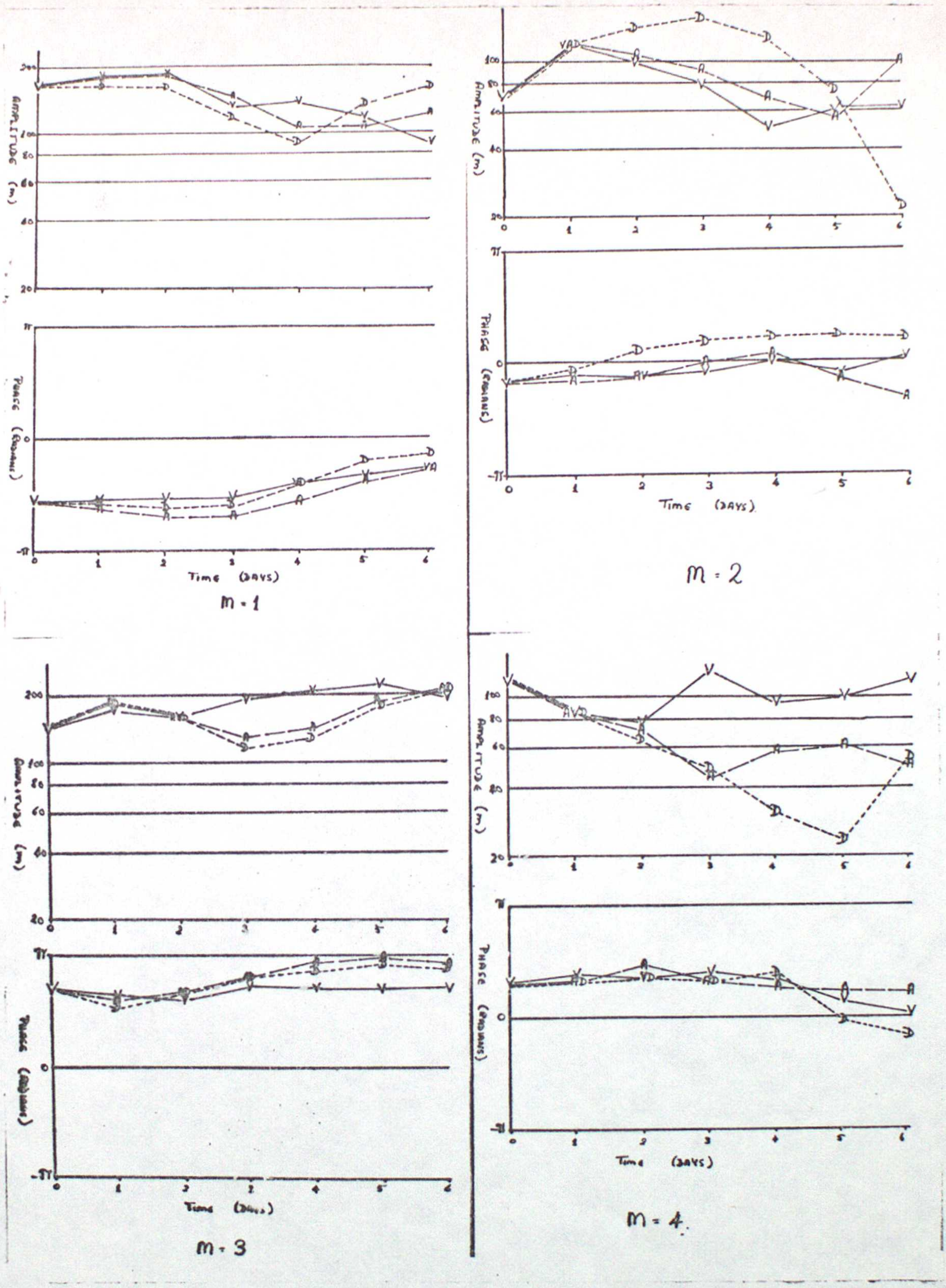

Fig.(2): Plots of amplitude and phase against time for wavenumbers 1–4 in the 500 mb geopotential height fields of sequences V, A and D.

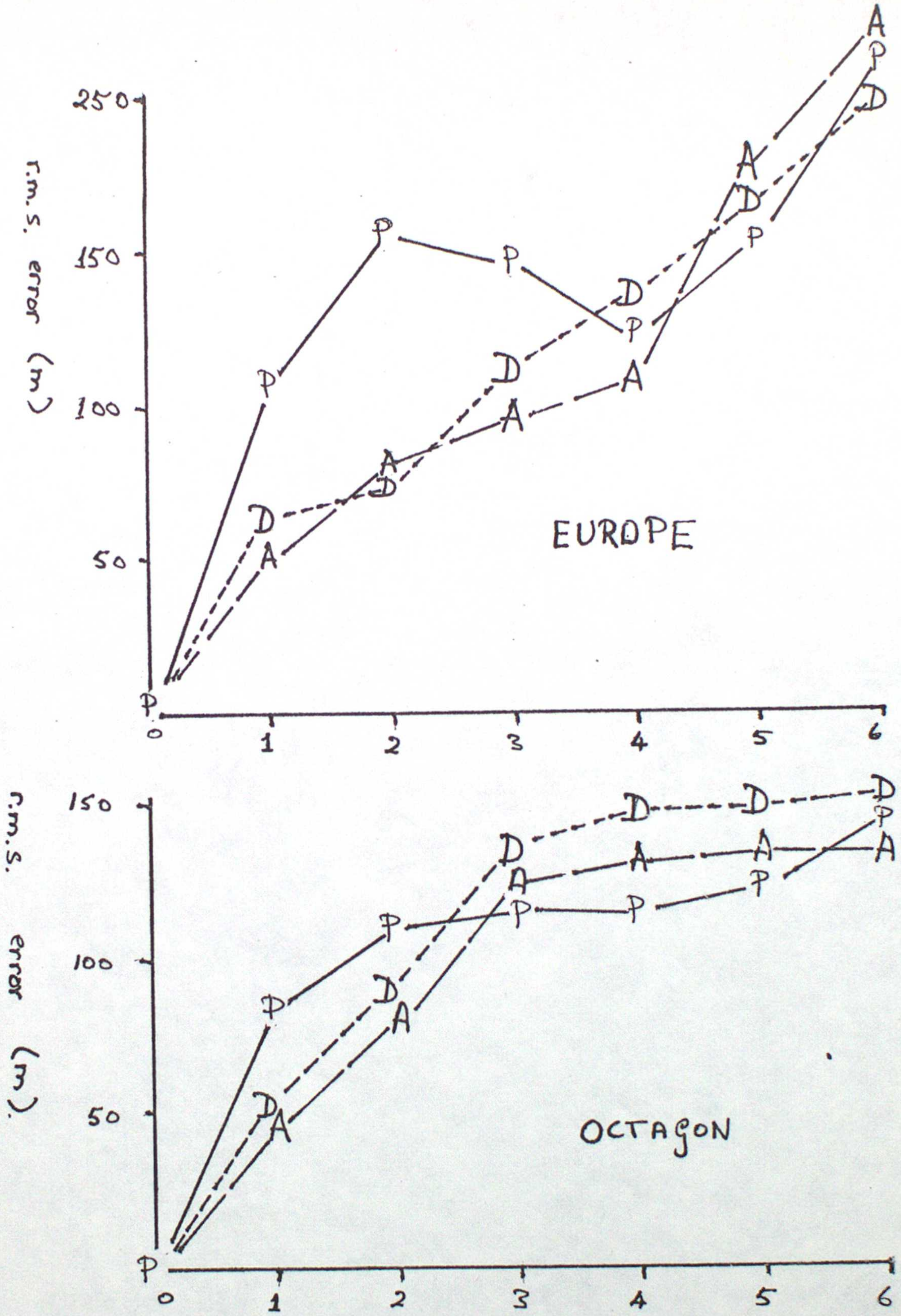

Fig.(3): Plots of root mean square error in the 500 mb geopotential height fields in sequences A and D. The upper plot is for the "European" area (see Fig.1) while the lower covers the entire octagon. The curve marked P denotes the rms errors of a persistence forecast.

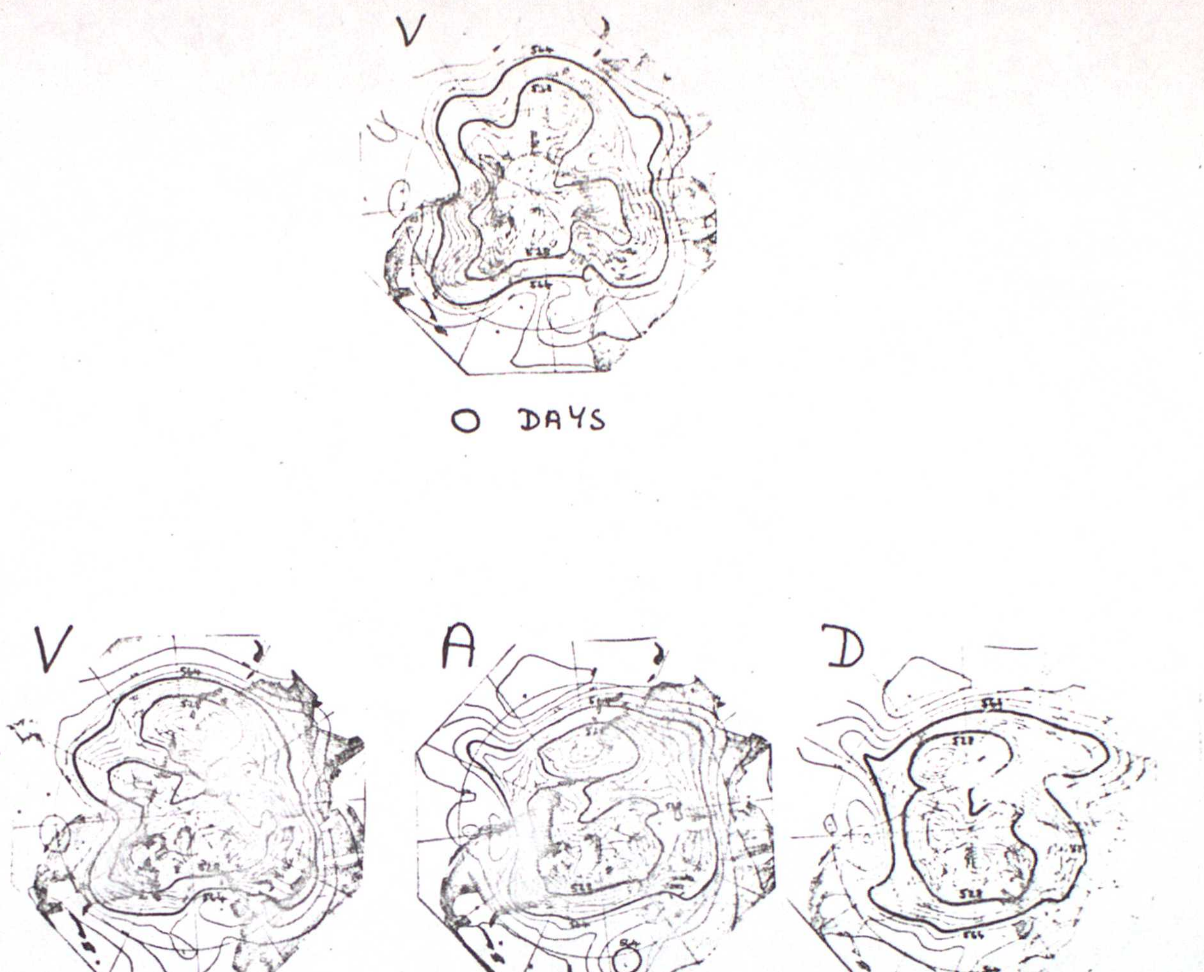

Fig.(4): The 500 mb geopotential height fields for the V, A and D sequences at 0, 3 and 6 days.

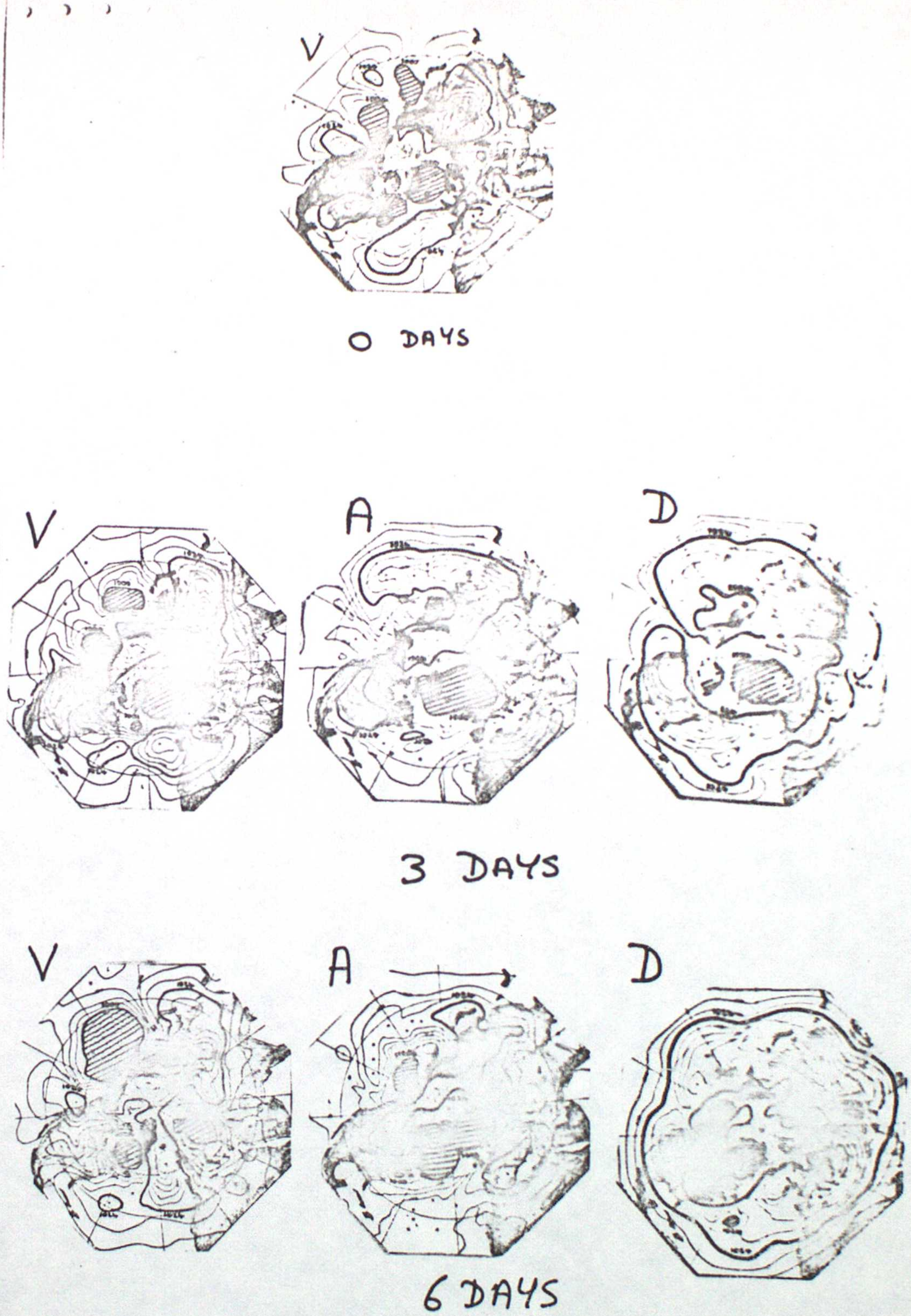

Fig.(5): The mean sea level surface pressure fields for the V, A and D sequences at 0, 3 and 6 days.

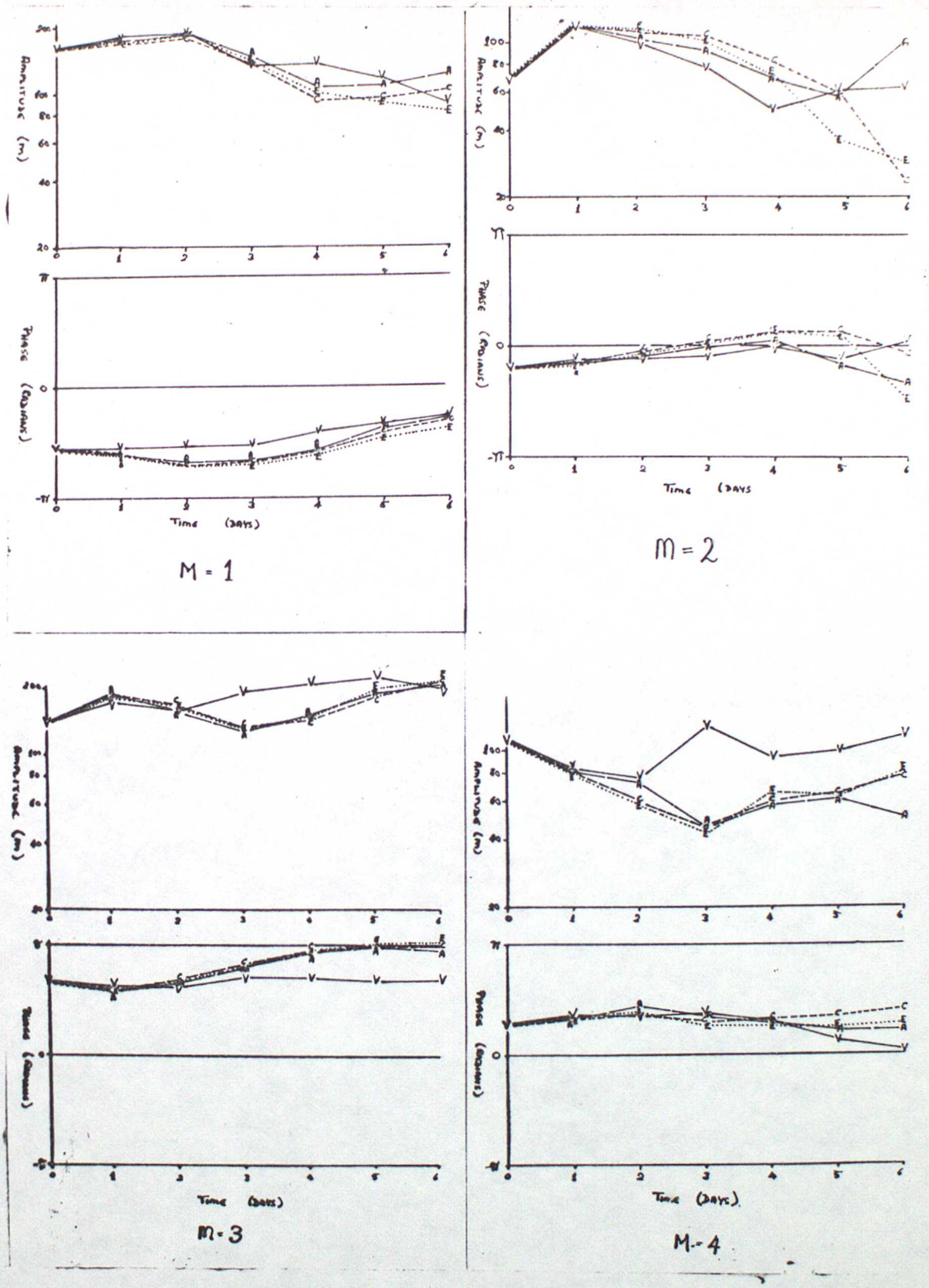

Fig.(6): Waveplots for sequences V, A,C and E. For other details see Fig.(2).

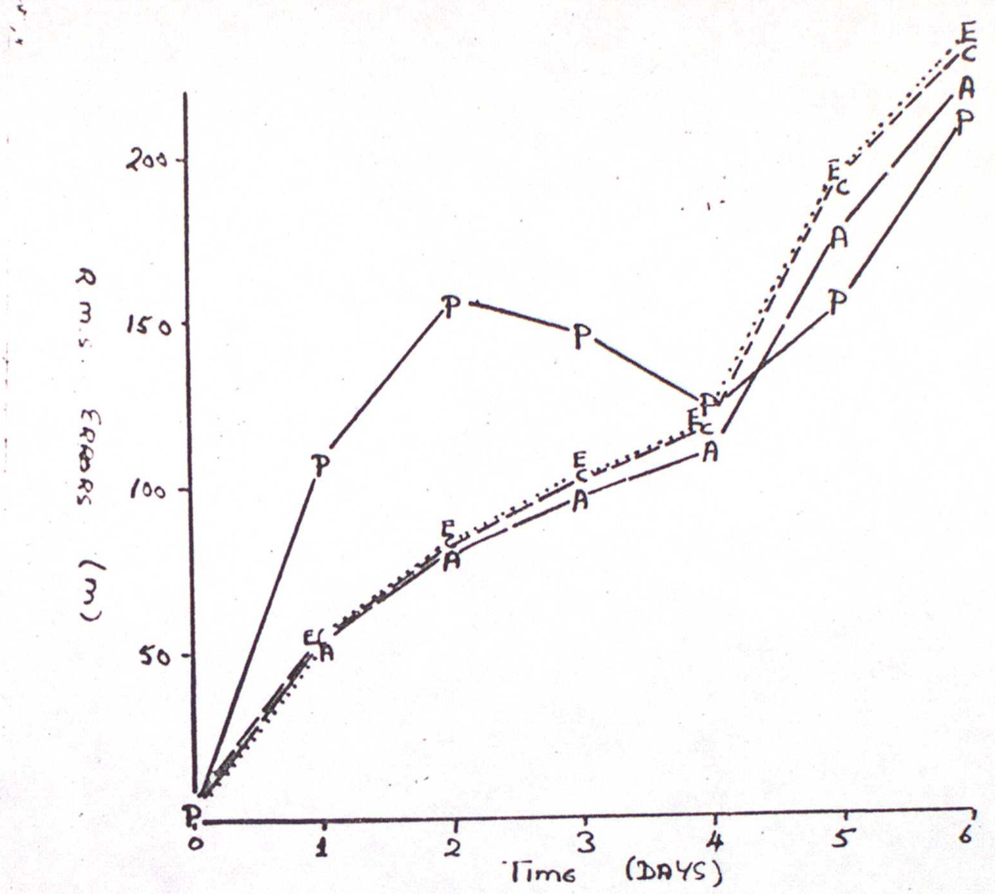

Fig.(7): 500 mb root mean square errors for sequences A, C and E over the European area.

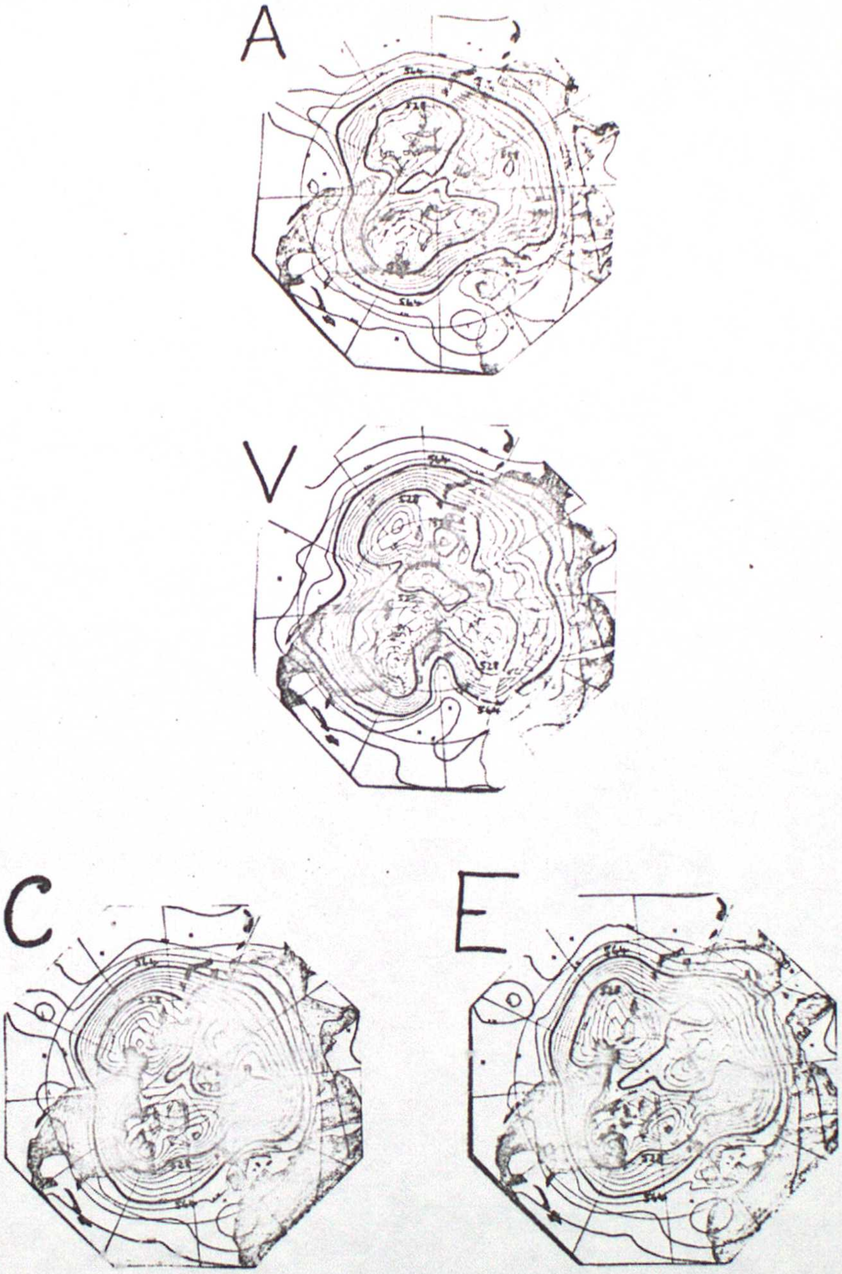

Fig.(8): 500 mb geopotential height fields at 6 days for sequences V, A, C and E.

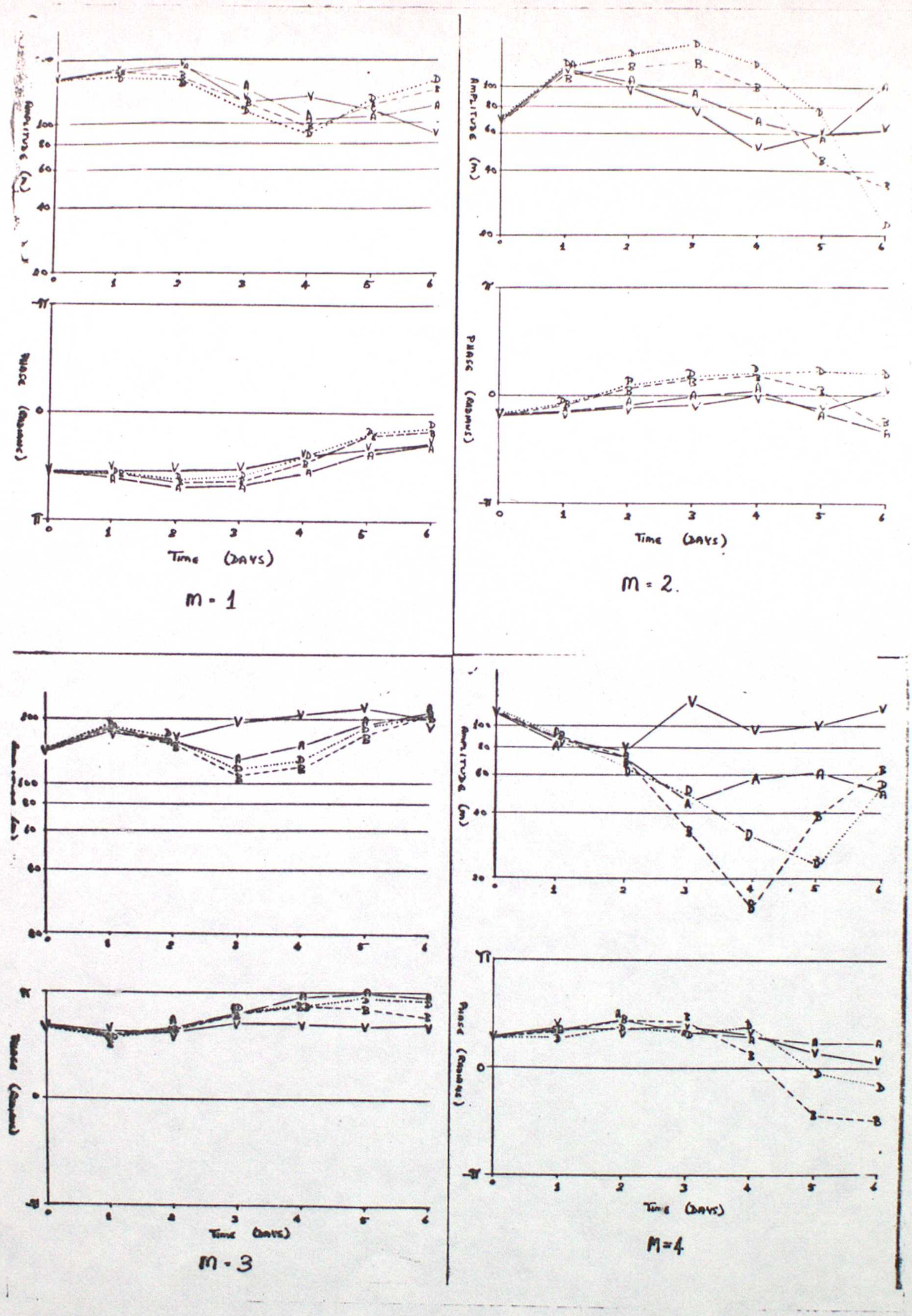

Fig.(9): Wave plots for sequences V, A, D and B. Other details as in Fig.(2).

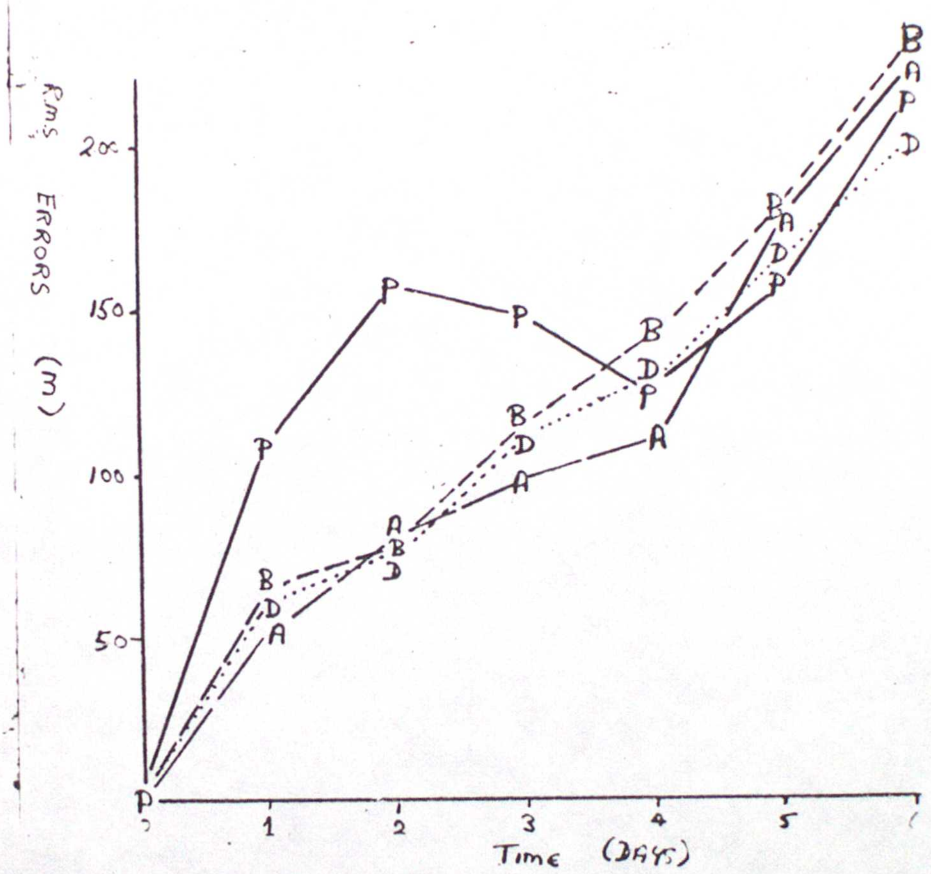

Fig.(10): 500 mb root mean square errors for sequences A, D and B.

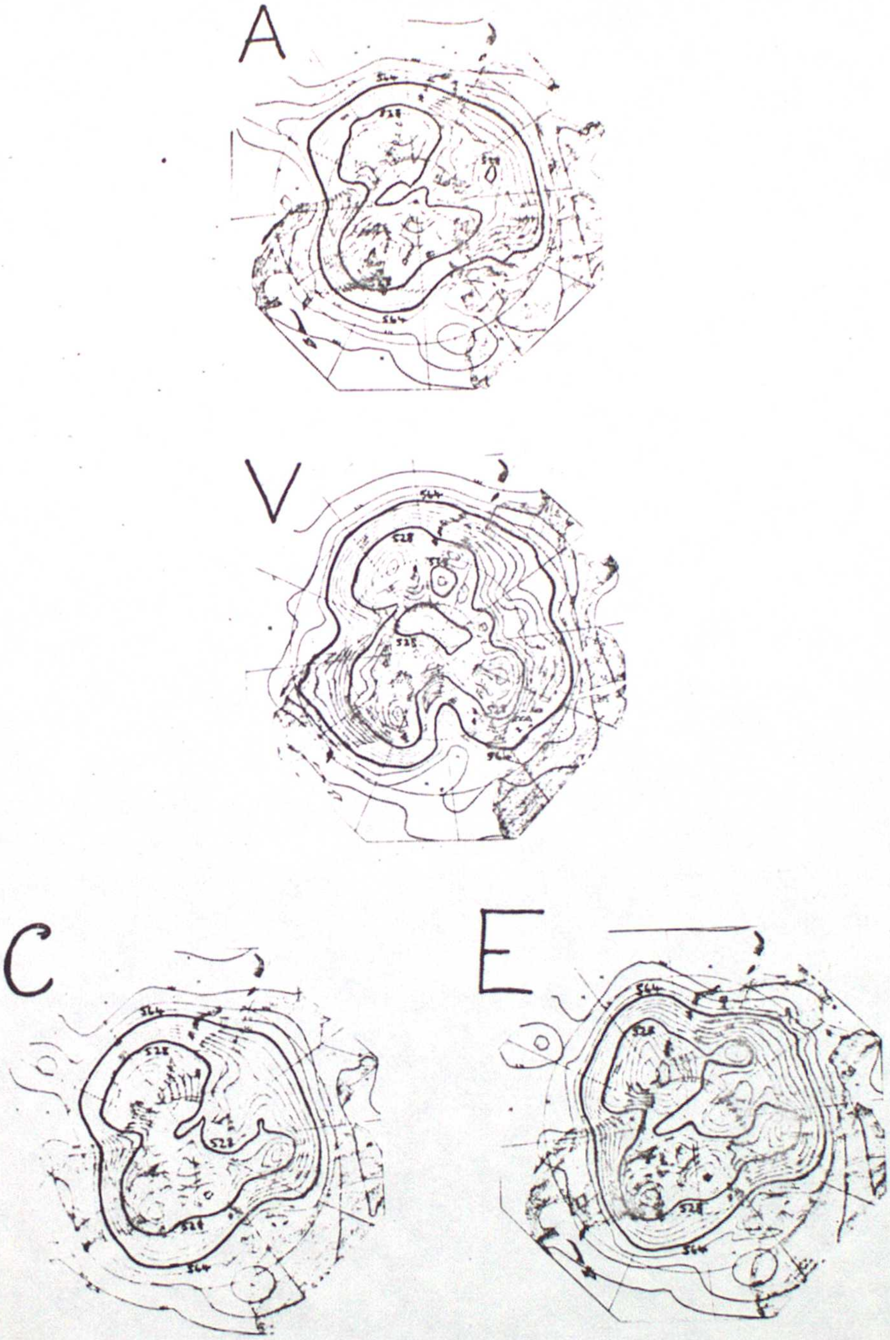

Fig.(11): 500 mb geopotential height fields at 6 days for sequences V, A, D and B.