MET O 11 Technical Note No 50

AN INVESTIGATION INTO THE BEHAVIOUR OF PLANETARY AND BAROCLINIC WAVES IN THE 10-LEVEL MODEL

by

IAN N JAMES

1. INTRODUCTION

Current evaluation of the 10-level model has been largely concerned with the description of the behaviour of various global quantities (such as kinetic energy, etc) and of individual synoptic features. In this paper I shall present an attempt to analyse the model in terms of the largest scale modes of motion, and in particular to describe the interaction between such scales of motion. This effort is complementary to earlier descriptions of the behaviour of small scale waves in the numerical scheme.

My results are based on Fourier analysis of data around a latitude circle, usually 50°N. The data to be analysed has been more or less dictated by the type of fields archived on magnetic tape over the past year or so, and which has formed the basis of much of this investigation. I had available in the archives the surface pressure, and the 500 mb, 300 mb, and 100 mb heights.

Much of the initial work used the 500-300 mb thickness; this quantity is a measure of the upper air temperature, and should adequately trace the development and notion of the upper waves. More detailed comprehensive work has subsequently involved analysis of the 500 mb heights. The two sets of results lead to very similar conclusion.

It is useful to review briefly the significance of the various large scale atmospheric motions in the mid-latitudes. I divide the wave number range into three divisions reflecting the physical genesis of the wave:

(a) Wave numbers 1-5 are the so-called planetary waves.

(b) Wave numbers 6-10 represent the baroclinically unstable waves.

(c) Wave numbers 11 and upwards can be described as the "inertial subrange".

The planetary waves are the largest scale modes in the atmosphere. They are generally present with large amplitudes in the upper air patterns, and can be generated by the action of topography and the non-axisymmetric distribution of surface heating and moisture sources on the mean zonal flow. This is particularly true of wave numbers 1 to 3. They are also generated by the non-linear interactions between these modes and smaller scales of motion. This feature is common to all rotating turbulent flows which are two dimensional. The large scale quasi-geostrophic motions in the atmosphere form a two dimensional turbulent field and so must satisfy Fjortoft's theorem. The theorem states that in order to conserve both the energy and enstrophy (the mean square vorticity) of two dimensional turbulent flow, energy must be passed onto larger as well as onto smaller scales. This contrasts strongly with three dimensional turbulence, where energy "cascades" only to smaller scales.

The stability of these waves is a matter of some debate. It has been considered that such a wave in isolation would be stable, and would propagate with the Rossby-wave speed. This is now challenged and it is suggested that an instability associated with the non-linear advection terms (the so-called "barotropic instability") would disrupt even an isolated wave (see Hoskins 1973). The mathematical difficulties in establishing such an instability are considerable, and the debate is not resolved.

The observed motions of the long waves are erratic. They are frequently stationary, but may show periods of fairly rapid progressive motion. These periods are more often observed for wave numbers 4 and 5. They have long posed problems for numerical forecasting. In the early barotropic models, they retrogressed rapidly, an effect which was removed by introducing an artificial divergence term into the vorticity equation. A basic thesis of the present paper (confirming that of other workers with independent models, eg Miyakoda et al 1971) is that all is still not well in the handling of these waves, even when using a sophisticated multilevel primitive equation model.

The group of waves from wave numbers 6 to 10 are the most unstable waves according to the linear theory of baroclinic instability developed by Eady (1949) and extended by later workers. These scales are primarily responsible for injecting kinetic energy into the atmosphere. They are generally of fairly large amplitude and are progressive. Their standing component is relatively unimportant. A principal objective of multilevel forecast models has been to represent these waves.

Baroclinic waves in the laboratory, under suitable circumstances, exhibit a periodic variation of amplitude, phase speed and possibly of dominant wave numbers. The phenomenon is known as vacillation and has been described by Hide 1958, Fowlis and Pfeffer (1969), and by Hide et al (in preparation). Vacillation probably arises as a result of resonant non-linear interactions between a set of three (or possibly more) individual waves. When the results of vacillation experiments are Fourier-analysed, the amplitude of a single wave rises and falls periodically, while the phase speed is constant when the amplitude is large, but changes considerably (often to a retrogressive motion) when the amplitude is small and the wave is strongly modified by non-linear interactions.

Vacillation is probably present in the atmosphere, though its effects are obscured by the complications and irregularities introduced by a variety of physical processes. However I shall show a number of examples in section (2) which indicate that vacillation certainly occurs, at least over limited periods.

The final group of waves, from wave number 11 to 15 upwards, obtain their energy almost solely through non-linear interactions with other waves. Energy is passed through these scales until it is dissipated at very small wave-lengths. Both experimental and theoretical results for two dimensional turbulence suggest that the energy spectrum for these waves should be proportional to m^{-3}, m being the wave number. On a sufficiently small scale, the turbulence is probably three dimensional in character and the energy spectrum will depend on $m^{-5/3}$.

It is not expected that anything but a statistically correct forecast of these waves is possible. They are resolved by less than eight points at 50°N and are probably not resolved at all (except in a few regions) by the observing system. Nevertheless, their presence is required in the model to interact with the larger waves, and so they must be represented in a physically realistic way.

In subsequent sections, I shall describe the results of a detailed comparison of the observed and forecast amplitudes and phases of the waves up to wave number 10. On the basis of these results I shall draw some broad conclusions about the behaviour of the 10-level model.

2. DISCUSSION OF RESULTS

2.1 Variation of Forecast Waves with Times

Figures (1-10) show the variation of amplitude and phase for wave-numbers 1-10 at 500 mb during the period 1974 February 26th to 1974 March 29th. This period is representative of a number of such periods which have been used in compiling the statistics presented below; the dates involved are given in Appendix 2. The heavy line in each diagram connects the values of the analysed amplitudes and phases, while each of the lighter lines join the values for a single 3-day forecast. The plotted figures indicate the 0, 1, 2 and 3 day forecast levels. Using these diagrams it is possible to compare the results of any forecast with the corresponding analyses.

The analysis curves are based on the "update" analysis, which include late data which could not be included in the operational analyses, together with a certain amount of intervention. Hence the analysis curves represent the best analyses available on a routine basis.

First I consider the objective analyses. These exhibit a systematic change of character as wave number increases. In general the largest waves (m = 1 to 3) show a fairly steady amplitude, and a generally steady phase; however the periods of steady phase are interspersed with spells of often rapid motion (see for example fig. 3, days 6 to 16). Periods of progressive (that is, west to east) motion become more frequent as wave number increases, so that for m = 4 or 5, the waves are typically progressive, though still with periods of standing behaviour. A quasi-periodic fluctuation of amplitude is frequently noticeable for these and larger wave numbers.

The remaining waves are baroclinically unstable and are rapidly progressive. The amplitude and phase fluctuations tend to be correlated in a way highly suggestive of laboratory observations of vacillating baroclinic waves (see section 1). A very good example of this is shown in fig. (11) and will be described below.

The errors for these waves are rather more systematic than for the longer waves, and so I will describe them first. Wave number 8 (fig. 8) is a typical example. The forecast amplitudes are frequently rather low, though a systematic loss of amplitude is much more pronounced for the larger wavenumbers, m = 9 and 10. Errors tend to be most pronounced when the amplitude is small - notice the minimum at day 12. A serious and generally observable trend is that developments in the amplitude of the waves tend to be late in the model. In fig. (8), the fall shown for days 1 to 3 is late at all forecast times, as are the declines of amplitude around days 9 to 12 and 18 to 20. Many other examples will be found on carefully examining figures 5-10.

A similar effect is very noticeable in the phase/time plots, a good example occurring in fig. 8 around day 20. The backward jump of the wave is late for some forecasts, and completely missed by others.

Other phase errors are even more systematic for these waves. While the wave is progressing steadily, the forecast waves show an increasing lag, indicating that waves in the model tend to move too slowly. (For a good example, see fig. 8, days 25 to 28). On the other hand, the forecast waves tend to have phase leads during the periods of retrogression and (presumably) non-linear interaction (see fig. 8, days 14 and 15). This phase lead can be interpreted again in terms of the interaction being late in the model.

To summarize, it appears that the baroclinic waves in the model tend to lose amplitude slowly and to move with rather lower phase speeds than in the real atmosphere. Sudden changes of phase speed and amplitude are poorly represented and often do not occur at all; the lateness of some of the developments in the forecast curves suggests that they are not manifested in the model until forced in by the analysis.

It is not possible to understand these sudden changes of phase and amplitude in terms of linear theory. To some extent they may be due to small scale physical processes. But it seems likely that they are best understood as arising from the non-linear interactions between waves. This conclusion is based on a comparison of results (such as I show in this paper) with laboratory experiments, and also because it is difficult to understand how physical processes, operating generally only on a restricted region, could lead to large changes on the timescales observed.

I turn now to the errors in the long waves. Figure 2, for wavenumber 2, may be taken as a typical example. The wave loses amplitude fairly consistently, and often to a large degree. Wavenumber 1 also tends to lose amplitude during a forecast, though not so markedly, while wavenumber 3 is the only one to consistently gain amplitude. This trend is repeated in other groups of data, though sometimes a somewhat smaller loss of amplitude is characteristic of all these waves. The model has some difficulty in predicting sudden changes in the amplitude of the long waves- note for example the behaviour around day 24, when the drop in amplitude abruptly ceases. Many other similar examples could be given; in general it seems that the long waves frequently exhibit the lateness of developments already described for the baroclinic waves.

The most noticeable feature of the phase/time plot in fig. (2) is that the forecast wave is far too mobile, and often changes considerably a phase during a forecast, whereas the analysed wave remains stationary or nearly so. This is particularly marked from day 15 onwards. A similar phenomenon characterizes all the long waves (that is, up to $m = 5$) during periods when they are observed to be stationary.

Fig. (11) shows a particularly fine example of a vacillating $m = 7$ wave during the period 1973 November 14th to 1973 December 17th. The analysis shows the amplitude varying fairly regularly with a period of around six days. The errors are fairly small, though with a distinct tendence to lose amplitude. The more abrupt changes in amplitude are late and often distorted in the 3 day forecasts. Corresponding to this, the phase diagram shows a steadily progressing wave, lagging by the 3 day forecast, when the amplitude is large, changing over to short periods of rapid retrogression with forecast waves leading the analysed waves, during periods when the amplitude is small.

It is suggested that this behaviour is closely parallel to the behaviour of a "vacillating wave" undergoing resonant non-linear interations in a laboratory system. Though the errors in this example are smaller than for the examples shown in figures 6-10, their behaviour is very similar, and so it seems likely that the model has an inherent tendency to distort the non-linear interactions.

In the ensuing sections, I shall discuss these results more carefully, and by means of statistical analyses, put the discussion of errors on a more quantitative basis. But I should emphasize that these statistical results are not necessarily very reliable. In particular the property whereby large errors are associated with the short period of non-linear interaction, and that these errors frequently are of a different character from those found for the "linear wave" means that even a fairly large data sample may not lead to reliable conclusions. I shall therefore reinforce my conclusions by reference to other case studies not fully presented in this paper.

2.2 The mean phase errors

Fig. (12) shows the variation of mean phase error with wavenumber. The means involved are for the entire sample of 327 forecasts. The solid line joins the 1 day forecasts, the dashed line the 2 day and the dotted line the 3 day.

There are considerable difficulties in obtaining this statistic reliably when the individual phases approach $\pm\pi$. These arise because it is impossible to distinguish a phase lag of around $-\pi$ with a phase lead of around $+\pi$. Since these cases will come to dominate the statistics, the results may not show much useful information.

The most noticeable feature of the diagram is the large phase leads of the baroclinic waves for the 1 day forecast. Reference to the appropriate figures shows that this must be interpreted as being due (to a few very large phase errors) (rather than) to the phase error being consistently positive. At later forecast times, the occasional large positive errors very nearly balance the more usual, fairly small phase lags, and so the curve shows few systematic effects at larger wavenumbers by day 3.

The curves are rather different for waves longer than m = 5. These show a generally increasing phase lead as the forecast procedes, agreeing with the tendencies suggested in section 2.1.

2.3 <u>Mean amplitude errors</u>

Fig. (13) shows the mean relative amplitude errors plotted against wavenumber. The solid line represents the 1 day forecast, the dashed line the 2 day, and the dotted line the 3 day. The mean is based on all 327 forecasts available.

The diagram demonstrates that there is a distinct loss of amplitude in nearly all waves, except possibly the most baroclinically unstable waves, where the mean amplitude errors are small, and wavenumber 3, which generally behaves anomalously in this respect (see sec. 2.1).

Some comparisons of the mean spectra of the 500-300 mb thickness waves up to wavenumber 40 (the limit of resolution at 50°N) have been made and are shown in fig. (14). It will be noted that the gradient of both curves is near to -3, in accordance with theoretical ideas. There is a more or less constant loss of amplitude throughout the inertial subrange by the 3 day forecast, while the errors are more irregular for the longer waves.

It has long been obvious from the forecast fields that the flow becomes more zonal as the forecast proceeds – the effect is very pronounced after a 6-day integration. The effect is confirmed by figs. (13) and (14). It has recently been found (Lunnon 1975) that inclusion of a long wave radiation scheme preserves the amplitude of waves. However little improvement is noted in predicting amplitude changes or in the movement of the waves.

2.4 Root Mean Square Amplitude and Phase Errors

The mean errors discussed above give no guide to the degree of inconsistency between analysis and forecast, but serve to indicate whether there is any systematic trend in these errors. In this section I shall present the root mean square errors, which provide some measure of the accuracy of the forecast. There are difficulties in assessing the usefulness of these statistics. In particular, the root mean square error is dominated by the occasions when the error was unusually large. With a restricted sample and no selection of the data to be treated, this means that these r.m.s. errors may not typify the model for a great many forecasts. For this reason as larger a sample as possible (consisting of 325 forecasts) has been taken.

I consider first the relative amplitude errors, which are plotted against wavenumber in fig. (15a). At 1 day the errors are not strongly dependent on wavenumber, though a general increase with m is to be noted.

At 2 and 3 days, the error increases, and exhibits a characteristic dependence on wavenumber. Throughout the baroclinic range, the error is steadily increasing, as might be expected on crude arguments of resolution. However, a peak in the error occurs around wavenumbers 2 and 3. The error around wavenumber 6 appears somewhat large. It is most likely that wavenumber 6, being the first harmonic of wavenumber 3, is adversely affected by interactions with this wave.

A similar pattern emerges from a consideration of the root mean square phase errors, (measured in radians) shown in fig. (15b). Again by 2 and 3 days, there is a distinct maximum in the errors at wavenumbers 2 and 3.

At larger wavenumbers, the r.m.s. phase errors increase smoothly with wavenumber. Note, however that at wavenumbers above 7 or 8, the r.m.s. error begins to decrease by 3 days. This is certainly due to the increasing number of cases where the phase is in error by more than π radians; by always measuring the phase error so that it falls within the range $-\pi$ to π, I consistently tend to underestimate the r.m.s. phase error. The effect becomes more pronounced at larger wavenumbers and in the later stages of the forecast.

3. CONCLUSIONS AND RECOMMENDATIONS

3.1 Errors in Analysis

If it be accepted that a study of the long waves in the model indicates that there are serious deficiencies in the forecasts of the largest scales of motion, then we must endeavour to identify the causes of the difficulties. Perhaps the first question to be considered is whether the errors may be attributed to poor analyses or to inadequacies in the forecast model. Certainly no-one would claim that the analyses are perfect. In the operational forecast, a rather short data cut-off time must be accepted if the forecast is to be useful. Thus many observations, particularly from remote parts of the globe (eg. the Pacific), are frequently not used in the analysis. The distribution of remote stations will tend to lead to errors especially in the longest waves. Furthermore, there is little time in which to perform any useful intervention on the scale required.

There is certain evidence within the data contained in this paper that the analyses do not form an entirely consistent series. Considering the analysis curves in figs. (1-4), there are many very abrupt changes both of phase and amplitude. It seems unreasonable that such changes could have a physical origin, though as our understanding of the long waves is limited, I cannot place much confidence in this argument. This effect appears to be less pronounced for the shorter wavelengths. The behaviour of the long waves within a single forecast (regardless of whether or not it verifies well with the analyses or not) is much smoother.

Plots of error against time are readily obtained from figs. (1-10); they suggest that some long wave errors can be attributed to poor analysis. If a large error occurs in a single forecast, then the entire curve for that forecast will be in error. If, on the other hand, a single analysis is poor, then the forecast curves will tend to agree with one another, but not with the analysis curve. This does appear to happen on some occasions when the errors are large.

However, the operational forecast/analysis system is complicated, by the fact that the previous "update" analysis and forecast provides the background fields for the next analysis. In this way, errors in analysis can be propagated for several days in data sparse areas, while a forecast which is incorrect for some reason can upset subsequent analyses. Thus, it is very difficult to make any definitive statement about the role of poor analyses in leading to poor wave forecasts on the basis of the current data.

In order to eliminate as far as possible the effects of poor analyses on the quality of the forecasts it may be possible to make use of specially prepared sets of data such as those prepared in the Canadian Meteorological Service by Robert. They include all usable observations from many different sources, careful intervention and stringent quality control of observations. By making a series of experimental forecasts on such a data set, it should be possible to separate the effects of forecast and analysis errors. None the less, such a series of experiments would be less conclusive in as far as a much smaller sample must be accepted.

3.2 Errors in Forecasts

While it may be true that analysis errors can play a substantial role in degrading the forecast, the forecast model is undoubtedly not handling the large waves correctly. Errors in analysis may be expected to be more or less random (though they may predominate at certain wavenumbers); however systematic effects become established during the forecast period. The progressive loss of amplitude at nearly all wavenumbers has been noted above, as has the development of increasing phase leads for the stationary waves and phase lags for the mobile waves. It is not clear whether the anamalous variation of r.m.s. phase and amplitude errors can be attributed to the forecast model or to the analysis scheme, though the fact that the anomalies chiefly appear in the 2 and 3 day forecasts suggests that the forecast model is largely responsible for these.

An effect which does not emerge too clearly from the statistical presentation of data above, but which can be seen from figs. (1-10), and which persistently emerged from the study of individual forecasts, is the mistiming of, and the incorrect prediction of the energy exchanged by interactions between waves. To some extent this might be expected, as such interactions tend to affect a wave when its amplitude is small. Nonetheless it is important that the interaction be properly predicted since the subsequent evolution of the wave to large amplitude can be completely incorrect if this critical interaction period is not properly handled. This effect is present for both the planetary and baroclinic waves.

In general, I conclude one of the most serious errors in the 10-level model dynamics lies in the handling of non-linear wave interactions. Other errors (phase lag, amplitude loss, etc) are not nearly so troublesome since they are systematic, and the forecaster could to some extent compensate for them. I shall now consider some possible causes for the distortion of the interaction processes.

First, it must be recognized that the resolution of the model is limited. At $50^{o}N$, there are of order 90 grid-points around a latitude circle, hence wavenumbers 15-20 are resolved by only 4 grid points or so. Earlier studies have demonstrated that double gridlength waves (m = 30-40) are not advected at all, while waves resolved by only a few points will only be advected very slowly. It is probably true to say that some eight points are needed to resolve a wave adequately, (Kriess and Oliger 1973), so that the model is probably not treating wavenumbers above 10 very well in temperate latitudes.

Now if synoptic motions be regarded as a geostrophically turbulent field, the energy propagates onto larger scales as well as smaller. The longest planetary waves derive their energy by interactions with smaller waves, either directly or indirectly. Hence poor resolution of the smallest scales can distort the large scale flow, in a much shorter time-scale than would be possible in a linear system. Experiments by Miyakoda et al (1971) suggest that increasing the horizontal resolution of numerical prediction models has a beneficial effect on the large scale wave pattern.

Secondly, it is possible that the basic energy injecting mechanism (the baroclinic instability) is not adequately represented. This idea is supported by further recent, unpublished, experiments by Miyakoda (Newson 1974) in which doubling vertical resolution from 9 to 18 levels led to a greater subjective improvement in a forecast than a doubling of horizontal resolution. Care needs to be exercised in interpreting this result, as it is somewhat subjective, but it is an interesting possibility that high vertical resolution is more important than has been hitherto assumed.

A third hypothesis is that the resonant intereactions in the model do not correspond to those in the real atmosphere because of the restricted area and the shape of the lateral boundaries. Longuet-Higgins and Gill (1967) showed that resonant interactions between waves in opposite hemispheres are possible in a spherical system, suggesting that a global model will ultimately be required. Such an effect would be particularly pronounced for the largest waves; smaller modes are probably less influenced by a (distant) sidewall boundary. Analytic work on this hypothesis, which is possible in principle, would be very difficult, and numerical experiment offers a more practical mode of investigation.

It may be argued, of course, that the errors are due not to the interaction between waves, but to an incorrect handling of the topographic and thermal forcing mechanisms. However, I doubt that these effects could contribute more than rather small perturbuations to the flow during the course of a 3 day forecast (this, of course, would not be true for long term climatic integrations). The errors discussed in this paper involve very large energy transfers in short timescales; I would suggest that only dynamic processes are capable of accomplishing this. Nevertheless the point can only be properly resolved by careful examination of the model's dynamic and forcing processes separately.

3.3 Recommendations for Further Work

There are two aspects of further extensions to this work; firstly to consolidate and verify the statistical results presented in this paper, and secondly to devise some crucial experiments designed to isolate the prime causes of large-scale errors.

An important part of the first task is to separate the effects of analysis and the forecast scheme. In section 3.1 I discussed the possibility of a series of experiments with specially prepared high quality initial data. Other experiments and techniques of data analysis might be devised.

It may, or may not be considered worthwhile acquiring further statistical data of the forms discussed above. I feel that this is unlikely to lead to fundamentally new results, though certain other relationships ought to be examined. Thus, the behaviour of the waves at different latitudes have not been examined yet. It would probably be worth extending the work to consider a full spherical harmonic analysis of the two-dimensional flow. Further statistics should perhaps attempt to distinguish between travelling and standing periods of the wave motion or between "linear" and "interacting" modes of behaviour.

I turn now to the exploration of the major sources of error in the forecast. I have shown in the earlier sections that there are certain major systematic errors in the treatment of planetary and baroclinic waves. Many of these can be interpreted in terms of the poor representation of the non-linear interactions between waves. But it is essential to understand the causes for this poor representation if any reliable way of ameliorating the errors and extending the useful forecast period from 2 or 3 days is to be devised.

By their very nature, the complex system of non-linear effects occurring in the atmosphere is not theoretically understood to any great degree. Further, it is not possible to observe the real atmosphere with the resolution required, nor is it possible to devise laboratory scale experiments that exhibit many of the detailed physical processes occurring in the atmosphere. Thus the operational forecasts cetainly do not provide the best data for investigating the large scale dynamics of the model. The forecast system has so many degrees of freedom that it is impossible to separate the many causes and possible effects, and very difficult to decide what the model should have predicted.

I propose, then, that the next stage of the investigation will be to set up a simplified version of the 10-level model, including merely the dynamics and suppressing as many parameterized processes as is compatible with stability. Integrations for this simplified model will start from simple initial states consisting of one or two waves superposed on a zonal flow. There is limited theoretical understanding of such flows, while laboratory experiments on rotating flows are comparable with such a model.

Thus there would be two independent, and to some extent complementary checks on the model.

The simplified model will be based on the variable grid length version of the octagon forecast program, enabling experiments on the effect of changing the horizontal resolution, and on the location of sidewall boundaries to be carried out. These will have a direct bearing on the effects of truncating the spectrum of waves. Other experiments will investigate the interactions and resonances between waves, and will describe the dispersion relation for baroclinic waves in the model.

In conclusion, the feasibility of medium-range forecasting depends crucially on improving the predictability of the longest planetary waves. Similarly it is likely that major improviements to the present short-term forecasts will not be possible while the larger-scale features of the circulation are poorly handled. Again, it must be stressed that significant improvements in this direction cannot be expected until the sources of the major errors are properly identified. The system is far too complex for any "trial and error" or intituitive approach to have much probability of succeeding. Given this, the investigation cannot proceed much further using data from the operational forecasts. Carefully controlled experiments on a simplified model are the next stage in this task of urgent importance.

APPENDIX 1: REFERENCES

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Miyakoda K, Strickler R F, Nappo C J, Baker P L, and Hembree G D (1971): Journal of the Atmospheric Sciences, 28 481

Newson R (1974): Informal Met O 20 note: "Report of Visit to the United States".

APPENDIX 2: DATA USED TO COMPILE THE STATISTICS

The statistics presented in this paper are based on a number of periods of continuous collection of data from the operational forecasts. A few cases are missing, due to machine faults etc, but in total, 327 forecasts from the end of 1973 to summer 1974 are available.

The table summarizes the dates and number of cases of the various samples.

Dates	No of forecasts
ØZ 14/11/73 - 12Z 21/12/73	68
ØZ 22/13/73 - 12Z 15/ 1/74	49
ØZ 21/ 1/74 - 12Z 25/ 2/74	66
ØZ 26/ 2/74 - ØZ 26/ 3/74	56
ØZ 7/ 5/74 - ØZ 20/ 6/74	88

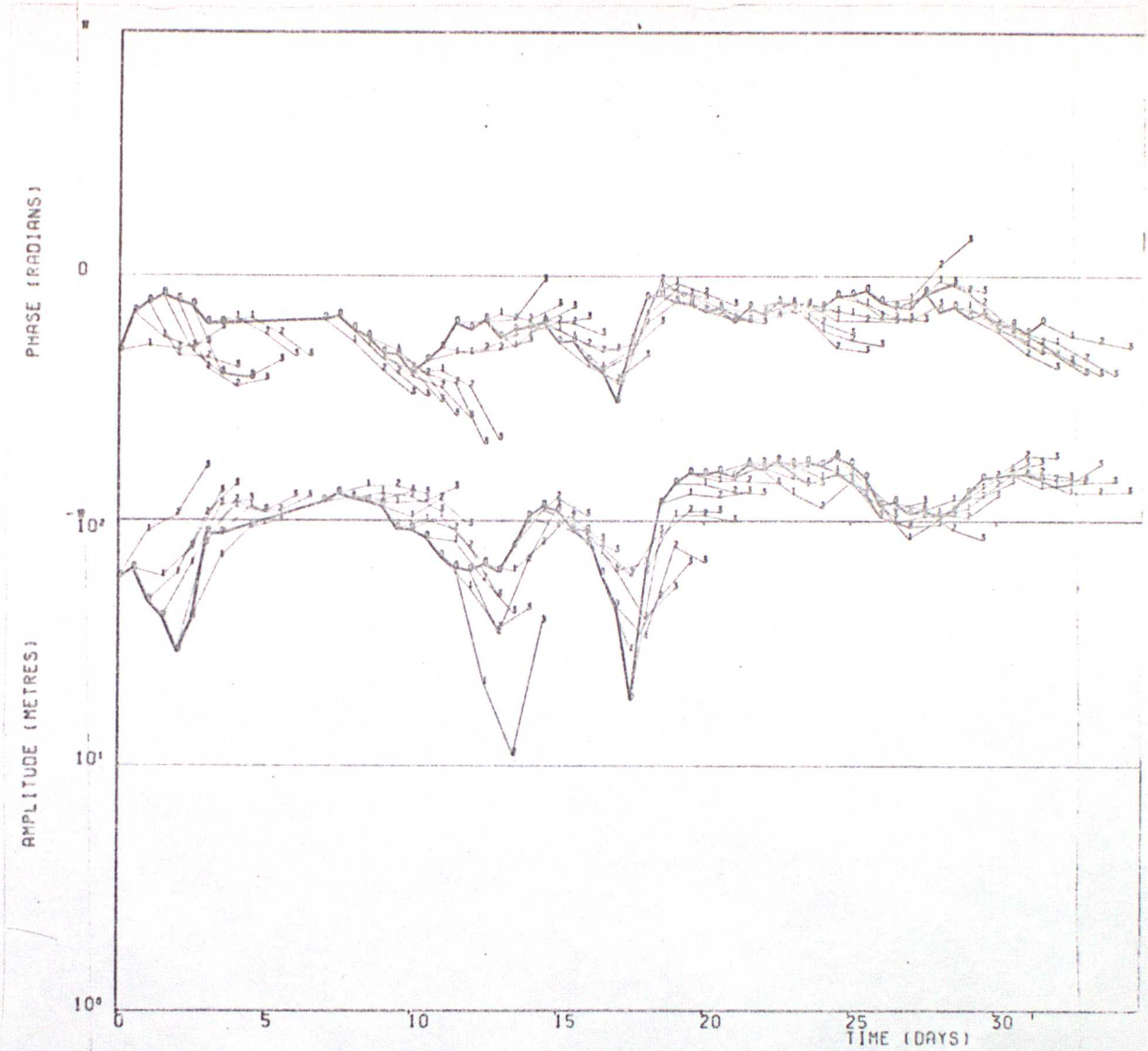

Fig.(1); Plots of the amplitude and phase of the m=1 wave against time, for the period 0Z 26/2/74 to 12Z 1/4/74. The analysis is of the 500mb heights at 50°N. The heavy line joins the analyses, and the lighter line the forecasts. The small figures represent the 1, 2, and 3 day forecast values.

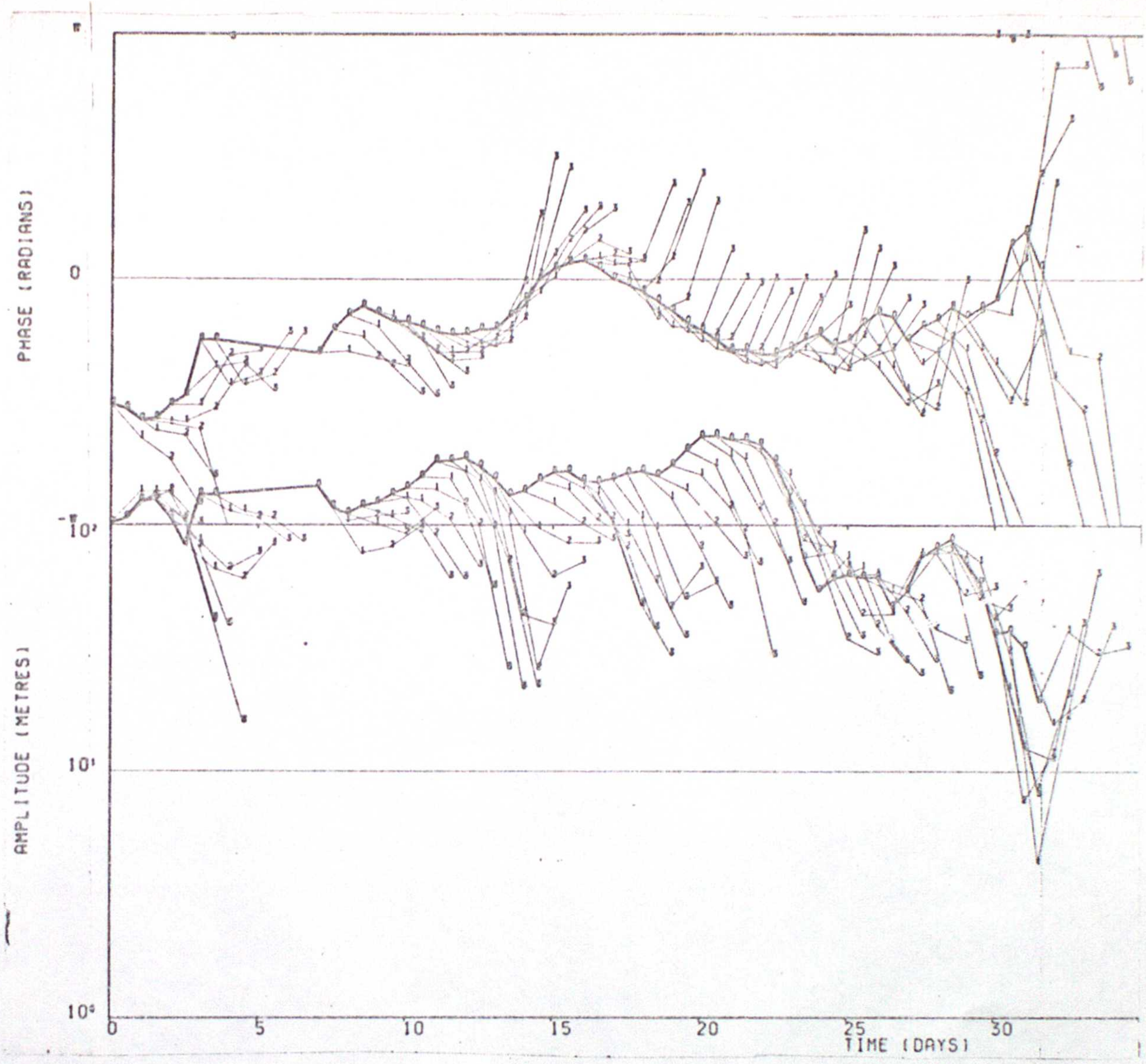

Fig.(2): Plots of the amplitude and phase of the m=2 wave against time. Other details are as for fig.(1).

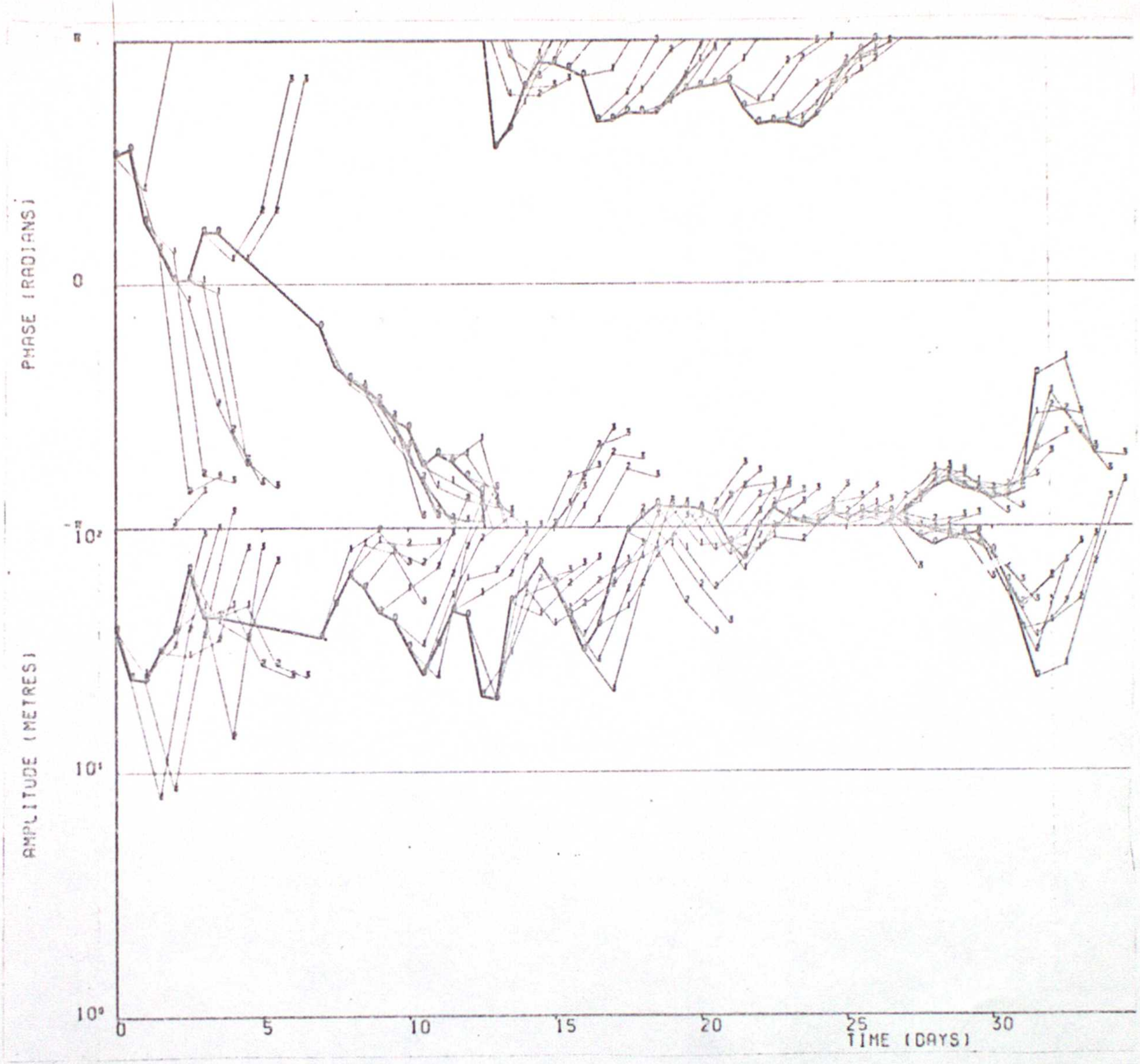

Fig.(3): Plots of the amplitude and phase of the m=3 wave against time. Other details as for fig.(1).

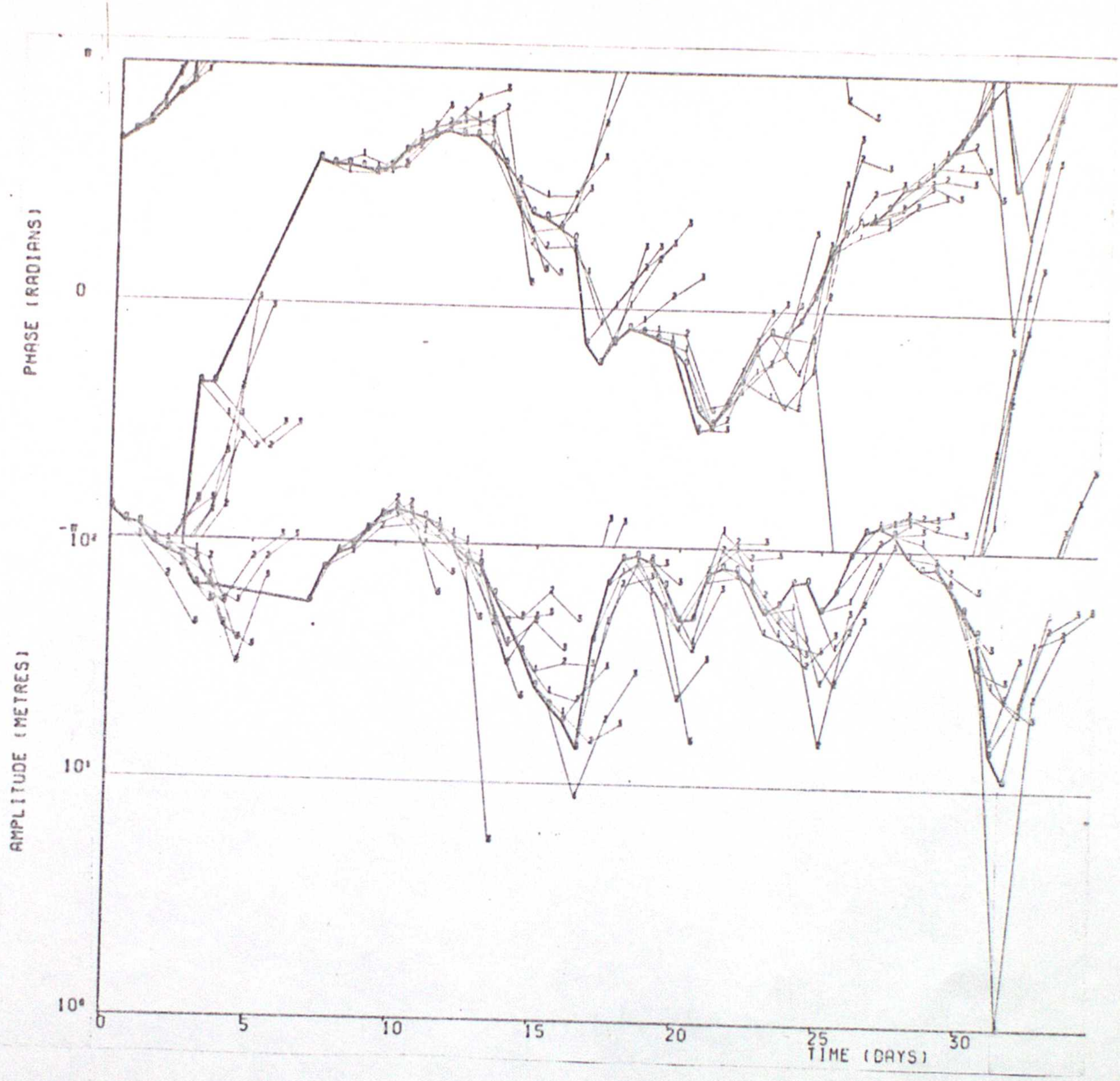

Fig.(4): Plots of the amplitude and phase of the m=4 wave against time. Other details as for fig.(1).

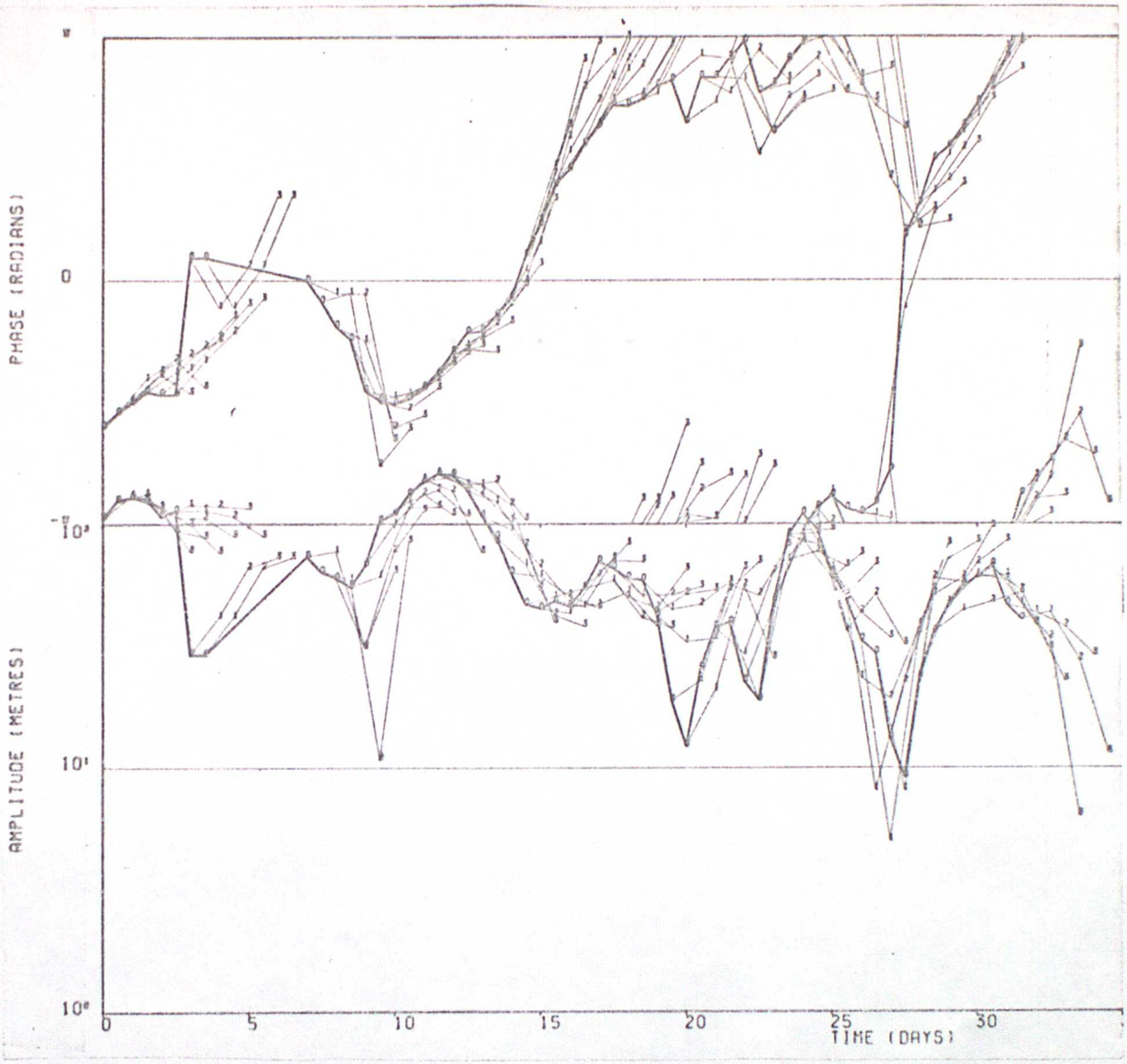

Fig.(5): Plot of the amplitude and phase of the m=5 wave against time. Other details are as for fig.(1).

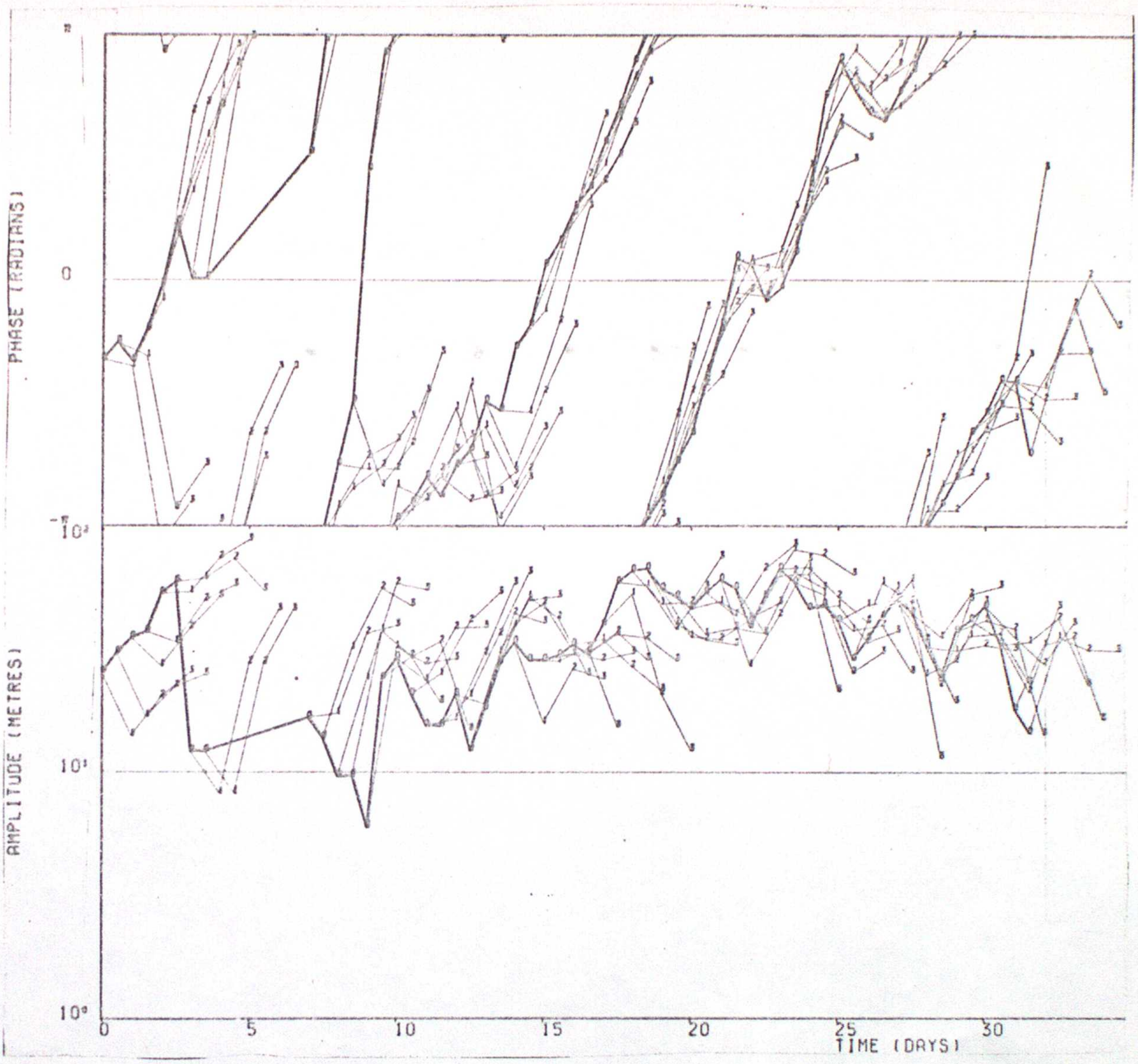

Fig.(6): Plot of the amplitude and phase of the m=6 wave against time. Other details as in fig.(6).

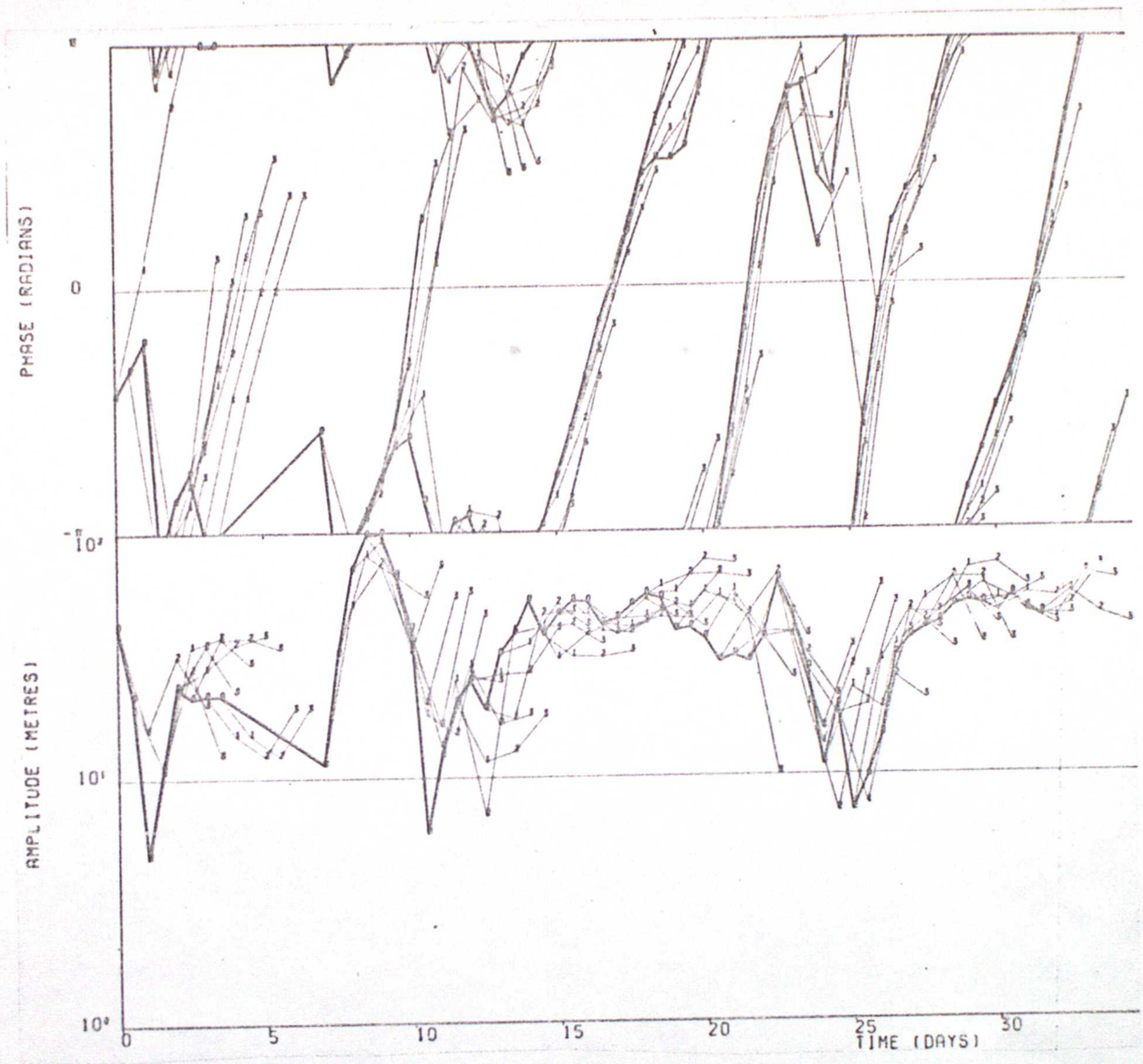

Fig.(7): Plots of the amplitude and phase of the m=7 wave. Other details as in fig.(1).

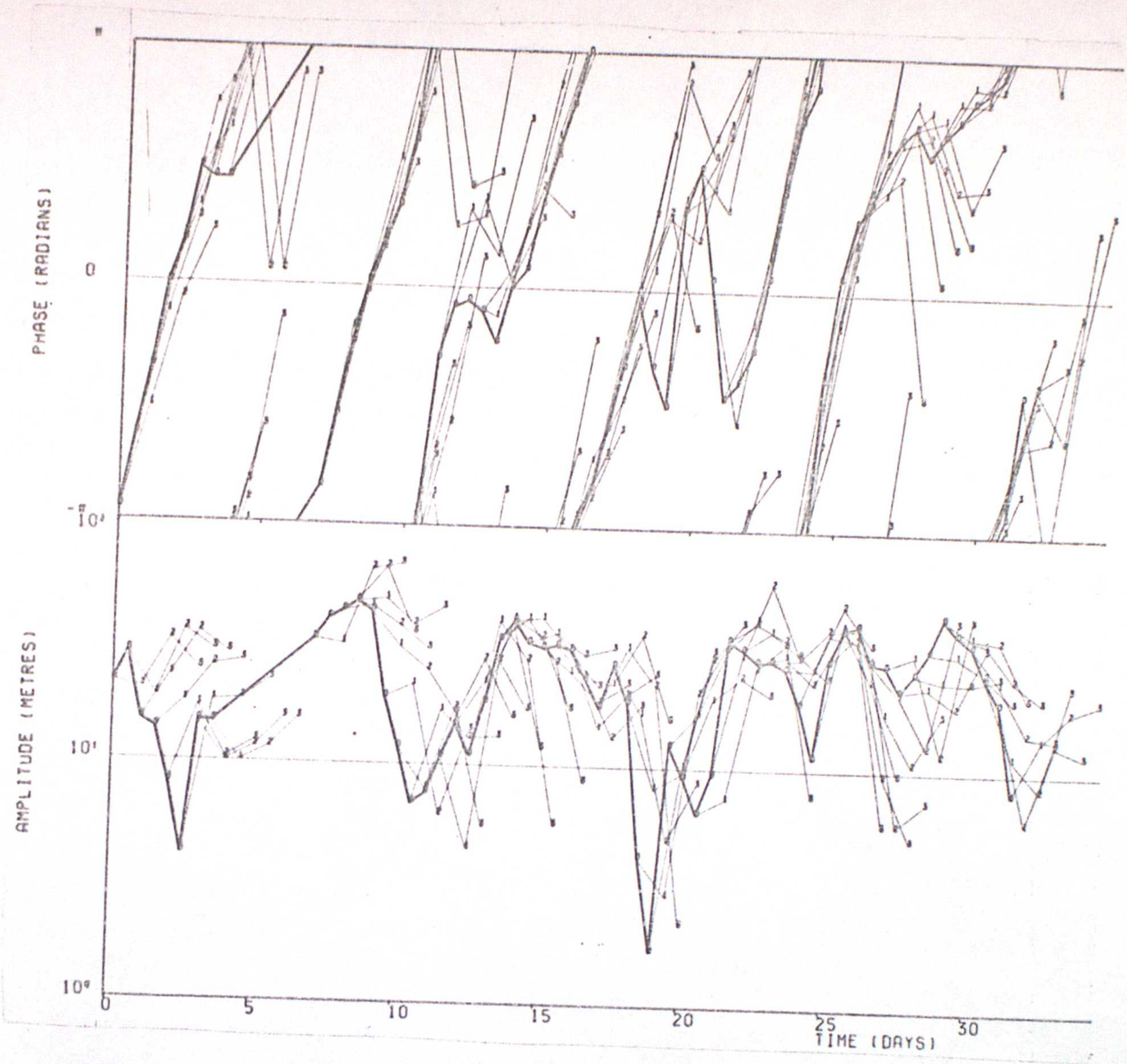

Fig.(8): Plots of amplitude and phase of the m=8 wave against time. Other details are as in fig.(1).

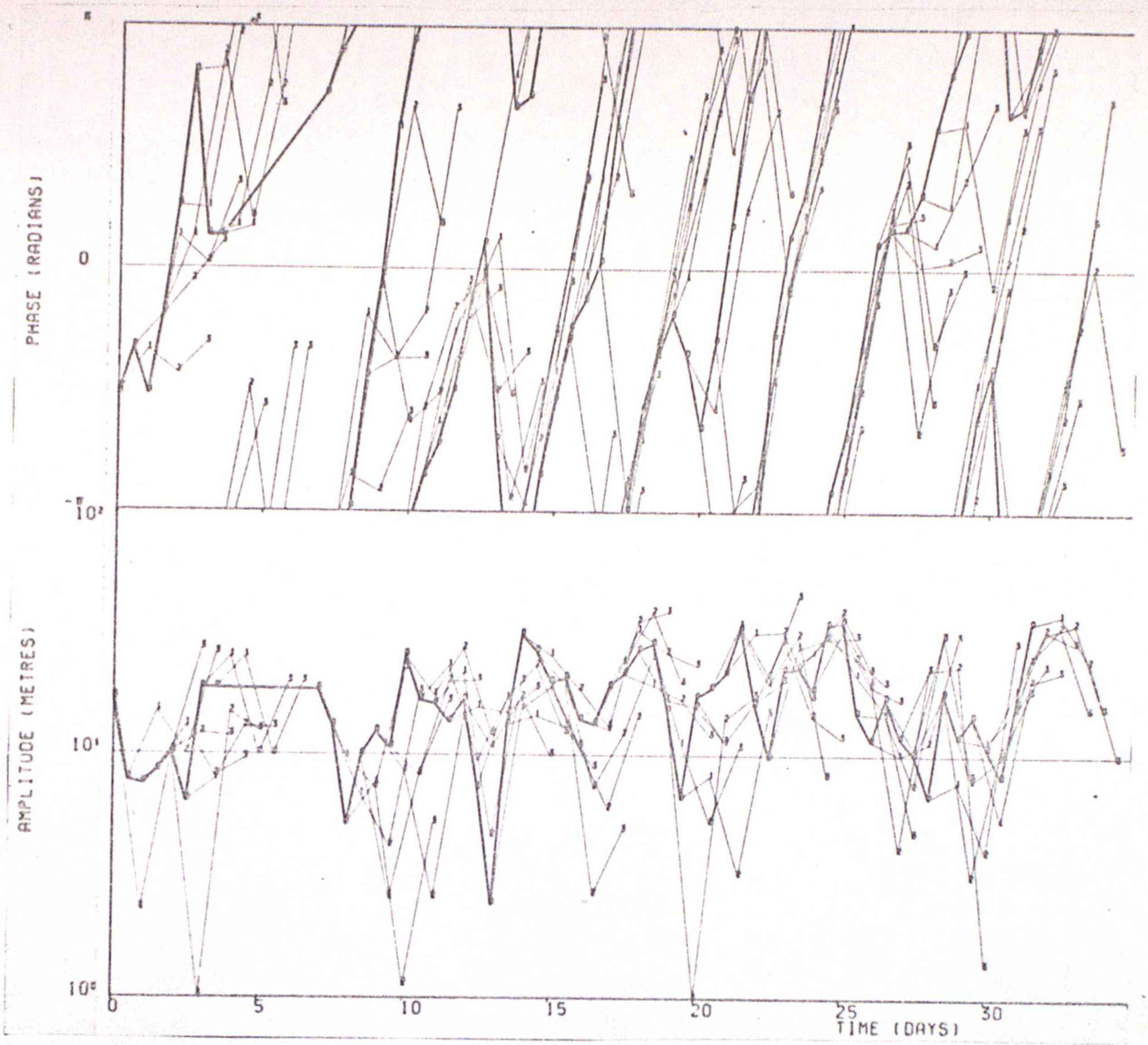

Fig.(9): Plots of the amplitude and phase of the m=9 wave against time. Other details are as in fig.(1).

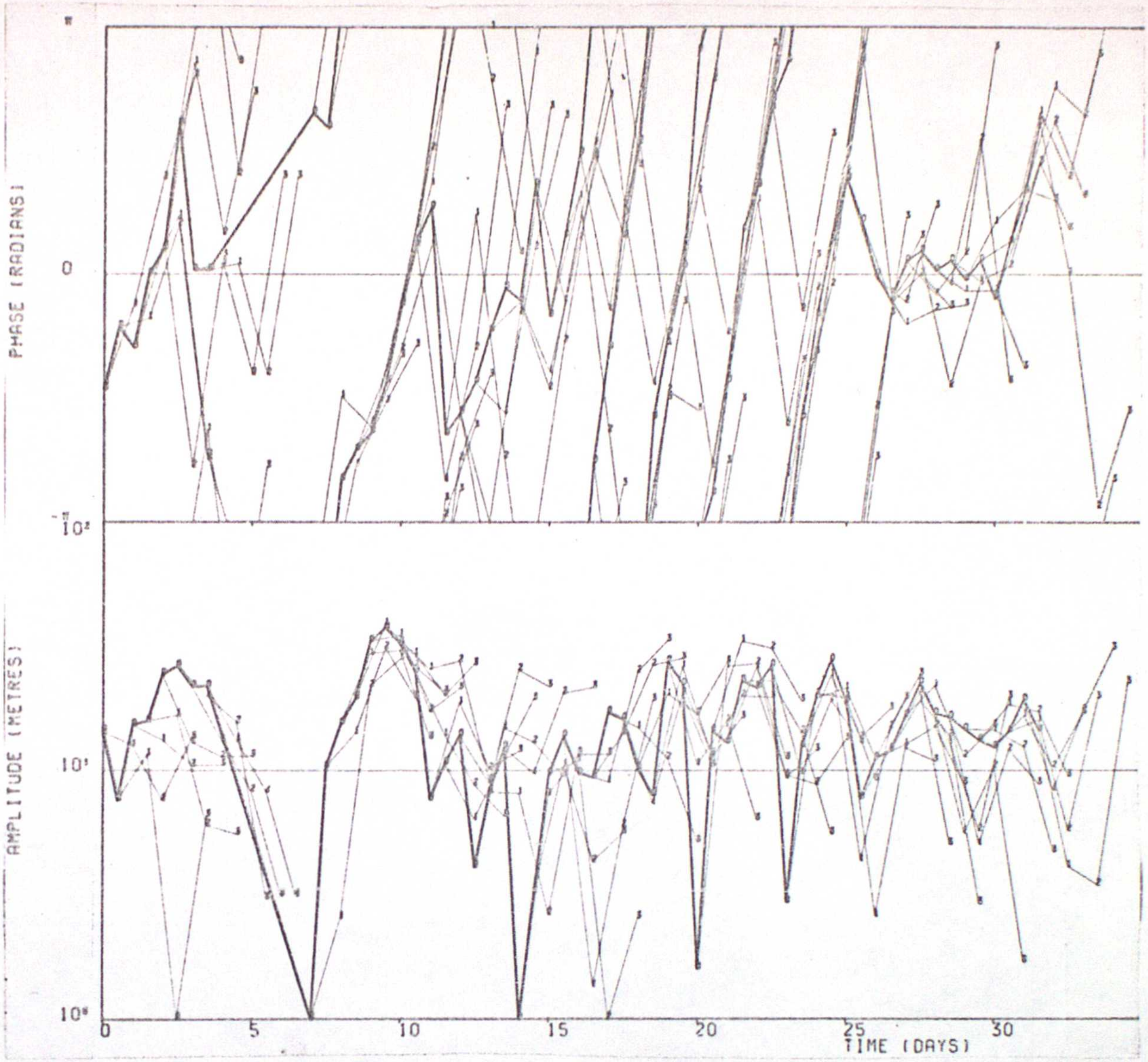

Fig.(10): Plots of the amplitude and phase of the m=10 wave against time. Other details are as for fig.(10).

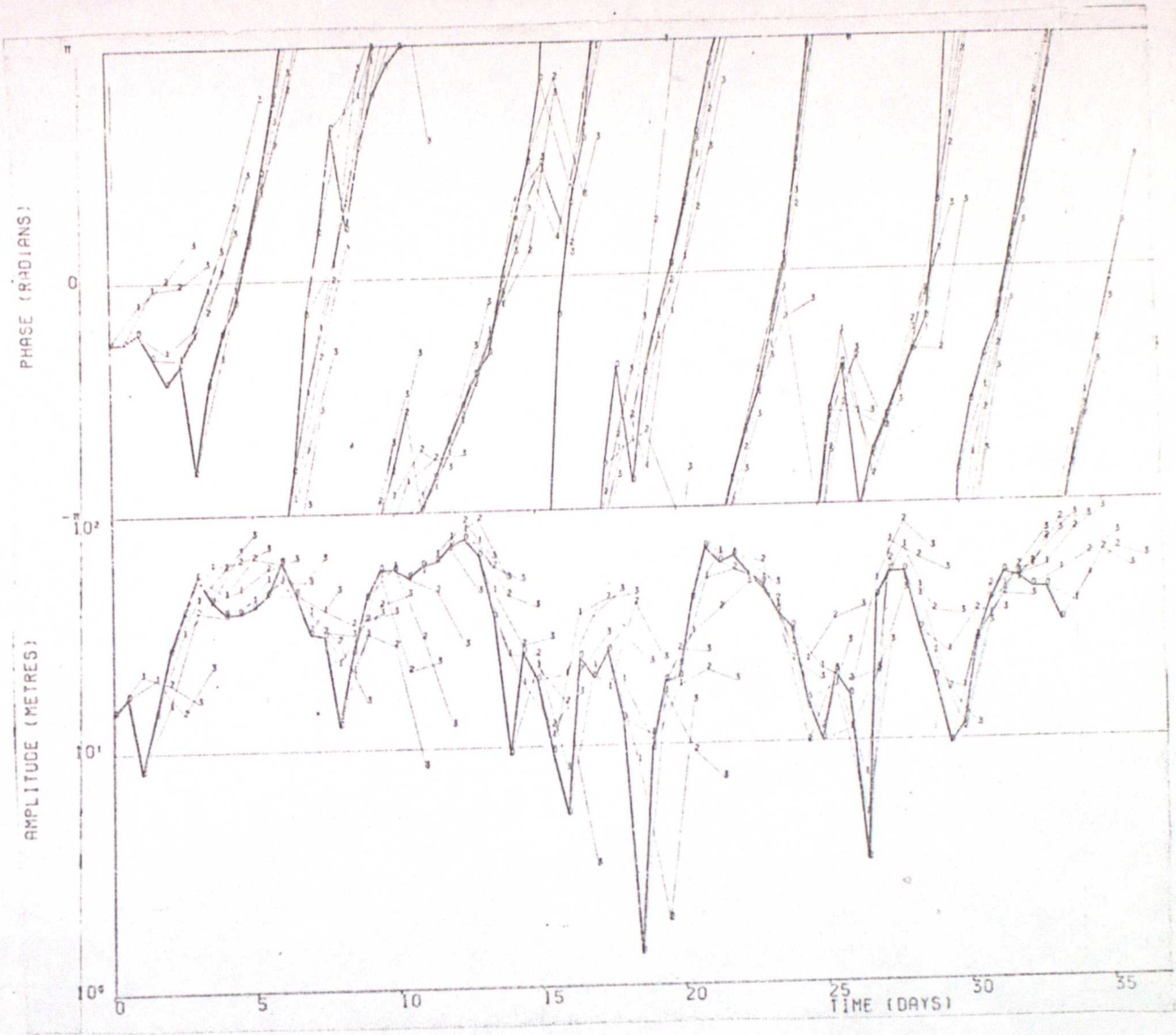

Fig.(11): Plots of the amplitude and phase of the m=7 wave against time, for the period OZ 14/11/73 to OZ 20/12/73. Other details are as for fig.(1). The quasi-periodic fluctations of amplitude and phase show a remarkable similarity to those seen in a"vacillating" laboratory system.

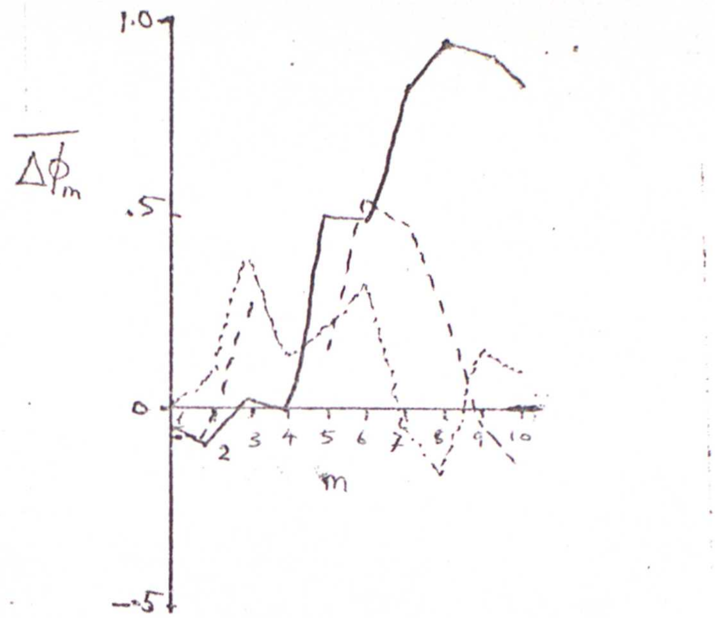

Fig.(12): The mean phase error plotted against wavenumber. The datawas for 500mb heights at 50°N, and the sample consisted of 327 operational forecasts.
——— - 1 day forecasts, - - - - - 2 day forecasts, ... - 3 day forecasts.

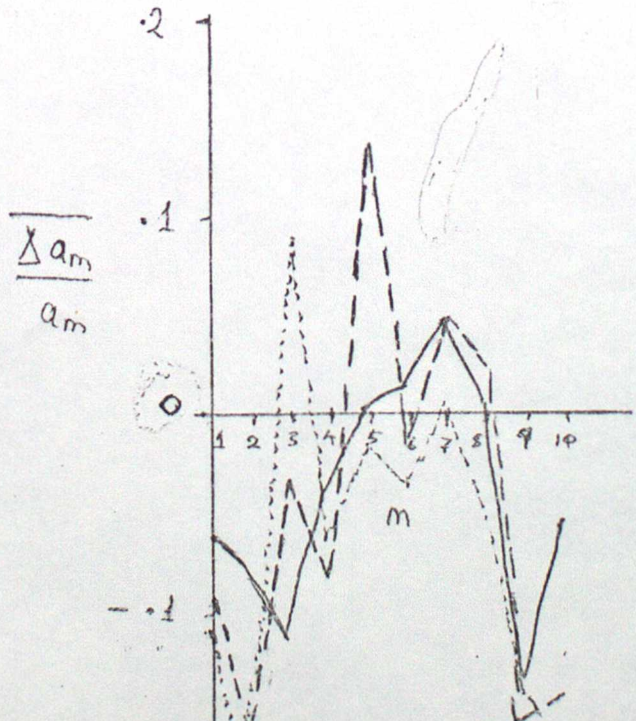

Fig.(13): The mean **relative** amplitude error plotted against wavenumber. Legend and other details are as for fig.(12).

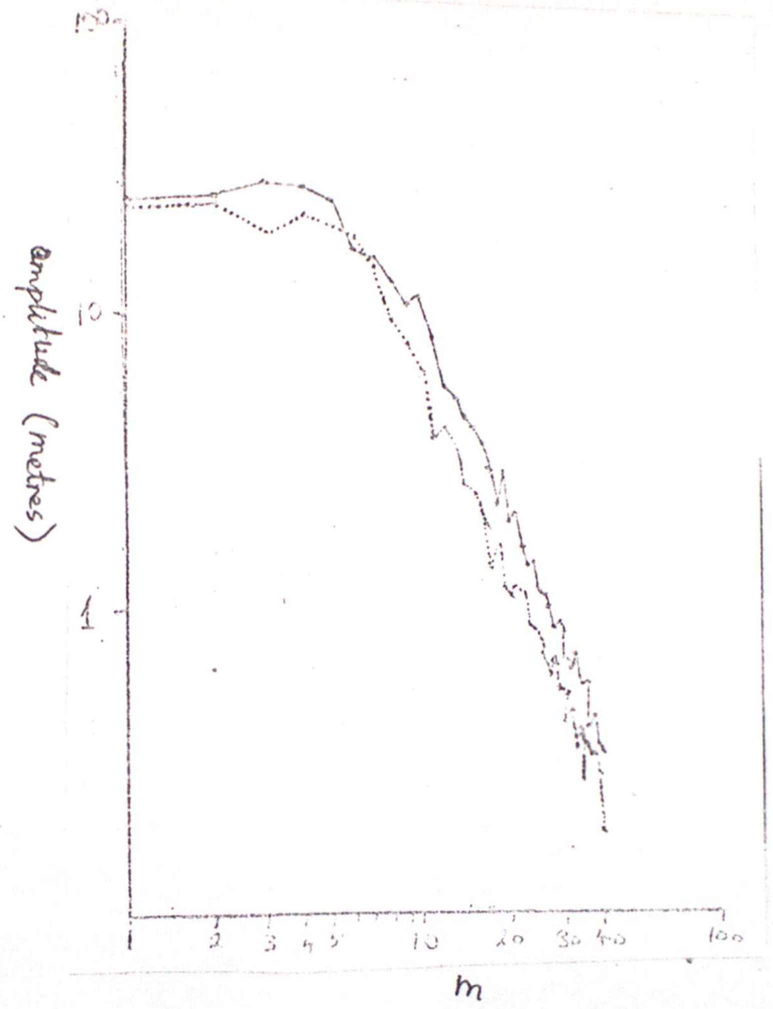

Fig.(14): Mean spectrum of the 500-300mb thickness for the period OZ 7/5/74 to OZ 25/5/74. ——— - spectrum of analyses, ... - spectrum of 3 day forecasts.

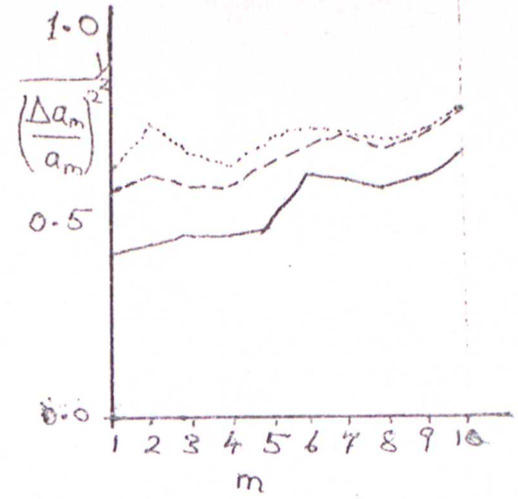

Fig.(15a): The root mean square relative amplitude error plotted against wavenumber. The sample consisted of 327 operational forecasts. ——— - 1 day forecasts, – – – - 2 day forecasts, ...- 3 day forecasts.

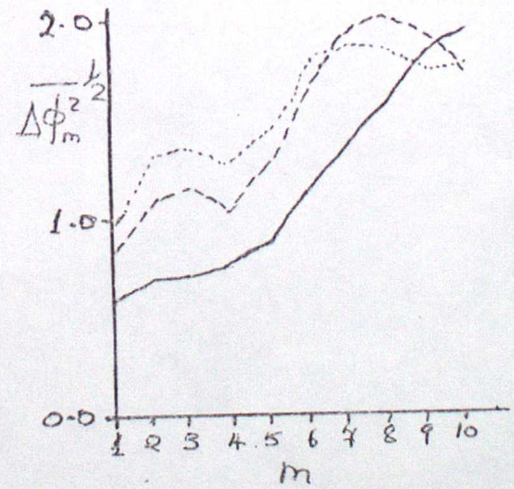

Fig.(15b): The root mean square phase error plotted against wavenumber.