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MET O 11 TECHNICAL NOTE No. 60

EXPERIMENTS WITH A STRIPPED VERSION OF THE QUASI-HEMISPHERIC 10-LEVEL MODEL

by

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SUMMARY

In order to investigate more fully certain aspects of the 10-level model performance, a simplified version of the model has been produced, retaining only the basic dynamics and omitting various parameterized processes. This has been run using as the initial state flows for which there exists some theoretical understanding. In particular, runs for a variety of Rossby-Haurwitz waves and for a growing baroclinic wave have been undertaken. Some provisional conclusions are drawn, and recomendations for the future course of this project are discussed.

1 WHY STRIP?

Earlier work concerned with the behaviour of large-scale planetary and baroclinic waves in the 10-level model (see James 1975) showed considerable errors in the large scale motion; in particular wavenumbers 2 and 3 were poorly handled, and systematic errors were noted for the shorter travelling waves. Generally, stationary waves are too mobile and non-linear interactions between waves are poorly predicted.

The errors in the long waves are of particular concern for medium-range forecasting, especially as the mechanics of the long waves are poorly understood. A number of possible sources of the errors may be enumerated:-

(a) Errors of observation and analysis

(b) Handling of topography and surface heat sources

(c) Poor resolution on the smallest scales must ultimately (via Fjortofts theorem) lead to errors on larger scales.

(d) Recent work suggests that an important energy source for long waves is via the interactions between baroclinic waves of similar wavenumber (see Hide, Mason & Plumb, 1976). If this is so then factors which affect the baroclinic waves should be significant, e.g. the number and disposition of levels, static stability calculations and so on.

Evidently in an operational forecast, these various factors will be inextricably linked, and it will not be possible to sort out one from another by the analysis of large bodies of data. Experiments of a controlled nature, whereby different sources of error can be singled out or suppressed, are called for. The philosophy of the stripped model is to isolate the dynamic processes in the model by

(a) Suppressing various microphysical and parameterized processes (the "physics")

(b) Starting the integration off with simple flows for which there exists some theoretical understanding.

Amongst other effects, this eliminates the data problem.

The remainder of this paper describes how this is achieved, and describes some experiments which have already been carried out. Section (6) suggests a further programme of experiments.

2 HOW TO STRIP

The stripped model excludes the following features of the operational model:-

(a) Moisture

(b) Surface exchanges of heat and moisture

(c) Radiation

(d) Topography, and land/sea distinctions. It would be desirable to reintroduce topography later (see section 6).

The following features are retained:

(a) Advection, coriolis, buoyancy and pressure gradient terms.

(b) thermodynamics of a dry statified atmosphere.

(c) dry convective adjustments.

(d) Internal diffusion. This performs the roles both of controlling computational noise, and parameterizing the effects of sub-grid scale motions. A high diffusion zone near the lateral boundaries is retained.

(e) Surface drag. This was included so that a boundary layer could form on the lower surface.

Two methods are used to "strip" the octagon. In some cases, the relevant subroutine has been replaced by a dummy subroutine which merely returns control to the calling program. This has been done (for example) with the surface exchanges subroutines and the condensation and evaporation subroutines. In the case of other processes, the stripping is achieved by zeroing appropriate words of the initial data set. This is done with topography and humidity. The land/sea distinction is abolished similarly (word 55 of the column is zeroed, since if it were greater than 200, this word would be interpreted as a sea surface temperature, otherwise as the longitude on land; thus the drag appropriate to a land surface is always obtained).

In setting up the initial states for the stripped experiments, I have always prescribed a streamfunction for each level. In the case of the barotropic flows, it is identical at all levels while in the case of baroclinic flows it varies according to the level. Differentiation of the stream function yields the velocities. The height (and hence thickness or temperature) fields are obtained assuming the geostrophic relationship by a solution of the linear balance equation:-

$$\nabla^2 h = \frac{1}{g}\left(f\nabla^2\psi + \underline{\nabla} f \cdot \underline{\nabla}\psi\right) \qquad (1)$$

Here, f is the coriolis parameter, and g is the acceleration due to gravity. The operators $\underline{\nabla}$ and ∇^2 refer to the horizontal operators.

A program has recently been written to solve the more complicated non-linear balance equation

$$\nabla^2 h = \frac{1}{g}\left(f\nabla^2\psi + \underline{\nabla} f \cdot \underline{\nabla}\psi + 2\left[\psi_{xx}\psi_{yy} - (\psi_{xy})^2\right]\right) \qquad (2)$$

These elliptic equations are solved by a simple Successive Overrelation (S.O.R.) method. The boundary conditions are taken to be the ICAO values at the equator. Since this initial flow is non-divergent, vertical velocities are initially zero.

Two stripped model load modules have been produced, (called ISTRIP and IFLEXY). The first is the usual 300 km gridlength model with a maximum of 61 points in either direction. IFLEXY is derived from the variable mesh version of the model. It has been used to run a equatorial model, with a 300 km grid length but with a maximum of 79 and a minimum of 35 points in each direction, forming an octagonal boundary which is approximately inscribed by the equator. This version of the model could also be used for runs with a finer mesh (down to 150 km grid length).

3 THE ROSSBY-HAURWITZ WAVE

The shallow water equations on a sphere yield the spherical harmonics as eigenmodes of the stream function. They have the form

$$Y_n^m(\mu,\lambda) = P_n^m(\mu)\, e^{im\lambda} \qquad (3)$$

where λ is longitude, $\mu = \cos(\theta)$, where θ is the co-latitude, and m is the wavenumber of the wave. The P_n^m are the associated Legendre functions of order m and degree n. Their form is described in standard text books; suffice it to say that n-m yields the number of zeros in the range $-1<\mu<1$. The form of the spherical harmonics is illustrated in figure (1).

These waves are the Rossby-Haurwitz waves and are the generalization of the usual Rossby waves on a β-plane. Like Rossby waves, they propagate (relative to the mean flow) from east to west at a constant speed. Their stability is a matter of some debate (Hoskins 1973) but it is generally agreed that waves up to m=4, n=5 are stable. Higher wavenumber waves may break up into other waves (the so-called "barotropic" instability).

Stream functions of the form in equation (3) provided the initial fields for runs of the stripped octagon. A number of different Rossby-Haurwitz waves have been integrated; they are summarized in table (1).

I shall describe the run BT45R02 in some detail; some of the questions raised by this run can be answered with reference to the remaining runs, which will be described more briefly.

Fig (2) shows the initial state of run BT45R02. Displayed are the 500 mb heights, 500 mb wind vectors, 500 mb absolute vorticity and the "vertical velocity" (= DP/Dt) at 550 mb. It will be noted that there is very considerable inflow and outflow around the boundaries of the octagon.

After integrating for just one day, the height fields are significantly distorted (fig 3). Large velocity shears develop near the boundary, since the boundary values are artificially held constant while the inner values are changed. This is particularly manifested in the very curious values of absolute vorticity attained near the edges.

The most noticeable feature in the height fields of fig (3) is the slope of the ridge and trough axes. This must lead to a northward flux of zonal momentum. The results are seen in fig (4), where the fields after integrating for 3 days are shown. The high pressure centres have moved inwards, breaking away from the boundaries, to form an independent set of circulating systems in higher latitudes. The mean zonal flow is from east to west at latitudes from 30 to 40°N. Finally, the 6 day integration (fig 5) shows a complete breakdown of the original flow, leaving the low pressure centres fixed on the diagonal walls, and complicated jet-like structures at higher latitudes.

The assymmetry in the behaviour of the high and low pressure systems was first attributed to some error in the boundary formulation for the diagonal walls. To test this hypothesis the runs BT45R03, which was similar to this run, but with the positions of the high and low centres reversed, and BT34R01, which had a three - rather than four-fold symmetry, were integrated. In both runs, the results were very similar to those for BT45R02. The lows remain more or less stationary near the boundary, while the high pressure centres more inwards and disperse, forming jets at various latitudes.

The crude lateral boundary conditions in which both velocities and heights are held fixed at all times affords a more likely explanation for the distortion than errors in the program. As shown in figure (6), low centres tend to move into outflow regions and so become fixed near the boundaries, while high pressure centres move into inflow region and so are advected inwards. The distortion of the trough axes due to the boundary condition accounts for the strong zonal jets formed at various latitudes. Of course, the Rossby-Haurwitz wave is a highly artificial flow to impose on the system, compared with observed fields, and so perhaps these results should occasion no surprise. Their value lies however, in demonstrating the great rapidity with which errors in the boundary formulation can propagate throughout the entire area of integration.

A second Rossby-Haurwitz wave was integrated to test the idea that the fixed inflow and outflow points might be causing the unrealistic behaviour of the Rossby-Haurwitz wave. The m=4, n=7 wave has much smaller in and outflow velocities, and there is initially no flow across a latitude circle near 24°N. Hence, north of this latitude, the effects of the boundaries should be considerably reduced, and the inner circulating systems might be expected to behave more realistically.

This was indeed found to be the case. The results of the integration are shown in Figs (7) and (8) which show the initial field and the integration after 3 days for the run BT47R01. Similar effects are seen near the lateral boundaries as for the earlier runs, but at high latitudes the flow is more realistic. Ultimately the flow does nevertheless break down a manner similar to the earlier runs; the important point is that the total breakdown is postponed by reducing the cross-flow at the boundaries.

4. THE BAROCLINIC WAVE

The next phase of the stripped model investigations was concerned with the simulation of growing baroclinic waves. The initial state of the atmosphere was defined by a zonal velocity everywhere, depending on colatitude θ as

$$u(\theta) \propto \sin^2\left[\pi \tan(\theta/2)\right] \tag{4}$$

This describes a broad jet, centred at about 37°N. In the vertical, the dependence of U on pressure is shown in Fig (9), a freely drawn curve which is a schematic representation of typical mean winter zonal winds in the northern hemisphere. The maximum winds are at 200 mb, which also represents a "tropopause" above which the temperature increases with height.

The solution of the balance equation described in Section 2 yields geopotential heights at each level and hence the thickness (or temperature) at each level. Figures (10) and (11) show the initial fields which result. A small spherical harmonic perturbation with m=8, n=11, was added into the stream function, amounting to around 5% of the total streamfunction. The greatest temperature variation is at 350 mb (where the vertical shear of velocity is greatest). The highest (150 mb) layer has a temperature maximum at the pole, and so has some of the properties of the real stratosphere.

Some 2-2½ days are required for the wave to organize itself as a growing baroclinic wave. Thereafter it grows steadily, moving from West to East at a steady rate. The fields at 500 mb after integrating for 6 days are shown in Fig (12). The jet has tightened considerably and has developed meanders of large amplitude, still at wavenumber 8. The tilts of trough and ridge axes associated with northward transport of zonal momentum are pronounced. It is not evident to what extent this is an effect of the wave being artificially retarded at the boundaries, and to what extent it represents a genuine physical development of the wave. The ω- field indicates some residual gravity wave activity in the polar regions (probably due to inaccuracies in the initialization via a linear balance equation), but is otherwise reasonable.

The wave attains its fullest development after 8 days or so, thereafter declining in amplitude and taking on a barotropic structure. The fields at 8 days are shown in figures (13) and (14). The tilting of troughs is very marked and there is evidence that the low centres are beginning to "occlude". This effect is seen more clearly in the 550 mb and 950 mb temperature fields. Further south, the temperature troughs are titled sharply backwards. This effect is certainly due to the boundaries and is spurious.

The 350 mb temperature field is somewhat irregular, though careful examination reveals that there is still a marked 4 or 8 fold symmetry in the fields. It is thought that the strong vertical shears at this level have destabilized harmonics of the wavenumber 8 perturbation, and so an irregular flow develops at this level.

Fig (15) shows the results of Fourier analysis of the 800 mb, 500 mb and 200 mb height fields, and shows the variation of amplitude and phase with time. The model requires 2-2½ days before the phase lags characteristic of a growing baroclinic wave develop. Thereafter they are maintained for several days while the wave progresses steadily. It is noteworthy that the wave spreads from the lower to the upper levels, and that the greatest variation in phase and amplitude occurs between the lower levels.

A curious result from the Fourier analysis is that, in addition to the harmonics of the perturbation of wavenumber 8, its subharmonics of wavenumber 2 and 4 (especially 4) are also excited as the wave grows. This is inexplicalbe in terms of linear theory, but may be the result of interactions with the boundaries which have a 4 fold symmetry. It would be of interest to simulate a wavenumber 10 perturbation and see whether wavenumber 5 (the subharmonic) or wavenumber 4 (the "boundary" wavenumber), or indeed either, is excited.

From a numerical point of view, the absolute vorticity field becomes very noisy after this time, and so it may not be meaningful to integrate the 10-level model beyond the 12 days or so to which this run extended. Of course the model was never designed to run much beyond 3 days, and it is known that there are various rather slow instabilities inherent in the formulation.

5 CONCLUSIONS

The work to date is at a fairly preliminary stage, and the time has not yet arrived when it is possible to draw very firm conclusions. It will be necessary to extend this work considerably before sufficient data from which to seek explanations of the long-wave errors will be available. In the next section I shall discuss possible lines along which further research might be continued. However, even at this stage, it seems likely that one source of error has been identified in the lateral boundary formulation.

This is evident both in the Rossby-Haurwitz wave experiments which show that boundary errors can propagate across the interior of the mesh on a very short timescale, and in the baroclinic wave experiments which seem to show the spurious forcing of wavenumber 4 by the boundaries, and also an erroneous tilting of the troughs, leading to spurious momentum transports.

Qualitatively, the growth of a pure baroclinic wave is well represented. Further work is necessary before quantitative assessment of the accuracy of the model can be made. The simulation described showed that much of the structure of the wave was confined to the lower levels of the model, a fact which may have some bearing on the optimal vertical structure required. It might be argued that additional lower layers should be incorporated into the model.

Finally, I would point out that the stripped model provides a powerful tool for investigating the dynamics of the model, and for assessing the significance of other processes. Experiments such as those described above should be used in testing future developments or reformulations of the model, thereby affording valuable information about the behaviour of the model in an efficient manner.

6. RECOMMENDATIONS FOR FUTURE WORK

The work described in this paper forms part of an oncoming project, and is only at a fairly early stage of its development. The conclusions to be drawn so far were discussed above; in this section I shall recommend some of the future lines of work which it might be possible to pursue. My recommendations fall into two categories, firstly, fairly specific suggestions for short and medium term objectives, and secondly, more general remarks about longer term plans.

The "equatorial" version of the stripped model has been used for a simulation similar to the wavenumber 8 baroclinic waves described above, but the results have not been discussed in the present paper since supporting diagnostic programs are not completed. It would be useful to re-run some of the Rossby-Haurwitz wave simulations using this model. Since there is no flow across the equator, it might be expected that the effects of the boundaries would be considerably reduced. In particular, the "trapping" of the low pressure centres should be removed. Similarly the distortion of the temperature fields for the baroclinic run might be reduced; it would be interesting to see whether the growth or movement of the wave were significantly changed.

However, removal of the boundaries to a region where their effect should be weaker is only a partial solution to the lateral boundary problem. The fixing of variables at the boundary still operates, and will ultimately distort the flow within the domain of integration. Efforts should be directed at an early stage to revise this boundary condition. My own view is that the best solution is probably to suppress cross-boundary flow entirely and represent the lateral boundary by a slippery rigid wall, since it is not possible to devise stable schemes whereby an inflow velocity can be updated on a boundary. This may need to be taken in conjunction with boundaries at the equator to afford the best results. The effects of such a formulation both on the growth of baroclinic waves and on the motion of the Rossby-Haurwitz wave should be investigated.

Much work remains to be carried out regarding the simulation of baroclinic waves. Simulation of waves of different wavenumber may shed further light on the boundary effects (I discussed this point in section 4). But beyond this, the general dispersion relation for baroclinic wave growth should be investigated. There is evidence that in models with a small number of levels, the larger wave numbers (above eight) are far too unstable, and that the usual instability maximum at wavenumber eight is poorly defined. The dispersion relation should be obtained by perturbing the zonal flow with a "white" mixture of waves, all of small amplitude and random phase. As long as the amplitudes remain small, non-linear effects should be second order, and the waves should grow independently.

In connection with these baroclinic experiments, there is evidence that the initial zonal jet used for the simulation was not a particularly good choice. This was particularly demonstrated by the noisy thermal field at 350 mb. The possibility of setting up a standard initial field which avoids this problem should be investigated.

A final medium term experiment is a collaborative project with the Reading group. It has been agreed that the 10-level model simulation of a wavenumber 8 baroclinic wave should be compared with simulations using 10-level versions of the U.K. Universities Modelling Group's spectral and gridpoint models. The initial states would be as nearly identical as possible, Such an experiment would be very useful, in affording a direct comparison of the independent formulations used by the various models.

I turn now to longer term objectives which should be pursued. Some depend on the work within the branch to be completed, while others can only be usefully set up when the results of some of the shorter term experiments are known.

An extension of the baroclinic wave experiment will be to investigate the effect of the vertical structure of the model. A new model is being prepared in which the number of levels and their spacing will be variable; a "stripped" version of this will be used to examine the modification of the dispersion relation as the number of levels is changed or as their distribution is altered. Such work is an important pre-requisite to the design of new models, and can easily be carried out by mean of stripped experiments, for there is no difficulty in defining consistent data at non-standard levels. Current opinion is that improved vertical resolution near the ground and around the tropopause, as well as more stratospheric levels, may be important in handling baroclinic instability at larger wavenumbers properly.

The next major step in the project will be to investigate the non-linear interactions between groups of waves in the 10-level model. The earlier work (James 1975) on data collected from the operational model strongly suggested that many of the large errors could be interpreted in terms of mishandling of non-linear interactions. Certainly this mechanism seems to be one of the few capable of transferring sufficient energy on short timescales to account for the fluctuations observed. In particular, the recent experimental work of Hide, Mason and Plumb (1976) lends greater importance to the interactions between baroclinic waves in determining the larger scale flow. It is likely that such mechanisms could be of considerable importance in the atmosphere, and their simulation by the 10-level model could be extremely important in elucidating the anomalous prediction of long waves.

I therefore suggest a comprehensive examination of wave interactions in the model, both between barotropic Rossby-Haurwitz waves and between baroclinic disturbances. The important "resonant" interactions should be mapped out, and the effects on the interaction of vertical resolution, lateral boundaries, and possibly of such matters as internal diffusion, etc. should be investigated. Such an investigation would be fairly novel, since most theoretical studies of numerical models have concentrated on confirming that linear phenomena can be well represented. It has been assumed that the numerical scheme must take care of the non-linear effects.

Further experiments to be described elesewhere (James 1976) have shown that, of all the elements removed from the model during the stripping process, topography and topographically dependent processes (such as surface drag) have the most marked influence on the forecast fields. The large scale flow is insensitive to physical processes, such as surface fluxes of heat and moisture, and latent heat release. It is therefore logical to consider the interaction of the simplified flows considered in this paper with simple topographic features. There is some theoretical discussion of these processes in the literature, while Met O 21 has undertaken experimental work on the effects of topography on baroclinic waves (Leach 1975). This work will probably be extended in the future. It should be emphasized that, although topography is an important element in the dynamics of the atmosphere and the model, the evidence of James (1976) is that fluid dynamic processes are probably more important on timescales up to 6 days. These priorities should be borne in mind in planning these longer term experiments.

REFERENCES

Hide, R., Mason, P J and Plumb, R A (1976): In preparation

Hoskins, B J (1973): Q J Roy Met Sec. 99 723

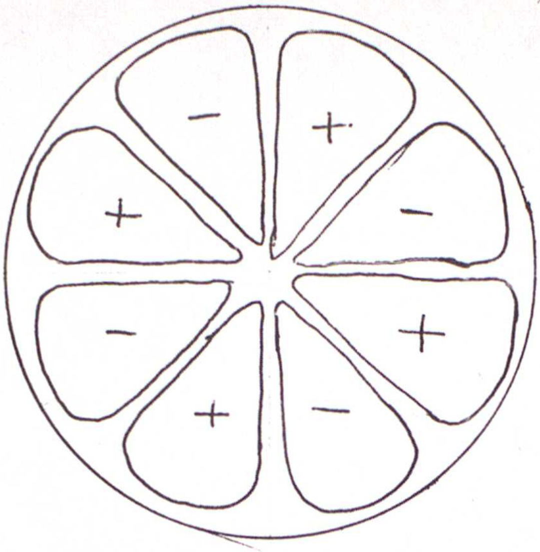
James, I N (1975): Met O 11 Technical Note No 50

James, I N (1976): Met O 11 Technical Note No 61 (in preparation)

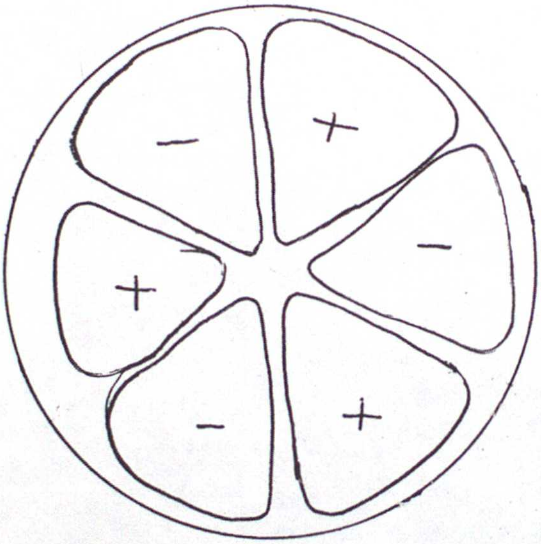
Leach, H (1975): Ph D Thesis, University of Reading and Geophysical Fluid Dynamics Laboratory, Meteorological Office.

run name	m	n	Remarks
BT45R02	4	5	
BT45R03	4	5	Phase differs by π from BT45RØ2
BT34R01	3	4	
BT47R01	4	7	

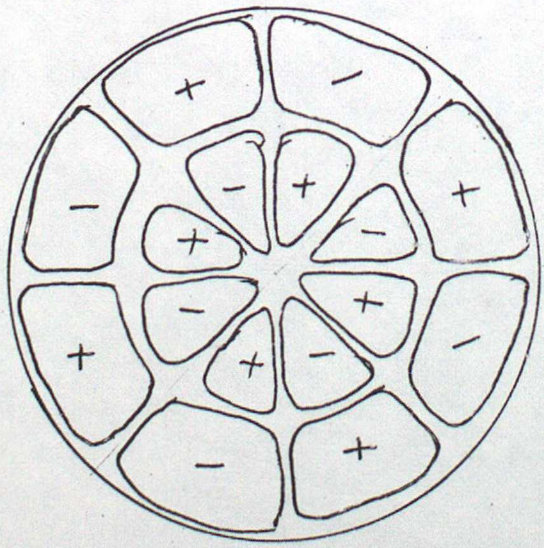
Table 1 : Summary of barotropic runs of the stripped model described in this note.



$m = 4, \quad n = 5$



$m = 3, \quad n = 4$



$m = 4, \quad n = 7$

Fig (1): Schematic examples of spherical harmonics

$$Y_n^m(\mu, \lambda) = P_n^m(\mu)\, e^{im\lambda}$$

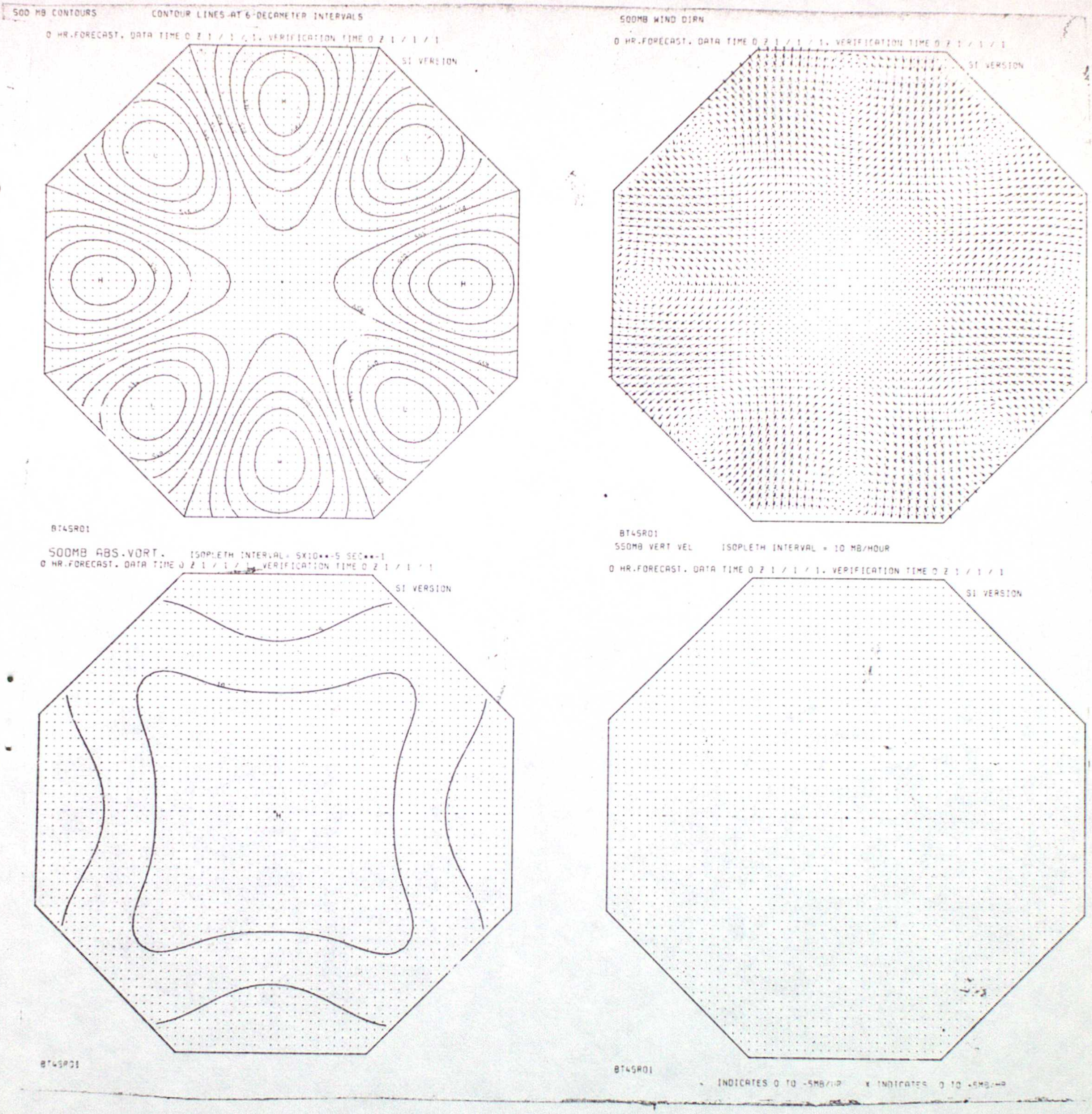


Fig (2) The initial state for the barotropic Rossby - Haurwitz wave run BT45RØ2

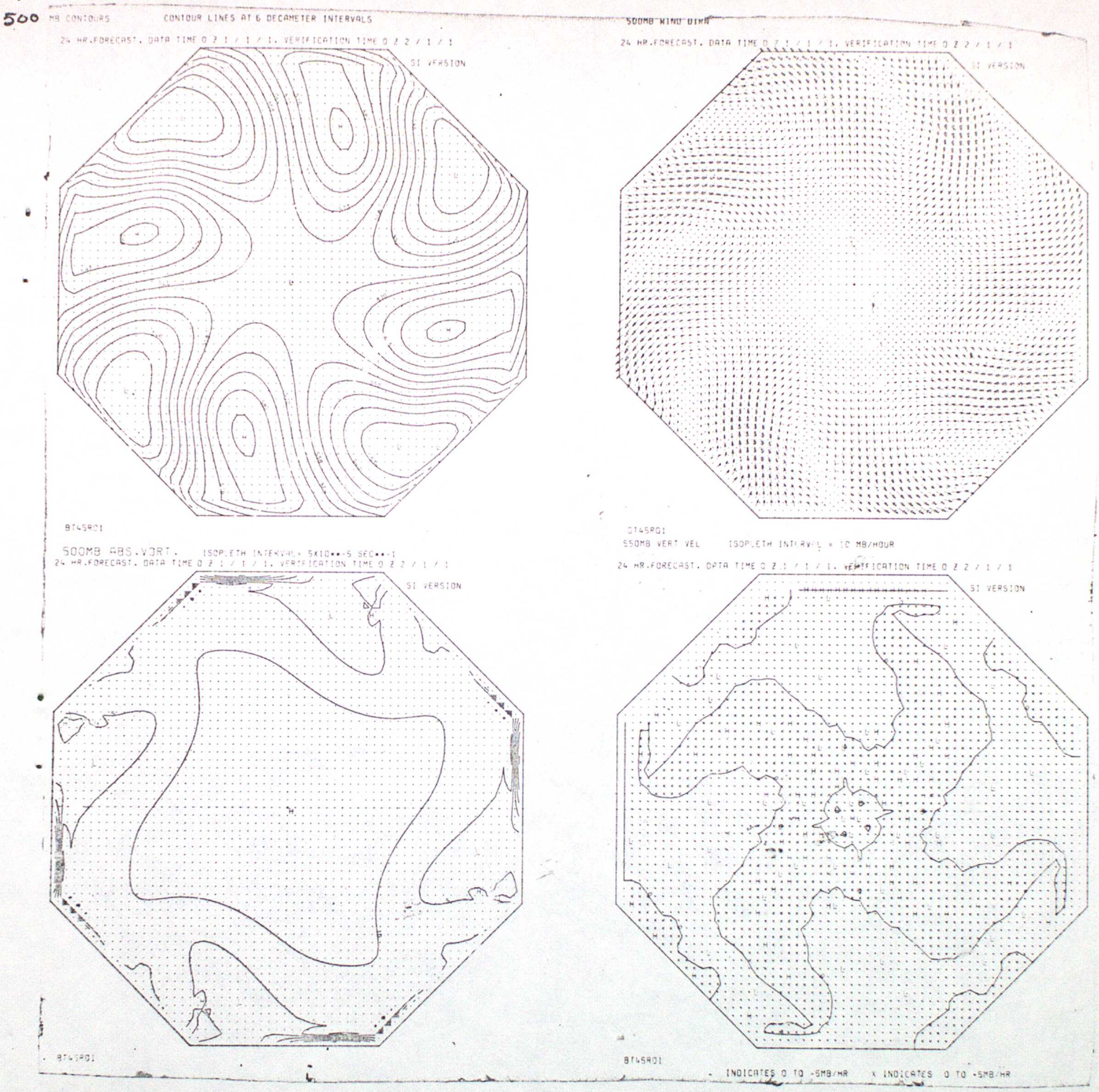


Fig (3) Run BT45RO2 after 1 day

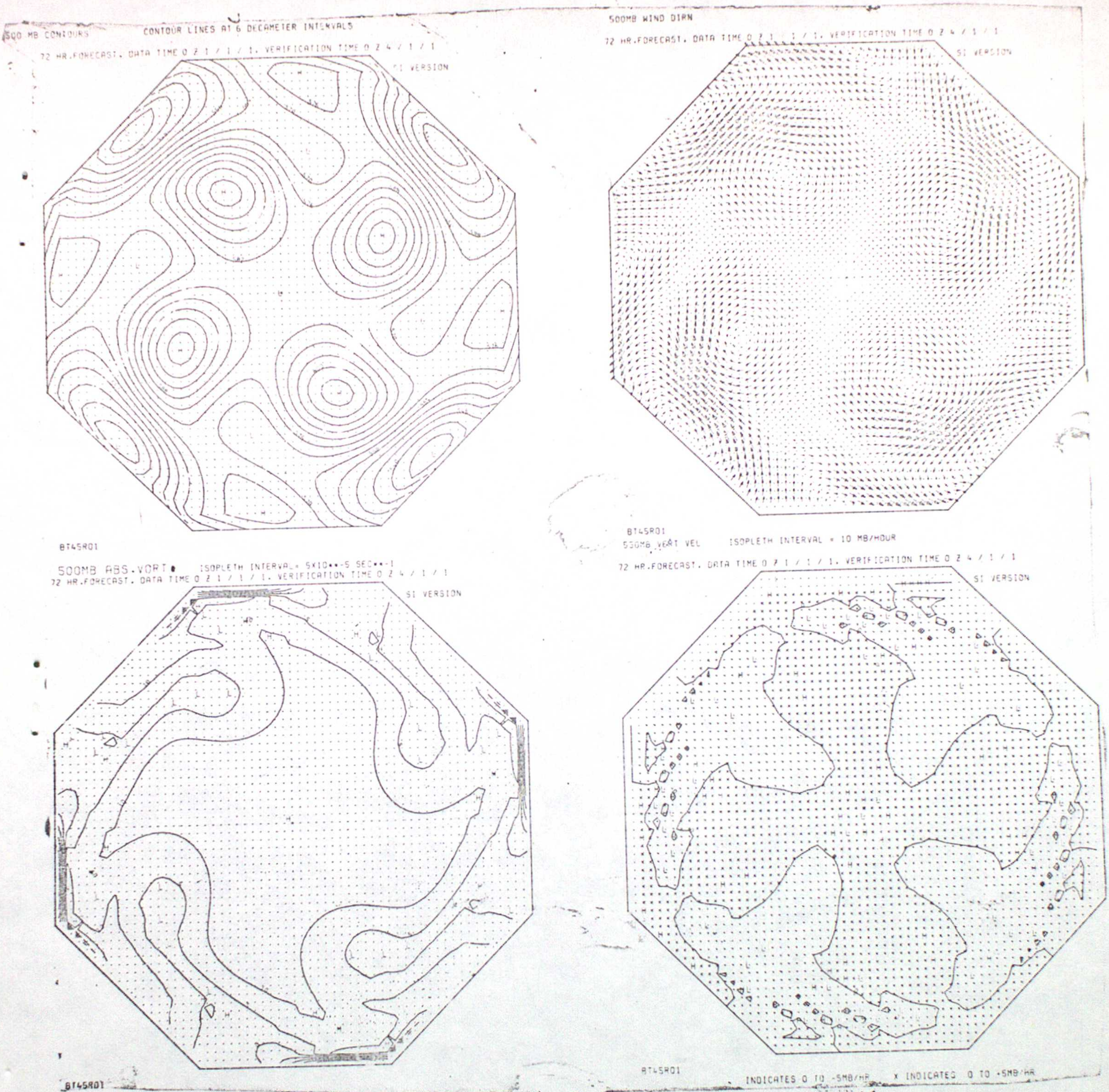


Fig (4) Run BT45R02 after 3 days

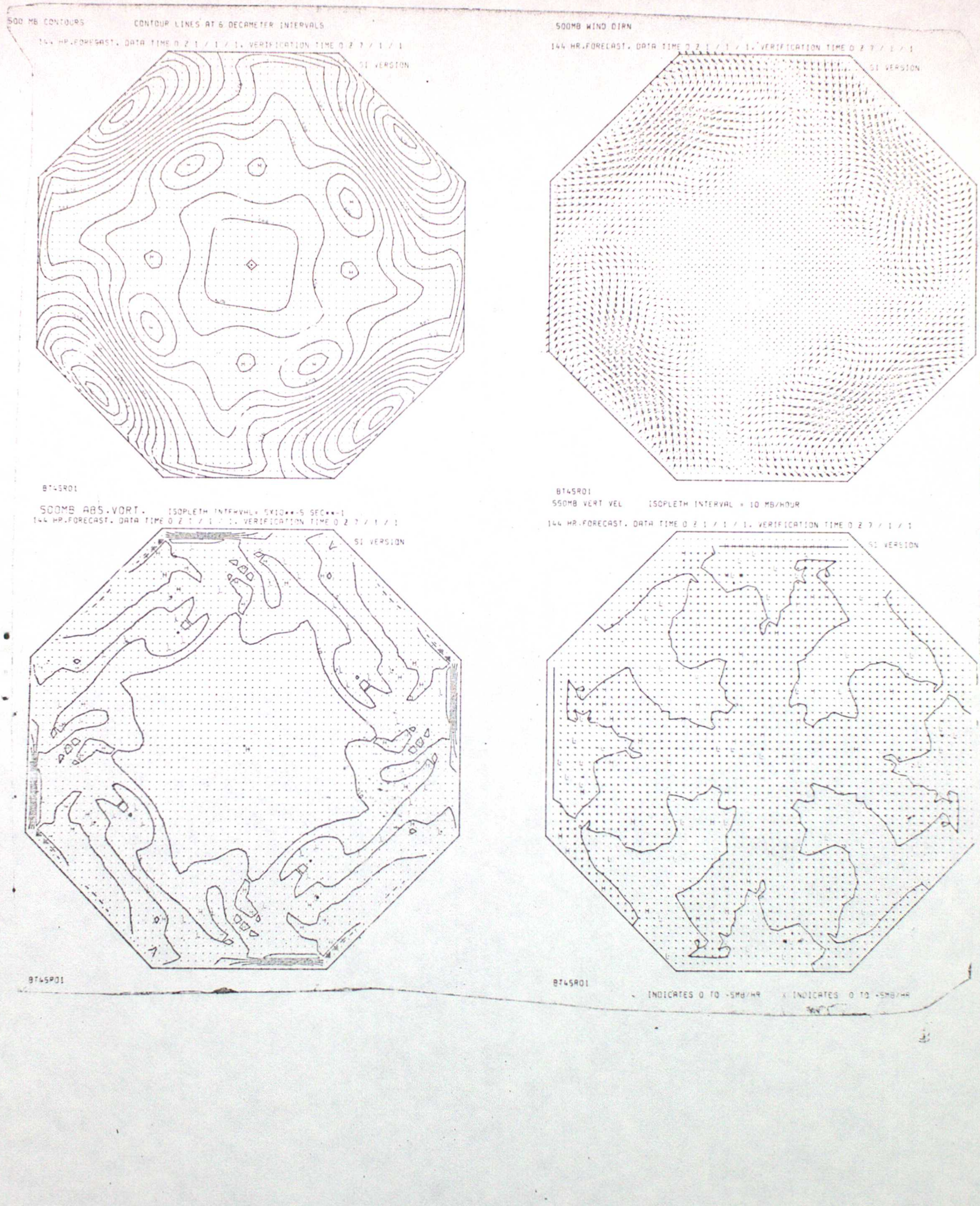


Fig (5) Run BT45R02 after 6 days

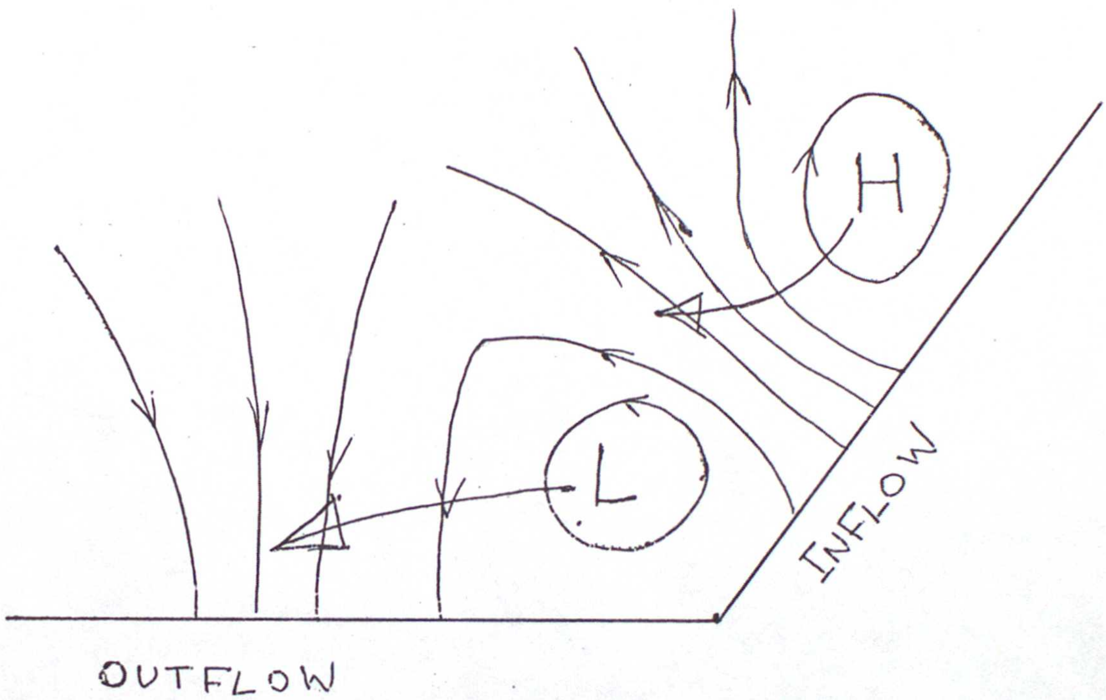


Fig (6) A schematic illustration of the behaviour of high and low pressure centres near the boundary of the 10 - level model

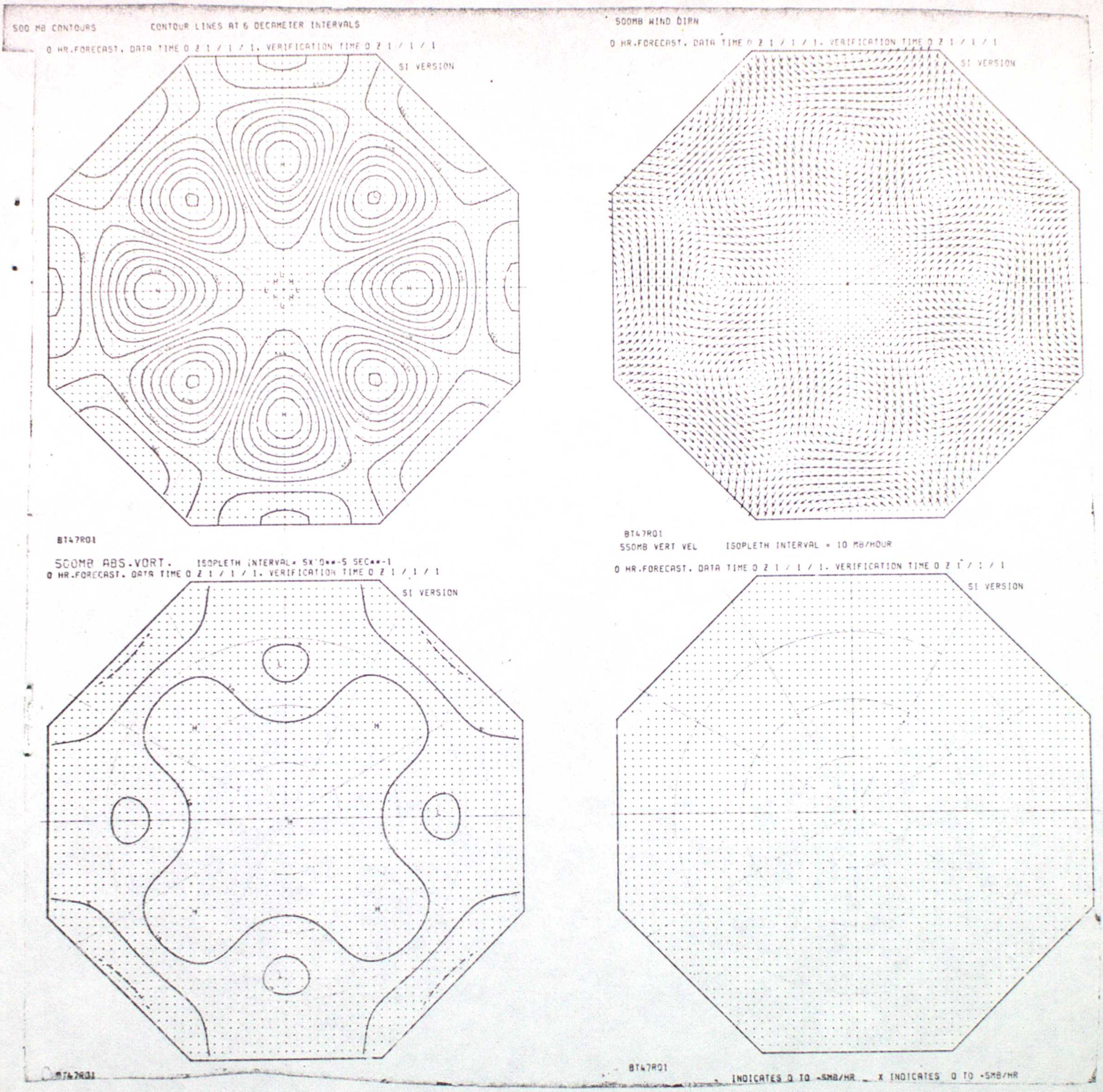


Fig (7) The initial state of run BT47R01

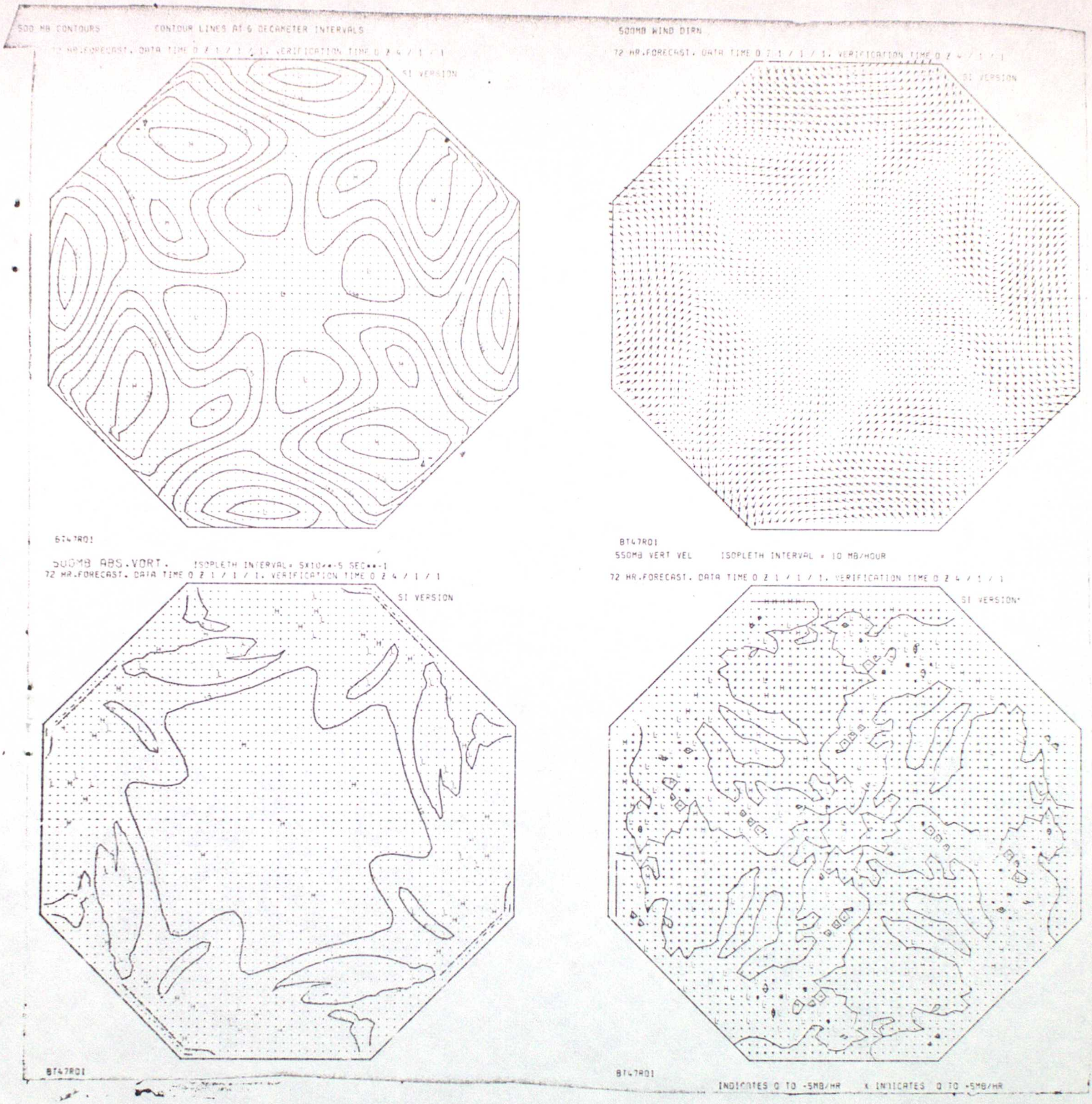


Fig (8) Run BT47R01 after 8 days

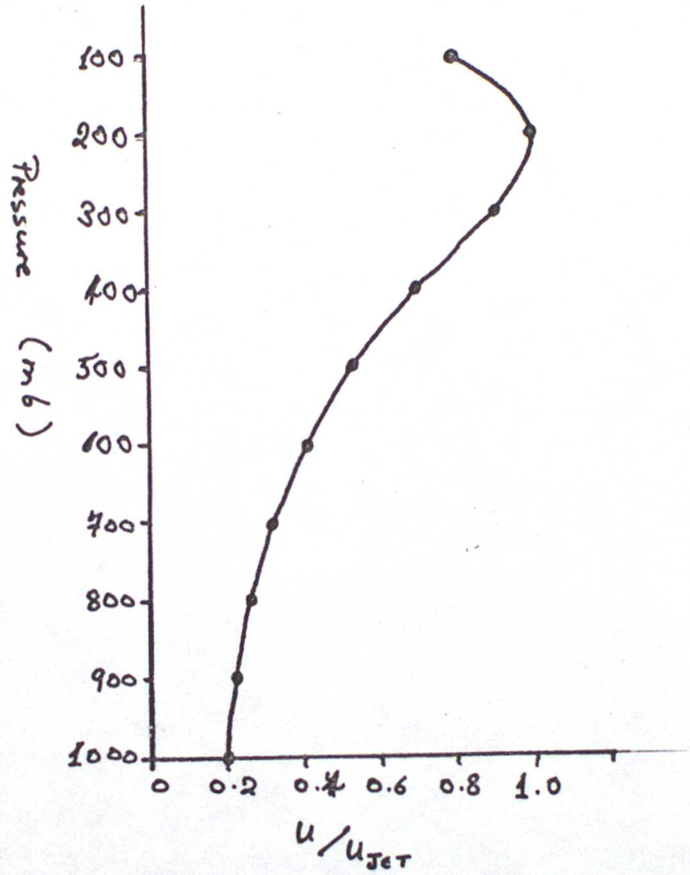


Fig (9) The vertical profile of zonal velocity employed at all points in the baroclinic simulations

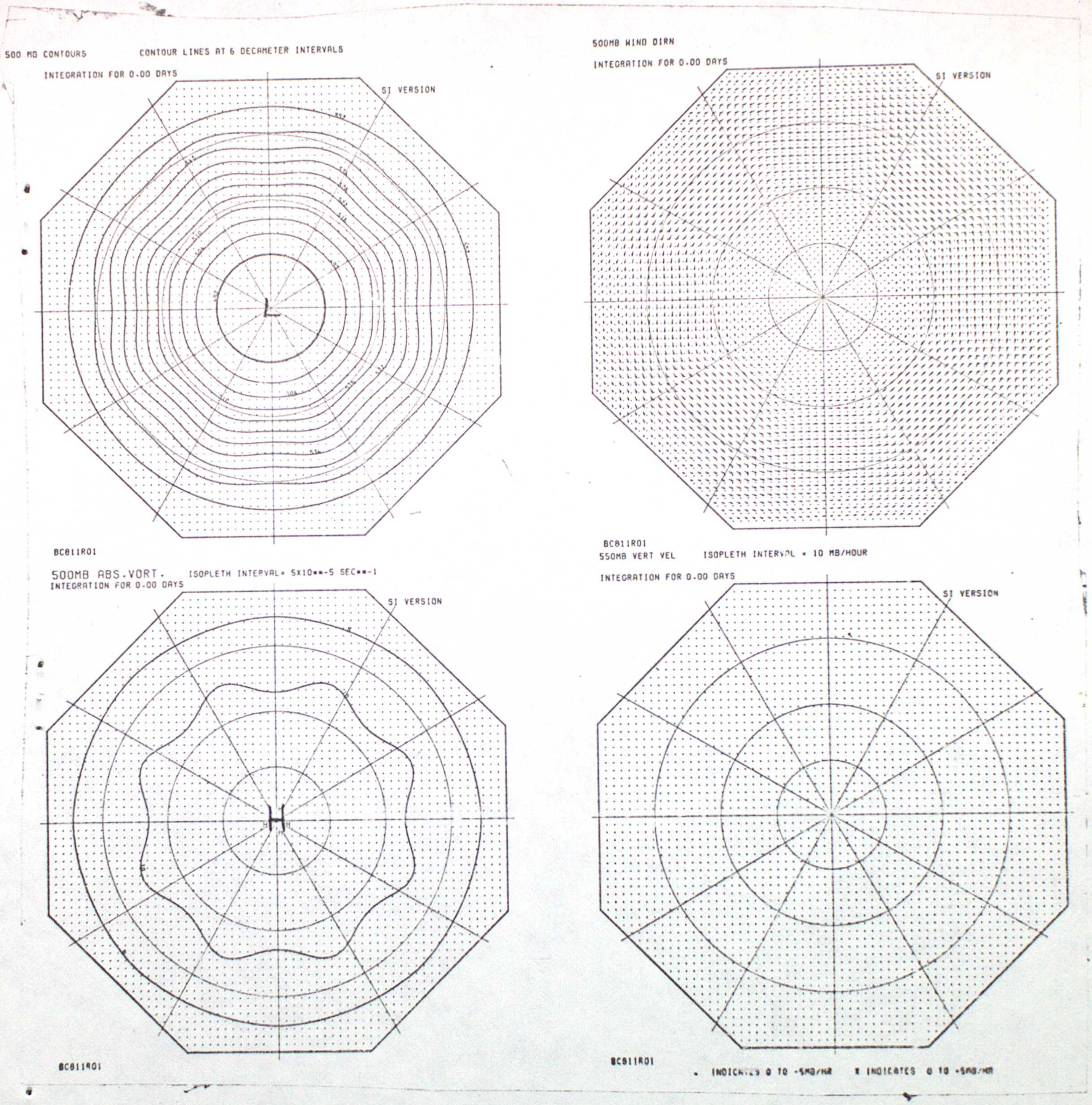


Fig (10) The initial state of run BC811R01 at 500 mb

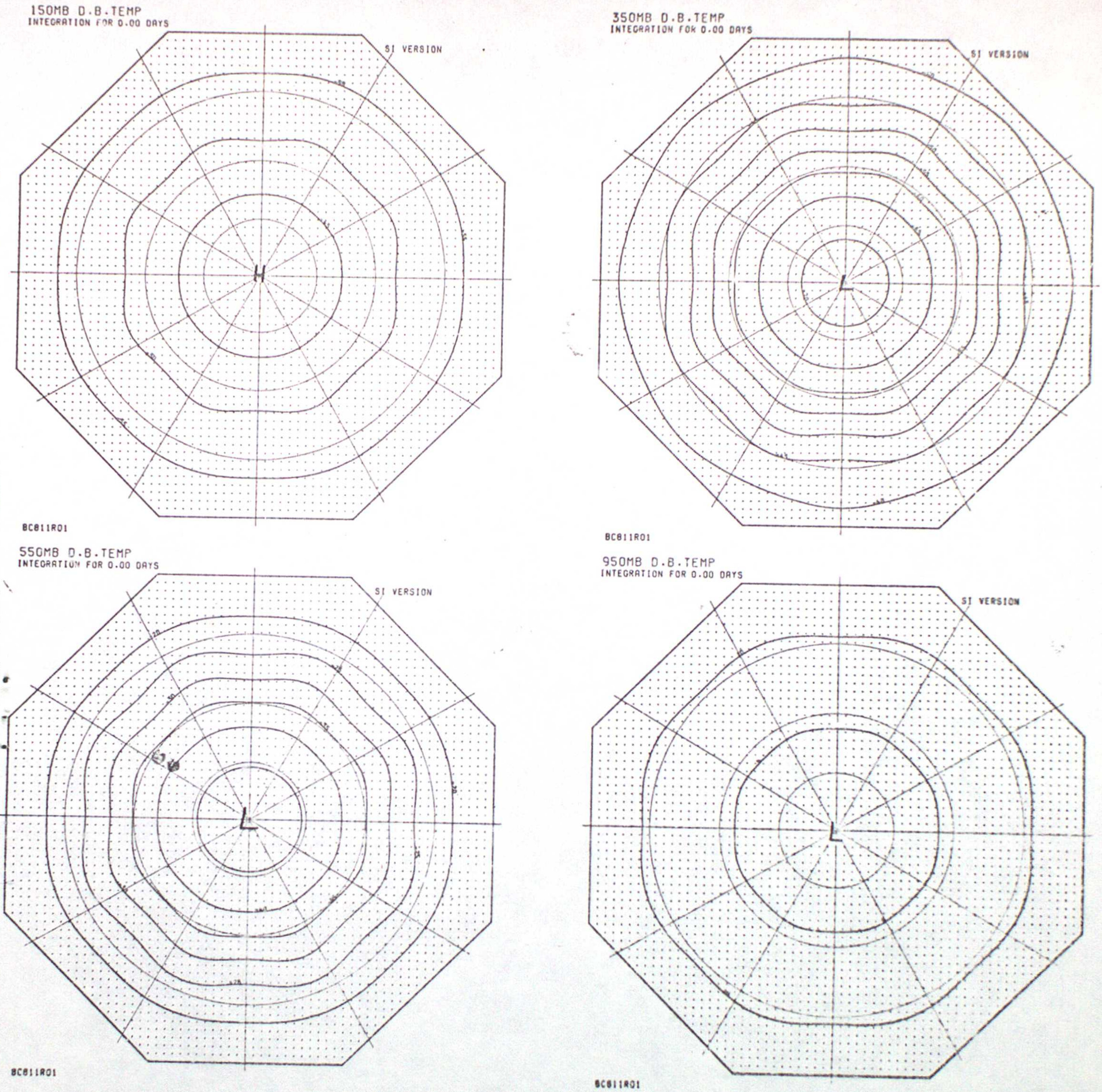


Fig (11) The initial temperature fields for run BC811R01

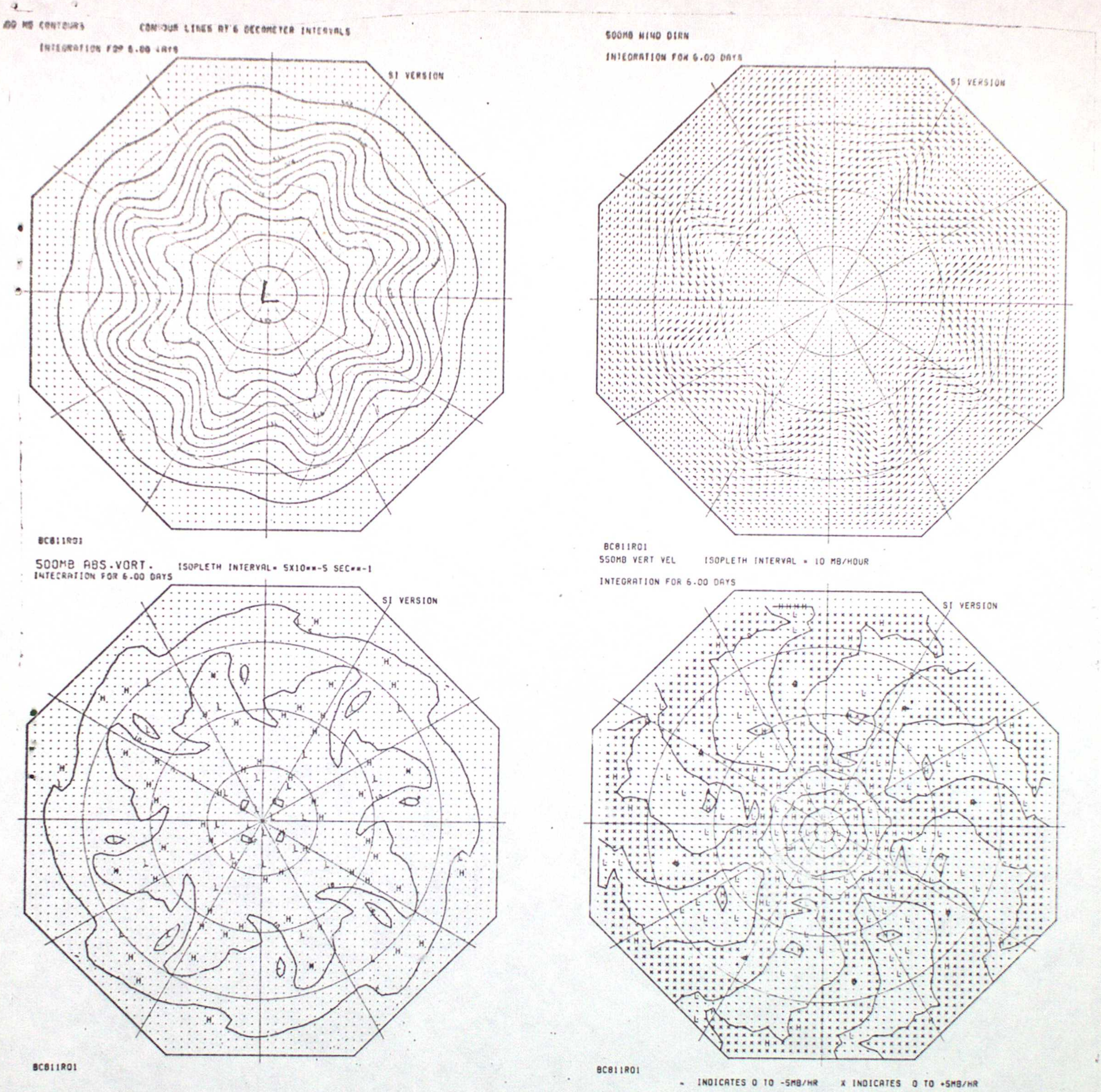


Fig (12) The 500 mb fields at 6 days for run BC811R01

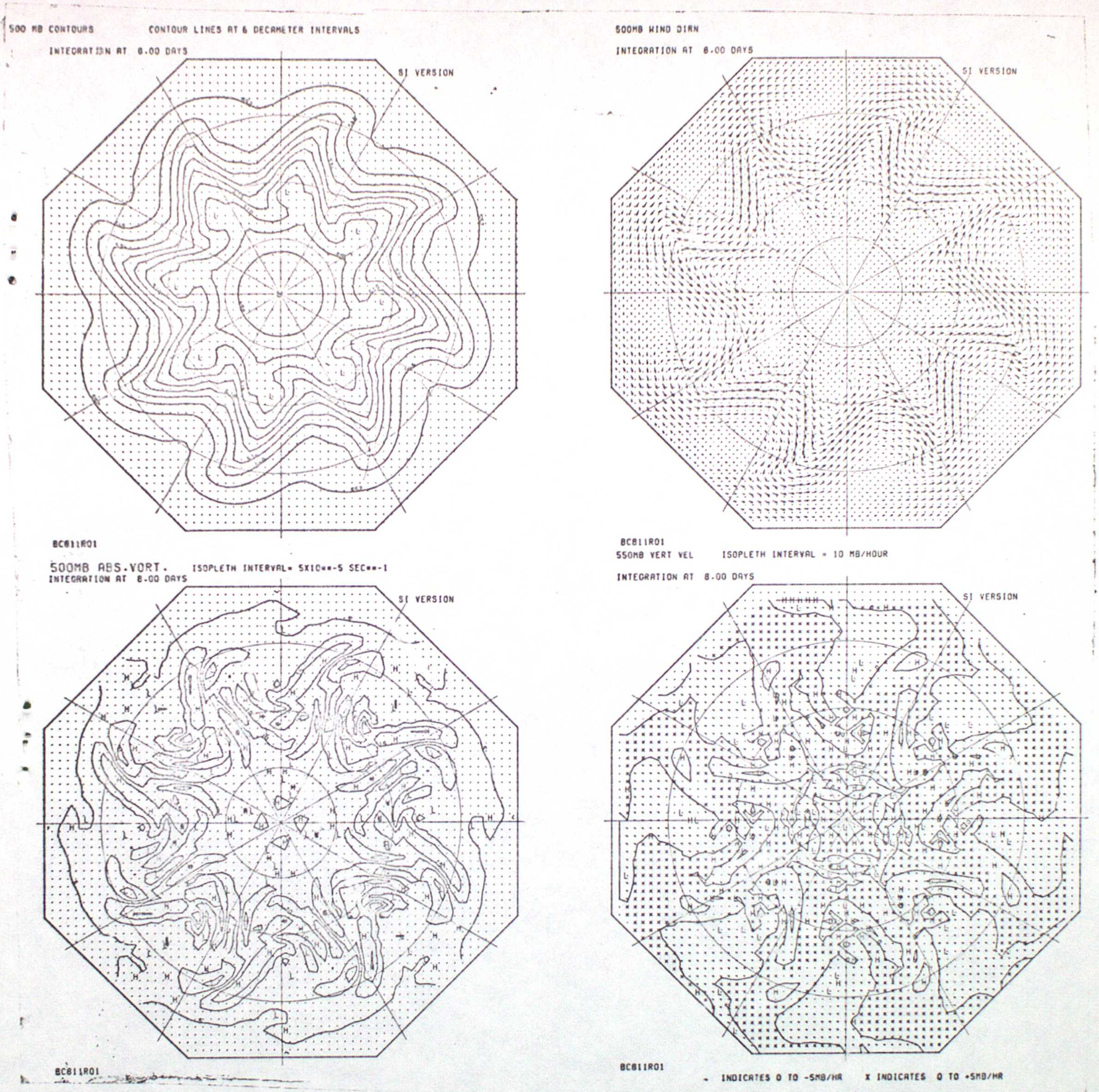


Fig (13) The 500 mb fields at 8 days for run BC811R01

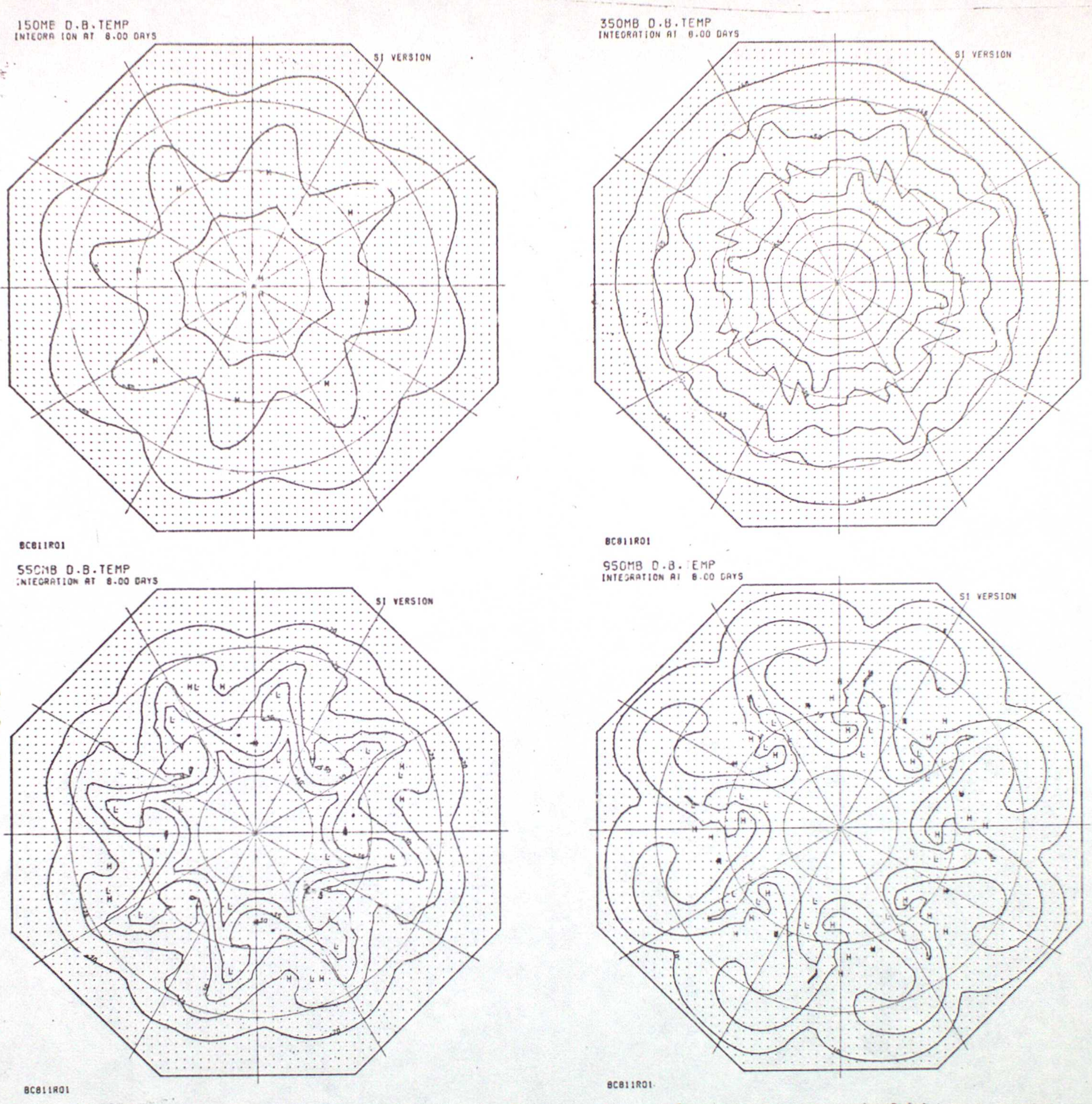


Fig (14) The temperature fields at 8 days for run BC811R01

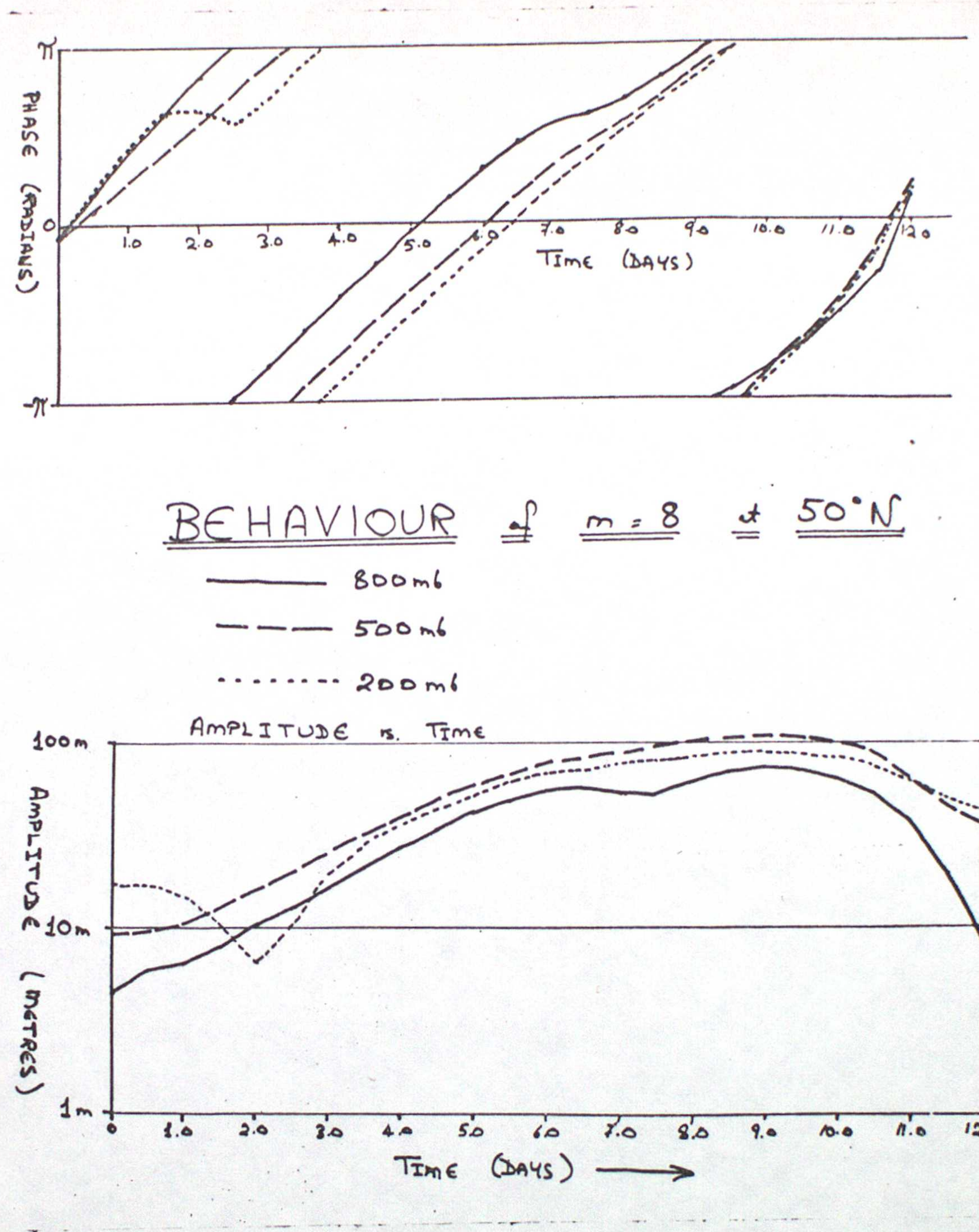


Fig (15) The phase ad amplitude of wavenumber 8 plotted against time, run BC811R01.