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Dynamic effects of orography on the large scale motion of the atmosphere

Part I : Zonal flow and elliptic barrier with maximum height of one km.

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LIST OF SYMBOLS

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u	:	Wind component in x direction; positive towards east
v	:	Wind component in y direction; positive towards north
ω	:	The vertical p velocity
f	:	Coriolis parameter
ϕ	:	Geopotential height
F_x, F_y	:	Frictional and diffusion terms in u and v momentum equations respectively
D_t	:	Diffusion term in thermal equation
R	:	Specific gas constant
T	:	Temperature in $^{\circ}A$
C_P	:	Specific heat at constant pressure
$\beta = \frac{df}{dy}$	:	The variation of coriolis parameter in y direction
Ps	:	Surface pressure
Psea	:	Sea level pressure
u_s, v_s	:	Wind components at surface in x, y direction
ω_s	:	Vertical p velocity at surface
A, B	:	Arbitrary variables
δ_i	:	Pressure interval of the layer at i^{th} point
Z	:	Height of the isobaric surface

$\overline{Z}$	:	Mean height
U	:	Constant wind (zonal)
H	:	Orographic height
Hm	:	Maximum height of the orography of the centre of the region
Rx	:	The maximum distance (from the centre) of orography in x direction
Ry	:	The maximum distance (from the centre) of orography in y direction
R	:	The horizontal distance between the point on elliptic orography and its centre
d	:	Grid length = 5°

DYNAMIC EFFECTS OF OROGRAPHY ON THE LARGE SCALE MOTION OF THE ATMOSPHERE

Part I : Zonal flow and elliptic barrier with maximum height of one km

By

S. N. Bavadekar and R. M. Khaladkar

ABSTRACT

The three level primitive equation model is being developed to simulate the dynamic effects of orography on the large scale motion of the atmosphere. The model performance is tested by conducting the experiment with zonal westerly flow and elliptic barrier with maximum height of one km. at the centre of the region. The model is integrated for 5 days. The forecast fields are presented and the results are discussed.

Introduction

The orography plays a dominant role in the dynamics of atmospheric flow. The semi permanent troughs and ridges formed in the mid-latitude westerlies in the upper troposphere are due to high orographic barriers such as, Rockies and Himalayas in the northern hemisphere and Andes in the southern hemisphere. The westerly jet stream and their speed maxima are also associated with high orographic barriers.

The pioneering work on this problem was done by Charney and Eliassen (1949) and Bolin (1950) by giving analytical treatment. Asai and Nitta (1963), Kasahara (1966) and Vergeiner and Ogura (1972) have studied these effects by using Barotropic Primitive equation model. The multi level P.E. model was used by Okamura (1976) and the general circulation model was used by Nakamura (1978).

The study of topographic complex of India has been done by some workers. Banerji (1930) explained that the typical southward bending of isobars over peninsular India is due to low level westerly flow crossing the barrier of western Ghats. The analytical treatment to this problem was given by Gadgil and Sikka (1975). Sarker (1965, 1966, 1967) and De (1971) have dealt with orographic rainfall due to western Ghats and mountain waves over northeast India but their models are for meso-scale circulation. Zonally symmetric model was used by Godbole (1973) for simulation of monsoon circulation which is properly developed when the Himalayas are included in the model. The numerical experiment was conducted by Das and Bedi (1976) by using three level P.E. model in σ coordinate system. They have used idealized wind and topography for the simulation purpose. They have, however, quoted about some difficulties regarding conversion of their results from σ to p system. The pressure gradient terms in σ coordinate system also create some problems.

The present experiment is conducted to simulate dynamic effects of orography using three level P.E. model in pressure coordinate system. The work on higher orographic barriers will be reported in part II. The purpose of these experiments is to develop suitable computer program and subroutines which will ultimately be used in regional limited area five level P.E. model of IITM, Pune.

The simplified version of this model was used by Singh and Saha (1976) for testing the computational stability of finite difference schemes. Since then the model is being developed to incorporate various physical processes such as friction, diabatic heating, sensible heating etc.

1. The model design

The model consists of following set of equations.

u and v momentum equations

$$\frac{\partial u}{\partial t} + \frac{\partial}{\partial x}(uu) + \frac{\partial}{\partial y}(uv) + \frac{\partial}{\partial p}(u\omega) - fv + \frac{\partial \phi}{\partial x} = F_x \quad \cdots\cdots\cdots\cdots(1)$$

$$\frac{\partial v}{\partial t} + \frac{\partial}{\partial x}(vu) + \frac{\partial}{\partial y}(vv) + \frac{\partial}{\partial p}(v\omega) + fu + \frac{\partial \phi}{\partial y} = F_y \quad \cdots\cdots\cdots\cdots(2)$$

Equation of continuity

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial \omega}{\partial p} = 0 \quad \cdots\cdots\cdots\cdots(3)$$

Hydrostatic approximation

$$\frac{\partial \phi}{\partial p} = -\frac{RT}{p} \quad \cdots\cdots\cdots\cdots(4)$$

Thermal equation

$$\frac{\partial}{\partial t}(c_p T) + \frac{\partial}{\partial x}(c_p T u) + \frac{\partial}{\partial y}(c_p T v) + \frac{\partial}{\partial p}(c_p T \omega) + \frac{\partial \phi}{\partial p}\omega = D_t \quad \cdots\cdots(5)$$

The dependent variables are u, v, ω, ϕ and T. The frictional and diffusion terms represented by F_x, F_y and D_t are dropped in the present experiment.

The coriolis parameter f is allowed to vary in β plane by using the expression

$$f = f_o + \beta y \qquad (6)$$

where $f_o = 10^{-4}\ sec^{-1}$ at 45^oN and corresponding β value is $1.62 \times 10^{-11}\ m^{-1}\ sec^{-1}$.

Boundary conditions

$\omega = 0$ at 100 mb which is also the top level of the model atmosphere. The lower boundary condition can be obtained by using surface pressure tendency equation

$$\frac{\partial p_s}{\partial t} + u_s \frac{\partial p_s}{\partial x} + v_s \frac{\partial p_s}{\partial y} - \omega_s = 0 \qquad (7)$$

The slipping walls are assumed at North and South boundaries of the domain of integration (see Fig. 1), whereas the cyclic boundary conditions are assumed in the east-west direction with the cycle of length L .

The vertical structure of the model

The numerical solution is obtained by integrating the model in time by using three level structure (see fig. 2).

The wind components u, v, and the geopotential ϕ are specified on 250, 550 and 850 mb levels. The temperature T is specified on 400, 700 and 925 mb levels. The temperature at 925 mb is assumed to remain constant throughout the period of integration. The dependent variable ω is specified on 400 and 700 mb levels whereas p_s and ω_s are the values at the surface having orographic height H .

Finite difference schemes

The primitive equations, in flux form, are having the space differential terms of the type $\frac{\partial}{\partial x}$ (AB) and $A\frac{\partial B}{\partial x}$. The finite difference expressions adopted for space differential are derived (Okamura, 1975) assuming the conservation of total mass and energy of the system. The finite difference notations and expressions for the above two terms are

$$D_x\,(A*B)_i = \frac{1}{8d\delta_i}\Big[\{A_{i+1}(\delta_{i+1}+\delta_i)+A_i\,(3\delta_i-\delta_{i+1})\}(B_{i+1}+B_i) - \{A_{i-1}(\delta_{i-1}+\delta_i)+A_i\,(3\delta_i-\delta_{i-1})\}(B_i+B_{i-1})\Big] \cdots (8)$$

and

$$G_x\,(A,B)_i = \frac{1}{4d}\{(A_{i+1}+A_i)(B_{i+1}-B_i)+(A_i+A_{i-1})(B_i-B_{i-1})\} \cdot\cdot (9)$$

respectively.

Here i represents the running index in x direction. Similar notations can be used for the space differentials in y direction.

The finite difference analogue of the primitive equations and the treatment regarding the points which are close to orography etc. are similar to that of Okamura (1976).

2. Initial fields and the specification of terrain

Initially the zonal flow U = 10 mps is assumed to be present without any shear in vertical as well as lateral in directions. The wind and height are related by geostrophic approximation. The height field, thus, can be obtained from wind by using the expression

$$Z_\ell = \bar{Z}_\ell - \frac{U}{g}\int_0^y f\,dy \qquad \cdots\cdots\cdots\cdots (10)$$

where ℓ varies from 1 to 3 for three different levels,

$\bar{Z}_1 = 10{,}326$ m $\bar{Z}_2 = 4{,}848$ m and $\bar{Z}_3 = 1{,}452$ m.

The sea level pressure is obtained by using the expression

$$P_{sea} = 1013 - \frac{1013 - 850}{\bar{Z}_3}\,\frac{U}{g}\int_0^y f\,dy \qquad \cdots\cdots\cdots (11)$$

The hydrostatic approximation is used to compute temperature T at different levels and assuming no mountains. The computed initial values are shown in Table 1.

The orographic heights are computed using the expression

$$H = H_m\sqrt{1-R^2} \quad \text{for } R \leq 1$$
$$= 0 \quad \text{for } R > 1 \qquad \cdots\cdots\cdots (12)$$

where

$$R^2 = \frac{x^2}{R_x^2} + \frac{y^2}{R_y^2} \qquad \cdots\cdots\cdots (13)$$

$H_m = 1000$ m

$R_x = 2000$ Km.

$R_y = 1000$ Km.

The surface pressure is now obtained by using again the hydrostatic approximation.

The computed height of the orography at various points and corresponding surface pressures are shown in Table 2.

Matsuno's (1966) time integration scheme is used for integration. The scheme has desirable effects of suppressing the high frequency gravity waves.

The model was integrated for 5 days using CDC-3600 computer without using any type of smoothing. The time step of 12 minutes was used for integration.

3. Results and discussion

The forecast results are obtained for all the five days, but the results for 5th day only are presented.

Geopotential height and wind fields : The forecast fields for 120 hours are shown in figure 3 to 5 for 250, 550 and 850 mb levels. The formation of the ridge on the windward side of the terrain and the trough on the leeward side are immediately apparent from the diagrams. The oscillation of the 'Rossby type' with secondary ridge towards the eastern side away from the barrier is also seen. The wind speed is reduced in central west part where the flow approaches towards orography. The southeast and northwest sectors near orography show enhancement in wind speed.

Surface pressure departure : The development of high pressure on the windward side and the low pressure on the lee-ward side of the orography and also the secondary high pressure development towards eastern side of the fully developed flow are observed (see fig. 6).

Initial development in 12 hours forecast indicates development of high pressure on the windward side (+ 4.9 mb) and symmetrical low pressure departure on leeward side (- 4.4 mb). The zero isopleth is almost in the direction of the y axis thro' the centre of the orography. Similarly the 2nd isopleth of zero line is towards eastern side more or less parallel to the first isoline. Subsequont forecast shows rapid development and changes especially in the leeward trough and the ridge.

Vertical p velocity and thermal changes : The upward vercal velocity is developed on the windward side of the mountain. This is due to forced ascent of the flow over the barrier. The vertical p velocity is downward on the leeward side as expected. Further east in some pockets the upward vertical motion is observed, which may be due to oscillatory type of development in pattern. The forecast ω fields are shown in figures 7, 8 and 9 and the temperature departures for 400 and 700 mb are shown in figures 10 and 11 respectively. The cooling on the windward side and the heating on the leeward side near orography are appropriate in view of the vertical velocity development in this region.

4. Concluding remarks : This experiment is performed without the inclusion of frictional and diffusion terms in the momentum and thermal equations. The effect of these terms on forecast fields will be studied in the seperate

experiment.

The present experiment shows the proper simulation of the dynamic effects of low type of orographic barrier. The conspicuous features are : (1) Development of up-stream ridge and upward vertical velocity due to forced ascent. The corresponding temperature changes are negative indicating cooling. (2) Development of downstream trough and downward vertical velocity and the associated positive temperature departure indicating heating and (3) The oscillation of the 'Rossby Type' on the leeward side indicated by the development of ridge on the eastern side.

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TABLE 1 : The specification of the initial values

Latitude deg-N	Heights of isobaric levels in meters Z1	Z2	Z3	Temperature in ^{o}A T1	T2	T3	Sea level pressure Psea, mb
85	9773	4295	899	249.5	270.7	281.2	951.1
80	9856	4378	982	249.5	270.7	281.2	960.5
75	9936	4458	1062	249.5	270.7	281.2	969.4
70	10011	4533	1137	249.5	270.7	281.2	977.9
65	10082	4604	1208	249.5	270.7	281.2	985.8
60	10149	4671	1275	249.5	270.7	281.2	1000.5
50	10271	4793	1397	249.5	270.7	281.2	1007.1
45	10326	4848	1452	249.5	270.7	281.2	1013.2
40	10376	4898	1502	249.5	270.7	281.2	1018.9
35	10422	4944	1548	249.5	270.7	281.2	1024.1
30	10465	4987	1591	249.5	270.7	281.2	1028.8
25	10503	5025	1629	249.5	270.7	281.2	1033.1
20	10537	5059	1663	249.5	270.7	281.2	1037.0
15	10567	5089	1693	249.5	270.7	281.2	1040.3
10	10592	5114	1718	249.5	270.7	281.2	1043.2
05	10614	5136	1740	249.5	270.7	281.2	1045.6

TABLE 2 : Orographic heights and corresponding surface pressure specifications

	440 (948.2)	630 (926.5)	720 (916.4)	750 (913.0)	720 (916.4)	630 (926.5)	440 (948.2)	
500 (948.0)	730 (921.8)	850 (908.5)	920 (900.8)	940 (898.6)	920 (900.8)	850 (908.5)	730 (921.8)	500 (948.0)
600 (942.8)	800 (920.1)	920 (906.8)	980 (900.2)	1000* (898.0)	980 (900.2)	920 (906.8)	800 (920.1)	600 (942.8)
500 (960.3)	730 (933.7)	850 (920.2)	920 (912.4)	940 (910.2)	920 (912.4)	850 (920.2)	730 (933.7)	500 (960.3)
	440 (972.8)	630 (950.5)	720 (940.2)	750 (936.7)	720 (940.2)	630 (950.5)	440 (972.8)	

Note : Bracketed figures are surface pressure values in mb.

* : Centre of the region with Hm = (1000 meters)

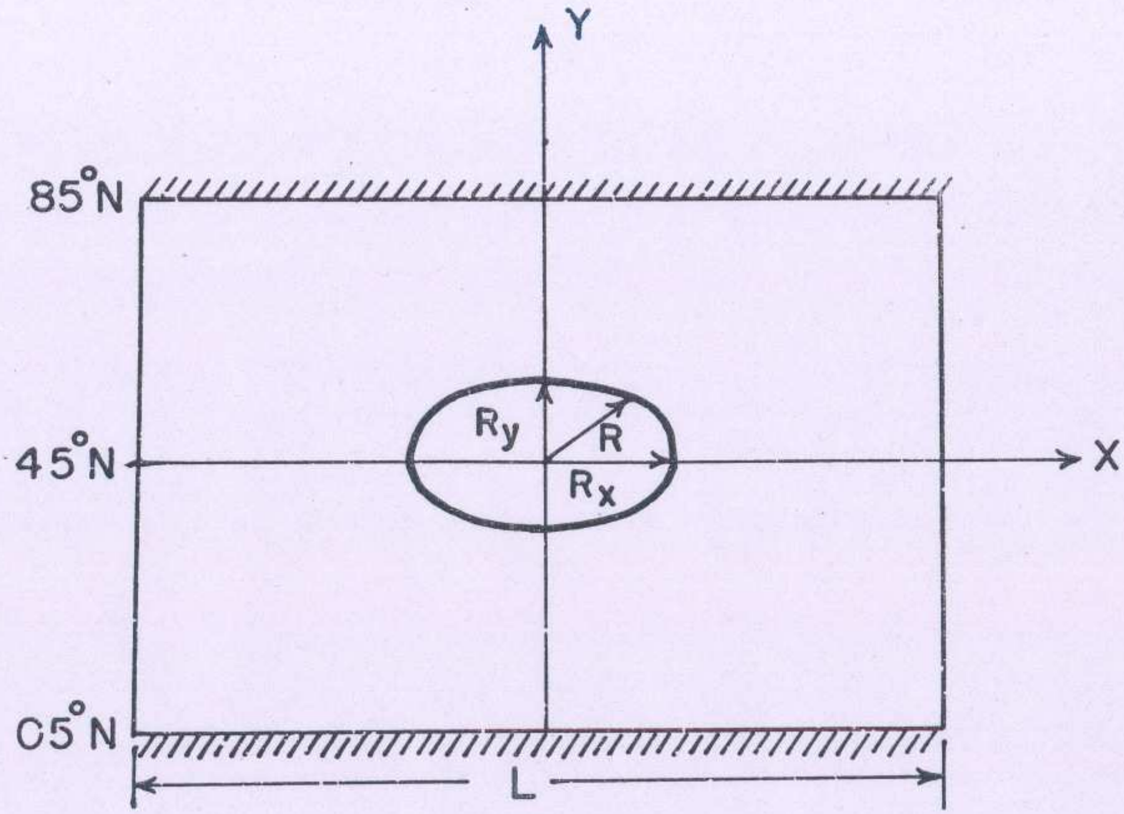

Fig. I. The domain of limited area P.E. model. The orography is shown at the centre of the region.

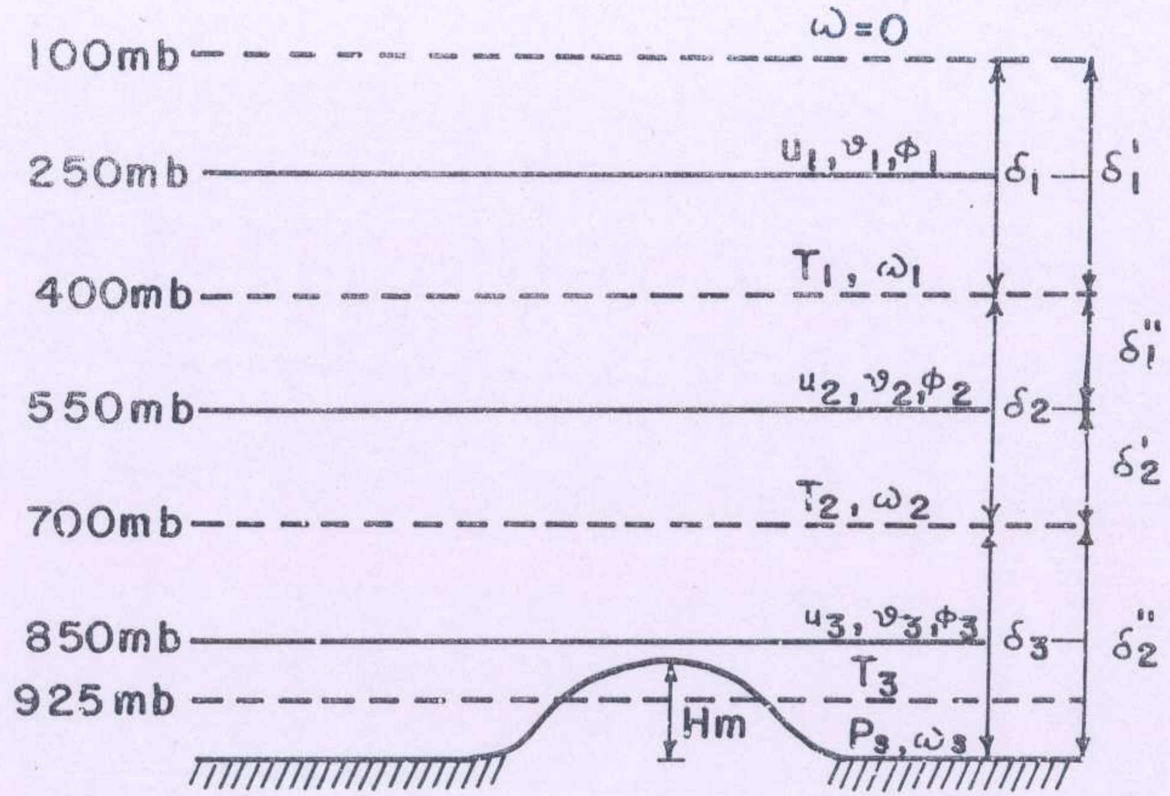

Fig. 2. Vertical structure of the three level P. E. model

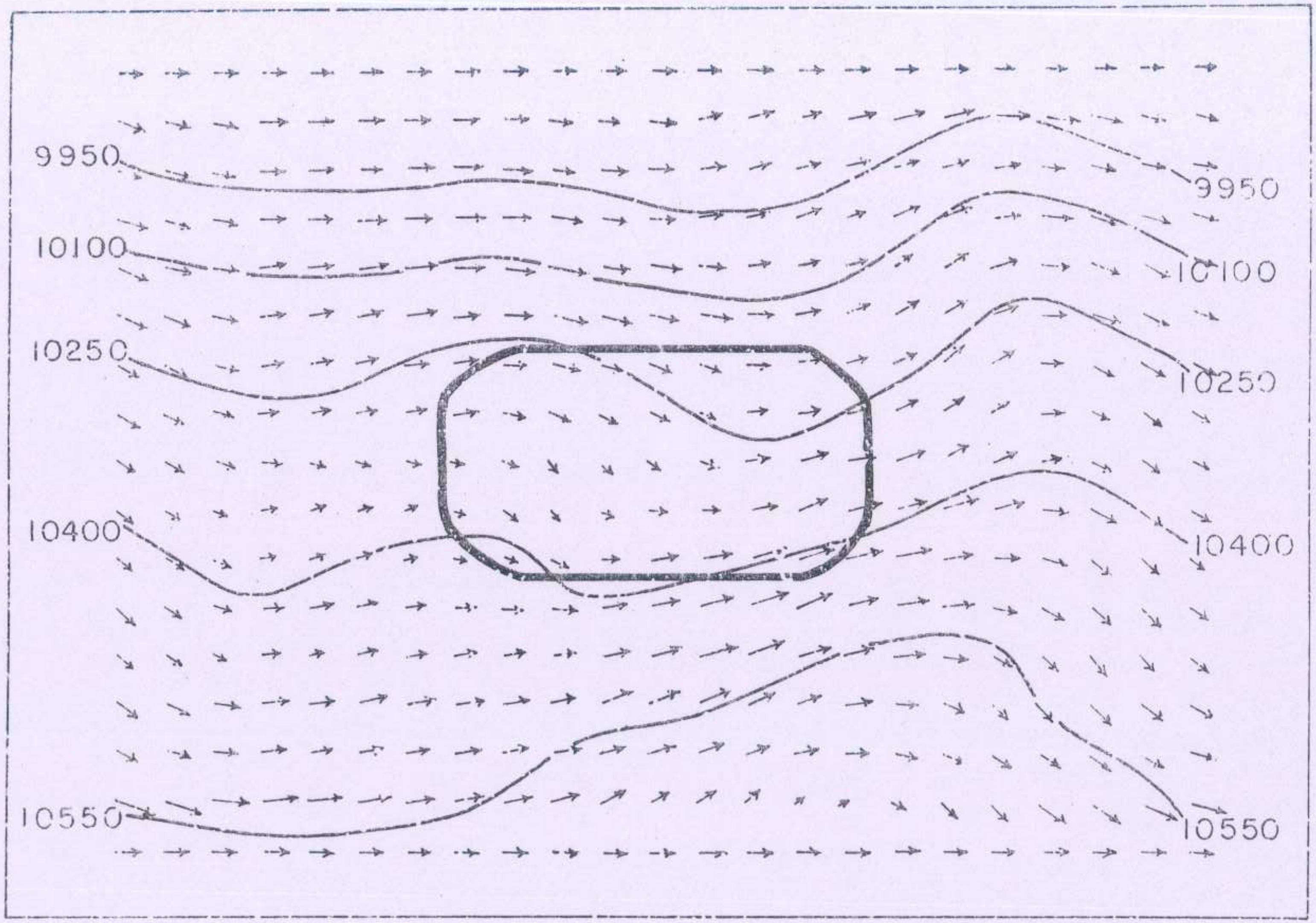

Fig. 3. Wind and height field at 250 mb level.
Forecast : 120 hours. Scale for wind speed · 1mm = 2 mps.

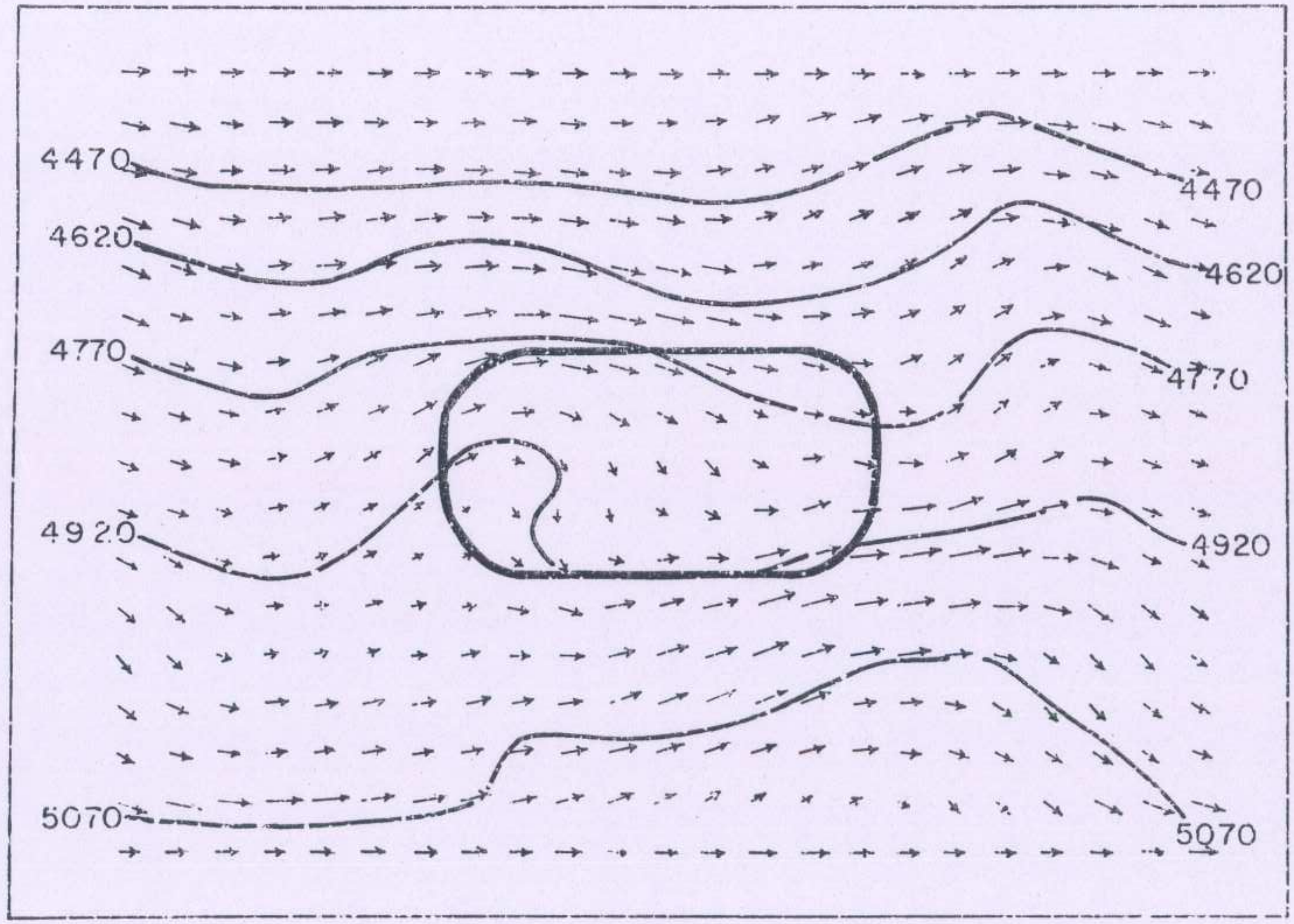

Fig.4. Wind and height field at 550 mb level.
Forecast : 120 hours. Scale of wind speed : 1mm = 2 mps.

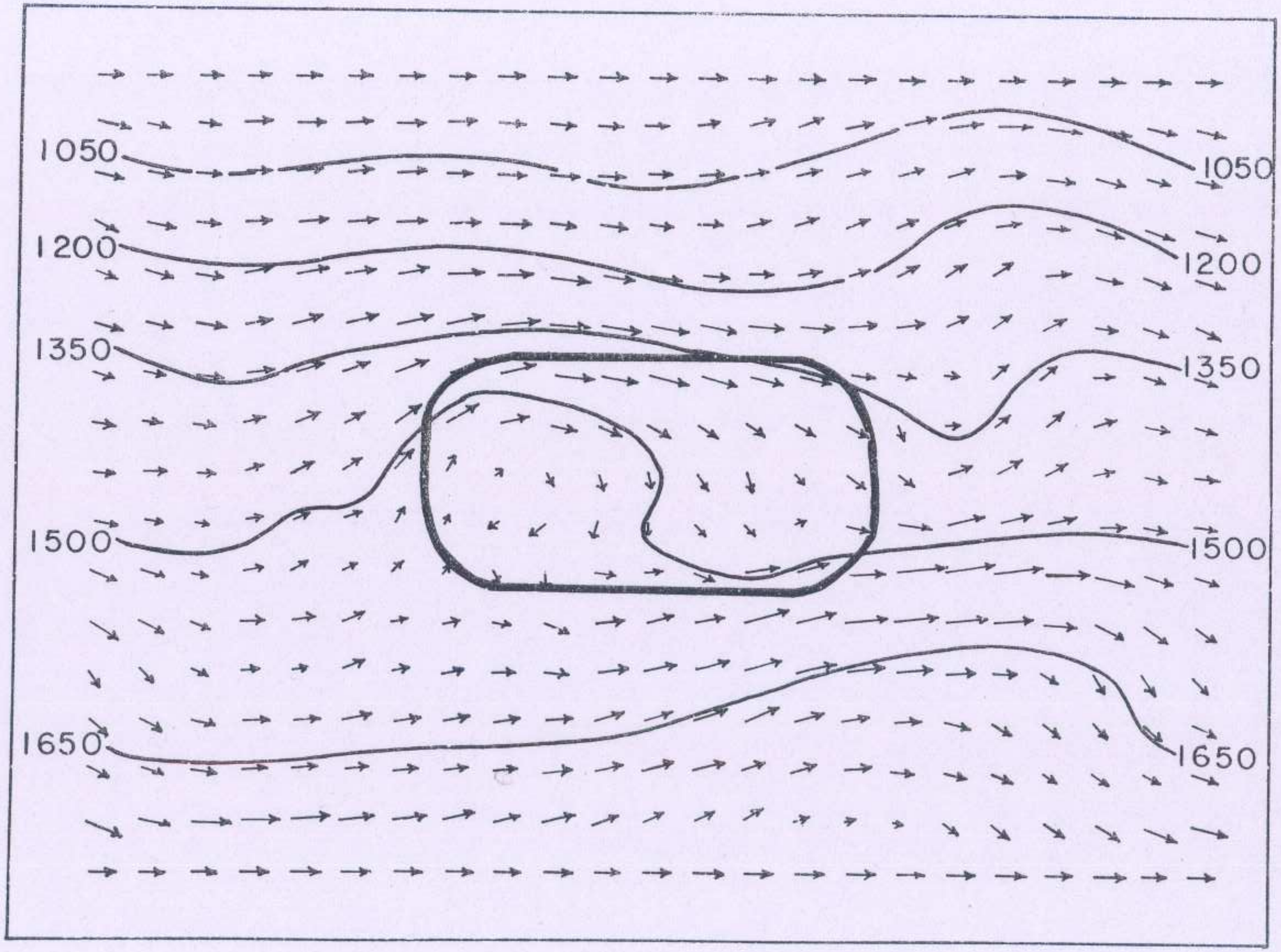

Fig.5. Wind and height field at 850 mb level.
Forecast : 120 hours. Scale of wind speed : 1mm = 2mps.

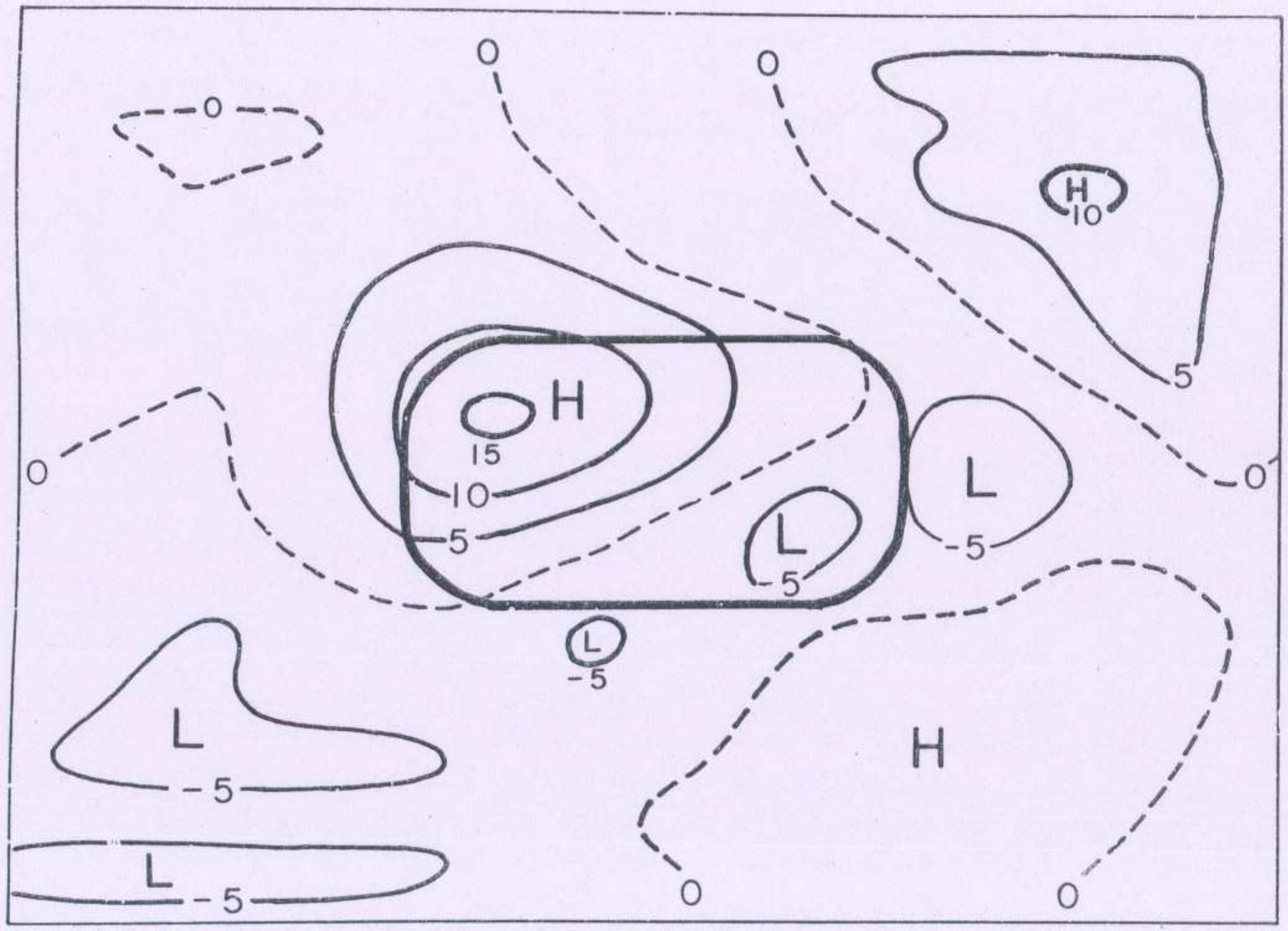

Fig. 6. Surface pressure departure $\Delta P_s = Ps_{120} - Ps_0$

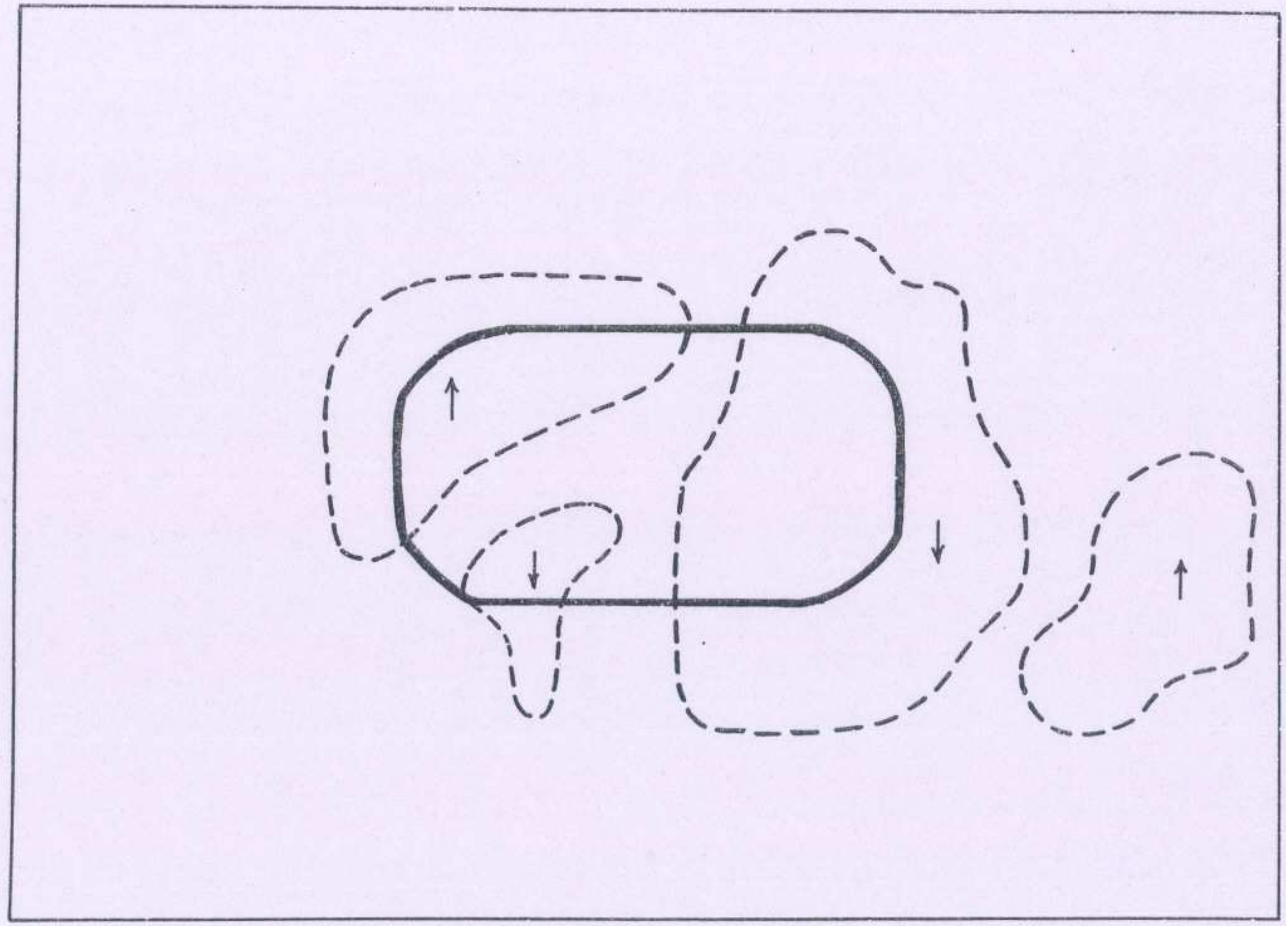

Fig. 7. Vertical velocity ω at 120 hours., Level : 400 mb., Unit : 10^{-3} mb sec^{-1}
Contour spacing is at 0·3 unit interval.

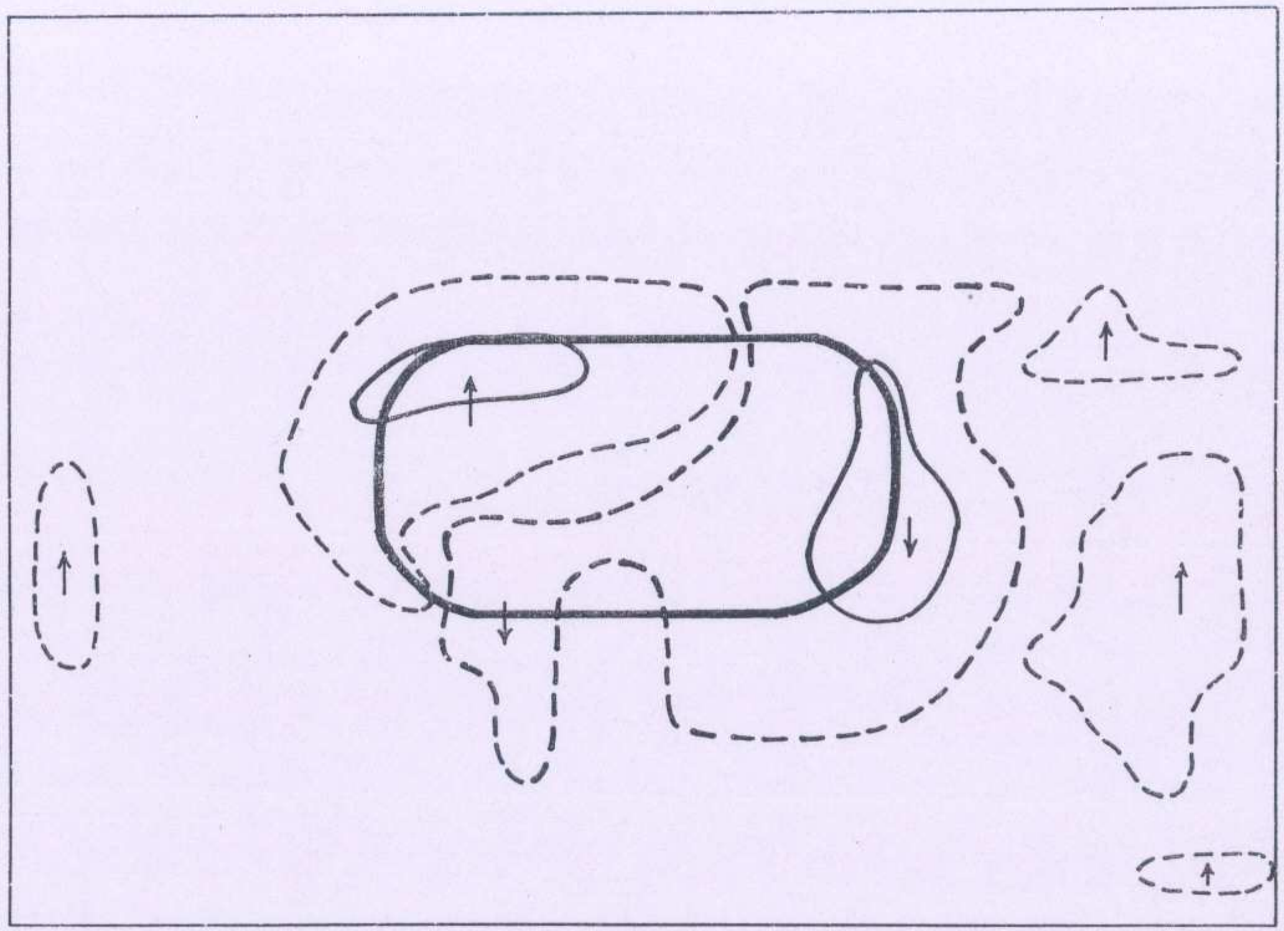

Fig. 8. Vertical velocity ω, at 120 hours.
Level : 700 mb , Unit 10^{-3} mb sec^{-1}.
Contour spacing is at 0·3 unit interval.

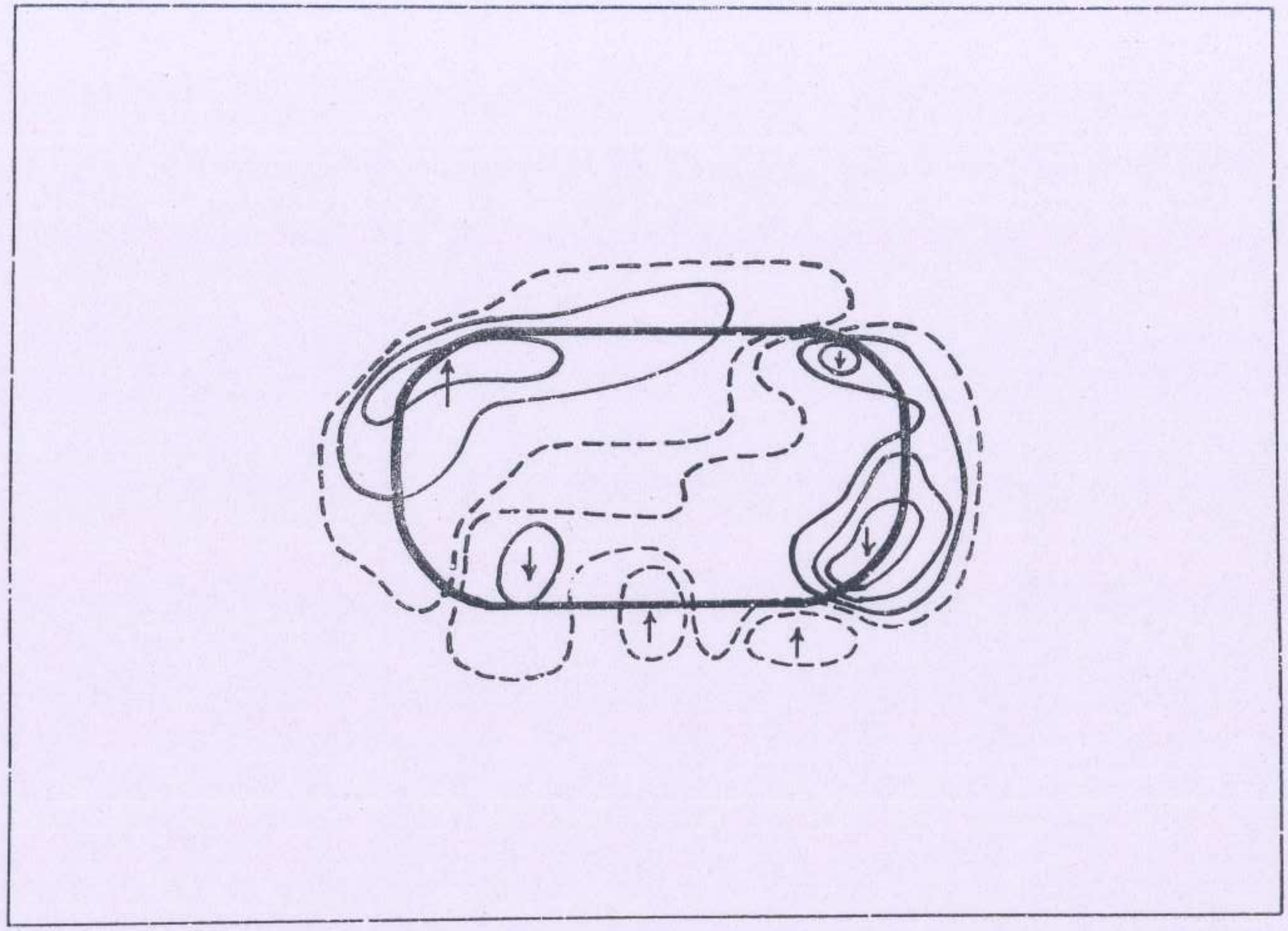

Fig. 9. Vertical velocity ω_s at 120 hours.
Level Surface, Unit 10^{-3} mb sec^{-1}.
Contour spacing is at 0·3 unit interval.

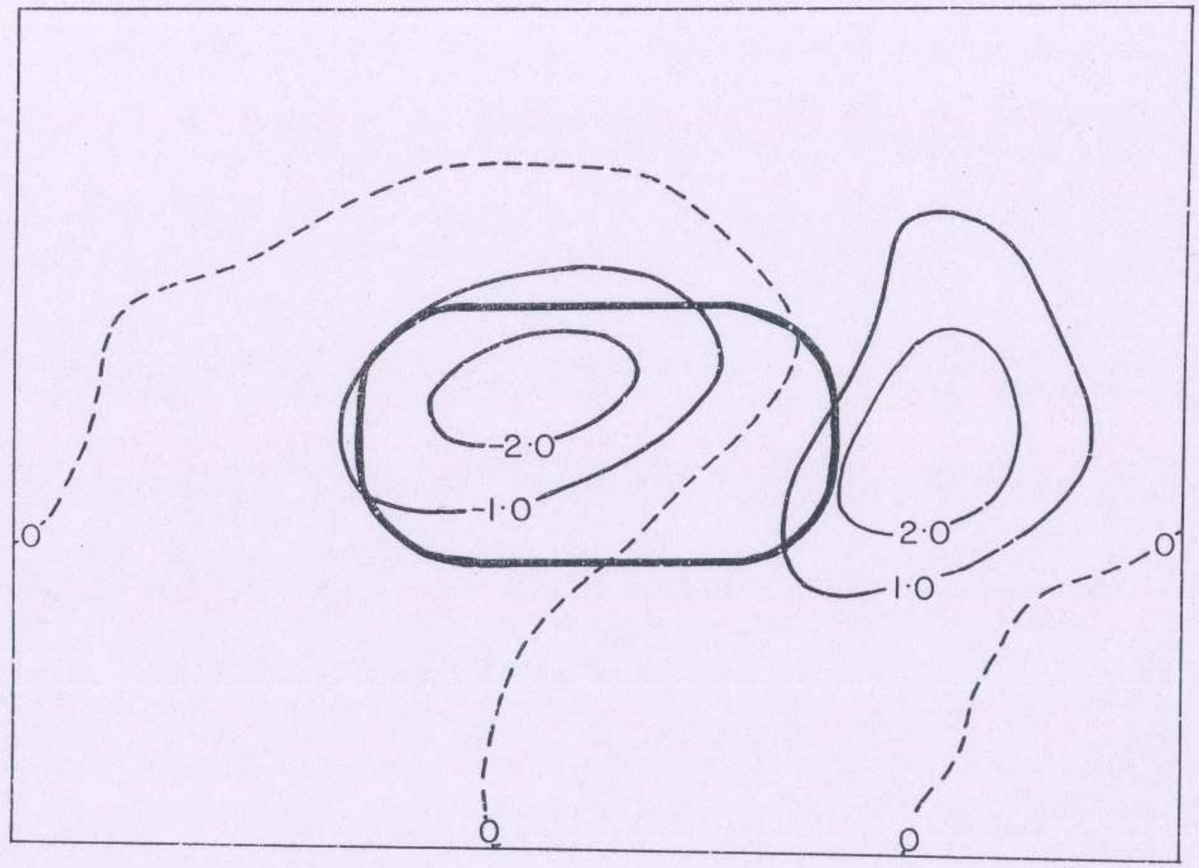

Fig.10. Temperature departure. $\Delta T = T_{120} - T_0$ (in deg. cent). Level : 400 mb

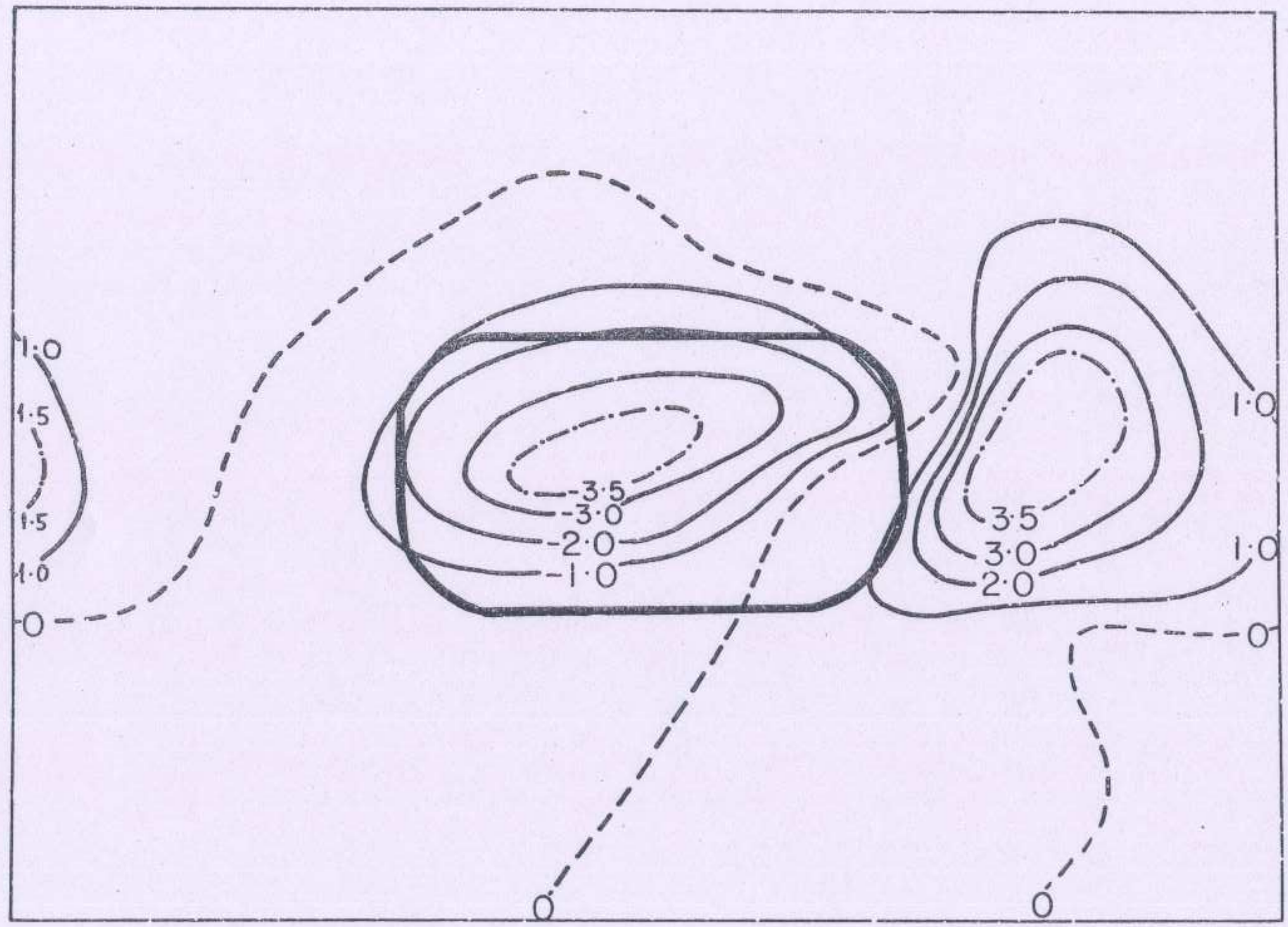

Fig. II. Temperature departure. $\Delta T = T_{120} - T_0$ (in deg. cent). LEVEL : 700 mb.