Results of Forecasting with the Barotropic Model on an Electronic Computer (BESK)

Staff Members, Institute of Meteorology, University of Stockholm

(Manuscript received May 19, 1954)

Abstract

A series of twenty-four 24-hour forecasts have been completed using the barotropic model of the atmosphere. The results of these forecasts are better than previous tests with this model have indicated. The average correlation coefficient between computed and observed height changes of the 500 mb surface is 0.77, the error in the forecast height changes is 89 m against an average observed change of 121 m. The errors are mainly due to the following factors:

1) Erroneous assumptions at the boundary of the forecast area.
2) Inaccurate analysis of the initial data over the Atlantic.
3) Inaccuracy in forecasting components of the motion of a scale only a few times larger than the grid size.
4) Baroclinic developments.

The computations indicate that the present results may be improved considerably by trying to eliminate errors listed under (1) – (3).

1. Introduction

During the last years a number of models of the atmosphere have been developed for numerical forecasting purposes, making use of information from one, two or several levels in the atmosphere. The computational schemes for these different models involve very large computing programs in order to obtain a 24-hour forecast for a significantly large region. The intention has been to test and evaluate the proposed methods by actual computations with the aid of electronic computing machines, but it is not until recently, that such machines have been available on a wider basis. Hence very few systematic and conclusive evaluations based on actual computations have been made up to the present time. The first more extensive study was published recently by CHARNEY and PHILLIPS (1953). Altogether six barotropic and six two-layer forecasts for 24 hours were presented. All these forecasts were made using data from a case of extreme baroclinic development and the two-layer model gave considerably better results than the barotropic one. Since then a few additiona forecasts hava been made at Princeton but no additional results have been published as yet. Therefore we do not yet know the value and limitations even of the barotropic model. It seems important to get a good idea of the potentiality of this simple model, since more complicated models should be tested with regard to the improvement they may represent in comparison with the barotropic one.

Partly for the reasons mentioned above, partly because of the limited capacity of the machine in Stockholm at the beginning of the present computational program, it was decided to investigate the barotropic model more extensively. Furthermore, it is reasonable to start with the simplest model to obtain experience before using more complicated ones. As will be seen from the results presented here of altogether twenty-four 24-hour forecasts a number of basic problems associated with numerical forecasting seem to require further consideration and are more easily studied with the aid of the barotropic model than with the more complicated ones.

The results presented in this report represent a continuation of work started during the autumn of 1951 by a group of meteorologists assembled at the University of Stockholm. The work of the group has since then been supported by grants from the Knut and Alice Wallenberg Foundation, the U.S. Office of Naval Research, the Swedish National Science Research Council, and the U.S. Weather Bureau. Very generously the Swedish electronic computer (BESK) has been placed at our disposal by the Computer Board. The participants in the active work have been: G. Arnason, Iceland; H. Bedient, U.S.A.; P. Bergthorson, Iceland; B. Bolin, Sweden; G. Dahlquist, Sweden, B. Döös, Sweden; N. Phillips, U.S.A. Some of the maps used in the series tested had previously been analysed by W. H. Hubert, U.S.A., Ch. Newton, U.S.A., and L. Vuorela, Finland.

2. Method and organization of the computations

By and large the computations have been done in the way described by CHARNEY and PHILLIPS (1953) and we shall here restrict ourselves to a very brief account of the procedure.

The integration is done by an iterative process in which each time step τ to $\tau + 1$ may be described by the following four equations

$$\eta^{\tau} = \frac{m^2}{f} \xi^{\tau} + f \quad \ldots\ldots\ldots\ldots \quad (1)$$

$$\left(\frac{\partial \xi}{\partial t}\right)^{\tau} = J(\eta^{\tau}, \varphi^{\tau}) \quad \ldots\ldots\ldots \quad (2)$$

$$\xi^{\tau+1} = \xi^{\tau-1} + 2\left(\frac{\partial \xi}{\partial t}\right)^{\tau} \Delta t \quad \ldots\ldots \quad (3)$$

$$\nabla^2 \varphi^{\tau+1} = \xi^{\tau+1} \quad \ldots\ldots\ldots \quad (4)$$

η is the absolute vorticity, m the magnification factor of the map projection used, f the Coriolis parameter, $\xi = f \cdot m^{-2} \cdot \zeta$, ζ being the relative vorticity, φ the geopotential and Δt is the timestep used in the extrapolation. $J(\eta, \varphi)$ is evaluated by finite differences and the Poisson equation (4) for φ is solved by relaxation. The history of the motion is thus carried by ξ, the relative vorticity, and the new values of φ are obtained from (4) at each time step.

Certain boundary conditions have to be formulated in order to be able to solve the system of the equations (1) – (4) uniquely over a limited area. It was shown by CHARNEY, FJØRTOFT and VON NEUMANN (1951) that a knowledge of φ at all times along all boundaries and of the vorticity, ζ, at points of inflow probably are necessary and sufficient conditions to determine the motion uniquely inside the area. We do not know what is going to happen along these artificial boundaries and we must make certain assumptions regarding φ and ξ. These assumptions are necessarily in error. They will influence the motion and introduce errors in the forecasts. However, it is hoped that these errors will not propagate far in from the boundaries over a period of 24-hours. We shall later obtain some informations about the validity of this statement. It was here assumed that $\partial\varphi/\partial t = 0$, e.g. φ = const. on the boundary. Furthermore ξ^{τ} was set equal to its initial value ξ^0 at points of inflow and also at points of outflow. This latter assumption at points of outflow really means an overspecification of the problem. It was done in order to simplify the code and save storage space in the machine. We shall furthermore see that the errors thus introduced usually are not larger over 24-hours than those introduced by the arbitrary assumption of $\xi^{\tau} = \xi^0$ at points of inflow. Both may, however, cause considerable errors quite far from the boundaries but they seem to be of quite a different nature. The values of ξ^0 on the boundaries were obtained by supplying information of φ^0 at one row of points outside the area later used for the computations. In that way no extrapolation procedure had to be used.

Equation (4) was solved by relaxation methods. The rapidity of convergence of this method depends to a large extent upon a good first guess. The best scheme is undoubtedly to extrapolate values of $\varphi^{\tau+1}$ linearly from the knowledge of $\varphi^{\tau-1}$ and φ^{τ}. This requires, however, the storage of four quantities at each grid point instead of three ($\xi^{\tau-1}$, ξ^{τ} and φ^{τ}). The limited present memory of the computer did not permit us to apply this method. φ^{τ} was

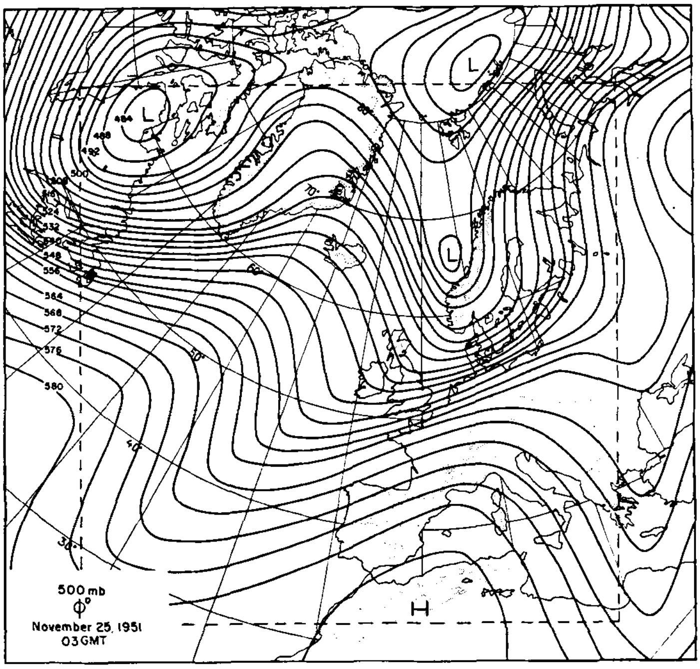

Fig. 1 a. 500 mb map at 0300 GMT November 25, 1951. Contour lines drawn for every 40 meters and labelled in decameters.

used as the first approximation in the relaxation to obtain $\varphi^{\tau+1}$.

The computations were made over a square-grid consisting of 20 × 20 points and the grid-size was chosen to be 300 km at 50° N. The map projection was polar stereographic. Thus the total area covered by the grid was about 5,700 × 5,700 km. The location of the area varied slightly for the different forecasts, but did never deviate much from the one shown in fig. 1 a. The forecasts were only verified over a grid 11 × 11 or 12 × 12, in the centre of the area since the effects of the boundaries were supposed to effect significantly the region outside this area (see fig. 1 b). The time step was 1 hour.

The computer used for the computation has an internal William-type memory of 512 words of 40 binary digits, which in the near future will be supplemented by two magnetic drums, each of which will be capable of holding 4,096 words. The adding time is 56 microseconds and the multiplication time is 364 microseconds.

It was already mentioned that three quantities were stored for each grid point, each of them with an accuracy of 13 or 14 binary digits making it possible to store all informations needed for one point in one word. The remaining 112 words were used for instructions. This was not sufficient for storing all instructions needed and thus new instructions had to be read in continuously during the computations. This fact, in addition to the poor initial guess when solving equation (4), increased the computation time by a factor of at least 4 or 5. With the method used here a 24-hour forecast required 40 minutes machine time, of which 6 minutes were used for printing the final results. The increase of the storage capacity of the machine will make it possible to decrease the actual computing time to about 1/5.

In a few cases the forecasts were made on an operational basis, e.g. the forecast was completed as soon as possible after the time of observation. This was done in order to gain experience for routine forecasting by numerical methods. The preparation of data for a forecast involves a series of steps. The time required for a forecast after a certain skill in the routine operations has been aquired may be estimated to the following values:

Checking and plotting of data for a 500 mb map (2 people) ...... 1 h. 30 m.
Analysis of 500 mb for the forecast area and adjacent regions 1 h. 30 m.

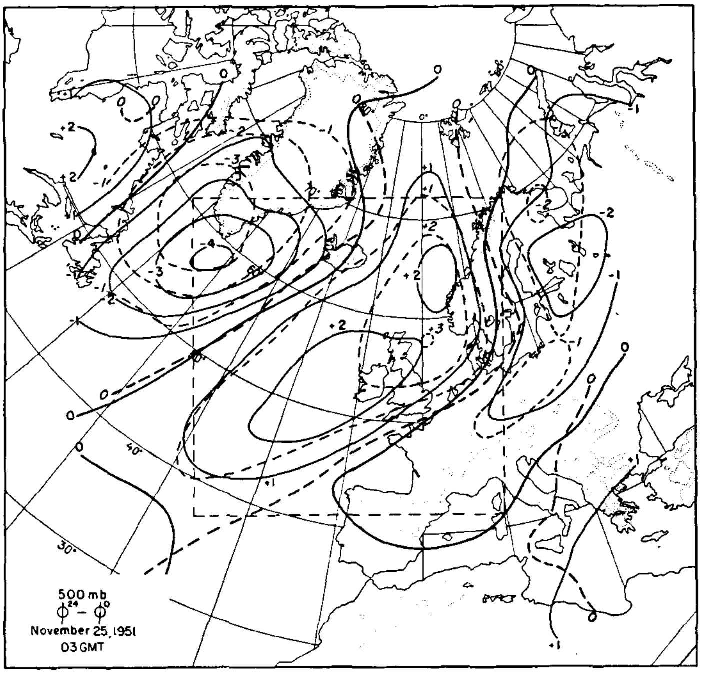

Fig. 1 b. Computed changes (dashed lines) and observed changes (solid lines) of the height of 500-mb surface from November 25, 1951, 0300 GMT to November 26, 1951, 0300 GMT. Lines are drawn for every 100 meters.

Reading off values of φ at 440 grid-points and checking (2 people) . .	1 h.	20 m.
Punching of input data on tape		40 m.
Checking and correcting tape . . .		20 m.
Forecasting with the machine . . .		40 m.
Plotting and analysis of the final forecast		30 m.
	6 h.	30 m.

Some of these steps may be speeded up, others carried out simultaneously, but the time to be gained in that way is very limited. In the case of the barotropic forecast the time given above is not prohibitive if one can extend the forecast range to 48 or 72 hours but as soon as we want to extend the computations to two or several layers in the atmosphere other schemes for preparation of the data have to be devised. Furthermore certain errors were still found in the initial values in spite of the checking routine which was adopted here. Some work to overcome the practical difficulties has been attempted:

1) A method of numerical synoptic analysis of the initial data seems very important from the point of view both of the time required using conventional methods of analysis and the probability of introducing errors by manual methods. This problem is at present being studied by some members of the group.

2) As long as methods for numerical analysis are not available the input program must be constructed in the most flexible way. Thus it should be possible to read in the data in a more or less arbitrary order and to introduce corrections to these data afterwards and without difficulties. The continuity and smoothness of the field should be checked automatically and if not fulfilling certain criteria automatic corrections should be applied. One such checking scheme was developed by H. Bedient. It consisted in computing $\nabla^2\nabla^2\varphi$ initially, which field quite clearly shows unreasonable values of φ. This field was printed with one significant sedecimal figure and inspected visually. It proved quite helpful on a number of occasions.

3) The final results were obtained as a table of the values of φ^{24} and ζ^{24} at all grid points. The machine may, however, be instructed to interpolate between the actual grid points and also print the results in the form of a map in the same scale as used for preparing the initial data. Such a scheme has been worked out by G. Dahlquist and H. Bedient and fig. 2 shows an example of such a representation of a map.

Fig. 2. The initial 500 mb height field on 24 April 1954, 0300 and its graphical representation by typewriter out put. The solid lines show the observed height contours of the 500 mb pressure surface and the typewriter figures fill the space between the lines 5,000 meter—5,040 meter; 5,080 meter—5,120 meter; etc. The memory of the computer contained height values in a coordinate system $x = i \triangle S$, $y = j \triangle S$ where $\triangle S$ is the grid interval on the map and i and j are integers. The typewriter prints digits located in a coordinate system $x' = i' \triangle S$, $y' = j' \triangle S$ where $i'j'$ are not integers but $\delta i' = \alpha K$, $\delta i'/\delta j' = \beta$. α is the ratio of the original map scale and the new scale made by the typewriter and β and K are constants depending on the construction of the typewriter. At each point $x' y'$ the height is interpolated from the four corner values of the grid square and converted to a single sedecimal figure (base 16) such that $0 = 5{,}000$ meters and the value increases by 80 meters for each unit. A decision to print the figure is made if the value lies between the integral value and $^1/_2$ unit higher. The decision is made to print nothing if the value lies between $^1/_2$ and the next integral value. Some "nervousness" is shown in the through west of Ireland because of the linear interpolation scheme. Also the low in the English channel is not well represented because of its small size in relation to the grid.

3. Results

Forecasts have been made from two series of maps: 24 November 03 GMT – 27 November 15 GMT 1951 consisting of eight 24-hour forecasts from maps with 12 hour intervals; 1 – 10 January 1954, altogether ten 24-hour forecasts from maps 24 hours apart. In addition to those a number of individual cases were treated, chosen for various particular reasons. The January series included the development of two severe storms within the forecast area.

The results of the forecasts are listed in table I. They represent evaluations over the verification area in the centre of the forecast area. r denotes the correlation between y, the computed 24 hour changes of φ, and x, the corresponding observed changes; σ_x and σ_y, are the root mean squares of the observed and computed changes respectively; ε denotes the errors of the computed changes; $\bar{x}$ and $\bar{y}$ represent the average observed and computed changes $\left(\bar{x} = \frac{1}{N}\Sigma x,\ \bar{y} = \frac{1}{N}\Sigma y\right)$.

The statistical treatment of the results obtained here is by no means exhaustive. It has often been pointed out that the correlation between observed and computed changes is not a satisfactory measure of the goodness of a forecast. This is certainly true. It is believed, however, that the quantities listed in table I will give a fairly good idea of the results. Furthermore the correlation coefficient often has been used in evaluating conventional methods of forecasting and a comparison with such evaluations is desirable (cf. Lönnquist, 1952). We shall later discuss the forecasts in terms of predicted changes in the winds over the British Isles.

The following remarks are of particular interest in connection with table I:

The average correlation coefficient for the 24 forecasts is 0.77, the error in the forecast height changes is 89 m in comparison with an average observed change of 121 m. The eight first forecasts (24 – 27 November) were made from very carefully analysed maps while the remaining 16 forecasts were based on analyses probably comparable with routine analyses in a weather service. There is a distinct difference between the results. The mean correlation coefficient for the eight forecasts in November is 0.90. The weather situation during this period was characterized by a series of regular long waves moving eastwards in a fairly strong westerly current in middle latitudes (cf. fig. 1 a). No particularly strong baroclinic developments occurred during this period. However, regular cyclones formed, occluded and dissolved while moving from west to east. The difference between this first series and the remaining forecasts cannot be explained merely as a result of the

Table I.

Date of initial map	r	σ_x (m)	σ_y (m)	ε (m)	$\bar{x}$ (m)	$\bar{y}$ (m)	σ_y/σ_x
24 Nov. -51, 03	0.83	114	116	70	— 16	— 41	1.02
24 » -51, 15	0.91	120	130	54	6	3	1.08
25 » -51, 03	0.95	155	153	48	26	24	0.99
25 » -51, 15	0.96	173	209	73	33	— 1	1.20
26 » -51, 03	0.79	148	164	99	34	37	1.11
26 » -51, 15	0.96	172	208	105	18	98	1.21
27 » -51, 03	0.95	160	185	67	32	44	1.16
27 » -51, 15	0.85	160	158	101	57	8	0.99
23 Sept. -52, 03	0.75	86	62	56	— 20	— 13	0.72
24 » -52, 03	0.91	140	93	71	— 75	— 29	0.66
1 Jan. -54, 03	0.17	72	204	169	45	180	2.83
2 » -54, 03	0.80	107	117	71	45	83	1.09
3 » -54, 03	0.76	126	104	89	— 20	11	0.83
4 » -53, 03	0.72	173	133	180	— 82	43	0.77
5 » -54, 03	0.92	182	209	84	7	— 6	1.14
6 » -54, 03	0.83	102	174	118	18	— 36	1.72
7 » -54, 03	0.38	67	148	124	30	130	2.21
8 » -54, 03	0.83	98	112	63	35	68	1.15
9 » -54, 03	0.73	83	77	65	20	11	0.93
10 » -54, 03	0.91	118	159	64	— 68	— 77	1.34
23 March -54, 03[1]	0.60	89	109	91	6	5	1.22
24 » -54, 03[1]	0.40	129	178	152	34	80	1.38
12 April -54, 03	0.77	89	88	65	20	— 5	0.99
24 » -54, 03	0.76	45	83	67	1	— 51	1.86
Over all means:	0.77	121	140	89	8	24	1.16
24—27 Nov. -51	0.90	150	165	77	—	—	1.10

[1] These forecasts were done on an operational basis.

different character of the general weather situation. The very best forecast ($r = 0.95$, $\varepsilon = 48$ m), was made during this November period: 25 November 03 GMT, which is shown in fig. 1.

Tendency computations had previously been carried out for one of the maps in the November series: November 25, 15 GMT (cf. STAFF MEMBERS, UNIVERSITY OF STOCKHOLM, 1952). It is of some interest to note that the complete 24-hour forecast gave considerably better result than the estimated 12 hour changes from the tendency computations.

The average computed 24-hour changes are 15 % larger than the observed ones. The ratio σ_y/σ_x varies, however, considerably from case to case. One reason for this can be found by comparing $\bar{x}$ and $\bar{y}$. It is seen that $\bar{x}$ and $\bar{y}$ usually are quite different in the cases where σ_y/σ_x deviates considerably from unity, e.g. an erroneous rise or fall over the whole area has been obtained from the computations in those cases. The errors (ε) of the prognostic height changes are also largest in these cases. This is particularly true on Jan. 1, Jan. 4, Jan. 7, March 24 and April 24. These forecasts are some of the least successfull.

It is quite obvious that we cannot expect to be able to forecast the motion and development of systems whose scale is larger than the size of the forecast area and it is therefore not surprising that $\bar{x} - \bar{y}$ may be quite large in some cases, even if there is a tendency for both $\bar{x}$ and $\bar{y}$ to approach zero when the size of the area increases. Let us introduce the notation

$$S = \frac{1}{B} \oint_B (\varphi^{24} - \varphi^{0})\, ds$$

where B is the periphery of the forecast area. The computed value of S is of course zero because of our boundary assumption, but this is not the case for the observed value of S. It may deviate from zero by 20 m or at a maximum 25 m, for an area the this size. The erroneous assumption concerning the value

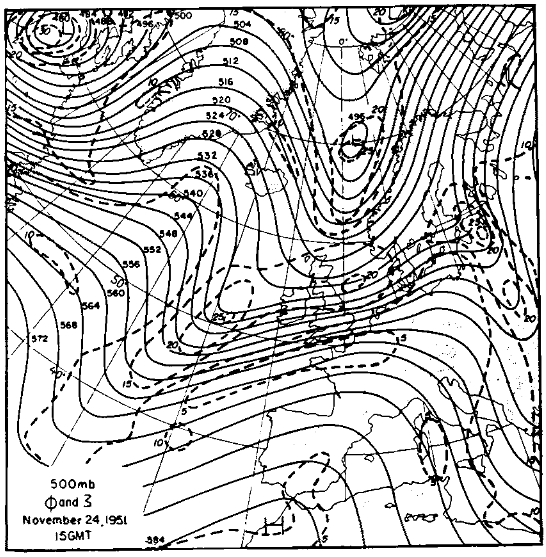

Fig. 3 a. Observed contours (solid lines) and absolute vorticity (dashed lines) on November 24, 1951, 1,500 GMT. The heights are given in decameter as unit and the vorticity-lines are labelled in units of 10^{-5} sec^{-1}.

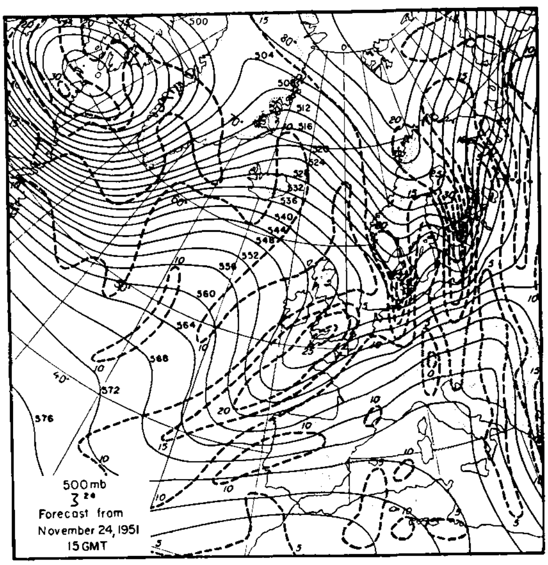

Fig. 3 b. 24-hour forecast from map shown in a.

of φ on the boundary then gives rise to an error within the verification area of about the same amount as the value of S.

More important in explaining the difference between $\bar{x}$ and $\bar{y}$ seems, however, the second boundary condition about the vorticity ξ^{τ}. It was earlier mentioned that we assumed $\xi^{\tau} = \xi^{0}$ at all boundary points. This is wrong in two respects:

a) It means an over-specification in that ξ at points of outflow is determined by the values of ξ inside the boundaries (if $\partial\varphi/\partial t = 0$ at the boundary) and cannot be prescribed. The effect is very clearly shown in fig. 3. First the vortex lines are advected towards the boundary and since $\xi^{\tau} = \xi^{0}$ on the boundary the gradients increase which means an amplification of higher harmonics in the flow field. The finite difference formula is quite inaccurate for these higher harmonics and they are distorted considerably during the computations. This gives rise to the for-

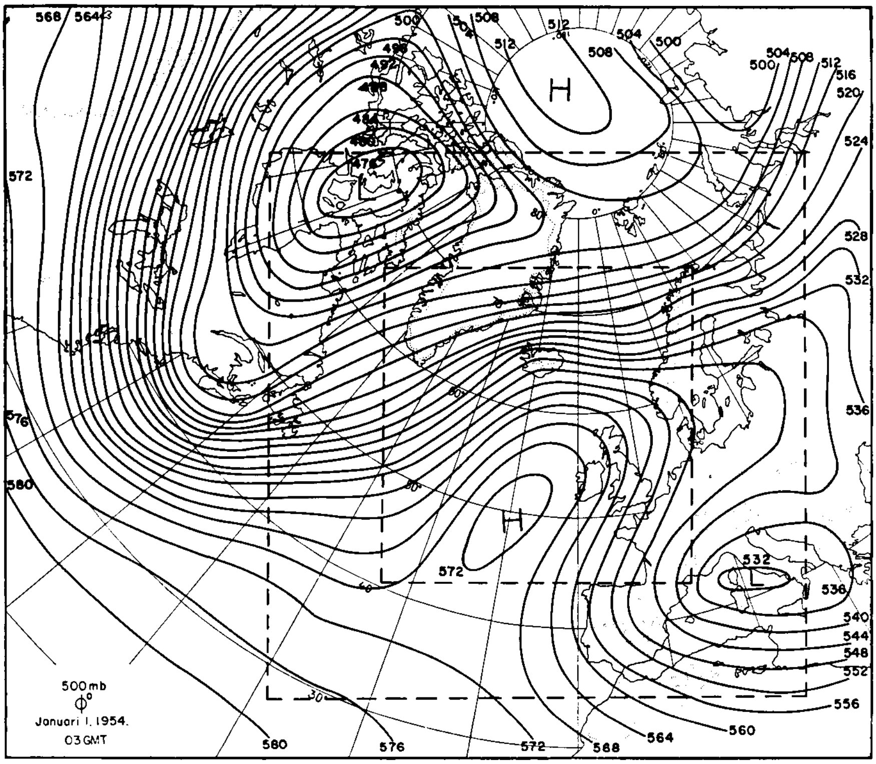

Fig. 4 a. 500-mb map at 0300 GMT January 1, 1954. Notations as in fig. 1.

mation of a system of waves. Gradually the effect spreads inwards from the boundary. In most cases it was, however, hardly noticeable in the φ-field inside the verification area. It should be remarked that a certain tendency for a "blocking" of this kind was present on the map shown in fig. 3. The pattern was, however, considerably distorted during the computations.

b) On the boundary segments with inflow the true value of the vorticity in reality is determined by the vorticity field outside the area. If such a boundary intersects a region of a strong gradient of the vorticity field perpendicular to the boundary the prescribed value of the vorticity on the boundary will differ considerably from the actual value within a few time steps. In the case of strong flow across the boundary the effect of such erroneous values of the advection of vorticity across the boundary may be noticed far away from it. The total gain or loss of vorticity over 24 hours for the whole forecast area by advection across the boundary is easily evaluated. It has been done in a few cases and the agreement is poor between the observed change of vorticity and the one computed on the basis of the boundary conditions. The forecast from January 1 is the most striking example of this effect (fig. 4). In this case the left boundary was placed to the east of a deep trough over western Atlantic. The initial values of the vorticity on the boundary were kept constant for the whole forecast period and gave rise to negative values of the vorticity advection over most of the western parts of the area. A very strong rise resulted. In reality, however, the trough to the west moved across the boundary, caused a considerable deepening and brought large values of absolute vorticity into the area. The forecast was an almost complete failure (cf. table I). It should be remarked that the analysis over the Atlantic never can be very accurate and analysis errors may to some extent have contributed to the poor result but there is nevertheless no doubt about the importance

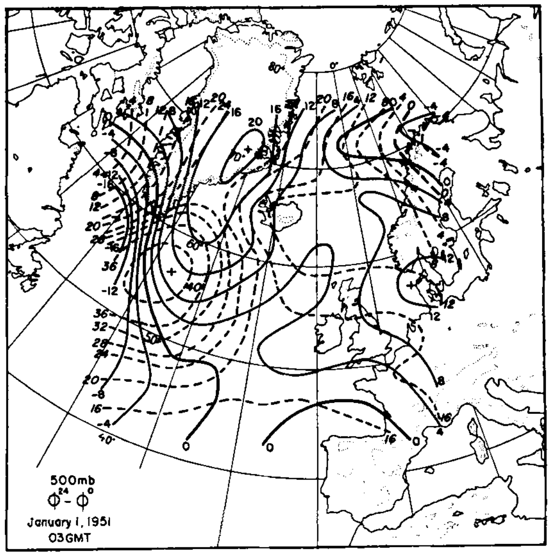

Fig. 4 b. Computed and observed 24-hour changes from map shown in fig. a. (Notations as in fig. 1.)

of the effect described above[1]. Also in some of the other cases of unsatisfactory results the same effect has played an important role.

It is quite evident both from table I and fig. 5 that the forecasts are better the more pronounced the actual changes of the flow pattern are. The same thing has been noticed with regard to standard methods of forecasting (LÖNNQVIST, 1952).

The goodness of the forecast in different parts of the verification area has been investigated in the same way as in the previous report (STAFF MEMBERS, UNIVERSITY OF STOCKHOLM, 1952). The result is shown in fig. 6 a in graphical form. We notice the relatively poor results in the western parts of the area, caused by the erroneous boundary values. Over northernmost England the average correlation is above 0.90 in spite of the fact that even the least successful forecasts have been included. This is certainly a very promising result. Fig. 7 shows the observed height changes at Liverpool (solid line) and the corresponding computed changes at a grid point close to this station (dashed line). We cannot forecast the mean height change ($\bar{y}$) with any accuracy. This fact influences the results considerably. It is conceivable that most of the errors thus introduced would be eliminated if a larger area could be used for the computations. We can get an approximate idea of the improvement it would represent by adding $(\bar{x} - \bar{y})$ to the forecast values at every point. Fig. 6 b shows the geographical distribution of the correlation coefficient after applying this correction and the dash-dotted curve in fig. 7 indicates the result of this correction at a particular point.

Since one of the main objectives of upper air

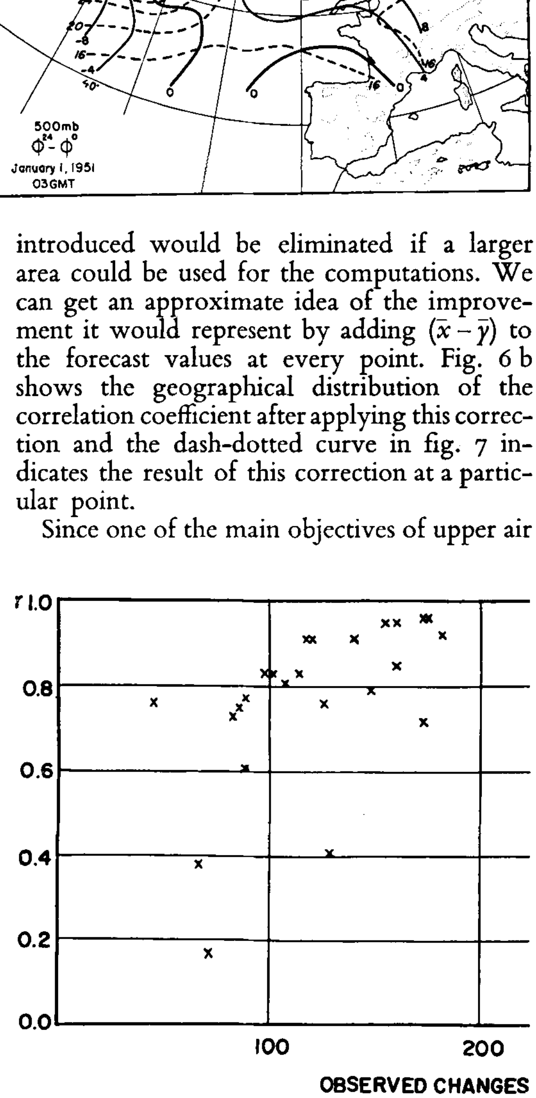

Fig. 5. Correlation coefficient (r) plotted as a function of observed changes ($\bar{x}$).

[1] Note added in proof: The map for January 1 has later been reanalysed and another 24-hour forecast has been performed. The results were slightly improved ($r = 0{,}30$) but the main features of the forecast changes as shown in fig. 4 remained unchanged.

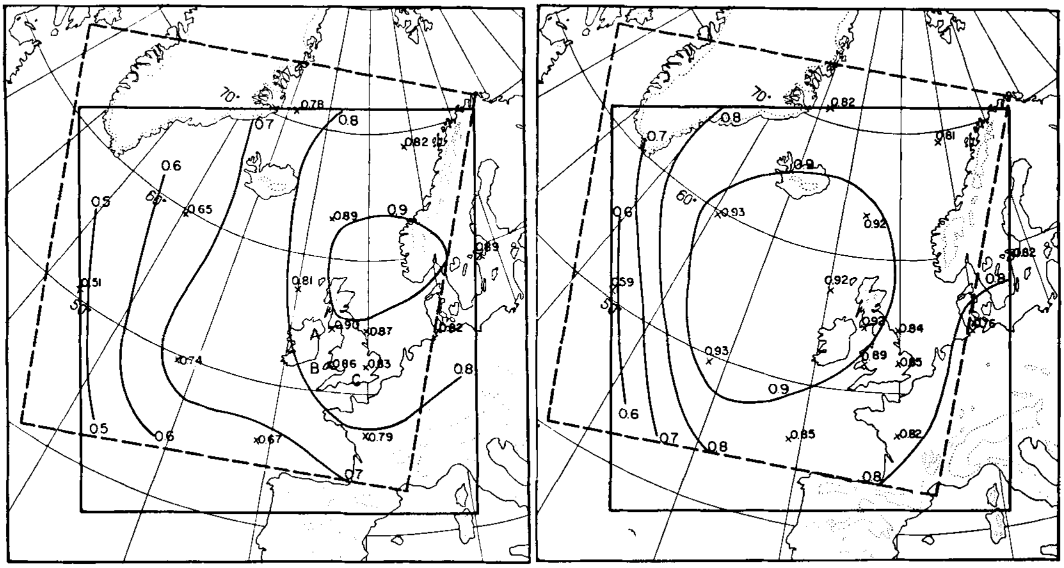

Fig. 6. Geographical distribution of the correlation between observed and computed 24-hour changes. Fig. a shows the correlation between x and y at 15 points, fig. b shows the correlation obtained between x and $(y+\bar{x}-\bar{y})$. The squares show the two most common locations of the verification area.

forecasting is wind forecasting it is of some interest to express the results obtained here in terms of the wind. The computed and observed height changes at three points (A), (B) and (C) (see fig. 6 a) have been used for evaluating the wind changes. The mean observed wind speed over this area was 26 m/s. The average observed change of the wind over 24 hours was 20 m/s against a computed value of 21 m/s. The mean error of the wind forecast was 13 m/s, which seems to be independent of the intensity of the wind field or the rapidity of its changes. All these values refer to the total wind. These results clearly show that considerable errors in the wind forecast exist in spite of the relatively high correlation ($r=0.90$). A verification of the computed wind changes should therefore be given as a complement of ordinary correlation coefficients.

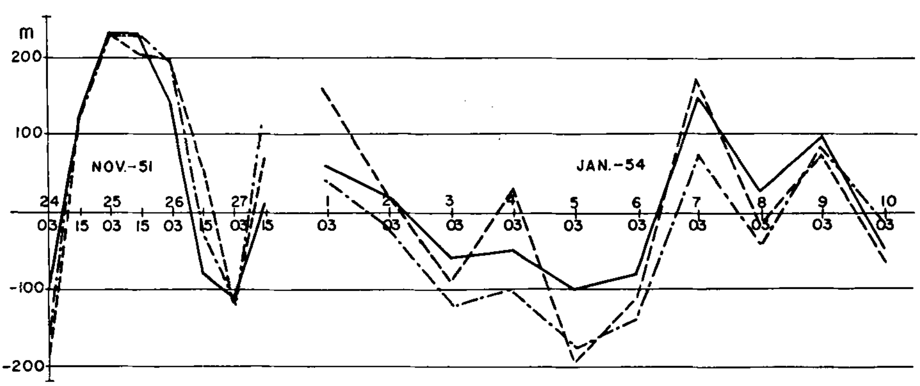

Fig. 7. Observed changes (x) of the 500 mb surface over Liverpool during November 24—27, 1951 and January 1—10, 1954 (solid line). Computed changes (y) (dashed line) and computed and corrected changes $(y+\bar{x}-\bar{y})$ (dash-dotted line) at gridpoint close to Liverpool.

4. Conclusions

The results of 24-hour forecasts with the barotropic model presented here are better than previous test (tendency computations and complete forecasts) have indicated. The errors seem to depend on the following factors, listed in the order of importance indicated by the present computations:

1) *Erroneous assumptions about the values of φ and in particular ζ on the boundary.* This defect may most effectively be eliminated by extending the forecast area beyond regions of strong vorticity gradients, e.g. by enclosing the larger portion of middle and high latitudes of the northern hemisphere. The memory of the machine after incorporating the magnetic drums, will easily permit the storage of this amount of data. It will then also be possible to extend the forecasts to 48 and 72 hours and investigate the break-down of the barotropic model (or of the computational scheme!). Such a program is under development.

2) *Inaccuracy of the initial analysis over areas with sparse data, e.g. the Atlantic.* For the next series of forecasts we are planning to utilize the result of the previous 24-hour forecast as an aid in the analysis over regions with sparse data. This method has previously been suggested to be one of the basic principles of numerical analysis of the initial data.

3) *Inaccuracy in forecasting components of the motion of a scale only a few times larger than the grid size.* For example, the speed of a wave of wave length 1,200 km is about 30% in error. This probably necessitates an intitial smoothing of the vorticity field to remove the small components of motion, which cannot be computed accurately. A continuous activation of the small scale motion takes place because of the non-linearity of the forecast equation. This tendency is noticeable in some of the forecasts and the wave pattern in fig. 3 may partly be looked upon as a result of this effect. When extending the forecasting to longer periods a smoothing even during the computations may therefore be necessary.

4) *Baroclinic developments.* The errors introduced by using the barotropic model are often obscured by the other sources of errors mentioned above. In extreme baroclinic developments as during the period studied by CHARNEY and PHILLIPS (l.c.) the barotropic model is not satisfactory. However, the results obtained by these writers do not seem to be representative for the applicability of the barotropic model in general. It is a common impression within our group that the results presented here by no means represent the ultimate limit of the potentialities of the barotropic model. On the contrary, a number of modifications may be carried through which will probably still improve these results significantly.

REFERENCES

CHARNEY, J., FJØRTOFT, R., VON NEUMANN, J., 1950: Numerical integration of the barotropic vorticity equation. *Tellus*, **2**, 237–254.

CHARNEY, J., PHILLIPS, N., 1953: Numerical integration of the quasi-geostrophic equations of motions for barotropic and simple baroclinic flows. *J. Meteor.* **10**, 71–99.

LÖNNQVIST, O., 1952: To the comparison between numerical methods and methods now in use for forecasting meteorological charts. *Tellus*, **4**, 195–200.

STAFF MEMBERS, THE INSTITUTE OF METEOROLOGY, UNIVERSITY OF STOCKHOLM, 1952: Preliminary report on the prognostic value of barotropic models in the forecasting of 500 mb height changes. *Tellus*, **4**, 21–30.