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One Year of Operational Numerical Weather Prediction

STAFF MEMBERS, JOINT NUMERICAL WEATHER PREDICTION UNIT *

ABSTRACT

This article is the first † of two brief reports on the activities and results of the Joint Numerical Weather Prediction Unit since the inauguration of routine numerical forecasting in May 1955. Following a broad statement of the Unit's objectives and a short chronology of the main changes of procedure over the past year, a description is given in general terms of the data processing and numerical forecasting routines of the JNWP Unit, together with the content and form of the numerical forecasts. The second report will deal with the accuracy and typical errors of such forecasts, as well as with the JNWP Unit's efforts to improve them.

INTRODUCTION

THE Joint Numerical Weather Prediction Unit was established by the Joint Meteorological Committee on 1 July 1954, with equal support from the U. S. Navy, the U. S. Weather Bureau, and the U.S.A.F. Air Weather Service. Its mission is "to produce on a current, routine, operational basis, prognostic charts of the 3-dimensional distribution of relevant meteorological elements by using numerical weather prediction techniques, in order to improve the meteorological forecasting capabilities of the participating weather services." The principal functions assigned to the Unit are operational and developmental. The operational function requires the unit to accomplish the daily computation of prognostic charts. The developmental function requires the unit to improve its capability to make forecasts both by extending the scope of the forecasts and by improving their accuracy.

This paper is intended to serve as a report to the meteorological profession on the first year of operational numerical weather prediction in the United States. The report discusses the operational procedures used and the general level of accuracy obtained. Principal sources of error which have been isolated are described along with the action believed necessary for their elimination. Since primary emphasis of the paper is on operations, only limited discussion is given to developmental projects under way or already completed. Papers on these projects will be submitted for publication separately.

COMPUTING FACILITIES

An International Business Machines Corp. Electronic Data Processing Machine Type 701 was acquired by the JNWP Unit on a rental

* Director, G. P. Cressman; Chief Development Section, Lt. Col. P. D. Thompson; Chief Analysis Section, E. B. Fawcett; Chief Computation Section, F. G. Shuman; previous Chiefs Computation Section, J. Smagorinsky, I. Silberman.

† The second and final article of this series will appear in the June issue of the BULLETIN.—*Ed.*

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basis early in March 1955. This model is equipped with an electrostatic memory of 2048 words of 36 binary digits each, including sign. The computer operates entirely automatically from an internally stored program. The arithmetic and control unit employs half-word logic, using single-address instructions. The addition time is 60 microseconds and the multiplication time is 456 microseconds, which can be reduced to 256 microseconds with optimum programming. External storage consists of four magnetic drums, each containing 2048 full words, and four magnetic tape units, each of which has practically unlimited storage capacity as far as meteorological problems are concerned. The rate of transfer of information from drums to electrostatic memory is 1000 full words per second and from tapes about twice as fast. All input is by means of punched cards. Output units are a card punch and a printer, which prints at the rate of 120 72-digit lines per minute.

Auxiliary equipment consists of four hand-operated card punches, a card sorter, a reproducer-punch, and a card printer. These are used for the processing of instruction and data cards.

CHRONOLOGY

Although the JNWP Unit was established in July 1954, the computer was not received until 28 February, 1955. Installation of the computer was complete by 17 March 1955. On 18 April, test forecasts with the 3-parameter model (Charney and Phillips [1]) described below were started on a once-daily 7 day per week schedule, and on 6 May distribution of the forecasts to the National Weather Analysis Center (NWAC), the Air Force, and Navy was begun. These baroclinic forecasts were made on a 19 × 29 grid covering the area inside the dashed line in FIGURE 1. The mesh length was a constant 0.8 inch on a polar stereographic map with a 1:15 million scale

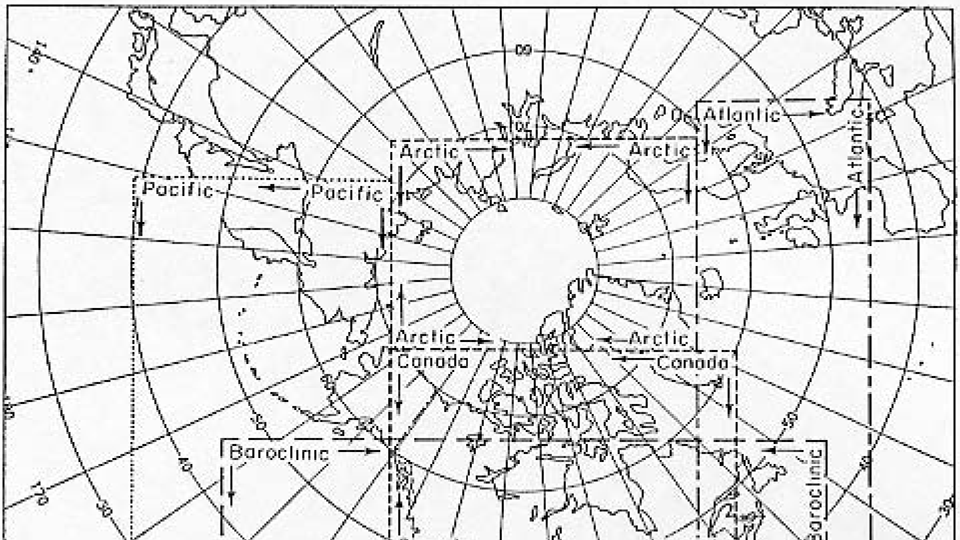

FIG. 1. 20 × 23 grid for barotropic forecasts (entire area), 19 × 29 grid for 3-level forecasts (inside dashed line), and verification areas.

at 60°N, which is about 240 km at 40°N. The initial data were produced by subjective analysis of the 1000, 700, and 400 mb charts. An interpolation routine was accomplished in the computer so the computation could be carried out at the 900, 700, and 400 mb levels. At the start of operations prognostic charts were printed at 12 hr intervals of the forecast for 900, 700, and 400 mb. Vertical velocities were computed and printed for the same times for the two layers between these surfaces. On 8 July 1955, issuance of 500 and 1000 mb prognostic charts in place of the 900 and 400 mb charts was started. These were obtained just before printing by interpolation and extrapolation from the data at 900, 700, and 400 mb, which were carried internally in the computer.

On 29 September, 1955, issuance of once daily barotropic forecasts at 24-hr intervals up to 72 hrs was begun. The initial data for this forecast are obtained by interpolation from the 03GCT 500 mb chart of the Northern Hemisphere analyzed by NWAC, and cover the entire area shown in Figure 1. The grid dimensions are 21 × 23 points, with a mesh length exactly twice as large as that used for the baroclinic forecasts. The first barotropic forecasts revealed a systematic error (truncation errors due to the large mesh length) which resulted in erroneously slow eastward displacement of troughs, ridges, etc. The systematic part of this truncation error was removed from the barotropic forecasts beginning on 10 October.

An objective analysis program similar to that of Gilchrist and Cressman [2] was tested during three weeks in July, 1955. At the conclusion of this period its use was discontinued until some modifications in the program could be made. The principal improvement required was a method for computer detection and removal of data errors. On 10 October, the modifications were completed and the improved objective analysis program was put into operational use.

On 10 November, the 3-level forecast program was changed by the addition of a smoothing routine done just before the 24 and 36 hr printing routines were entered. The smoothing routine, designed by F. G. Shuman [3], was designed to eliminate unsightly wiggles of small dimensions arising from truncation errors.

As the result of a discovery by G. 'Arnason (described later), certain coefficients used in the three-level program were changed to agree with the mean sounding for North America for the current month, beginning on 28 December. The new coefficients resulted in less erroneous anticyclogenesis and cyclogenesis in the prediction.

Data Preparation Methods

Experiments conducted at the Institute for Advanced Study, Princeton, N. J., and at Stockholm by Newton [4], have indicated that the highest quality analysis which can be produced should be used to arrive at the grid point data used as input for the numerical forecast. During approximately the first half year of operations, subjective analysis procedures were used. The analyses were developed with great care upward to 700 mb and 400 mb from the lowest pressure surface at 1000 mb with the aid of differential analysis techniques. Extensive use was made of weather reconnaissance and of reports from commercial aircraft.

The objective analysis program was prepared by LCdr. A. L. Stickles and G. P. Cressman in a form basically similar to that described in [2], with some important differences described below. In setting up a program to analyze the area for the baroclinic forecast, shown in Figure 1, one is faced with a dilemma. Insufficient upper air data exist for preparation of an analysis over much of the area, the Pacific area in particular. It is therefore necessary to supplement the data from a given time with other information. The use of normal values, as described by Bergthorson and Doos [5] was not considered seriously, since abnormal meteorological patterns often prove quite persistent in this area. The use of previously forecast information would be highly desirable, but impractical for this grid because the forecast deteriorates the most near the boundaries of the grid—which are just the areas where the least actual data are reported. In fact, the area where the forecast is the most reliable is also the area from which the greatest density of data is received. The solution arrived at was to compute an objective analysis for the whole grid area, but in areas of poor data coverage to supplement the reported data with information supplied by analysts. These data are derived from continuity (subjective forecast), vertical extrapolation, etc. Experimental runs of the objective analysis program with varying densities of data indicated that the large-scale atmospheric patterns could be reproduced with good accuracy from data points about 600 km apart, the data at each point consisting of one wind and one height, in agreement with Eliasson [6].

The total number of observations, real and supplemental, which must be punched on cards for the analysis program averages about 300 for each pressure surface. These observations receive only a cursory inspection for errors. The analysis program then proceeds with the computations, requiring about 4 minutes for the data preparation and 14 minutes for the analysis. The computation is completely checked in this time.

The data naturally contain errors of all types. Small errors are eliminated by the smoothing inherent in the analysis process. Large errors, however, cause analysis errors. It is not uncommon to have errors in the reported height of a pressure surface of from 500 to 5000 ft, due to observer errors and communication errors. These errors, however, can be detected in nearly all instances. In solving for the height of the pressure surface at a grid point, a minimum of 6 pieces of information is required (see [2]). A total of 10 is actually required before solution is attempted, resulting in a certain amount of smoothing. If one of these data, either a wind or a height, is considerably in error, the effect of the smoothing will be the greatest at that location, and that piece of data will differ the most from the smoothed analysis. If the error is extreme, the analysis will be a poor fit for some of the good data as well. However, with few exceptions, the fit will be the poorest for the erroneous data. The detection procedure then consists of (1) locating the pieces of data, both wind and height, which are poorly fit by the analysis and (2) within a given area of radius 2.6 grid units, determining the piece of data *most* poorly fit by the analysis. This is presumed to be in error and erased from the memory of the computer.

The errors, having been detected and erased, are listed by the computer for the information of the analyst who monitors the process. The computer then erases the analysis in the vicinity of the data which were removed, and re-analyzes using the correct data. The analysis is then given a final slight smoothing and with the aid of a contour program developed by Maj. H. A. Bedient, printed for final inspection by an analyst. The detection and removal of data errors and the re-analysis is done automatically, and requires about one minute plus about one more minute for the re-analysis around each piece of data removed. This time includes checking to eliminate the possibility of computer errors.

A rough estimate of the importance of the error sources would be that about 50 percent of the errors are introduced by the manual processing necessary before the analysis starts, about 25 percent by the teletypewriter net, and the remaining 25 percent by the observer in taking and working up the observation. It is doubtful whether any single method of error detection can detect 100 percent of the errors. However, the more checking that is introduced, the less is the probability of an error surviving all the checks undetected. It seems highly desirable to include some simple redundancy check in the actual teletype message to facilitate the detection of communication errors.

Our experience with objective analysis to date has led to the following plans for the next program of this type. First, the data input must be mechanized. It is an inefficient, slow, and error-generating procedure to have people read the teletype sheets, list the relevant data, and punch the cards. A program for complete mechanization and de-humanization of this process is nearing completion, and will be described in a future report. Secondly, a much larger grid area will be used for the forecast and analysis. This will be so arranged with respect to the data reporting areas that the forecast from one synoptic time will constitute valid analysis information for the next. Finally, an automatic method will be used for the vertical extrapolation of surface information in order to gain information at the upper levels.

This leads to some brief remarks on the data collection and distribution system. This system was, of course, not designed for and is not particularly suitable for numerical weather prediction purposes. It is hoped that, in the future, changes can be made to obtain the following:

(1) Increased upper air coverage over ocean areas, particularly the Pacific Ocean. This problem will be mentioned again.

(2) Increased priority for transmission of upper air data, particularly in the higher levels. It is not practical even to consider the use of data above 400 mb in an operational numerical prediction system with the present scheme of first and second transmissions.

(3) A more scientific use of redundancy to aid in detecting transmission errors. The usable redundancy at present consists of duplicate transmissions of winds in pilot balloon and radiosonde messages, or of duplicate transmissions on different circuits, or of the hydrostatic relation. One possible improvement would consist of the use of one digit in every ten to represent the last digit of the sum of the other nine.

(4) Greater regularity of upper-air code forms and units for international data exchange. For example, the automatic data processing system under development must anticipate receipt of at least three different upper wind codes and two different radiosonde codes, one of which contains three different possible combinations of units.

Such diversity can only serve the purposes of confusion.

(5) Some regular code for transmitting meteorological reports from aircraft other than reconnaissance. If the aircraft operators are unable to use a simple code, their "plain language" remarks should be encoded by someone else for distribution.

Some of the above remarks apply to the semantics of the communication problem. The technical means of communication present another problem which will not be discussed here.

Numerical Forecasting Procedure

The JNWP Unit's present method of numerical forecasting is based on the equations for the so-called "3-level model," substantially as described by Charney and Phillips [1]. The physical principles governing the behavior of this model are expressed in the thermodynamic energy equation and the potential vorticity ‡ equation for adiabatic nonviscous flow. Taken together with suitable boundary conditions and the hydrostatic and geostrophic-wind relations, these two equations provide the basis for a method of predicting the isobaric contours at all future times from a given initial height pattern.

Following Charney and Phillips [1], all vertical derivatives that enter into the adiabatic and potential vorticity equations are replaced by corresponding ratios of finite-differences, so that the equations refer explicitly only to the heights of a finite number of discrete isobaric surfaces—in the present case, the 900, 700, and 400 millibar surfaces. The fact that the heights of only three isobaric surfaces determine the state of this model places a restriction on its generality, since it cannot provide for vertical variations of static stability. In addition to this restriction, it is appropriate to summarize other approximations that are inherent in the present system of operational forecasting. It has been assumed that:

1) The flow is nonviscous and adiabatic.
2) The wind is very nearly geostrophic, for purposes of computing vorticity and horizontal advection of all quantities.
3) The vertical advection of potential vorticity (and vorticity production due to turning of vortex filaments) is negligible in comparison with its horizontal advection.
4) The vertical motions induced by large-scale irregularities of terrain are negligible in comparison with the maximum vertical motions of the free atmosphere.
5) The absolute vorticity and static stability may be replaced by constant standard values wherever they enter *undifferentiated* in the adiabatic and potential vorticity equations.
6) All derivatives may be computed with sufficient accuracy from height values at a network of discrete points, whose spacing is comparable with the distance between reporting stations.

As might be expected, the systematic errors to be discussed later are traceable to one or more of the approximations listed above.

The procedure by which the forecast is computed from the initial data is essentially one of advecting (or extrapolating) the initial potential vorticity pattern with the initial geostrophic wind over a very short period of time, in accordance with the equations and assumptions mentioned earlier. With arbitrarily specified height values on the lateral boundaries of the grid, one can then reconstruct the predicted height pattern from the predicted (*i.e.*, extrapolated) potential vorticity pattern, to obtain the predicted geostrophic wind. Thus, this process of extrapolation can be repeated again and again, until the short intervals of time over which the vorticity pattern is extrapolated add up to the required forecast period. At present, the 3-level forecasts are computed by repeated extrapolation over ½ hour increments of time.

The details of the numerical procedure by which the forecasts are computed are substantially as outlined by Charney and Phillips [1], with one important exception—namely, that certain coefficients containing the map scale factor and Coriolis parameter are not taken as constants in the process of computing the height pattern from a known potential vorticity pattern. These coefficients are allowed to vary from point to point, in accordance with changes of map scale on the polar stereographic projection.

To make the process of forecasting automatic, the computing procedure is reduced to a detailed step-by-step list of numerical and logical operations (or combinations of operations) that can be performed by the IBM 701. This list of instructions is next translated, according to a numerical code, into a series of orders that can be interpreted by the machine's logical control. This series of orders—known as a code—is unvarying

‡ "Potential" vorticity is proportional to the product of the absolute vorticity and static stability, and is conserved under the conditions specified.

and is recorded once and for all on punch cards.

The objective analysis of the initial data for 15GMT is generally completed by about 1600 EST. Shortly after that time, the deck of checked initial data is combined with the instruction deck and "read" into the machine. From this point onward the machine proceeds automatically, printing out 0, 12, 24, and 36 hour forecasts at intervals of about half an hour. The entire series of forecasts is usually printed out by 1800 EST, reproduced, and distributed to the Air Weather Service, the U. S. Navy and the National Weather Analysis Center (NWAC) by a half hour later.

The quantities forecast are the heights of the 1000, 700, and 500 millibar surfaces (obtained by interpolation and extrapolation from the 900, 700, and 400 millibar surfaces), and the vertical air speed at the 800 and 550 millibar surfaces, at the points of the baroclinic grid shown in FIGURE 1 and at times 12, 24, and 36 hours after initial map time. Heights are given in units of tens of feet, and vertical air speed in millimeters per second. The machine prints the forecast values in a rectangular array corresponding to the points of the actual grid. It also "shades in" (with densely printed characters) regions over which the height lies within previously specified ranges, so that the boundaries between shaded and unshaded regions are isobaric contours. Such contours are drawn in manually for ease of interpretation.

The JNWP Unit also computes daily 24, 48, and 72 hour forecasts of the 500 millibar height, based on the vorticity equation for the nondivergent barotropic model. In this case, the initial data for 0300Z are interpolated "by eye" from the National Weather Analysis Center (NWAC) chart at the points of the barotropic grid shown in FIGURE 1, and punched on cards. Since the absolute vorticity is conserved in nondivergent barotropic flow, the method by which the barotropic forecasts are computed is essentially a special case of the procedure for calculating the 3-level forecasts. The details of numerical method, coding, and computing are exactly analogous, with the following exception: The relative vorticity advection was multiplied by an empirical factor of 1.2, to correct a tendency to predict too little movement of the large-scale troughs and ridges. Although this tendency was probably due to the systematic effects of truncation error, it could equally well be attributed to differences between the 500 millibar wind and the wind at a somewhat higher "level of equivalence," whose precise location is rather uncertain and ill defined.

The barotropic forecast is given in terms of the 500 millibar height (in units of tens of feet) at the points of the 21 × 23 grid, and is represented graphically by the contour printout mentioned earlier. The barotropic forecasts are usually completed by about 1200 EST each day, and distributed to the participating services by about 1330 EST. Limited distribution of the 48 and 72 hour barotropic forecasts is made by facsimile at about 1500 EST.

The foregoing description of the JNWP Unit's actual end product completes the discussion of the physical basis and procedures of operational numerical weather forecasting, and concludes the present report.§ A second report, to be published in the next issue of the BULLETIN, will deal with the accuracy and characteristic errors of the JNWP Unit's numerical forecasts, and with the Unit's efforts to isolate and remedy such errors.

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§ Since the time when this report was prepared, a number of changes have been introduced into the operating routine. These include: (a) conversion from the 3-level model described here to a simple 2-level baroclinic model. This change, effective in July 1956, permits the use of a much larger forecasting area. (b) removal of the geostrophic approximation from the computation of barotropic forecasts, effective in April 1956. (c) the gradual introduction of automatic data-processing methods. These and other changes will be described in later reports.

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One Year of Operational Numerical Weather Prediction, Part II *

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ABSTRACT

This is the second of two brief reports on the activities and results of the Joint Numerical Weather Prediction Unit since May 1955, and is concerned primarily with the accuracy and characteristic errors of the numerical forecasts described in the previous report. The quality of the barotropic and 3-level forecasts has been measured by several statistical indices of error, and compared with that of the subjective forecasts issued by the National Weather Analysis Center. A breakdown of these statistics shows the dependence of forecasting accuracy on length of forecast period, level, data coverage, and proximity of lateral boundaries. Various sources of systematic error are discussed with reference to the JNWP Unit's efforts to isolate and remedy them.

After almost a year of experimentation and operational numerical weather forecasting, it is concluded that the quality of the numerical 500 millibar forecasts is not significantly different from that of the best subjective forecasts prepared by methods in current use. Recent results indicate that a significant improvement can be expected in the near future. The numerical 1000 mb forecasts are worse, but recent changes of model show promise of matching the performance of subjective methods. Finally, the most glaring systematic errors of the present numerical forecasts have adequate explanation in existing theory, and can be (or have already been) corrected by generalization of the models.

INTRODUCTION

IN an earlier report [1], the authors have stated the broad objectives and functions of the Joint Numerical Weather Prediction Unit, and have outlined the main changes in its procedure of operational numerical forecasting since May 1955. That report also included a description of the physical basis for the Unit's present methods of numerical forecasting, its data-analysis and computing procedures and, finally, the form and content of its completed numerical forecasts.

The purpose of the present report is to compare the accuracy of the JNWP Unit's numerical forecasts with several convenient standards of performance, and to discuss the nature and origins of certain types of systematic error. This article is concluded with a statement of the JNWP Unit's general impressions of the present status of numerical weather forecasting, after a year of operational experience.

* The first article of this series appeared in Vol. 38, No. 5 (May) of the BULLETIN.—Ed.

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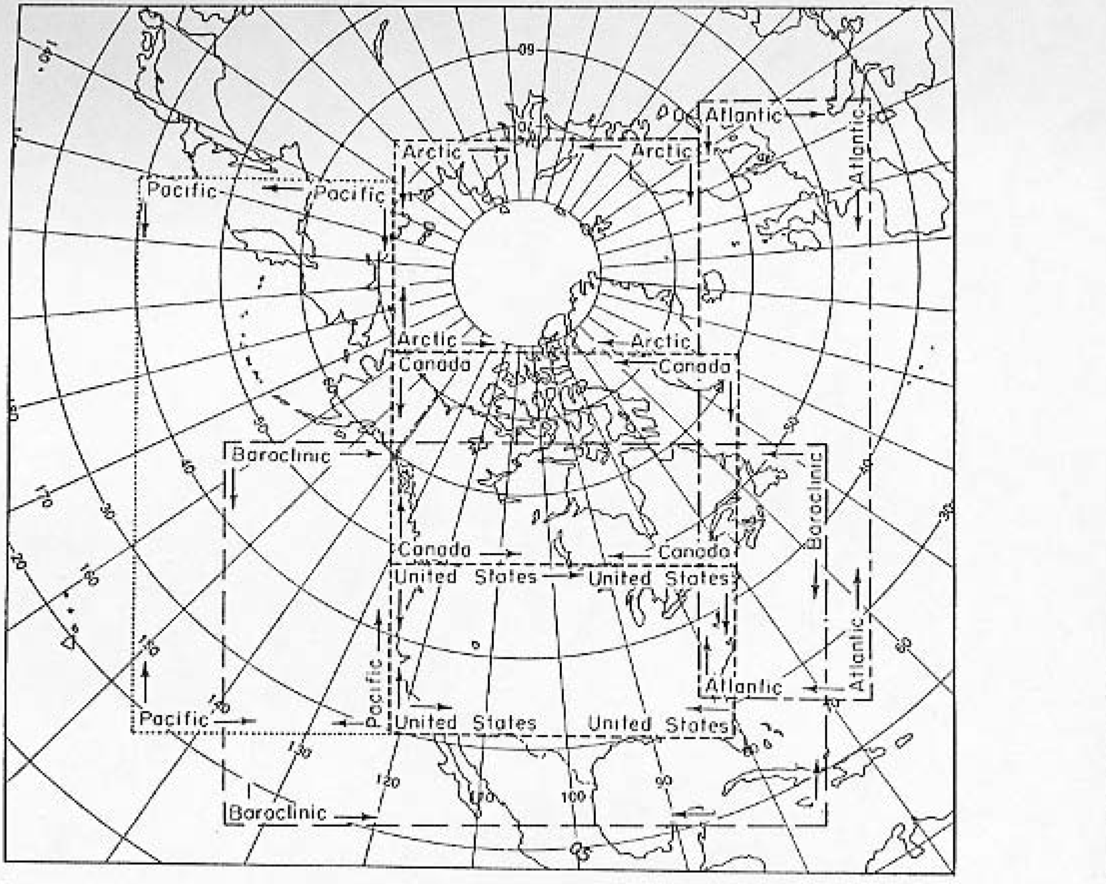


FIG. 1. 20 × 23 grid for barotropic forecasts (entire area), 19 × 29 grid for 3-level forecasts (inside dashed line), and verification areas.

VERIFICATION SCORES

Verifications of the barotropic and baroclinic forecasts have been made in terms of the root-mean-square (r.m.s.) vector error of the forecast geostrophic wind, measured over distances equal to the mesh length in the barotropic grid (or twice the mesh length of the baroclinic grid). The r.m.s. values are then determined from the total number of grid points in the area in question, with one value from each point. In the tables that follow, O refers to the r.m.s. geostrophic wind, O–F to the r.m.s. vector error of the forecast geostrophic wind, and O–I to the r.m.s. change of the geostrophic wind vector through the forecast period.

Verifications of the barotropic forecasts have been completed from November through March, and are summarized below for each of five areas designated on FIGURE 1.

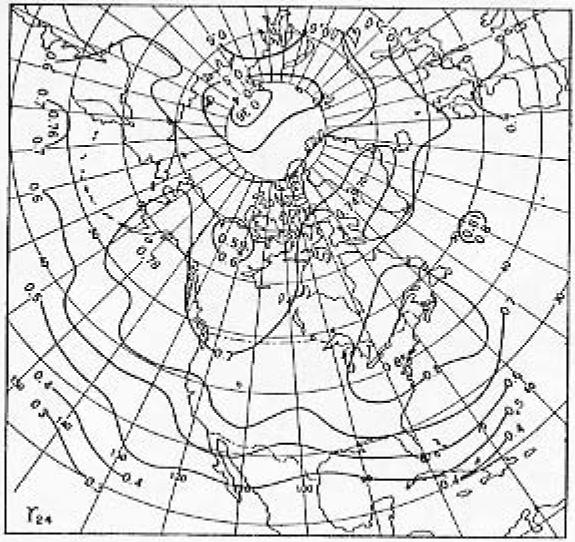
Additional verifications of these barotropic forecasts have been made by computing the correlation coefficient of forecast height change against observed height change at each grid point for each of the above months. These five monthly charts, averaged together for each time period, are shown in FIGURE 2 a, b, and c.

From TABLE I and FIGURE 2 it is seen that the barotropic forecasts are better than no change (or persistence) forecasts for all areas at all periods

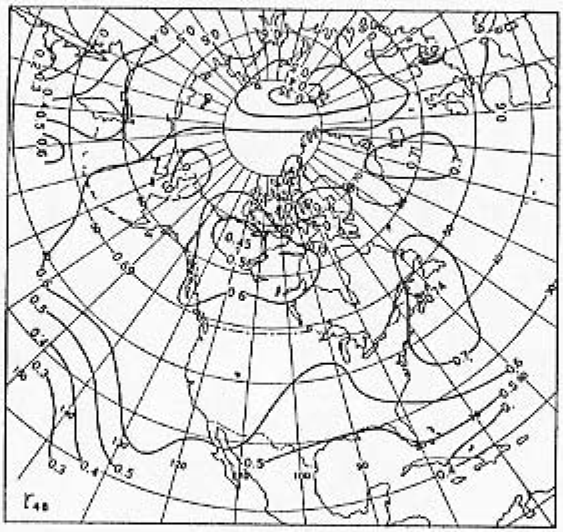
TABLE I

BAROTROPIC VERIFICATIONS (500 MB)
NOVEMBER 1955 THROUGH MARCH 1956
(r.m.s. values in knots)

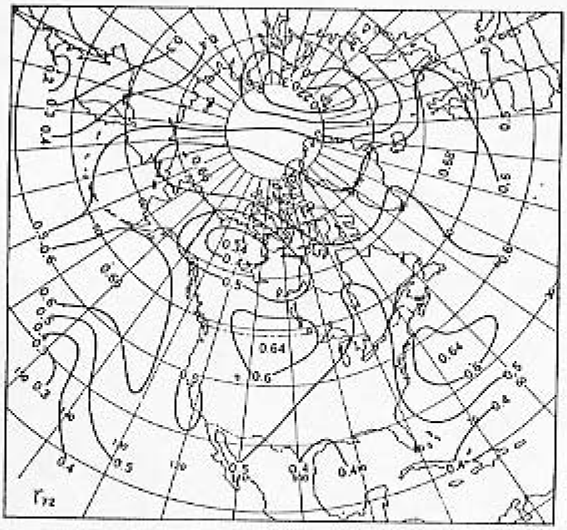
Area	24 hours			48 hours		72 hours	
	O	O–F / O	O–F / O–I	O–F / O	O–F / O–I	O–F / O	O–F / O–I
United States	51.6	0.42	0.69	0.63	0.85	0.77	0.98
Atlantic	47.8	0.43	0.63	0.63	0.78	0.78	0.93
Canada	34.2	0.56	0.70	0.82	0.80	1.01	0.90
Arctic	28.5	0.59	0.80	0.78	0.83	0.95	0.92
Pacific	42.9	0.54	0.76	0.75	0.85	0.93	0.95



a



b



c

FIG. 2, a, b and c. Time-averaged coefficients of correlation between observed height changes and changes predicted with barotropic model, over forecast periods of (a) 24 hours, (b) 48 hours and (c) 72 hours.

up to 72 hours. Generally, the barotropic forecasts for the Atlantic seem to verify better than those for any other area. This is in good agreement with the fact that the Stockholm group [2] has had very good results with barotropic forecasts for this area.

Verifications of the baroclinic forecasts for 24 hours (including the interpolated 500 mb forecast) are presented in the same form in TABLE II. The United States area is covered by these scores.

The following additional conclusions can be gained from TABLES I AND II.

(1) The 500 mb baroclinic forecasts were better than the barotropic forecasts for the United States area for 24 hours.

(2) The baroclinic model used gives the best forecasts at the highest level, with the worst forecast quality at the lowest level.

The second conclusion is verified by subjective impressions gained through the year. The forecasts at 900 or 1000 mb need considerable improvement before they can be considered competitive with subjective forecasting. At the higher levels, the numerical forecasts are highly competitive, as will be shown below.

A comparative verification program has been conducted by verifying the JNWP 500 mb 36 hr forecasts from the baroclinic model against 500 mb forecasts prepared in the National Weather Anal-

TABLE II

BAROCLINIC VERIFICATIONS (24 HR FORECASTS)
(rms values in knots)

		July 55 through Oct. 55	Nov. 55 through March 56
900 mb	O	14.0	17.9
	O–F/O.	0.86	0.92
	O–F/O–I	0.92	0.93
700 mb	O	17.9	28.7
	O–F/O	0.63	0.50
	O–F/O–I	0.85	0.81
500 mb	O–F/O		0.38
400 mb	O	34.2	59.3
	O–F/O	0.46	0.37
	O–F/O–I	0.72	0.64

ysis Center (NWAC). In interpreting the scores, it should be remembered that the subjective forecasters have some later data as well as the numerical forecasts available before finalizing the prognosis. Although no barotropic forecasts are prepared from the 15Z starting time, the 36 hr scores from the barotropic forecasts made from 03Z are included for comparison.

The following points of interest can be mentioned:

(1) The barotropic forecasts have a higher level of accuracy at 36 hrs than either the baroclinic 500 mb forecasts or the subjectively prepared forecasts. In partial explanation, it is clear that the 36 hour baroclinic forecasts, computed over a much smaller area than the barotropic forecasts, suffer from boundary errors which do not seriously affect the barotropic forecasts.

(2) Through 1955 the subjectively prepared 500 mb prognoses were better than the 500 mb baroclinic prognoses. However, after the end of the year the baroclinic prognoses were better than the subjective ones. This can be attributed at least in part to the model improvement introduced on 28 December, described elsewhere in this paper.

CHARACTERISTIC ERRORS, THEIR ORIGINS AND REMEDIES

Daily inspection and verification of more than 300 numerical forecasts has revealed a number of typical defects of the current operational forecasting system. One of the most frequent and pernicious of these is a tendency to overpredict the intensification of anticyclones or to predict anticyclogenesis where none in fact occurred. This general fault is symptomatic of either or both of two different types of error. The first is confined mainly to the lower levels (whence it is characteristic of the baroclinic forecasts), and is manifested in a rapid intensification of the vorticity minimum associated with surface highs. This process is frequently so rapid that the predicted circulation around surface highs is quite as strong as around lows, whereas there is actually a marked asymmetry in the flow patterns around highs and lows. A typical example of this kind of error is exhibited in FIGURE 3, which shows the observed 1000 and 500 mb charts for 1500Z on 7 Nov. 1955 and 0300Z on 9 Nov. 1955, together with the 36 hour forecasts of the 1000 and 500 mb heights, based on the 3-level model. The worst single aspect of these forecasts was the predicted surface anticyclogenesis over the western U.S., which completely failed to materialize. It is noteworthy that the maximum height errors at 1000 mb were nearly 1000 feet, but diminished to less than 200 feet at 500 mb over the same area, verifying that this type of error is peculiar to baroclinic models. One should also note that the associated minimum of surface vorticity was much intensified, showing that the predicted vorticity was being "destroyed" much too rapidly by low level divergence.

In connection with this type of error, one must bear in mind that potential vorticity is not actually conserved in the 3-level model, simply because the absolute vorticity and static stability have been replaced by constant standard values where they appear undifferentiated in the potential vorticity equation. In general, this approximation overestimates the initial absolute vorticity in anticy-

TABLE III

COMPARATIVE VERIFICATIONS, 36 HRS, 500 MB

O–F/O U. S. Area	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
JNWP 3-level	0.678	0.706	0.604	0.586	0.543	0.638	0.481	0.494	0.548
JNWP barotropic				0.505	0.502	0.595	0.538	0.468	0.563
NWAC	0.621	0.622	0.597	0.540	0.508	0.641	0.518	0.512	0.589

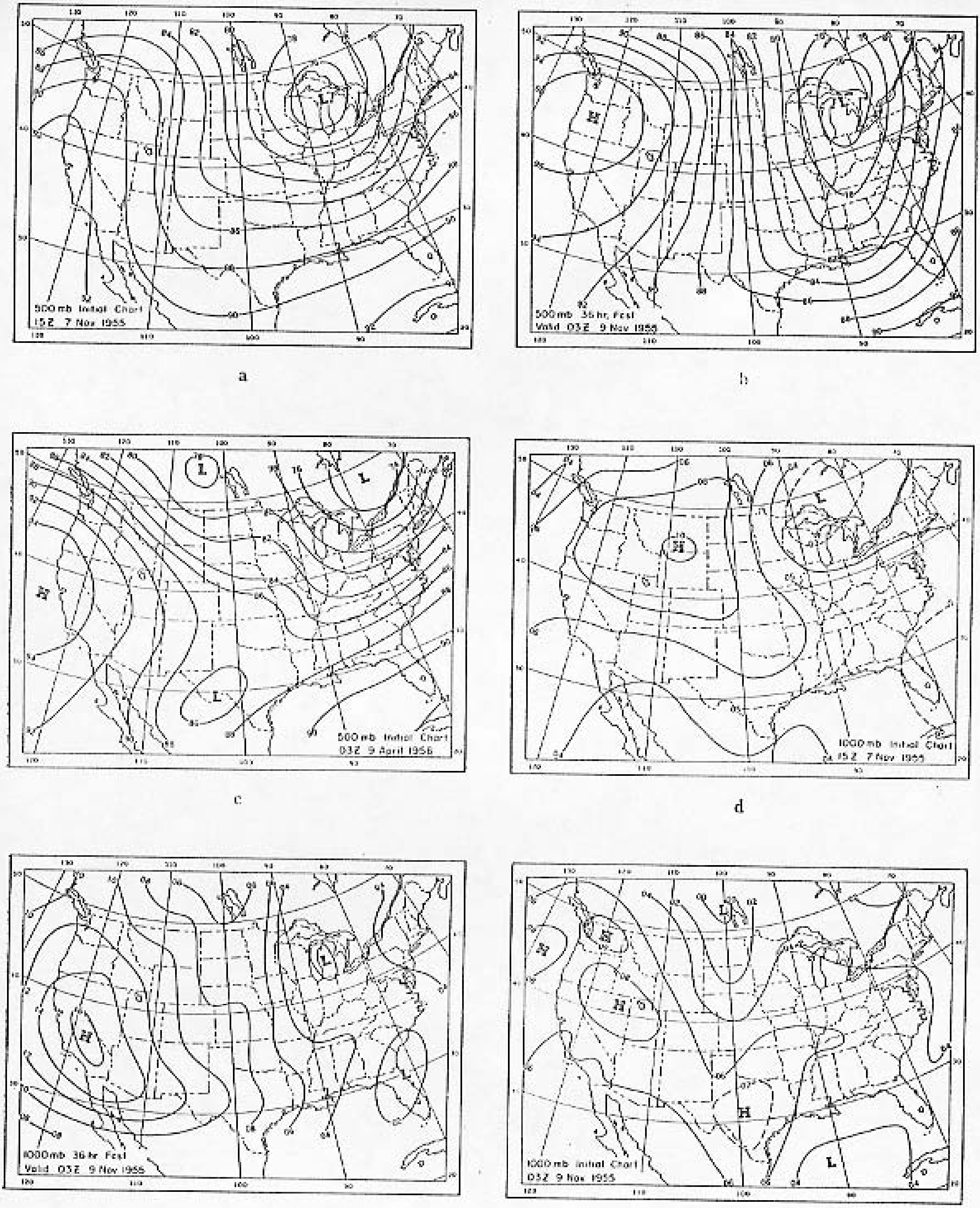
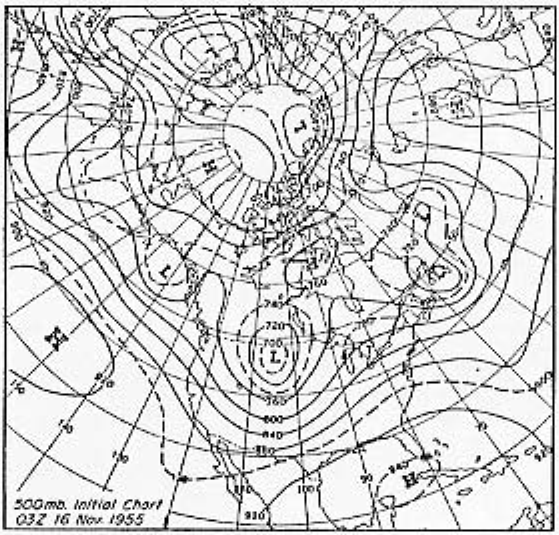


Fig. 3, a–f. Initial data, 36 hour forecasts, and verification for 1000 and 500 mb in a case of spurious "baroclinic" anticyclogenesis.

clones, and under-estimates the static stability. The latter leads to an overly intense field of horizontal divergence, and the former magnifies its effect on the vorticity field, so that there is (in principle) no lower limit to the predicted absolute vorticity. The exact equations, on the other hand, indicate that the minimum absolute vorticity is limited from below by the minimum initial potential vorticity and the static stability (which cannot remain negative over large areas). These conclusions have been borne out by numerical experiment, which show that increased static stability leads to less pronounced anticyclogenesis, and that the use of a more nearly correct value of absolute vorticity in the divergence term of the vorticity equation reduces false surface anticyclogenesis even further. As a result of such experiments, carried out by Arnason, Carstensen, and Zartner, the JNWP Unit now changes the static stability of the 3-level model from month to month, in accordance with the observed average monthly values. The latter were found to exceed the static stability of the Standard Atmosphere in all months.

A second source of "false anticyclogenesis" is the geostrophic approximation. This type of error—which shows up in the 3-level forecasts at all levels



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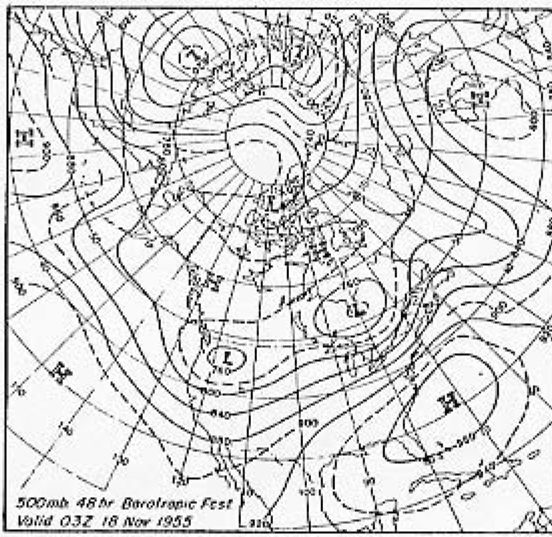

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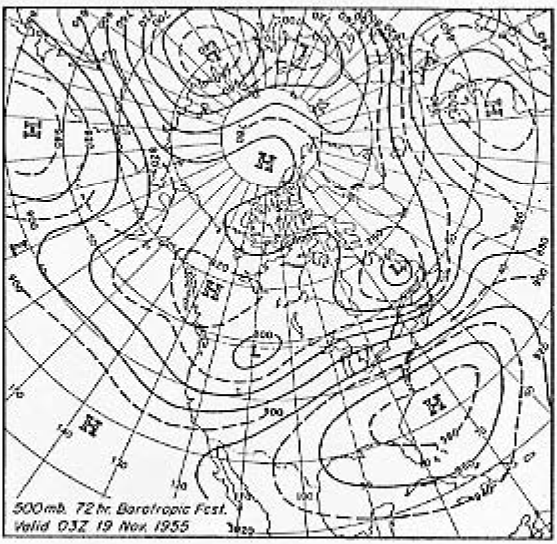

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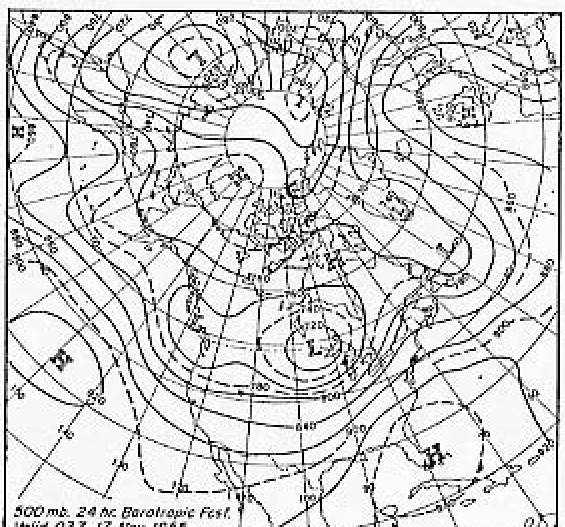

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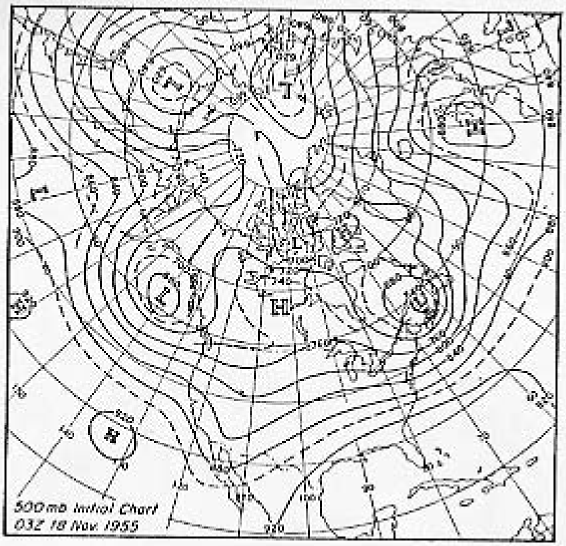

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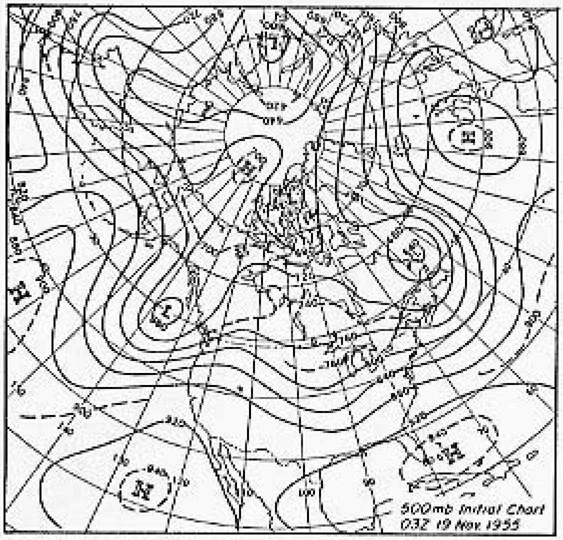

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FIG. 4, a–f. Initial data, 24, 48, and 72 hour barotropic 500 mb forecasts, with verification at 48 and 72 hours, in a case of spurious "barotropic" anticyclogenesis.

and, what is more significant, in the barotropic forecasts—frequently occurs along a warm ridge with southwest flow originating in low latitudes, and with a strong minimum of geostrophic vorticity south of a jet in the southeast sector of the trough to the west. Although the *geostrophic absolute vorticity may be conserved* (as it is in the barotropic forecasts), the net effect is to increase the anticyclonic contour curvature along a warm ridge very rapidly, and to "blow up" the subtropical highs—producing height errors of several hundred feet in 24 hours. A representative example of this kind of error is displayed in FIGURE 4, which shows the observed 500 mb charts for 0300Z on the 16, 18, and 19 Nov. 1955, together with the 24, 48, and 72 hour barotropic forecasts made from initial data at 0300Z, 16 Nov. 1955. The most striking feature of the 48 and 72 hour forecasts was the gradual building up of the subtropical high east of Georgia, with attendant errors of four or five hundred feet near the center after 48 hours. After 72 hours, the effects of these errors had spread over much of the Atlantic and U. S., retarding the oncoming trough to the west by nearly a half wavelength.

Since the type of error described above is contained in pure form in the geostrophic-barotropic forecasts, it cannot be due to the approximations discussed previously. A large number of barotropic forecasts has been made from initially nongeostrophic wind fields, computed from the "balance equation" through a method devised by Shuman. The results indicate that this particular type of "false anticyclogenesis" is due primarily to the geostrophic approximation, and simultaneously point out the way to reduce it.*

Another type of error from which all methods of numerical prediction suffer is caused by incorrectly specified future conditions on the lateral boundaries of the grid. Such boundary conditions are necessary to solve the equations, but are not actually known. In the current operational system, the height is arbitrarily held fixed at all points on the lateral boundaries, and the relative vorticity is set equal to zero. This procedure frequently leads to errors of several hundred feet in 24 hours in regions adjacent to the boundaries; moreover, these errors are propagated inward rapidly enough that a whole quadrant of the 19 × 29 grid can be seriously affected in a day's time. The only uniformly effective remedy for this type of error is to extend the grid over an entire hemisphere, so that the lateral boundaries lie in the relatively quiescent equatorial regions. Short of that, the JNWP Unit has extended the area (covered by all recently developed forecasting systems) far enough that the central portions of the grid are not contaminated within the period of the forecast.

The rate at which the influence of a particular feature of the upper air pattern propagates to great distances has been treated extensively in meteoro-

* The use of nongeostrophic initial wind fields for the barotropic forecasts was adopted as a matter of routine on 20 April 1956.

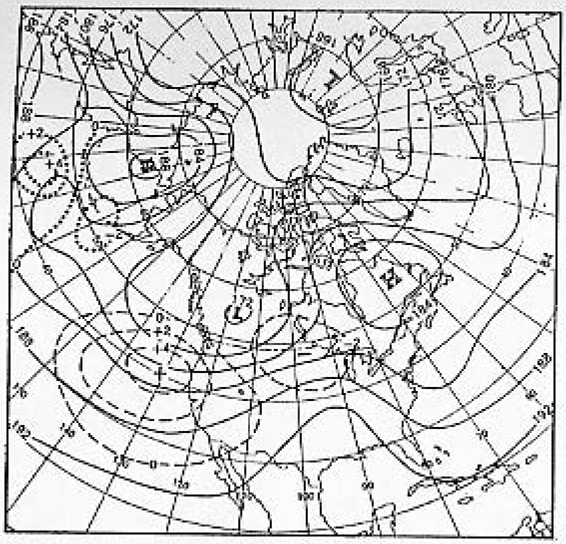


FIG. 5. Changes (dashed lines) in 48 hour barotropic 500 mb forecasts resulting from correction (dotted lines) in the initial contour analysis over the N. Pacific.

logical literature for a number of years (for example, see Namias [3], 1943). It is clear that if the west and north boundaries of a given forecast area are set in the Gulf of Alaska, errors in the forecast are due essentially to ignorance of what is going on in the central and west Pacific at the initial time. Similar errors are introduced into the forecast when a much larger initial area is used, provided that data coverage in the same area is insufficient for a reasonably correct specification of initial conditions. An example of this difficulty is shown in FIGURE 5. It was determined from late data and subsequent events in the central Pacific that the barotropic forecast from 03Z, 31 October, 1955 had been made from an incorrect initial analysis. The initial analysis was corrected and a new forecast was made. The difference between the two starting analyses is shown by the dotted lines in FIGURE 5 (second minus first). The resulting difference in the two 48-hour forecasts is shown by the dashed lines. The difference between the two forecasts was in the right direction to reduce a serious error in the original 48 hour forecast. This example illustrates the fact that very large errors in some forecasts for much of the United States are due to lack of adequate upper air data in the Pacific. It is encouraging to note that a rapid expansion of the program of radiosonde observations from travelling ships in the Pacific is planned.

Considerable error may also be introduced into a forecast if the variations in elevation of the lower boundary, *i.e.*, the surface of the ground, are ignored. This type of error is often reflected in a tendency to underpredict (or to miss entirely) cyclogenesis in the lee of an extensive mountain system or in a tendency to underpredict the converse anticyclogenesis upstream of a mountain system. The first experiments successfully concluded were carried out with a 2-parameter model using a special form of the vorticity equation in which the divergence is multiplied by a non-geostrophic absolute vorticity (see Shuman [4]). In this model the terrain-induced vertical motions were included by (a) imagining that the atmosphere extended everywhere to 1000 mb but by (b) computing the vertical velocities at 1000 mb as given by the horizontal advection of terrain height by the geostrophic wind interpolated to the height of the terrain.

This procedure, although inexact, appears to give forecasts which successfully include the observable large-scale terrain effects on the 2-parameter model. However, when applied to the 3-parameter model which is used operationally, the computation of mountain effects was found to be exaggerated. Since the computation is contaminated by errors from several other sources, it is difficult to specify the exact reason for this difficulty. Two possible reasons are: (a) the less correct use of the vorticity equation in the 3-parameter model (the absolute vorticity having been replaced by the Coriolis parameter where used as a coefficient of the divergence) and (b) the use of some non-centered quantities in a finite-difference system of computations (*i.e.*, the wind which advects terrain height is taken at the height of the terrain).

It seems likely that the first of these two reasons is the more valid, since the overestimation of mountain effects is pronounced in anticyclonic regimes, but not noticeable in cyclonic regimes.

Since the assumption of a flat lower boundary is obviously incorrect, it was believed desirable to include in the 3-parameter forecasts the best available computation of mountain effects. This was done by reducing the computed values of the terrain-induced vertical motions by an empirically determined factor of 0.4. An extensive series of tests with this type of forecast indicated that the results were never significantly worse than the flat-terrain forecasts, but were occasionally much better. This change in the daily forecast routine was made on 10 May 1956.

A sample of this type of forecast is shown in FIGURE 6. The most striking difference between "mountain" and "non-mountain" forecasts are (a)

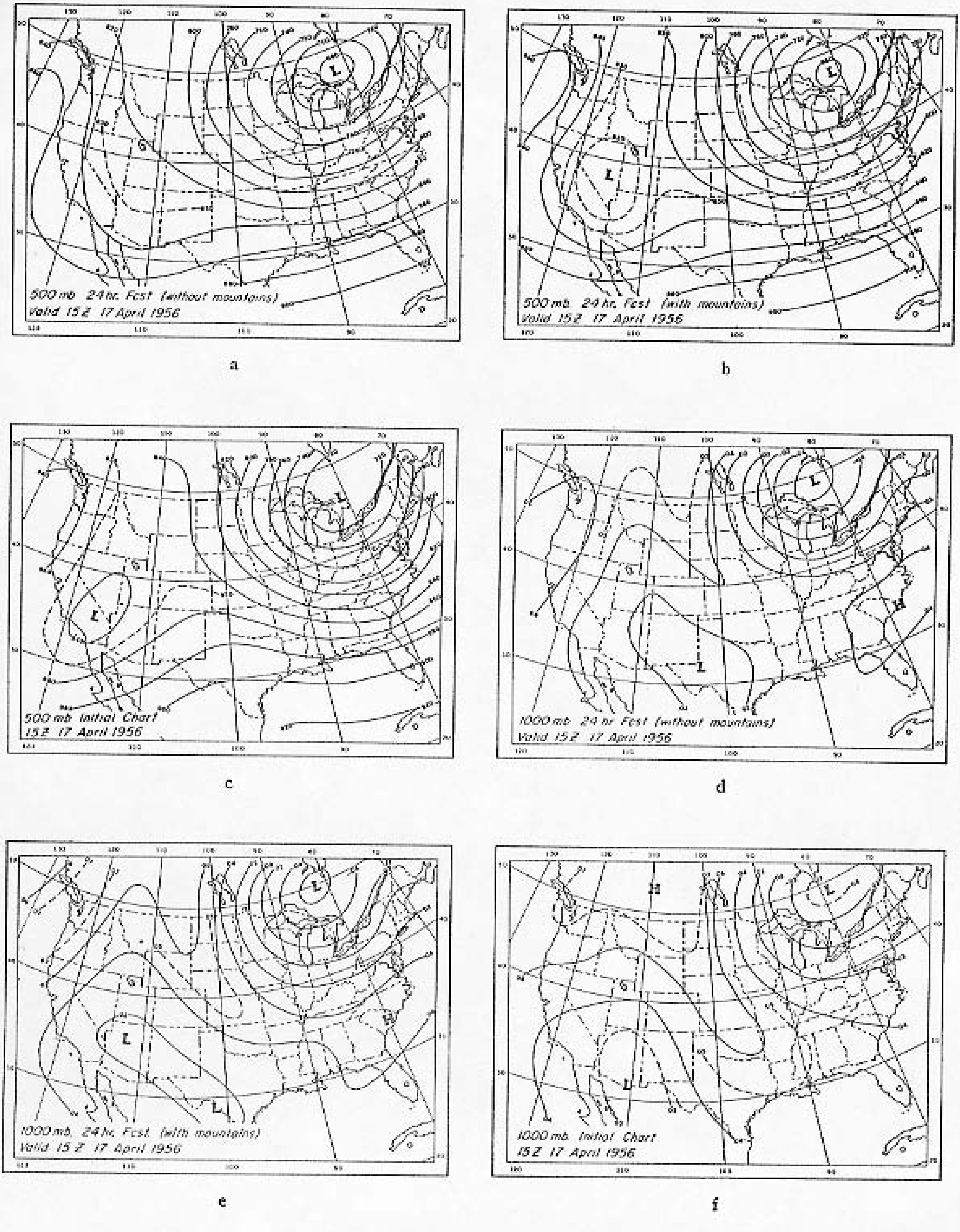


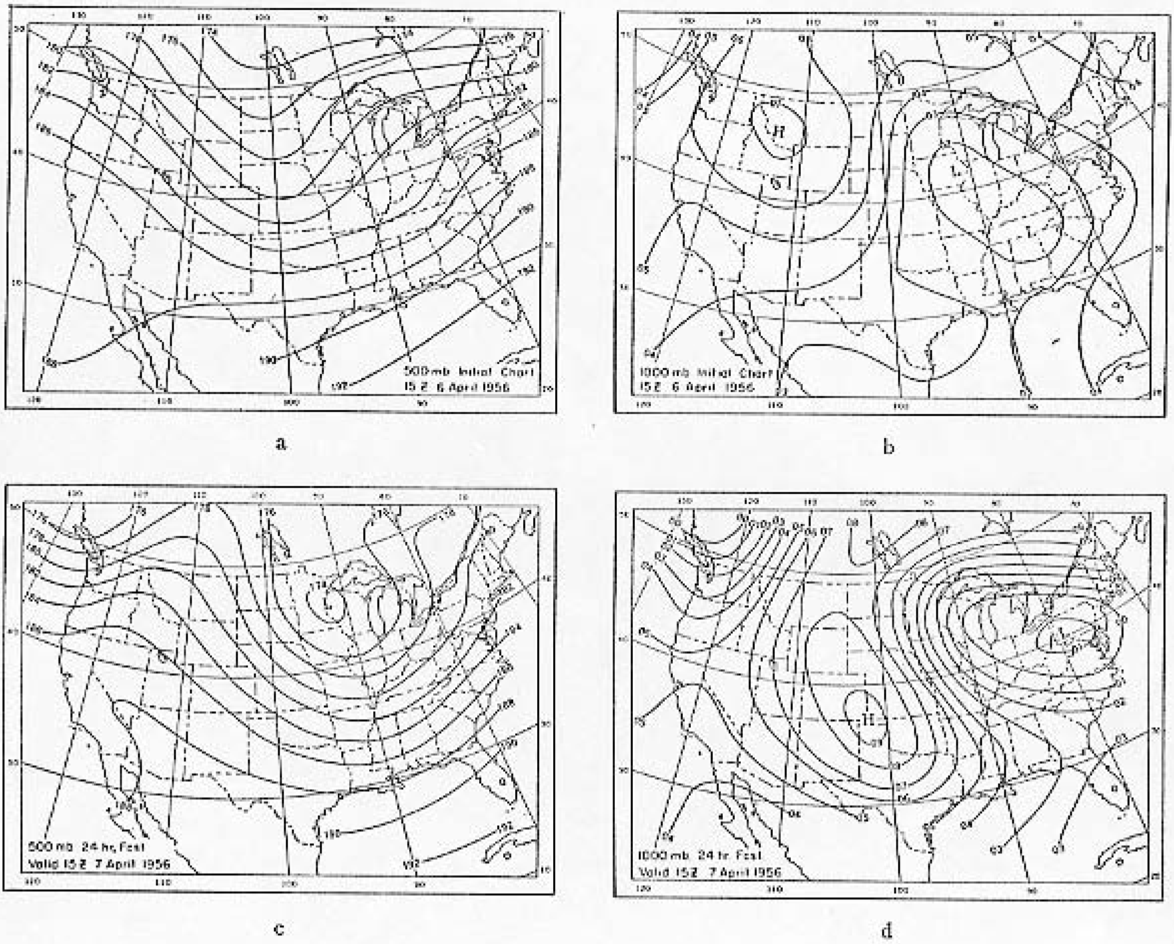
FIG. 6, a–f.. 24 hour forecasts of 1000 and 500 mb height, with and without the large-scale effects of mountains, and verification.

the formation of the closed low in the Southwest at 500 mb as a result of mountain effects and (b) the improvement of the 1000 mb ridge intensity in the central U. S.

Truncation errors—*i.e.*, errors of approximating differential quotients by ratios of finite-differences—have been found to affect the forecasts in two ways. One effect, due to systematic underestimation of horizontal advection, results in too slow a rate of displacement of distinct synoptic features, particularly those of short wavelength. As mentioned earlier, an empirical correction for this type of error has been introduced into the barotropic forecasts by Cressman. More general and exact techniques for reducing systematic truncation error, based on higher order finite-difference approximations, have been devised and tested by Shuman.

The second effect of truncation error is to generate quasi-random fluctuations with wavelengths of 2–4 grid intervals. In the course of a 3-day forecast, these "wiggles" may amplify to the point of obscuring all features of meteorological interest. Lacking a complete knowledge of the nonlinear manner in which such small-scale fluctuations interact, the JNWP Unit has experimented with several methods of intermittent smoothing, designed to remove fluctuations whose wavelengths are four grid increments or less, but which leaves features of larger scale substantially intact. A smoothing operator having the characteristics of a "low-pass filter," devised by Shuman, is at present being applied at each time stage of the barotropic forecast, with the desired effect of suppressing "wiggles."

Since the development of improved methods of numerical prediction is centered around the failures of existing methods, it is natural that much of the foregoing discussion should be concerned with the errors of numerical forecasts. Lest the reader get the impression that all numerical forecasts are hopelessly contaminated by half a dozen different types of errors, a rather good numerical forecast is displayed in FIGURE 7. FIGURE 7 shows



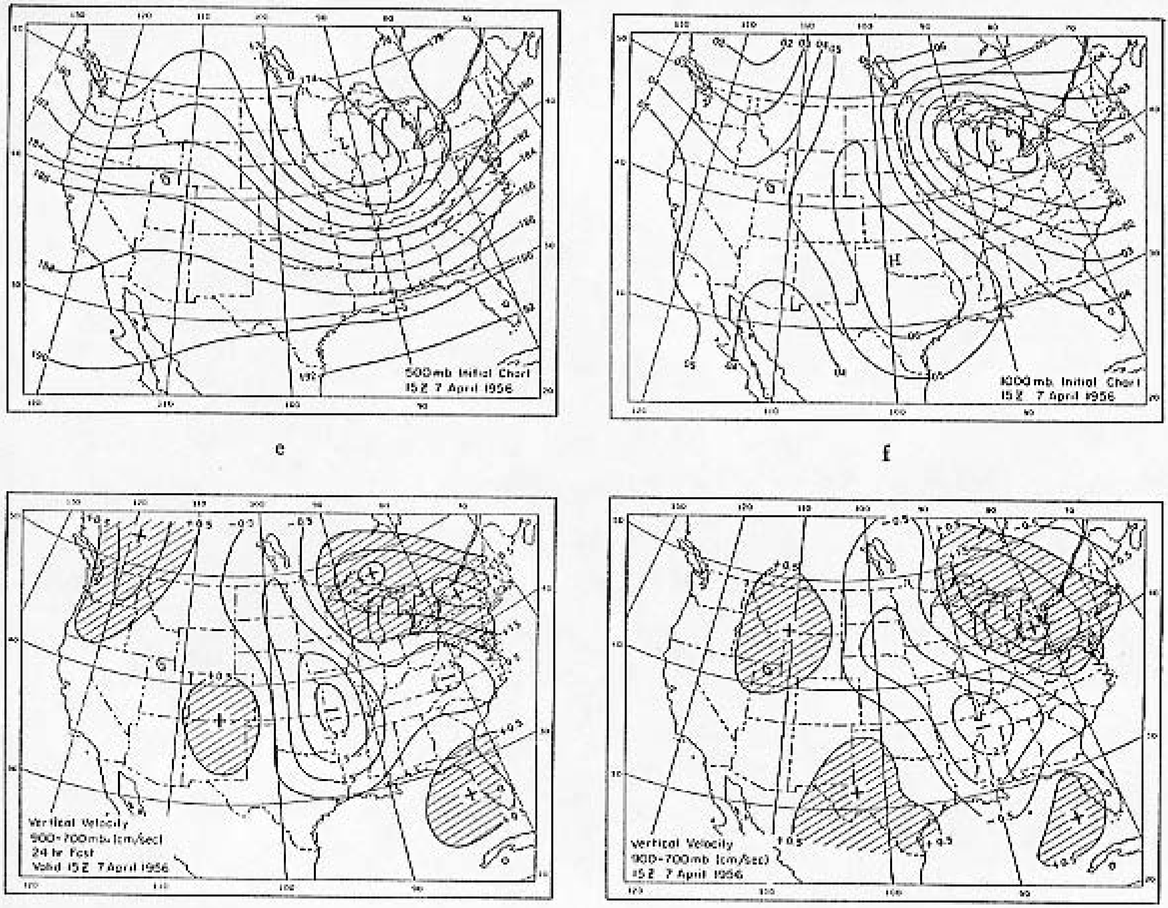


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FIG. 7, a–h. **Initial data, 24 hour forecasts of 1000 mb height, 500 mb height and vertical air speed, with verification.**

the 1000 and 500 mb charts, along with the vertical motion forecast, from the 3-layer model for a 24 hr forecast from 15Z, 6 April, 1956. During this period a baroclinic development occurred, which led to an unseasonable snowstorm over the northeastern states. The deepening at 500 mb was successfully forecast, as well as the deepening at 1000 mb. Although the forecast low center at 1000 mb is not located exactly correctly, the general features are accurately forecast. Note the strengthening of the gradients on the forecast and verifying 1000 mb charts. A characteristic error of the 3-level forecasts can be observed on the 1000 mb chart, where the height gradients are forecast to intensify slightly too much.

The vertical velocities computed from the initial time on April 7 are used as verification for the forecast from April 6. Although there are some differences in detail, it is suggested that a forecaster charged with the responsibility of forecasting the actual weather should find such prognostic charts very helpful.

FIGURE 8 shows two barotropic forecasts (48 hr and 72 hr) for the 03Z 28 November 1955 map. The initial charts for the 25th and 26th, as well as the map for the 27th, show the evolutions of the flow pattern through the 3-day period. Four features of interest are:

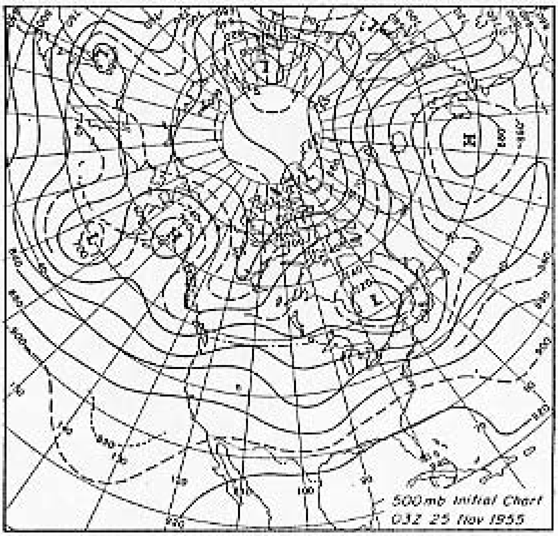
a) The generation of a pronounced trough over the Mississippi valley as a result of advection of high vorticity from western Canada. This was evidently barotropically produced as indicated by the success of the forecasts. One can suspect some baroclinic amplification of this cyclonic system since both the 48 and 72 hr barotropic prognostic charts had too small amplitude forecast in this area.

b) A strong baroclinic development which resulted in an intense low east of Labrador. The barotropic forecasts show the correct position for this feature, but much too weak intensity.

c) The breaking up of a blocking situation over the east Atlantic through the three day period. The barotropic forecasts of this were highly successful.

d) The forecasts for the central and west Pacific, which are as a rule not very successful. This is a result of lack of initial data and of propagation of boundary errors from the vicinity of Japan across the Pacific.

The barotropic model's inability to predict true cyclogenesis arises, of course, from the fact that the number and intensity of distinct maxima and minima of vorticity remains unchanged in non-divergent barotropic flow. It should also be pointed out, however, that many of the developments that the synoptic meteorologist might regard as "new" are due primarily to the internal re-distribution of an already existing vorticity field, and to the barotropic exchange of kinetic energy between the mean zonal flow and the large-scale disturbances.



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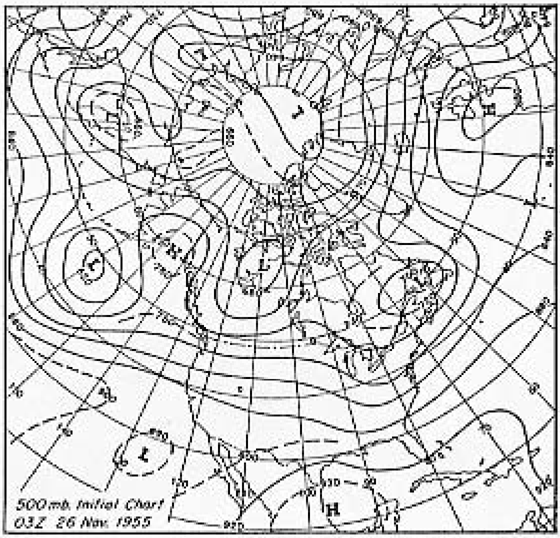

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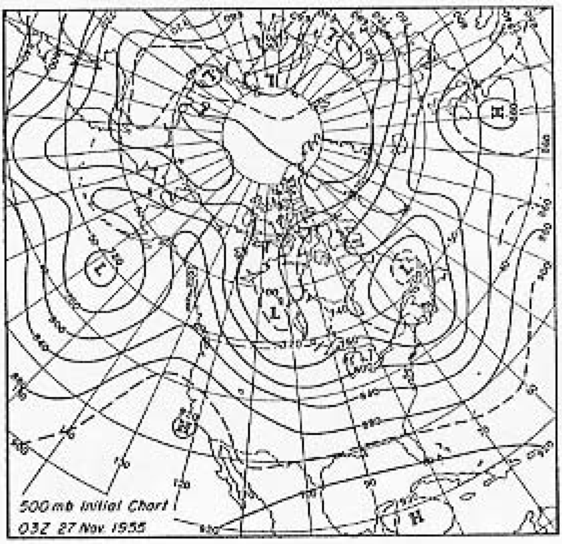

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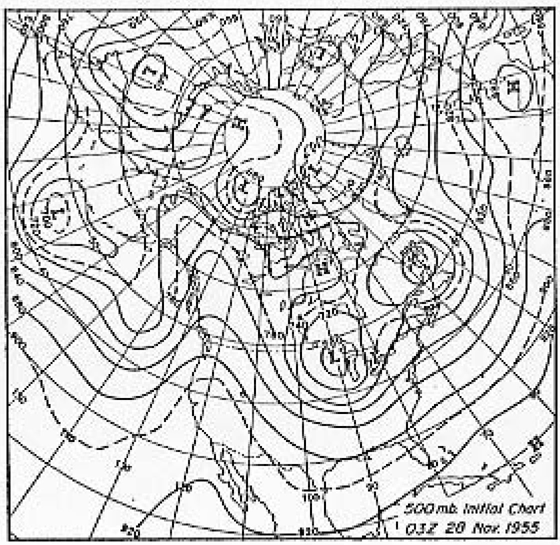

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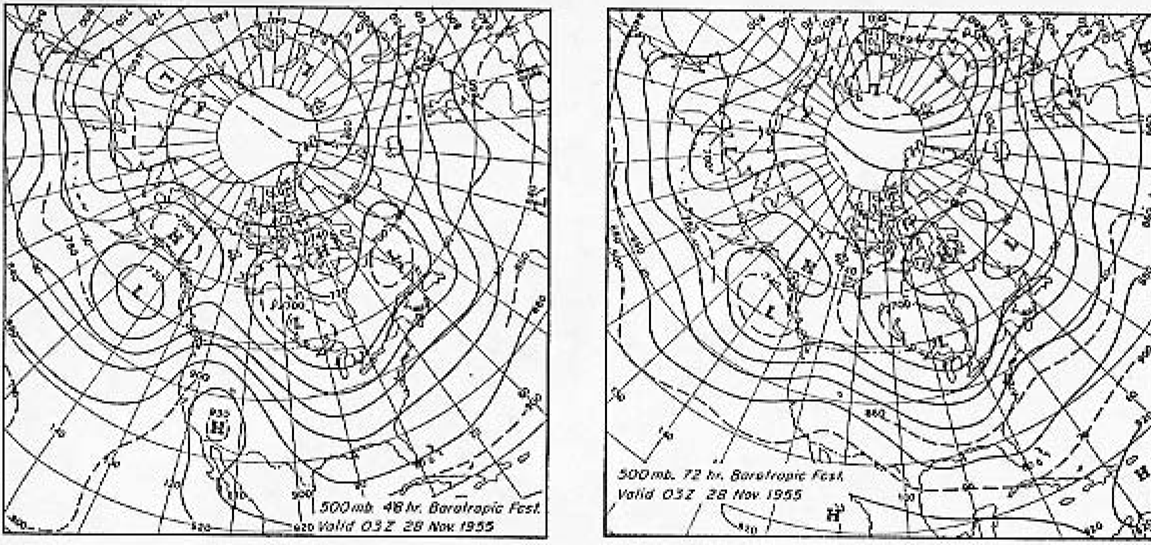

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FIG. 8, a–f. Initial data, 48 and 72 hour barotropic 500 mb forecasts, and verification.

ANTICIPATED CHANGES OF OPERATIONAL ROUTINE

As a result of its researches into the origin and effects of various types of error, the JNWP Unit is contemplating or actively preparing for the following changes in the operational forecasting system:

1) The use of non-divergent, non-geostrophic winds for advection of vorticity and thickness in baroclinic forecasting. One improvement expected as a result of this change will be a reduction in the predicted over-intensification of subtropical anticyclones.

2) The use of a model in which the coefficient of the "divergence" term in the vorticity is *not* replaced by a standard constant value of absolute vorticity. As indicated earlier, this is expected to reduce false anticyclogenesis in the lower levels.

3) Application of intermittent smoothing and higher order finite-difference approximations to reduce truncation error.

4) Introduction of an automatic data-processing system, coupled with objective analysis over a very large area. The present system of manual editing, data checking, and card punching is unsatisfactory, if only from the standpoint of time economy.

CONCLUSIONS AND PRESENT STATE OF OPERATIONAL NUMERICAL WEATHER FORECASTING

After almost a year of daily forecasting, verification, and post mortem evaluation, personnel of the JNWP Unit have concluded that the overall level of accuracy of the numerical forecasts produced by the *present* operational system is comparable with that attained by more subjective methods in the hands of a skilled forecaster who has a *practical* maximum of meteorological information. Judged by subjective standards, the numerical forecasts for the lower levels are worse. Judged either subjectively or by the *S* scores officially favored by the National Weather Analysis Center, the numerical forecasts for the middle troposphere are quite as good or slightly better. Curiously enough, the barotropic 500 millibar forecasts exceed the performance of both the conventional method and the 3-level model, a fact that is especially apparent in the 36 and 48 hour barotropic forecasts.

Daily examination of the more than 300 numerical forecasts that have been produced in the last year has also revealed several types of characteristic errors which, by their systematic nature, might be expected to yield to corrective action—either through empirical relationships, or through generalization of the underlying physical theory and perfection of mathematical procedure. The most serious sources of error have been isolated and found to have adequate explanations in existing theory. Controlled numerical experiments in a representative variety of cases indicate that the quality of the forecasts is improved by the modifications of procedure outlined in the preceding section and, further, that those modifications can be incorporated into the operating routine without a disproportionate increase of manpower or computing time.

A recently completed series of experimental forecasts, based on the thermotropic model [5] and incorporating several of the modifications described above, indicates that operational numerical forecasts for the middle and upper troposphere will soon be significantly more accurate than subjective forecasts, particularly for periods of 36–72 hours. Further improvements resulting from the use of nongeostrophic (balanced) initial wind fields have already been achieved in the barotropic forecasts, and are expected to appear in baroclinic forecasts in the near future.

CONCLUSION

It is our view that numerical weather prediction is still in the highly experimental stage, but that it will probably show a clear advantage over subjective methods of area prognosis within the next year or so. It is significant that numerical weather prediction has, in its earliest stages of development, essentially matched the subjective skill and wisdom of 30 years' experience. It is also significant that this approach to forecasting is one of directable progress, in the sense that errors are traceable to idealizations of the general laws of fluid dynamics, and that more general hypotheses may be subjected to controlled numerical experiment.

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