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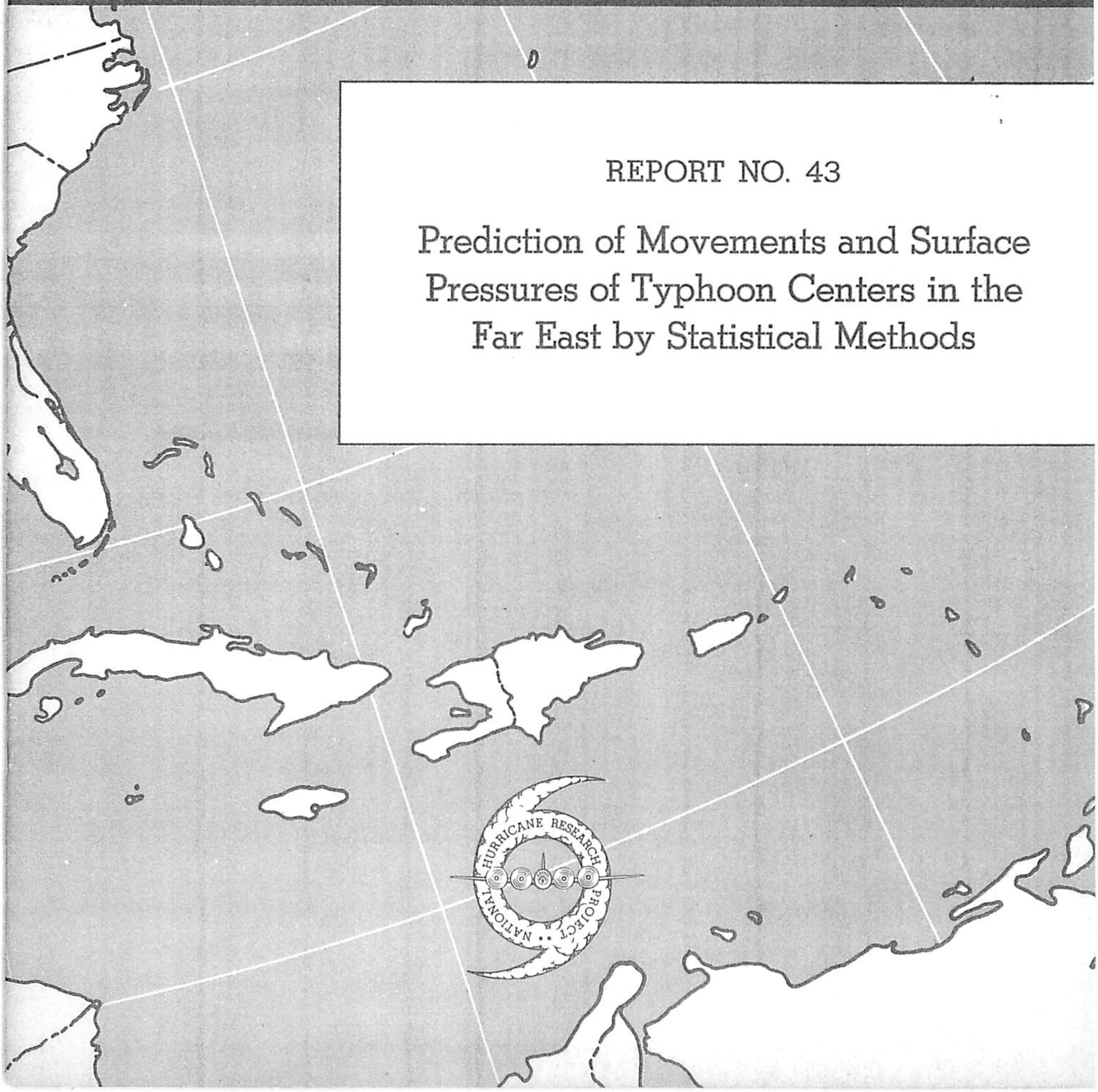

REPORT NO. 43

Prediction of Movements and Surface Pressures of Typhoon Centers in the Far East by Statistical Methods

U. S. DEPARTMENT OF COMMERCE
Luther H. Hodges, Secretary
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Prediction of Movements and Surface Pressures of Typhoon Centers in the Far East by Statistical Methods

by

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NATIONAL HURRICANE RESEARCH PROJECT REPORTS

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PREDICTION OF MOVEMENTS AND SURFACE PRESSURES OF TYPHOON CENTERS IN THE FAR EAST BY STATISTICAL METHODS

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INTRODUCTION

The prediction of movement and central surface pressures of typhoons 24 hours and/or 48 hours after chart time is very important in the Japanese weather service. The technique of numerical weather prediction has been applied to this problem but the movement and surface pressure of typhoon centers cannot be accurately predicted by numerical means at present. The mathematical difficulties in solving a complicated system of hydrodynamic and thermodynamic non-linear differential equations are compounded by the inadequacy of the obervational data by which the initial state of the atmosphere is described. It appears that any immediate improvement in typhoon predictions must be based on methods more or less statistical or probabilistic in nature. The objective of the present study is to follow the method of probabilistic prediction by Veigas, Miller, and Howe [4], which has been reported as a powerful tool in forecasting hurricane movement in the North Atlantic.

During the course of this study in the Far East and its operational application in the typhoon season, July - October 1960, it was felt that the method in its original form could be extended in the Pacific. It seemed advisable to revise this method to predict the departure of the forecast position from the simple persistence forecast of typhoon movement rather than the typhoon movements themselves. An extensive study showed that the original method was better than my supposition.

Extensions of this procedure to predict the surface pressure of a typhoon center in advance should be made, because there is no reliable procedure for this at present and because the method appears to have the capability of forecasting such things as deepening and filling of typhoons. Past experience in dynamic meteorology shows that upper-level charts (for instance, 700-mb. synoptic charts) may also contribute to the prediction of typhoon movement, so an effort should be made to include upper-air data also.

PART I: THE PREDICTION EQUATIONS

Among practical forecasters, the surface circulation pattern as depicted by the surface weather chart is considered an important factor determining the movement and central surface pressure of typhoons. The path and deepening or filling of a tropical cyclone normally appear to be reasonable in post-analysis when interpreted in terms of the synoptic weather patterns, though prediction of these changes in advance is often difficult. In the present study, to express the circulation pattern, a 5° pressure grid is taken relative to the 1° grid point nearest the current typhoon position, since the grid points of the synoptic map base used are marked at the intersections of whole degrees of longitude and latitude. The 5° pressure grid used by Veigas, Miller, and Howe [4] was taken relative to the 5° grid point nearest the current hurricane position.

Because of the greater frequency of typhoons in the Far East, a sufficient sample size can be obtained from recent data, and the prediction equations were obtained by month and time of the day. Making use of continuity, we may test the reliability of these prediction equations. Predictands were the positions and central sea level pressures 24 hours after chart time. Sea level pressures are used as rough intensity indicators.

The surface weather charts at 0600 GMT (1500 I) and 1800 GMT (0300 I) for the typhoon seasons of 1949 - 1959 (already plotted and analysed) were obtained from the Japan Meteorological Agency file. Attention was concentrated on the chart periods extending from one day prior to the development of a tropical storm (including those of typhoon* intensity) to one day after its dissipation. The plotters, using available synoptic data including published collections, added previously unplotted observations to the charts. The analysts, making maximum use of post-analysed typhoon tracks and continuity, amended the analyses of these charts and put them in final form for the card punchers. A 5° moving coordinate grid was centered on those storms which were located in the area from 20° to 34° N. latitude and 120° to 150° E. longitude as shown in figure 1. This area was chosen to provide ample coverage for all typhoons which might hit Japan proper. Pressures were read at 5° intervals extending 25° west and 30° east of the grid center and 15° north and south of the grid center (see fig. 2). These data, amounting to 84 pressure values, provided information on the circulation pattern.

To derive multiple regression equations giving the predicted movement and central surface pressure (λ_{24}, ϕ_{24}, p_{24}) of a typhoon 24 hours after prediction time, the predictors of the equations were selected from the set of the above 84 pressure values (x_1, x_2, x_3 ... x_{84}), two position coordinates (λ_0, ϕ_0) for the prediction time, and two position coordinates (λ_{-24}, ϕ_{-24}) and the central surface pressure (p_{-24}) 24 hours prior to the prediction time (i.e. 89 variables). The number of typhoon positions falling within the above mentioned zone during the period 1949-1959 is shown in Table 1.

Table 1. - Number of typhoons located within the zone (see fig. 1) for the years 1949-1959.

Time	July	Aug.	Sept.	Oct.
0300 I	92	144	119	(61)
1500 I	(90)	140	126	(58)

Numbers in parentheses are smaller than the number of predictors, 89 (or 92 in the revised method).

*Hereafter the word "typhoon" will be used for a tropical cyclone with winds of 35 knots or higher.

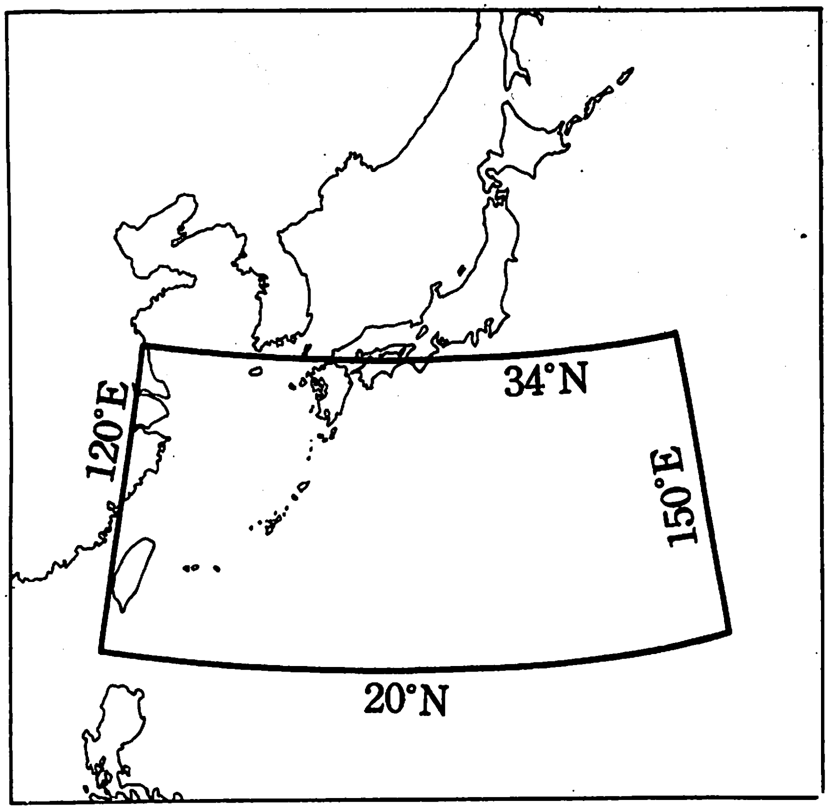

Figure 1. - If the current location of the storm center was in the zone outlined, 84 discrete surface pressure values were read at the points shown in figure 2.

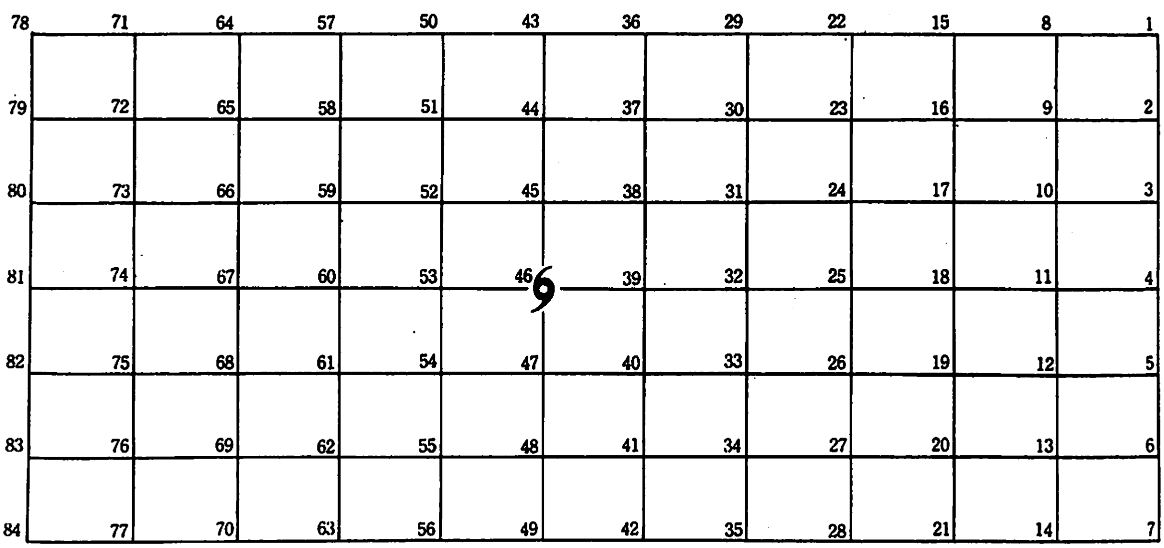

Figure 2. - The 5° grid used for reading surface pressures. Center of grid was placed at nearest 1° point to center of storm and pressures were read at the numbered intersections.

Table 2. - Typhoon Predictors

λ_{24}, longitude (degr. and tenths) ϕ_{24}, latitude (degr. and tenths) p_{24}, central surface pressure (mb.)	of typhoon center 24 hours after chart time, a set of predictands.
λ_0, longitude (degr. and tenths) ϕ_0, latitude (degr. and tenths) p_0, central surface pressure (mb.)	of typhoon center at chart time.
λ_{-24}, longitude (degr. and tenths) ϕ_{-24}, latitude (degr. and tenths) p_{-24}, central surface pressure (mb.)	of typhoon center 24 hours prior to chart time.

$x_1, x_2, x_3 \ldots x_{84}$; 84 pieces of information on pressure values (mb.) at each chart time. It should be noted that $p_0 = x_{46}$.

From the basic set of 89 variables, a multiple linear regression procedure was used to select only those which contributed significantly to predicting the subsequent 24-hour position coordinates and the central surface pressure. Five sets of prediction equations for the movement and central surface pressure of typhoons (July, 0300 I; August, 0300 I; September, 0300 I; August, 1500 I; September, 1500 I) were computed. For any particular prediction, then, only those selected predictors shown in table 2 are required. The particular multiple regression screening procedure used here is described by Miller [2,3] and Veigas et al.[4]. The computation for this procedure has been programmed for the IBM-704 (Miller's Screening Program).

The five sets of prediction equations for longitude, latitude, and central surface pressure are presented at right. The parameters with numbered subscripts correspond to the values read at the grid points shown in figure 2. The percentage reduction of variance is indicated by the abbreviation "P.R."

As an operational test on independent data, it was intended that these prediction equations would be used by official forecasters of the Japan Meteorological Agency during the typhoon season, July-September 1960 to predict the movement and central surface pressure of typhoons. But the operational test was carried out for only a few cases, the reasons being: (1) Typhoon movements during this season were quite abnormal. During July and September 1960, practically no typhoons occurred centered within the bounded area as shown in figure 1. During August 1960, many midget typhoons were generated over the sea to the south of Japan and moved along erratic paths. (2) Programming difficulty was encountered in establishing the position of

Table of five sets of probabilistic prediction equations

For July (chart time 0300 I)

$$\lambda_{24})_{\text{pred.}}=-276.3+1.4833\lambda_0-0.5973\lambda_{-24}-0.1236X_1+0.3622X_{27}+0.3242X_{67}-0.2717X_{37},\quad \text{P.R.}=93.9\,\%$$

$$\Phi_{24})_{\text{pred.}}=+219.9+1.4798\Phi_0-0.5118\Phi_{-24}-0.2340X_{81}+0.2391X_{19}-0.4956X_{61}+0.2731X_{62},\quad \text{P.R.}=89.9\,\%$$

$$p_{24})_{\text{pred.}}=-1523.8+1.0105p_0-0.3539p_{-24}+0.7173\Phi_0+0.9589X_{38}-1.0234X_{68}+1.8877X_{42},\quad \text{P.R.}=85.0\,\%$$

For August (chart time 0300 I)

$$\lambda_{24})_{\text{pred.}}=-316.7+1.5586\lambda_0-0.6123\lambda_{-24}+0.1881\Phi_0+0.1620X_{27}-0.1390X_{29}+0.2937X_{41},\quad \text{P.R.}=95.5\,\%$$

$$\Phi_{24})_{\text{pred.}}=+14.6+1.7323\Phi_0-0.6183\Phi_{-24}+0.1312X_{25}-0.0998X_{72}-0.1806X_{27}+0.1329X_{33},\quad \text{P.R.}=86.2\,\%$$

$$p_{24})_{\text{pred.}}=+874.1+0.6576p_0+0.5581\Phi_0+1.5124X_{51}-0.8831X_{36}-2.2906X_{84}+1.1162X_{76},\quad \text{P.R.}=78.3\,\%$$

For August (chart time 1500 I)

$$\lambda_{24})_{\text{pred.}}=-541.3+1.3098\lambda_0-0.3330\lambda_{-24}+0.4646X_{13}-0.0992X_{31}+0.3825X_{48}-0.2086X_{38},\quad \text{P.R.}=93.1\,\%$$

$$\Phi_{24})_{\text{pred.}}=-209.4+1.6726\Phi_0-0.6339\Phi_{-24}+0.1155X_{31}-0.3007X_{81}+0.2195X_{74}+0.1729X_7,\quad \text{P.R.}=88.2\,\%$$

$$p_{24})_{\text{pred.}}=+3273.5+0.5652p_0+1.4361\Phi_0-2.4604X_{56}+1.5315X_{47}-1.2413X_{13}-0.6845X_{60},\quad \text{P.R.}=76.8\,\%$$

For September (chart time 0300 I)

$$\lambda_{24})_{\text{pred.}}=-348.0+1.7476\lambda_0-0.8224\lambda_{-24}+0.7999\Phi_0-0.5708\Phi_{-24}+0.4760X_{14}-0.1262X_{38},\quad \text{P.R.}=94.5\,\%$$

$$\Phi_{24})_{\text{pred.}}=-375.6+2.1619\Phi_0-0.9940\Phi_{-24}-0.2527X_{45}+0.2326X_{83}+0.2091X_{40}+0.1801X_{14},\quad \text{P.R.}=95.3\,\%$$

$$p_{24})_{\text{pred.}}=-669.5+0.8388p_0-0.2225p_{-24}+1.3751\Phi_0-0.6306\lambda_{-24}+2.5399X_{21}-1.4545X_{27},\quad \text{P.R.}=70.7\,\%$$

For September (chart time 1500 I)

$$\lambda_{24})_{\text{pred.}}=-66.9+1.6243\lambda_0-0.6736\lambda_{-24}+0.7432\Phi_0-0.4778\Phi_{-24}-0.2977X_{37}+0.3655X_{82},\quad \text{P.R.}=94.9\,\%$$

$$\Phi_{24})_{\text{pred.}}=-200.0+1.7050\Phi_0-0.5798\Phi_{-24}-0.3738X_{45}+0.2615X_{82}+0.3094X_{40},\quad \text{P.R.}=90.4\,\%$$

$$p_{24})_{\text{pred.}}=-416.5+0.7966p_0-0.1391p_{-24}+3.2742\Phi_0-0.5289\lambda_{-24}-2.2213\Phi_{-24}+0.7838X_{83},\quad \text{P.R.}=73.3\,\%$$

the decimal point during the early phase of these computations. It should be noted that the procedure was tested on only a few abnormal samples. However some results suggesting that these statistical equations might serve operational forecasters will be shown later on.

Veigas et al. [4] also showed that there seems to be a tendency for the system to be unable to predict the rapid accelerations of storms which become extratropical in their northern zone. However the predicted surface pressure of the typhoon centers gave very encouraging results. Since deepening and/or filling of typhoons cannot be objectively predicted by any other method at present, this technique appears highly desirable from an operational point of view.

The following example for September (0300 I) illustrates this point. During the course of deriving the above prediction equations, the author obtained the following prediction equation for the central surface pressure of a typhoon:

$$p_{24\ pred.} = +421.3 + 0.8144\ p_0 - 0.2001\ p_{-24} + 1.4445\ \phi_0 - 0.6079\ \lambda_{-24},$$

P.R. = 68.9%

Figure 3 shows the predicted change of the central surface pressure $[p_{24\ pred.} - p_0]$ against the observed change $[p_{24} - p_0]$ for 119 typhoons during 1949-1959. Each dot corresponds to one pair of cases, and a straight line has been drawn through the origin making an angle of 45° with the horizontal axis. The points cluster about the straight line, but with a good deal of scatter. Thus this method appears to have the ability to predict deepening and filling of typhoons.

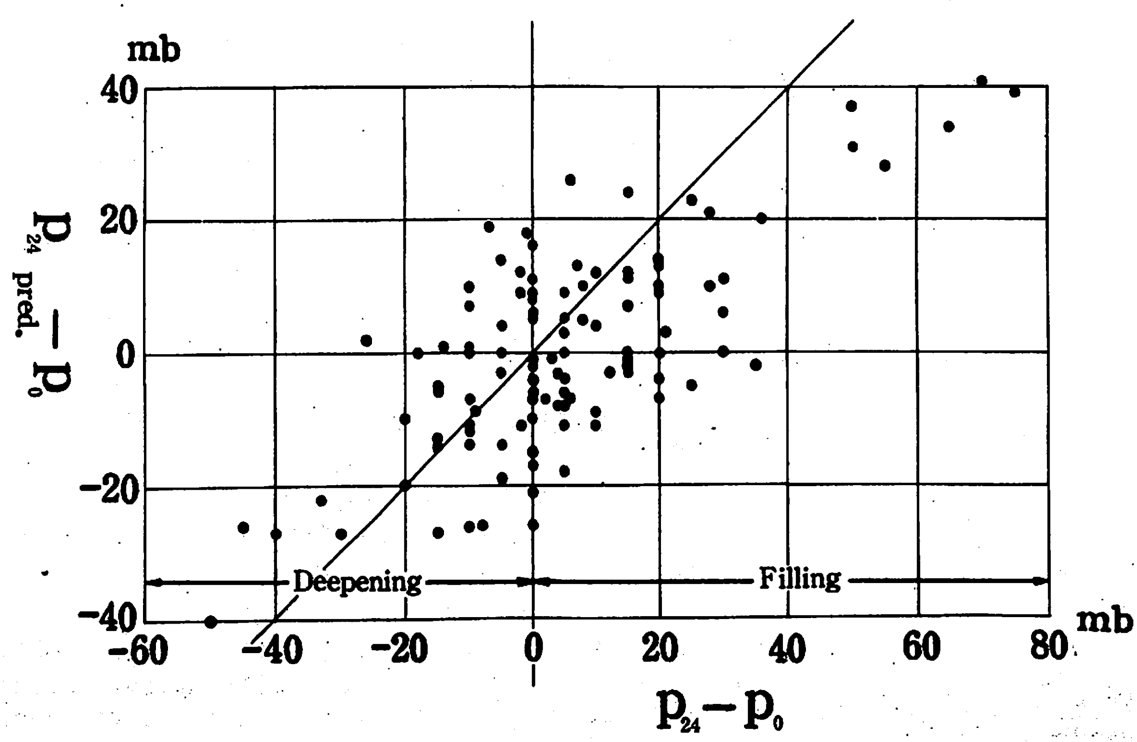

Figure 3. - Relation between the predicted change of the central surface pressure $[p_{24\ pred.} - p_0]$ and the observed change $[p_{24} - p_0]$, 1949-1959.

PART II: THE REVISED METHOD

On the basis of the results obtained during the course of this study, we were convinced that research should be undertaken along the following lines for possible improvement and extension in this screening procedure.

(1) It seemed advisable to derive prediction equations containing longitude, latitude, and central surface pressure both 24 and 12 hours prior to chart time.

(2) It seemed advisable to derive prediction equations to provide forecasts for departure of the forecast position from simple persistence forecasts of the typhoon movements instead of forecasts of the typhoon movements themselves.

(3) It was felt that extensions of this procedure should be made, attempting to use climatological data in terms of the more significant upper-air circulation patterns to incorporate the information suggested by modern meteorology.

An attempt to use climatological data in terms of the 700-mb. synoptic weather pattern has just been started, and will be reported on in the near future. In the following, the revised prediction equations for typhoon movement are explained and tested.

For each of the revised procedures in the developmental sample there were 92 variables. These consisted of the 84 grid pressure values (x_1, x_2, ... x_{84}), two position coordinates for the prediction time (λ_0, ϕ_0), two position coordinates and the central surface pressure 24 hours prior to prediction time (λ_{-24}, ϕ_{-24}, p_{-24}), and two position coordinates and the central surface pressure 12 hours prior to prediction time (λ_{-12}, ϕ_{-12}, p_{-12}).

From this basic set of 92 predictors, a simple multiple linear regression procedure was used for those predictors which contribute significantly to the prediction of the departures ($\Delta\lambda_{24}$, $\Delta\phi_{24}$) of the subsequent 24-hour position coordinates from the position forecast by persistence.

As the persistence forecast, the author defined the quadratic extrapolation of position coordinates for a 24-hour movement based on the observed movement during the past 24 hours. It was assumed that the position coordinates of a typhoon center take successive positions according to the following relationships.

$$\lambda = \lambda_0 + A_1 t + A_2 t^2, \ \phi = \phi_0 + B_1 t + B_2 t^2,$$

where t is the time and (λ, ϕ) are the position coordinates. The following relations were obtained:

$$\lambda_{-24} = \lambda_0 + (-24)A_1 + (-24)^2 A_2,$$
$$\lambda_{-12} = \lambda_0 + (-12)A_1 + (-12)^2 A_2,$$
$$\phi_{-24} = \phi_0 + (-24)B_1 + (-24)^2 B_2,$$
$$\phi_{-12} = \phi_0 + (-12)B_1 + (-12)^2 B_2.$$

Solving with respect to A_1, A_2, B_1 and B_2, we get

$$12A_1 = (3\lambda_0 - 4\lambda_{-12} + \lambda_{-24})/2,$$
$$(12)^2 A_2 = (\lambda_0 - 2\lambda_{-12} + \lambda_{-24})/2,$$
$$12B_1 = (3\phi_0 - 4\phi_{-12} + \phi_{-24})/2,$$
$$(12)^2 B_2 = (\phi_0 - 2\phi_{-12} + \phi_{-24})/2.$$

The forecast position coordinates 24 hours after prediction time by means of simple "extrapolation" then become

$$\lambda_{24\ \text{extrap.}} = 6\lambda_0 - 8\lambda_{-12} + 3\lambda_{-24},$$
$$\phi_{24\ \text{extrap.}} = 6\phi_0 - 8\phi_{-12} + 3\phi_{-24},$$

or

$$\lambda_{24\ \text{extrap.}} - \lambda_0 = 5(\lambda_0 - \lambda_{-12}) - 3\,(\lambda_{-12} - \lambda_{-24}),$$
$$\phi_{24\ \text{extrap.}} - \phi_0 = 5(\phi_0 - \phi_{-12}) - 3\,(\phi_{-12} - \phi_{-24}).$$

After the experience obtained during the course of this study it was felt reasonable to predict the deviations ($\Delta\lambda_{24}$, $\Delta\phi_{24}$) of the observed position from the position forecast by means of the persistence or "extrapolation" forecast; i.e.

$$\Delta\lambda_{24} = \lambda_{24} - \lambda_{24\ \text{extrap.}}$$

$$\Delta\phi_{24} = \phi_{24} - \phi_{24\ \text{extrap.}}$$

Then the prediction equations derived from the analysis have the form

$$\lambda_{24\ \text{pred.}} = \lambda_{24\ \text{extrap.}} + \Delta\lambda_{24\ \text{pred.}} = 6\lambda_0 - 8\lambda_{-12} + 3\lambda_{-24} + \Delta\lambda_{24\ \text{pred.}}$$
$$\phi_{24\ \text{pred.}} = \phi_{24\ \text{extrap.}} + \Delta\phi_{24\ \text{pred.}} = 6\phi_0 - 8\phi_{-12} + 3\phi_{-24} + \Delta\phi_{24\ \text{pred.}}$$

and

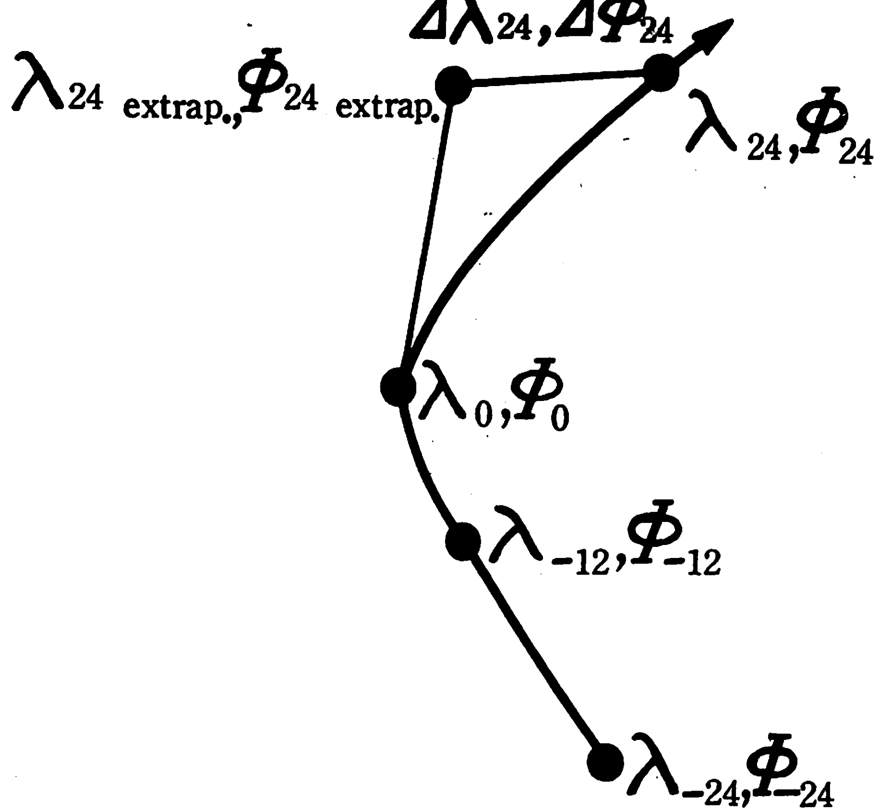

Figure 4. - Illustration of $\Delta\lambda_{24}$ and $\Delta\phi_{24}$.

$$p_{24\ pred.} = p_{24\ extrap.} + \Delta p_{24\ pred.} = 6\ p_0 - 8\ p_{-12} + 3\ p_{-24} + \Delta p_{24\ pred.}$$

The following prediction equations for the departures of longitude, latitude, and central surface pressure for September (0300 I) have been obtained by the screening procedure:

For September (chart time 0300 I)

$$\Delta\lambda_{24\ pred.} = -327.1 + 0.3588 X_{26} - 0.2974 X_{47} + 0.1019 X_1 + 0.1098 X_{71} - 0.1164 X_{22} + 0.1652 X_{38}, \qquad P.R. = 20.9\ \%$$

$$\Delta\Phi_{24\ pred.} = +496.6 - 0.8960\,\Phi_0 + 1.0565\,\Phi_{-12} - 0.1188 X_{37} - 0.3209 X_{84} - 0.0543 X_{81}, \qquad P.R. = 61.5\ \%$$

$$\Delta p_{24\ pred.} = +590.8 - 2.9813 p_{-24} + 7.0193 p_{-12} - 4.4024 p_0 + 2.7233\,\Phi_0 - 0.4863\,\lambda_{-24} - 1.4166\,\Phi_{-24} - 0.7486 X_{79} + 0.5444 X_{57}, \qquad P.R. = 92.3\ \%$$

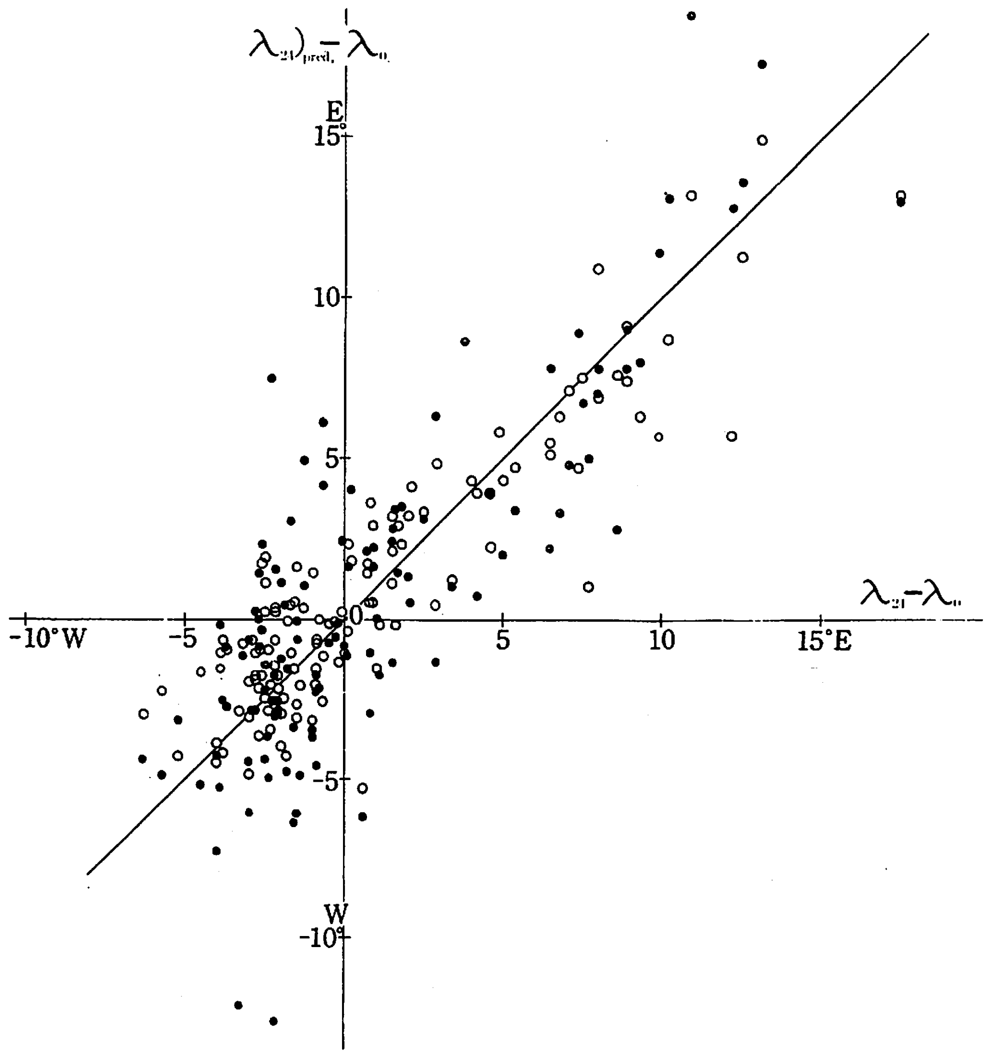

Figure 5. - Scatter diagram of the predicted longitudinal displacement and the observed longitudinal displacement. Open circles stand for the original prediction methods, dots, for the revised method.

The overall mean square errors (MSE) and overall root mean square errors (δ) for the 0300 I September storms are:

		Longitude (°)	Latitude (°)	Central pressure (mb.)
		λ_{24}	ϕ_{24}	p_{24}
Original method	MSE	21.51	6.01	306.92
	δ	4.6	2.5	17.5
		$\Delta\lambda_{24}$	$\Delta\phi_{24}$	Δp_{24}
Revised method	MSE	10.71	7.79	2069.39
	δ	3.3	2.8	45.5

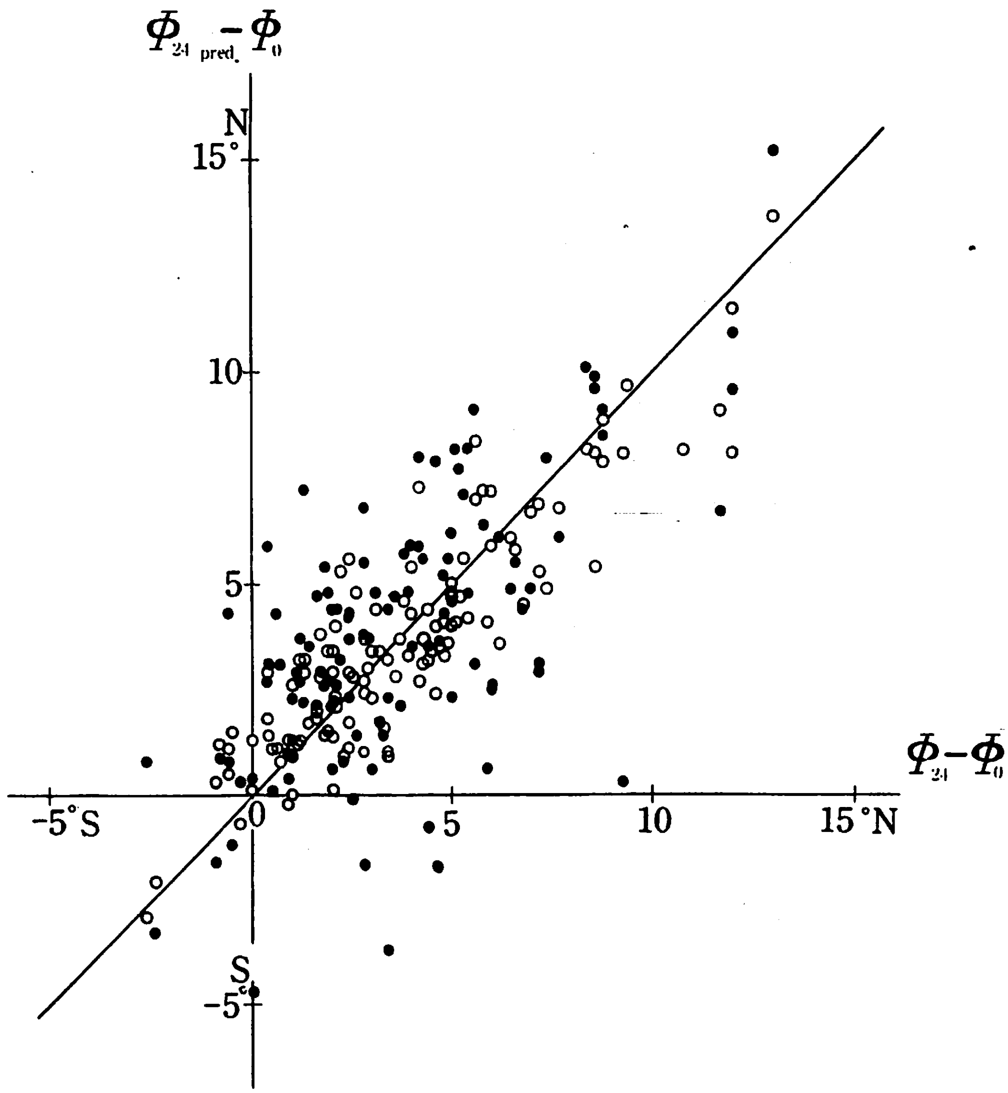

Figure 6. - Scatter diagram of the predicted latitudinal displacement and the observed latitudinal displacement. Open circles indicate original prediction method, dots revised method.

PART III. DISCUSSION AND DEPENDENT DATA TEST

As a test on dependent data the prediction equations were used to forecast 24-hour position coordinates and central surface pressure values of typhoons centered in the area extending from 20° to 34° N. latitude and 120° to 150° E. longitude at chart time 0300 I. It seemed desirable to measure the relationship between the predicted series and observed series. Figures 5 and 6 show the predicted displacement of storm centers plotted against the observed displacement at verification time. Each open circle shows a forecast or predicted displacement, $\lambda_{24\ pred.} - \lambda_0$, plotted against the observed, the displacement being forecast by the original method (discussed in PART I). Each dot corresponds to a forecast or predicted displacement plotted against the observed displacement, the forecasts being made by the revised method (discussed in PART II). Straight lines have been drawn through the origins making an angle

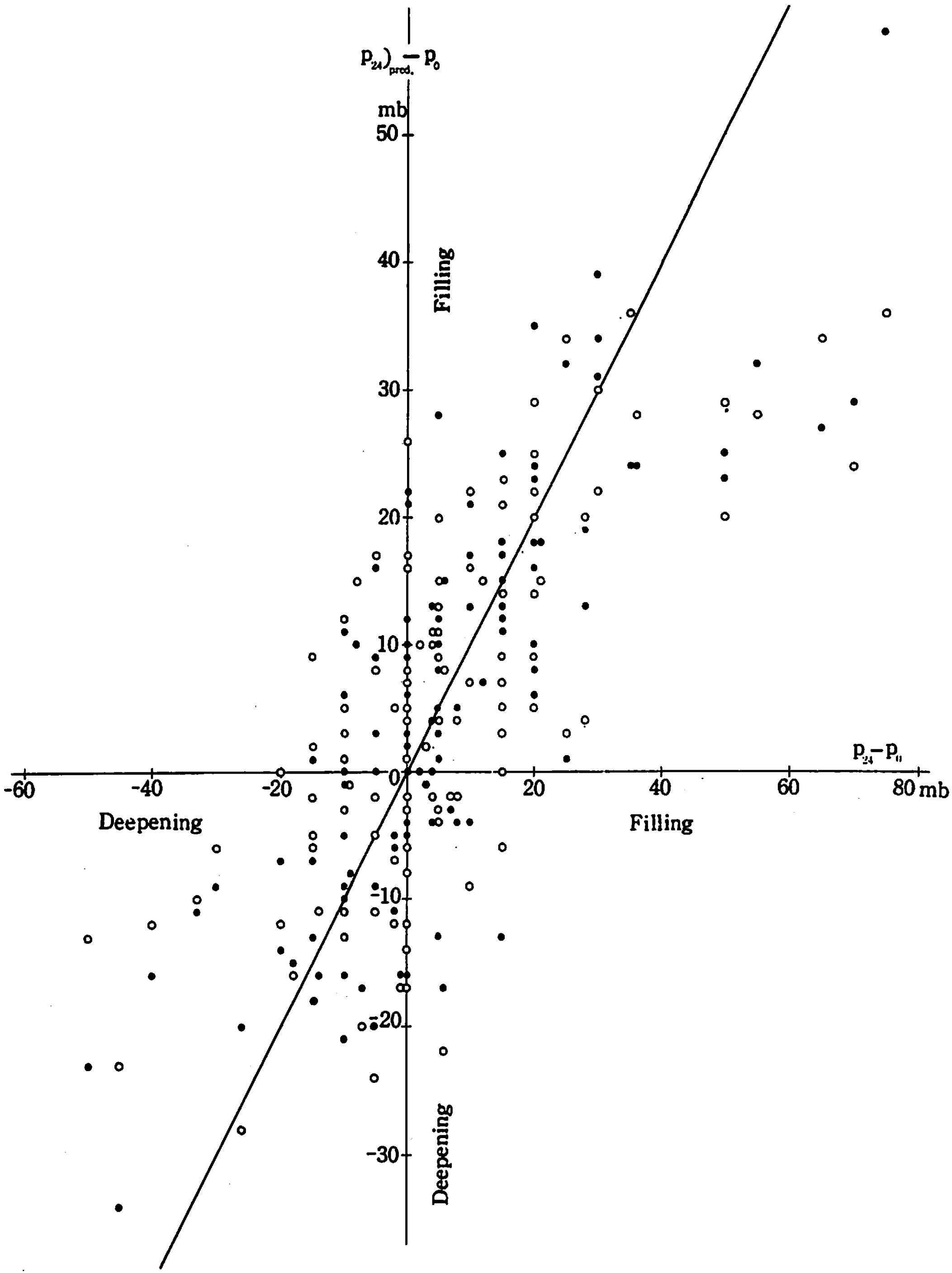

Figure 7. - Scatter diagram of the predicted deepening or filling of central surface pressure and that observed. Open circles stand for the original prediction method, dots for the revised method.

of 45° with the horizontal axis. It should be noted that the dots in figures 5 and 6 show greater departures from the indicated line than do the open circles, and hence a less perfect relationship. To my surprise, figures 5 and 6 clearly show that the original procedure described by Veigas et al. will give a better prediction of the movement of typhoons than the revised method discussed in PART II.

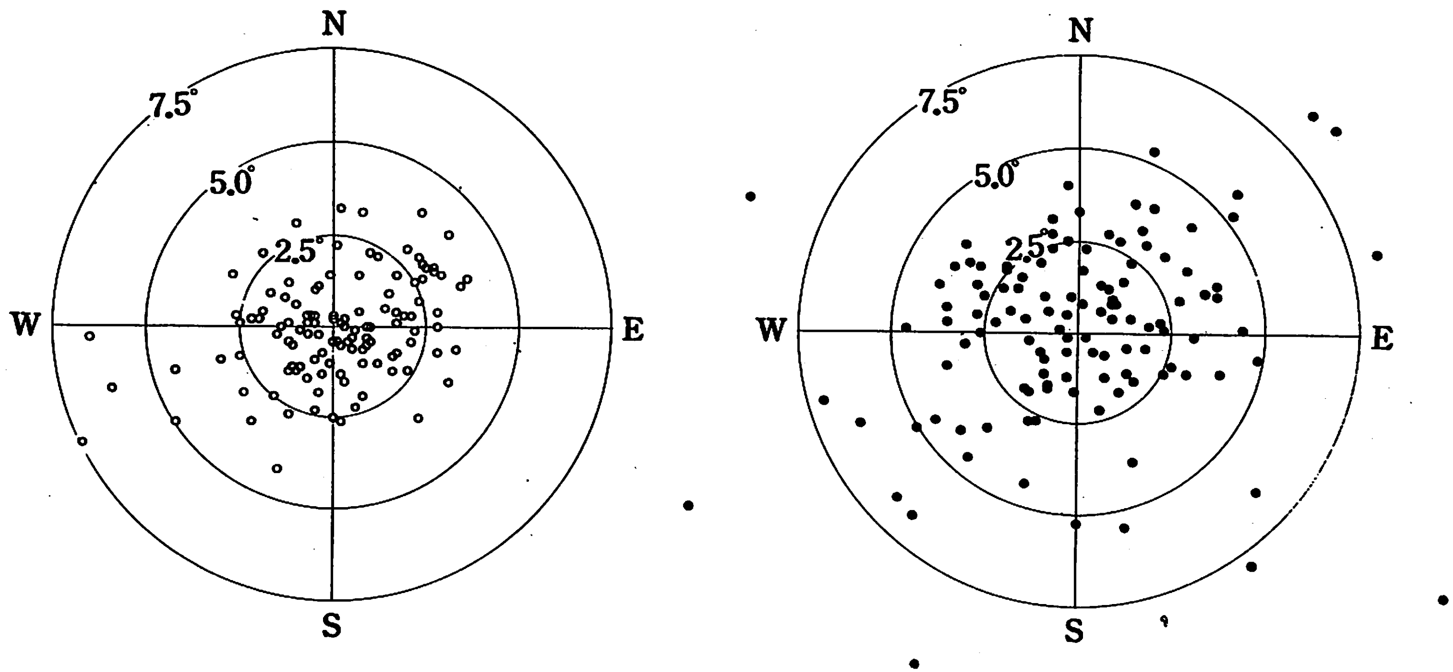

Figure 8. - Left: - Scatter diagram of the vector departures [λ_{24} pred. - λ_{24}, ϕ_{24} pred. - ϕ_{24}] computed by the original method described in PART I. Right: - Scatter diagram of the same vector departures computed by the revised method described in PART II. There is a higher degree of verification in the former case. No correction for the variation between the degree of longitude and a degree of latitude , been made in this presentation.

Figure 7 shows the predicted deepening or filling of the storm center against the observed deepening or filling. A straight line has been drawn through the origin making an angle of 63.5° with the horizontal axis. Figure 7 seems to show that the original method gives a slightly greater scatter and hence a slightly less perfect prediction than the revised method.

In the left-hand side of figure 8 the origin represents the actual position at verification time and the open circles represent the forecast position of the storm at verification time computed by the original method. In the right-hand side of figure 8 the origin represents the observed position at verification time and the dots represent the forecast position of the storm at verification time computed by the revised method. It is a surprise to learn that the dots show a greater scatter about the origin than the open circles do, and that the open circles are confined to a narrower area about the origin.

The histogram shown in figure 9 was constructed from a frequency distribution of errors of the predicted central surface pressure. Rectangles were erected for 5-mb. class intervals and the height indicates the frequency of occurrence of each class interval. The errors in predicted surface pressure of the storm center at verification time are relatively large. Of the 119 forecasts by the original procedure 44 percent fell within the error ± 7.5 mb., while of the 119 forecasts by the revised procedure 49 percent fell within the same error.

Figure 10 shows the series of forecasts made for Typhoon Vera. Typhoon Vera (Japanese name: Isewan Taifu or literally Ise Bay Typhoon) hit Central Japan in the late afternoon of September 26, 1959 and caused the most severe disaster in Japanese history (Arakawa, [1]). The Japanese official police survey (as of December 1, 1959) showed that the death toll from Typhoon Vera was 4696 persons, and 355 persons were still missing. Cities and villages along the shore of Ise Bay caught the fury of this storm and all were practically destroyed by the typhoon-induced storm tide.

The observed positions at 0300 I are indicated by small dots along the track, where the dates of observation are indicated in Roman numerals next to each observed position, while the observed central surface pressures are indicated by discrete values in mb. immediately below the dates. The predicted positions by the original method are shown by open circles, and the predicted positions by the revised method by dots, with the predicted central surface pressures entered next to each predicted position. These predicted positions are connected to the current (chart time) location of the storm center (grid center) by dashed lines. As can be seen, the predicted track was excellent, and the encouraging feature of the forecast for Vera is that the tendency for recurvature was forecast quite well.

Throughout this study, the longitudinal displacements were not converted to degrees of latitude.

In conclusion, the complete synoptic climatological forecast expresses not only the most probable subsequent location of a typhoon, but also the most probable deepening and filling of the typhoon (as indicated by the central

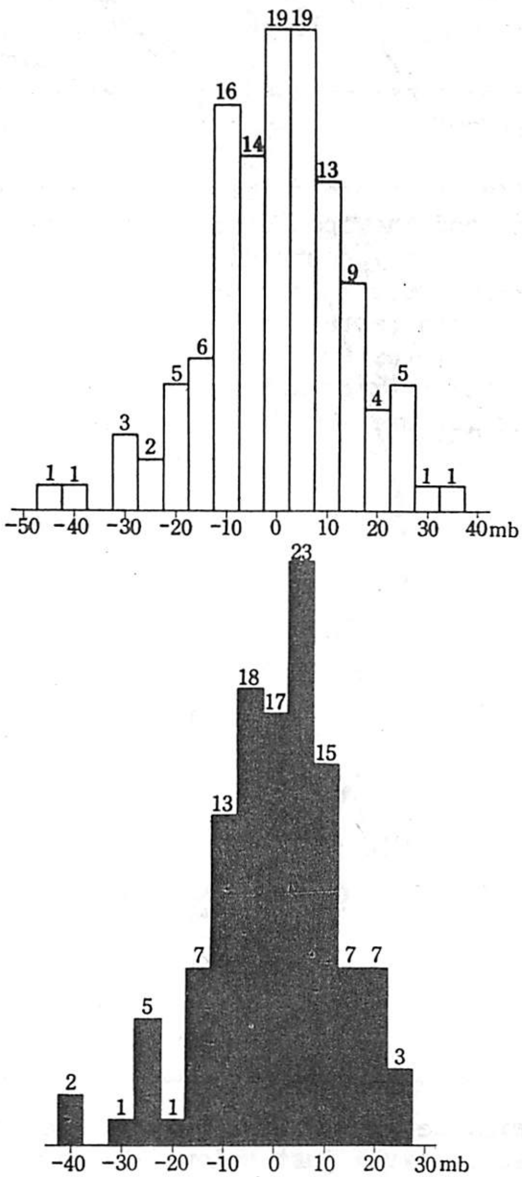

Figure 9. - Histogram showing the frequency of errors of the predicted central surface pressure, in 5 mb. class intervals. Open rectangles indicate the original prediction method described in PART I, while black rectangles stand for revised prediction method described in PART II.

surface pressure). The study indicated that the subsequent location of a typhoon can be better predicted without attempting to include persistence explicitly in the regression formula, while the probable deepening or filling of a typhoon can be predicted by either the original method or revised method incorporating persistence. Further efforts are being made through analysis of residuals to incorporate the information contained in the reconnaisance flight data as well as the upper-air chart data. Extensions of this procedure are also being made to provide forecasts for periods of 12 and 48 hours from chart time.

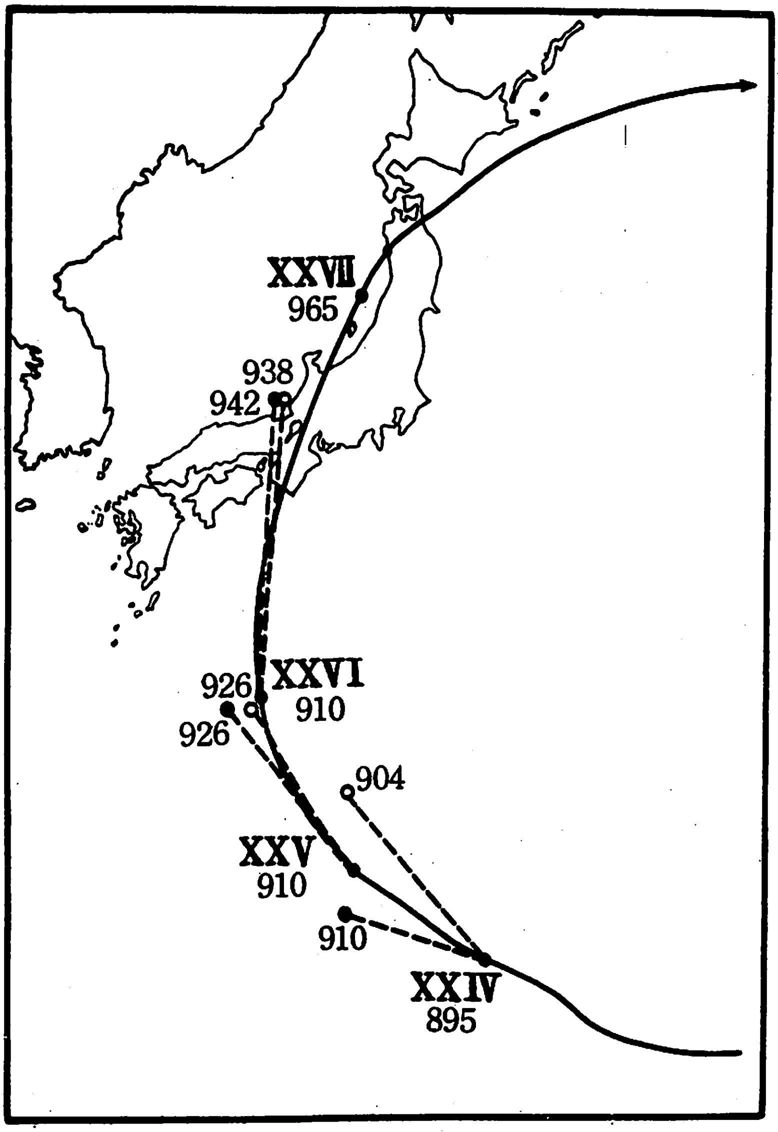

Figure 10. - Typhoon Vera, September 20-27, 1959. Dates in Roman numerals, with observed central pressure just below. Predicted positions by original method (open circles) and revised method (solid circles) with predicted central pressure are connected to the position at forecast time by dashed lines.

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REFERENCES

1. H. Arakawa, "Typhoon Vera and Its Induced Storm Tide," Weatherwise, vol. 13, No. 4, Aug. 1960, pp. 150-152.

2. R. G. Miller, "Statistics and Predictability of Weather" in Studies in Statistical Weather Prediction, Final Report, AF 19(604)-1590, The Travelers Weather Research Center, 1958, pp. 137-153.

3. R. G. Miller, "The Screening Procedure" in Studies in Statistical Weather Prediction, Final Report, AF 19(604)-1590, The Travelers Weather Research Center, 1958, pp. 86-96.

4. K. W. Veigas, R. G. Miller, and G. M. Howe, "Probabilistic Prediction of Hurricane Movements by Synoptic Climatology," Occasional Papers in Meteorology, No. 2, The Travelers Weather Research Center, June 1959, 54 pp.

APPENDIX

Since the preceding was written equations have been derived from the combined data for the period October through July, in order to obtain a larger sample than was possible for separate months. The number of typhoon positions falling within the above mentioned zone amounted to

	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July
0300 I	144	119	61	42	13	4	–	–	10	7	21	92
			Oct.–July: 250									
1500 I	140	126	58	42	9	5	–	–	11	8	24	90
			Oct.–July: 247									

By using all of these data for October-July, the following statistical equations are obtained:

For October ~ July (chart time 0300 I)

$$\lambda_{24\,\text{pred.}} = -614.2 + 1.4185\lambda_0 - 0.6007\lambda_{-24} + 0.5920\Phi_0 - 0.4430\Phi_{-24} + 0.4888X_{82} + 0.3666X_{19} - 0.2253X_{37}, \quad \text{P. R.} = 90.8\,\%$$

$$\Phi_{24\,\text{pred.}} = -146.4 + 1.5589\Phi_0 - 0.6309\Phi_{-24} - 0.2879X_{45} + 0.1678X_{11} + 0.0686X_{76} + 0.1502X_{40} + 0.1387X_{22} - 0.0902X_{15}, \quad \text{P. R.} = 85.0\,\%$$

$$p_{24\,\text{pred.}} = -149.3 + 0.9228p_0 - 0.2971p_{-24} + 1.4303\Phi_0 - 0.8196\Phi_{-24} + 0.7493X_{39} + 0.7428X_{72} - 0.5448X_{61} - 0.4499X_{64}, \quad \text{P. R.} = 77.7\,\%$$

For October ~ July (chart time 1500 I)

$$\lambda_{24\,\text{pred.}} = -708.1 + 1.5328\lambda_0 - 0.7014\lambda_{-24} + 0.3516X_{81} + 0.5713X_{19} - 0.2875X_{37} + 0.0898X_{71}, \quad \text{P. R.} = 88.9\,\%$$

$$\Phi_{24\,\text{pred.}} = -39.2 + 1.5673\Phi_0 - 0.6772\Phi_{-24} - 0.1219X_{45} + 0.2094X_{26} + 0.1067X_{22} - 0.0672X_{24} - 0.0844X_{37}, \quad \text{P. R.} = 84.0\,\%$$

$$p_{24\,\text{pred.}} = -596.2 + 0.8094p_0 - 0.1753p_{-24} + 1.6671\Phi_0 - 1.1828\Phi_{-24} - 0.2186\lambda_{-24} + 0.9655X_{40}, \quad \text{P. R.} = 74.7\,\%$$

By comparing the equations for July (in the text) and the above equations, the effect of a monthly stratification is very clear.