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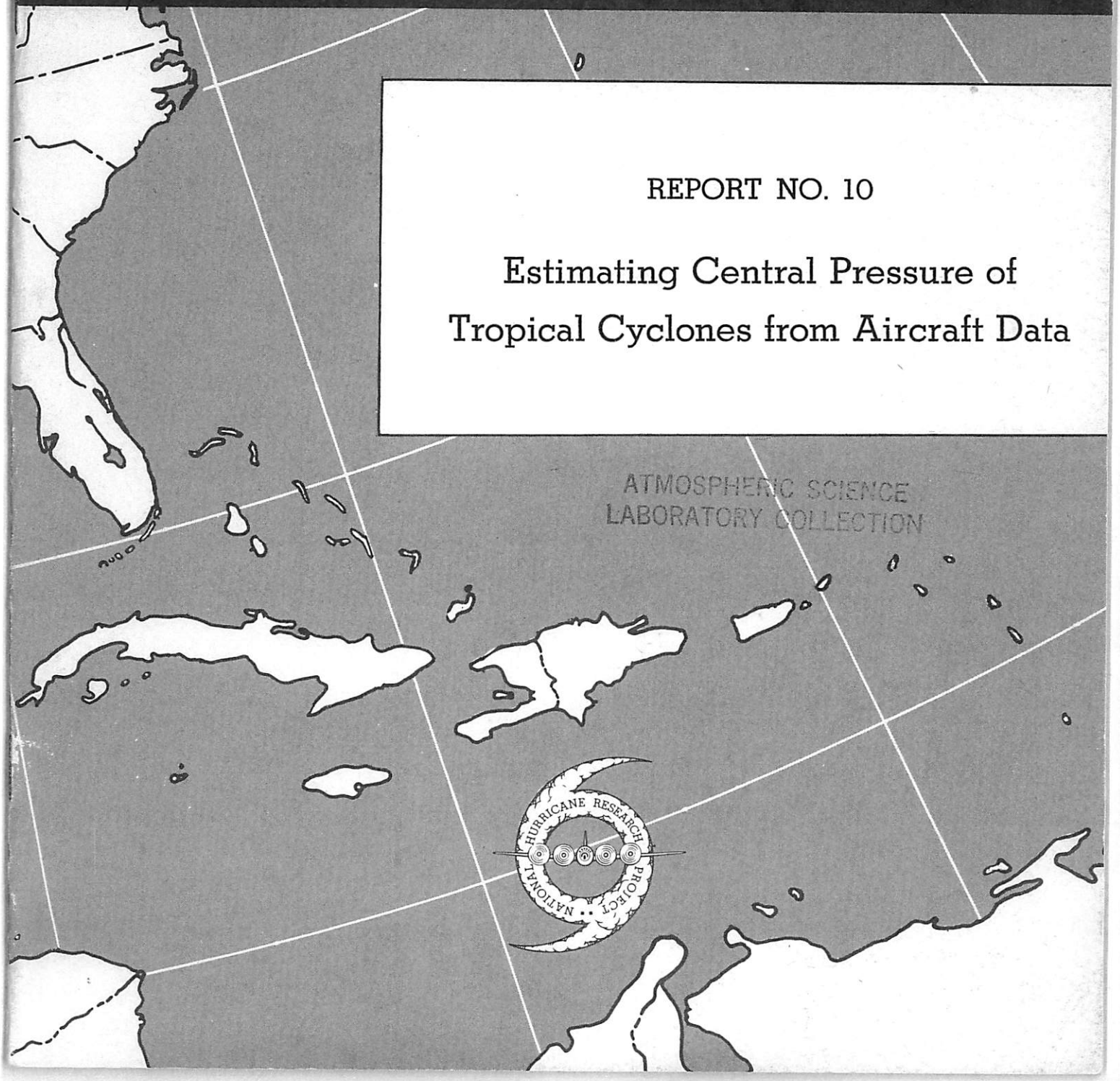

REPORT NO. 10

Estimating Central Pressure of Tropical Cyclones from Aircraft Data

ATMOSPHERIC SCIENCE
LABORATORY COLLECTION

U. S. DEPARTMENT OF COMMERCE
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NATIONAL HURRICANE RESEARCH PROJECT

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by

C. L. Jordan

National Hurricane Research Project, West Palm Beach, Fla.

Washington, D. C.
August 1957

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ESTIMATING CENTRAL PRESSURE OF TROPICAL CYCLONES FROM AIRCRAFT DATA

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ABSTRACT

Dropsonde data for the eye of tropical cyclones are used for testing and deriving empirical relationships between the surface pressure and the heights of constant pressure surfaces. The derived regressions are used for the preparation of a nomogram which can be used for estimating surface pressure in the eye of tropical cyclones from airdraft data at any level up to 500 mb. The regressions also provide a basis for some comments on the mean thermal structure of the eye.

INTRODUCTION

Dropsonde data for the eye of tropical cyclones have revealed a high correlation between the reported surface pressure and the 700-mb. height. A linear regression between these parameters, shown in the 1952 Annual Report of the Air Force Typhoon Post Analysis Board, has been widely used in typhoon forecasting centers in recent years. The primary use of this regression has been in estimating the surface pressure in cases where there are aircraft reports for the eye at the 700-mb. level, but dropsonde observations are not available. Dropsonde data for the Atlantic area have been much less plentiful and, probably because of the sparsity of these data, a similar empirical relationship has not been derived for hurricanes[1]. However, the original Pacific regression, and refinements of it (Watanabe [10], Showalter [8]) have been used to some extent by the hurricane forecasting centers.

This investigation has been aimed primarily at assessing the reliability and the physical significance of the correlation between the surface pressure and 700-mb. height in the eye of tropical cyclones shown by dropsonde data. Data from both Atlantic and Pacific storms have been used, and the investigation has been extended to include 500-mb. data to the extent possible with the limited information available for this level. The empirical relationships suggested by the dropsonde data provide a basis for a discussion of some features of the mean thermal structure of the eye.

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1 The term "hurricane" will always refer to tropical cyclones in the western North Atlantic-Caribbean - Gulf of Mexico area; similarly, "typhoon" will be used only for tropical cyclones in the western North Pacific-China Sea area.

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ACCURACY OF DROPSONDE OBSERVATIONS

The dropsonde computation is similar to that made for the radiosonde except that it is worked downward using the flight level information as a starting point. Since the calibration of the instrument is made on the ground prior to the flight, the temperature and humidity data are independent of errors in the aircraft instruments except at the very top of the sounding where the dropsonde data are joined with the aircraft values. In contrast, the pressure-height information at all levels, including the surface pressure, is sensitive to errors in the aircraft altimetry. Similarly, temperature errors at any level will influence the accuracy of pressure-height computations for all lower levels. Although the data obtained by a single aircraft or from a given series of dropsonde instruments may show some bias toward high or low values, there is no evidence that errors of the types discussed above should not tend to be random over a large sample of reconnaissance data.

Details of the lapse rates from the dropsonde record may be obscured by the relatively large lag of the bimetallic temperature element used in the instrument. However, procedures have been established for compensating for this lag (Air Weather Service [1]) so that its effect on pressure-height computations should be very small.

The absolute accuracy of central pressures obtained from dropsonde computations is difficult to determine since station or ship pressures for the eye are very rare. Comparisons can occasionally be made with independent computations of the surface pressure by aircraft flying at low levels or with dropsondes made a few hours earlier or later. Qualitative comparisons of this type in relatively steady-state storms suggest that differences between independent observations are less than 3 millibars in most cases even with time differences up to 6 hours. Of course, such differences arise not only from errors but also from fluctuations in the central pressure and from the fact that the individual dropsondes may reach the surface in different portions of the eye. Despite these limitations, at the present time the observations of central pressure provided by the dropsonde appear to be adequate for most, if not all, operational needs.

TYPHOON DATA

The well-known empirical relationship between surface pressure and 700-mb. height for the typhoon eye was derived from 164 observations from typhoons and tropical storms in 1951 and early 1952 (McKown and Collaborators [5]). The basic data and the regression line have been replotted in figure 1. The regression equation can be written:

$$p_o = 637 + .358H_7 \qquad (1)$$

where p_o is the surface pressure in millibars and H_7 is the 700-mb. height in tens of feet. The values plotted in figure 1 represent data obtained mainly by dropsonde, but very likely some aircraft soundings were included. It is

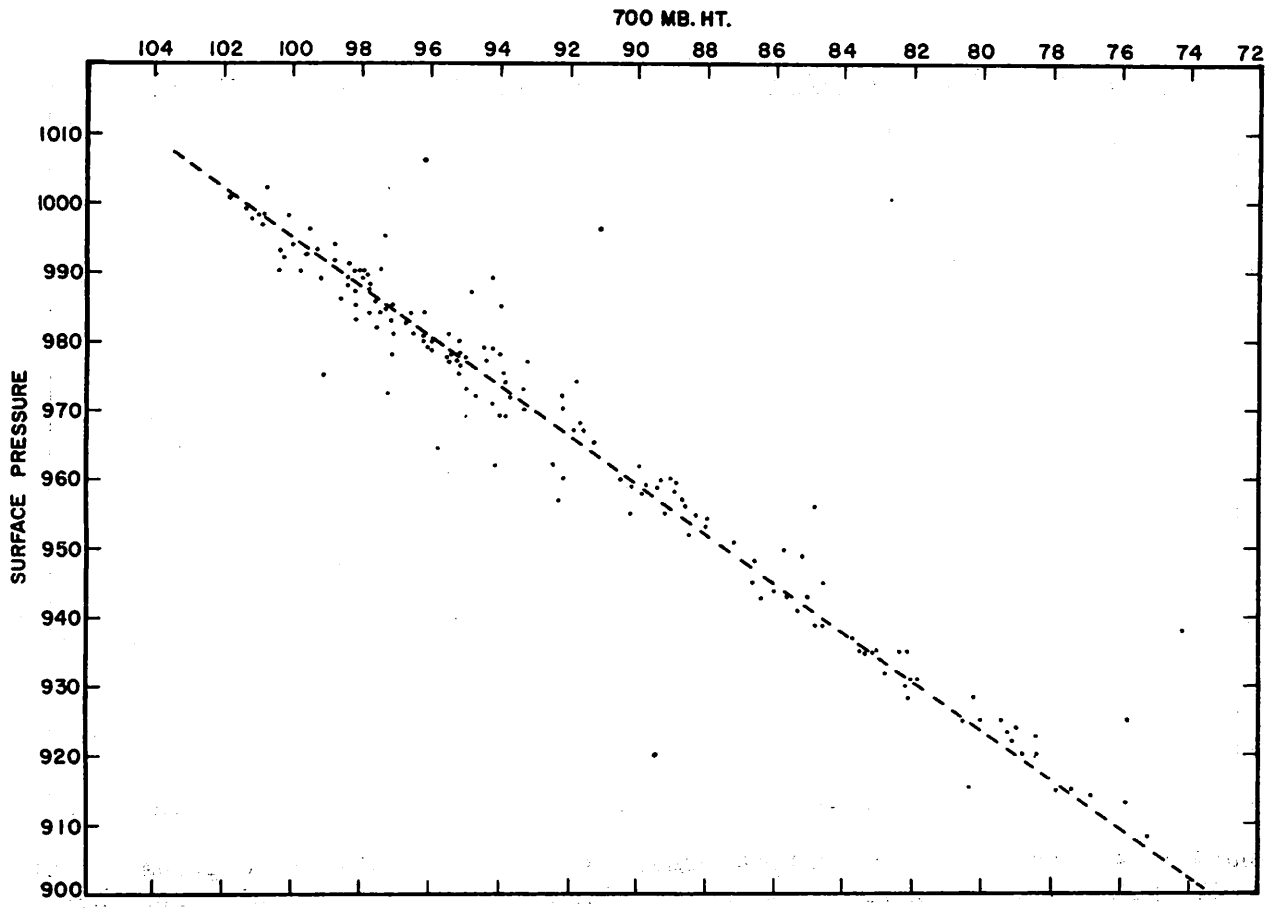

Figure 1. - Plot of 700-mb. height (hundreds of feet) vs. surface pressure for 164 typhoon eye dropsonde observations in 1951 and early 1952. (From [5])

not known whether any data were excluded on the basis of the season or the location of the storm.

All available eye sounding data from typhoons and named tropical storms during the latter part of the 1952 season and from the 1953 and 1954 seasons have been utilized in an independent test of the correlation indicated by figure 1. More than 95 percent of this new data sample was provided by dropsondes, but the available aircraft soundings have been included. The data were initially stratified by season and latitude for the preparation of a number of individual scatter diagrams. Seasonal differences were not apparent from these analyses even when the data from the off-season typhoons (December through May) were compared with those from the principal part of the season (August through September). The division into latitude belts revealed that data taken north of 30°N. latitude often showed appreciable departures from a linear relationship. However, there were no apparent differences between the 10°-20° and 20°-30° latitude belts. The greater scatter north of 30° is not surprising since many of the typhoons were undoubtedly acquiring extratropical characteristics.

On the basis of the qualitative checks cited above, the observations taken north of 30° latitude were excluded but all other data have been grouped together irrespective of latitude and season. These data, consisting of a total

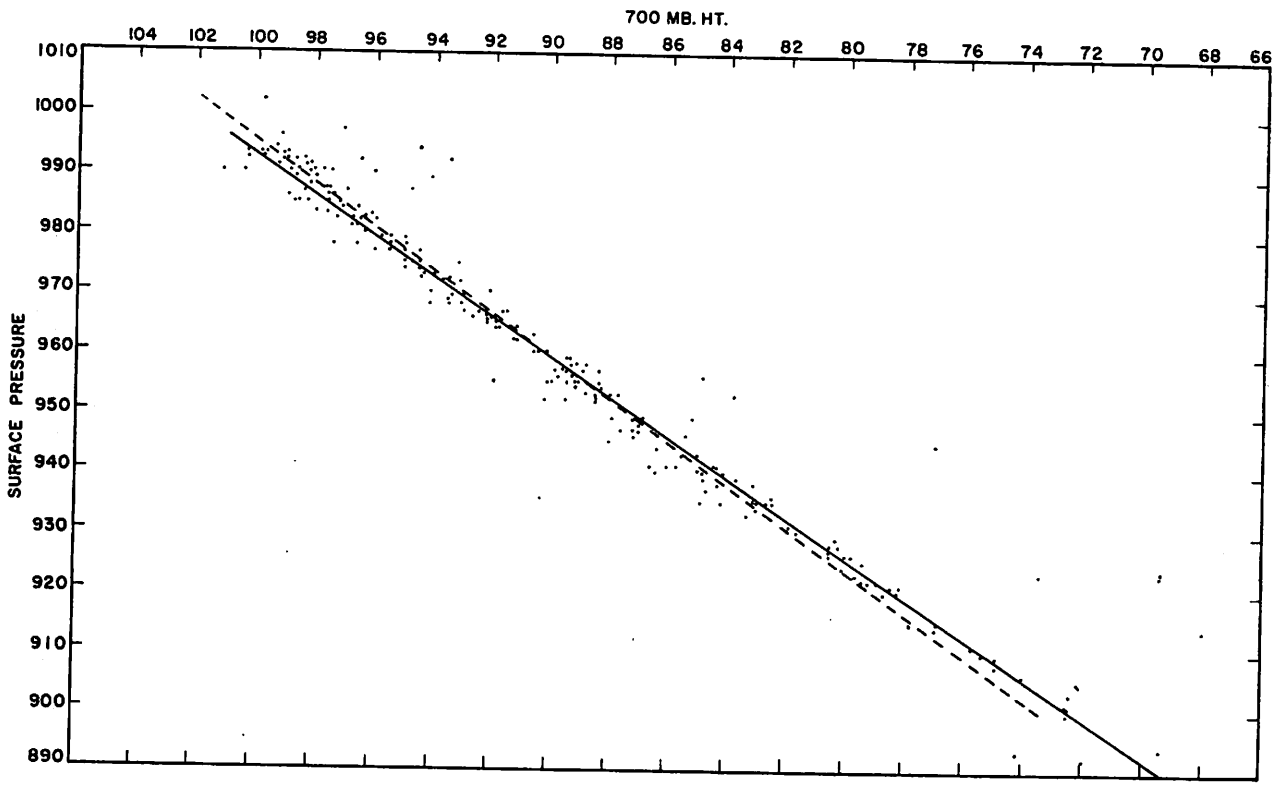

Figure 2. - Plot of 700-mb. height (hundreds of feet) vs. surface pressure for 245 typhoon eye dropsonde observations in late 1952, 1953, and 1954. Regression line from figure 1 is shown as dashed line.

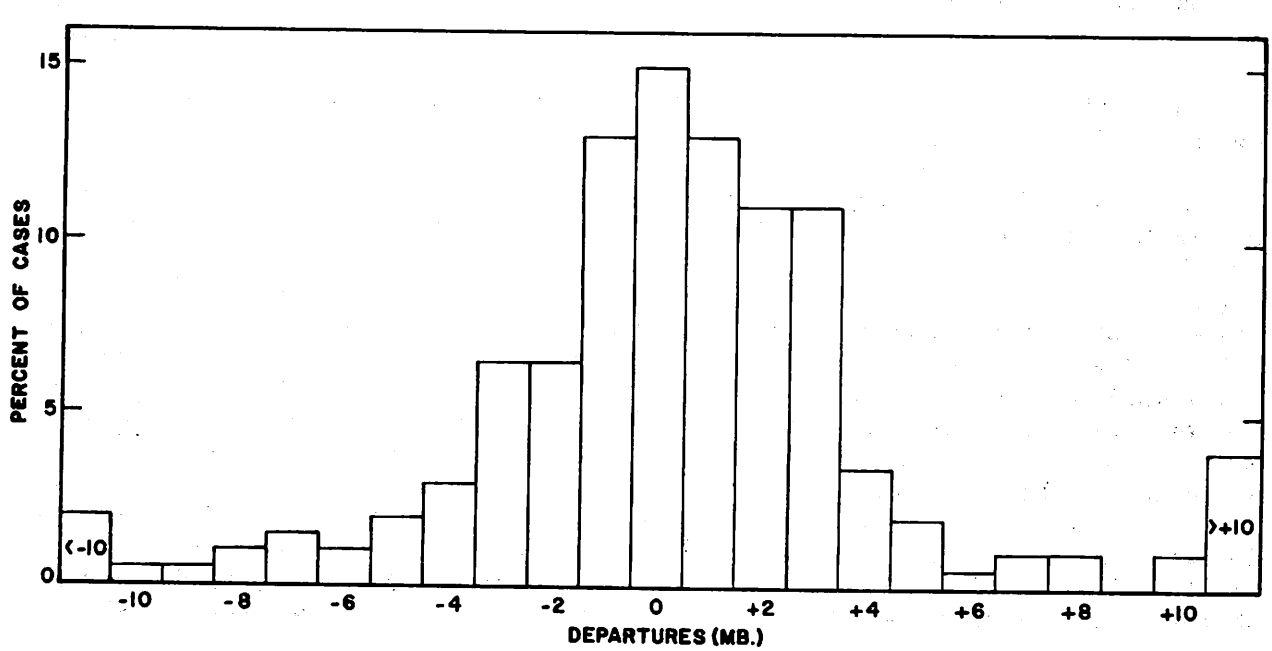

Figure 3. - Histogram of deviations of estimated surface pressures from dropsonde values in the 245 typhoon cases shown in figure 2. Reported 700-mb. heights were used in equation (1) for estimating surface pressure.

of 245 pairs of 700-mb. heights and surface pressures, have been plotted in figure 2. The solid line, representing the approximate linear regression indicated by this set of data, can be expressed by the equation

$$p_o = 657 + .336H_7 \qquad (2)$$

where p_o and H_7 have the same units as above. The regression line from figure 1 is reproduced on figure 2 as the dashed line. The differences in the two curves are relatively minor. This has been shown by using the original regression to "predict" the surface pressures corresponding to the 245 700-mb. heights in the independent set of data. These values were then compared with the reported surface pressures from dropsonde observations. The distribution of the departures of the extrapolated from the observed values (fig. 3) shows that in this set of independent data the reported surface pressure could have been specified to within ± 1 mb. in 40 percent of the cases and to within ± 4 mb. in 85 percent of the cases. Four percent of the observations indicated deviations greater than 10 mb.; but, as discussed below, these large values can be attributed to errors in nearly all cases.

The correlation indicated by the combination of the two sets of data can be approximated by a simpler regression equation

$$p_o = 645 + .35H_7 \qquad (3)$$

which is recommended for general use. The deviations which can be expected from the use of any of the three empirical equations are quite small considering the uses which the typhoon forecaster normally makes of the central pressure. For example, differences of 5 mb. at central pressures as low as 980 mb. have little effect on the forecasts of maximum wind speed made by subjective techniques or by empirical methods such as presented by Fletcher [3] and Myers [6]. However, when the central pressure is higher, a difference of this size becomes much more important in specifying the wind speed. Also, since the scatter of the values is greater at the higher pressures, (figs. 1 and 2) the practical utility of the regression is much less for storms of this type. The greater scatter at pressures above 980 mb. is not surprising since most of these data came from forming and dissipating typhoons.

The scatter shown in figures 1 and 2 reflects variability in the thermal conditions within the eye as well as the effect of instrumental and computational errors. The range of temperature at the surface and 700-mb. levels within the typhoon eye is known with sufficient accuracy so that an approximation can be made of the total effect which can be attributed to changes in thermal structure. The use of the coldest and warmest observed eye soundings in place of the mean soundings would result in a maximum deviation from the linear relationship of about 4 mb. Therefore, it appears quite definite that the deviations in excess of 5 mb. shown in figures 1 and 2 must have resulted from errors introduced in evaluating the soundings and processing the data. Of course, this discussion offers little information on the actual errors in the dropsonde surface pressure since they are not independent of errors in the 700-mb. heights.

HURRICANE DATA

The linear regression between the surface pressure and the 700-mb. height, given by equation (3), has been tested on hurricane data taken during the 1955 and 1956 seasons. Data were readily available only from these years, but the inclusion of all available years would not have even doubled the data sample.

A total of 65 hurricane eye dropsonde records was available for the 1955 and 1956 seasons. The 700-mb. heights from these records have been used for the determination of the surface pressure from equation (3). The values determined in this manner were then compared with pressures computed from the dropsonde. The tabulation of the frequency of the departures (table 1) shows that, for the data taken south of 30°N. latitude, 60 percent of the "predicted" surface pressures were within ± 1 mb. and 90 percent were within ± 3 mb. There were no deviations greater than 5 mb. If only the cases are considered for which the 700-mb. height was less than 9700 feet, then almost three-fourths of the extrapolated values were within 1 millibar.

The data taken north of 30°N. latitude indicated a slightly larger dispersion, and one error of 8 mb. was noted. However, deviations in this latter set of data are small compared with the typhoon results. This can probably be attributed to the fact that none of the hurricanes of 1955 and 1956 transformed rapidly into extratropical cyclones.

There were more positive than negative deviations in the data taken south of 30°N. latitude, but the average was near zero. A separation of the deviations corresponding to the 700-mb. heights above and below 9600 feet showed that the estimates were in the mean about 1 mb. too low at the higher 700-mb. heights and too high by the same amount at the lower 700-mb. heights. This was also apparent from the deviations shown in individual storms. For example, there was only one positive value in 12 cases in hurricane Edith which was never reported deeper than 984 mb. In contrast, there were no negative deviations in hurricane Connie, which had a central pressure below 970mb. during most of its history. These observations suggest that the slope given by equation (3) should be altered slightly for application to hurricanes. However, in view of the small size of the data sample and the relative insignificance

Table 1. - Frequency distribution of deviations of estimated surface pressures from dropsonde values in 65 hurricane cases in 1955 and 1956. Reported 700-mb. heights were used in equation (3) for estimating surface pressures.

	>+5	+5	+4	+3	+2	+1	0	-1	-2	-3	-4	-5	<-5mb.
South of 30°N. lat.	0	2	2	1	3	11	11	5	6	4	1	0	0
North of 30°N. lat.	0	0	2	0	3	4	4	1	0	2	2	0	1

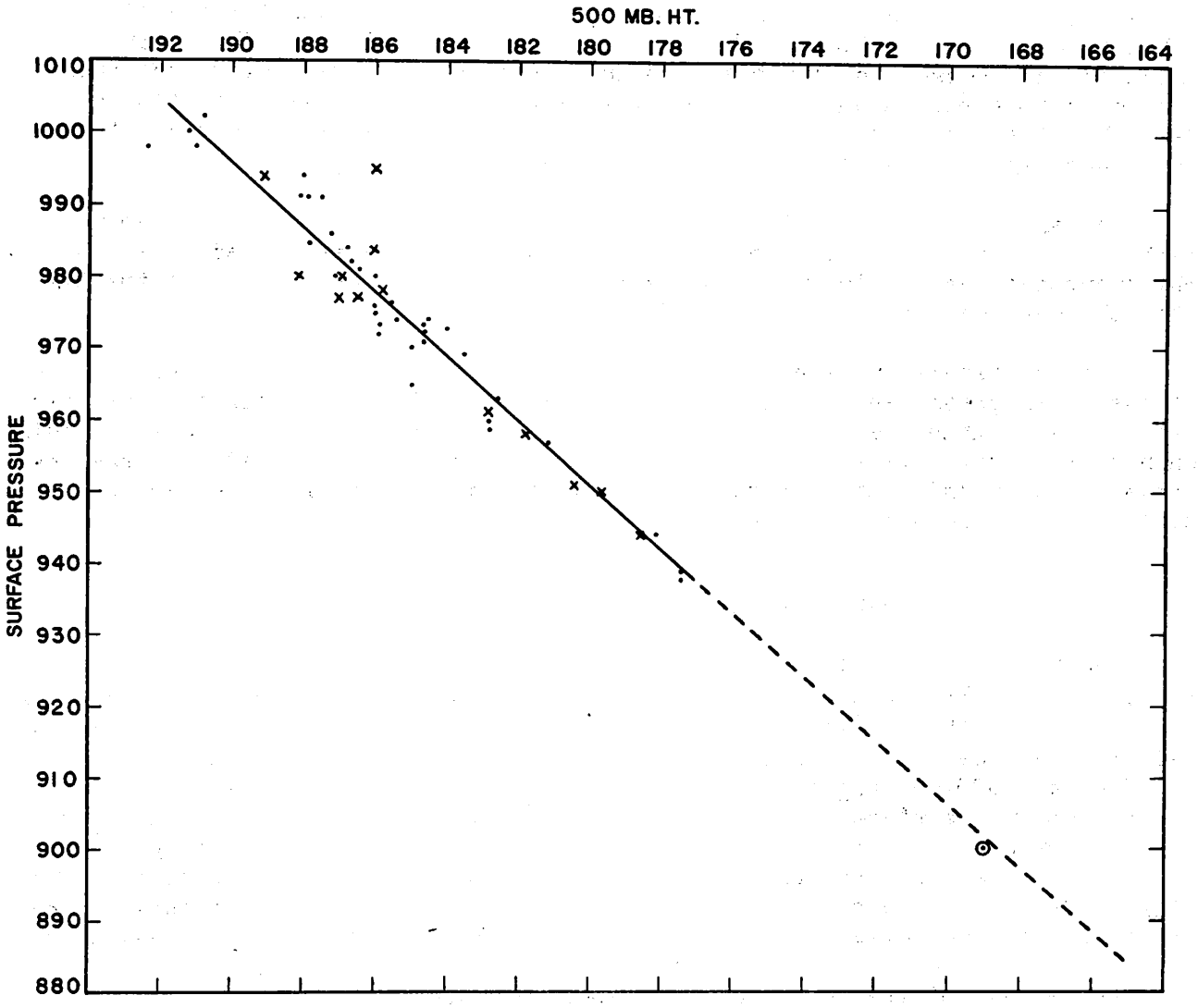

Figure 4. - Plot of 500-mb. height (hundreds of feet) vs. surface pressure for 48 hurricane eye dropsonde observations in 1955 and 1956. Dots denote observations taken south of 30°N. latitude, and crosses, those obtained north of this latitude. The circled observation in the lower right was made in typhoon Marge of 1951.

of the differences noted, no attempt has been made to modify the typhoon regression for use with hurricanes.

A sizeable number of eye dropsondes was made from the 500-mb. level for the first time in 1955. In fact, the 48 available observations from the 500-mb. level in hurricanes in 1955 and 1956 represent a sample several times as large as all previous eye soundings taken from this level. The plot of the 500-mb. heights against the surface pressure (fig. 4) suggests a linear relationship of the form

$$P_o = 141 + .45H_5 \qquad (4)$$

Since the number of reports was quite small, all observations irrespective of latitude have been included. The observations made north of 30°N. latitude, shown by the crosses in figure 4, appear to fit in quite well with the other data except at the higher pressures. This appears to be consistent with the fact that the hurricanes of 1955 and 1956 retained tropical characteristics to rather high latitudes.

The extension of the linear regression beyond 940 mb., which is shown dashed in figure 4, is open to question. However, it is supported by a 500-mb. dropsonde observation made in the eye of typhoon Marge in 1951 at the time when the surface pressure was near 900 mb.

The relatively small size of the data sample and the lack of observations at the lower pressures should tend to make the 500-mb. regression considerably less reliable than the 700-mb. regression (equation (3)). The current emphasis on higher flight levels in hurricane reconnaissance should provide a large increase in dropsonde data for the surface to 500-mb. layer and offer an opportunity for refinement of the relationship suggested by figure 4.

USE OF DATA FROM NON-STANDARD LEVELS

The basic information provided by the linear regression equations at the individual levels can be combined for estimating surface pressure from pressure-height data in the eye at any level between the surface and 500 mb. Pressure-height curves can be constructed for arbitrary surface pressure values using the 700- and 500-mb. regression equations (3) and (4) and a similar equation for the 850-mb. surface[2]. The essential data provided by individual pressure-height curves of this type have been consolidated into a nomogram (fig. 5) by using "D" values[3] rather than the heights of arbitrary pressure surfaces. This diagram provides a means of estimating surface pressure from "D" values at any pressure altitude between the surface and 18,280 ft. Height scales have been entered on the nomogram for the 850-, 700-, and 500-mb. surfaces so that direct use can be made of the reported height data for these levels.

THERMAL STRUCTURE OF THE EYE

The linear regressions between the surface and 700- and 500-mb. heights, equations (3) and (4), imply certain features of the mean thermal structure of the eye. By using the hypsometric equation, the mean virtual temperature of

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2 The 850-mb. regression ($p_o = 837 + .35H_{850}$) was developed from the same set of data used for the 500-mb. regression.

3 The "D" value is the difference between the observed height of a pressure surface and the height of the same pressure surface in the U. S. Standard Atmosphere.

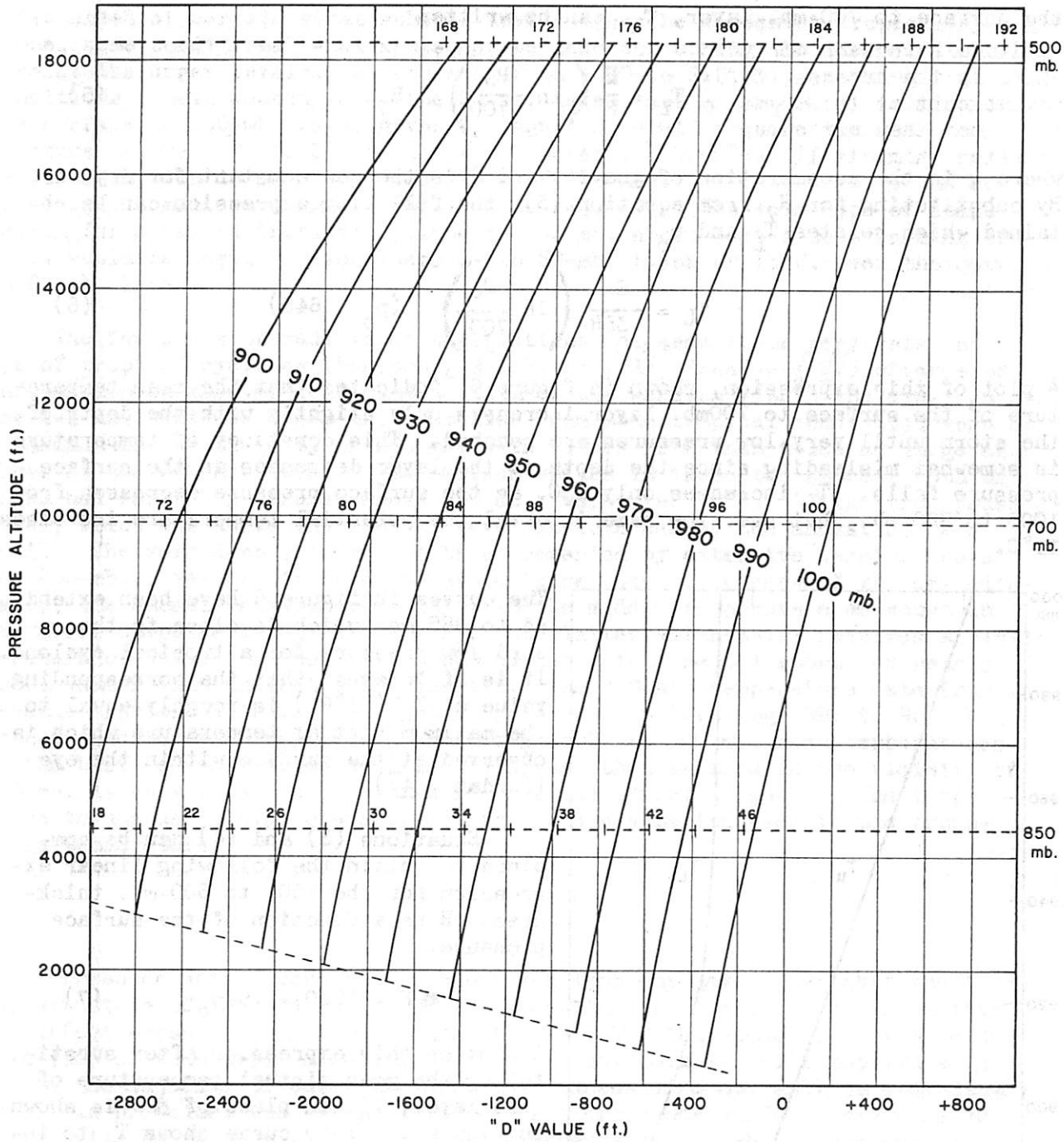

Figure 5. - Nomogram for estimating surface pressure in the eye of tropical cyclones. Height scales, in hundreds of feet, are shown on the three standard pressure surfaces.

the surface to 700-mb. layer, T_L, can be written

$$T_L = \frac{g}{R}\left(\ln \frac{p_o}{700}\right)^{-1} H_7 \qquad (5)$$

where g is the acceleration of gravity and R is the gas constant for dry air. By substituting for H_7 from equation (3), the following expression can be obtained which relates T_L and p_o

$$T_L = \frac{g}{.35R}\left(\ln \frac{p_o}{700}\right)^{-1} (p_o - 645) \qquad (6)$$

A plot of this expression, shown in figure 6, indicates that the mean temperature of the surface to 700mb. layer increases only slightly with the depth of the storm until very low pressures are reached. This constancy of temperature is somewhat misleading since the depth of the layer decreases as the surface pressure falls. T_L increases only 2°C. as the surface pressure decreases from 1000 to 920 mb., but over the same interval the potential temperature increases 11°C.

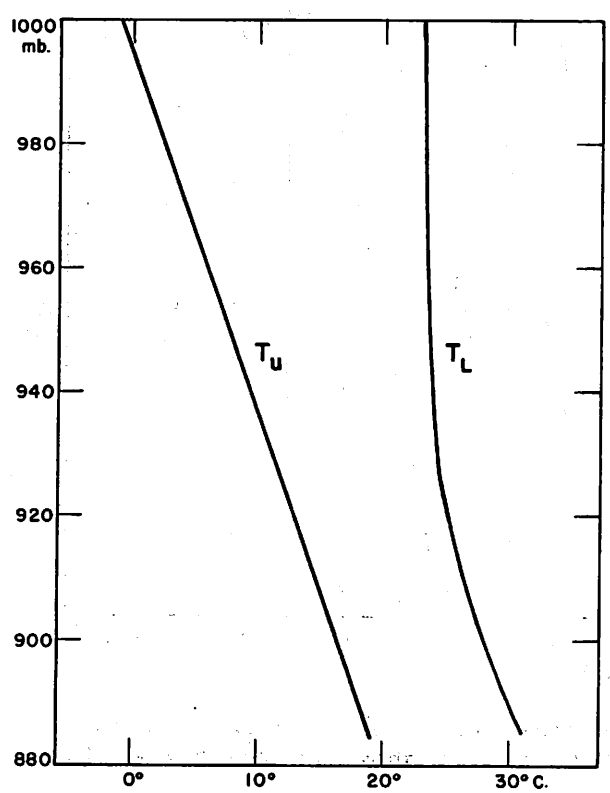

Figure 6. - Variation of mean temperature of surface to 700-mb. layer (T_L) and 700- to 500-mb. layer (T_u) as a function of surface pressure implied by regression equations (3) and (4).

The curves in figure 6 have been extended to 885 mb. which is close to the record low pressure for a tropical cyclone. It is of interest that the corresponding value of T_L (31°C.) is roughly equal to the maximum virtual temperature which is observed at the surface within the eye (Jordan [4]).

Equations (3) and (4) can be combined to obtain the following linear expression for the 700- to 500-mb. thickness H as a function of the surface pressure:

$$\Delta H = 1530 - .64p_o \qquad (7)$$

A plot of this expression after substituting the mean virtual temperature of the layer, T_u, in place of ΔH is shown in figure 6. This curve shows T_u to increase over 10°C. in the range where T_L is nearly constant.

The lack of information for the higher levels makes it difficult to extend this analysis of the hydrostatic aspects of the deepening process to the upper levels. However, by making the assumption that the height field remains

undisturbed at certain stratospheric levels over the deepening tropical cyclone, some conditional statements can be made concerning the thermal structure at the upper levels. A deepening from 1000 to 940 mb., assuming that conditions remain unchanged at the 50-mb. level, and an amount of warming in the surface to 500-mb. layer given by figure 6, would require the mean temperature of the 500- to 50-mb. layer to increase over 6°C. If the more realistic assumption is made that the storm effect does not extend above the 80-mb. level, a mean warming of over 7°C. is required. The same type of computation for a record tropical cyclone of 885 mb. shows that a mean warming of 12°C. would be required over the 500- to 50-mb. layer or 15°C. over the 500- to 80-mb. layer.

The few cases of radiosonde observations released in or very near the eye of tropical cyclones (Simpson [9], Riehl [7], Arakawa [2]) offer some information on the vertical distribution of the warming within the eye. In the two most intense cases the anomalies from mean tropical conditions were at a maximum in the vicinity of 200 mb. with values more than twice as large as those at the 500-mb. level. The maximum values in these two storms, both of which had central pressures above 960 mb., were over 15°C. At the tropopause level, which was above the 100-mb. level in both cases, the anomalies were small. The very deep storms must be accompanied by extensive warming above the 200-mb. level or, in order to avoid lapse rates in excess of the dry adiabatic, the anomaly maximum must shift to the middle troposphere as shown in the model computed by Showalter [8]. The latter alternative requires a temperature of 29°C. for the 700-to 500-mb. layer in a record storm, or nearly 10°C. warmer than indicated by figure 6. The 700-mb. temperature data from several typhoons with minimum central pressures in the range 892 to 905 mb. do not tend to offer support for such high 700- to 500-mb. mean temperatures. On the basis of this evidence it would appear that warming in the vicinity of 100 mb. is very likely and this would have the effect of pushing the tropopause to unusually high elevations with perhaps some increase in the tropopause temperature.

CONCLUSIONS

Dropsonde data taken in hurricanes and typhoons have shown that the thermal structure of the eye is sufficiently constant for reliable determination of surface pressure from 700-mb. height data. The individual errors in extrapolations of this type, assuming correct 700-mb. heights, will not exceed 2 mb. in the majority of cases and errors in excess of 5 mb. will be exceedingly rare. In practice, the extrapolations - and dropsonde surface pressures as well - will be subject to greater errors because of 700-mb. height errors.

The regression relating surface pressure and 700-mb. height should prove of practical value in several circumstances. The most important case is when an aircraft penetration is made at the 700-mb. level but, for some reason, the dropsonde observation is not made or the report does not reach the forecast center. Similarly, the estimated values should be useful during the hour or more which may elapse between the receipt of the eye message containing the 700-mb. height and the receipt of the dropsonde report. The estimated values can also serve an important role in detecting large errors which occasionally arise in dropsonde observations (cf. figs. 1 and 2).

The small deviations obtained for the independent data shown in table 1 suggest that the extrapolated values obtained from the regression might remove the requirement for eye dropsondes when the 700-mb. height is less than about 9700 feet, provided the other information furnished by the dropsonde is not considered essential. The available evidence suggests that the additional information, such as the temperature and moisture stratification within the eye, has thus far proved to be of little, if any, use in hurricane or typhoon forecasting.

The regressions for the 850- and 500-mb. surfaces are based on a relatively small data sample and have not been tested on an independent set of observations. However, the scatter is sufficiently small to suggest that operationally useful estimates of the surface pressure in the eye of tropical cyclones can be made from height data at these surfaces.

The nomogram based on the regressions (fig. 5) facilitates surface pressure estimates from height data at the three pressure surfaces and, in addition, enables estimates from aircraft data at any level up to 500 mb. No check has been made of the accuracy of estimates made from data at non-standard levels. However, it would be expected that below 10,000 feet errors would be no greater than those indicated for the 700-mb. surface.

ACKNOWLEDGMENTS

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