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U.S. DEPARTMENT OF COMMERCE
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National Environmental Satellite Service

Evaluation of a Technique for the Analysis and Forecasting of Tropical Cyclone Intensities From Satellite Pictures

CARL O. ERICKSON

WASHINGTON, D.C.
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EVALUATION OF A TECHNIQUE FOR THE ANALYSIS AND FORECASTING OF TROPICAL CYCLONE INTENSITIES FROM SATELLITE PICTURES

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ABSTRACT. The technique itself is described elsewhere (Dvorak 1972). This report concerns an experiment carried out in March 1972 to evaluate the technique as it existed at that time. Eleven participants made estimates of current storm intensity (C.I.) from 33 tropical storms and disturbances in the Atlantic and Pacific. These estimates were compared with independent measurements of maximum wind speed (MWS) and central sea-level pressure (PPP). Favorable results using the Dvorak technique to estimate MWS, particularly for weak storms, have led to its adoption operationally in modified form. Three-way correlations between C.I., MWS, and PPP are discussed. The results for the Atlantic were significantly different from those for the Western Pacific.

1. INTRODUCTION

Since 1964, the Analysis Branch of the National Environmental Satellite Service has routinely classified tropical cyclones on the basis of their appearance in satellite cloud photographs. That older classification method, based on the work of Fritz, Hubert and Timchalk (1966) and Fett (1964), was developed by using the earlier TIROS satellite cloud pictures. Although that method proved useful in providing estimates of the maximum wind speed (MWS) in tropical cyclones, there were certain deficiencies, such as the tendency to underestimate the MWS for small but intense hurricanes and typhoons. Another deficiency was the ambiguous classification of certain kinds of weaker storms and disturbances.

The technique referred to in the title was developed by Vernon F. Dvorak of the Analysis Branch (Dvorak 1972).

The new technique represents an effort to overcome the recognized deficiencies of the older method. It provides a more unified and detailed system of storm classification and, hopefully, a better relation between classification and the observed MWS. The technique also permits forecasts of storm intensity for the next day. For these reasons, it has seemed desirable to conduct an experiment to assess objectively, as nearly as possible, the results obtainable from the new method. This report concerns such an experiment.

A second purpose of the experiment was to determine whether there were any systematic differences between the results obtained by using the method on Atlantic storms and Pacific storms. Since the technique was developed from satellite photographs of Western Pacific storms and disturbances only, it was expected that the results for Atlantic storms might be different. This experiment showed that systematic differences did indeed exist; the reasons for the differences are not entirely clear.

In the picture-classification portion of the experiment, and also in the initial evaluation that followed, the desired parameter was Maximum Wind Speed (MWS). Sea-level pressure was not considered. However, eventually it became apparent that a rather good relationship also existed between the picture-derived estimates of current storm intensity (C.I.) and the central sea-level pressure (PPP). Consequently, a second evaluation was done with respect to PPP. Both sets of results are included in this report.

The expected relation between C.I. and PPP was not stated prior to the evaluation. Therefore, the approach of this study with respect to PPP has been to determine best-fit relations using the existing data. Best-fit relations also have been established for C.I. to MWS and for PPP to MWS, so that comparisons between the three relations may be made. All the data thus become dependent data,i.e., data used to establish the relation. Further tests against independent data probably would yield results that are slightly worse than the best-fit values quoted herein.

2. THE EXPERIMENT

The experiment was conducted during the week of March 13-17, 1972. It consisted of 3 days of instruction and practice in the new technique, after which each participant was given a set of satellite photographs not used in the training and was asked to make his own independent classifications while working at his own speed.

There were eleven particpants, including Dvorak. He instructed the others during the first 3 days, and later made his own classifications of the same photographs given to the rest of the group. Eight of the ten student participants were meteorologists experienced with satellite cloud pictures. A few of those persons also had some prior knowledge of Dvorak's classification system. The other two participants had had limited experience with pictures and no prior knowledge of Dvorak's system.

The photographs used for the experiment included 33 representative cases of typhoons, tropical storms, and weaker disturbances over both the North Atlantic and North Pacific Oceans. Collectively, these 33 storms and disturbances exhibited a broad range of development, from little or none to super-storm intensity ($\geqslant$130 kt). Cases were selected from the 4-year period 1967-70. The photographs were from satellites ESSA 3, ESSA 5, ESSA 7, ESSA 9, and ITOS 1. For each case, pictures covered a period ranging from 3 to 18 consecutive days. There were 15 cases from the Atlantic (including the Caribbean and Gulf of Mexico), 15 from the Western North Pacific, and 3 from the Eastern North Pacific.

In the independent classification by the participants, we attempted to simulate operational conditions insofar as possible. Each person was given pictures covering the history of the storm or disturbance, but was required to evaluate each day before looking at the next. Pictures for the first day of each case were not evaluated, but were used only as history.

Four conditions of this experiment were different from actual operations:

1) Each person made 300 classifications. This was a much larger number of decisions than would normally occur in a like period of time.

2) Participants had no knowledge of independent measurements or estimates of storm intensity, such as wind estimates from aircraft reconnaissance or from the storm advisories. These are more stringent conditions than exist operationally.

3) The sample contained a larger proportion of intense disturbances than occurs in nature. This was necessary to obtain independent (reconnaissance) wind measurements for a sufficient number of cases.

4) A few of the participants may have recognized one or more of the storms in the sample and may have remembered the wind speeds associated with the storm. This factor, however, is probably minor.

The initial results showed that the classifications by one of the two persons with limited experience differed significantly from the group average in a number of cases. Another participant tended to underclassify most storms. Because such errors are correctible with experience, the figures for those two persons omitted from the results.

3. THE PARAMETERS AND THE VERIFICATION DATA

For each storm day or disturbance day, the Dvorak technique permits the determination of up to five interrelated parameters. Two of these translate directly into wind speed:

The Current Intensity (C.I.), which is the estimate of wind speed at picture time, and

The Forecast Intensity (F.I.), which is the estimate of wind speed for the next day.

Those two parameters are compared with the independent measurements of MWS.

A third parameter, the T-number, forms the basic classification of the storm or disturbance. (The T-number does not translate directly into wind speed, but it is the major factor for determining the values assigned to C.I. and F.I.). In this report, the T-number is evaluated only with respect to consistency of classification among the participants.

This report also compares C.I. with independent measurements of PPP. A moderately good relationship existed between C.I. and PPP.

Aircraft reconnaissance provided most of the MWS and PPP verification data. For the Western Pacific, the MWS and PPP data were taken from the best-track intensities available in the Annual Typhoon Reports for the years 1967-70 (U.S. Fleet Weather Central/Joint Typhoon Warning Center). In the Atlantic, MWS and PPP data were obtained from reconnaissance reports and from published articles (Simpson and Pelissier 1971, Sugg and Hebert 1969, Sugg and Pelissier 1968).

For both oceans, the above sources were supplemented by surface reports and analyses. These additional verifications from surface data were available mainly for the weaker disturbances or for those in the early stages of development when no aircraft reports were available. However, for many of the weaker disturbances there were no verification data.

Three Eastern Pacific storms, all of which occurred during 1970, were included in the experiment. Data for these storms were obtained from the Annual Typhoon Report (1970) and Denney (1971). These storms are omitted from most of the results.

With respect to MWS, the number of days for which there is verification of C.I. and F.I. is much less than the total number of disturbance days (300). There are three reasons for this:

(1) MWS data do not exist for many weaker storms.

(2) Values of C.I. and F.I. at the low end of the scale--1.0 and 1.5--do not translate into wind speed (a value of 2.0 is equivalent to 30 kt). Thus, many weak disturbances are not evaluated in terms of wind speed. (NOTE: This is in accordance with the technique as it existed in mid-March 1972. Slight changes to the technique have been made since (Dvorak 1972)).

(3) Days on which the storm center was over land are not included.*

Item 2 also accounts for the differing number of verifications between participants. Many weaker disturbances were classified as 2.0 (30 kt) by some persons, and therefore may be compared with the MWS, whereas the same weaker disturbances were classified 1.5 by other persons and cannot then be compared.

As a result of the three factors listed above, the number of verifications of C.I. and F.I. averaged somewhat more than half the total number of days (300). The total number of MWS verifications varied between participants, ranging from 185 to 217 for C.I. and from 158 to 196 for F.I.

With respect to PPP, the situation was similar. The total number of comparisons of PPP with C.I. was very nearly the same as for MWS with C.I. PPP data were not verified against F.I.

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*The initial compilation also omitted those storms with their centers near, but not over, land. Because it was later determined that the statistics for C.I. (but not for F.I.) were not adversely affected for these storms, they have been included in the verifications of C.I.

Each PPP measurement or estimate was assigned a code figure indicating degree of confidence or reliability. The code figures and their explanations are listed below, in descending order of confidence:

Code	Description
1.	Eye penetration by reconnaissance aircraft within 30 min of picture time--actual PPP value used.
2.	Eye penetration 1/2 to 2 hr away from picture time--PPP determined through linear interpolation or extrapolation.
3.	Eye penetration 2 to 6 hr away from picture time, and indicated rate of pressure change $\leqslant 1$ mb/hr--PPP determined through linear interpolation or extrapolation.
4.	Same as 3, except rate of pressure change > 1 mb/hr.
5.	No penetration within 6 hr of picture time--PPP estimated from plotted storm track.
6.	PPP estimated from surface observations and analyses.
9.	PPP missing.

Eye penetrations for the Western Pacific storms of this study were more frequent than for the Atlantic storms. Consequently, confidence in the Pacific PPP data is somewhat higher than in the Atlantic data. In the Pacific, approximately two-thirds of all PPP observations were of confidence 1, 2, or 3. For the Atlantic, the corresponding ratio was about one-half.

4. RESULTS AND DISCUSSION

A. Internal Consistency of the Technique.

Table 1 shows that the basic T-number classification is moderately consistent between different persons, with few large deviations from Dvorak's work. Approximately 70 percent of all classifications deviated 0.5 or less from Dvorak, about 90 percent 1.0 or less, and about 10 percent more than 1.0. Differences of 1.0 or greater were more frequent in the middle ranges than at either end of the scale (table 1b). This greater spread in the middle ranges showed up in larger percentage deviations from the MWS in the middle ranges of wind speed.

Table 1a reveals that the student group used the half-values of T-number (1.5, 2.5, etc.) less frequently than whole-number values. To correct this bias, the percentages of table 1b are obtained by using a three-point binomial smoother.

Table 2 is a presentation of deviations from Dvorak's values for the parameter C.I., the Current Intensity, in kt, as estimated from the pictures. R is the correlation coefficient and b the slope of the linear regression.

Table 1a.--Percentages of T-number classifications by the group of eight persons (abscissa) vs. Dvorak's T-number classifications (ordinate)

Dvorak's T-number	Classification by 8 students														
T-No.	1	1½	2	2½	3	3½	4	4½	5	5½	6	6½	7	7½	8
1	51	20	22	5	2	0	0	0	0	0	0	0	0	0	0
1½	29	24	27	14	5	1	1	0	0	0	0	0	0	0	0
2	11	14	40	15	13	5	2	0	0	0	0	0	0	0	0
2½	4	10	26	23	25	7	5	1	0	0	0	0	0	0	0
3	2	0	9	13	37	14	9	4	1	0	0	0	0	0	0
3½	1	1	2	8	24	15	32	11	5	1	0	0	0	0	0
4	0	0	2	2	9	16	29	19	15	7	3	0	0	0	0
4½	0	0	0	0	4	9	20	24	23	8	9	2	0	0	0
5	0	0	0	0	2	2	10	17	24	24	18	1	1	0	0
5½	0	0	0	0	0	0	0	4	11	26	22	21	11	3	1
6	0	0	0	0	0	0	1	1	16	25	33	11	10	1	1
6½	0	0	0	0	1	0	0	0	7	10	23	24	28	7	0
7	0	0	0	0	0	0	0	0	0	0	0	38	13	38	13
7½															
8															

Table 1b.--Smoothed percentages and cumulative percentages (parentheses) of class deviations from Dvorak's T-number

Dvorak's T-number	Deviations from Dvorak's T-number					
	0	½	1	1½	2	2½ or more*
1	47 (47)	25 (72)	21 (93)	5 (98)	2 (100)	0 (100)
1½	40 (40)	33 (73)	20 (93)	5 (98)	2 (100)	+ (100)
2	33 (33)	38 (72)	21 (93)	6 (98)	2 (100)	0 (100)
2½	31 (31)	39 (70)	22 (92)	6 (98)	2 (100)	0 (100)
3	29 (29)	39 (68)	23 (92)	6 (98)	2 (100)	0 (100)
3½	27 (27)	40 (67)	24 (90)	7 (97)	3 (100)	+ (100)
4	25 (25)	41 (66)	21 (88)	9 (97)	3 (100)	0 (100)
4½	26 (26)	41 (66)	21 (87)	10 (97)	3 (100)	0 (100)
5	25 (25)	41 (66)	24 (89)	8 (97)	3 (100)	0 (100)
5½	27 (27)	37 (64)	26 (90)	6 (96)	3 (99)	1 (100)
6	29 (29)	40 (68)	23 (92)	6 (98)	2 (100)	0 (100)
6½	26 (26)	47 (73)	20 (93)	5 (98)	1 (99)	1 (100)
7	21 (21)	58 (80)	16 (95)	5 (100)	0 (100)	0 (100)
7½						
8						

*The plus sign indicates a percentage greater than zero but less than 0.5

Table 2.--Statistical comparisons of the current intensity (C.I.) obtained by eight student participants with the C.I. obtained by Dvorak

Person	RMSE (kt)	R	b	Mean deviation (kt)	Algebraic mean difference (kt) (student-Dvorak)
1.	15.06	.92	.77	10.00	+ 8.77
2.	16.25	.87	.76	12.66	+ 7.34
3.	11.30	.91	1.01	10.64	- 3.78
4.	11.06	.91	1.03	10.94	+ 1.46
5.	18.59	.90	.66	11.56	+ 7.93
6.	14.64	.87	.77	13.04	+ 0.41
7.	12.82	.91	.78	10.56	+ 3.18
8.	12.96	.90	.80	11.07	+ 3.05
Average for group	14.28	.88	.78	12.21	+ 3.58

Legend: R = correlation coefficient
b = regression slope

All participants showed a moderate degree of scatter (mean deviation 12.21 kt, mean RMSE 14.28 kt). Persons 1, 2, and 5 also displayed a marked tendency to obtain values of C.I. higher than Dvorak's in the middle and upper ranges. This is revealed by positive mean algebraic differences of 7 to 8 kt together with regression slopes (b) considerably less than unity.

The participants were initially unfamiliar with the technique, and performed for the record after only 3 days of instruction and practice. Although nearly all felt that their understanding was adequate, several also felt that they were continuing to improve and that more experience would improve their results significantly.

B. The Estimation of Wind.

At the time of the March 1972 experiment, the expected relationship between C.I. and the maximum sustained wind speed was as follows:

C.I. No.	Wind speed (kt)	C.I. No.	Wind speed (kt)
1.0	(not specified)	5.0	75
1.5	(not specified)	5.5	87
2.0	30	6.0	100
2.5	35	6.5	115
3.0	40	7.0	130
3.5	47	7.5	145
4.0	55	8.0	160
4.5	65		

No allowance was made for possible differences between Atlantic and Pacific oceans--indeed, it was one of the purposes of the experiment to discover whether such differences exist.

Because the present working relation of C.I. to wind speed is slightly different from that above (Dvorak 1972), the verification statistics for C.I. vs. MWS based on the above tabulation are not given. However, the important conclusions are:

- Dvorak was significantly better than the student group in some respects.
- There was a large and quite consistent negative bias for Atlantic storms.
- The method was quite accurate for estimating the low wind speeds ($\leqslant$50 kt), was fairly accurate for intense storms (>100 kt), but was least accurate for storms of intermediate strength (55-100 kt).
- The new technique appears definitely superior to the old for estimating the MWS in weak storms, but not for intermediate and intense storms. For an assessment of the older method, see Hubert and Timchalk (1969).

Because the Dvorak technique was developed using photographs of Pacific storms and disturbances, the technique should be expected to work better in the Pacific than in the Atlantic. As noted above, the experiment resulted in a strong negative bias for Atlantic storms. Every person underestimated the mean MWS for Atlantic storms and disturbances (group average: -10.9 kt). No systematic bias was noted for the Pacific Storms.

During the experiment, the sequence of storms was random, so the bias should not have arisen from that source. Two reasons are suggested to account for the negative bias in the Atlantic:

(1) There is a real physical difference between Atlantic storms and Pacific storms, or

(2) there is a systematic difference in the measurements by reconnaissance between the Atlantic and Pacific, with the Atlantic measurements tending to be higher than the Pacific measurements.

The author inclines toward the first as being more likely.*

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*It is possible that some of the Atlantic values of MWS used in this study may be a bit too high. After the C.I.-MWS evaluation had been completed, a comparison was made between the U.S. Navy Best-track MWS values (not used in this study) and values from other sources (which were used) for 65 Atlantic cases where both existed. The latter averaged 56.9 kt, the former 55.4 kt or 1.5 kt less. Thus, the use of the U. S. Navy MWS values would slightly reduce the observed difference in technique performance between Atlantic and Western Pacific oceans, but it certainly would not eliminate that difference.

The greater degree of error in the intermediate (55- to 100-kt) range of MWS might be attributed to the fact that rapidly developing and rapidly weakening storms tend to fall in this range. Such storms probably are more difficult to "hit."

Hurricane Beulah of 1967 may be offered as evidence. Beulah was included in this experiment and was a difficult storm to assess, as it underwent rapid intensification, pronounced weakening, and then re-intensification. As might be expected, the scatter of scores for Beulah was greater than for most of the storms. Many large deviations from the MWS occurred, nearly all negative. Although nearly everyone correctly interpreted the direction of major changes, the changes tended to occur sooner than expected.

In assessing the results from this technique (and, specifically, in comparing C.I. with MWS), it is useful to eliminate the systematic error. This is done through construction of regression lines fitted to the data by least squares so that the scatter is minimized. Table 3 presents some statistics for such linear best-fit relations between C.I. and MWS. These are given for each of the eight student participants and for Dvorak. Different relations for the Atlantic and Western Pacific oceans can be seen by comparing the slopes of the regression lines. For each person, the slope for the Atlantic is greater than that for the Western Pacific.

Table 3.--Best-fit linear relations between current intensity (C.I.) and maximum wind speed (MWS). MWS (kt) is the dependent variable. Includes all cases where both C.I. and MWS are reported, except storms over land

	Western Pacific						Atlantic					
Person	b	MWS inter-cept (kt)	R	RMSE (kt)	Mean abs. error (kt)	N	b	MWS inter-cept (kt)	R	RMSE (kt)	Mean abs. error (kt)	N
1.	.82	5.2	.815	18.8	14.3	115	1.09	1.8	.843	14.5	11.6	61
2.	.77	11.1	.761	21.1	17.3	116	1.23	-6.2	.760	17.8	14.1	76
3.	1.05	3.2	.815	18.6	14.9	113	1.56	-8.4	.760	18.3	14.9	62
4.	1.08	-2.4	.794	19.8	15.4	117	1.32	-10.7	.830	15.2	12.4	82
5.	.64	20.2	.752	20.8	17.3	109	1.03	8.7	.822	15.3	12.9	66
6.	.78	17.2	.771	20.2	16.0	111	1.29	-2.4	.835	15.6	12.6	59
7.	.83	9.6	.814	18.8	15.1	113	1.09	7.4	.814	15.8	13.6	60
8.	.86	8.5	.825	18.2	14.6	113	1.01	9.7	.806	16.0	13.2	65
Mean			.793	19.5	15.6				.809	16.1	13.2	
Dvorak	1.06	-1.4	.887	14.7	11.7	111	1.25	0.3	.841	14.5	12.2	67

Legend: b = slope
R = correlation coefficient
N = number of cases

The Western Pacific sample contains a higher proportion of intense storms (high MWS) than does the Atlantic. Therefore, although the Western Pacific RMS errors and mean absolute errors seen in table 3 are slightly larger numerically than the Atlantic errors, they are not larger in percent. The MWS intercept is (a) and the number of cases N.

Figures 1 through 4 (appendix) display some of the C.I.-MWS regression curves and the plotted data from which they are derived. Data are presented for Dvorak and for one representative participant from the group of eight students. In each figure, both the linear regression and the best-fit 2nd-degree polynomial curve are shown.

Of importance to the forecaster is the direction of the changes in intensity of a tropical cyclone. In this respect, the Dvorak technique produces good results (see table 4). For the group of eight persons, the satellite-derived estimates of past 24-hr changes in intensity (C.I. today minus C.I. yesterday) had the correct sign on nearly 90 percent of all cases. The correlation with the observed changes was +0.62. For Dvorak, the figures were even better; 91 percent and +0.70. On the whole, it appears that the technique is much better for recognizing changes in intensity than it is for indicating the intensity itself.

Table 4.--Correlation coefficients (R) (columns A and C) between observed 24-hr changes in MWS, as determined from independent data, and the 24-hr changes in intensity estimated from satellite photographs (see legend). Columns B and D are the percentages of satellite-derived estimates having the correct algebraic sign.

	For past 24 hr		For next 24 hr	
Person	A (R)	B (%)	C (R)	D (%)
1.	.68	90	.53	83
2.	.55	89	.41	75
3.	.61	92	.51	86
4.	.62	91	.42	76
5.	.60	87	.52	83
6.	.63	89	.51	81
7.	.65	86	.50	77
8.	.66	88	.53	78
Average for group	.62	89	.49	80
Dvorak	.70	91	.56	83

*For past 24 hr: Change estimated from photos = C.I. today minus C.I. yesterday,
Observed change = MWS today minus MWS yesterday.

For next 24 hr: Change estimated from photos = F.I. minus C.I.,
Observed change = MWS tomorrow minus MWS today.

R = correlation coefficient

Forecast changes in intensity for the next 24 hr (columns C and D of table 4) were not as accurate as were the estimates of past change. However, the correct sign was obtained for 80 percent of all forecasts.

Two other conclusions, based on limited evidence, are offered:

(1) Poor picture quality has an adverse effect on classification, and

(2) the influence of land masses has an adverse effect in that wind speeds tend to be overestimated after the storm has moved inland.

Evidence for the former comes mainly from two Western Pacific storms of August 1968 that were viewed by ESSA 5 in the late afternoon. The standard deviations of the group T-number classifications for those two storms were larger than those for nearly all other cases. The comparisons with the MWS data also were worse than the average. The author believes that low sun and resultant below-average picture quality were partly responsible.

C. Estimating Pressure.

As noted in the Introduction, there was no stated relation between C.I. and PPP prior to this study. Therefore, the approach has been to determine best-fit relations using the existing values. Table 5 gives statistics for such linear best-fit relations for C.I. to PPP (similar to that presented for C.I. to MWS in table 3). The data are for all PPP.

Table 5.--Best fit linear relations between current intensity (C.I.) and central sea-level pressure (PPP). PPP (mb) is the dependent variable. Includes all cases where both C.I. and PPP are reported and storm center is not over land

	Western Pacific						Atlantic					
Person	Slope (mb per kt)	PPP intercept (mb)*	R	RMSE (mb)	Mean abs. error (mb)	N	Slope (mb per kt)	PPP intercept (mb)*	R	RMSE (mb)	Mean abs. error (mb)	N
1.	-.69	23.5	-.858	13.6	9.9	117	-.77	35.4	-.876	8.8	6.7	61
2.	-.68	21.4	-.811	15.8	12.7	118	-.82	37.6	-.794	10.5	7.4	78
3.	-.89	25.6	-.850	13.8	10.3	113	-1.04	39.4	-.778	11.4	8.3	65
4.	-.94	32.7	-.854	14.1	10.5	121	-.88	40.3	-.870	8.4	6.2	85
5.	-.55	12.1	-.799	15.5	12.6	108	-.73	30.5	-.873	8.7	6.5	67
6.	-.67	15.5	-.813	15.3	11.4	111	-.91	37.8	-.890	8.4	6.0	63
7.	-.69	19.1	-.857	13.4	10.5	111	-.78	31.6	-.853	9.6	7.2	62
8.	-.71	19.9	-.848	14.0	10.8	113	-.72	30.1	-.873	8.6	6.6	69
Mean			-.836	14.4	11.1				-.851	9.3	6.9	
Dvorak	-.88	28.4	-.909	10.9	7.7	111	-.87	35.2	-.878	8.5	5.8	67

*Add 1000 mb to PPP intercept.

R = correlation coefficient
N = number of cases

Differences in the confidence level of PPP seem to have little effect on the result. For the relations C.I. to PPP and PPP to MWS, the RMS errors were slightly larger for confidence levels 1, 2, and 3 (not shown in table 5) than for all confidence levels. Perhaps this is because confidence levels 1, 2, and 3 generally correspond to the much lower values of PPP that occur in the intense storms that are penetrated more frequently by reconnaissance aircraft. Thus, the assumed greater reliability of the measurement is more than offset by the larger range of the values to be measured. In any event, the net effect is small.

As with the C.I. to MWS relation, the numerical values of the mean errors for the C.I.-to-PPP relation, given in table 5, are larger in the Pacific than in the Atlantic. However, the goodness-of-fit, as shown by the correlation coefficients, is approximately the same for both oceans.

Figures 5 and 6 (appendix) show the plotted data and regression curves for Dvorak.

D. Comparison of Wind Estimates with Pressure Estimates.

Table 6 gives comparative statistics for the three best-fit relations C.I. to PPP, PPP to MWS, and C.I. to MWS. All the linear correlation coefficients are relatively large, indicating useful basic relations between the parameters. Correlations are best for PPP to MWS (-.903 to -.930). They are not quite as good for C.I. to PPP (-.820 to -.903), and are slightly lower yet for C.I. to MWS (.783 to .886). This indicates that classifications according to the Dvorak technique correlate a bit better with pressure than with wind.

However, if wind is the desired end product, the direct relation between C.I. and MWS will, on balance, be better than the combined relation of C.I. with PPP and PPP with MWS (see table 7). This is true even though both C.I. vs. PPP and PPP vs. MWS are better than C.I. vs. MWS.

PPP is generally believed to be a more conservative parameter than MWS. Usually it is measured more accurately, and it occurs in the center or eye of the storm, in contrast to the banana-shaped areas of MWS that fluctuate in intensity and may rotate around the storm at some distance from the center. For these reasons, PPP may be more valuable than wind speed for tropical cyclone analysis and forecasting. But when a storm goes ashore, the private citizen whose house is blowing away has no interest in PPP! Prior wind knowledge is essential. Perhaps the most helpful operational use of the Dvorak technique would be to supply estimates of both parameters.

The results shown in table 6 are influenced by two differences between Atlantic and Pacific data. Over the Western Pacific much of the basic MWS data is derived from the published best-track intensities, which, in turn, have been influenced by the reported reconnaissance values of PPP. This leads to a built-in correlation between PPP and MWS. Therefore, the large negative coefficients (-.930) shown for PPP to MWS over the Western Pacific probably are excessive. In the Atlantic, the measurements or estimates of

Table 6.--Comparisons of best-fit relations between C.I. and PPP, PPP and MWS, and C.I. and MWS (see legend). Includes only cases where all three quantities were reported and storm center was not over land

Predictor (independent) to Predictand (dependent)			Western Pacific R	Western Pacific RMSE	Western Pacific Mean abs. error	Western Pacific N	Atlantic R	Atlantic RMSE	Atlantic Mean abs. error	Atlantic N
C.I. to PPP				(mb)	(mb)			(mb)	(mb)	
	Group mean	A	-.820	14.6	11.3	(107)	-.857	9.3	6.8	(65)
		B		14.4	11.0	(107)		9.1	6.7	(65)
	Dvorak	A	-.903	11.0	7.8	107	-.883	8.4	5.7	66
		B		10.9	7.6	107		8.4	5.7	66
PPP to MWS				(kt)	(kt)			(kt)	(kt)	
	Group mean	A	-.930	11.6	8.9	(107)	-.908	11.5	9.6	(65)
		B		11.4	8.8	(107)		10.5	8.2	(65)
	Dvorak	A	-.930	11.7	9.0	107	-.903	11.6	9.6	66
		B		11.4	8.9	107		10.7	8.5	66
C.I. to MWS				(kt)	(kt)			(kt)	(kt)	
	Group mean	A	+.783	19.7	15.8	(107)	+.806	16.2	13.3	(65)
		B		18.9	14.9	(107)		15.9	12.9	(65)
	Dvorak	A	+.886	14.8	11.7	107	+.840	14.6	12.3	66
		B		14.3	11.1	107		13.8	11.5	66

*Legend: C.I. = current storm intensity (kt), as estimated from satellite photographs.

PPP = minimum central sea-level pressure (mb) in storm, as measured by reconnaissance aircraft or as estimated from interpolation or from other sources.

MWS = maximum wind speed (kt), as determined from post-analysis best track, aircraft reconnaissance, or other sources.

A = Linear Regression (least-squares best fit).

B = 2nd-degree Polynomial (least-squares best fit).

R = correlation coefficient.

N = number of cases (values enclosed in parentheses are averages for the group of 8 persons).

PPP and MWS were more nearly independent, and the excess of correlation should be less.

Table 7.--Comparison of the linear correlation coefficients between current intensity (C.I.) and maximum wind speed (MWS) with the automatic correlation coefficients obtained by going from C.I. to MWS through central sea-level pressure (PPP)

A = Automatic correlation (through PPP)
B = Direct correlation

	Western Pacific			Atlantic		
	A	B	(B - A)	A	B	(B - A)
Group mean	(-.820) x(-.930) .763	.783	+.020	(-.857) x(-.908) .778	.806	+.028
Dvorak	(-.903) x(-.930) .840	.886	+.046	(-.883) x(-.903) .797	.840	+.043

The second difference between oceans is that the Western Pacific contains a higher percentage of the more intense storms. Again, the reader of table 6 should note that the larger numerical errors seen for the Western Pacific estimates of MWS are not larger in percent than those for the Atlantic.

Table 6 also contains mean error data for the best-fit 2nd-degree polynomials (lines B) as well as for the best-fit linear regressions (lines A). Because the 2nd-degree curves are nearly linear, their use gives only slight reductions in the mean errors--usually a few tenths of a knot, or a few tenths of a millibar. An exception is the PPP to MWS relationship for the Atlantic, where the 2nd-degree curve departs moderately from the linear regression (also see figure 8). In that relationship, the reduction in mean MWS errors obtained by use of the 2nd-degree curve is approximately 1.0 kt.

If wind is the desired end product, it has been shown that the direct route from C.I. to MWS will, on the average, yield better results than will the indirect route through PPP. However, because the demonstrably good relation between PPP and MWS will remain useful for some purposes, figures 7 through 10, showing that relation, are included in the appendix. Those figures display the regression curves and the plotted data segregated by ocean and by two classes of PPP.

Figures 7 through 10, and especially the Pacific data of figures 7 and 9, contain the built-in correlation noted earlier. For a similar figure without such built-in correlation, see Shea (1972). Shea's diagram (his figure 80) is derived from reconnaissance spot measurements that presumably are independent, and shows a larger scatter in the plot of PPP vs. MWS.

Figure 11 shows the differences between the PPP-MWS regression curves for the Atlantic and the Western Pacific. It is apparent that the same PPP-to-MWS relation cannot be used for both oceans. For the pairs C.I. to MWS and C.I. to PPP, the oceanic differences are less, but they are large enough to require different curves for each ocean.

In operational tropical cyclone analysis, the estimation of MWS from central pressure is an old and imperfect procedure. A number of empirically-derived equations have been used by the various field forecast offices (Holliday 1969). Several of those equations have been compared with the PPP-MWS data of the present study. In the Atlantic, Kraft's equation ($MWS = 14\sqrt{1013 - PPP}$) most nearly fits these data. The equation was close to both the linear and the 2nd-degree curves of figure 8 through the middle range of wind speeds (30 to 100 kt). In the Western Pacific, Takahashi's equation ($MWS = 13.4\sqrt{1010 - PPP}$) was best for intense storms and Myers' equation ($MWS = 11\sqrt{1010 - PPP}$) was best for weaker storms.

5. CONCLUSIONS

The new technique is better for estimating the MWS in weak storms ($\leqslant$50 kt) than is the storm classification method previously in use.

The technique is much better for estimating changes in storm intensity over the past 24 hours than it is for estimating the intensity itself. The sign of the 24-hour past changes was correct in nearly 90 percent of cases. The sign of the forecast changes was 80 percent correct. The author believes that the forecasts of sign would be useful operationally.

There was a large and quite consistent negative bias in the MWS estimates for Atlantic storms. No such systematic bias was noted for Pacific storms.

The linear correlation between C.I. and PPP is slightly better than the correlation between C.I. and MWS. However, if wind is the desired end product, the direct relation, C.I. to MWS, will yield better results than will the indirect relation, C.I. to PPP to MWS.

Best-fit relations yielded the following ranges of mean absolute error:

C.I. to MWS	MWS	11 to 16 kt
C.I. to PPP	PPP	6 to 11 mb
PPP to MWS	MWS	8 to 10 kt

Tests using independent data probably would show slightly larger mean errors than these.

The best-fit regression equations all show considerable differences between Atlantic and Western Pacific storms. It appears that different working relations should be used for each ocean.

Classification errors tend to be larger with poor quality photographs and with storms of rapidly changing intensity.

Experience helps. Dvorak averaged better than any of his students.

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APPENDIX

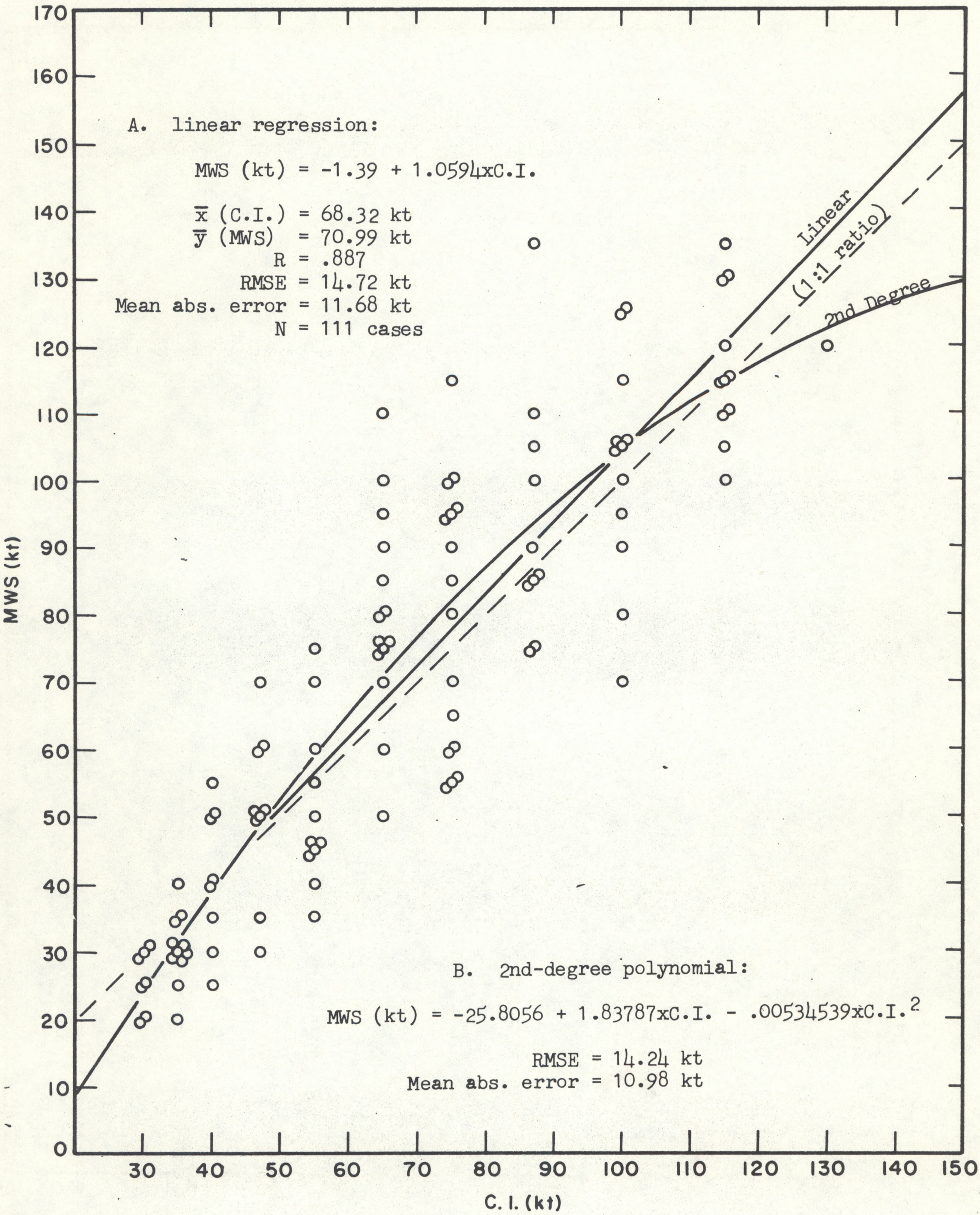

Figure 1.--Estimates of maximum wind speed (MWS) from current intensity (C.I.). Western Pacific storms, 111 cases. Includes Dvorak data only--all Western Pacific cases where both MWS and C.I. were reported and storm center was not over land.

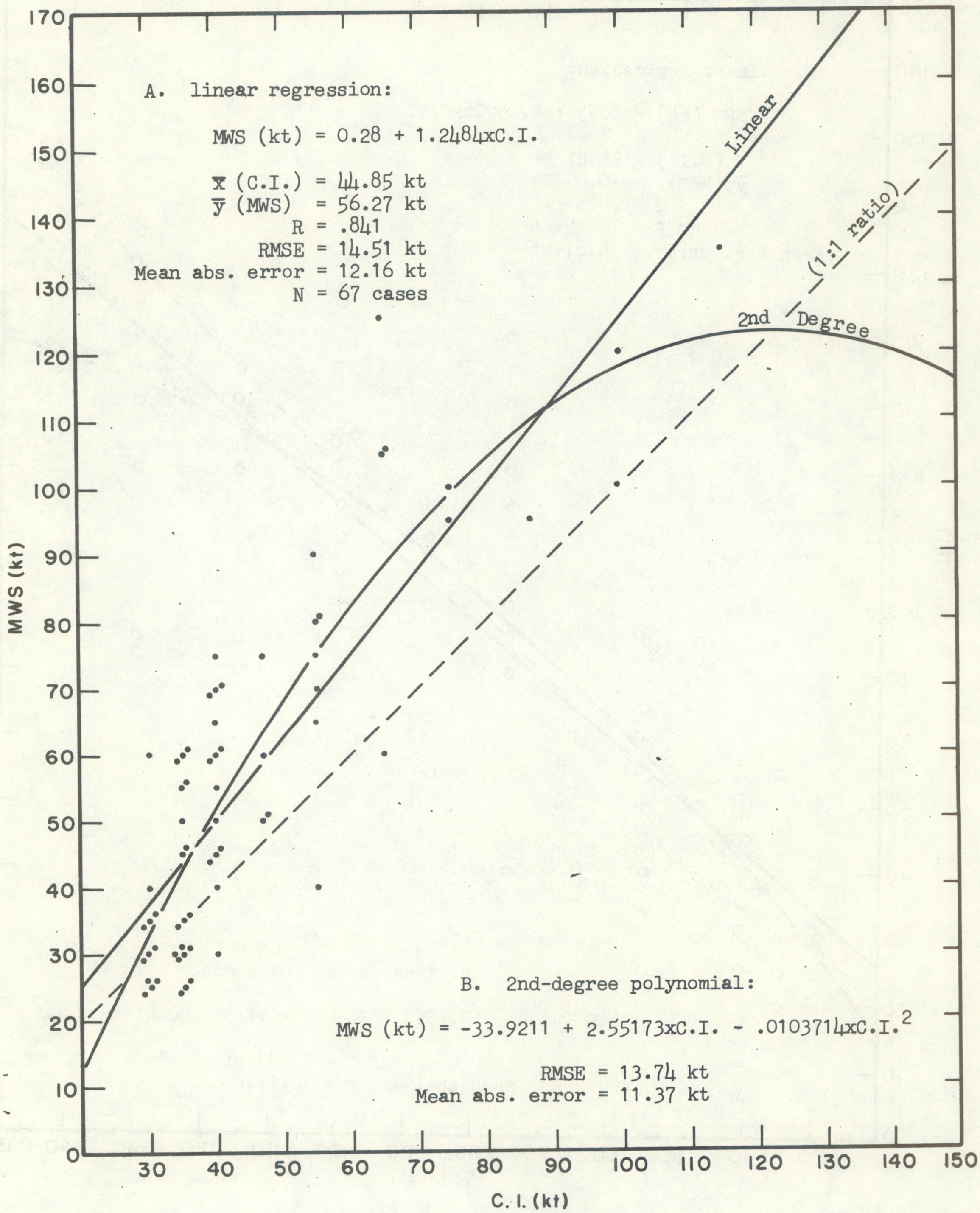

Figure 2.--Estimates of maximum wind speed (MWS) from current intensity (C.I.), Atlantic storms, 67 cases. Includes Dvorak data only--all Atlantic cases where both MWS and C.I. were reported and storm center was not over land.

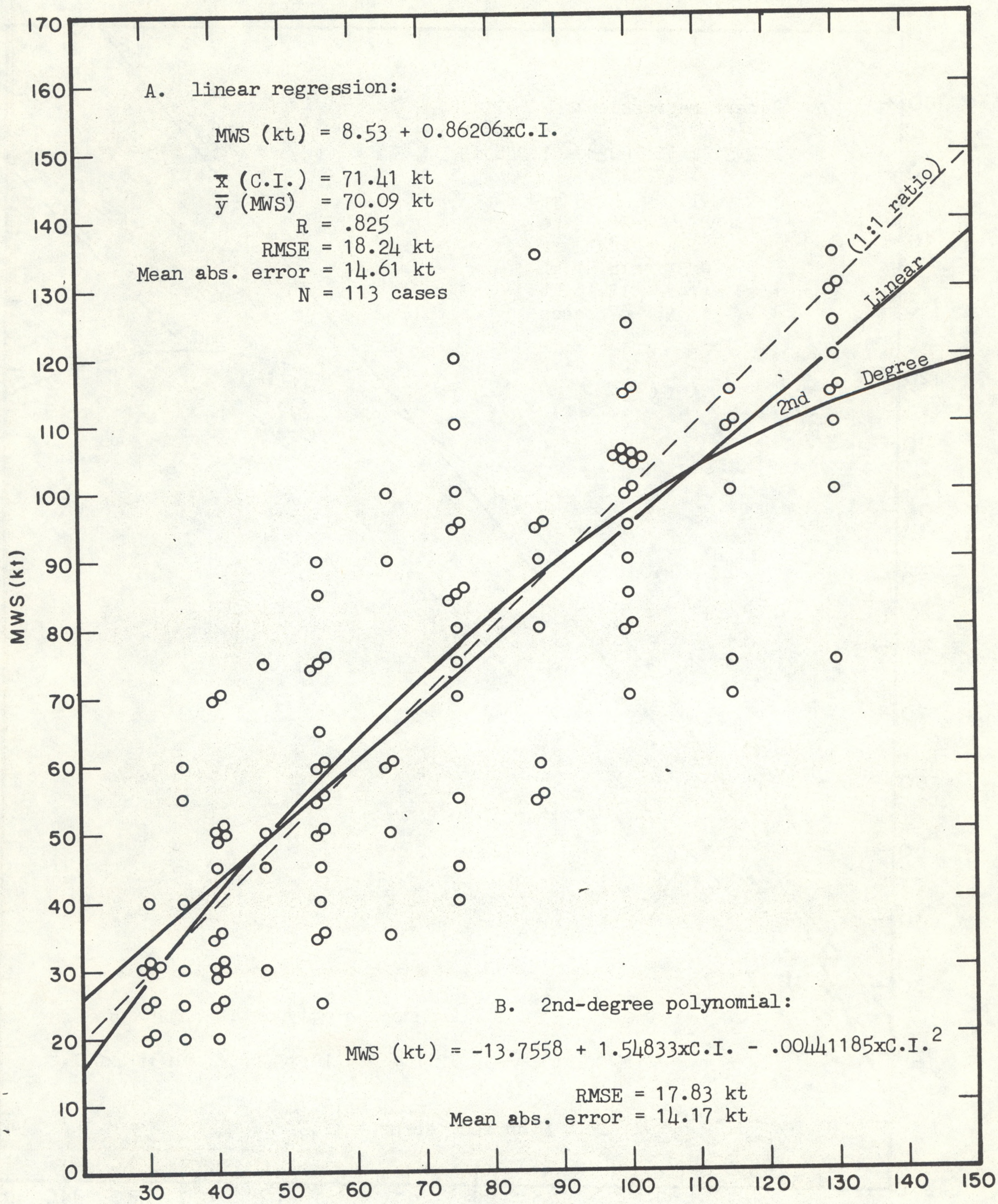

Figure 3.--Estimates of maximum wind speed (MWS) from current intensity (C.I.), Western Pacific storms, 113 cases. (for Person No. 8--all Western Pacific cases where both MWS and C.I. were reported and storm center was not over land).

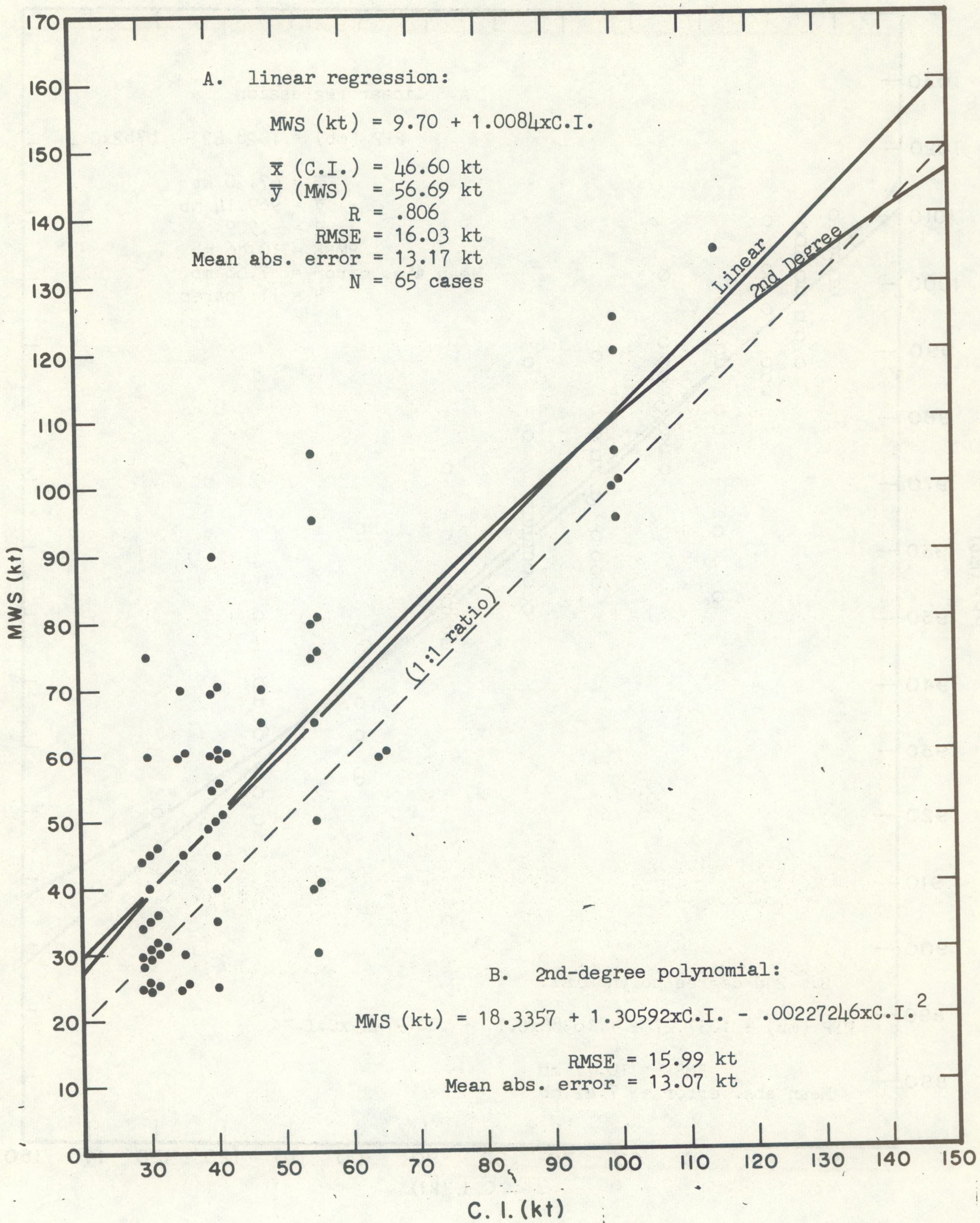

Figure 4.--Estimates of maximum wind speed (MWS) from current intensity (C.I.), Atlantic storms, 65 cases. (for Person No. 8--all Atlantic cases where both MWS and C.I. were reported, and storm center was not over land).

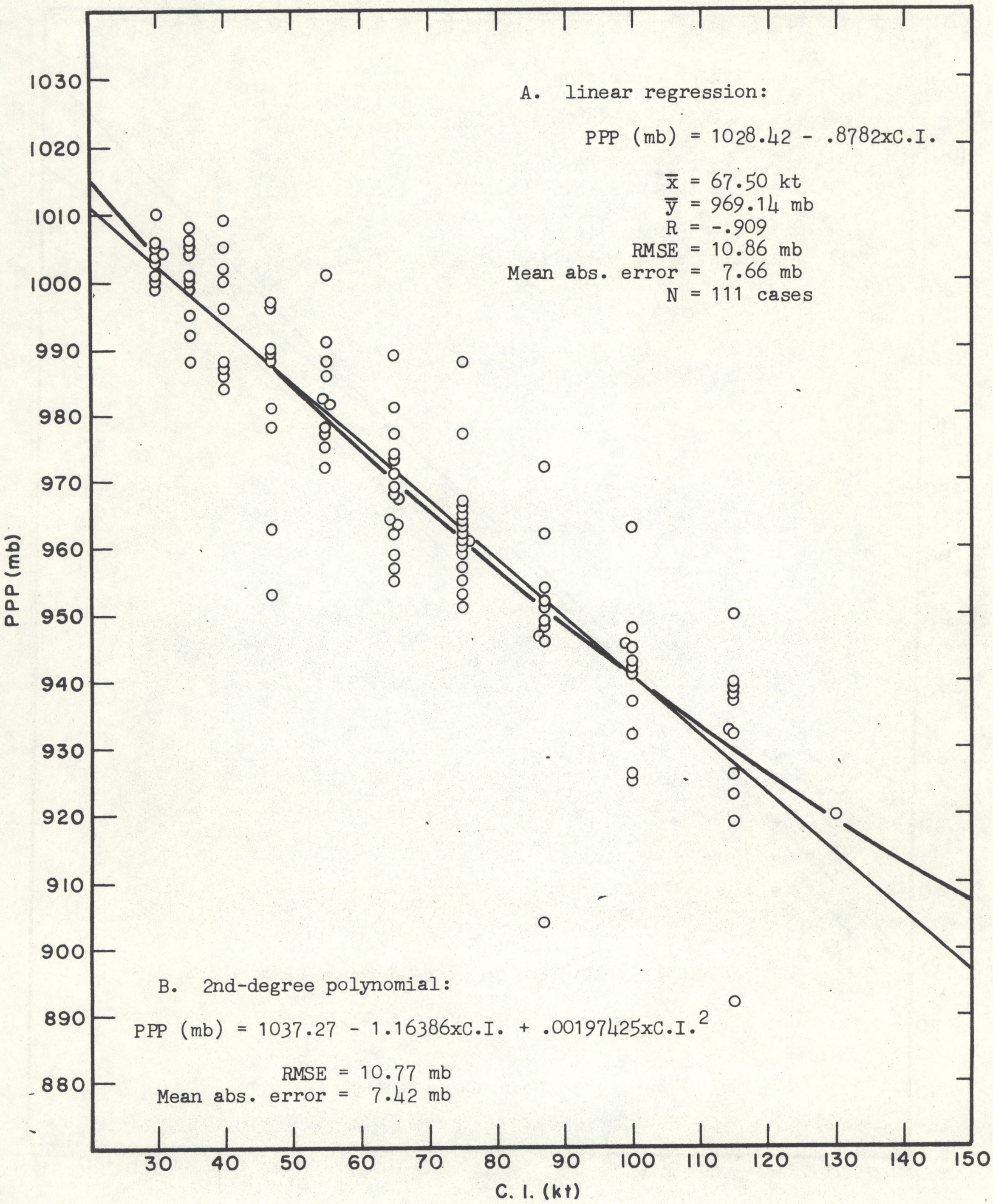

Figure 5.--Estimates of central sea-level pressure (PPP) from current intensity (C.I.), Western Pacific storms, 111 cases. Includes Dvorak data only--all Western Pacific cases where both PPP and C.I. were reported and storm center was not over land.

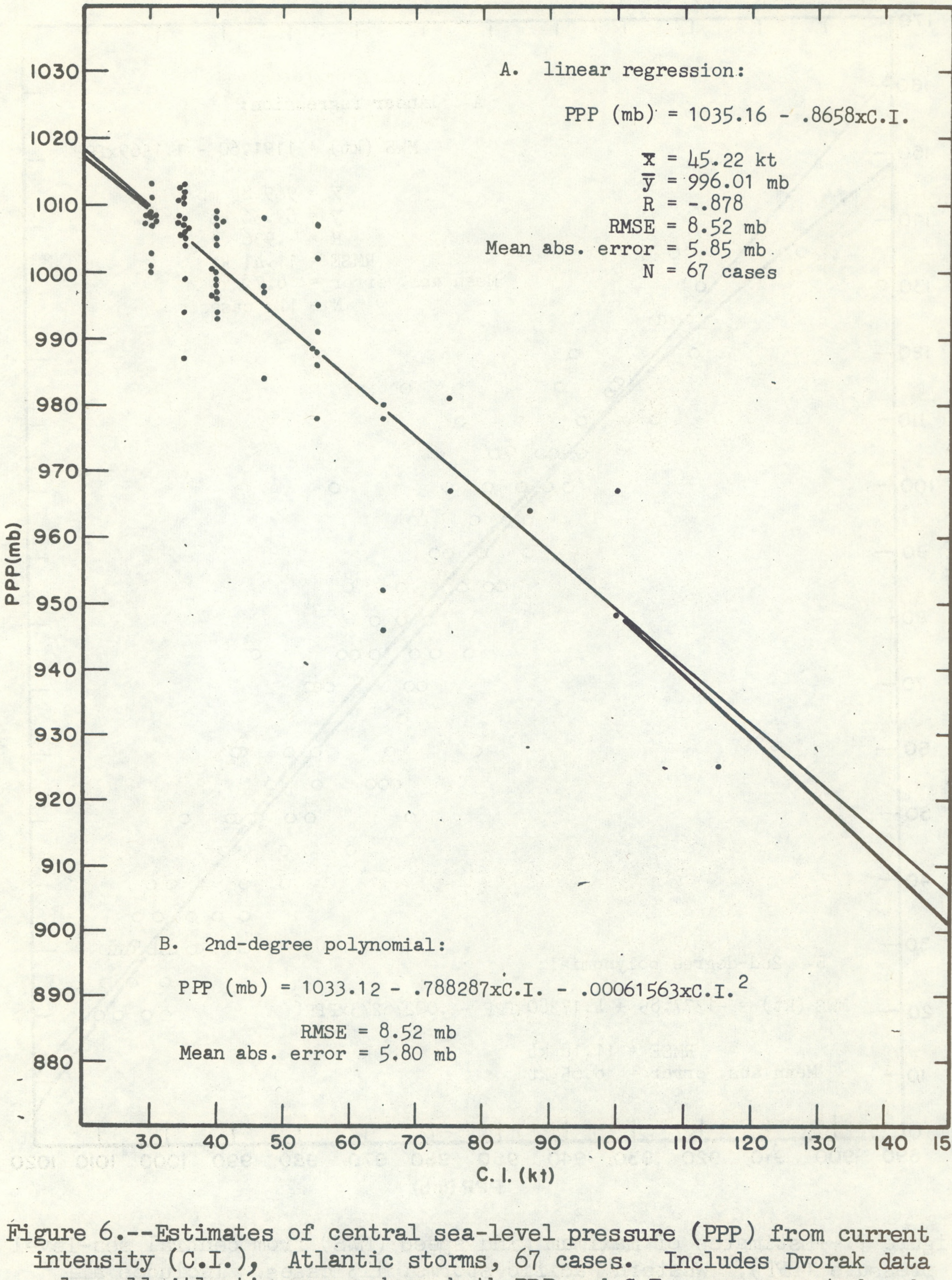

Figure 6.--Estimates of central sea-level pressure (PPP) from current intensity (C.I.), Atlantic storms, 67 cases. Includes Dvorak data only--all Atlantic cases where both PPP and C.I. were reported and storm center was not over land.

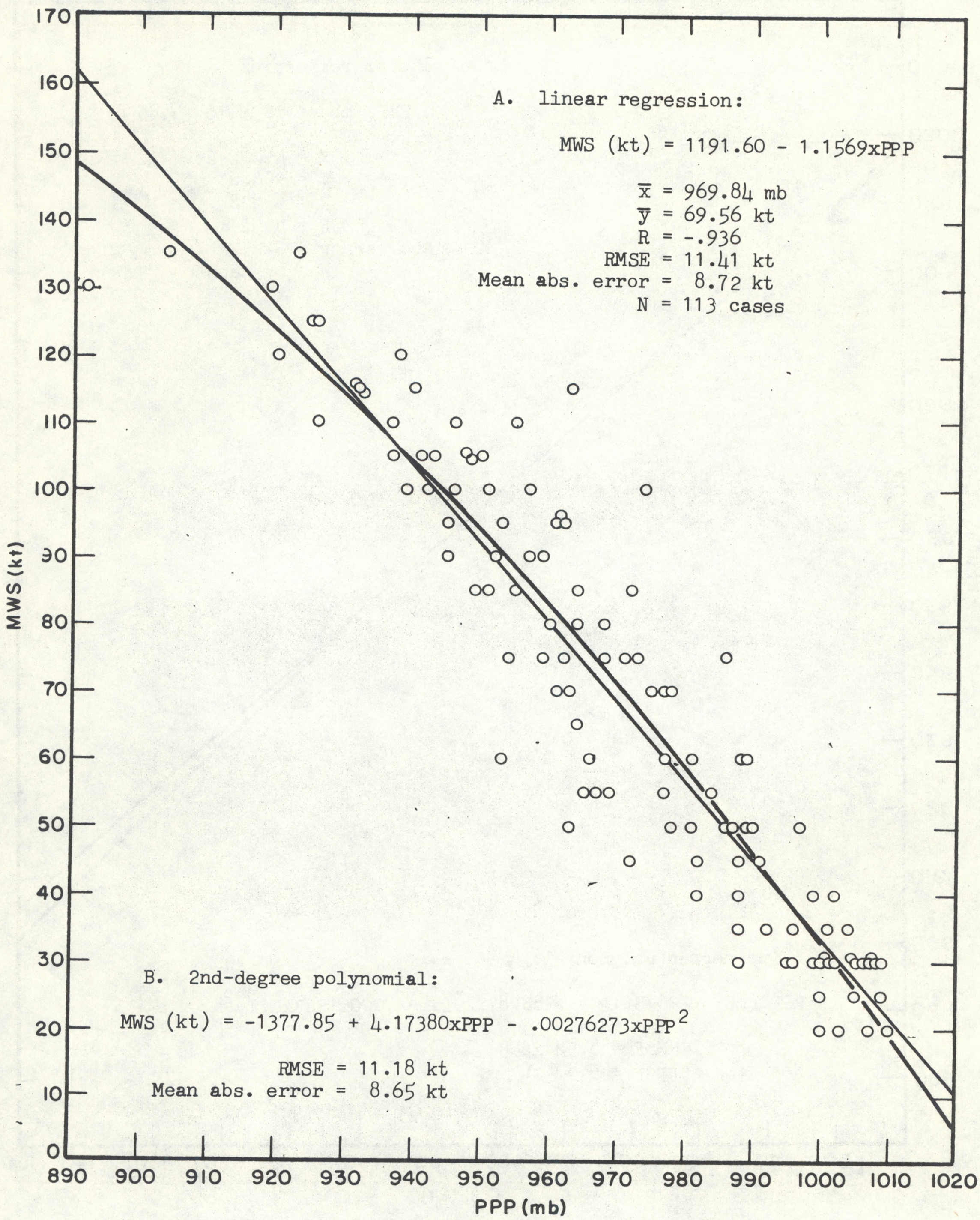

Figure 7.--Estimates of maximum wind speed (MWS) from central sea-level pressure (PPP), Western Pacific storms, 113 cases. Includes all Western Pacific cases where both PPP and MWS were reported and storm center was not over land.

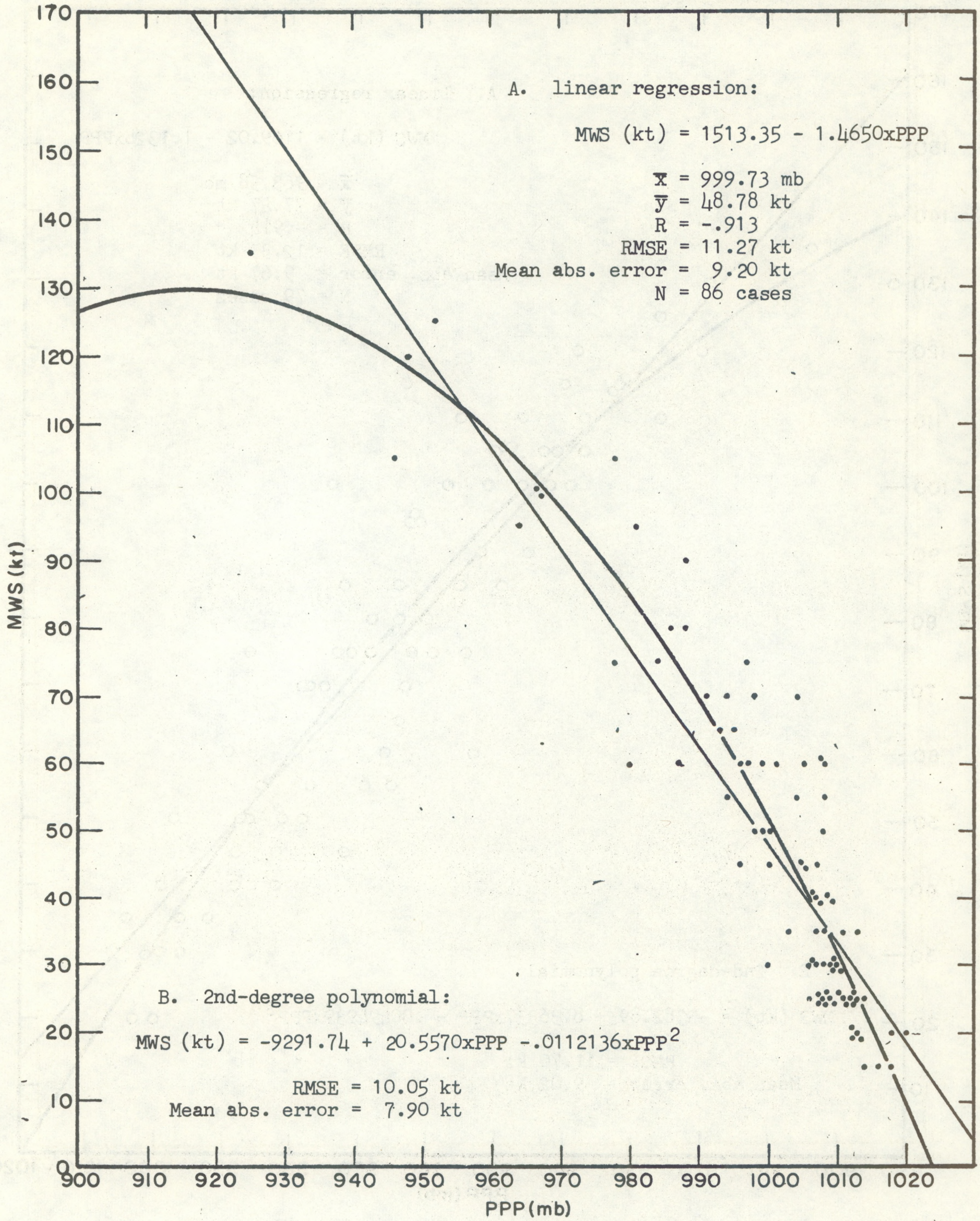

Figure 8.--Estimates of maximum wind speed (MWS) from central sea-level pressure (PPP), Atlantic storms, 86 cases. Includes all Atlantic cases where both PPP and MWS were reported and storm center was not over land.

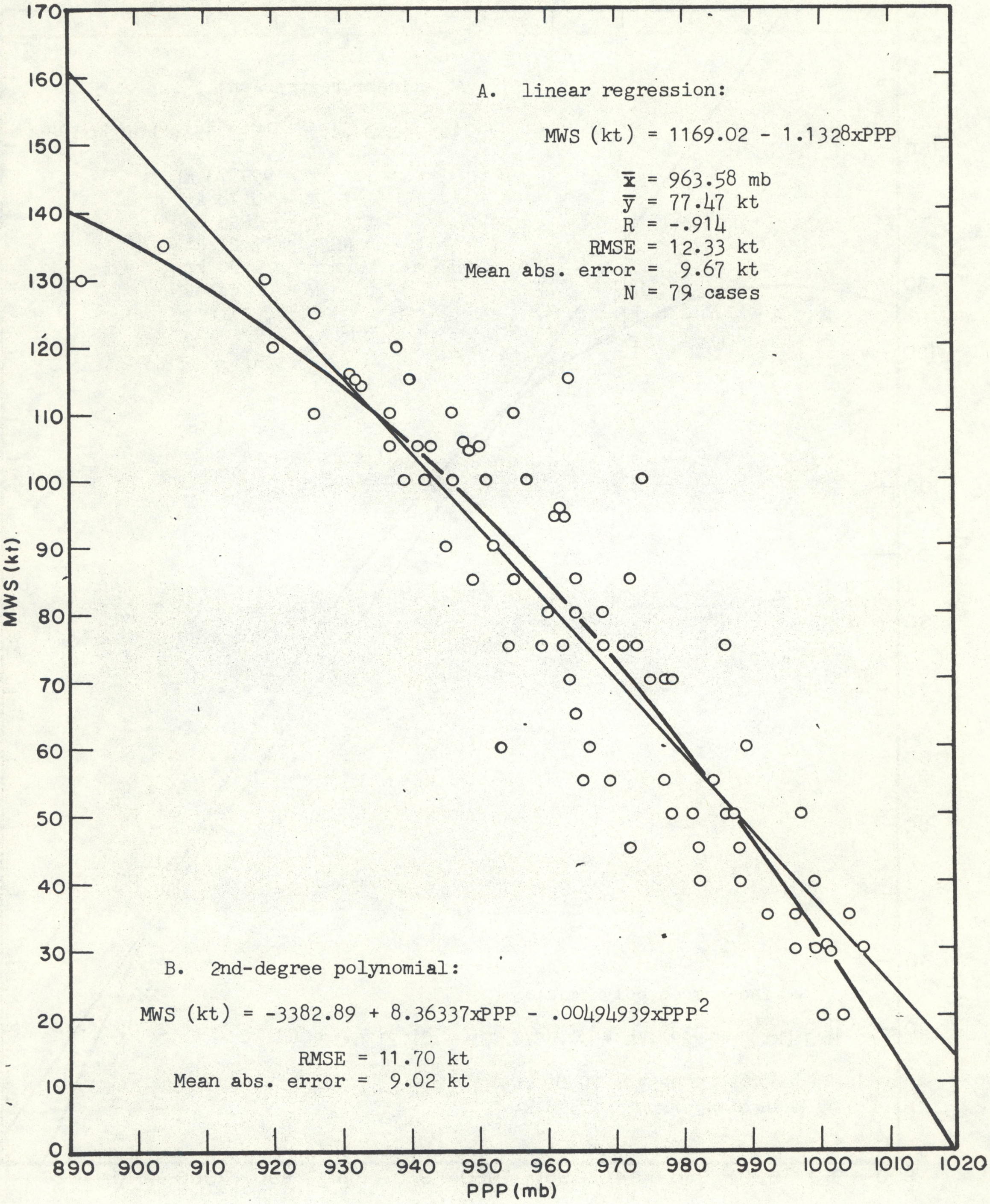

Figure 9.--Estimates of maximum wind speed (MWS) from central sea-level pressure (PPP), Western Pacific storms, 79 cases. Includes only those Western Pacific cases where PPP of confidence 1, 2, or 3 existed.

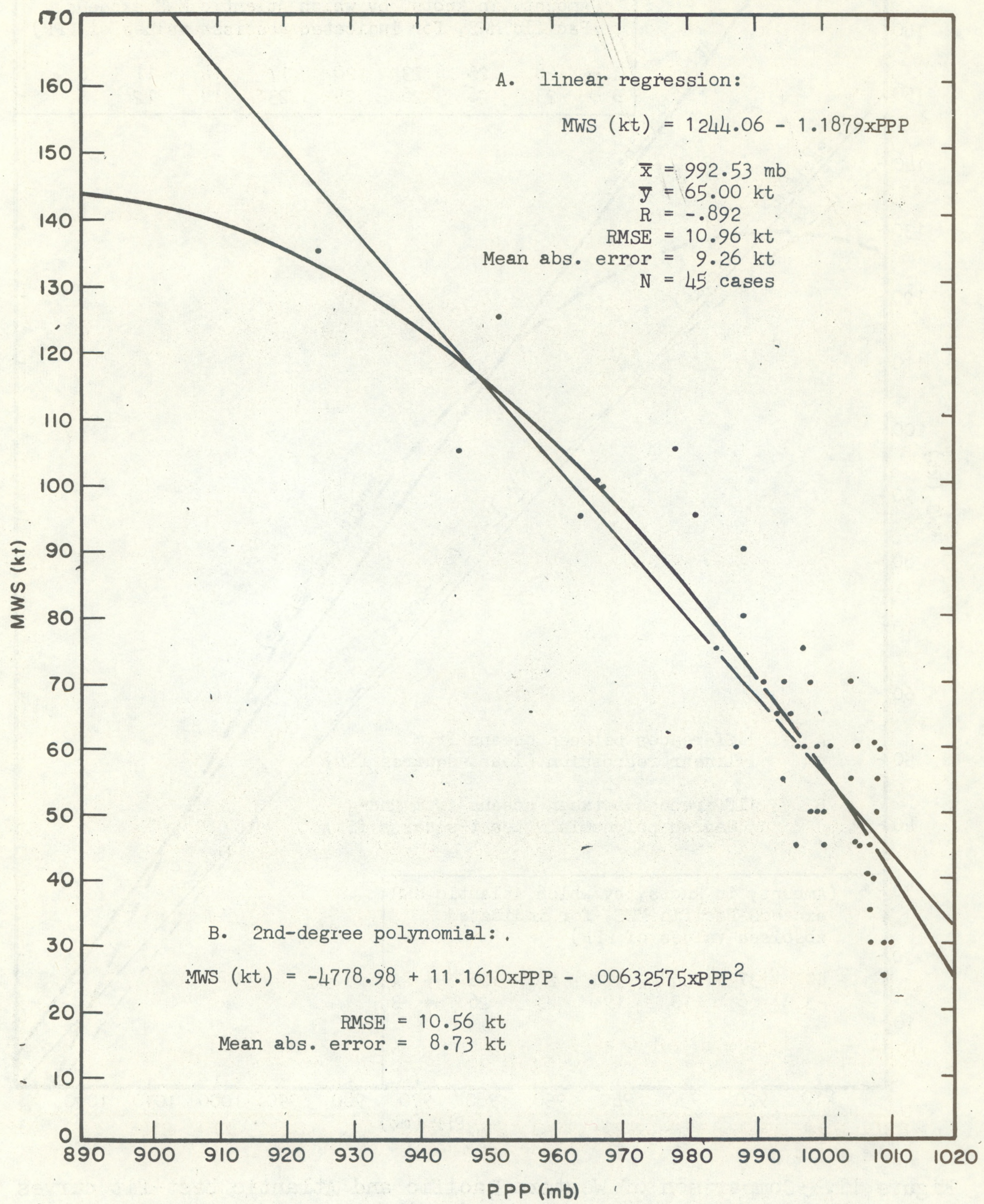

Figure 10.--Estimates of maximum wind speed (MWS) from central sea-level pressure (PPP), Atlántic storms, 45 cases. Includes only those Atlantic cases where PPP of confidence 1, 2, or 3 existed.

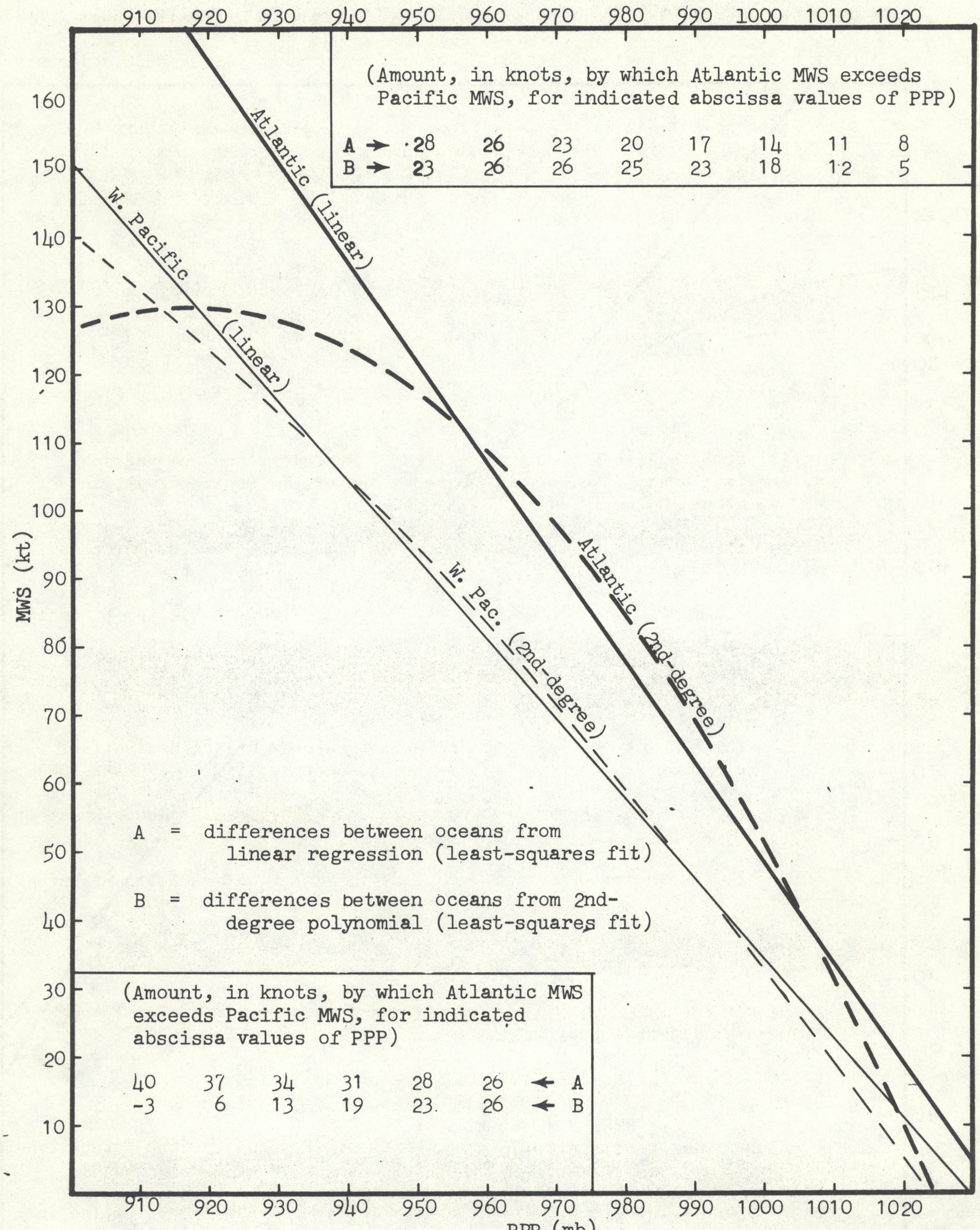

Figure 11.--Comparison of Western Pacific and Atlantic best-fit curves for estimating maximum wind speed (MWS) from central sea-level pressure (PPP). Derived from all cases where both PPP and MWS are reported and storm center was not over land.

(Continued from inside front cover)

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