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Relationships between CI Number and Minimum Sea Level Pressure/ Maximum Wind Speed of Tropical Cyclones*

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Abstract: The relationship between current intensity number (CI number) and minimum sea level pressure (MSLP) or maximum wind speed (MWS) of tropical cyclones was examined. The CI numbers examined were obtained through analyzing the GMS images with Dvorak's Enhanced Infrared (EIR) technique. The MSLP and MWS were obtained from the JMA best track. The number of analyzed cases was 855 from 50 typhoons that appeared during the period from 1981 to 1986.

The analyzed CI number showed a tendency of overestimation (underestimation) for intense (weak) cyclones when compared with MSLP using the empirical relationship between CI number and MSLP proposed by Dvorak in 1984 (Dvorak, 1984).

In this paper, we explore a more suitable relationship between CI number and MSLP or MWS through quadratic regression analyses and propose a new table of the relation between them. The new table can reduce the overestimation (underestimation) considerably.

1. Introduction

In the Dvorak method (Dvorak; 1975, 1984), CI (current intensity) numbers are firstly related to maximum wind speeds (MWS) of tropical cyclones. And the relationship between CI numbers and minimum sea level pressures (MSLP) is led from a statistical relationship between MWS and MSLP.

Some evaluational studies on the CI number were carried out by meteorologists in the United States. In the early days of cyclone intensity estimation through satellite images, Sheets and Grieman (1975) examined differences of the estimated results among the analysts and among the different satellites. They also evaluated CI numbers by comparison with MWS and MSLP. At that time, only visible (VIS) images from orbital satellites and earlier geostationary satellites were available. Shewchuck and Wier (1980) evaluated the CI numbers of the Northwestern Pacific cyclones which were obtained in operational work of the Joint Typhoon Warning Center (JTWC), Guam. These CI numbers were obtained by analyzing the VIS images from the Defense Meteorological Satellite Program (DMSP) satellite, and were compared with MWS of the JTWC best track. Gaby *et al.* (1980) evaluated the CI numbers of the North Atlantic cyclones which were provided by operational estimation in the Satellite Field Services Station (SFSS), Miami, from 1971 to 1978. Their CI numbers were also obtained from VIS images except for the cyclones of 1978, in which year SFSS used additionally the Enhanced Infrared (EIR) image technique (Dvorak, 1984). Their evaluation was made by comparison with MWS of the National Hurricane Center (NHC) best track.

The tables of the relation between CI number and MWS or MSLP proposed by Dvorak are shown in Table 1. He modified the table between CI number and MSLP for the Pacific cyclones in 1984. This modification was based

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on the recommendation by Shewchuk and Weir (1980), in whose evaluational study on the CI number of the Northwestern Pacific cyclones they recommended the use of the relationship between MWS and MSLP proposed by Atkinson and Holliday (1977) to convert CI number to MSLP. But up to today, there have been few evaluational studies in which CI numbers were evaluated by direct comparison with MSLP using Dvorak's 1984 table.

The Meteorological Satellite Center (MSC) obtains CI numbers using the EIR technique, which can produce smaller RMS errors than the VIS technique (Akashi *et al.*, 1988), and makes consistent analyses possible through day and night. But so far there have been few evaluations in which a sufficient quantity of CI numbers obtained by EIR technique were examined.

In this paper we attempt to evaluate CI numbers obtained in the MSC through direct comparison with MSLP or MWS of the JMA best track for the cyclones of the period when aircraft reconnaissance data were available, and to find a more suitable relationship between them.

Table 1. The table of the relation between CI number and MSLP and MWS proposed by Dvorak in 1975 and 1984.

CI num.	MWS (kt)	MSLP (hPa)		
		Atlantic 1975/1984	Northwestern Pacific 1975	Northwestern Pacific 1984
1.0	25	—	—	—
1.5	25	—	—	—
2.0	30	1009	1003	1000
2.5	35	1005	999	997
3.0	45	1000	994	991
3.5	55	994	988	984
4.0	65	987	981	976
4.5	77	979	973	966
5.0	90	970	964	954
5.5	102	960	954	941
6.0	115	948	942	921
6.5	127	935	929	914
7.0	140	921	915	898
7.5	155	906	900	879
8.0	170	890	884	858

2. Data used

The CI numbers used here were obtained from 50 typhoons whose MSLP reached to 950 hPa or less at their peak stage (at the time of the most developed stage) during the years from 1981 to 1986. The list of the 50 typhoons analyzed and their tracks are shown in Table 2 and Fig. 1, respectively. Four skilled analysts analyzed these typhoons by the EIR technique every 12 hours through their lifecycle (from the time of upgrading to TS (tropical storm) to the time of downgrading to TD (tropical depression) or extratropical cyclone). The analyses were made on an image processing display by man-machine interactive procedure, which is the same as the routine analyses in the MSC, under the condition that no other meteorological data (such as MSLP which were already available) should influence the analyzing

Table 2. List of analyzed typhoons.

1981	8101 (FREDA),	8120 (AGNES),	8122 (CLARA),	8124 (ELSIE),	8126 (GAY),
	8128 (KIT),	8129 (LEE)			
1982	8202 (NELSON),	8204 (PAT),	8209 (ANDY),	8210 (BESS),	8211 (CECIL)
	8213 (ELLIS),	8215 (GORDON),	8217 (IRVING),	8218 (JUDY),	8219 (KEN)
	8221 (MAC),	8222 (NANCY),	8223 (OWEN),	8224 (PAMELA)	
1983	8304 (WAYNE),	8305 (ABBY),	8309 (ELLEN),	8310 (FORREST),	8317 (MARGE)
	8319 (ORCHID)				
1984	8406 (DAINAH),	8407 (ED),	8411 (IKE),	8421 (THAD),	8422 (VANESSA)
	8424 (AGNES),	8425 (BILL),	8426 (CLARA),		
1985	8503 (GAY),	8511 (NELSON),	8522 (DOT),	8526 (HOPE)	
1986	8603 (LOLA),	8607 (PEGGY),	8613 (VERA),	8616 (ABBY),	8617 (BEN)
	8621 (CARMEN),	8625 (FORREST),	8626 (JOE),	8628 (MARGE)	

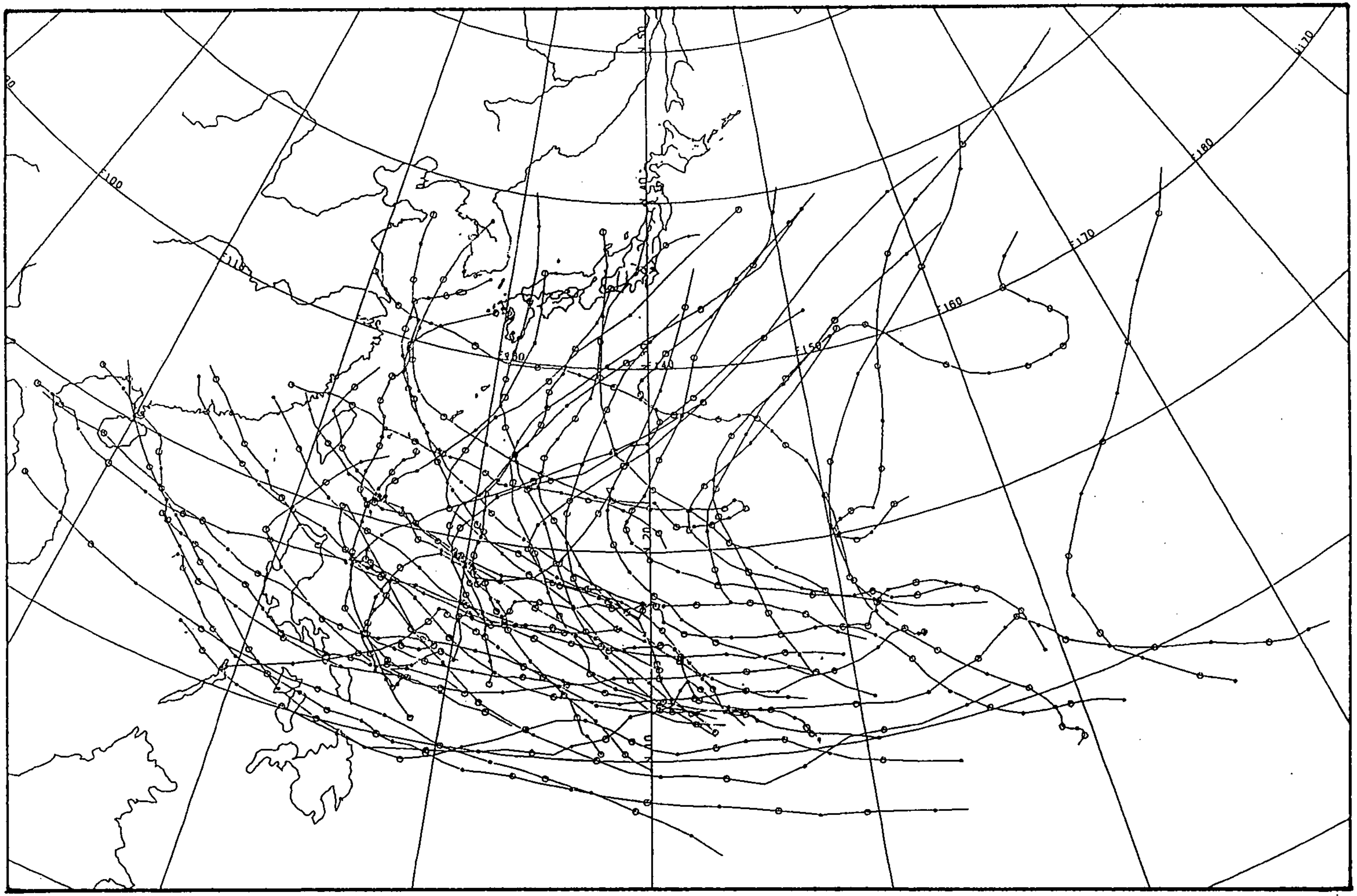

Fig. 1. Tracks of the analyzed typhoons.
White and black circles depict locations at 00 and 12 UTC respectively.

process. 855 CI numbers were obtained through these analyses. The CI numbers of cyclones passing the islands were decided using Koba's criteria (Koba *et al.*, 1989; see the second paper in this issue). MSLP and MWS were obtained from the JMA best track.

3. Comparison with Dvorak's 1984 table

In this section we compare the CI numbers analyzed with MSLP through Dvorak's 1984 table (Dvorak, 1984; shown in Table 1). Prior to the comparison, MSLP were converted into CI numbers through Dvorak's table. Hereafter, we designate the CI numbers obtained by analyzing satellite images as CI_s, and those converted from MSLP as CI_p. We compare CI_s with CI_p instead of MSLP.

To find the characteristics of CI numbers in different lifestages of cyclones, three data sets were provided. The first data set includes all 855 cases (hereafter called "all cases"), the second set consists of the data of cyclones in developing stage (444 cases; to be called "developing stage cases"), the third set consists of cyclones in weakening stage (411 cases; to be called "weakening stage cases"). The term "developing" ("weakening") describes a cyclone whose CI number is equal (not equal) to the T number. Comparisons were made among the three sets.

Results are shown as mean differences between them (CI_s minus CI_p) in terms of CI_s from 1.5 to 7.5 (no case of CI_s equal to 1.0 and 8.0) in Fig. 2, where heavy solid line, light solid line and broken line depict the mean differences of the all cases, the developing stage cases and the weakening stage cases respectively. The vertical bars attached on the heavy line indicate the standard deviation. Although the average value of the difference is the very small value of 0.1 when it was taken over all data (in all cases), evident inclinations are observed in the three plots: that is, CI_s is apt to overestimate the intensity for an intense cyclone and underestimate for a weak cyclone. When CI_s is 7.5, the mean difference reaches to 0.79, i.e. CI_s overestimates the intensity by 0.79 compared with CI_p. The standard deviation exceeds 0.5 for all CI_s levels (except for CI_s of 7.5) with an average of 0.74.

4. Regression analyses and a new table for MSLP

As mentioned above, the CI number obtained in the MSC tends to underestimate the intensity of a weak cyclone and overestimate that of an intense one, as we compared with MSLP through Dvorak's 1984 table. Therefore we tried to find a more suitable relationship between the CI number obtained in the

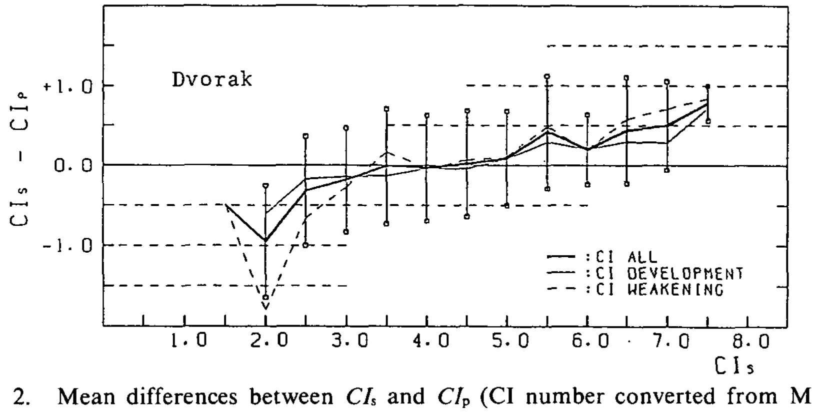

Fig. 2. Mean differences between CI_s and CI_p (CI number converted from MSLP using Dvorak's 1984 table).

The heavy solid line, the light solid line and the broken line show the differences for the all cases, the developing stage cases and the weakening stage cases respectively. Vertical bars attached on heavy solid line are the standard deviation.

MSC and MSLP by regression analysis.

(1) *Regression analysis*

Figure 3 (a), (b) and (c) are scatter diagrams of CI_s versus MSLP. They depict the scatters of all cases, developing stage cases and weakening stage cases, respectively. These diagrams suggest that a quadratic relation is more reasonable than a linear relation. Therefore we made a

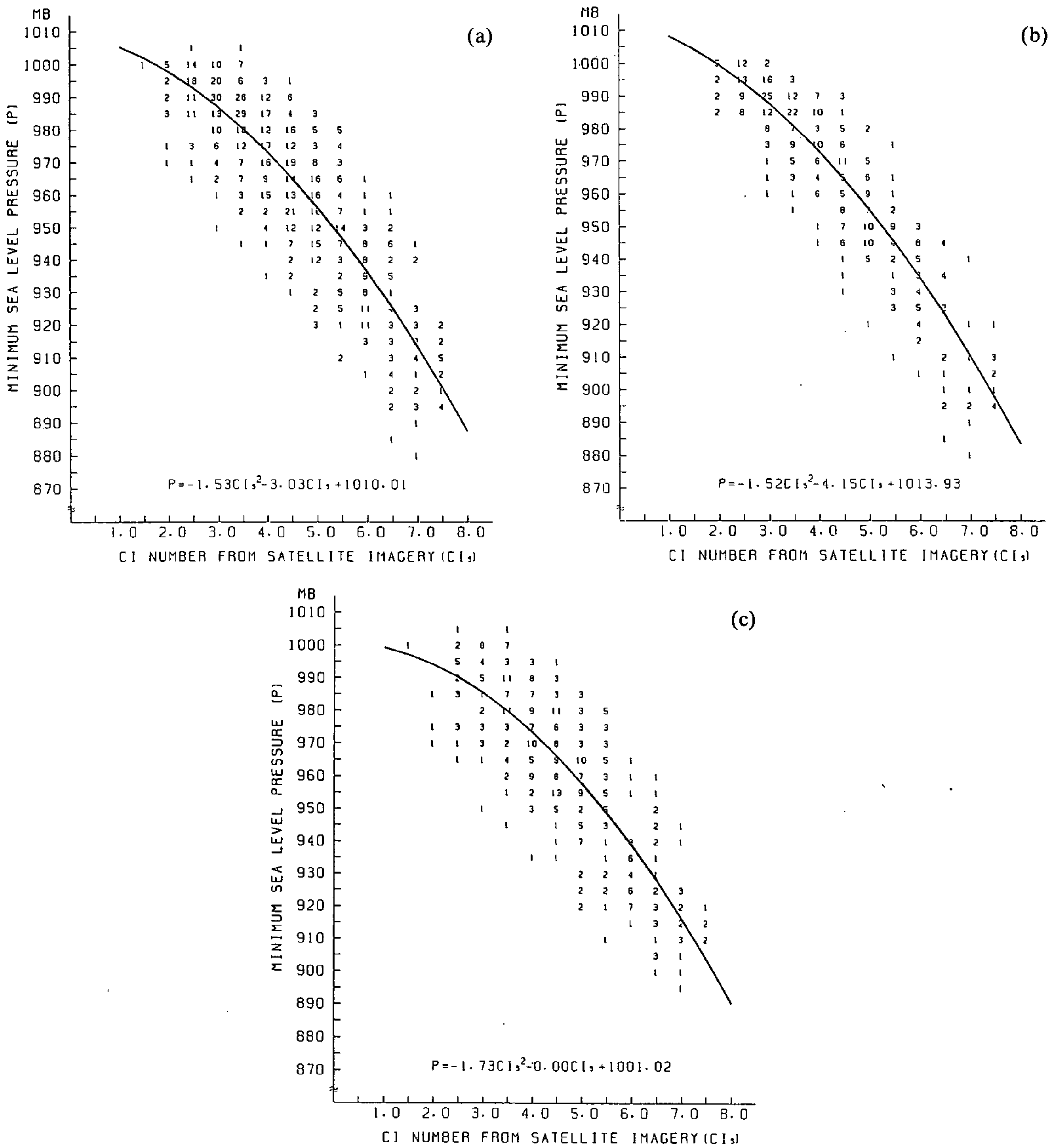

Fig. 3. Scatter diagrams and quadratic regression curves of CI_s versus MSLP.
The letters a, b and c denote the data sets of the all cases, the developing stage cases and the weakening stage cases respectively.

quadratic regression analysis from CI_s to MSLP. The equations obtained are

for all cases,

$$P=-1.53\ CI_s{}^2-3.03\ CI_s+1010.01 \qquad (1)$$

for developing stage cases,

$$P=-1.52\ CI_s{}^2-4.15\ CI_s+1013.93 \qquad (2)$$

and for weakening stage cases,

$$P=-1.73\ CI_s{}^2+1001.02 \qquad (3)$$

where P is MSLP. The regression curves are also illustrated in the figure.

Table 3 is the table of the relation between the CI number and MSLP calculated using the above equations. The three columns of MSLPs denoted by A, D and W are the results calculated using the equations (1), (2) and (3) respectively. From this table, we can find that

i) MSLP in the column D are ranked higher than those in the column W for CI number 3.5 or less and lower than those of W for CI number 4.5 or more,

ii) the difference of MSLP between D and W reaches 0.5 when the difference is translated into a CI number (note that the value of 0.5 is a unit of CI number definition) at CI number 2.0, and reaches about 0.25 for CI number 6.5 or more, and

iii) MSLP in A fall between the values of D and W. They are closer to those of D for CI number 3.5 or less and closer to those of W for CI number 6.0 or more. When compared with Table 1 (for the Pacific cyclones), MSLP in A are close to those of the 1984 table for CI number 4.5 or less but they are close to those of the 1975 table at CI number 5.0 or more.

Table 3. Calculated table showing the relation between CI number and MSLP. The columns A, D and W are calculated using the regression equation of (1), (2) and (3) respectively.

CI num.	MSLP (hPa)		
	A	D	W
1.0	1005	1008	999
1.5	1002	1004	997
2.0	998	1000	994
2.5	993	994	990
3.0	987	988	985
3.5	981	981	980
4.0	973	973	973
4.5	965	964	966
5.0	956	955	958
5.5	947	945	949
6.0	937	934	939
6.5	926	923	928
7.0	914	910	916
7.5	901	897	904
8.0	888	883	890

(2) *Applicability of the tables*

In this subsection we discuss the merits and demerits of the three tables obtained in the preceding subsection. MSLP in the three data sets were converted to CI numbers (hereafter CI_p) using three tables (A, D and W). Consequently we got 9 sets of CI_p. Examination was done by comparing the coefficients of linear regression analyses between CI_s and CI_p (slopes and intercepts). The correlation coefficients between CI_s and CI_p and the mean difference (CI_s–CI_p) and its standard deviation for the 9 sets of CI_p are also examined.

i) coefficients of linear regression equations

Table 4 shows the slopes and intercepts of linear regression equations for 9 sets of CI_p. Each table exhibits the best performance when it is applied to the data of the corresponding data set, i.e., the slope takes the closest value to 1.0 and the intercept to zero (for example, when the table D is applied to the developing stage cases). Intercepts in the table W are slightly larger than those of other tables.

ii) correlation coefficients

The correlation coefficients between CI_s and CI_p are shown in Table 5. No significant differences among the three tables are seen in the three data sets and all tables show the highest correlation when applied to the developing stage cases.

iii) mean difference and standard deviation

The mean differences and standard deviations are also shown in Table 5. The signs of

Table 4. Slopes and intersepts of linear regression equations for CI_s and CI_p.

		CATEGORIES		
		all cases (n=855)	dev. stage. (n=444)	weak. stage (n=411)
SLOPE	A	0.999	1.051	0.939
	D	0.942	0.990	0.888
	W	1.110	1.163	1.023
INTERCEPT	A	−0.058	−0.249	0.184
	D	−0.174	0.002	0.391
	W	−0.546	−0.793	−0.218

Table 5. Correlation coefficients between CI_s and CI_p, mean differences (CI_s minus CI_p) and standard deviation.

		CATEGORIES		
		all cases (n=855)	dev. stage. (n=444)	weak. stage (n=411)
cor. coef.	A	0.852	0.901	0.787
	D	0.853	0.902	0.788
	W	0.849	0.899	0.780
mean dif.	A	0.060	0.003	0.092
	D	0.077	0.038	0.120
	W	0.103	0.098	0.109
S.D.	A	0.778	0.666	0.883
	D	0.737	0.623	0.841
	W	0.879	0.774	0.981

the differences are all positive, which show that CI_s is apt to overestimate the intensity. However the differences are less than 0.12 for all 9 sets. Table A makes smaller mean differences than others for all the data sets. All tables produce the smallest mean difference when applied to the developing stage cases. The standard deviation is smallest for the developing stage cases and largest for the weakening stage cases.

Summing up, the CI number gives a good estimation of the intensity of the cyclone in its developing stage but gives a relatively poor estimation in the weakening stage. This is attributable mainly to the unsuitability of the method for weakening cyclones which are transforming into extratropical cyclones. (As is shown in Fig. 2, large minus values of the mean difference for CI numbers 2.5 and 2.0 in the weakening stage (dotted curve) correspond to the transformation into an extratropical cyclone.)

Though three tables were obtained, we can consult only one for operational use. As a matter of fact, we cannot know, by watching, whether the intensity of a given cyclone has come to its peak or not. In other words, we cannot definitely know if it is in the developing or the weakening stage. Therefore for actual use, we had to make, so to speak, a compromising table which is applicable to all the life stages of a cyclone. We chose Table A for actual use.

The scatter diagram of CI_s versus CI_p converted using table A for 855 cases is shown in Fig. 4. The linear regression line (solid) and lines of deviation of 1.0 (dotted) are also shown. 89.2% of the data are included within the deviation of 1.0 and 65.5% within the deviation of 0.5. Figure 5 shows mean difference (solid) and its standard deviation (broken) against CI_s.

The mean differences lie within the range of ±0.3 except for CI_s of 2.0. The standard deviations range from 0.35 to 0.95 with an average of 0.78 which is equivalent to 7 to 19 hPa in MSLP.

5. Relationship between CI_s and MWS

The same examination as on the MSLP for the same typhoons was made on the MWS which were determined by the JMA. In the JMA, 10-minute average wind speed maximum is adopted as MWS. Here an examination was made only for the data set of all cases. Figure 6 is a scatter diagram of CI_s versus MWS with a quadratic regression curve superim posed. The quadratic regression equation is given as

$$V = 0.09\, CI_s{}^2 + 13.49\, CI_s + 8.38 \qquad (4)$$

where V is MWS. As shown in the quation, the coefficient of the term $CI_s{}^2$ is so small that the relationship between CI_s and MWS can be regarded as linear rather than quadratic. Table 6 is the table of the relation between CI_s and MWS derived from the equation.

Figure 7 shows a scatter and a linear regression line (solid) of CI_s and CI_w (CI number converted from MWS using Table 6). 81.2% of the data fall within the deviation range of ±1.0, and 70.1% within ±0.5. Mean differences and standard deviations for each CI_s are shown in Fig. 8. The former are less than ±0.2 except for CI_s of 2.0 (mean difference of −0.59) and 7.5 (0.27), and the latter range between 0.50 and 0.82 with an average of 0.75, which is equivalent to 7 to 12 kts in MWS.

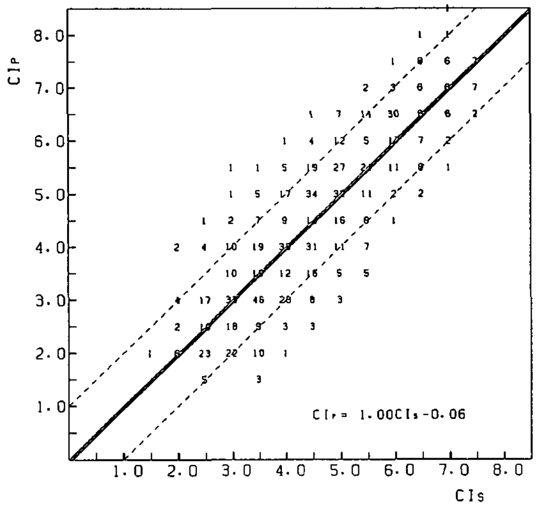

Fig. 4. Scatter diagram and linear regression line of CI_s versus CI_p for the data set of the all cases.
CI_p are converted from MSLP using Table 3.

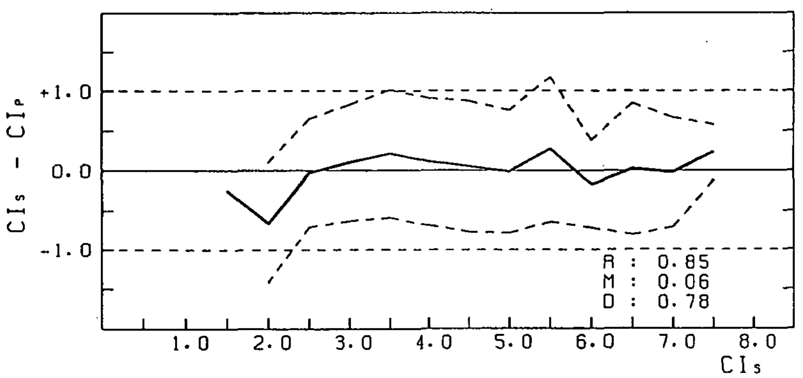

Fig. 5. Mean differences between CI_s and CI_p (solid) and their standard deviations (broken) against CI_s for the data set of the all cases.
The letters R, M and D denote the correlation coefficient, the average of mean differences and standard deviation for all 855 data.

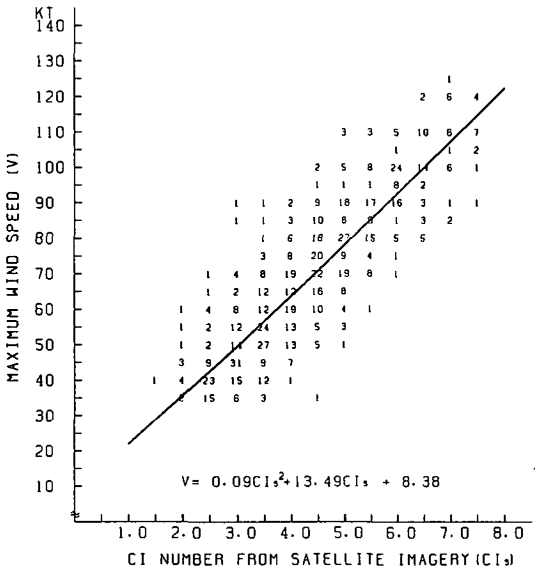

Fig. 6. Same as Fig. 3 except for CI_s versus MWS for the data set of the all cases.

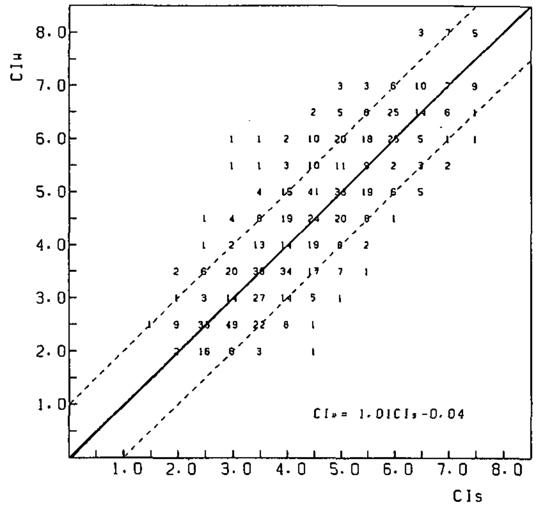

Fig. 7. Same as Fig. 4 except for CI_s versus CI_w. CI_w are converted from MWS using Table 6.

Table 6. The table showing the relation between CI number and MWS calculated using regression equation (4).

CI num.	MWS(kt)
1.0	22
1.5	29
2.0	36
2.5	43
3.0	50
3.5	57
4.0	64
4.5	71
5.0	78
5.5	85
6.0	93
6.5	100
7.0	107
7.5	115
8.0	122

6. Conclusion and summary

Relationship between the CI number obtained in the MSC using Dvorak's EIR technique and MSLP or MWS determined by the JMA was examined. It was found that Dvorak's 1984 table (empirical relationship between CI number and MSLP for the Northwestern Pacific cyclones) overestimates intensity for intense cyclones and underestimates it for weak cyclones.

To find a more suitable relationship between CI number and MSLP, direct regression analyses were done using 855 cases in 50 typhoons. The regression equation was given as

$$P=-1.53\,CI_s{}^2-3.03CI_s+1010.01$$

where P is MSLP and CI_s is the satellite-derived CI number.

A new table of the relation between CI number and MSLP was made using the above equation. MSLP of the 855 cases were converted to CI numbers by using the new table and were compared with CI_s values. The correlation coefficient between them was 0.85, and mean differences for each CI_s were within ± 0.3 (average of 0.06) with standard deviations ranging from 0.35 to 0.95 (average of 0.78). This table can reduce the over- and underestimates of intensity due to Dvorak's 1984 table.

The regression equation was also made for MWS, which is given as

$$V=0.09\,CI_s{}^2+13.49\,CI_s+8.38$$

where V is MWS.

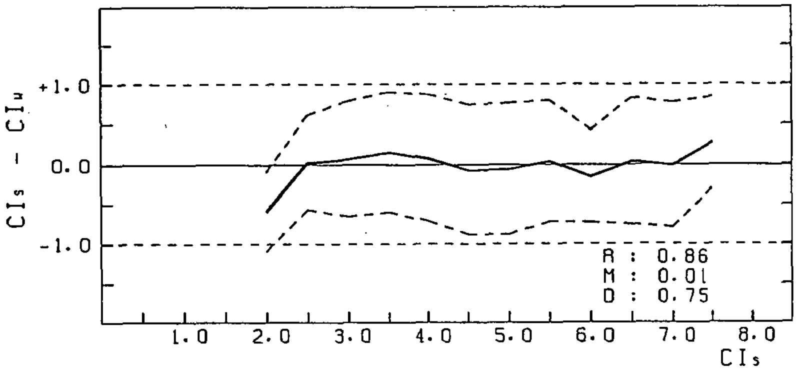

Fig. 8. Same as Fig. 5 except for CI_s versus CI_w.

The new table of the relation between CI number and MSLP or MWS are summarized in Table 7. The table has been adopted by the JMA for routine analysis of tropical cyclones.

Table 7. The table showing the relation between CI number and MSLP and MWS as a summary of Table 3 and Table 6.

CI num.	MSLP(hPa)	MWS(kt)
1.0	1005	22
1.5	1002	29
2.0	998	36
2.5	993	43
3.0	987	50
3.5	981	57
4.0	973	64
4.5	965	71
5.0	956	78
5.5	947	85
6.0	937	93
6.5	926	100
7.0	914	107
7.5	901	115
8.0	888	122

References

Akashi, S., H. Koba, T. Harada and T. Ichinari (1988): Comparison between visible and enhanced infrared analyses by Dvorak's method for tropical cyclone intensity estimation. J. Meteorol. Res. (in Japanese), **40**, 169–174.

Atkinson, G. D. and C. R. Holliday (1977): Tropical cyclone minimum sea level pressure/maximum sustained wind relationship for the western North Pacific. Mon. Weather Rev., **105**, 421–427.

Dvorak, V. F. (1975): Tropical cyclone intensity analysis and forecasting from satellite imagery. Mon. Weather Rev., **103**, 420–430.

Dvorak, V. F. (1984): Tropical cyclone intensity analysis using satellite data. NOAA Tech. Rep., NESDIS **11**, 47pp.

Gaby, D. C., J. B. Lushine, B. M. Mayfield, S. C. Pearce and F. E. Torres (1980): Satellite classification of Atlantic tropical and subtropical cyclones: A review of eight years of classification at Miami. Mon. Weather Rev., **108**, 587–595.

Koba, H., S. Osano, T. Hagiwara, S. Akashi and T. Kikuchi (1989): An evaluation of the rule of CI number determination in Dvorak technique for tropical cyclone crossing the Philippine Islands. J. Meteorol. Res. (in Japanese), **41**, 157–162.

Sheets, R. C. and P. Grieman (1975): An evaluation of the accuracy of tropical cyclone intensities and locations determined from satellite pictures. NOAA Tech. Memo., ERL WMPO-20, 36pp.

Shewchuk, J. D. and R. C. Weir (1980): An evaluation of the Dvorak technique for estimating tropical cyclone intensities from satellite imagery. NOCC/JTWC Tech. Note 80–2, 25pp.

台風のCI数と中心気圧／最大風速の関係

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気象衛星センターで解析した台風のCI数と中心気圧・最大風速の関係を評価するため，1981～1986年の50個の台風を赤外強調画像法（EIR法）で解析し，855個のCI数を得た．得られたCI数と，気象庁のベストトラックの中心気圧をDvorak（1984）の対応表によってCI数に変換した値を比較した結果，衛星から得たCI数は弱い台風に対しては強度を弱めに，強い台風に対しては強度を強めに表現することが分かった．

より適切な対応表を求めるために，CI数を説明変数，中心気圧を目的変数として2次回帰分析を行った．新しい対応表によって中心気圧をCI数に変換した値と，衛星から得たCI数の差の平均は，台風のどの強度でもほぼ±0.3（CI数）以内におさまり，系統的な過少・過大見積もりは改善された．この対応表によるCI数と中心気圧の相関係数は0.85，差の標準偏差は0.78（CI数）であった．

最大風速についても同様な解析を行い新しい対応表を求めた．これらの対応表は現在気象衛星センター及び気象庁の現業業務で使用されている．

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