The Relationship between Sea Surface Temperature and Typhoon Intensity over the Western North Pacific Ocean

Ke-Mao Wu
Department of Tourism and Leisure,
Diwan College of Management, Tainan 721, ROC

Abstract

The purpose of this study is to derive an empirical equation to relate the sea surface temperature (SST) and typhoon intensity over the western North Pacific Ocean. A linear empirical equation was developed by using 33 years (1965-1997) of monthly sea surface temperature data and typhoon intensities. Each value of typhoon intensity was accompanied by a SST. The SSTs were stratified into 11 evenly spaced groups by 1℃ intervals from 20.5℃ to 31.5℃. Maximum intensities were found after search of the largest value of intensity in each SST group. Linear regression was used to find a curve to represent the maximum intensity. The derived linear function, called maximum potential intensity (MPI), represents most groups of maximum intensities very well. The results revealed that this derived MPI function provided an effective upper bound on the intensification and development of typhoons.

1. Introduction

The relationship between sea surface temperature (SST) and the intensity of tropical cyclones has been observed and studied in recent years. The SST is a significant factor which influences the formation and intensification of tropical cyclones (Palmén, 1948: Miller, 1958). Although SST along is not a sufficient predictor of tropical cyclone intensity (Evans, 1993), Miller (1958) and Merrill (1987) concluded that SST could be a capping function and provide an upper bound on the maximum potential intensity of tropical cyclones.

The empirical relationship between climatological SST and the maximum intensity of tropical cyclones for North Atlantic and Eastern North Pacific Ocean have been developed by DeMaria and Kaplan (1994) and Whitney and Hobgood (1997) respectively. The purpose of this study is to establish the similar relationship for Western North Pacific Ocean. Once the empirical maximum potential intensity (MPI) function is derived, it can be used to compare with the actual typhoon intensities to investigate how close the typhoon intensity can reach their MPI.

2. Data and Methodology

The purpose of this study is to establish an empirical relationship between climatological sea surface temperature (SST) and maximum potential intensity for Western North Pacific typhoons. The establishment of this relationship is hoped to be useful in further study of predicting intensity change in the Western North Pacific areas.

2.1 Western North Pacific Best Track Data

The Western North Pacific typhoons data was obtained from the Annual Tropical Cyclone Report printed by the staff of the Joint Typhoon Warning Center (JTWC). The best track file includes the position (latitude and longitude), intensities and date at 6-hour intervals (00Z, 06Z, 12Z, 18Z) of all Western North Pacific typhoons. 33-year period (1965-1997) of samples was adopted in this study.

The maximum 1-minute sustained surface wind was used to represent the intensity of typhoon. Sea surface pressures were not adopted in this study due to surface pressure data were not reported as often as the surface wind. The sustained surface wind would not be used directly to relate the SST in this study. In the study of DeMaria and Kaplan (1994), the translational speed of tropical cyclones should be subtracted from the sustained wind speed to represent the relative wind speed of tropical cyclones. The reason is that some fast moving tropical cyclones with abnormally high wind speeds can not reveal the real maximum wind speed. To avoid such situation occur, the translational speed of each typhoons at each position must be calculated. To obtain the translational speed, calculate the distance between two positions from the reports of typhoon record, then divided by the observational time interval (6 hour usually).

In some few cases, the negative wind speeds were found after the translational speeds were subtracted from the sustained wind. This indicates that the wind speed was slower than the moving velocity of typhoon. Those cases were removed from our study.

2.2 Climatological Sea Surface Temperature Data

The climatological sea surface temperature (SST) data used in this study were obtained from Columbia University. Two sets of SST data were adopted in this study. The first one is from the Comprehensive Ocean-Atmosphere Data Set (COADS) which used 2-degree latitude · 2-degree longitude boxes for each month of the period from 1854 - 1992. The 27-year (1965 - 1991) samples were used in this study to relate the SSTs and typhoon Intensities, then derive an empirical function.

The second set is weekly SST by 1-degree latitude and longitude grid from Integrated Global Ocean Service System (IGOSS). The SST data were derived from in situ (ship and buoy) and satellite observations by blended analysis (Reynolds, 1988) and improved by using sea ice data to simulate SSTs in ice-covered regions (Reynolds and Marsico, 1993). Reynolds and Smith (1994) used optimum interpolation (OI) to analyze in situ and corrected satellite data weekly and daily for keeping the bias correction and improving the spatial and temporal resolution of the blend in their study. These SST data were used from 1992 - 1997 for testing the derived empirical function.

3. ANALYSIS AND RESULTS

3.1 Climatological SST versus Typhoon Intensity

In this section, the relationship between the maximum potential intensity and SST is derived for 27 years (1965-1991) of data. This result is also tested for the 6 years (1992-1997) data, which represent an independent sample, to examine whether this empirical equation can provide an upper bound for the typhoon intensity in the western North Pacific Ocean.

3.1.1. Empirical equation for SST and Typhoon Intensity

To present the initial relationship between the climatological SST and typhoon intensity in western North Pacific areas, Fig. 1 shows a scatter diagram that plots all 12089 cases of intensities associated with SSTs. The linear relationship between these two variables is not very significant, but the SSTs do have the pattern of a capping function for the maximum intensities.

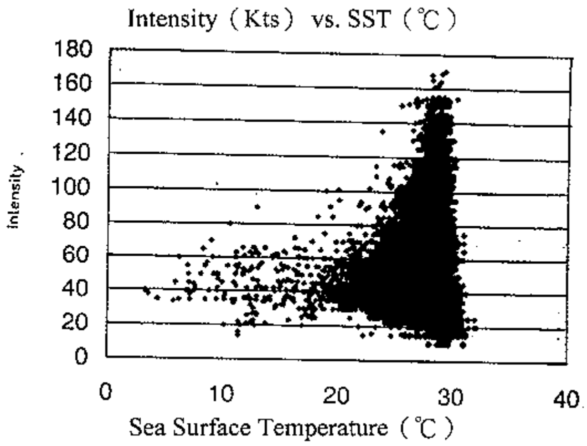

Figure .1: Scatter diagram indicates the typhoon intensities and SSTs of all 12089 observations in the 27-year sample (1965 - 1991).

The following step was to stratify the SST group from 20.5°C to 31.5°C into 11 evenly spaced groups by 1℃ interval. Maximum intensities were found after a search of the largest value of wind speed in each SST group. Table 1 shows the properties of the SST groups and associated maximum intensities. The SST cases below 20.5°C were not considered due to the fact that each group contains only 10 to 20 observations that were much fewer than the higher SST groups. The 21° - 25°C groups contain 4.92% of the cases, and the 26° - 31°C groups contain 95.08% of the cases.

The maximum typhoon intensity and its 99th, 95th, 90th, and 50th intensity percentiles for each group were determined and presented in Table 2. The percentiles indicate the percentage of cases in each group under the certain value of intensity. For example, the 50th percentile for the 23°C SST group reveals that 50% of the cases in this group exceeded the standard of tropical storm intensity (17 m s^{-1}). The 95th percentile for the 31°C SST group indicates that only 5% of the cases reached the intensity of typhoon (33 m s^{-1}).

SST Mid-point (°C)	No. of Obser-vations	Avg. SST (°C)	Avg. Intensity (m/s)	Max. Intensity (m/s)
21.0	44	20.98	22.894	30.41
22.0	62	22.00	25.169	38.60
23.0	105	23.08	25.281	55.52
24.0	140	24.01	28.323	53.39
25.0	230	25.06	28.256	63.49
26.0	456	26.07	30.339	66.84
27.0	1215	27.06	32.262	71.85
28.0	3254	28.06	31.440	81.53
29.0	4864	28.98	24.835	80.00
30.0	1303	29.78	21.185	72.26
31.0	120	30.92	15.259	36.07

Table 1: SST group properties

SST Group (°C)	99% (m/s)	95% (m/s)	90% (m/s)	50% (m/s)
21.0	29.41	27.86	25.31	12.56
22.0	38.00	37.10	32.99	15.65
23.0	54.15	37.03	33.85	17.27
24.0	48.29	30.44	25.85	12.59
25.0	48.19	37.99	28.30	12.49
26.0	51.54	41.34	37.26	18.39
27.0	63.62	53.80	48.70	23.75
28.0	68.78	58.58	53.48	22.88
29.0	64.70	51.95	41.75	13.15
30.0	67.08	49.31	38.56	12.06
31.0	35.56	33.52	28.42	10.57

Table 2: Intensity Percentiles

Figure 2 shows the maximum and percentile intensities associated with SSTs. The curve for the 50th percentile dose not change significantly with SST. This is similar to the results found by DeMaria and Kaplan (1994) for the Atlantic and Whitney and Hobgood (1997) for the eastern North Pacific. The other percentiles and maximum intensity curve suggest a linear relationship between SST and intensity by the range from 21°C to 29°C. The pronounced decrease of intensity in the warmest SST range (30°C and 31°C) is interesting.

The possible explanation is that the higher SST (30°C - 31°C) regions are usually concentrated in the area ranging from equator to 20°N, and from 150°E to 170°E. However, typhoons usually originate in this area and move westward or northwestward, but the development and intensification of typhoons occur beyond this area and most typhoons reach their maximum intensity west of 150°E. So the highest SSTs are not the locations where the strongest wind speeds are observed.

The maximum intensity data in Table 1 were used to derive an empirical function for the relationship of maximum intensity and SST in the western North Pacific Ocean. Those data points were from 7 intense typhoons shown in Table 3. To smooth the maximum intensity curve in Figure 3, the method of least squares was used to fit the maximum intensity cases. According to the shape of maximum intensity and 99th percentile curves, a linear form of function was selected to represent the best fit line:

$$V = A + B(SST)$$

where V is the maximum wind (m s^{-1}) and is referred to as the maximum potential intensity (MPI) for the Western North Pacific typhoons, SST is the sea surface temperature (°C). These two constants A and B are -70.685 m s^{-1} and 5.178 m s^{-1} $°C^{-1}$ respectively. Figure 3 shows the observed maximum typhoon intensity and its least squares function fit for each 1°C SST group.

The appropriate range of SST for using in the empirical MPI function is from 13.65°C up to 32°C. SST below the value of 13.65°C will result in the maximum intensity to be negative. It dose not make sense to have a negative intensity. Most typhoons that move over sea surface with 13°C or cooler are usually in the stage of dissipation. These cases are not relevant to this research project.

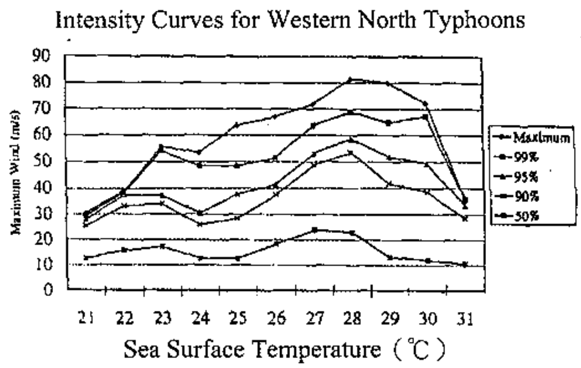

Figure 2: The maximum typhoon intensity and the 99th, 95th, 90th, and 50th intensity percentiles associated with 1°C SST group.

SST Group (℃)	Typhoon Name	Year	Lat/Lon	Max. Intensity (m/s)
21.0	Bess	1965	37.2/150.8	30.41
22.0	Kathy	1966	35.5/172.2	38.60
23.0	Bess	1965	35.3/148.5	55.52
24.0	Carmen	1965	32.0/147.8	53.39
25.0	Carmen	1965	29.1/147.0	63.49
26.0	Carmen	1965	26.6/146.6	66.84
27.0	Carmen	1965	24.9/145.8	71.85
28.0	Tip	1979	16.9/137.2	81.53
29.0	Kit	1968	20.7/130.9	80.00
30.0	Olive	1965	22.2/147.9	72.26
31.0	Pamela	1976	7.6/153.0	36.07

Table 3: Western North Pacific typhoons containing the maximum intensity data point.

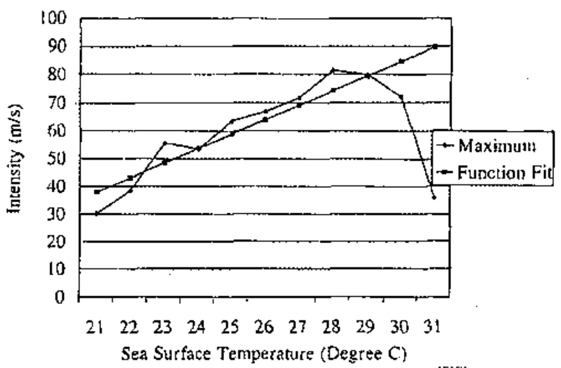

Figure 3: The observed maximum typhoon intensity associated with 1°C SST group and the least squares function fit.

3.2. Case Study of the Empirical Maximum Potential Intensity Function

The monthly SST data of 27-year (1965 - 1991) were used to relate the intensity of typhoons and derived an empirical function. To test the accuracy of the MPI function, weekly SST data from 6 years (1992 - 1997) were adopted in this test. Typhoon data of the same period were also used, tropical depressions and tropical storms were not selected in this study because it only focused on how close the typhoon intensities could reach their maximum potential intensity (MPI).

The SSTs associated with the time and position of typhoons were put into the empirical MPI function, and the maximum potential intensities in the same time and position were obtained, then all typhoon intensities were compared with their MPI to see how much difference between them. Because the motion of western North Pacific typhoons are influenced by the Pacific high pressure system. Most typhoons move to the west-northwest then north-northeast to the higher latitudes where the colder waters located. Cold waters reduce the amount of evaporation and the energy provided for the typhoons is also decreased. The reduction of the available energy results in the weakening of typhoons. The following figures reveal the actual change of intensities of typhoons associated with their MPI.

Figure 4 reveals that the intensities of typhoon Elsie (27 Oct.-9 Nov. 1992) decreased as the system moved to north of 30°N. At its peak intensity typhoon Elsie approached its MPI. During the dissipation stage, lower SST accompanied by the lower MPI provided an upper bound on the actual intensity. At no time did the intensity exceed MPI derived from the empirical equation.

Figure 5 reveals that there is a similar pattern and trend for the actual intensities and their MPIs during the intensification and dissipation. Typhoon Ward (23 Sep.-7 Oct. 1992) was a weaker storm. MPI decreased gradually with the typhoon Ward moving northward. It is very apparent that SSTs play a significant role on the development of typhoon Ward. Figure 6 and 7 indicate the cases of rapid reduction of MPI during the dissipation of northward moving typhoons. As these typhoons moved northward to cold water regions very fast, the reduction of available energy results in rapid weakening of the systems. Figure 8 is the case of similar trend between actual intensities and MPI during the stage of dissipation. The reason is that typhoon Hunt (13-21 Nov. 1992) recurved to higher latitude areas with cold water.

In conclusion, there is none of the typhoons in the independent sample exceeded the MPI during the initial and intensification stage. Only some cases came very close to their MPI (up to 99%) (Fig. 4,6,7). The pattern of the typhoon intensity is similar to the MPI during the stage of dissipation in those cases (Fig. 4～8). This situation often occurred while typhoons moved northward and experienced cooler and cooler waters.

The number of cases and percentage of typhoons to reach their 50% and 80% MPI are shown in Table 4. There were more intense typhoons in the year of 1992 and 1997. Almost 60% of cases reached their 50% of MPI in both years, and 11.3% and 27.6% of cases attained 80% of their MPI in 1992 and 1997, respectively. For the total cases, 41.9% of typhoon intensity reached their 50% MPI, 10.7% attained 80% of MPI.

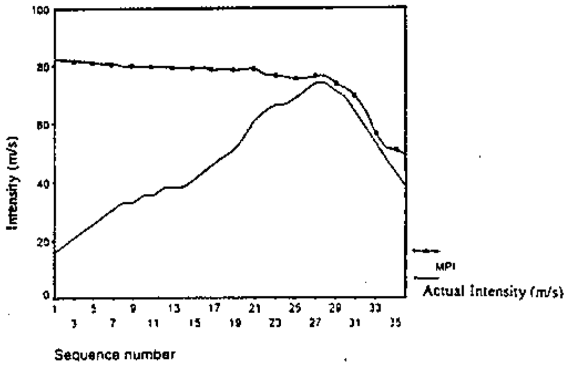

Figure 4: The observed intensities of typhoon Elsie (27 Oct.-9 Nov. 1992) and its associated maximum potential intensity (MPI).

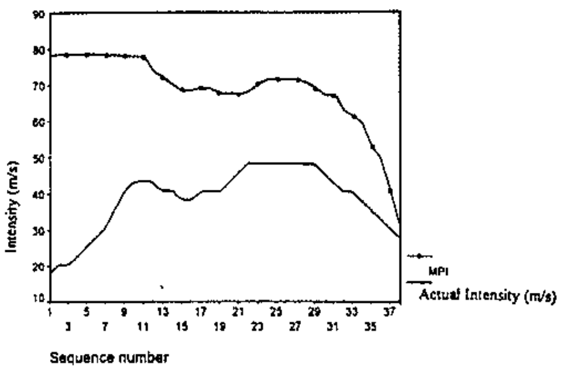

Figure 5: The observed intensities of typhoon Ward (23 Sep.-7 Oct. 1992) and its associated maximum potential intensity (MPI).

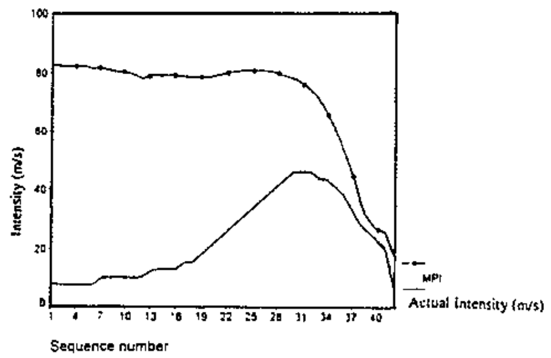

Figure 6: The observed intensities of typhoon Page (8-18 May 1994) and its associated maximum potential intensity (MPI).

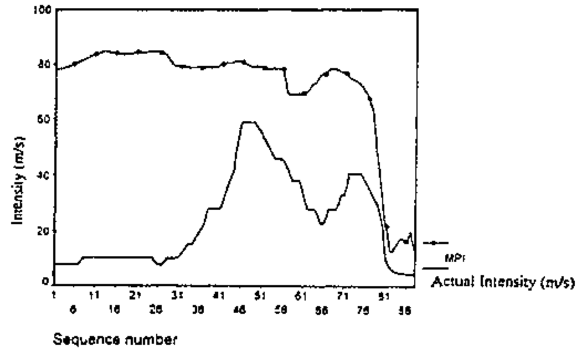

Figure 7: The observed intensities of typhoon Orson (21 Aug.-3 Sep. 1992) and its associated maximum potential intensity (MPI)

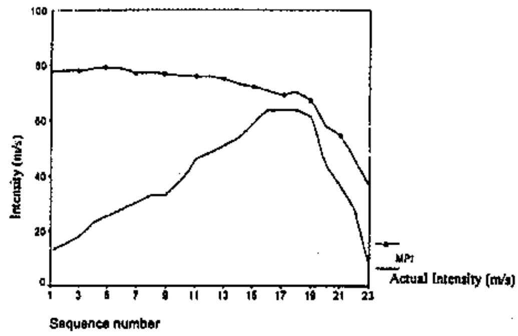

Figure 8: The observed intensities of typhoon Hunt (13-21 Nov. 1992) and its associated maximum potential intensity (MPI).

	50% of MPI	80% of MPI	Total
1992	270 (59.87%)	51 (11.31%)	451
1993	72 (38.50%)	2 (1.07%)	187
1994	200 (30.86%)	32 (4.94%)	648
1995	57 (27.54%)	14 (6.67%)	207
1996	185 (32.86%)	47 (8.53%)	563
1997	265 (59.95%)	122 (27.60%)	442
Total	1049 (41.94%)	268 (10.73%)	2491

Table 4: The number of cases and percentage of typhoons to reach their 50% and 80% MPI

4. CONCLUSIONS

The major purpose of this study was to derive an empirical equation to relate the sea surface temperature and typhoon intensity over the Western North Pacific Ocean. It is well known that sea surface temperature (SST) plays an important role on the intensification of typhoons. Many researchers related the SST and typhoon intensity changes by climatological data (Miller, 1948; Malkus and Riehl, 1960; Merrill, 1987, 1988; Emanuel, 1986; Evans, 1993, Chu, 1994; DeMaria and Kaplan, 1994; Whitney and Hobgood, 1997, Wu, 2000). These results reveal that the SST along is not a good predictor for the intensification of a typhoon, but the SST can be a capping function to provide an upper bound for the typhoon intensities. It is believed that using the climatological SST data of western North Pacific can also derive an empirical equation related to the typhoon intensity in this area. This relationship would specify the capping function for the western Pacific.

A linear empirical equation was developed by using 27 years (1965 – 1991) monthly sea surface temperature data and typhoon intensities. Each value of typhoon intensity was accompanied by a SST. The SSTs were stratified into 11 evenly spaced groups by 1°C interval from 20.5°C to 31.5°C. Maximum intensities were found after a search of the largest value of intensity in each SST group.

Linear regression was used to find a line to represent the line of maximum intensity. In this study, a straight line was selected to fit the maximum intensities. The derived linear function, called maximum potential intensity (MPI), represents most groups of maximum intensities very well except the 31.5°C group (cf. Fig. 3). The lack of intense typhoons in the 31.5°C group results in the overestimate of intensity in this group by the MPI function. Although the overestimate of intensity is possible, it is not a serious problem, because the higher SST regions are in the genesis areas of typhoons. Typhoons often intensify and reach their maximum intensity after moving out of this area. Thus, warmer SSTs do not by themselves guarantee higher intensity. The performance of this empirical equation is still very good as a capping function. In the future study, a two-degree curve line can be considered to replace the one-degree straight line to obtain better results.

To test the accuracy of the derived empirical equation, a weekly SST data set for 6 years (1992 – 1997) was used. The SSTs associated with the time and position of typhoons were put into the empirical MPI function. Then the maximum potential intensity was obtained. This value was compared to the actual intensity in the same time and position to see the difference between them. The results revealed that this derived MPI function provided an effective upper bound on the intensification and development of typhoons. There were no actual intensities that exceeded the maximum potential intensity during the development and intensification stage. Some cases occurred at final stage due to the typhoon moving to extremely cold water area, but that was not the focus of this research.

In this study, 41.4% of typhoon intensity reached their 50% maximum potential intensity (MPI), and 10.7% attained 80% of MPI. These numbers are less than those from the study of DeMaria and Kaplan (1994), in which 58% and 19% cases reached their 50% and 80% MPI in the Atlantic Ocean. The numbers are similar to the finding (42% and 11%) by Whitney and Hobgood (1997) for the eastern North Pacific Ocean. It is found that in the eastern and western North Pacific Ocean tropical cyclones are less likely to approach their MPI as are similar storm over the Atlantic Ocean.

The explanation for this difference between ocean basins is not immediately apparent. One possible reason is that Atlantic hurricanes usually recurve rapidly northward and move over cold water. The MPI is decreased due to the colder SST, but if the hurricane can maintain the strong intensity before spinning down, it has a chance to get closer to its MPI. The problem is complicated by the different atmospheric environment over each basin. The thermal structure, upper-level flow pattern, upwelling of colder oceanic and variation of SST are reasons that affect the intensity attained by a tropical cyclone.

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