A statistical comparison of the potential intensity index for tropical cyclones over the Western North Pacific

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Abstract
Potential intensity (PI), an upper thermodynamic limit of tropical cyclone (TC) intensity, is a useful index in TC statistical forecasting. This study evaluated the relationship between the current intensity of TCs and four PI indexes calculated with different sea surface indicators over the Western North Pacific (WNP) from 2009 to 2016. To mirror the degree of sea cooling caused by TCs, three sea surface temperature (SST) indicators (pre-SST, 80 m depth mean sea temperature, and dynamic mixed mean sea temperature) were compared with real-time SST obtained from HYbrid Coordinate Ocean Model (HYCOM) data. The results showed that four versions of PI all overestimated the current intensity of developing TCs. In contrast, when a TC at its strongest or in its weakening stages in a favorable atmospheric environment, pre-sea conditions were strongly correlated with TC intensity. For strong TCs, the ocean-coupled PI index was best able to describe TC intensity.

KEYWORDS
potential intensity, sea cooling, tropical cyclone

1 INTRODUCTION

A tropical cyclone (TC) is a low-pressure system generated over the tropical warm ocean, where mesoscale air–sea interaction is of great significance and cannot be ignored. Because of differences in air–sea temperature and humidity, a large amount of enthalpy energy, including the sensible heat flux and latent heat fluxes, are transferred from the warm ocean into TCs (Lin et al., 2009). When a TC passes over the ocean surface, its strong sea surface wind can stir up the upper ocean and allow the deep cold water to upwell to the surface, leading to the formation of a cold wake on the right side behind the TC in the Northern Hemisphere. (Price, 1981; Jacob et al., 2000; D’Asaro et al., 2007; Sanford et al., 2011). Both the pre-TC cold ocean and the cold wake around its path can diminish the TC (Loyd and Vecchi, 2010).

In the late 1980s, a thermodynamic model was established to describe the development of a TC by regarding it as an ideal Carnot heat engine (Emanuel, 1986). The efficiency of this ideal engine generally depends on the difference between the sea surface temperature (SST) and the tropopause temperature ($T_0$). The potential maximum intensity index of a TC (hereafter referred to as SST_PI) can then be determined based on a formula from Emanuel (1999):

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where $V^2$ is the square of the TC’s maximum wind speed, $C_k$ is the enthalpy exchange coefficient, $C_D$ is the drag coefficient, $k^*$ is the enthalphy of the sea surface, and $k$ is the surface enthalphy in the environmental field around the TC. When SST_PI is calculated, SST in Equation (1) means the pre-sea conditions ahead of the TC passage (hereafter referred to as $T_{\text{pre}}$). Since SST_PI was proposed, it has been widely used in various statistical forecasting models, for example, the Statistical Hurricane Intensity Prediction Scheme (SHIPS) (Demaria et al., 2005). However, improvements to this index are still required due to its uncertain performance in overestimating or underestimating TC intensity, which can be attributed to the lack of a comprehensive description of the physical processes and influential components associated with TC development (Xu and Wang, 2010). There are several reasons for the overestimations of this index. On the one hand, Equation (1) fails to consider the effects of atmospheric conditions and TC dynamic processes (e.g., strong wind shear and weak upper outflow) that can inhibit TC development (Zeng et al., 2007; Kaplan et al., 2007; Shu et al., 2012). On the other hand, the SST under a TC is changeable. Cione and Uhlhorn (2003) revealed that pre-SST (i.e., the ambient SST located well ahead of the storm center) has no significant effect on subsequent changes in TC intensity, but the SST under the TC inner core ($SST_{IC}$) does have a strong effect. Even a small SSTIC disturbance can cause large changes in sea surface fluxes. Therefore, SSTIC should be the best temperature indicator to use for PI estimation. However, because it is impossible to validate the real-time SST under TC circulation (hereafter referred to as $SST_{\text{real}}$) by observations, many studies have been conducted to determine how best to replace SST in Equation (1).

Lin et al. (2013) replaced $T_{\text{pre}}$ with the mean sea temperature from the sea surface to an 80 m depth ($T_{80}$). Their new calculation formula was called the ocean-coupling PI (OC_PI). Although statistical results indicate that OC.PI has stronger correlation with the actual maximum wind speed ($V_{\text{max}}$) than the SST.PI, it still has a poor ability to improve the forecasting accuracy for weak TCs. To solve this problem, Balaguru et al. (2015) developed a dynamic PI (D.PI) by replacing $T_{\text{pre}}$ with the mean sea temperature from the surface to depth $L$ ($T_{\text{dy}}$) and thought that D.PI was more relevant to the TC growth rate than SST.PI and OC.PI. In their study, the sea-mixing depth $L$ was calculated based on a one-dimensional ocean model, in which only the ocean vertical mixing process was considered. However, the actual mixing process of sea water, which involves complex and undefined relationships between the thermal structure of the ocean and TC characteristics (Price, 2009; Yablonsky and Ginis, 2009), not only experiences a wind-forced vertical mixing motion but also horizontal advection and upwelling.

Although many versions of the PI index have been developed, an objective and general assessment of each version is still lacking. Some studies associate the PI with the rate of change of TC intensity, while others associate it with the magnitude. Additionally, many researchers have not excluded the impact of the ambient atmosphere. Therefore, a uniform standard for evaluating the effects of PIs is proposed in Section 2. Based on this, we attempted to determine the differences of spatial distribution between four temperature indicators ($T_{\text{pre}}, T_{80}, T_{\text{dy}}, SST_{\text{real}}$) in Section 3. In Section 4, we determined the predicted effects of SST.PI, OC.PI, D.PI and Real.PI at different TC stages in a favorable atmospheric environment and investigated under what circumstances that Real.PI can reflect the current TC intensity. Section 5 presents the conclusions.

2 | PREMISES, DATA, AND METHODS

2.1 | Premises and sample selection

To enhance the credibility of the comparisons, three common sense premises were established prior to the statistical analysis.

Premise 1: The local PI is more important than the regionally averaged PI when the intensity of TC is evaluated.

A warm ocean is a necessary condition for TC development, and TC intensity is very sensitive to SST changes. Once a TC moves from the warm ocean to a cold surface, or encounters the cold wake that it caused, it weakens rapidly. Hence, the mean PI over the whole TC’s life cycle (Lin et al., 2013) is appropriate for climatic analysis, but is not suitable for real-time forecasting of an individual TC. In this study, PI was the value calculated at each location along a TC track (Cione and Uhlhorn, 2003; Balaguru et al., 2015).

Premise 2: PI represents the TC intensity but not the rate of change of intensity.

The definition of PI is the maximum intensity that a TC may reach when it passes over a certain sea area. Therefore, PI is an empirical parameter for describing the TC intensity rather than the change in intensity; thus, it is unscientific to establish a relationship between PI and the rate of increase of a TC. Although many studies have proven that PI can be used to estimate intensity changes
in intensity (Gao et al., 2016; Balaguru et al., 2018), a numerical correlation does not mean a physical coincidence. The formula that calculates the rate of intensification which is more dependent on $C_k$ (Emanuel, 2012; Ozawa and Shimokawa, 2015) is more suitable for use in such studies than the PI formula. Therefore, we considered the relationship between the PI and TC intensity in this study.

**Premise 3:** Only in a favorable atmospheric environment can a TC’s intensity reach the PI.

A favorable large-scale ambient atmosphere is essential for the sustainable development of a TC (Kaplan and DeMaria, 2003). Strong vertical wind shear (VWS), low relative humidity in the lower layer (RHLO), and small relative eddy angular momentum flux convergence in the upper troposphere (REFC) are the three most significant factors restricting TC growth (Zeng et al., 2007; Kaplan et al., 2010; Hendricks et al., 2010; Shu et al., 2012). To study how the ocean influences the variation of TC intensity, the adverse atmospheric effects on TC increase in TC intensity should be reduced as much as possible, so ensuring that the ocean is the only factor influencing TC development. Considering the outcomes of previous studies and the results of our own statistical analysis, an atmosphere with $\text{REFC} \geq 10 \, \text{m} \, \text{s}^{-1} \, \text{day}^{-1}$, $\text{VWS} \leq 9 \, \text{m} \, \text{s}^{-1}$, and $\text{RHLO} \geq 70\%$ is considered favorable for TC development (the calculation for a favorable atmosphere is shown in S1).

### 2.2 Data and methods

The sea temperature, salinity from sea surface to 5,000 m depth, and mixed-layer depth data were obtained from HYbrid Coordinate Ocean Model (HYCOM) reanalysis data at one-day intervals (see S2 for more). The six-hourly Joint Typhoon Warning Center (JTWC) best-track data were used to calculate the $V_{\text{max}}$, locations and translational speed of TCs, which were stronger than a category 1 typhoon without landing during the eight-year period from 2009 to 2016 over the Western North Pacific (WNP) and South China Sea.

#### 2.2.1 The calculation of $T_{\text{pre}}$, $T_{80}$, $T_{\text{dy}}$, and SST$_{\text{real}}$

$T_{\text{pre}}$, $T_{80}$, and $T_{\text{dy}}$ represent pre-SST, vertically averaged temperatures from the sea surface to an 80 m depth and averaged temperature from the sea surface to the $L$ depth 2 days ahead of the TC’s center, respectively. The formulas for $L$ and $T_{\text{dy}}$ are from Balaguru et al. (2015):

$$L = h + \left( \frac{2\rho_0 u_* t}{k g a} \right)^{1/3} \quad (2)$$

$$T_{\text{dy}} = \frac{1}{L} \int_0^L T(z) \, dz \quad (3)$$

where $h$ represents the initial mixed-layer depth, $\rho_0$ is the sea density, $u_*$ is the friction velocity, $t$ is the mixing time obtained by dividing TC speed by a distance of 50 km, $k = 0.4$ is the von Karman constant, $g$ is the gravitational acceleration, and $\alpha$ represents the rate of increase of potential density with depth beneath the mixed layer. HYCOM reanalyzed SST data were used with linear interpolations to the six-hourly TC’s location with one-day as a substitute for the real-time data.

In the tropical region of the WNP, there is less sea cooling after the passage of a TC due to the weak initial TCs and thick warm water. Even if a TC causes deep vertical mixing, there are few essentially differences between $T_{\text{pre}}$, $T_{80}$, and $T_{\text{dy}}$ (see fig. 2 of Balaguru et al. (2015) for comparison). Therefore, we chose two other open ocean regions with obvious differences, to compare the spatial distribution of the four temperature indicators in Section 3. One was the subtropical WNP (120°E–165°E, 20°N–45°N) with 598 TC samples, and the other was the South China Sea (105°E–120°E, 15°N–25°N), with 112 samples.

#### 2.2.2 Composite analysis

A composite analysis was used to obtain the mean values of the four temperature indicators according to Mei and Pasquero (2013). Firstly, we established a coordinate system $(x, y)$ whose domain center moved consistently with each six-hourly TC location. Then, we constructed a grid domain that was 1,000 km in length perpendicular to the TC track $(x$ direction) and 200 km parallel to the track $(y$ direction), with a spacing resolution of 20 km × 20 km. $T_{\text{pre}}$, $T_{80}$, $T_{\text{dy}}$, and SST$_{\text{real}}$ were bilinearly interpolated onto those grids to obtain $T_{\text{pre}}(x, y)$, $T_{80}(x, y)$, $T_{\text{dy}}(x, y)$, and SST$_{\text{real}}(x, y)$. Finally, composites of the differences between $T_{\text{pre}}$, $T_{80}$, $T_{\text{dy}}$, and SST$_{\text{real}}$ were made according to the TC’s speed and intensity of the TC.

#### 2.2.3 The calculation of PI

The calculation area of PI was a $2^\circ \times 2^\circ$ box centered on each TC location. SST_PI was calculated using Equation (1). OC_PI, D_PI and Real_PI were calculated by...
replacing $T_{\text{pre}}$ in Equation (1) with $T_{80}$, $T_{dy}$, and SST$_{\text{real}}$, respectively (see more in S3).

3 | COMPARISON OF TEMPERATURE INDICATORS

It is well known that SST$_{\text{real}}$ plays a significant role in TC development. Within the PI framework, if the temperature indicator is close to SST$_{\text{real}}$, the corresponding PI should theoretically show little deviation from $V_{\text{max}}$. To determine which was the best temperature indicator for PI calculation, the relationships between $T_{\text{pre}}$, $T_{80}$, $T_{dy}$, and SST$_{\text{real}}$ were investigated. The averaged differences between SST$_{\text{real}}$ and other indicators are shown in Figures 1 and 2. The warm colors indicate where the temperature indicator was higher than the SST$_{\text{real}}$, while the cold colors indicate a lower temperature. The black solids mean where the null hypothesis of a paired-sample t test cannot be rejected at the 5% significance level, indicating that there were few differences between SST$_{\text{real}}$ and other indicators.

SST$_{\text{real}} - T_{\text{pre}}$ (Figures 1a,b and 2a,b) is the difference between the real SST under TC circulation and the pre-SST ahead of the TC passage, and means the degree of ocean cooling caused by the TC. As in previous studies (Mei et al., 2015), the cooling area was mainly distributed on the right side of the TC path, and strong, slow-moving TCs led to a colder and larger wake than weak and fast-moving TCs.

The figures show that $T_{80}$ is much smaller than the SST$_{\text{real}}$, especially for weak TCs with a speed greater than 4 m s$^{-1}$. This is because the ocean vertical mixing depth caused by fast-moving and weak TCs cannot extent to a depth of 80 m; thus, $T_{80}$ will understate the SST$_{\text{real}}$. The underestimations are more significant on the left side of the TC track than on the right side. In contrast, if a TC moves slowly (speed <4 m s$^{-1}$), the resulting Ekman pumping process will lead to upwelling from the deeper ocean, which reduces the difference between $T_{80}$ and SST$_{\text{real}}$. At the same time, SST cooling is distributed on both sides of the TCs’ path. In particular, for cat-4 and cat-5 TCs (Figure 2d), SST$_{\text{real}} - T_{80}$ increases obviously,
and SST_{real} could become even smaller than T_{80} within a radius of 200 km as a result of the deeper ocean mixing. Figure 1e,f show that T_{dy} could perfectly reflect SST_{real} on the right side of the tracks of a fast-moving TC within 200 km, regardless of whether the TC is weak or strong, but in other regions, sea cooling does not reach the degree expected. However, when strong TCs move slowly (Figure 2f), T_{dy} is much smaller than SST_{real}. Because the formula for calculating T_{dy} only includes vertical mixing effects, T_{dy} has a lesser magnitude than the actual cooling. Therefore, for slower-moving and stronger storms, SST declines nonlinearly, and the one-dimensional ocean model is no longer applicable (Mei and Pasquero, 2012). The importance of upwelling relative to vertical mixing should be emphasized (Yablonsky and Ginis, 2009).

### FIGURE 2
As in Figure 1, but for cat-3 (left) and cat-4, cat-5 (right) TCs

### FIGURE 3
A schematic diagram of the relationship between a TC’s maximum intensity and the PI during a TC’s life (see legend)

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### 4 | COMPARISON OF PI

In a TC intensity forecasting model (e.g., SHIPS), PI is an important predictor, that needs to have a strong relevance with V_{max}. The definition of PI is the maximum intensity that a TC may reach when it passes over a certain sea area. At the early stage of TC development, TC intensity is usually much smaller than the PI and the TC intensity is often overestimated by PI. In contrast, during the TC’s strongest period and weakening stages of a TC, PI is likely to become the theoretical limit of the TC’s development (Figure 3). Figures 4 and 5 attempt to prove this concept.
Figure 4 shows the relationship between the PI calculated by four temperature indicators and the TC current maximum wind speed $V_{\text{max}}$ during the TC enhancement stage of a TC. A total of 778 samples were selected in the developing periods of 57 individual TCs in a favorable atmosphere over the WNP to calculate PIs. The decisive coefficient ($R^2$), mean absolute error (MAE) and root mean square error (RMSE) were determined to evaluate the accuracy of modeling $V_{\text{max}}$. For all versions of PI, there is a marked overestimation. Even for the Real_PI, the MAE is 60 m/s and the correlation coefficient between PI and $V_{\text{max}}$ was only 0.002. In this case, PI is no longer suitable as a predictor in statistical forecasting.

A total of 264 samples were selected from 38 individual TCs during their strongest and weakening periods (Figure 5). As a result of the differences between the temperature indicators and SSTreal, each PI formula proposed in previous studies has its own drawbacks and problems. In terms of the correlations between the PIs and $V_{\text{max}}$, the $R^2$ values of all PIs are almost the same, except for that of D_PI (=0.10, slope = 0.31). The $R^2$ values of SST_PI and OC_PI are 0.42 and 0.46, respectively, which demonstrates that pre-sea conditions, especially pre-thermal conditions, truly affected a TC’s intensity. It should be noted that the $R^2$ values calculated in this study are generally larger than that used in Lin et al. (2013). This difference is probably because the PI values used in their study were the mean values calculated throughout the whole TC developmental stage of a TC regardless of the influence of the atmosphere, in which $V_{\text{max}}$ had a very poor correlation with the PIs. The $R^2$ values obtained in Figure 5 were calculated when TCs were weakening and were only influenced by the ocean.

Can Real_PI represent the TCs’ true intensity of a TC? Based on the statistics, the answer may be no. Figure 6 provides a more intuitive way to extract the change pattern of changes in forecast errors at weakening stages of TC. As discussed in Section 3, because SST is significantly higher than SSTreal without sea cooling, SST_PI concentrated (RMSE = 11.2 m/s) above the reference line in Figure 5a yields the largest errors (MAE = 25.3 m/s). Although Real_PI helps to reduce MAE, its errors are still located above the zero-line compared to SST_PI. It is possible that other factors (e.g., such as the sea surface roughness, sea spray, high-level outflow temperature) or the PI formula influence the accuracy of the results. Given these errors, OC_PI has a better performance. The overestimations of OC_PI are significantly reduced (Figure 6), especially for cat-5 TCs, and the MAE is only 6.95 m/s. Although Figure 2d indicates that $T_{80}$ is less than SSTreal when a TC was slow and strong, OC_PI and Real_PI are fairly close through spatial averaging. However, for weak TCs, the number of OC_PI underestimations increased, which is attributed to the fact that $T_{80}$ is much cooler than SSTreal. Furthermore, the maximum wind speed calculated by OC_PI...
vanishes for some weak TCs, and therefore the OC_PI distribution is more discrete than for the other PIs.

It can also be seen from Figure 6 that D_PI has different degrees of overvaluation at various TC developmental phases. When a TC is stronger than cat-3, D_PI is no longer the limit on PI development. According to the analysis in Section 3, $T_{dy}$ can reflect the SST_{real} on the right side of the TC path well, but is less than SST_{real} on the left side of its path. After being spatially averaged, D_PI will inevitably be less than the actual intensity of the TC. When TC is stronger than cat-3, $T_{dy}$ is much lower than SST_{real}, such that the errors increase with the TC’s development. The $R^2$ between D_PI and $V_{max}$ is only 0.1 (Figure 5c).

Considering the physical processes, coefficients, errors and dispersion, it was concluded that among the different versions of PI, OC_PI was closest to the Real_PI and had the best effects on the $V_{max}$ prediction, with fewest errors.

5 | CONCLUSIONS

Based on HYCOM ocean data and JTWC best-track data for TCs in the WNP during 2009–2016, the effects of four PI temperature indicators ($T_{pre}$, $T_{80}$, $T_{dy}$, and SST_{real}) were statistically analyzed in a favorable atmospheric
environment. To provide more convincing results, three premises were established at the beginning of the analysis. Then four temperature indicators and PIs were compared for TCs of different intensity and in different stages of development.

The results showed that the PI was weakly correlated with current TC intensity $V_{\text{max}}$ when TCs were in the enhancing stage. The use of all PI values overestimated the $V_{\text{max}}$ to a large extent. In contrast, at its strongest moment or weakening stages, TC intensity could reach the theoretical upper limit. At this time, the difference between the temperature indicators and SST$_{\text{real}}$ led directly to a variances among the PI values. Because pre-situations, with different ocean thermal structures and SST$_{\text{real}}$, led to the right side of a fast TC’s path. After spatial averaging, the correlation between D$_{\text{PI}}$ calculated with $T_{\text{dy}}$ and $V_{\text{max}}$ was quite poor, and therefore D$_{\text{PI}}$ was not suitable for TC intensity prediction. Compared with SST$_{\text{PI}}$, Real$_{\text{PI}}$, and D$_{\text{PI}}$, the error distributions between OC$_{\text{PI}}$ and $V_{\text{max}}$ were the most uniform in all situations, with different ocean thermal structures and TC characteristics. Although $T_{\text{dy}}$ is more physically responsive to SST cooling, $T_{\text{dy}}$ is numerically closer to the real situation. Overall, with the exception of some under-estimations, OC$_{\text{PI}}$ is a good index for predicting a TC’s intensity in the weakening stages.

This study also shows that PI is not a perfect predictor of TCs intensity, even when the real SST is known for individual TCs, especially for developing TCs. It has some value when applied to TCs where weakening is only caused by ocean cooling, because PI is just an upper limit to TC development. However, PI still plays a very important role before the high resolution coupled ocean-wave model is widely used. The processes of TC intensification, especially the rapidly intensifying process, still need further evaluation in future studies.

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**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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