Dependence of Tropical Cyclone Intensification Rate on Sea Surface Temperature, Storm Intensity, and Size in the Western North Pacific

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ABSTRACT

This study extends the statistical analysis on the dependence of tropical cyclone (TC) intensification rate (IR) on sea surface temperature (SST), storm initial intensity (maximum sustained surface wind speed \( V_{\text{max}} \)), and storm size, in terms of the radius of maximum wind (RMW), the radius of 34-kt (AR34; 1 kt = 0.51 m s\(^{-1}\)) wind, and the outer-core wind skirt parameter DR34 (= AR34 – RMW), for North Atlantic TCs to western North Pacific (WNP) TCs during 1982–2015. Results show that the relationship between the TC maximum potential intensification rate (MPIR) and SST also exists in the WNP. TC IR depends strongly on TC intensity and structure, consistent with the findings for North Atlantic TCs. TC IR is positively (negatively) correlated with storm intensity when \( V_{\text{max}} \) is below (above) 70 kt and negatively correlated with the RMW. Rapid intensification (RI) occurs only in a relatively narrow range of parameter space in storm intensity and both inner- and outer-core sizes, with the highest IR appearing for \( V_{\text{max}} \geq 70 \) kt, RMW \( \leq 40 \) km, AR34 = 150 km, and DR34 = 100 km. The highest frequency of occurrence of intensifying TCs occurs for \( V_{\text{max}} \); 40–60 kt, RMW; 20–60 km, AR34 = 200 km, and DR34 = 120 km. Overall, these values are very similar to those for TCs in the North Atlantic. These results suggest the need for the realistic initialization of TC structure in numerical models and the inclusion of size parameters in statistical TC intensity prediction schemes.

1. Introduction

It has been widely accepted that a tropical cyclone (TC) can be treated as a Carnot heat engine, which gains energy from the underlying ocean in the form of a surface entropy flux that is largely determined by sea surface temperature (SST); it loses mechanical energy to the underlying surface because of surface friction, and a small amount of kinetic energy is used for the development of an upper-level anticyclone (Kleinschmidt 1951; Emanuel 1988). A TC intensifies as a result of the energy production being greater than the energy dissipation (Wang and Xu 2010; Wang 2012; Ozawa and Shimokawa 2015). Once a balance between the energy production and energy dissipation is reached, the TC achieves its theoretical, steady-state maximum potential intensity (MPI; Emanuel 1997; Wang 2012). In this regard, SST is a key factor in the formation and intensification of a TC (Malkus and Riehl 1960) and largely determines the MPI that a TC can achieve given favorable environmental atmospheric and oceanic conditions (Miller 1958; Emanuel 1986, 1988, 1995, 1997; Holland 1997).

Since TC intensification and maintenance are controlled by similar physical processes, a natural extension of the MPI is the concept of the maximum potential intensification rate (MPIR), introduced by Xu et al. (2016, hereafter XWT16). Based on the best-track data of TCs over the North Atlantic, XWT16 showed that SST determines not only the MPI but also the MPIR, with the latter reflecting the upper bound of the intensification rate that a TC can reach given favorable environmental conditions. XWT16 also constructed an empirical relationship between the MPIR and SST for TCs over the North Atlantic based on best-track TC
data and observed SSTs during 1988–2014. Similar to the empirical relationship between MPI and SST, XWT16 showed that the MPIR increases with increasing SST, with a more rapidly increasing trend when SST is higher than 27°C in the North Atlantic. It is unclear whether a similar SST–MPIR relationship exists for TCs over the western North Pacific (WNP). These are issues to be addressed in this study.

In addition to SST, the intensification rate (IR) of a TC also depends on the inertial stability in its inner core, which determines the dynamical efficiency of eyewall heating, as inferred from balanced dynamics (Schubert and Hack 1982). Since inner-core inertial stability is a strong function of the inner-core size [i.e., the radius of maximum wind (RMW)] and the intensity \(V_{\text{max}}\) of the TC itself, the IR of a TC may depend on its intensity and inner-core size as well (Kaplan et al. 2010; Rogers et al. 2013; Carrasco et al. 2014). Kaplan et al. (2010) statistically analyzed the rapid intensification (RI) of TCs over the North Atlantic based on the best-track data from 1989 to 2006 and found that TCs with initial intensities of 65–70 kt (1 kt = 0.51 m s\(^{-1}\)) were most likely to satisfy the 35-kt RI threshold [35 kt (24 h)-\(^{-1}\)]. They hypothesized that TCs of 65–70-kt intensity often had well-organized eyewall structures while still far from their theoretical MPIs. Rogers et al. (2013) examined differences in the composite structures of the intensifying and quasi-steady TCs over the North Atlantic based on airborne radar data and found that the tangential wind outside the RMW decays more rapidly with radius in intensifying TCs than in quasi-steady TCs. Since the slower radial decay of tangential wind outside the RMW implies relatively higher inertial stability outside the RMW, the results suggest that high inertial stability outside the RMW may be unfavorable for TC intensification. Carrasco et al. (2014) compared the RMW and average 34-kt wind radius (AR34) of TCs that underwent RI versus those that slowly intensified or were steady state over a 24-h period for North Atlantic TCs during 1990–2010. They found that the intensity change was negatively correlated with both RMW and AR34.

More recently, Xu and Wang (2015, hereafter XW15) examined the dependence of TC IR on both TC intensity and structure based on the best-track data for North Atlantic TCs. They found that TC IR depends strongly on storm intensity, the RMW, the average radius of gale-force winds, and the outer-core wind skirt parameter (DR34 = AR34 − RMW) for North Atlantic TCs during 1988–2014. XW15 showed that TC IR increases with increasing storm intensity when \(V_{\text{max}}\) was below about 80 kt, but decreases with increasing intensity afterward and is negatively correlated with the RMW, AR34, and DR34. They also found that RI can only happen in a relatively narrow range of the parameter space of storm intensity and both the RMW and AR34 (or DR34).

It is well known that TCs over the WNP and the North Atlantic have different climatologies, and the best-track datasets are obtained based on different observational data and approaches in the two basins (e.g., Knaff et al. 2007, 2014, 2016). For example, TCs in the WNP, on average, are larger in size than those in the North Atlantic (Merrill 1984; Chavas and Emanuel 2010; Hendricks et al. 2010; McTaggart-Cowan et al. 2013). In addition to the differences in the TCs themselves, the best-track (and real time) TC data in the two basins are obtained based on different observations and algorithms. Different from the North Atlantic, where aircraft reconnaissance data are routinely available, the TC intensity and size parameters over the WNP are mainly determined based on satellite remote sensing data often without in situ observations (Knaff et al. 2014, 2016; Chavas et al. 2016). In this sense, the best-track dataset in the North Atlantic is considered more reliable than that in the WNP. This partly explains why most previous studies have focused on statistical analyses of the relationship between TC IR and initial TC intensity, inner-core size (such as the RMW), and the radial decay rate of tangential wind outside the RMW over the North Atlantic (Kaplan et al. 2010; Rogers et al. 2013; Carrasco et al. 2014; XW15; XWT16). Nevertheless, Chen et al. (2011) found that compact TCs (with either a small RMW or rapid radial decay of tangential wind outside the RMW, or both) had higher IRs and more frequent RIs than larger storms over the WNP, suggesting that some similar behavior in the dependence of TC IR on storm structure might also exist for WNP TCs as found for North Atlantic TCs mentioned above.

The objective of this study is to extend the analyses in XW15 and XWT16 to TCs over the WNP based on best-track TC data during 1982–2015 and to examine the similarities and differences in the dependence of the MPIR and IR on SST and other storm parameters between the two basins. The rest of the paper is organized as follows. Section 2 describes the data and analysis methods used in the study. Sections 3 and 4 discuss the SST–MPIR relationship and the dependence of TC IR on storm intensity and structure, respectively. The main conclusions are given in the last section.

### 2. Dataset and analysis methods

The best-track data for TCs over the WNP during 1982–2015 used in this study were obtained from the Joint Typhoon Warning Center (JTWC). The data
include the latitude and longitude of the TC center, $V_{\text{max}}$, RMW, and AR34, all recorded at 6-h intervals. The TC translational speeds were calculated using centered time differencing based on changes in latitude and longitude at 12-h intervals, except for the first and the last cases where one-sided time differencing was used. The RMW and AR34 were used to express the inner- and outer-core sizes of a TC. A total of 940 TCs with 5239 intensification cases were included in the following analysis. TC cases at extratropical or subtropical transition stages and after landfall were all excluded from our analysis. The TC translational speed multiplied by 0.4 was further subtracted from $V_{\text{max}}$ to eliminate the influence of TC motion on intensity (Emanuel et al. 2004; XWT16). The resultant surface wind speed was then used to represent TC intensity and to calculate the TC IR, which is defined as the increase in $V_{\text{max}}$ over the subsequent 24-h period. The intensification cases are those with IRs greater than zero.

The daily optimum interpolation (OI) SST data (OISST; Reynolds et al. 2007) produced by the National Oceanic and Atmospheric Administration (NOAA) with a spatial resolution of 0.25° were used in this study. The SST for each TC case was calculated by averaging gridded SSTs within a radius of 100 km from the TC center. To facilitate the comparison of the relationships between TC IR, intensity, and structure, and SST over the WNP with those over the North Atlantic, the non-parametric regression technique (Green and Silverman 1994) used in XW15 and XWT16 was also employed in this study (see section 2 in XW15 for details).

Since XWT16 showed that environmental vertical wind shear (VWS) is the primary limiting factor preventing TCs from reaching their empirical MPIRs, we also calculated environmental VWS using the European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalysis (ERA-Interim), following the method described in Wang et al. (2015). Namely, the VWS was defined as the difference in vector winds between 200 and 850 hPa averaged within a radius of 1000 km from the TC center.

3. Maximum potential intensification rate and SST

Figure 1 shows the scatter diagram of IR compared with SST together with its 99th, 90th, and 75th percentiles for all intensifying TC cases in the WNP during 1982–2015. Consistent with the findings in XWT16, TC IR shows an increasing trend with increasing SST. Note that almost all intensifying TCs in Fig. 1 occur over SSTs ranging between 26° and 30.5°C, a much narrower spread than for those between 20° and 30.5°C in the North Atlantic. The fitted curve for the MPIR is close to a linear function of SST in the WNP in the following form:

$$\text{MPIR} = A + B \times \text{SST},$$

where the least squares estimation gives $A = -486.94 \text{kt day}^{-1}$ and $B = 19.77 \text{kt day}^{-1}$ with SST in degrees Celsius. For comparison, the SST–MPIR curve for North Atlantic TCs obtained in XWT16 is presented in light blue in Fig. 1, which shows an exponential function of SST given as

$$\text{MPIR} = 27.58 + 74.03 e^{0.1903 \times (\text{SST} - 30)}.$$  

It appears that when SST is above (below) 28°C, the MPIR in the WNP is higher (lower) than that in the North Atlantic. This indicates that TCs in the WNP have the potential to intensify faster than those in the North Atlantic when SST is above 28°C. This agrees with the fact that when SST is above 25°C, the MPI in the WNP is higher than that in the North Atlantic (Zeng et al. 2007, 2008) since the MPIR is a monotonic function of MPI as shown in XWT16.

The difference in the dependence of MPIR on SST is found to be closely related to the spatial distributions of climatological mean environmental VWS and SST during June–October in the two basins (Fig. 2). Overall, most intensifying TCs were in regions of SSTs higher...
than 28°C with relatively weaker VWS over the WNP than over the North Atlantic, consistent with relatively higher fitted MPIR over the WNP than over the North Atlantic for the same SST bins on the high SST side (Fig. 1). Regions of SSTs lower than 26°C occur with much stronger VWS over the WNP than over the North Atlantic. As a result, intensifying TCs were relatively rare in regions with SSTs lower than 26°C over the WNP (Fig. 2a), while some intensifying TCs were found in regions with SSTs lower than 26°C over the North Atlantic where VWS was relatively weak (Fig. 2b). The results suggest that the different functional MPIR–SST relationships between the WNP and the North Atlantic are primarily related to the different climatological VWS–SST relationships in the two basins. Note that the fitted functional relationship for the WNP for SSTs above 28°C is based only on five samples (Fig. 1), and the differences for high SSTs between the two basins are not statistically significant at the 95% confidence level (see Table 1). Nevertheless, such differences are consistent with the different spatial distributions in the climatological SST and VWS discussed above.

To quantify the relationship between TC IR and SST, intensifying TC cases are assigned to one of the six evenly spaced SST bins between 25° and 31°C (Table 1). Figure 3 shows the frequency distributions of TC IRs and the lifetime maximum IRs (IRmax) in each SST bin together with the fitted MPIR curve. About 99.8% and 84.4% (5231 and 4427 out of 5239; see Table 1) of intensifying cases occurred with SSTs greater than 26°C and 28°C, respectively, in the WNP. Both the average IRs and the average top 50% of IRs over each SST bin show increasing trends with increasing SST, which is consistent with the findings in the North Atlantic (XWT16). In addition, all the lifetime IRmax values occurred over SSTs higher than 26°C and about 92.2% of IRmax values occurred over SSTs between 27° and 30°C. The average IRmax values (the top 50% of IRmax values) over the three SST intervals starting from 28°, 29°, and 30°C in the WNP are 24.1 (37.7), 25.0 (38.8), and 34.0 (50.9) kt day⁻¹, respectively. These results suggest that the MPIR is largely controlled by the underlying SST but the actual IR is largely determined by both the underlying SST and the environmental VWS in both the North Atlantic and the WNP as will be discussed below.
Although the fitted empirical MPIR is a function of SST only, the actual IR of a TC rarely reaches its SST-fitted MPIR because there are detrimental environmental conditions (such as the large-scale VWS) and internal dynamics (such as the asymmetries in the eyewall and concentric eyewall cycles) that prevent a TC from reaching its MPIR. XWT16 showed that only about 28% of intensifying TCs reached 50% of their MPIRs and only 7% reached 80% of their MPIRs when they were at their lifetime IRmax values over the North Atlantic. Similar analysis into the frequency and cumulative frequency distributions of the relative IR (RIR) and relative lifetime IRmax (RIRmax), defined as the IR and IRmax normalized by the corresponding MPIR at the given time, respectively, for all intensifying TC cases in the WNP during 1982–2015 were carried out with the results shown in Fig. 4. It can be seen that the probability decreases monotonically with the RIR, indicating that RI cases are rare events and most TCs intensified slowly; for example, about 33% of intensifying TC cases appeared in the frequency distribution of RIR at 10%, only 5% of intensifying TC cases were at 50%, and only about 1% of cases were at RIR of greater than 70% RIR (the green bars in Fig. 4a). The RIR distribution can also be inferred from its cumulative distribution function, shown as the green curve in Fig. 4b. About 40% of the intensifying TC cases reached more than 20% of their MPIR, only 20% reached 30% of their MPIR, and 10% reached 40% of their MPIR. This distribution is very similar to that in the North Atlantic (Table 1; XWT16).

The frequency distribution of the lifetime RIRmax shows a different pattern from that of the RIR. The frequency of the lifetime RIRmax reaches the highest

<table>
<thead>
<tr>
<th>SST range (°C)</th>
<th>No. of intensifying TC cases (%)</th>
<th>Avg IR (kt day(^{-1}))</th>
<th>Avg IR of the top 50% IR (kt day(^{-1}))</th>
<th>No. of intensifying TCs (%)</th>
<th>Avg lifetime IRmax (kt day(^{-1}))</th>
<th>Avg IR of the top 50% lifetime IRmax (kt day(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(25–26]</td>
<td>8 (0.2)</td>
<td>2.97(^a)</td>
<td>5.17(^a)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(26–27]</td>
<td>118 (2.3)</td>
<td>9.04(^a)</td>
<td>15.34(^a)</td>
<td>12 (2.8)</td>
<td>17.72(^a)</td>
<td>28.97</td>
</tr>
<tr>
<td>(27–28]</td>
<td>686 (13.1)</td>
<td>12.87(^a)</td>
<td>21.61(^a)</td>
<td>52 (12.3)</td>
<td>24.11(^a)</td>
<td>37.67</td>
</tr>
<tr>
<td>(28–29]</td>
<td>2177 (41.6)</td>
<td>14.92</td>
<td>24.01(^a)</td>
<td>175 (41.5)</td>
<td>25.00</td>
<td>38.80</td>
</tr>
<tr>
<td>(29–30]</td>
<td>1979 (37.8)</td>
<td>18.92</td>
<td>29.90</td>
<td>162 (38.4)</td>
<td>34.00</td>
<td>50.85(^a)</td>
</tr>
<tr>
<td>(30–31]</td>
<td>271 (5.2)</td>
<td>17.47</td>
<td>27.49</td>
<td>21 (5.0)</td>
<td>29.61</td>
<td>43.34</td>
</tr>
</tbody>
</table>

\(^a\) Difference from the North Atlantic is statistically significant at the 95% confidence level based on a Wilcoxon rank sum test.

![FIG. 3. (a) Frequency of TC IR (kt day\(^{-1}\)) and (b) frequency and scatter diagram of the lifetime IRmax (kt day\(^{-1}\)) against SST (°C). The empirically fitted MPIR (kt day\(^{-1}\)) as a function of SST (°C) as given in Fig. 1 is also shown in both (a) and (b) by the dashed blue line for reference.](image)
probability of 20% at \( RIR_{\text{max}} = 20\% \), and then goes down to 18% at \( RIR_{\text{max}} = 30\% \) and 15% at \( RIR_{\text{max}} = 40\% \) (the red bars in Fig. 4a). The cumulative frequency distribution of the lifetime \( RIR_{\text{max}} \) is similar to that over the North Atlantic as well (Table 1). Namely, about 24% and 15% of intensifying cases reached 50% and 60% of their MPIRs in the WNP, compared with 28% and 17% for the same percentages in the North Atlantic, respectively (the red curve in Fig. 4b vs the red curve in Fig. 5b in XWT16). The small differences in the percentages seem to result from the fact that most TCs reach their lifetime \( RIR_{\text{max}} \) values over SSTs higher than 28°C, where the MPIRs are generally higher over the WNP than over the North Atlantic (Fig. 1).

Figure 5a gives the location of each TC at the time of its lifetime \( RIR_{\text{max}} \) and the distribution of the smoothed lifetime \( RIR_{\text{max}} \) overlapped with the climatological SSTs averaged during June–October between 1982 and 2015. The smoothed distribution of \( RIR_{\text{max}} \) gives an overview of the spatial pattern and is obtained by fitting a two-dimensional nonparametric regression to the observed \( RIR_{\text{max}} \) points as described in XW15. Note that the spatial pattern of SST in the WNP has lower meridional gradients than that in the North Atlantic shown in Fig. 2. The relatively more uniform warm SSTs (higher than 28°C) are collocated with a broader area where most TCs reached their lifetime \( RIR_{\text{max}} \). Note that only a small number of TCs reached their lifetime \( RIR_{\text{max}} \) south of 10°N, especially east of 150°E, even with the warmest SSTs. This pattern develops because most TCs were at their genesis or early development stages and often reached their lifetime \( RIR_{\text{max}} \) as they traveled poleward and westward in the basin. The smoothed contours of lifetime \( RIR_{\text{max}} \) greater than 30 kt day\(^{-1}\) (i.e., RI) cover the area with SSTs higher than 29°C around 7°–23°N, 125°–172°E. The area of lifetime \( IR_{\text{max}} \) satisfying the RI criterion is much broader than that in the North Atlantic (see Fig. 4 in XWT16), mainly because of the warmer SSTs and weaker VWS (Fig. 5b). Figure 5b shows that almost all lifetime \( IR_{\text{max}} \) samples occurred in the region with VWS lower than 10 m s\(^{-1}\), which is favorable for TC intensification (DeMaria and Kaplan 1999; DeMaria et al. 2005; Zeng et al. 2010; Wang et al. 2015).

To further examine the dependence of TC IR and MPIR on the underlying SST, we show in Fig. 5c the spatial distribution of the lifetime \( RIR_{\text{max}} \) and also the fitted \( RIR_{\text{max}} \). We can see that lifetime \( RIR_{\text{max}} \) shows a pattern very similar to that of the \( IR_{\text{max}} \) in Fig. 5a. There is a zonally elongated region between 10° and 17°N with high SSTs where TCs reached 40% of \( RIR_{\text{max}} \). There are three areas with larger \( RIR_{\text{max}} \) labeled as A, B, and C in Fig. 5 where \( IR_{\text{max}} \) and \( RIR_{\text{max}} \) are greater than 35 kt day\(^{-1}\) and 45%, respectively. These areas with high SST and relatively low VWS (Fig. 5b) are centered at around 15°N, 132°E; 14.8°N, 160°E; and 10°N, 144°E. Note that the high value of lifetime \( RIR_{\text{max}} \) over low SST north of 30°N is not representative because of the small number of cases. In addition, the SST-fitted MPIR might also be underestimated, because VWS in the midlatitude westerlies over the WNP is relatively high.

4. Dependence of TC IR on TC intensity and structure

Although SST determines the MPIR, large numbers of TCs cannot reach their MPIR even over high SSTs...
and in favorable environmental conditions, such as weak VWS. In addition to SST and VWS, TC IR also depends on other factors, such as the TC intensity and size, as already documented for the North Atlantic in XW15. In this section, the analysis for North Atlantic TCs in XW15 is extended to WNP TCs. It is shown that most of the results are consistent with those discussed in XW15, suggesting that the dependence of TC IR on storm intensity and size/structure is robust and is basin independent.
a. Dependence on storm intensity

Figure 6 shows the frequency of IR against TC intensity, together with the fitted 95th percentiles for three SST bins with 1.5°C ranges starting at 27°C, 28°C, and 29°C. To have sufficient samples for the percentile fitting in each SST bin, consecutive SST bins are allowed to have a 0.5°C overlap. The IR increases as TC intensity increases when the $V_{\text{max}}$ is below about 60–75 kt for all three SST bins, but decreases with TC intensity afterward. For the given 27°C, 28°C, and 29°C SST bins, the maximum IRs of the 95th percentiles of IR are 50, 58, and 64 kt day$^{-1}$ at the TC intensities of 60, 70, and 75 kt, respectively. Note that the intensity at which the maximum IR of the 95th percentile of IR occurs increases with increasing SST.

Since the MPI is a function of SST, MPIR is also a function of the MPI, as discussed in XWT16. For a given intensity, the 95th percentile of IR is always larger for higher SST, implying that the underlying SST is not only key to the MPIR but also a factor determining the IR of a TC under favorable environmental conditions. In addition, since the 95th percentile of IR is representative of RI (Kaplan and DeMaria 2003), the above result also suggests that a $V_{\text{max}}$ of 60–75 kt is the most favorable initial TC intensity for RI to occur. This intensity threshold of about 60–75 kt is consistent with the findings of Kaplan et al. (2010), who showed that TCs with intensities of 35–40 m s$^{-1}$ (about 68–78 kt) are most likely to undergo RI over the WNP.

Table 2 shows that IR is positively (negatively) correlated with initial storm intensity when $V_{\text{max}}$ is less (greater) than 70 kt with a correlation coefficient of 0.24 ($-0.28$), significant at the 95% confidence level and above. A possible explanation for the intensity dependence of TC IR has been speculated upon in several previous studies (Kaplan et al. 2010; XW15). When a TC is relatively weak, the IR tends to increase as the TC intensifies because of the increasing dynamical efficiency of eyewall heating due to the increasing inner-core inertial stability (Schubert and Hack 1982; Pendergrass and Willoughby 2009). Once a TC becomes stronger and approaches its MPI, it would have no room to intensify further. As a result, there exists a turning point for $V_{\text{max}}$ where a balance is reached between the intensification potential and the MPI of the TC (XW15). Nevertheless, a quantitative description of the intensity dependence of TC IR is left to be developed in a future study for a full understanding.

b. Dependence on storm size

Figures 7a–7c show the scatter diagrams of the subsequent 24-h IR against size parameters, including the RMW, AR34, and DR34 together with the 95th and 50th percentiles of IR for the corresponding given size parameters for all TCs during 1982–2015 over the WNP. The IR–RMW relationship displays an overall decreasing trend of TC IR with increasing RMW. This means that IR is negatively correlated with RMW, with a linear correlation coefficient of $-0.21$, compared with $-0.173$ in the North Atlantic (XW15; see their Fig. 1b). The difference between the two basins is not statistically significant. This negative correlation can also be seen from the smoothed curves for the 95th and 50th percentiles of IR as a function of the RMW (Fig. 7a). The increasing trend before the turning point is due to the fact that a smaller RMW generally implies larger inner-core inertial stability and higher dynamical efficiency of eyewall heating, resulting in a higher IR (Schubert and Hack 1982; Pendergrass and Willoughby 2009).

The scatter diagram of TC IR against outer-core size AR34 (Fig. 7b) shows an increasing trend of IR with increasing AR34 before AR34 reaches 150 km and then a decreasing trend with increasing AR34 larger than 150 km, with a negative correlation coefficient of $-0.21$ (Table 2), which is consistent with results in the North Atlantic (XW15). The increasing trend before the turning point is due to the fact that TC intensification is often accompanied by eyewall contraction and an outer-core expansion (note that AR34 is zero for a TC just reaching its tropical storm intensity) (Kaplan et al. 2010; XW15). The decreasing trend of IR with increasing
AR34 after the turning point confirms that smaller outer-core size, and thus relatively lower outer-core inertial stability, is preferred for TC intensification, in particular for RI (Rogers et al. 2013; Chen et al. 2011). As a result, TC IR shows a maximum response for AR34 of 150 km as seen from the 95th percentile of IR in Fig. 7b, which is the same as that found for North Atlantic TCs (XW15; see their Fig. 1c) even though the best-track data for the WNP and the North Atlantic are different and produced by the JTWC and National Hurricane Center (NHC), respectively.

For a given $V_{\text{max}}$, a larger difference between AR34 and RMW implies a slower radial decay rate of tangential wind outside the RMW, which can be used as a parameter to measure the outer-core size (DR34). The scatter diagram of IR against DR34 together with the 95th and 50th percentiles of IR for a given DR34 is shown in Fig. 7c. Both the 95th and 50th percentiles show an increasing (decreasing) trend in IR with increasing DR34 when DR34 is smaller (larger) than about 100 km with a correlation coefficient of 0.11 (−0.16), which is significant at the 95% confidence level and above. Large IR (or RI) cases occur mainly for DR34 between 50 and 200 km in the WNP, similar to that in the North Atlantic. The dependence of IR on DR34 is very similar to that for AR34 with similar physical reasons as discussed above for AR34. The result is consistent with Rogers et al. (2013), who showed that a slowly decaying outer-core wind with radius is unfavorable for TC intensification. The above discussion indicates that both inner- and outer-core sizes are important factors in determining the TC IR.

c. Combined effects of storm intensity and size

In previous sections, it was shown that both the initial TC intensity and size can influence the subsequent TC IR significantly. The combined effects of TC intensity and size will be examined in this section. As was done in XW15, thin-plate smoothing spline fitting was employed to obtain the functional relationships between the IR, TC intensity, and size parameters for all intensifying cases, all non-RI cases, and RI cases only (IR greater than 30 kt day$^{-1}$; Fig. 8). The shaded area in each panel in Fig. 8 indicates the combined parameter space in which the corresponding IRs were sampled. We can see from Figs. 8a, 8d, and 8g that the IR increases as the RMW decreases and relatively higher IR (RI) occurs for TCs with intensities predominantly between 40 and 120 kt. The highest IRs occur when $V_{\text{max}}$ is about 60–75 kt and the RMW is around 20 km for all and RI cases.

### Table 2: List of sample sizes, TC cases, and correlation coefficients between TC IR and the storm intensity of various size parameters.

<table>
<thead>
<tr>
<th>Size Parameter</th>
<th>Sample Size</th>
<th>TC Cases</th>
<th>Correlation Coefficient</th>
<th>$p$ Value (S)</th>
<th>$p$ Value (C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$34 \leq V_{\text{max}} \leq 70$ kt</td>
<td>1883</td>
<td>305</td>
<td>0.24</td>
<td>$2.2 \times 10^{-16}$</td>
<td>$2.2 \times 10^{-16}$</td>
</tr>
<tr>
<td>$V_{\text{max}} &gt; 70$ kt</td>
<td>1022</td>
<td>170</td>
<td>−0.02</td>
<td>$2.2 \times 10^{-16}$</td>
<td>$2.2 \times 10^{-16}$</td>
</tr>
<tr>
<td>RMW (km)</td>
<td>4495</td>
<td>422</td>
<td>−0.21</td>
<td>$2.2 \times 10^{-16}$</td>
<td>$1.7 \times 10^{-4}$</td>
</tr>
<tr>
<td>$AR34 &gt; 150$ km</td>
<td>1574</td>
<td>210</td>
<td>0.01</td>
<td>−0.11</td>
<td>$2.2 \times 10^{-16}$</td>
</tr>
<tr>
<td>$DR34 \leq 100$ km</td>
<td>1089</td>
<td>255</td>
<td>0.11</td>
<td>$2.2 \times 10^{-16}$</td>
<td>$5.7 \times 10^{-11}$</td>
</tr>
<tr>
<td>$DR34 &gt; 100$ km</td>
<td>1665</td>
<td>215</td>
<td>0.16</td>
<td>$2.2 \times 10^{-16}$</td>
<td>$2.2 \times 10^{-16}$</td>
</tr>
</tbody>
</table>

Fig. 7. Scatter diagrams of TC IR against (a) RMW, (b) AR34, and (c) DR34 ($= AR34 − RMW$). The red and black curves are the 95th and 50th percentiles of IR for the given storm intensity, respectively, for the corresponding size parameters.
(Figs. 8a,g), while the highest RI occurs when $V_{\text{max}}$ is about 70 kt, which is consistent with the results in the North Atlantic (see Fig. 3 in XW15). Note that the area in the parameter space of $V_{\text{max}}$–RMW for RI cases is much smaller than that for non-RI cases, indicating that RI can occur only for TCs with moderate intensity and small inner-core size. TCs with their RMWs greater than 120 km almost have no chance to intensify rapidly (Fig. 8g), consistent with the results for the North Atlantic (Fig. 4g in XW15).

Similar to the result for the dependence of IR on the RMW, the IR decreases as the outer-core size, AR34, increases for a given intensity in Figs. 8b, 8e, and 8h. The RI cases (Fig. 8h) occur only in a much smaller parameter space for $V_{\text{max}}$–AR34 than the non-RI cases (Fig. 8e). The highest RI appears when $V_{\text{max}}$ is about 70–80 kt and AR34 is about 100–120 km (Fig. 8h), which is consistent with the results in the North Atlantic. A similar pattern of IR exists for the parameter space for $V_{\text{max}}$–DR34 (Figs. 8c,f,i). Since a small DR34 is often related to relatively weak TCs ($V_{\text{max}}$ less than 50 kt), small DR34 is unfavorable for RI. On the contrary, a larger DR34 implies a slower radial decay rate of tangential wind outside the RMW, which is often accompanied by relatively high inertial stability outside the RMW. Previous studies have shown that a relatively broad outer-core tangential wind structure, which implies relatively high inertial stability outside the RMW, could reduce the boundary layer inflow penetrating into the eyewall, reducing the mass flux into the eyewall and suppressing eyewall convection, thus being unfavorable for RI (Wang and Xu 2010; Xu and Wang 2010; Rogers et al. 2013). Moreover, strong outer-core tangential winds may also contribute to active outer spiral rainbands through enhanced surface entropy fluxes in the outer-core region. Diabatic heating in active outer spiral rainbands, in turn, could lead to an outward expansion of tangential wind, that is, an increase in size that is unfavorable for TC intensification (Wang 2009; Xu and Wang 2010, Hill and Lackmann 2009). Moreover, under

![Figure 8](image-url)
favorable conditions, axisymmeterization of spiral rainbands may lead to secondary eyewall formation (May and Holland 1999; Wang 2009; Wang et al. 2016), which may result in considerable intensity change as well. Since we defined intensification as the IR greater than zero in this study, TC cases experiencing reintensification after eyewall replacement cycles (ERCs) were included in our analysis. As a result, ERCs could contribute to the dependence of IR on TC size parameters (e.g., Sitkowski et al. 2011; Kossin and DeMaria 2016), and the small IRs associated with both large outer-core size and large RMW would be partly contributed by reintensification cases after ERCs. A detailed analysis to specifically examine whether ERCs may have any significant effect on the results documented herein is reserved for a future study.

The frequency distributions of all intensifying TC cases, non-RI cases, and RI cases in the joint parameter spaces of $V_{\text{max}}$–RMW, $V_{\text{max}}$–AR34, and $V_{\text{max}}$–DR34 are shown in Fig. 9. Overall, the frequencies of occurrence of both all-intensifying cases and non-RI cases are very similar because RI cases are rare events by definition (Figs. 9a,d). Most of the intensifying cases occur for TCs with RMWs between 20 and 100 km and intensities between 34 and 80 kt in the $V_{\text{max}}$–RMW space (Fig. 9a). However, the RI cases show a higher frequency for TCs with RMWs between 40 and 100 km in weak TCs ($V_{\text{max}} \leq 40$ kt) and the RMWs less than about 60 km for medium intensity TCs ($V_{\text{max}}$ between 40 and 80 kt; Fig. 9g). Although the frequency distribution in the $V_{\text{max}}$–RMW space shows patterns similar to the distribution of IR in the $V_{\text{max}}$–RMW space shown in Fig. 8, the centers of the maximum IR and the centers of the highest frequency of occurrence in the same group are often displaced in the $V_{\text{max}}$–RMW space. This displacement is mainly due to the fact that large IRs (or RI) are rare, and most intensifying cases only experience small and moderate IRs in their lifetime and could not reach their MPIR due to unfavorable effects, such as the environmental VWS.

The frequency distribution in the $V_{\text{max}}$–AR34 space is quite different from that in the $V_{\text{max}}$–RMW space. As the AR34 increases, the maximum frequency of occurrence increases with increasing $V_{\text{max}}$ for all intensifying cases, non-RI cases, and RI cases initially, but then decreases with increasing $V_{\text{max}}$ (Figs. 9b,e,h), as mentioned...
already in section 4b. Note that the AR34 corresponding to the maximum frequency of intensifying, non-RI, and RI cases increases with increasing $V_{\text{max}}$. The RI cases occur mostly for AR34 less than 100 km for weak TCs, and 150 and 200 km for moderate and intense TCs (Fig. 9h). The frequency distribution pattern in the $V_{\text{max}}$–DR34 space (Figs. 9c, f, i) is very similar to that in the $V_{\text{max}}$–AR34 space (Figs. 9b, e, h). Namely, the DR34 corresponding to the maximum frequency of intensifying, non-RI, and RI cases increases with increasing $V_{\text{max}}$. This may partly reflect the fact that stronger TCs often have larger AR34 and DR34. Note that although some TCs still intensified for AR34 and DR34 greater than 250 km, few cases intensified rapidly. Another possible explanation for this feature is that both AR34 and DR34 increase as a TC intensifies, but at the later intensification stages, as the storm intensity approaches its MPI, the TC IR decreases with increasing TC intensity.

5. Conclusions and discussion

In this study, based on TC best-track data, the OISST dataset, and ERA-Interim reanalysis during 1982–2015, the dependence of TC IR on SST, storm intensity, and structure over the WNP was analyzed and compared with that over the North Atlantic. The results show that TC IR strongly depends on SST, storm intensity (the maximum sustained near-surface wind speed $V_{\text{max}}$), and structure (including the inner- and outer-core sizes, and outer-core wind shape), consistent with the results found for the North Atlantic previously reported in XW15 and XWT16. Almost all intensifying TCs in the WNP occur over SSTs greater than 26°C, much warmer than that of 20°C in the North Atlantic. About 99.8% and 84.4% of intensifying TC cases occurred over SSTs greater than 26° and 28°C in the WNP, compared with 88.3% and 41.3% of cases in the North Atlantic. A robust feature is the increase in both the average IR of all intensifying cases and the average IR of the top 50% of IRS with increasing SST, with the average IR of the top 50% being larger than 20 kt day$^{-1}$ and occurring over SSTs higher than 27°C for both the North Atlantic and the WNP.

Following the recent study for the North Atlantic in XWT16, we constructed an empirical relationship between the MPIR and SST for TCs over the WNP. The SST-determined MPIR shows a linear increasing trend of MPIR with increasing SST (Fig. 9b). The frequency distribution pattern in the $V_{\text{max}}$–DR34 space (Figs. 9c, f, i) is very similar to that in the $V_{\text{max}}$–AR34 space (Figs. 9b, e, h). Namely, the DR34 corresponding to the maximum frequency of intensifying, non-RI, and RI cases increases with increasing $V_{\text{max}}$. This may partly reflect the fact that stronger TCs often have larger AR34 and DR34. Note that although some TCs still intensified for AR34 and DR34 greater than 250 km, few cases intensified rapidly. Another possible explanation for this feature is that both AR34 and DR34 increase as a TC intensifies, but at the later intensification stages, as the storm intensity approaches its MPI, the TC IR decreases with increasing TC intensity.

The IR is positively correlated with TC intensity when $V_{\text{max}}$ is less than 70 kt, while negatively correlated with TC intensity when $V_{\text{max}}$ is greater than 70 kt over the WNP (Table 2), compared with the threshold $V_{\text{max}}$ of around 80 kt in North Atlantic in XW15. In general, for a given intensity, IR increases with increasing SST. The peak in the fitted 95th percentile of IR increases with the increase in SST. Similar to that in the North Atlantic, the turning point at medium intensity is due to the fact that TCs of this intensity are both sufficiently well organized and relatively far from their MPI and, thus, are favorable for RI (Kaplan et al. 2010). The IR is negatively correlated with the RMW (or the inner-core size; Table 2) because for a given intensity, the small RMW implies higher inertial stability in the inner core of the TC, corresponding to higher dynamical efficiency of eyewall heating and, thus, higher IR. The 95th percentile of IR shows a maximum response when AR34 is around 150 km, with the negative effect of AR34 on IR for AR34 larger than 150 km. Since, for the given $V_{\text{max}}$ and RMW, a larger AR34 indicates a slower radial decay
rate of tangential wind outside the RMW, this result suggests that large outer-core wind (and relatively larger inertial stability) is unfavorable for high IR. Since DR34 is highly correlated with AR34 by definition, a similar pattern also applies to DR34. We found that RI mainly occurs when AR34 is between 50 and 250 km.

Further analyses based on the combined parameter space show that the highest IR occurs for $V_{\text{max}}$ around 60–75 kt, RMW $\sim$ 10–30 km, AR34 $\sim$ 80–150 km, and DR34 $\sim$ 50–120 km, very similar to the results for the North Atlantic discussed in XW15. The results also demonstrate that RI is favored to occur in a relatively small parameter space with respect to storm intensity and both the inner- and outer-core sizes. The highest frequency of intensifying TC cases occurs for $V_{\text{max}} \leq 80$ kt, and the RMW between 20 and 80 km, AR34 $\leq 200$ km, and DR34 $\geq 150$ km. The maximum frequency of intensifying cases increases with increasing TC intensity.

Results from this study, together with those from XW15 and XWT16, have provided the observational evidence for the existence of an upper bound on TC IR, namely the MPIR, given favorable thermodynamic ocean and atmospheric conditions, similar to the MPI. We show that the different functional dependences of the MPIR on SST between the WNP and the North Atlantic are primarily due to the different climatological VWS–SST relationships in the two basins. Since, theoretically, the MPIR should not be a function of environmental VWS, similar to the theoretical MPI, a physically based theory for the MPIR could be developed in a future study. Note that the difference in the functional dependence of the fitted MPIR on SST could also be partly related to other effects, such as the difference in the upper-ocean thermodynamic structures in the two basins. Nevertheless, the effect of the ocean thermodynamic structure on the MPIR could be considered as a feedback process in the MPIR.

In addition, although both SST and the initial storm intensity have been included in some operational statistical intensity prediction schemes (e.g., SHIPS; DeMaria et al. 2005; Kaplan et al. 2015), storm size parameters have not been considered in RI schemes (e.g., Rozoff et al. 2015). This might be partly due to the lack of a systematic analysis of the dependency of TC IR on storm structure based on observations and partly due to the lack of accurate measurements of storm size (structure) parameters from observations. Note also that although the RMW is currently estimated routinely in various ocean basins, the shape parameter for the radial tangential wind profile is not routinely provided in real time in any ocean basin (Chavas and Emanuel 2010; Knaff et al. 2011; Elsberry et al. 2013). Nevertheless, results from this study together with those of Carrasco et al. (2014) and XW15 strongly suggest that it is important to consider TC size parameters in statistical intensity prediction schemes and to accurately represent the initial TC structure in numerical prediction models in order to achieve improved TC intensity forecasts (e.g., Kaplan et al. 2015; Bender et al. 2017). Furthermore, the SST-dependent MPIR could also be considered as a predictor in operational statistical intensity prediction schemes.

Finally, we should mention that results from this study might be subject to uncertainties resulting from the data sources (e.g., Knaff et al. 2014, 2016; Wu et al. 2015; Chavas et al. 2016; Morris and Ruf 2017). The small differences in the dependence on storm size parameters between the WNP and the North Atlantic could be partly attributed to the uncertainties in the size parameters over the two basins (Kossin et al. 2007; Knaff et al. 2007). Nevertheless, the results are all qualitatively consistent between the two basins, suggesting that the major findings from this study should be robust and not be significantly affected by the data quality.

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REFERENCES


