Increasing lifetime maximum intensity of rapidly intensifying tropical cyclones over the western North Pacific

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Abstract
The long-term trend in the annual mean lifetime maximum intensity (LMI) of rapidly intensifying tropical cyclones (RI-TCs) over the western North Pacific (WNP) is investigated in this study. During 1970–2019, a notable upward trend is observed in the average RI-TC LMI, which is primarily linked to a significant increase in the mean intensification rate prior to LMI. This intensification rate increase is caused by an increase in the mean magnitude of RI cases. By contrast there is no significant change in the RI ratio, which is calculated as the proportion of 24 h RI records to all 24 h records before a RI-TC reaches its LMI. Furthermore, there is a significantly greater RI magnitude west of 155°E, where the vast majority of RI cases occur on average. Over this region, there are significant increases in sea surface temperatures, TC heat potential, 700–500 hPa relative humidity and 200 hPa divergence during 1970–2019. Only a small region of significantly reduced 850–200 hPa vertical wind shear is observed to the northeast of the Philippines from 1970–2019. These results imply that both thermodynamic and dynamic variables play an important role in modulating RI magnitude over the WNP.

1. Introduction
Tropical cyclones (TCs) are one of the severest natural disasters around the globe, inducing high winds, storm surge and intense rainfall that pose a significant threat to life and property over coastal regions. Although TC track forecasts have substantially improved during the past several decades, less improvement in forecasting TC intensity, particularly rapid intensification (RI), has been achieved during this same period (Rappaport et al 2009, Huang et al 2021). RI is usually defined as a maximum sustained surface wind speed increase of at least 30 kt over a 24 h period (Kaplan and DeMaria 2003). TCs that experience RI during their lifetimes (RI-TCs) are more likely to attain a larger lifetime maximum intensity (LMI) than other TCs, since the majority (79%) of global TCs reaching major TC intensity (LMI ≥ 96 kt; Category 3+ on the Saffir–Simpson Hurricane Wind Scale) are RI-TCs (Lee et al 2016). Given that RI-TCs are typically of higher intensity, they also can generate extremely heavy losses. For example, Super Typhoon Haiyan (2013), one of the strongest TCs in the western North Pacific (WNP) on record, underwent an RI of 60 kt in 24 h (Lander et al 2014) and caused over 6300 fatalities and ~$2 billion US dollars in damage in the Philippines (Galvin 2014).

Given the scientific question of climate change’s impacts on TCs, several studies (Wang and Zhou 2008, Wang et al 2015, Wang and Liu 2016, Fudeyasu et al 2018, Kang and Elsner 2019, Song et al 2020, Zhang et al 2020) have investigated interannual-to-interdecadal variations as well as long-term trends related to RI over the WNP, which is the most TC-active basin around the world on an annually averaged basis (Chan 2005). On interannual timescales, the average number of RI-TC occurrences in El Niño years was notably higher than in La Niña years and so was the occurrence ratio of RI-TCs (Wang and Zhou 2008, Fudeyasu et al 2018). This El Niño year increase in RI-TCs was linked to more TCs forming over the southeast quadrant of the WNP. TCs forming in this area have a greater chance of passing through the region where RI events typically occur (Fudeyasu et al 2018). When examining RI events on interdecadal timescales from 1960 to 2016, Zhang et al (2020) found two active periods (1960–1972 and 2000–2016) with more RI-TC occurrences and a
higher RI-TC ratio, and one inactive period (1973–
1999) with fewer RI-TC occurrences and a lower RI-
TC ratio (Zhang et al 2020). TCs developing during the
period from 1973 to 1999 had a lower chance of expe-
riencing RI, because environmental conditions
were less favorable for RI development over the WNP
(Zhang et al 2020). Additionally, Kang and Elsner
(2019) reported an increasing proportion of RI-TCs
to the total number of TCs from 1986 to 2015, which
they largely attributed to global warming. They did
not find any significant trend in RI-TC number.

The aforementioned publications have mainly
focused on variations in the occurrence number of
RI-TCs, but few studies have investigated changes in
RI-TC intensity. Compared with other metrics of TC
intensity, LMI is considered to be an important stat-
tic for TC intensification, with the LMI distribution
being a vital property of the TC climatology (Emanuel
2000, Kossin et al 2014, Lee et al 2016). Several stud-
ies have found an increasing trend in the annual mean
LMI of the strongest TCs (TCs of at least typhoon
intensity) over the globe as well as in the WNP, spe-
cifically since the 1980s (Elsner et al 2008, Kang and
Elsner 2016, Sobel et al 2016, Song et al 2018, Knutson
et al 2019, Elsner 2020). Elsner (2020) recently repor-
ted that the 95th-percentile LMI of WNP typhoons
increased by 6.4% from 1981–2006 to 2007–2019,
while the largest increase for any basin and quantile
was 7.4% for the 75th-percentile LMI over the WNP.
The above results were primarily linked to the con-
tinued warming of the tropical oceans, with other envir-
onmental factors playing a lesser role (Elsner 2020).

Given that RI-TCs account for a large propor-
tion of intense TCs (Kaplan and DeMaria 2003, Lee
et al 2016), there has likely been an increasing tend-
ency in the mean LMI of WNP RI-TCs in recent
decades. Nonetheless, it has yet to be documented
how the annual mean LMI of RI-TCs has changed
over the WNP, and the impact of changes in envi-
ronmental variables on this potential trend remains
unclear. Therefore, these questions are investigated in
our study.

The paper is arranged as follows. Section 2 intro-
duces the datasets and methodology used in this
study. Section 3 discusses changes in the mean LMI
of WNP RI-TCs and its contributing factors. Section 4
provides a summary.

2. Data and methods

This study uses 6 h WNP TC best track data from the
Joint Typhoon Warning Center (JTWC) as provided
by the International Best Track Archive for Climate
Stewardship v04r00 (Knapp et al 2010). There are
known systematic errors in intensity estimates from
best track data, which are induced by inconsistent and
changing measurement technologies and reporting
practices (Emanuel 2000). To minimize these prob-
lems, this study uses best track data since 1970, as an
increasing fraction of intensity estimates have been
obtained entirely through satellite data since that time
(Emanuel 2000). Several other studies have also used
1970 as a starting point for their WNP TC ana-
lysis (Emanuel 2000, Kowch and Emanuel 2015, Wu
et al 2020). In addition, only TCs with an LMI of at
least 34 kt are considered in this study, in order to
reduce the uncertainty in detecting tropical depres-
sions (Klotzbach and Landsea 2015). TC LMI is iden-
tified when a TC first reaches its maximum intensity
(Kossin et al 2014). TC genesis is defined as the first
record when a TC reaches an intensity of at least 25 kt
(Schreck et al 2011). We use a 25 kt genesis threshold
for two reasons. First, 25 kt is the minimum intensity
that can be converted to a Dvorak current intensity
value from satellite imagery (Velden et al 2006),
implying that intensity estimates below 25 kt are of
low accuracy. Second, the LMI of a TC is theoretically
determined by both its lifetime average intensification
rate and its initial intensity. Having a fixed genesis
intensity means that the LMI of a TC is solely related
to its intensification rate. Our following results are
not significantly influenced by using other intensity
thresholds for genesis (e.g. 34 kt; figures not shown).
Since we focus on the intensification stage for TCs, a
RI-TC is defined as a TC experiencing at least one RI
process prior to its LMI. The RI ratio is computed as
the proportion of the number of 24 h periods where
RI cases occur (counted at 6 h intervals) to the num-
ber of all 24 h periods (counted at 6 h intervals) before
a RI-TC reaches its LMI. The magnitude of RI di-
rectly refers to the 24 h intensity change for individual
RI events (Balaguru et al 2018, Song et al 2020).
Our results that follow are not substantially changed if TC
best track data from either the Hong Kong Observa-
tory or the China Meteorological Administration are
used instead of JTWC (figures not shown).

Favorable large-scale oceanic and atmospheric
environmental factors are critical for WNP RI activ-
ity, including warm sea surface temperatures (SSTs),
high TC heat potential (TCHP), a moist lower and middle troposphere, low vertical wind shear
(VWS) and positive upper-level divergence (DIV)
(Shu et al 2012, Fudeyasu et al 2018, Knaff et al
2018). Monthly mean SST data on a 1° × 1° grid
are obtained from the Hadley Centre Sea Ice and
Sea Surface Temperature dataset (HadISST; Rayner
et al 2003). The HadISST-based monthly Niño 3.4
SST anomaly (SSTA) and Pacific Decadal Oscilla-
tion (PDO) index are obtained from the National
Oceanic and Atmospheric Administration (NOAA)
Earth System Research Laboratory’s Physical Sciences
Division (PSD). TCHP is estimated from monthly
subsurface temperature profiles provided by the
European Centre for Medium-Range Weather Fore-
casts (ECMWF) Ocean Reanalysis System, version 4
(ORAS4; Balmaseda et al 2013), with a 1° × 1° res-
olution. In addition, two atmospheric variables on
a monthly timescale, 700–500 hPa relative humidity

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and Liu \( p = 0.03 \). If we consider the period from 1982 to 2008 \( p = 0.01 \). If we consider the period from 1982 to 2008 \( p = 0.01 \). If we consider the period from 1982 to 2008 \( p = 0.01 \). If we consider the period from 1982 to 2008 \( p = 0.01 \).

3. Results

3.1. Increasing annual mean LMI of WNP RI-TCs

Figures 1(a) and (b) displays the annual mean LMI for all TCs and for RI-TCs over the WNP from 1970 to 2019. We find that the LMIs for all TCs and RI-TCs correlate significantly \((r = 0.58, p < 0.01)\), implying that they are modulated by similar factors on interannual timescales. However, we find a significant difference when investigating the long-term trends in the LMIs between all TCs and RI-TCs. During 1970–2019, there is little trend in the annual mean LMI for all TCs, whereas the annual mean LMI of RI-TCs significantly increases at a rate of 0.22 kt yr\(^{-1}\) \((p = 0.01)\). If we consider the period from 1982 to 2019, when TC best track data are likely of higher quality due to the near-global coverage of geostationary satellites (Kossin et al. 2014), the increase in annual mean RI-TC LMI remains significant \((0.27 \text{ kt yr}^{-1}, p = 0.03)\).

Figures 1(c) and (d) displays linear trends in individual quantiles of LMI for all TCs and RI-TCs over the WNP from 1970 to 2019, which are derived by least squares for individual quantiles of LMI as a function of year. Consistent with previous publications (Elsner et al. 2008, Song et al. 2018), higher and lower quantiles of LMI of all TCs generally yield positive and negative trends, respectively (figure 1(c)), implying that the weakest and strongest WNP TCs have occurred more frequently since 1970. Despite the fact that most strong TCs undergo RI (Lee et al. 2016), we find different features for trends in LMI quantiles for RI-TCs (figure 1(d)), compared with those for all TCs. There are significant positive tendencies in all LMI quantiles for RI-TCs from 1970 to 2019, indicating that both weak and strong RI-TCs attain a greater LMI. In addition, the LMI trend becomes slightly smaller with increasing quantile. These results indicate that RI-TCs exhibit greater increasing LMI trends for lower quantiles but do not experience a greater increasing trend in higher quantiles like all TCs do.

Given that WNP RI-TCs can be modulated by both El Niño-Southern Oscillation (ENSO) and the PDO (Wang and Zhou 2008, Wang et al. 2015, Wang and Liu 2016, Fudeyasu et al. 2018), the observed increase in RI-TC LMI could result from changes in ENSO or the PDO on decadal timescales. To test this, we use a technique similar to what was employed by Kossin et al. (2014) and linearly eliminate the contribution of ENSO or the PDO by regressing the RI-TC LMI time series onto the Niño 3.4 SSTA index and the PDO index, respectively. After performing this linear elimination, there are still no significant trends in the LMI residuals for all TCs (figure 1(e)). By comparison, the RI-TC LMI residuals continue to exhibit an increasing trend during 1970–2019, with a slope of 0.17 kt yr\(^{-1}\) \((p = 0.03)\) when the ENSO effect is removed and a slope of 0.24 kt yr\(^{-1}\) \((p < 0.01)\) when the PDO effect is removed (figure 1(f)). The change in the LMI residuals when both the ENSO and PDO effects are removed simultaneously is very similar to that when only the ENSO influence is excluded (figures not shown). These results imply that ENSO or PDO variability likely plays only a minor role in the observed increasing trend of RI-TC LMI.

3.2. Contributors to the increasing RI-TC LMI

It is well accepted that a TC spending a longer time over warm SSTs often attains a higher LMI (Wang and Chan 2002). However, we do not find a significant trend in the annual mean duration time from genesis to LMI for WNP RI-TCs from 1970 to 2019 (figure 2(a)). By comparison, the annual mean pre-LMI intensification rate for RI-TCs has significantly increased at a rate of 0.07 kt yr\(^{-1}\) \((p = 0.04)\) (figure 2(b)), serving as the primary reason for the aforementioned increase in the mean RI-TC LMI. Our findings are consistent with the increasing intensification trend for all WNP TCs during 1986–2010 shown by Kistawtal et al. (2012).

Bhatia et al. (2019) examined global and Atlantic TC intensification trends and found an increasing ratio of RI events globally, which induced an upward trend in TC intensification rates over the globe and in the Atlantic. However, when we only examine TC records prior to LMI over the WNP, the proportion of RI events has only increased slightly from 1970 to 2019 (figure 2(c)). Instead, we find a significant increasing trend in the mean magnitude of pre-LMI RI cases \((0.08 \text{ kt yr}^{-1}; p < 0.01)\) (figure 2(d)). Note that this trend is consistent with the increasing magnitude for all WNP RI events from 1979 to 2018 documented by Song et al. (2020). We also compute the correlation coefficients between the annual mean LMI of RI-TCs and the four metrics in figure 2. The change in the mean RI-TC LMI correlates significantly with the change in the mean RI magnitude \((r = 0.62, p < 0.01)\), whereas it does not significantly correlate with the variation in the average of duration time from genesis to LMI \((r = 0.24, p = 0.10)\), pre-LMI intensification rate \((r = 0.23, p = 0.11)\) or ratio of RI cases \((r = 0.11, p = 0.45)\). These results indicate that the observed increasing RI magnitude is the
primary reason for the increasing pre-LMI intensification rate over the WNP in the past half century.

There are two factors that may have led to the observed increase in RI magnitude. One possible factor is that more RI-TCs are passing through regions where more TCs climatologically have reached higher RI thresholds, and the other factor is that RI magnitudes have increased over certain portions of the WNP. Climatologically, WNP RI-TCs primarily exhibit westward or northwestward tracks prior to LMI (figure 3(a)). RI occurrence concentrates over the RI main development region (MDR: 10–20° N, 125–145° E), with nearly half (48%) of RI cases occurring in this area (figure 3(b)). There are also greater RI magnitudes over the MDR, with an average RI magnitude of 40 kt and 38 kt inside and outside the MDR, respectively (figure 3(c)). Although the difference in mean RI magnitude is small, it is statistically significant ($p < 0.01$).

Figure 3(d) shows that there are more northwestward moving RI-TCs and fewer westward moving RI-TCs over the WNP from 1970 to 2019, indicating a growing threat of RI-TCs to East Asia. This track change for RI-TCs over the past few decades is similar to that for typhoons as reported in Wu et al. (2005) and Park et al. (2014). However, there are no significant changes in TC occurrence over the MDR during 1970–2019, with only slight increases over the northwestern part of the MDR and slight decreases over the southeastern part of the MDR. We find that 167 out of 257 (65%) RI-TCs and 197 out of 281 (70%) RI-TCs passed through the MDR before reaching their LMIs in 1970–1994 and in 1995–2019, respectively. The difference in these two ratios is not
Statistically significant. In addition, consistent with changes in RI-TC tracks, there are more RI occurrences over the northern portion of the WNP and fewer RI occurrences over the southern portion of the WNP during 1970–2019 (figure 3(e)). Significant changes in RI occurrence are only found outside of the MDR, whereas the ratio of RI cases occurring inside the MDR remains virtually unchanged from 1970–1994 (54%; 574 out of 1054) to 1995–2019 (53%; 689 out of 1297).

By contrast, changes in RI magnitude from 1970 to 2019 exhibit distinctly different features compared with changes in RI occurrence (figure 3(f)). Although RI magnitude has slightly decreased east of 155° E, RI magnitude has increased west of 155° E where 90% (2110 out of 2351) of RI cases occurred during 1970–2019. The significant increase in RI magnitude west of 155° E can lead to an increase in intensification rate, as already shown in Park et al. (2013). Furthermore, significant RI magnitude increases are observed not only over the MDR but also to the north and east of the MDR. The above results imply that the observed increase in annual mean RI magnitude over the WNP is likely not caused by changes in RI-TC track but is largely induced by RI magnitude increases west of 155° E.

3.3. Environmental conditions influencing RI magnitude
As in previous studies (Wang et al. 2015, Ma et al. 2020, Song et al. 2020), variations in five oceanic and atmospheric factors (SST, TCHP, 700–500 hPa RH, 850–200 hPa VWS and 200 hPa DIV) are considered here to potentially impact changes in RI magnitude. Figure 4(a) shows significantly greater SSTs over almost all of the entire WNP in 1995–2019 than in 1970–1994, which is likely mostly due to anthropogenic global warming since 1970 (Brönnimann 2018). Moreover, there are significantly higher TCHPs over the tropical WNP from 1970 to 2019, with the largest TCHP increases concentrated over the region bounded by 10–20° N and 135–165° E (figure 4(b)). Although mid-level moisture has significantly decreased over the eastern portion of the Asian continent from 1970 to 2019, there are significant increases in 700–500 hPa RH over the tropical WNP south of 20° N, with the maximum increase in RH occurring over the equatorial WNP (figure 4(c)). Changes in SST and TCHP favor an increase in RI magnitude over nearly the entire tropical WNP, while changes in RH mainly favor an increase in RI magnitude south of 20° N. Our results are consistent with Park et al. (2013), which reported an important role of thermodynamic variables in the modulation of the intensification rate of WNP TCs.

Unlike thermodynamic factors which show RI-enhancing changes over relatively large regions, 850–200 hPa VWSs are significantly reduced from 1970 to 2019 only over a small region to the northeast of the Philippines (figure 4(d)), which could potentially enhance RI activity in this area. By contrast,
there are significant increases in 850–200 hPa VWS over the southeastern corner of the WNP, which is unfavorable for RI activity. Over the tropical WNP east of 155° E, it is very likely that the RI-suppressing effect of increased VWS offsets the RI-favoring effect of the warming ocean and the moistening atmosphere, leading to only slight changes in RI magnitude over this region from 1970 to 2019. In addition, there are greater 200 hPa DIVs over the region bounded by 10–20° N and 135–165° E (figure 4(e)), favoring RI development (Knaff et al. 2018). Over the same region, the increase in 200 hPa DIV is larger in the eastern part than in the western part, indicating that the RI-favorable effect of increasing 200 hPa DIV becomes more significant with increasing longitude. This result may explain why the RI magnitude increase is much greater east of 145° E than west of 145° E, as shown in figure 3(f).

RI-TC frequency over the WNP has been investigated in several previous papers (Wang and Zhou 2008, Fudeyasu et al. 2018, Zhao et al. 2018, Kang and Elsner 2019, Gao et al. 2020). During recent decades, there has been no noticeable long-term trend in the frequency of RI-TCs (Zhao et al. 2018, Kang and Elsner 2019, Gao et al. 2020). This finding indicates that the RI-favorable environment over the western WNP (figure 4) has a limited impact on increasing RI-TC frequency. Fudeyasu et al. (2018) reported that TCs forming over the southeastern quadrant of the WNP were more likely to go through the MDR and subsequently had a greater chance of experiencing RI. Therefore climate modes that influence TC formation over the eastern part of the WNP (e.g. the ENSO; Fudeyasu et al. 2018) can significantly modulate RI-TC frequency. If there were an increasing trend from 1970 to 2019 for TCs forming in the eastern portion of the WNP, more RI-TCs would be observed. However, the favorable effect of the warming ocean is likely balanced by the suppressing effect of increasing VWS over this region (figure 4), leading
Figure 4. Linear trends in May–November mean (a) SST, (b) TCHP, (c) 700–500 hPa RH, (d) 850–200 hPa VWS and (e) 200 hPa DIV from 1970 to 2019. Slopes significant at the 0.05 level are stippled.

to minor changes in RI-TC genesis (figure 3(b)) and a nearly unchanged RI-TC frequency.

4. Summary

This study investigates the long-term trend in the annual mean LMI of RI-TCs over the WNP as well as its causes from 1970 to 2019. Although there is no significant trend in the mean LMI for all TCs, there is a significant upward trend in the mean RI-TC LMI during 1970–2019. This significant upward trend is also observed when the effects of ENSO or the PDO are removed. These results are consistent with previous studies that have reported an increasing intensity of typhoons, in which RI-TCs account for a large proportion. We find no significant trend in the duration time for RI-TCs from genesis to LMI or the proportion of RI events. By contrast, the annual-average RI magnitude increased significantly between 1970 and 2019, likely inducing the observed increasing LMI of RI-TCs.

Although there has been a trend towards more (fewer) WNP RI-TCs with northwestward (westward) tracks prior to LMI from 1970 to 2019, there are no significant changes in TC occurrence over the MDR, where larger RI magnitudes are observed climatologically. This finding means that RI-TCs do not show an increasing tendency to pass through the MDR, so the observed increase in the mean LMI of RI-TCs is likely not due to changes in RI-TC tracks. By comparison, there are significantly greater RI magnitudes west of 155° E from 1970 to 2019, with slightly lower RI magnitudes east of 155° E. Since 90% of RI cases occur west of 155° E climatologically, the RI magnitude increases in this area are likely the primary reason for the observed increase in RI magnitude averaged over the entire WNP.

We find that changes in environmental conditions are likely responsible for the observed changes in RI magnitude over different sub-regions of the WNP. There are significantly greater SSTs, TCHPs, 700–500 hPa RHs and 200 hPa DIVs west of 155° E from 1970 to 2019, while significantly lower 850–200 hPa VWSs are only observed over a small region to the northeast of the Philippines. During 1970–2019, the RI-suppressing effect of increased VWS has likely offset the RI-favoring effect of the warming ocean and the moistening atmosphere east of 155° E, leading
to only slight changes in the RI magnitude in this region. These findings imply that both thermodynamic and dynamic variables have played an important role in modulating RI magnitude over the WNP. Their effects on RI magnitude may be of the same sign in some regions but may cancel each other out in other regions. In order to forecast changes in mean RI-TC LMI and RI magnitude over the WNP, we should not only consider the favorable effect of continued ocean warming that is projected by most climate models (IPCC 2013) but also examine projected changes in the large-scale atmospheric circulation.

Data availability statements

The data that support the findings of this study are openly available.

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