**Variability of Environmental Conditions for Tropical Cyclone Rapid Intensification in the Western North Pacific**

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(Manuscript received 27 September 2021, in final form 11 March 2022)

ABSTRACT: How environmental conditions vary among rapidly intensifying tropical cyclones (TCs) and which factors can help offset negative factors for intensification were examined using a dataset of geostationary satellites and environmental diagnostics. The dataset contains TCs in the western North Pacific from 1995 to 2020. A cluster analysis was performed to classify different morphologies of TC cloud patterns at the onset of rapid intensification (RI). Six clusters were identified, and each cluster had a distinct set of environmental conditions. Three clusters (clusters 1, 3, and 5) had some conditions unfavorable for RI. Cluster 1 TCs were exposed to moderate vertical (850–200 hPa) shear (\(\sim 6 \text{ m s}^{-1}\)). Relatively high sea surface temperature, a moist environment, and movement toward environments with weak vertical shear, high equivalent potential temperature, and high ocean heat content are potential factors that resist the effects of vertical shear. Cluster 3 TCs were characterized by a large 30-kt wind radius and moderate vertical shear (1 kt \(\approx 0.51 \text{ m s}^{-1}\)). Large storm size and a moist environment caused by large-scale, strong, low-level convergence are possible factors for vortex resiliency against shear. Cluster 5 TCs were located in a very dry environment. Weak vertical shear and small storm size are factors that may offset the negative effects of dry air and ocean cooling. The results suggest that in the case of RI with negative conditions for intensification, other factors can offset the negative impacts of those conditions and that suitable combinations of environmental conditions and TC structural features are important for RI.

KEYWORDS: Wind shear; Tropical cyclones; Hurricanes/typhoons; Storm environments

1. Introduction

It is essential for operational centers to issue tropical cyclone (TC) intensity forecasts as accurately as possible to reduce the risks of disaster and number of victims from TCs. Currently, rapid intensification (RI) prediction is the biggest challenge (e.g., Courtney et al. 2019). Improving our understanding of RI and the accuracy of RI prediction is especially important because almost all intense TCs experience RI (e.g., Kaplan and DeMaria 2003).

The basic requirement for TCs to experience RI is favorable environmental conditions. RI events occur in an environment with weak vertical shear, high sea surface temperature (SST), high ocean heat content (OHC), high relative humidity (RH), and strong upper-level divergence (Kaplan and DeMaria 2003; Kaplan et al. 2010; Hendricks et al. 2010), although strong upper-level divergence may be just a result of strong outflow from intensifying storms (e.g., Komaromi and Doyle 2017). In contrast, strong vertical shear and a dry environment are known to be factors that can adversely impact intensification (e.g., DeMaria and Kaplan 1994, 1999; DeMaria et al. 2005; Paterson et al. 2005; Wang et al. 2015; Rios-Berrios and Torn 2017). The mechanisms of TC weakening by vertical shear include 1) the ventilation effect of an upper-level warm core by relatively strong upper-level wind (Frank and Ritchie 2001), 2) the midlevel ventilation of dry air into the eyewall (Tang and Emanuel 2010), and 3) a process in which low equivalent potential temperature \(\left(\theta_e\right)\) air caused by shear-induced downdrafts enters the eyewall region through the inflow boundary layer (Riemer et al. 2010). It is important to note, however, that the existence of dry air does not necessarily lead to TC weakening because the effect of dry air on TC intensity can vary depending on the location of the dry air relative to the TC (Ge et al. 2013; Wu et al. 2015).

However, intensification rate is not determined solely by environmental conditions. Hendricks et al. (2010) showed that there was little difference in environmental conditions between rapidly intensifying and slowly intensifying TCs. They hypothesized that internal processes could cause differences in intensity change. Recent studies have shown that internal processes characterized by structural features are closely related to intensity changes. At around the onset of RI, the distributions of potential vorticity and precipitation become symmetric (e.g., Miyamoto and Takemi 2013; Shimada et al. 2017) and the vortex becomes upright (e.g., Finocchio et al. 2016; Munsell et al. 2017; Miyamoto and Nolan 2018). TCs undergoing RI also tend to be more compact than other TCs (Carrasco et al. 2014), and vigorous convection preferentially occurs inside the radius of maximum wind (RMW) during RI (e.g., Rogers et al. 2013). RI ceases, however, during eyewall replacement cycles (e.g., Sitkowski et al. 2011).

RI occurs under different conditions, including in hostile environments (e.g., Molinari and Vollaro 2010; Shimada and Horinouchi 2018). Rios-Berrios and Torn (2017) investigated...
Intensifying and steady-state TCs under moderate vertical shear (4.5–11.5 m s\(^{-1}\) between 850 and 200 hPa levels) and found that intensifying TCs were larger and more intense than steady-state TCs, and they moved toward environments with higher SSTs and greater midlevel humidities. Hendricks et al. (2010) investigated environmental variability in RI TCs in the western North Pacific (WNP) and the North Atlantic (ATL). They found the following relationships for RI TCs: (i) a positive correlation between upper-level divergence and deep-layer shear, (ii) a positive correlation between upper-level divergence and SST, (iii) no relationship between SST and deep-layer shear in the WNP, but a positive correlation between them in the ATL, and (iv) a negative correlation between convective instability and deep-layer shear. They reported that in many RI events, unfavorable conditions were overcome by compensating factors. The variability of environmental conditions for RI may make RI prediction difficult.

How can the variety of environmental conditions associated with RI be classified? And, if there are unfavorable conditions for RI events, what factors can nonetheless allow for intensification? As far as we know, no study has examined representative combinations of environmental conditions associated with RI. If some representative combinations are found, they may enable RI prediction to be improved. RI TCs are considered to have various structural features that can be attributed to differences in environments and internal processes. Therefore, the different conditions associated with RI events may be categorized based on TC structure.

The purpose of this study is to identify the different environmental conditions associated with RI that can be classified by the structural features of the TCs, to examine how those conditions contribute to RI, and to determine which factors can help offset any unfavorable conditions. We performed a cluster analysis using geostationary satellite data to identify the different morphologies of TC cloud patterns at the onset of RI in the western North Pacific during 1995–2020. We then used a composite approach to identify differences in synoptic flow patterns, thermodynamic conditions, and TC structures between clusters. The results can lead to a better understanding of the different possible scenarios leading to RI.

2. Data and methods

a. Data

The dataset used in this study includes best track data from the Regional Specialized Meteorological Center (RSMC) Tokyo, Dvorak analysis (Dvorak 1984) data performed by the Japan Meteorological Agency (JMA), hourly geostationary satellite data, the Japanese 55-year Reanalysis (JRA-55) data (Kobayashi et al. 2015), and the developmental data for the JMA version of the Statistical Hurricane Intensity Prediction Scheme (SHIPS), which has been named the Typhoon Intensity Forecast Scheme based on SHIPS (TIFS; Ono et al. 2019). The dataset covers the period from 1995 to 2020. In 1995, the Himawari-5 satellite (Geostationary Meteorological Satellite 5) began observations with both infrared (IR) and water vapor (WV) channels. The Dvorak data are the same as those used by Shimada et al. (2020) and do not include three TCs (Angela, Zack, and Brian) that occurred in 1995.

The TIFS developmental data include best track intensity, various kinds of atmospheric environmental conditions associated with TCs obtained from JRA-55 data, OHC obtained from the Meteorological Research Institute multivariate ocean variational estimation system (MOVE/MRI.COM; Usui et al. 2006), and SST from the Centennial Observation-Based Estimates of SST (COBE-SST; Ishii et al. 2005). The maximum 10-min sustained wind speed (Vmax) of a tropical depression before reaching the strength of a tropical storm was set to 30 kt (1 kt ≈ 0.51 m s\(^{-1}\)) in accord with conventional JMA practice (e.g., Shimada et al. 2018). Table 1 lists the TIFS predictors used in this study. Vertical shear parameters (both 850–200-hPa shear and 850–500-hPa shear) in the TIFS developmental data were not calculated by removing a TC vortex. We confirm in section 3 that vertical shear parameters calculated from large-scale flow in which small disturbances were filtered out (Kurihara et al. 1993; Wang et al. 2015) are consistent with vertical shear parameters

<table>
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<tr>
<th>TABLE 1. Description of TC information and TIFS predictors used in this study. Note that although the size of storms varies from case to case, the same parameters as TIFS predictors are used here.</th>
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<tr>
<td><strong>Description</strong></td>
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<tr>
<td>Size (R30) (km)</td>
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<tr>
<td>Forward speed (m s(^{-1}))</td>
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<td>SST (°C)</td>
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<td>OHC (kJ cm(^{-2}))</td>
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<td>850–200-hPa shear (m s(^{-1}))</td>
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<td>700–500-hPa RH (%)</td>
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taken from the TIFS developmental data. Furthermore, we calculated vertical shear by the method used in Davis et al. (2008) and Galarnue and Davis (2013), in which a vortex is removed by a Poisson equation. The magnitude of the calculated vertical shear was slightly larger than that of the TIFS data, but the differences in the magnitude of the vertical shears between clusters were similar to those of the TIFS data (not shown). In this study, we thus decided to use the vertical shear from the TIFS developmental data and to use the synoptic shear flow patterns in which small disturbances were filtered out. This decision enabled us to compare between the RI sample mean and TIFS sample mean of vertical shear parameters.

To use the historical geostationary satellite data properly, recalibration was conducted to correct biases in the satellite data by using regression coefficients provided by Tabata et al. (2019). In this recalibration, polar orbiting sounders were used as references (John et al. 2019). To reduce differences in brightness temperatures between the satellite sensors (due to spectral differences between sensors), the brightness temperatures were then converted to values that were equivalent to the temperatures of the Multifunctional Transport Satellite 2 (MTSAT-2) by applying spectral band adjustment factors. In this study, the horizontal resolution of the satellite data used was converted to 0.05°.

b. RI definition

In this study, RI events were selected based on intensity from the Dvorak data. Best track data were not used because it has been found that the quality of the best track data has changed as a result of the recent increase in observations (Shimada et al. 2020). In this study, RI is defined as a T-number1 increase of at least 2 over a 24-h period. This increase is equivalent to an increase of 28–30 kt (maximum 10-min sustained wind) according to the conversion table (according to the conversion table provided by Koba et al. (1991) and corresponds approximately to the 95th percentile of T-number changes over a 24-h period (not shown). Although JMA estimates intensities even below a T number of 2.0 for tropical disturbances and depressions (Tsuchiya et al. 2001; Kishimoto et al. 2007; Kishimoto 2009), the onset of RI in this study was limited only when the T number is 2.0 or more. Note that Dvorak intensity is not the same as best track intensity because the best track intensity is determined by various kinds of observations. Thus, there were 23 cases in which the best track intensity was below the strength of tropical storm at the onset of RI. Additionally, if the T number remained the same during the first 6-h period that satisfied the RI definition, that period was excluded from the RI period to determine the onset of RI. Each successive period satisfying the RI definition was counted as one RI event.

In total, 239 RI events were identified. To perform a cluster analysis of cloud patterns within a domain of 10°×10° in the Northern Hemisphere, one RI event (Typhoon Bopha in 2012) was tossed out because its satellite domain was partially in the Southern Hemisphere.

c. Methods

1) Cluster analysis

A K-means cluster analysis was performed to identify different morphological types of TC clouds at the onset of RI. To eliminate the effect of transient strong convection on the morphology, IR brightness temperature data averaged from 0 h (i.e., RI onset) to +6 h with a spatial resolution of 0.15° in a region of 10°×10° centered at the TC center were used for the cluster analysis. In this study, the candidate number of clusters was initially determined to be 5–7 by using the elbow method, which finds the number of clusters that significantly decreases the sum of squared distances between samples in each cluster. We also tried to identify the number of clusters via the silhouette analysis (Rousseeuw 1987), which determines the number of clusters based on a metric of both the degree of cohesion within each cluster and the degree of separation between clusters. However, the metric of the silhouette analysis did not show an optimal number of clusters within the range from 3 to 8. We then used the following three criteria:

(i) clusters include comparable numbers of samples,
(ii) the mean morphologies of the clusters differ between clusters, and
(iii) the morphologies of samples within each cluster do not differ greatly.

We found that 6 was an optimal number of clusters.

2) Large-scale flow

We made a composite of environmental conditions for each cluster using JRA-55 data. To obtain the large-scale environment within which small disturbances were removed, we applied the filtering method used by Kurihara et al. (1993) and Wang et al. (2015). Filtering was performed in both zonal and meridional directions to remove disturbances with a wavelength of less than ~10°. The resultant large-scale flow was used to calculate large-scale vertical shear with no vortex.

3) Okubo–Weiss parameter

Whether dry air adversely impacts a TC depends on the magnitude of the vertical shear and on whether the storm-relative flow is a closed circulation from a Lagrangian perspective (e.g., Dunkerton et al. 2009; Raymond et al. 2011; Wu et al. 2015). A large strain can disrupt rotational flow and can lead to the entrainment of environmental dry air into the inner core. Raymond et al. (2011) proposed a metric for the relative strength of the strain, the normalized Okubo–Weiss (OW) parameter, NOW, which quantifies the extent to which the horizontal flow is rotational or strained as follows:

$$\text{NOW} = \frac{\xi^2 - \sigma_1^2 - \sigma_2^2}{\xi^2 + \sigma_1^2 + \sigma_2^2}$$

1 The T number is determined based on TC cloud patterns in the Dvorak analysis.
2 T-number 2.0 is equivalent to ~36 kt in the conversion table used by the JMA (Koba et al. 1991).
where $\zeta$ is the relative vorticity, $\zeta = (\partial v/\partial x) - (\partial u/\partial y)$, $\sigma_1 = (\partial v/\partial x) + (\partial u/\partial y)$, and $\sigma_2 = (\partial u/\partial x) - (\partial v/\partial y)$. Here, $u$ is the zonal wind, and $v$ is the meridional wind. NOW = 1 indicates complete rotational flow, whereas NOW = −1 indicates complete strained flow. We use this parameter for the composite analysis.

3. Cluster analysis results

a. Six clusters

The composite-mean IR cloud patterns of the six clusters (Fig. 1) show that while cloud morphology varies between clusters at the onset of RI, the asymmetry of the vortex is related to the direction and magnitude of vertical wind shear.3 Roughly speaking, clusters 1 and 2 are northerly shear cases, cluster 3 is an easterly shear case, cluster 4 is a southerly shear case, and clusters 5 and 6 are westerly shear cases. The areal extent of low brightness temperatures is larger on the downshear side than on the upshear side. The cloud morphology is more asymmetric for the clusters with relatively strong vertical shear (i.e., clusters 1 and 3) than for the other clusters. The structure is symmetric for the weak shear case (i.e., cluster 5). Note that the direction of vertical shear varies more widely in cluster 5 TCs than in the other TCs (not shown) because relatively weak shear has little effect on an asymmetric cloud pattern. One might expect that smaller sets of clusters could be obtained if the morphology of TC cloud patterns was put in a shear-relative coordinate system. We, however, found that characteristics such as location, season, and large-scale environmental conditions differed between the clusters obtained here. In this study, we therefore show the variability of RI events based on the six clusters obtained.

The evolution of the mean $V_{\text{max}}$ for each cluster from 24 h prior to 24 h after the onset of RI reveals little difference between the clusters (Fig. 2). The mean $V_{\text{max}}$ at the onset of RI is about 25 m s$^{-1}$, and it increases to 38 m s$^{-1}$ in 24 h. This increase in $V_{\text{max}}$ of 13 m s$^{-1}$ over a 24-h period is equivalent to an increase of $\sim 25$ kt, which is slightly less than the common definition (30 kt over a 24-h period) of RI (i.e., Kaplan and DeMaria 2003 or the increase of 28–30 kt in the conversion table of Koba et al. 1991). This discrepancy is due mainly to the fact that the 24-h intensity changes in best track data provided by RSMC Tokyo tended to be smaller than the values from the conversion table before 2006 when microwave satellite data started to be used for constructing best track data (Shimada et al. 2020).

Locations and seasons of RI occurrence differ between the clusters. Each cluster tends to be concentrated in a specific area (Fig. 3a). Roughly speaking, cluster 1 tends to be in the waters off the eastern coast of the Philippines. Clusters 2 and 4 are located mainly between 10° and 20°N. Cluster 3 is located mainly south of 17°N. Cluster 5 tends to be located mainly north of 20°N latitude. Cluster 6 is located mainly between 15° and 25°N. There is no occurrence over the South China Sea for clusters 5 and 6. Forward speed, however, does

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3. The composite-mean shear direction was calculated in a complex coordinate system.
not differ significantly between the clusters (Fig. 3b), although 51% of the forward speeds of cluster 4 TCs exceed 6.0 m s$^{-1}$. Although most of the RI events occurred during the active season for typhoons (defined as the period from June to October) (Fig. 3c), about 40%-50% of the cluster 3 and 4 TCs occurred in the typhoon inactive season (defined as the period from January to May and from November to December). The difference of the seasons of RI occurrence between the clusters may be related to the latitudinal differences between the clusters.

The features shown above suggest that TC cloud patterns are affected by specific environmental conditions, including monsoonal flows as well as seasonal and intraseasonal changes. Yoshida and Ishikawa (2013) categorized environmental flow patterns at the time of TC genesis into five groups (monsoon shear line, monsoon confluence region, monsoon gyre, easterly wave, and preexisting TC). Fudeyasu and Yoshida (2018) investigated TCs classified based on these five flow groups and indicated that differences in genesis environment affected TC size and intensification after genesis. As with their findings, six clusters may be characterized by environmental flow patterns that can determine the variability of structural features at the onset of RI.

b. Environmental conditions associated with the six clusters

To characterize environmental conditions associated with the six clusters, some of the structural parameters and TIFS predictors at the onset of RI were examined first (Fig. 4, Table 2). TIFS predictors have often been used for not only statistical–dynamical models, but also the characterization of environmental conditions associated with TCs. Welch’s $t$ test was used to determine whether there was a statistical difference between the mean value of a given cluster and the mean value of the other clusters at the 5% significance level. In addition to the predictors that are actually used in the TIFS regression equation (Ono et al. 2019; Yamaguchi et al. 2018), SST, low-level (850–500 hPa) vertical shear, and temperature at 100 hPa (T100) were also examined. Furthermore, maximum potential intensity (MPI; Bister and Emanuel 2002) was examined. The radius of 30-kt wind speed (R30) is proportional to the radial extent of the low brightness temperature (Fig. 1g). The T100 value is related to the tropopause temperature, which increases with latitude. The magnitude of MPI is determined mainly by the temperature at 200 hPa (T200) and SST; the MPI increases with an increase of SST and a decrease of T200.

Compared to the sample mean values of TIFS predictors and their signs in the coefficients of the multiple regression equation for the 24-h TIFS forecast ($t = 24$ h), the mean values of TIFS predictors in each cluster are generally favorable for intensification (Table 2). Some parameters, however, vary greatly from cluster to cluster, and some clusters have apparently negative factors, including 700–500-hPa RH (%) and 200-hPa divergence.

Clusters 1 and 3 are similar to each other in that there are stronger vertical shear, richer midlevel moisture, and higher temperatures at 200 hPa than there are in the other clusters. In addition, cluster 1 TCs intensify in an environment with relatively high SST (29.7°C). For cluster 3, the R30 and upper-level divergence are the largest among the clusters (335.5 km and 91.6 $\times$ 10$^{-7}$ s$^{-1}$, respectively). Cluster 2 is characterized by a relatively large R30 (318.4 km), weak deep-layer shear (4.1 m $s^{-1}$), rich midlevel moisture (62.1%), and large upper-level divergence (84.6 $\times$ 10$^{-7}$ s$^{-1}$). From the perspective of TIFS prediction, cluster 2 TCs reside in very favorable conditions. For cluster 4, R30 is relatively small (242.7 km), SST is the lowest among the clusters (29.1°C), and midlevel humidity is relatively poor (54.2%). Compared to the predictor values of the TIFS model, however, these values are not necessarily unfavorable. Also, not significant though, the slightly fast forward speed of cluster 4 TCs is a factor that can offset the impact of SST cooling. Clusters 5 and 6 are similar to each other in that they are characterized by a relatively small R30, dry atmosphere, and weak upper-level divergence. Weak upper-level divergence implies less upper-level outflow and a field where large-scale upward motion in the troposphere tends to be suppressed. For cluster 5, 18% of the TCs are present in an environment with negative upper-level divergence. SST is relatively low compared to the other clusters, although even this low value is much higher than the mean SST of TIFS prediction; 29% of cluster 5 TCs intensify over the ocean with OHCs less than 50 kJ cm$^{-2}$. The very weak deep-layer shear (3.4 m $s^{-1}$), however, is the only environmental factor favorable for intensification for cluster 5. The largest MPI among the clusters (75.4 m $s^{-1}$) that characterizes cluster 6 is attributed to its lowest temperature at 200 hPa among the clusters with normal SST.

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**FIG. 2.** Temporal evolution of Vmax from 24 h prior (${-24}$ h) to 24 h after (+24 h) the onset of RI. Note that there are 27, 12, and 4 cases that are not described in the best track data at $-24$, $-18$, and $-12$ h because they did not even become a tropical depression at those times. They are not included in the calculation of the mean values. C1, 2, 3, 4, 5, and 6 denote clusters 1, 2, 3, 4, 5, and 6, respectively.

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*Here, the radius of 30-kt wind speed (R30) needed to be averaged from 0 to +6 h after RI onset because 23 and 3 cases in this study were below tropical storm strength as of 0 and 6 h, respectively. As a result, 3 cases were not included in the calculation of R30.*
In summary, each cluster is characterized by a distinct set of environmental conditions. In particular, clusters 1, 3, and 5 are characterized by some conditions unfavorable for RI, including relatively strong vertical shear (moderate vertical shear) and a dry environment. In the next section, synoptic-scale flow patterns that surround RI TCs are examined through a composite analysis to determine what factors can help offset the negative factors.

4. Composite analysis

In this section, clusters 1, 3, and 6 are first examined from the perspective of how the detrimental impact of vertical shear is offset by other factors. Cluster 5 is then examined with a focus on the effect of a dry environment, and then finally the other two clusters are briefly examined. The composite analysis was conducted in an Earth-relative coordinate system to reveal common synoptic atmospheric situations in which a TC for each cluster was located at the onset of RI. Additionally, the composited OHC distribution 2 days before the onset of RI is provided to characterize an oceanic condition before the passage of a TC. The composite fields are plotted relative to the mean center position of each cluster. A significance test is conducted to check whether the environments for a given cluster are statistically different from the others.

a. TCs under moderate vertical shear

1) CLUSTER 1

The cluster 1 TC is, on average, located on the southeast side of a high pressure system at 200 hPa (Fig. 5a), where northeasterly divergent flow dominates and produces moderate vertical shear (Fig. 5b). The large-scale wind field where small disturbances are filtered out provides slightly stronger vertical shear (~7.2 m s\(^{-1}\)) than the TIFS’s vertical shear (~6.2 m s\(^{-1}\)). The cluster 1 TC, however, is moving toward an area where vertical shear is relatively weak and midlevel dry air exists under the high pressure system when RI starts (Figs. 5b,d,e). The weaker vertical shear on the upshear side than on the downshear side implies that it is difficult for midlevel dry air to flow into the storm on the upshear side, whereas it is easy for low-level moist air to flow into the storm on the downshear side. In addition, the normalized OW parameter indicates that strain is small relative to vorticity in the inner core, although vorticity distribution is slightly displaced toward the downshear side likely due to vortex tilt (e.g., Reasor et al. 2013) in the reanalysis data (Fig. 5f). The movement of cluster 1 TCs to a dry area thus does not appear to prevent intensification because the vertical shear and strain around the TCs are weak.

Cluster 1 lies near an area where there is large-scale, low-level convergence associated with southwesterly moist flow and upper-level northeasterly divergence (Figs. 6a,b). A pair of large-scale convergence and divergence can often be seen in the WNP in an area of a monsoon trough, in which the low-level wind in the equatorward portion is westerly. Also, the spatial pattern of large-scale, low-level flow is similar to a phase of the boreal summer intraseasonal oscillation (BSISO) (Lee et al. 2013). While monsoonal flow conveys moisture to the downshear side of a storm, large surface latent heat fluxes southeast of the TC provide moisture mainly on the upshear side (Fig. 6c). In addition, cluster 1 tends to include cases that move toward areas with higher \(u_e\), higher convective available potential energy (CAPE), and higher OHC (e.g., warm eddies) than the areas around the TCs (Figs. 6d–f). Thermodynamically,
these factors as well as high SST (Table 2) are presumably favorable for offsetting low-\(\theta_e\) air caused by downdrafts associated with moderate vertical shear (Riemer et al. 2010).

The environmental conditions are consistent with the evolution of actual convective activity on both the upshear and downshear sides of cluster 1 TCs (Fig. 7). Infrared minus water vapor (IRWV) channel brightness temperatures provide an indication of vigorous convection because negative values of IRWV indicate that convection is overshooting into the stratosphere (Olander and Velden 2009). A Hovmoller diagram shows that downshear convection is already active well before the onset of RI, whereas upshear convection becomes as active as downshear convection after the onset of RI. The enhancement of upshear convection after RI is consistent with the decrease in vertical shear. Areas with negative composite-mean IRWV values extend to 150 km from the center on the upshear side as RI continues, and the cloud structure with negative composite-mean IRWV values becomes more symmetric by 24 h after the onset of RI compared to the cloud structure at the onset of RI. The cloud pattern, however, remains very asymmetric outside a radius of 150 km, even after RI.

2) CLUSTER 3

The cluster 3 TC is, on average, located southwest of an upper-level anticyclone (Fig. 8a). It is sandwiched by strong vertical shear zones on its north and south sides (Fig. 8b). Since 37% of cluster 3 TCs occurred in the inactive typhoon season (Fig. 3c), it is likely that the strong vertical shear on the north side of the TC reflects a jet south of Japan during the inactive season. Both deep-layer shear and low-level shear are relatively strong on the downshear side for cluster 3 (Figs. 8b,d). The magnitude of deep-layer shear does not change during RI (Fig. 8e). Although very dry air at 500 hPa is seen more than 600 km north of the TC, RH is more than 70%
within ~270 km from the TC center (Fig. 8e), which is broader than the other clusters. Also, the areal extent of midlevel humid air is larger on the southeastern side of the TC, where the normalized OW parameter is relatively large (Fig. 8f).

Large cluster 3 TCs are located in a large-scale cyclonic circulation (Fig. 9a), which may be referred to as a monsoon gyre (Lander 1994). The magnitudes of low-level convergence and upper-level divergence are more than twice the corresponding magnitudes of small-size cluster 5 TCs (see section 4b). The synoptic patterns of the upper-level anticyclone northeast of cluster 3 TCs and the low-level cyclonic circulation are similar to those of the RI composite in the WNP reported by Hendricks et al. (2010). The large-scale, strong low-level convergence, large surface latent heat fluxes over a broad area, surface θe air greater than 360 K around the TC center, surface CAPE greater than 1000 J kg\(^{-1}\) (though lower than the other clusters), and OHC greater than 90 J cm\(^{-2}\) in a region within ~400 km from the TC center (Figs. 9a,c-f) are favorable to maintain a moist, midlevel environment. As with cluster 1, rich moisture environment could alleviate the effect of low-θe air caused by vertical shear (Riemer et al. 2010).

The characteristics of cluster 3 TCs are consistent with previous studies that have shown that in a moist environment, a large TC develops with active rainbands and strong winds in its outer region (Kimball 2006; Hill and Lackmann 2009; Wang 2009). In addition, Chen et al. (2018) found through a statistical analysis that when an Earth-relative, low-level mean flow was directed in a right-of-shear orientation, surface fluxes increased more on the upshear side than on the downshear side, and storm-relative low-level moist outflow on the upshear side enhanced downshear rainbands, leading to an expansion of the TC. Cluster 3 is characterized by a low-level flow directed toward a right-of-shear orientation on the upshear side (e.g., Fig. 9c). Large storm size may favor resistance to moderate vertical shear (5.9 m s\(^{-1}\)). Section 5 includes further discussion of this point.

The more vigorous convection in the region of negative IRWV values on the downshear side than on the upshear side near the center of cluster 3 TCs before the onset of RI is consistent with the magnitude of vertical shear (Fig. 10). The area of active convection gradually expands on both the downshear and upshear sides within 12 h of the onset of RI, but the expansion stops after an eye emerges around the center. Outside a radius of 200 km, the continuity of the very asymmetric cloud pattern, even after the onset of RI, is consistent with the presence of dry air.

3) CLUSTER 6

Figures of cluster 6 TCs are provided in the online supplement. Except for vertical shear, the synoptic features of cluster 6 (Fig. S7) are similar to those of cluster 5, which is shown in the next subsection. The characteristics of vertical shear for cluster 6 are briefly described here. Cluster 6 TCs tend to be located east of an upper-level high pressure system. The deep-layer vertical shear is strong on the northeastern side of cluster 6 TCs (Fig. S7b). The mean value of the deep-layer vertical shear is near the average for all RI TCs (Table 2), but 32% of cluster 6 TCs experience RI in an environment with deep-layer vertical shear greater than 6 m s\(^{-1}\) (e.g., Fig. 4e). Low-level vertical shear, however, is weak compared to the other clusters (Fig. S7d); 89% of cluster 6 TCs occurs in an environment with low-level vertical shear less than 3 m s\(^{-1}\) (Fig. 4f). Finocchio et al. (2016) demonstrated through idealized numerical simulations that differences in vertical shear
profiles affected intensification; small shear increments at low levels were more favorable for intensification than large shear increments at low levels under the same magnitude of 200–850-hPa shear.

b. TCs in a dry environment

Cluster 5 TCs have unusual features compared to what statistics indicates to be generally favorable conditions for RI: a dry environment and less upper-level divergence (Fig. 4, Table 2). The composite analysis shows that the cluster 5 TC is surrounded by dry air with an RH of less than 50% at midtroposphere (Fig. 11e). The dry environment is likely related to the small size of cluster 5 TCs. The TC is located under an upper-level, Tibetan, high pressure system that expands eastward (Fig. 11a). This configuration results in a weak deep-layer shear of less than 4 m s\(^{-1}\) (Fig. 11b). Low-level vertical shear is also weak (Fig. 11d). RI starts when vertical shear is a minimum (Fig. 11c).

The effects of dry air on intensification have been investigated through numerical experiments and observations. The proximity of a dry-air environment can be a negative factor through dry intrusion (e.g., Kimball 2006; Shu and Wu 2009). The impact of dry air, however, depends on its location relative to the direction of vertical shear and to the eyewall (e.g., Braun et al. 2012; Ge et al. 2013), horizontal flow patterns (Wu et al. 2015), storm intensity and size (Riemer and Montgomery 2011; Sippel et al. 2011), and the magnitude of vertical shear (Riemer and Montgomery 2011). Braun et al. (2012) showed in their numerical experiments that the existence of midlevel dry air outside ~3 times the RMW under no shear condition can shrink the size of a storm but has no
impact on storm development. Ge et al. (2013) investigated the effect of midlevel dry air on intensification under shear conditions through idealized experiments. They demonstrated that a TC cannot intensify due to the suppression of downshear convection when dry air exists on the downshear side. In contrast, the development of downshear convection enhances the secondary circulation, and a TC can eventually intensify when there is dry air on the upshear side. Wu et al. (2015) showed that the impact of a dry-air environment on intensification is insignificant and that moist air perturbation prescribed ahead of the storm path can rather have a negative impact on intensity. They mentioned that the key point is whether there is dry air in a region where entrainment into the inner core occurs in a Lagrangian circulation. In general, low-level outflow is present in the upshear region (e.g., Reasor et al. 2013), and thus dry air upshear of the TC may not affect the inner core convection for TCs of tropical storm strength if vertical shear is weak.

Cluster 5 TCs are surrounded by dry air, especially on their upshear side under weak vertical shear (Fig. 11e). A normalized OW parameter is low at a radius of 500 km from the center, but it is as high as the values of the other clusters near the TC center (Fig. 11f). These characteristics may prevent dry air from flowing into the inner core of cluster 5 TCs. Cluster 5 demonstrates that the proximity of dry air does not necessarily impede RI. Further studies will be needed to elucidate under what conditions the presence of dry air can impede RI in the western North Pacific. Those studies should involve analyses of non-RI TCs in a dry environment similar to cluster 5.

Large-scale, low-level convergence and upper-level divergence are both weak for cluster 5 compared to the other clusters (Figs. 12a,b). At the surface, the easterly wind is dominant (Fig. 12c). This fact suggests that cluster 5 TCs are located in easterly waves. Streamlines derived from the composite-mean storm-relative flow indicate that low-$\theta_e$ air on the
western side of a cluster 5 TC does not move directly toward the center (Fig. 12d). Instead, it moves to the eastern side of the storm, where the wind is stronger than in other areas because of the steep pressure gradient between the storm and a subtropical, high pressure system. This configuration leads to enhanced sea surface latent heat fluxes there (Fig. 12c).

The air then moves to the center while acquiring high $\theta_e$ (Fig. 12d). Although cluster 5 TCs are embedded in regions with low $\theta_e$ and CAPE at the surface because of their higher latitude locations (Fig. 3a), values of $\theta_e$ and CAPE within 500 km from the TC center (Figs. 12d,e) are comparable to those of the other clusters. These environments potentially

![Fig. 7. (a) Hovmöller diagram of composite-mean, downshear-mean differenced IR and WV brightness temperature for cluster 1 TCs. (b) As in (a), but for the upshear mean.](image)

![Fig. 8. As in Fig. 5, but for cluster 3 TCs.](image)
contribute to active convection in the inner core of cluster 5 TCs. Rappin and Nolan (2012) showed that when the direction of vertical shear is opposite to the direction of the surface wind, enhanced surface fluxes on the left of shear moisten the upshear region and allow convection to propagate upshear. That upshear propagation leads to a small vortex tilt, TC genesis, and subsequent intensification. In this sense, RI in cluster 5 occurs in a configuration that offsets effects associated with the dry environment. The composite-mean OHC of cluster 5 is significantly lower than that of the other clusters, which is discussed in section 5. The evolution of the IRWV channel brightness temperatures shows that convection becomes active on both the downshear and upshear sides simultaneously around the onset of RI, and cloud structure becomes symmetric (Fig. 13).

![Graph](image-url)

**Fig. 9.** As in Fig. 6, but for cluster 3 TCs.

![Graph](image-url)

**Fig. 10.** As in Fig. 7, but for cluster 3 TCs.
c. Other TCs

Clusters 2 and 4 do not have distinct negative factors for intensification compared with the other clusters, as described in section 3b. Here, their features are briefly presented. The supplement includes the figures for clusters 2 and 4.

1) CLUSTER 2

Cluster 2 has conditions more favorable for RI than the other clusters (Fig. S1). Specifically, not significant though, the deep-layer shear is relatively weak on the northwestern side of cluster 2 TCs. RI occurs when cluster 2 TCs move...
toward an area of weak vertical shear; the magnitude of vertical shear gradually decreases from well before the onset of RI to 12 h after the onset of RI. The trend of decreasing vertical shear is similar to that of cluster 1. Also, cluster 2 TCs are located in a couplet of large-scale, low-level convergence and upper-level divergence comparable in magnitude to those of cluster 3 and have a very moist midlevel environment. At the surface, relatively high surface latent heat fluxes are estimated on the southeastern side of cluster 2 TCs, and air with high $u_e$ and high CAPE is apparent in the upwind direction (i.e., in the downshear-right quadrant).

2) CLUSTER 4

Cluster 4 TCs have very strong vertical shear north of cluster 4 TCs. This situation is similar to cluster 3 and is related to the fact that nearly half of the TCs occur in the typhoon-inactive season when a jet moves southward. Also, very dry air with an RH of less than 30% is present at midlevel more than $\sim$500 km northwest of the TC on the downshear side and ahead of the moving storm. This condition, however, does not lead to weakening, although it appears to be unfavorable for intensification. Both deep-layer and low-level shears are weak near the center. The normalized Okubo–Weiss parameter in the inner core is comparable to that of the other clusters. These factors may potentially prevent the entrainment of very dry air into a TC. Additionally, the strongest Earth-relative surface wind is directed toward the downshear-left quadrant, and the surface latent heat fluxes are the largest in the downshear-right quadrant. This configuration is similar to the configuration that Chen et al. (2019) demonstrated through idealized simulations to be favorable for RI. They showed that a downshear-left oriented, low-level flow promotes inner-core convection on the downshear side that is favorable for RI.

5. Discussion

In this section, we discuss the effects of ocean conditions and vertical shear on intensification from the perspective of TC size. Interestingly, 29% of cluster 5 storms were located over the ocean with OHCs less than 50 kJ cm$^{-2}$. This percentage was much higher than those of the other clusters. Considering the relatively weak effect of storms with small R30 on SST cooling (e.g., Knaff et al. 2013; Pun et al. 2018), it may be possible for small TCs (i.e., cluster 5) to intensify rapidly even over relatively low-OHC waters if the SST is high enough. Small TCs, however, are vulnerable to vertical shear. According to the theory of shear resiliency (Reasor and Montgomery 2015), large TCs can resist vertical shear more effectively under the same intensity. Therefore, weak vertical shear is needed for small TCs. This requirement explains why vertical shear is, on average, much weaker for cluster 5 RI TCs than for the other clusters.

In contrast, it is likely that large TCs (i.e., cluster 3), which were in an environment with moderate vertical shear, were helped by stronger shear resiliency than the small TCs. In addition to the dynamic resiliency of storm size to vertical shear (Reasor and Montgomery 2015), Riemer and Montgomery (2011) proposed the idea that a broad vortex has the ability to thermodynamically isolate the vortex from a dry environment. Furthermore, an environment rich in moisture can potentially alleviate the effect of dry air with low $\theta_e$ caused by vertical shear on intensity (e.g., Riemer et al. 2010; Tang and Emanuel 2012). Tao and Zhang (2014) showed through numerical experiments that a reduction in ambient moisture content in the whole layer.

Fig. 13. As in Fig. 7, but for cluster 5 TCs.
around a vortex leads to a delay or failure of the intensification of incipient storms under the same magnitude of vertical shear because the suppression of convection in the inner core causes a loss of resistance to vertical shear. It is also important that the OHC be high enough to avoid the impact of SST cooling by a broad vortex. Cluster 3 TCs are therefore likely to be able to experience RI under moderate vertical shear because of their moist environment, large size, and near-average OHC.

Statistical–dynamical models such as TIFS currently use environmental predictors that are linearly related to their corresponding mean values. The results of this study, however, revealed that some RI events in the western North Pacific in fact occurred even under some conditions unfavorable for RI. Possible RI scenarios differed among clusters. Although in the framework of TIFS (e.g., Yamaguchi et al. 2018) and RI index (Kaplan et al. 2010, 2015), strong upper-level divergence is a positive factor, this study found that the magnitude of divergence for RI cases in fact depended strongly on storm size. To improve the accuracy of RI prediction, structural features of TCs should therefore be considered as well as environmental conditions. This issue will be addressed in future work.

6. Conclusions

This study has identified different combinations of environmental conditions for RI that are classified by TC structural features and has examined how they contribute to RI and which factors can help offset conditions unfavorable for RI. A cluster analysis was conducted to classify different morphologies of TC cloud patterns at the onset of RI in the western North Pacific from 1995 to 2020. Six clusters were identified. Each cluster was characterized by a distinct set of environmental conditions. Some of the conditions of three clusters (clusters 1, 3, and 5) were unfavorable for RI.

These three clusters were intensively examined through a composite analysis of environmental conditions, including synoptic flow patterns and thermodynamic conditions. Figure 14 shows schematics of the three clusters. Cluster 1 TCs were exposed to moderate vertical shear. Relatively high SST, a moist environment, and movement toward an area of environments with weak vertical shear, high-\(\theta_v\) air, and high OHC were identified as factors that could possibly alleviate the effect of low-\(\theta_v\) air that could be caused by vertical shear. Cluster 3 TCs were characterized by their large size (i.e., a large 30-kt wind radius) and location in an environment with moderate vertical shear. A moist environment caused by large-scale, strong, low-level convergence and a large storm size were positive factors that could potentially resist the effects of vertical shear, including low-\(\theta_v\) air and vortex tilt. Cluster 5 TCs were located in a very dry environment with little upper-level divergence; 29% of cluster 5 TCs intensified over the ocean with OHCs less than 50 \(\text{kJ cm}^{-2}\). Weak vertical shear was a possible key factor that prevented dry air from intruding into the inner core, and the small size of cluster 5 storms likely minimized SST cooling. The variability of environmental conditions for RI depends mainly on TC structural features. If there are negative factors for intensification, some other factors can therefore overcome the negative impacts.

We hypothesize that for small TCs, relatively low OHC does not diminish the potential for RI if the SST is high enough, but weak shear is necessary for RI. In contrast, large TCs can resist vertical shear to some extent, but the OHC needs to be high enough. The findings of this study suggest that suitable combinations of environmental conditions and TC structural features are important for RI. Statistical–dynamical RI prediction should therefore be performed by considering both environmental conditions and TC structural features. Structural information such as size and rainfall distribution has recently begun to be used in some statistical–dynamical models: a rapid intensification prediction aid (Knaff et al. 2018, 2020); an upgraded TIFS model (Shimada et al. 2018).

Further studies are needed in the future to clarify whether there are multiple pathways to RI that differ with respect to environmental conditions and TC structures. In this study, we identified some combinations of environmental conditions conducive to RI as a function of TC structure (e.g., storm size). Meanwhile, environmental conditions can determine TC structure. Also, it should be noted that results of a cluster...
analysis could depend on storm samples applied, which might slightly change combinations of environmental conditions. Further studies should thus seek to identify the relationships between environmental conditions and structural features that can lead to RI. Numerical experiments should be used to better understand possible RI scenarios and their relationships to environmental conditions.

Acknowledgments. TIFS developmental data were created using a tool provided by Dr. K. Musgrave and Dr. M. DeMaria. MPI and CAPE were calculated by using a code publicly provided by K. Emanuel. U. Shimada thanks T. Tabata for his help in recalibrating historical geostationary satellite data. We are deeply grateful to our colleagues at JMA who provided the historical Dvorak analysis data. We thank three anonymous reviewers for valuable comments. This work was supported by a grant from the Ministry of Education, Culture, Sports, Science and Technology (MEXT) KAKENHI Grants 19K14797, 19H00705, and 21H01164.

Data availability statement. All of the data used in this study including Dvorak and Himawari satellite data have been archived. Best track data from RSMC Tokyo are available at their website (Japan Meteorological Agency 2021a). JRA-55 data are available at JMA’s website (Japan Meteorological Agency 2021b).

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