Relative contributions of environmental factors on different time scales to tropical cyclogenesis over the eastern North Pacific

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Abstract
The present study investigates relative contributions of large-scale environmental factors on interannual, intraseasonal, and synoptic time scales to tropical cyclone (TC) genesis over the eastern North Pacific (ENP) during TC seasons of 1979–2013 from the perspective of TC genesis time and position. Conditional sorting displays that the synoptic component is more important in the contribution of lower-level vorticity and mid-level specific humidity to TC genesis compared to interannual and intraseasonal components. The convection contributes to TC genesis mainly through synoptic and intraseasonal components. Synoptic-scale tropical disturbances mainly obtain barotropic eddy energy from climatological mean flows. TCs appear most frequently when vertical wind shear anomalies are between 0 and 3 m s⁻¹, in which interannual and intraseasonal westerly wind anomalies make a positive contribution due to climatological easterly wind shear. When total SST exceeds 28°C, the interannual component of sea surface temperature (SST) is positive, and then it has a positive contribution to TC genesis. In addition, there are notable differences of relative contributions of different time scale components of large-scale factors among the ENP, northern Atlantic Ocean, and western North Pacific.

Keywords
different time scales, environmental factors, TC genesis, the eastern North Pacific

1 | INTRODUCTION

The average number of tropical cyclones (TCs) with maximum sustained winds of at least 35 knots over the eastern North Pacific (ENP) ranks second over the globe following the western North Pacific (Schreck III et al., 2014). TCs over the ENP not only affect continental North America but also may affect the Hawaiian Islands (Chu and Wang, 1997). Thus, it is important to understand the mechanisms responsible for tropical cyclogenesis over the ENP.

Most previous studies diagnose the conditions of TC genesis on a large spatial scale and during a certain time period through a composite of different fields according
to the phases of climate modes over the Pacific Ocean (e.g., Maloney and Hartmann, 2000a, 2000b, 2001; Camargo et al., 2007, 2009; Jien et al., 2015). For example, studies have compared the TC genesis over the western North Pacific domain during El Niño and La Niña years (e.g., Wang and Chan, 2002; Camargo et al., 2007; Cao et al., 2014) and during the active and inactive phases of the Madden-Julian Oscillation (MJO, Camargo et al., 2009; Cao et al., 2012). TC genesis, however, is a synoptic-scale event occurring in a local region. The conditions of TC genesis are determined by a combination of different time scale components of large-scale environmental factors. Therefore, it is necessary to focus on the instantaneous state and specific location of TC genesis to examine relative contributions of different time scale components of large-scale environmental factors. This perspective from TC genesis position and time was recently employed by Cao et al. (2018, 2019), who has diagnosed large-scale conditions of TC genesis over the western North Pacific and northern Atlantic Ocean.

TC genesis is closely associated with regional dynamic and thermodynamic factors (Gray, 1968, 1979; Cheung, 2004; Camargo et al., 2007; Collins and Roache, 2011). In the interannual time scale, these large-scale environmental factors over the ENP are significantly modulated by the El Niño–Southern Oscillation (ENSO) (e.g., Irwin and Davis, 1999; Camargo et al., 2007; Kim et al., 2011; Jien et al., 2015; Zhao and Raga, 2015). For instance, Camargo et al. (2007) identified that vertical wind shear is the main contributor to the difference of genesis potential anomaly composites between El Niño and La Niña years and potential intensity plays a secondary role. Kim et al. (2011) showed that during the central Pacific warming, the descending motion with dry air induces the suppression of TC activity over the ENP, whereas during the eastern Pacific warming, the reduction of vertical wind shear induces the enhancement of TC activity over the ENP, which is consistent with Camargo et al. (2007).

In the intraseasonal time scale, the large-scale environmental conditions of TC genesis over the ENP are significantly modulated by the MJO with a period of 30–60 days (Molinari et al., 1997, 2000; Maloney and Hartmann, 2000a, 2000b, 2001; Aiyyer and Molinari, 2008; Camargo et al., 2009; Jiang et al., 2012; Crosbie and Serra, 2014) and quasi-biweekly oscillation with a period of 10–20 days (e.g., Zhao et al., 2018). Jiang et al. (2012) and Zhao et al. (2018) found that mid-level relative humidity and lower-level relative vorticity are the two most important factors affecting the TC genesis frequency associated with the MJO and quasi-biweekly oscillation over the ENP. Maloney and Hartmann (2001) suggested that the lower-level barotropic dynamics in terms of barotropic energy conversion help explain the modulation of TC activity by the MJO over the ENP. In the synoptic time scale, African easterly waves often create the necessary precursors for TC genesis, not only over the northern Atlantic Ocean (Landsea, 1993; Thorncroft and Hodges, 2001; Russell et al., 2017), but also over the eastern Pacific Ocean (Avila, 1991; Molinari and Vollaro, 2000; Leppert II et al., 2013a, 2013b; Rydbeck et al., 2017; Yepes et al., 2019). For example, Leppert II et al. (2013a) pointed out that there is a significant distinction between developing easterly waves and non-developing easterly waves, including infrared threshold coverage, lightning flash rates, and lower-level precipitation radar reflectivity. In addition, the waves are more likely to develop into TCs when they move through environments characterized by high sea surface temperature (SST), weak vertical wind shear, high moisture, and strong lower-level vorticity (Agudelo et al., 2011; Leppert II et al., 2013a, 2013b).

These previous results indicate that the contribution of various factors to ENP TC genesis may depend on the time scales. Thus, this work attempts to address two questions through a new composite method used in Cao et al. (2018, 2019). First, we investigate relative contributions of various environmental factors to TC genesis over the ENP on three time scales. The three time scales comprise interannual, intraseasonal, and synoptic components. Second, we compare the contribution differences of three time scale variations of large-scale factors to TC genesis over the ENP with those over the northern Atlantic Ocean and western North Pacific.

The remainder of the paper is arranged as follows. Section 2 describes the data and methods. Section 3 examines the relative contributions of three time scale components of various large-scale environmental factors to TC genesis over the ENP. Contributions of different time scale components to TC genesis among the three basins are compared in Section 4. A summary is provided in Section 5 along with a short discussion.

## 2 | DATA AND METHODS

The TC genesis data over the ENP come from the U.S. best-track hurricane database (HURDAT1), archived in National Climate Data Center’s International Best Track Archive for Climate Stewardship (IBTrACS) v03r10 (Knapp et al., 2010). The time of TC genesis is defined when the maximum wind speed exceeds 25 kts at the first time over the ENP. There are no non-developing tropical cloud clusters in this dataset (Hennon et al., 2013). The present analysis focuses on the period
from 1979 to 2013. Note that we have performed a parallel analysis using the maximum wind speed of 34 kts as the criterion for TC genesis. The obtained results are almost the same (figures not shown).

The daily mean interpolated satellite Outgoing Longwave Radiation (OLR) is obtained from the National Oceanic and Atmosphere Administration (NOAA) (Liebmann and Smith, 1996). OLR is often used as a proxy for deep convection in the tropical and subtropical regions because cloud top temperature is an indicator of cloud height (Wheeler and Kiladis, 1999; Gu and Zhang, 2002). Conventional dynamic and thermodynamic variables come from the European Centre for Medium-Range Weather Forecasts Reanalysis (ERA-Interim) dataset with a horizontal resolution of 0.5° × 0.5° in latitude and longitude (Dee et al., 2011).

The monthly mean SST dataset is obtained from the Hadley Center, which has a horizontal resolution of 1° × 1° and is available from 1870 to the present (Rayner, 2003). The daily mean SST is extracted from the NOAA Optimum Interpolation (OI) SST V2 data with a 0.25° horizontal resolution starting from September 1981 (Reynolds et al., 2007). The original OI SST data of 0.25° horizontal resolution are converted to 1° horizontal resolution. Due to the length limitation of SST data, only the period 1982–2013 is chosen.

The interannual, intraseasonal, and synoptic components of various environmental factors are obtained using the same method as Cao et al. (2017, 2018). The daily anomaly time series are obtained by subtracting climatological daily mean time series from the original daily mean time series for each environmental variable. The interannual component more than 90 days is obtained by applying a 91-day running mean to the daily anomaly time series and the intraseasonal component with a period of 10–90 days is obtained by subtracting a 91-day running mean from a 9-day running mean of the daily anomaly time series. The synoptic component with a period of 3–8 days is obtained in a similar manner.

In the present study, we use eddy kinetic energy as an indicator of synoptic disturbances and examine the relative contribution of barotropic energy conversion from climatological mean flows, interannual and intraseasonal wind flows to TC genesis. The basic flows are separated into climatological mean winds, interannual and intraseasonal wind flows in the formula of barotropic energy conversion. Eddy winds are similar to the above synoptic component of environmental factors.

The percent contributions of different time scale variations of large-scale environmental factors to TC genesis are calculated according to the procedure shown in Figure 1. First, we calculate total daily anomalies of environmental quantities and the components on the three time scales averaged in a 7.5° × 7.5° box centered at the TC genesis location except for SST for which the average is in a 5° × 5° box at the time of TC genesis. Third, we average the total anomalies and the three components in each bin to get their averaged values in that bin. Last, we calculate the ratio of the averaged anomalies of the three components with respect to absolute value of the averaged total anomalies in each bin, which is the percent contribution of the three time-scale components in that bin. Formula to calculate the percent contributions in the fourth step is as follows:

\[
P_{\text{int}} = \frac{X_{\text{int}}}{|X|}; P_{\text{iso}} = \frac{X_{\text{iso}}}{|X|}; P_{\text{syn}} = \frac{X_{\text{syn}}}{|X|}
\]

where \(|X|\) is absolute averaged total anomaly in each bin at the time of TC genesis, \(X_{\text{int}}\) is averaged interannual anomaly in each bin, \(X_{\text{iso}}\) is averaged intraseasonal anomaly in each bin, \(X_{\text{syn}}\) is averaged synoptic anomaly in each bin. For a given variable, the total percent contribution in each bin is equal to 100% (such as vorticity) or −100% (such as OLR). The percentage of TC genesis

![Flow chart of procedure to calculate percent contributions of different time scale components of large-scale environmental factors to TC genesis](image-url)
frequency number in each bin is also calculated in a similar manner.

3 | CONTRIBUTIONS OF DIFFERENT TIME SCALE COMPONENTS TO TROPICAL CYCLOGENESIS

In this section, we examine the relative contributions of different time scale components of environmental factors to TC genesis over the ENP. Figure 2a shows the climatological monthly mean TC number forming over the ENP (0°–25°N and 180°–80°W). The maximum number of TC genesis is in August. There is no TC genesis in February and April. The most active TC genesis season is from July to October, which is the same as that over the northern Atlantic Ocean and western North Pacific (Cao et al., 2018, 2019). Thus, we mainly focus on the season from July to October (JASO for brevity) for the following analysis. Zhao and Raga (2015) show that the peak season extends from June to October since both June and October have the same frequency of TC occurrence. This discrepancy is because Zhao and Raga (2015) used 17 m s\(^{-1}\) threshold for TC genesis and their analysis covered a longer time period. The TC genesis over the ENP is mainly located in the region of 6°–22.5°N and 140°–85°W (Figure 2b). In this region, climatological mean winds are easterly in the lower level, which is the same as that over the northern Atlantic Ocean (Cao et al., 2019). Additionally, most TCs are generated in the region with the SST value above 27.5°C. The number of TC genesis cases is 488 in this box region during JASO of 1979–2013. For JASO of 1982–2013, there are 457 TC cases in the ENP. We perform a conditional sorting analysis for these TC cases centered at the TC genesis location at times of TC genesis.

We analyze the relative contributions of different time scale components of six environmental factors to TC genesis over the ENP including OLR, 850-hPa relative vorticity, 850-hPa barotropic energy conversion, 700-hPa specific humidity, SST, and vertical zonal wind shear between 200 hPa and 850 hPa. Note that when relative vorticity, barotropic energy conversion, specific humidity, and SST anomalies are larger than zero or when OLR anomalies are smaller than zero, the contribution from these factors to TC genesis is positive. Conversely, the contribution is negative. Figure 3 displays the relative contributions in percent of OLR, relative vorticity, specific humidity anomalies due to interannual, intraseasonal, and synoptic time scales and the percentage of TC genesis frequency represented by the probability density function. Barotropic energy conversion due to climatological mean, interannual, and intraseasonal wind flows is also shown together in Figure 3.

For OLR, the relative contributions of the different time scales are variable, depending on the OLR range. Approximately 73% of TCs (358/488) form when the OLR anomalies are between −70 W m\(^{-2}\) and −10 W m\(^{-2}\). In this range, the contributions from the synoptic and intraseasonal variations are comparable (Figure 3a). About 14% (69/488) of TCs form when the OLR anomalies are between −10 W m\(^{-2}\) and 0 (Figure 3a). For this range of OLR anomalies, the synoptic variation has the greatest positive contribution, and the intraseasonal variation plays a secondary role. There are 60 TC genesis cases (12%) when the OLR anomalies are positive. Within this range, the most negative contribution is from the synoptic variability (Figure 3a).

Approximately 93% of TCs (485/488) appear when the relative vorticity anomalies are larger than 0 (Figure 3b). In this range, the synoptic component has the largest positive contribution, followed by the intraseasonal

![Figure 2](https://example.com/figure2.png)  
**FIGURE 2**  (a) The climatological monthly mean variation of the number of TC genesis frequency over the ENP during 1979–2013. (b) The long-term mean SST (shaded, °C), 850-hPa winds (vector, m s\(^{-1}\)) and vertical zonal wind shear between 200 hPa and 850 hPa (green contour, m s\(^{-1}\)) during JASO of 1979–2013. All JASO TC genesis locations are shown with blue dots. The blue box is the main TC development region.
component. In addition, there are 34 TC genesis cases (7%) when the relative vorticity anomalies are negative, in which the negative contribution is mainly from the intraseasonal component (Figure 3b).

High mid-level humidity is closely associated with the development of convection, which is a necessary condition for TC genesis (Gray, 1968; Cheung, 2004). Approximately 55% of TCs (269/488) appear when the mid-level specific humidity anomalies are between 0 and 1 g kg\(^{-1}\), with the major positive contribution from the synoptic component (Figure 3c). A few TCs (33%, 162/488) occur when the specific humidity anomalies are between 1 g kg\(^{-1}\) and 3 g kg\(^{-1}\). Within this range, the contribution from the intraseasonal component is comparable to that from the synoptic component (Figure 3c). There are 52 TC cases (10%) forming within negative mid-level specific humidity anomalies (Figure 3c). The interannual and intraseasonal components make the major negative contributions to TC genesis when the total mid-level specific humidity anomalies are below zero. Cao et al. (2018) indicated that TC genesis may be more dependent on dynamical factors than thermodynamic factors over the western North Pacific because more TCs are generated when the mid-level specific humidity anomalies are unfavorable for TC genesis. However, over the ENP, the rates of TCs forming in the unfavorable vorticity and humidity conditions do not show a significant difference. Thus, it is inferred that TC genesis over the ENP may depend not only on dynamical factors but also on thermodynamic factors. This appears to agree with Zhao and Raga (2015) who found that relative vorticity and relative humidity favored TC genesis during inactive years over the ENP basin.

Barotropic energy conversion is an important source for developing synoptic disturbances in the eastern Pacific basin, through which the synoptic-scale disturbances could obtain energy from the large-scale basic flows (Molinari et al., 1997). Approximately 82% of TCs (403/488) are generated over the ENP when the barotropic energy conversion is between 0 and \(1.8 \times 10^{-5}\) m\(^2\) s\(^{-3}\) (Figure 3d). The greatest contribution is related to climatological mean flows. When the barotropic energy conversion value is larger than \(1.8 \times 10^{-5}\) m\(^2\) s\(^{-3}\), the synoptic-scale disturbances mainly obtain energy from the climatological mean and intraseasonal flows. Approximately 15% of TCs (75/488) form when the barotropic eddy conversion is below zero (Figure 3d), which is smaller than that over the western North Pacific (Cao et al., 2018). This indicates that barotropic energy conversion may play a greater role in TC genesis over the ENP.

Weak vertical wind shear is a necessary condition for TC genesis, which is useful for the accumulated condensational heating to remain in the center of a tropical disturbance and impel the tropical disturbance to develop into TC (DeMaria, 1996). The warm SST provides the moisture and heat energy to spawn TC genesis (Gray, 1979). With respect to vertical wind shear and SST distribution, we calculate the percent contribution of different time scale components, not only based on the total
anomalies but also based on the total value. Climatological mean vertical wind shear is easterly wind shear with an absolute value smaller than 5 m s$^{-1}$ over the ENP (Figure 2). Thus, weak vertical westerly shear anomalies are expected to be the most favorable for TC genesis over the ENP (Figure 4a). The most frequent TCs appear when the vertical wind shear anomalies are between 0 and 3 m s$^{-1}$ (Figure 4a). Among the three components, the interannual and intraseasonal components make the largest positive contribution. When absolute vertical wind shear anomalies are gradually large, the intraseasonal component is the most unfavorable due to the greatest value.

TC genesis is directly associated with total vertical wind shear. Approximately 34% (168/488) of TCs over the ENP form in the range of easterly wind shear between $-4$ m s$^{-1}$ and 0 (Figure 4b). The main positive contribution is from the interannual and intraseasonal components because interannual and intraseasonal westerly wind shear anomalies are against climatological easterly wind shear. This result is consistent with Figure 4a. Intraseasonal wind shear is the largest component when the total shear is larger than 0 and smaller than $-4$ m s$^{-1}$ (Figure 4b). Because there is no clear threshold value of vertical wind shear for TC genesis, it is only inferred that with the increase in the total absolute wind shear, the intraseasonal component makes the largest negative contribution due to the great value and the interannual and synoptic components have the least unfavorable contribution due to the small value (Figure 4b).

Approximately 39% (179/457) of TCs occur when the SST anomalies are positive. In this case, the interannual component has a robustly largest positive contribution to TC genesis, which is followed by intraseasonal component (Figure 4c). Approximately 61% of TCs appear within negative SST anomalies, and all three components make negative contributions to TC genesis (Figure 4c). This result is consistent with that over the western North Pacific and northern Atlantic Ocean (Cao et al., 2018, 2019). When the climatological mean SST is included, almost all the TCs (only one exception) form when the total SST value is above 26°C (Figure 4d), which is thought to be a necessary condition for TC genesis (Gray, 1968, 1979). Approximately 25% (113/457) of TCs are generated when the SST value is between 28°C and 28.5°C (Figure 4d). In this range, the positive contribution is from the interannual component, and the synoptic and intraseasonal components make negative contributions to TC genesis. When the SST value is larger than 28.5°C, the interannual component still has the largest positive contribution (Figure 4d). When the SST value is smaller than 28°C, the three component anomalies are below zero with the largest negative contribution from the intraseasonal component.

4 | THE COMPARISON AMONG VARIOUS BASINS

TC genesis over the different basins may be associated with various time scale components of environmental factors. Thus, it is necessary to compare the relative contribution discrepancy of different time scale components...
of environmental factors to TC genesis among the ENP, western North Pacific and northern Atlantic Ocean. Figure 5 shows the total averaged positive contribution of four factors over the three basins. There are palpable similarities and remarkable differences among these three basins. The contributions of vorticity and humidity to TC genesis are similar over the ENP and northern Atlantic Ocean, with the main positive contribution from the synoptic component (Figure 5b,c). On the other hand, the major contribution of barotropic energy conversion is similar over the ENP and western North Pacific (Figure 5d). In contrast, the positive contribution of convection from the synoptic and intraseasonal components is comparable over the ENP, which is different from the northern Atlantic Ocean and western North Pacific (Figure 5a).

To identify the reasons for the discrepancy in the relative contributions of these factors to TC genesis among three basins, the ratio of the standard deviations of OLR, vorticity, and humidity between the synoptic and intraseasonal time scales over the Pacific and Atlantic Ocean
intraseasonal components is shown in Figure 6. The standard deviations of OLR, vorticity, and humidity are larger on the synoptic time scale than on the intraseasonal time scale over the ENP and northern Atlantic Ocean, particularly for relative vorticity (Figure 6b). Over the western North Pacific, the standard deviations of specific humidity are larger on the intraseasonal time scale than on the synoptic time scale in most of the domain (Figure 6c). In addition, the standard deviations of OLR and vorticity are larger on the synoptic time scale than on the intraseasonal time scale over the western North Pacific but with smaller magnitude than that over the ENP and northern Atlantic Ocean. Thus, it is concluded that the contribution of OLR, relative vorticity and specific humidity to TC genesis over the ENP is closer to that over the Atlantic Ocean than that over the western North Pacific.

5 | SUMMARY AND DISCUSSION

This present study examines the contributions of six large-scale environmental factors to TC genesis over the ENP from a local and instantaneous perspective, which has been performed previously in the western North Pacific and Atlantic Ocean (Cao et al., 2018, 2019). The total anomalies of each variable centered around the TC genesis location are separated into interannual, intraseasonal, and synoptic time scale components. Then we analyze and compare the relative contributions of different time scale components to TC genesis. Furthermore, the contributions of the three time scale components over the ENP are compared with those over the northern Atlantic Ocean and western North Pacific.

On the one hand, the composite results based on the TC genesis time and position over the ENP show that the major positive contribution of relative vorticity and specific humidity to TC genesis are due to synoptic component. The contribution from the synoptic component of convection is nearly comparable to that from the intraseasonal component. The synoptic scale tropical disturbances obtain eddy kinetic energy mainly from climatological mean flows. On the other hand, most TCs form when the total vertical zonal wind shear is between −4 m s⁻¹ and 0 with the major positive contributions from intraseasonal and interannual components. In addition, the TC genesis over the ENP is, to a great extent, associated with climatological mean and interannual component of SST.

The main conclusions and comparisons among the three basins are summarized in Table 1. The synoptic components of relative vorticity and specific humidity are the most significant over the ENP and northern Atlantic Ocean, whereas the synoptic scale tropical disturbances obtain the barotropic eddy energy mainly from climatological mean flows over the ENP and western North Pacific. The contribution of different time scale components of OLR shows various characteristics among these three basins. Over the ENP, the positive contribution from the synoptic and intraseasonal components is comparable, while the contributions from the synoptic and intraseasonal components are the largest over the northern Atlantic Ocean and western North Pacific, respectively.

The present study indicates that the synoptic variations of vorticity and humidity are the highest over the ENP. The relationship between the magnitude of synoptic component and the interannual variation of TC genesis over the ENP will be examined in future work. This is currently being planned.

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| Table 1 | The summary of the main contribution component of various factors to tropical cyclogenesis over the eastern North Pacific, western North Pacific, and northern tropical Atlantic Ocean |
|---------|---------------------------------|-----------------|-----------------|-----------------|-----------------|
| OLR     | Vorticity                      | Humidity        | Barotropic energy conversion |
| Eastern North Pacific | Synoptic + intraseasonal | Synoptic | Synoptic | Climatological mean |
| Northern Tropical Atlantic | Synoptic | Synoptic | Synoptic | Climatological mean + intraseasonal |
| Western North Pacific | Intraseasonal | Intraseasonal + synoptic | Intraseasonal | Climatological mean |

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