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Key Points:

- The Pacific Decadal Oscillation (PDO) modulates the number of tropical cyclone (TC) days in the North Pacific Ocean
- An increase of 60% of the number of TC days south of 30°N is found, during the positive PDO phase, compared to the negative PDO phase
- Improving decadal forecasts to predict the temporal evolution of the PDO can be of interest to predict the future number of TC days

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The Pacific Decadal Oscillation Modulates Tropical Cyclone Days on the Interannual Timescale in the North Pacific Ocean

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Abstract The North Pacific Ocean is the most active region on our planet in terms of tropical cyclone (TC) activity. These storms are responsible for numerous fatalities and economic damages, affecting the livelihood of those living in the impacted areas. Historically the examination of TCs in the North Pacific Ocean has been performed separately for its two main sub-basins: the West North Pacific and the East North Pacific. Here, we consider the TC activity in the North Pacific as a single basin and examine the climate processes responsible for its number of TC days. We show that the Pacific Decadal Oscillation modulates the number of TC days in the North Pacific Ocean through its connection to the sea surface temperature. The insights from this work will advance the understanding of the climate processes responsible for these storms, and will provide valuable information toward our preparation and adaptation efforts on long timescales.

Plain Language Summary This work investigates the effects of different sea surface temperature patterns on the spatial distribution of tropical cyclone (TC) genesis in the North Pacific leading to conditions that are more favorable to long-lasting TCs under the positive phase of the Pacific Decadal Oscillation, a dominant year-round pattern of monthly North Pacific sea surface temperature variability.

1. Introduction

Tropical cyclones (TCs) in the North Pacific Ocean claim a major socio-economic toll on a yearly basis (e.g., Peduzzi et al., 2012; Zhang et al., 2009), and their impacts are projected to be exacerbated due to climate change and increased exposure and vulnerability (e.g., Gettelman et al., 2018; Mendelsohn et al., 2012). Recent examples of Typhoons Mangkhut (2018) and Haggis (2019) are a reminder of the devastating impacts these storms can have.

The West North Pacific (WNP) is the most active sub-basin in terms of TC count (Hu et al., 2018) and intensity (Wu et al., 2008). The TC record exhibits high variability on multiple timescales, with different climate processes responsible for it. For instance, at the intraseasonal timescale the TC activity in this basin is modulated by the Madden-Julian Oscillation (Zhao et al., 2019) and the quasi-biweekly oscillation (Li & Zhou, 2013). At the interannual timescale, many processes modulate the TC activity, mainly through sea surface temperature (SST) anomalies over different domains (e.g., Tao et al., 2012; Zhang et al., 2016, 2017; Wang & Chan, 2002); among them, the well-known El Niño-Southern Oscillation (ENSO; Wallace et al., 1998) represents the dominant one (e.g., Camargo & Sobel, 2005; Chan, 1985; Kim et al., 2011). The climate drivers responsible for the variability of TC activity in the WNP at longer timescales (e.g., decadal) have received much less attention, in part due to the complications associated with disentangling the role of climate processes that operate over multiple decades from a limited record length. Among the existing studies, the focus was on large-scale environmental drivers (e.g., Camargo & Sobel, 2010; Chu, 2002; Chu & Clark, 1999) and on the ENSO-associated decadal changes (e.g., Liu et al., 2019). Overall, previous work suggested that the Pacific Decadal Oscillation (PDO) only played a minor role.

Different from the WNP, there is increasing evidence that TC activity in the East North Pacific (ENP) at the interannual scale is not primarily driven by ENSO, despite its influence on some large-scale fields associated with cyclogenesis (Caron, Boudreault, & Camargo, 2015; Caron, Hermanson, & Doblas-Reyes, 2015). On longer timescales, ENP TC variability has been associated with the Atlantic multidecadal variability (Raga et al., 2013; Wang & Lee, 2009), the vertical circulation over the tropical Atlantic (Zhang & Wang, 2015), the quasi-biennial oscillation (Camargo & Sobel, 2010; Whitney & Hobgood, 1997), and the PDO (Martinez-Sanchez & Cavazos, 2014).

Therefore, while the TC activity in the WNP and ENP has been the subject of extensive investigation, these basins are generally treated separately, rather than considering the storm activity in the North Pacific as a single basin. The influence of climate processes, such as the PDO that operate across the entire North Pacific may not have been fully considered by focusing on the sub-basins, especially if we are interested in multi-annual and decadal changes. It is well known that PDO is the result of a combination of different physical processes also affecting TC activity, including both remote tropical forcing and local North Pacific atmosphere–ocean interactions, operating on different timescales (Newman et al., 2016). It is reasonable to hypothesize that a climate mode like the PDO could play an important role in terms of TC activity over the whole basin. However, as mentioned above, there is limited evidence that connects these storms and the PDO. Our expectation is that the number of TC days is related to the PDO through its modulation of the SST in the regions where these storms develop. In particular, during the positive phase of the PDO, warm waters close to the equator would lead to conditions favorable to the development of longer lasting storms compared to the negative PDO phase, which is characterized by lower SST values. We believe that this connection has not been sufficiently explored in the literature because the North Pacific Ocean was not considered as a single basin but broken up into WNP and ENP, confounding the detection of a potential PDO signal.

In this paper, we focus on the potential role of the PDO in modulating TC activity, with emphasis on the number of TC active days in the entire North Pacific Ocean. We have selected this metric because the number of TC days provides an integrated information about TC genesis, lifespan, and tracks (Wang et al., 2010), and because it exhibits substantial decadal-scale oscillations in TC activity compared to other metrics used to highlight TC activity (Webster et al., 2005). We aim to verify the effects of different SST patterns on the spatial distribution of TC genesis in the North Pacific leading to conditions that are more/less favorable to long-lasting TCs under positive/negative PDO phases.

2. Data and Methods

Our study period ranges from 1949 to 2019, and we focus our analyses on August–October because it corresponds to the highest TC activity in the North Pacific Ocean. The monthly time series of the PDO index is obtained from the KNMI Climate Explorer portal (Oldenborgh et al., 2009). TC day count over the WNP and ENP is derived starting from the International Best Track Archive for Climate Stewardship (Knapp et al., 2010) data base at the 6-hourly timescale. Prior to the 1970s, the TC database is affected by large uncertainties due to the absence of satellites, making the records for weak TCs (e.g., tropical depressions) not reliable; therefore, we limit our analyses to 6-hourly samples of tropical storms or higher. The observed SST data are obtained from the MetOffice Hadley Center data portal (Rayner et al., 2003). Wind fields for the computation of 850 mb vorticity, 200 mb divergence and wind shear are from the National Centers for Environmental Prediction - National Center for Atmospheric Research reanalysis (Kalnay et al., 1996). The ENSO index used is the nino3.4 SST anomaly provided by the National Oceanic and Atmospheric Administration (https://psl.noaa.gov/).

The statistical significance of the Pearson correlation coefficients mentioned throughout the paper is set at the 5% level and estimated via a simple random sampling with replacement bootstrap (simple bootstrap). The correlation coefficients, where not otherwise stated, are computed after linear detrending of the considered time series.

We define the positive (high) and negative (low) PDO conditions based on the 25th and 75th percentile of the PDO index averaged during August–October, respectively. We select these thresholds because we want to avoid “neutral” PDO years; however, we explored the sensitivity of the results using a binary positive/negative definition of PDO conditions obtaining similar results. Moreover, if we average the PDO index over July–November rather than August–October, we obtain similar results, with the main difference that the values of the correlation coefficient decrease by ∼0.1.

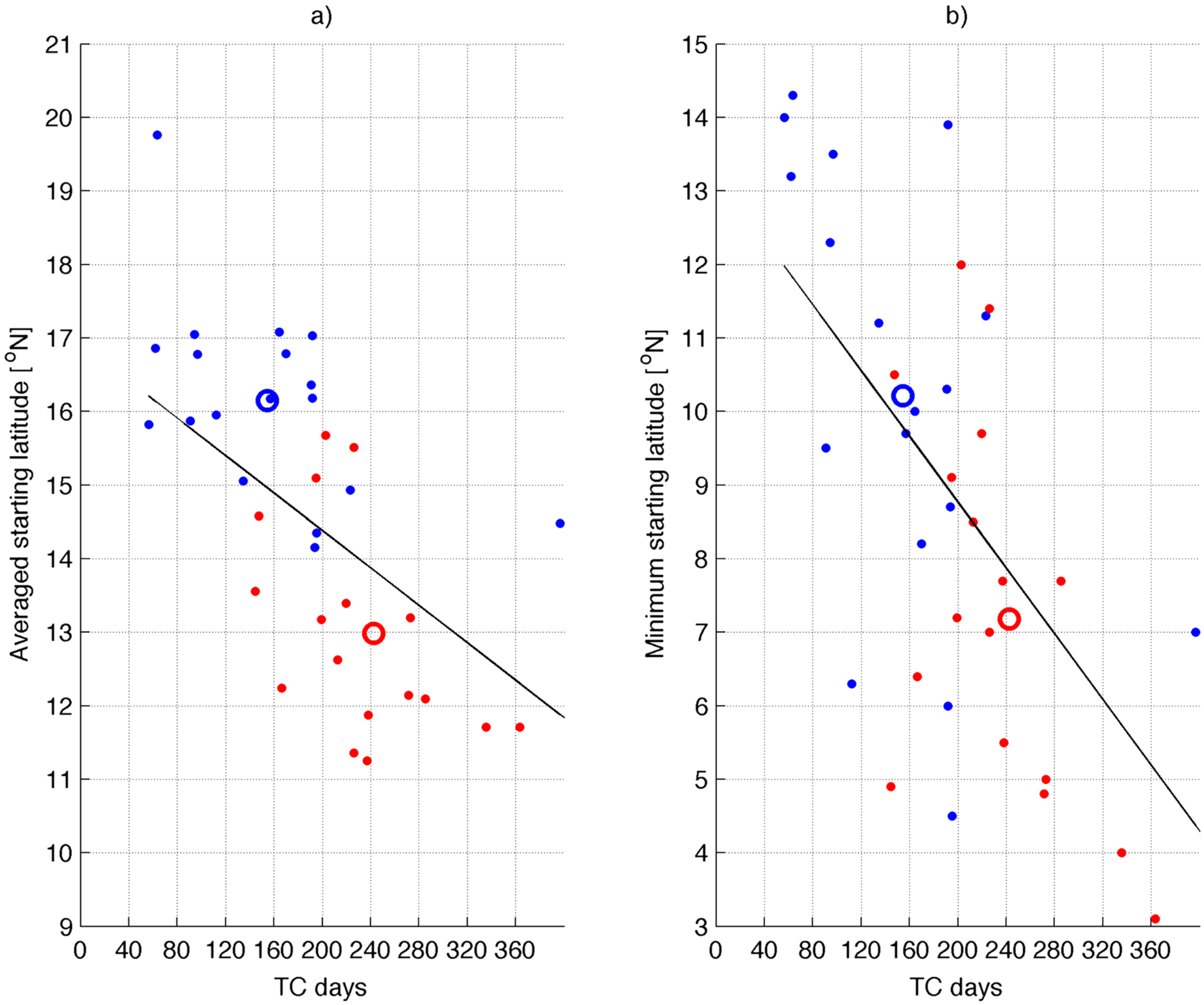

Figure 1. Scatter plots of meridional (a) averaged and (b) minimum tropical cyclone (TC) starting point position versus TC day count during August–October 1949–2019. The solid black line is the regression line for all the points. Red/blue dots represent positive/negative Pacific Decadal Oscillation phases. The larger red/blue hollow circles represent the average of the corresponding set of dots.

3. Results

3.1. Dependence of TC Duration on Averaged Genesis Position

In the North Pacific Ocean, the August–October number of TC days tends to be higher during years in which TCs start to develop closer to the equator (Figure 1a). In particular, the years with the largest number of TC days are those in which the average latitude they form is between 11 and 12°N. As these storms tend to form further north, this metric tends to show smaller and smaller values. The inverse relationship between TC genesis latitude and TC day count is even stronger considering the annual minimum (Figure 1b) instead of the averaged TC genesis latitude (Figure 1a). These results suggest that even a few TCs developing closer to the equator can lead to a large increase in the annual count of TC days because of the generally longer amount of time they spend over warm waters.

SST is one of the parameters considered by genesis potential indices (e.g., Tippett et al., 2011) and it is well known that, on average, TC genesis in the Pacific Ocean tends to be associated with anomalously warm SST (Camargo et al., 2007); moreover, over certain regions, higher SSTs can lead to the genesis of long-lasting TCs (Zhao & Wang, 2019). For instance, during El Niño, the locations of TC genesis move southeastward in WNP (Chan, 1985) and TCs' mean life span increases (Wang & Chan, 2002), and in the ENP the mean TC duration increases (Gray & Sheaffer, 1991).

3.2. Relationship Between the Number of TC Days and the PDO

During a positive/negative PDO phase, the western part of the Pacific Ocean north of 20°N becomes cooler/warmer and part of the equatorial and eastern ocean warms/cools (Mantua et al., 1997). Among the possible drivers, SST is one of the physical mechanisms that are likely associated with the interannual variability in TC genesis position (Chia & Ropelewski, 2002). To verify and quantify the potential role of PDO in determining North Pacific TC activity, we compare the PDO index time series with that of the TC activity in the basin. The correlation coefficient between the two time series is 0.7, and 0.6 after detrending the two 10-year filtered time series. Wang et al. (2010) found the same correlation value when focusing on TC days at the global scale and annual PDO.

To better highlight the signal at the low latitudes, we focus on the fraction of time spent by these storms below 20°N with respect to the total TC days in a year in the North Pacific Ocean (ENP + WNP TC days) and compare it to the PDO index (Figure 2). A strong correlation (i.e., higher than 0.7/0.8) is found when the time series are filtered with a moving window of 5/10 years over the 1949–2019 period (Figure 2a shows the two curves filtered with a 10-year moving window). It is worth mentioning that the values of these correlation coefficients decrease by 0.1 (0.2) if we focus on WNP (ENP) only. There are large increases in the number of TC days starting from the early 1960s, and peaking in the 1980s, followed by a sharp decrease ever since. This pattern is matched closely by the PDO, with the exception of the last decade, in which the PDO has been increasing while the number of TC days has not. This strong relationship persists even when we consider different starting and ending years and without time filtering (Figure 2b): There is a broad band with high correlation values when we start in the 1960s and end in the 2010s.

There is a higher number of TC days south of 30°N during the positive PDO phase (Figure 3a). The largest difference is over the tropical belt located between 10 and 20°N, with two times more TC days during the positive PDO phase compared to the negative one. Such increase is present across the whole Pacific Ocean east of 130°E (Figure 3b), with the maximum percentage difference greater than 250% located over the Central Pacific Ocean (see green circles in Figure 3b), and an average increase in TC days of about 60% during the positive PDO phase compared to the negative one. Considering the Pacific Ocean as a whole allows us to better highlight the PDO effect on the meridional distribution of TC days (solid lines in Figure 3a), compared to the analyses that focused on individual basins (thin dashed lines in Figure 3a).

The correlation results can be understood in terms of changes in the SST, which appears to be the driving factor. To better highlight the spatial differences in TC day count associated with the positive and negative PDO phases (Figure 4, top and middle panels, respectively), we compute the difference between them (Figure 4, bottom panel): South of 30°N, there are more TC days, with a peak of up to 25 TC days more at several locations, between 10 and 20°N during the positive PDO phase compared with the negative one. This is true for both WNP and ENP, and is consistent with the higher SST appearing over the aforementioned regions during the positive PDO phase (Figure 4, contour lines). It is well known that PDO is the longer lived cousin of ENSO (Beaufort & Grelaud, 2017) and that the two indices are well correlated (>0.5 in the observations; Nidheesh et al., 2017). To verify whether the signal found in TC day count is only due to the relative frequency of El Niño versus La Niña that causes the observed interdecadal differences, we plotted the TC density difference using only ENSO-neutral years (defined as years with the nino3.4 anomaly value between −0.5 and 0.5°C; Scoccimarro et al., 2020). Stratifying TC count under high and low PDO using only the ENSO-neutral years, the pattern is very similar to what presented in Figure 4 (figure not shown).

In addition, there are more favorable conditions to TC development and intensification, as shown in terms of lower level (850 mb) absolute vorticity (Figure 5, bottom panel) and upper level (200 mb) divergence (e.g., Tippett et al., 2011; Goh & Chan, 2010; Sears & Velden, 2014) (Figure 5, top panel) during positive PDO phases; this is especially evident in the NWP where these mechanisms seem to be the main driver, while a higher SST drives the ENP TC days' increase. In agreement with previous studies (Aiyyer & Thorncroft, 2011), we did not find any consistent relationship between changes in PDO and changes in vertical wind shear potentially leading to changes in TC days in the Pacific.

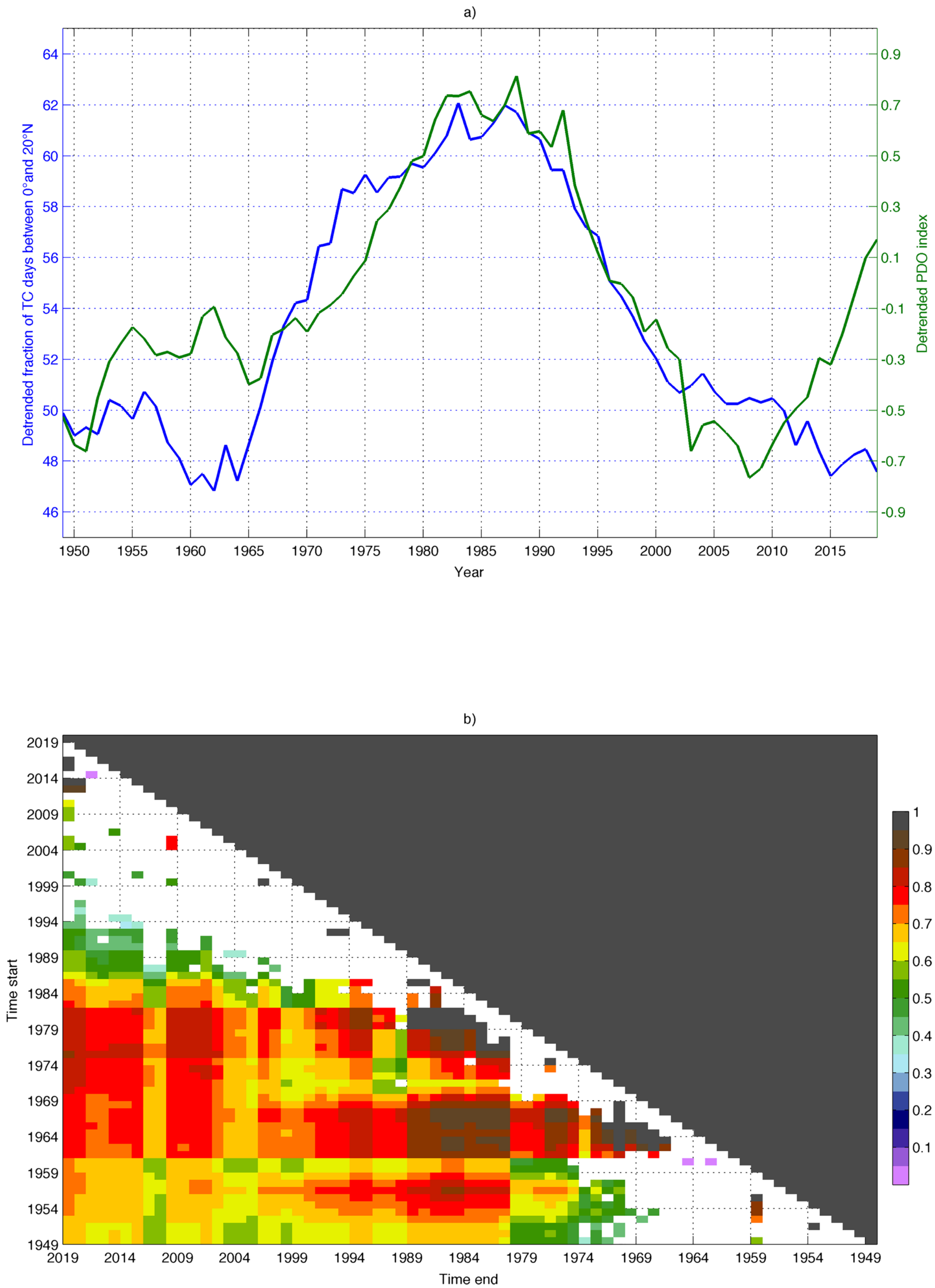

Figure 2. August–October average Pacific Decadal Oscillation (PDO) and tropical cyclone (TC) day fraction at latitudes lower than 20°N compared to the total TC days in the North Pacific Ocean. The upper panel shows the time series of the PDO index (green), together with the TC day fraction time series (blue). The lower panel shows the Pearson correlation between the two time series for all possible combinations of starting and ending years within the 1949–2019 period. The Pearson correlation coefficients are computed after detrending both time series, with the results that are not statistically significant at the 5% level in white.

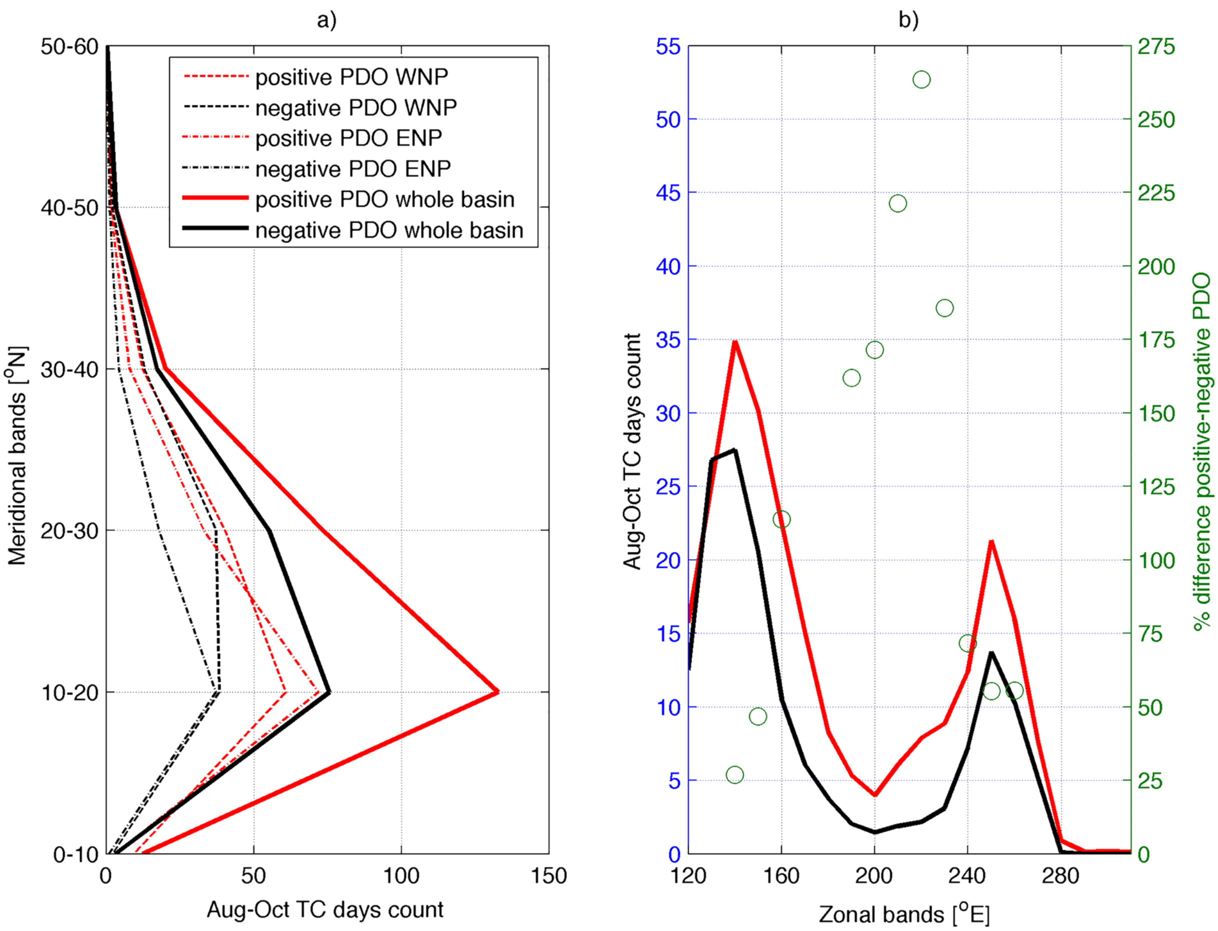

Figure 3. Meridional (panel a) and zonal (panel b) distribution of tropical cyclone (TC) days during positive (red) and negative (black) Pacific Decadal Oscillation (PDO) phases within the 1949–2019 period. The green circles in panel (b) show the percent increase of TC days during the positive PDO phase compared to the negative one (only statistically significant values at the 5% level are shown). Zonal and meridional bands have a width of 10°.

The larger number of TC days for storms that tend to occur in the tropics during the positive PDO phase is clearly shown in Figure 1a (red dots). When we stratify the years according to the sign of the PDO phase, those associated with the positive phase tend to have storms that form at a lower latitude and that last longer (most of the red dots are located in the bottom-right part of the panel) compared with the negative phase (most of the black dots tend to be shifted toward the top-left corner). On average, these storms tend to form around 13°N and result in 245 TC days; during the negative PDO phase, TCs tend to form around 16°N, for a total of 155 TC days: This difference in TC days is statistically significant at the 1% level.

4. Discussion and Conclusions

In recent years, an increasing number of studies (e.g., Boer et al., 2013; Caron, Boudreault, & Camargo, 2015; ; Caron, Hermanson, & Doblas-Reyes, 2015; Cassou et al., 2018; Doblas-Reyes et al., 2013; Kushnir et al., 2019; Smith et al., 2019) has focused on the prediction skill on timescales of a year or longer, with some emphasis on the PDO (Boer & Sospedra-Alfonso, 2019). The PDO is recognized as a dominant mode of variability of the North Pacific, and the skill in predicting this climate mode represents a large portion of the total predictive skill for North Pacific SST (Boer & Sospedra-Alfonso, 2019) at decadal timescales. Because the annual number of TC days is a meaningful measure of the TC activ-

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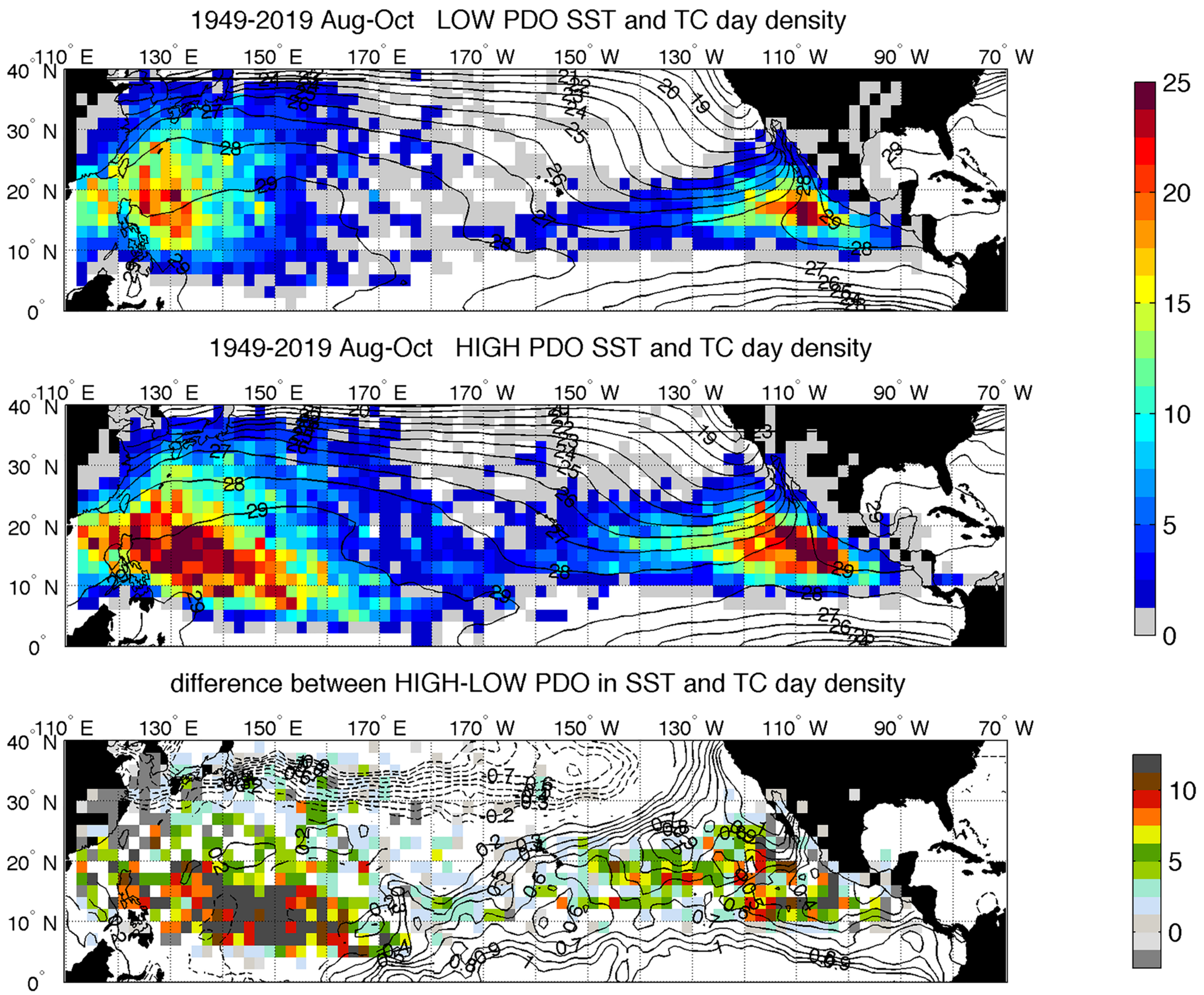

Figure 4. Sea surface temperature (contours; units are [°C]) and tropical cyclone (TC) day density (colors; units are [TC days in a 2° × 2° grid]) during high (top panel) and low (middle panel) Pacific Decadal Oscillation phases during the 1949–2019 period. The bottom panel shows the difference between the top two panels. Differences are shown only for statistically significant values (1% significance level).

ity (Wang et al., 2010), the improved understanding of the climate processes driving such a metric can provide basic information to enhance our preparation against these storms at decadal timescales. Here, we showed that the PDO plays a significant role in modulating the number of TC days in the North Pacific Ocean, with a particularly strong signal in the band between 10 and 20°N. More TC days at low latitudes in the Pacific Ocean can have implications on the general circulation, and in particular on the processes associated with the Maritime Continent circulation (Neale & Slingo, 2003), through the drying of the Maritime Continent atmosphere (Scoccimarro et al., 2020) determined by low latitude WNP TCs. Therefore, it is of crucial importance that we work toward improving the capability of climate models in representing the PDO patterns. Moreover, increasing the performance of decadal forecasting systems to skilfully predict the temporal evolution of the PDO can be of interest not only in terms of future number of TC days, but also in terms of their modulation of the equatorial circulation in the Pacific Ocean.

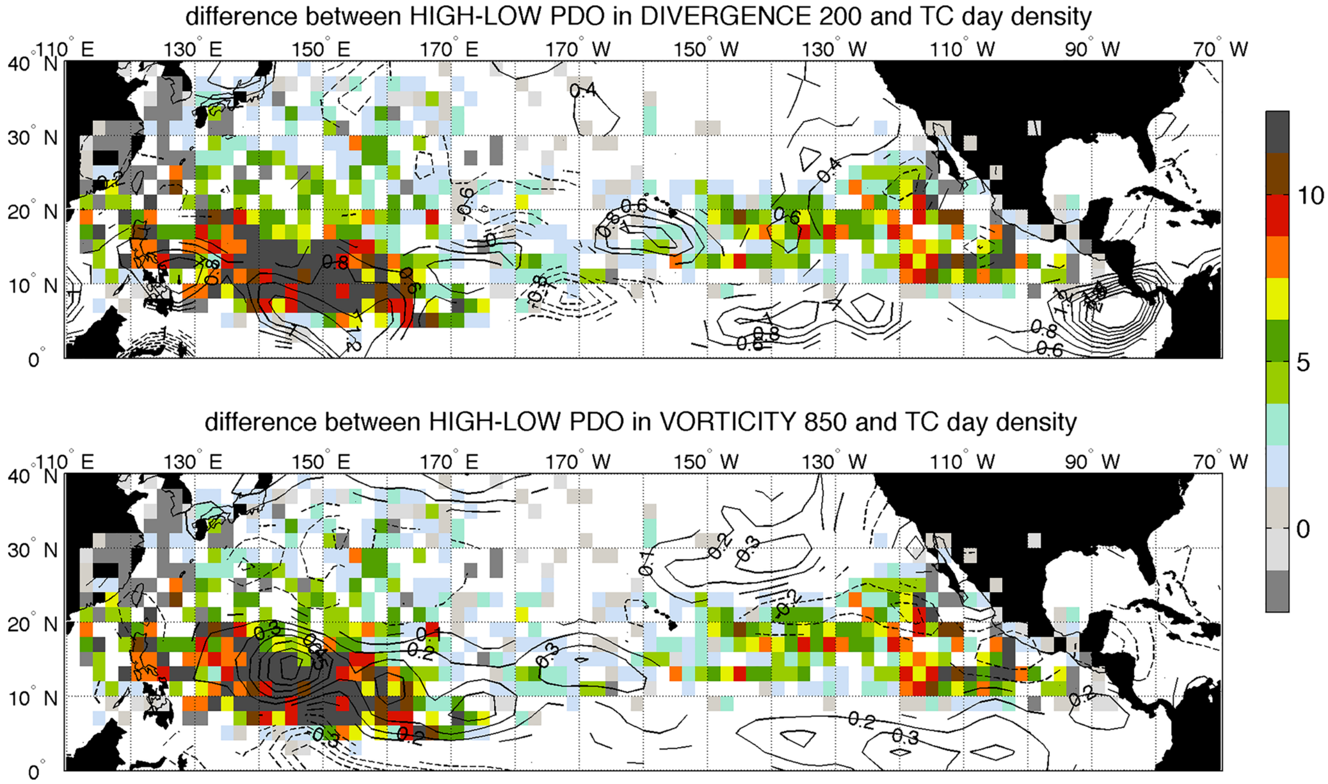

Figure 5. Difference between high and low Pacific Decadal Oscillation phases in terms of upper-tropospheric (200 mb) divergence (contours in upper panel; units are [10^{-6} s^{-1}]) and lower-tropospheric (850 mb) absolute vorticity (contours in the lower panel; units are [10^{-5} s^{-1}]) together with tropical cyclone (TC) day density (colors, units are [TC days in a 2° × 2° grid]). Differences are shown only for statistically significant values (1% significance level).

Data Availability Statement

Data sets for this research are available in these in-text data citation references: Oldenborgh et al. (2009); Rayner et al. (2003); Kalnay et al. (1996). See Data and Methods section for the relative links for download. All data and indexes used in this work are available for downloading at the following web sites: PDO index: https://climexp.knmi.nl/, Sea Surface Temperature: https://www.metoffice.gov.uk/hadobs/hadisst/, Winds: http://www.psl.noaa.gov/data/gridded/data.ncep.reanalysis.derived.html, Tropical Cyclone tracks and positions: https://www.ncdc.noaa.gov/ibtracs/, ENSO Nino3.4 index: https://psl.noaa.gov/data/correlation/nina34.anom.data.

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