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Changes of tropical cyclone activity in a warming world are sensitive to sea surface temperature environment

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Supplementary material for this article is available online

Abstract

While there is considerable agreement in the scientific community about the intensification of tropical cyclones (TCs) in a warming world, that consensus does not exist for TC frequency. In order to shed new light on this uncertainty, we classified the global oceans into three pools based on SST percentiles: the (a) warm (⩾90th percentiles), (a) moderate (65th–90th percentiles) and (c) cool (<65th percentiles) pools, and found that TC frequency increases significantly over the cool SST pool but decreases in the warm and moderate SST pools. The differences in TC frequency change is large among the three pools, contrasting to the small trend differences of TC intensity.

1. Introduction

Tropical cyclones (TCs) have considerable socio-economic impacts, making assessments of their variations, long-term changes in intensity and frequency are of considerable interest. There is a broad agreement that TC intensity strengthens in a warming climate based on observations [1–3] and on high-resolution numerical simulations [4–7]. Given that overall TC intensity has increased since the 1970s [8, 9], stronger storms have been observed more frequently in the North Atlantic [10] and over the globe [11, 12]. However, no increase has been found in the frequency of the weaker storms in the North Atlantic [10]. Particularly, in the western North Pacific, there has been a doubling in the proportion of storms in Saffir–Simpson category 4 and 5 storms [13]. Furthermore, some high-resolution numerical models have simulated a reduction in TC frequency in a changing climate of warmer SSTs [6, 7, 14–17], while other models gave an opposite conclusion [9, 18–22]. The results from model simulations and observations show considerably more uncertainty in changes of TC frequency compared to TC intensity [23]. Increased TC frequency in a warming world can be explained by an increase in the TC genesis potential index [24], which empirically relates tropical cyclogenesis to large-scale environmental parameters [18, 19]. On the other hand, decreased TC frequency can be attributed to increased vertical wind shear [25] and a decrease in specific humidity [26, 27].

The analysis of the conditional probability of TC genesis with environmental SST shows that increasing SST favors TC genesis only for SSTs colder than the most frequent main development region environmental SST [28]. Thus, it is possible that a better classification of environmental conditions could assist in reducing uncertainty associated with changes in TC frequency in a warming world. In this study, the 2°× 2 monthly global SST background (ERSSTv5) [29] was divided, by the SST percentile-based classification approach, into (a) warm (⩾90th percentiles), (a) moderate (65th–90th percentiles) and (c) cool (<65th percentiles) pools, respectively (see data and method in supporting information

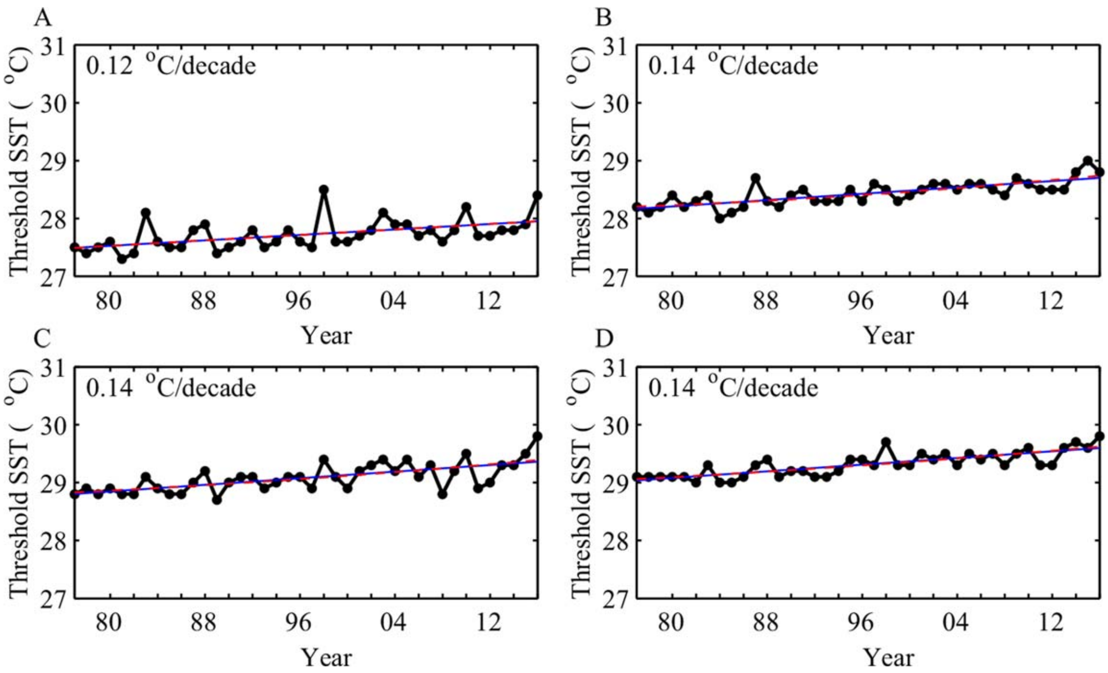

Figure 1. 1977–2016 annual mean SST threshold values of the cool pools in (A) the SH TC season (January–March) and (B) the NH TC season (June–October). The SST thresholds selected were based on the ocean areas 35° latitudes of either side of the equator. (C) and (D) are the same as (A) and (B) except of the warm pools. The heavy solid black curve shows the SST threshold time series. The solid blue line shows the best fit linear trend, and the dashed red line shows the best fit quadratic trend. The linear trend (unit: °C per decade) are shown at the top of each panel, which are all statistically significant at the 99% confidence level.

section is available online at stacks.iop.org/ERL/14/124052/mmedia). And, the TC activity change in these three pools will be the main focus of this paper.

TC data during 1977–2016 were obtained from the International Best-Track Archive for Climate Stewardship version v03r10 database (IBTrACS) [30, 31]. All TCs reaching the tropical storm category, i.e. maximum sustained wind speed reaching 34 knots, were selected. The TCs were assigned to each SST category according to the locations at the moments when they first reached 34 knots. Their intensities and frequencies are calculated on a seasonal basis for the three pools as well as for the entire globe. To investigate the sensitivity of TC intensity and frequency to changes in environmental SST, simple linear trend analyses are performed on the annual mean of Lifetime Maximum Intensity (LMI), which is comparatively insensitive to some of the past data uncertainties and is a better measure of TC intensity [30], and storm counts of TCs with and without the SST percentile-based classification. The correlations of SST anomalies (SSTAs) from the climatological mean with LMI and storm counts are further calculated to investigate the relationships of TC intensity and frequency with SSTAs in the three SST percentile pools.

2. TC activity trends over different SST pools under global warming

Under the global warming background, the mean SSTs of the warm and cool pools had been increasing during 1977–2016 (figure 1). In this period, the minimum SST threshold values of the cool pool in the SH and NH are found to be 27.2 °C and 28.0 °C, while that of the warm pool are 28.7 °C and 29.0 °C, respectively. The SST thresholds increased at a rate of approximately 0.12–0.14 °C/decade, reaching the 99% confidence level, over the 40 year period. As an example, figure 2 gives the spatial coverage of the three pools in February and August 2016. During the SH TC season, the warm pool mainly covers the ocean around maritime continent and north Australia; that during the NH TC season is observed over the West Pacific Warm Pool and the Gulf of Mexico, with the moderate pool surrounding them.

The time series of the annual storm counts over the entire globe and the three pools are shown in figure 3. As listed in table 1, the linear increasing trend of storm counts in the cool pool is the greatest (+1.92 storms per decade, significant at the 95% confidence level); the storm counts in the moderate and warm pools are declining at a rate of −0.79 storms per decade (not significant) and −1.08 storms per decade (significant at the 90% confidence level), respectively. The insignificant trend of entire globe storm counts (+0.33 storm counts per decade) represents the combined effect of the significant positive trend in the cool pool and the negative trends in the moderate and warm pools.

The negative trends of TC counts in the moderate and warm pools (figure 3), where the SST values are already very high (>27 °C, figure 1), indicate that global warming has an opposite impact on the TC counts

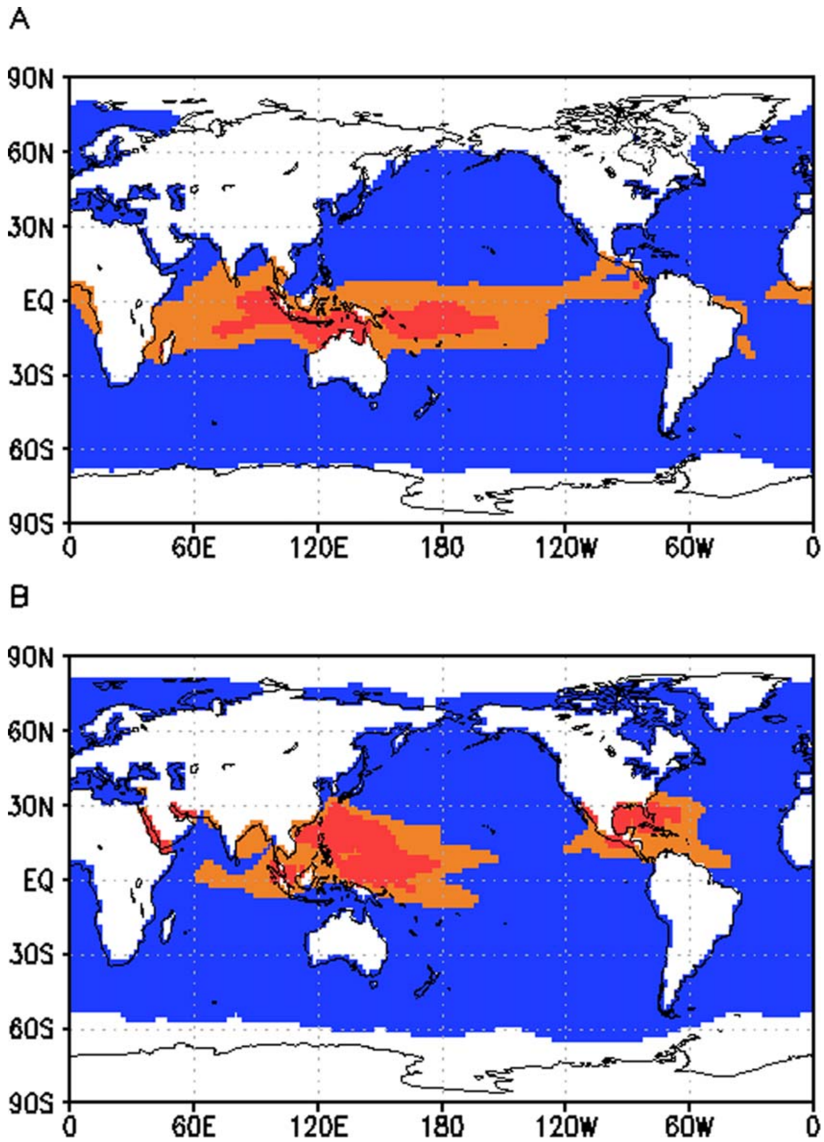

Figure 2. SST classification in (A) February and (B) August 2016 based on the Southern and Northern Hemispheric SST percentile threshold values. The warm, moderate and cool pools are shaded in red, orange and blue, respectively.

in the warm pool to that in the cool pool. The storm count trends show large differences between moderate pool and cool pool (−2.71 storms per decade, and between warm pool and cool pool (−3.00 storms per decade, both significant at the 99% confidence level), meaning that global warming decreases (increases) TCs frequency in the warmer (cooler) environment. The significant positive trend in the cool pool areas is most likely due to the expansion of TC genesis areas exceeding the TC genesis SST threshold value (26.5 °C) [31, 32]. Figure 4 plotted the total areas greater than 26.5 °C in the cool and warm pools from Equator to 35 °N/S summing over the NH and SH TC seasons. The area with SST above 26.5 °C expanded significantly over the cool pool, but stayed about the same over the warm pool, supporting the above explanation that the expanding area favoring TC genesis lead to the more frequent TCs over the cool pool. These results may explain why storm frequency trends have been found to be so uncertain in previous studies, which did not consider the impact of environmental SST, and could imply that opposing trends may effectively 'cancel out' any notable trends in TC frequency. The above analysis excluded TC data from the Northern Indian basin for reasons explained in the supporting information section. TC frequencies and their linear trends also exhibit large hemispheric differences, as listed in table 1. Nevertheless, there are clear and contrasting linear trends of TC storm counts among the three SST percentile pools in both hemispheres.

The LMI and their linear trends are also listed in table 1. The LMI strengthens over the entire globe, with the largest trends being over the cool and warm pools. The LMI trend is 1.39 knots per decade (significant at the 80% confidence level) and 2.38 knots per decade (significant at the 99% confidence level) in the cool and warm pool, respectively. The LMI and

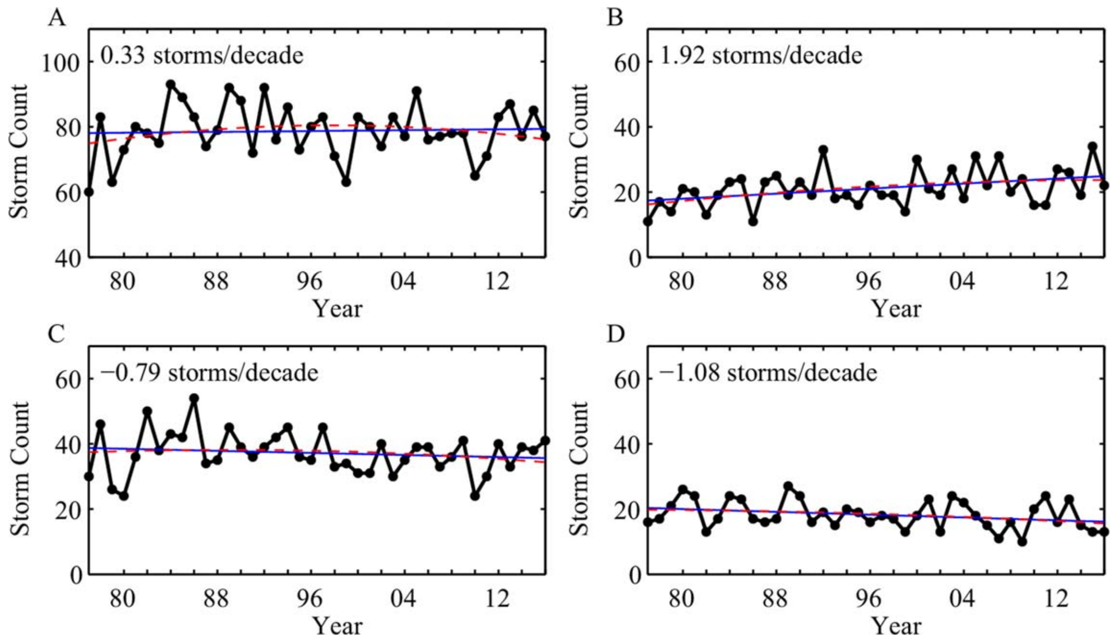

Figure 3. 1977–2016 annual TC counts (heavy solid black), their linear (solid blue) and quadratic (dashed red) trends over (A) the entire globe, (B) cool pool, (C) moderate pool and (D) warm pool. The linear trends (unit: counts per decade) of the annual TC counts are respectively 0.33 (statistically insignificant), 1.92 (significant at the 99.0% confidence level), −0.79 (statistically insignificant), and −1.08 (significant at the 90.0% confidence level) storms/decade, respectively.

Table 1. Linear trends of storm count (unit: storms per decade) and LMI (unit: knots per decade) time series.

Areas	Storm count				Storm LMI			
	Entire globe	Cool pool	Moderate pool	Warm pool	Entire globe	Cool pool	Moderate pool	Warm pool
Global	0.33	**1.92**	–0.79	**–1.08**	**0.64**	**1.39**	0.41	**2.38**
SH	**–0.79**	0.16	–0.13	**–0.82**	**1.86**	0.27	**2.63**	**3.20**
NH	1.12	**1.77**	–0.66	–0.26	0.07	**1.62**	–0.67	**2.14**

Linear trends of storm count and LMI over the entire group and the three SST pools in both hemispheres, respectively. Bold black text denotes trends significant at the 95% confidence level, while bold red text indicates a confidence level reaching 80% but lower than 95%.

their linear trends also exhibit considerable hemispheric differences. Since the grid areas greater than 26.5 °C stay about the same over the warm pool, the empirical framework by Kang and Elsner, which projects global ocean temperature variation onto a two-dimensional continuous frequency–intensity space, could be used to explain physically why increasing the opposite trends of TC intensities and TC frequency [33].

3. Relationships of TC frequency and SSTAs over different SST pools

The correlation coefficients between detrended total TC storm counts and SSTAs are shown in figure 5 over the entire globe and the three pools. Significant positive correlations exist between TC storm counts in the cool pool and SSTAs of almost all the oceanic regions, as shown in figure 5(B), while there are significant anti-correlations between SSTAs and storm counts in the moderate and warm pools, especially over the Indo-Pacific-Atlantic warm pools, as shown in figures 5(C) and (D). The observed opposite correlations of SSTAs with TC storm counts in different SST pools are the main reason for the insignificant correlation observed between SSTAs and all TC cases over the entire globe, as shown in figure 5(A). The different relationships of storm frequency/count with SSTAs in various pools show the complexity of the impacts of global warming on TC frequency, which is similar to the trend analysis results. This highlights the usefulness of applying the SST percentile-based classification approach on studying the TC activity responses to global warming.

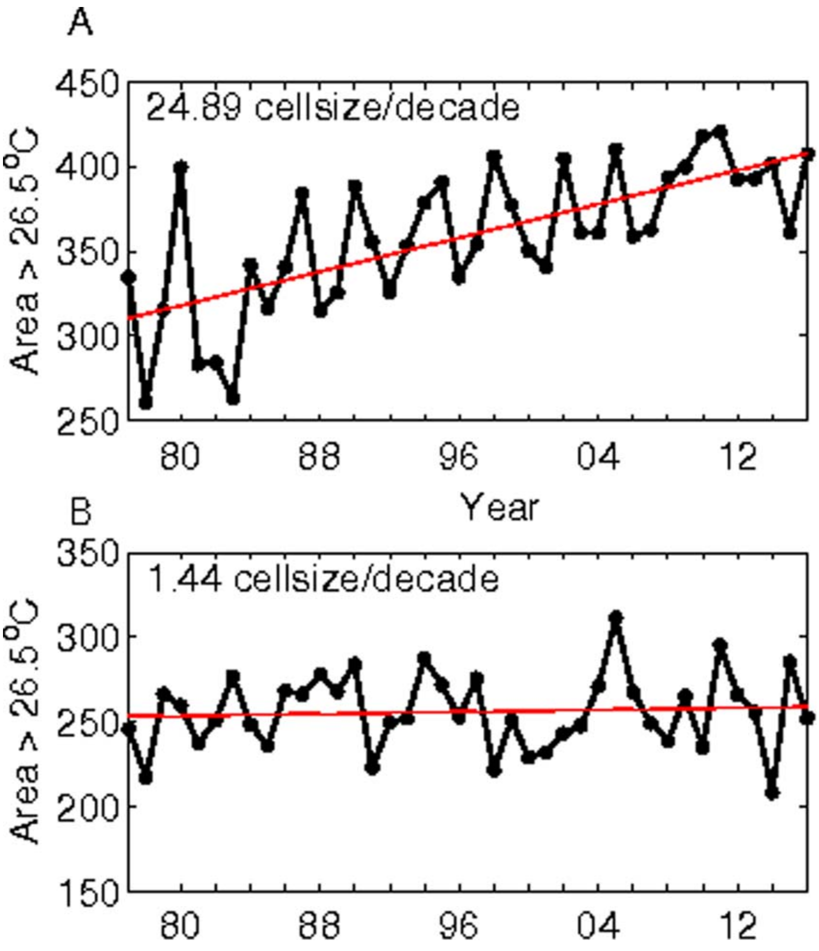

Figure 4. Time series of the total areas (heavy solid black, unit: 222 km × 222 km) greater than 26.5 °C over the (A) cool and (B) warm pools from Equator to 35 °N/S summing over the NH and SH TC seasons. Red line shows the best fit linear trend. Note that considering the TC season length difference, the area sums during the two TC season were weighted in the analysis such that both TC seasons contribute the same to the annual sum of area. The annual areas for cool pools increase by 24.89 cell size (1 cell size = 222 km × 222 km) per decade, which is significant at the 99.9% confidence level. However, that for warm pools stay about the same.

4. Relationships of TC LMI and SSTAs over different SST pools

The correlation coefficients between SSTAs and the TC LMI are plotted in figure 6. As shown in figure 6(C) the LMI of TCs in the moderate pool was positively correlated with SSTAs only over the Equatorial Eastern Pacific Ocean (EEPO), corresponding to the main activity area of the El Niño-Southern Oscillation (ENSO). In contrast, the LMI of TCs over both the cool and warm pool are significantly correlated with the global SST warming pattern, except over the EEPO (figures 6(B) and (D)). The big differences between the correlations of the counts and LMI of TCs in the warm pool with SSTAs (figure 5(D) versus Figure 6(D)) are of interest. Thus, in the areas where the background temperature is already high, the response of TC genesis to the global warming pattern is negative and results in a decreasing trend. However, once the storms were developed, they could be much more powerful due to the higher environmental SST. In the cool pool areas, global warming favors both TC genesis and TC intensification.

5. Conclusions and discussions

In past studies, global warming impacts on TC behaviors were masked due to differences in the background climatic state of SST conditions. The SST percentile-based classification method presented here helps one identify the relationship between changes in TC activity and SST, leading to a clearer and statistically significant picture of the global warming impact on TC frequency. By classifying the ocean into cool, moderate and warm pools, we found that TC storm counts increased everywhere in the cool pool areas, and in contrast, TC storm counts decreased in the moderate and warm pool areas. The correlations of TC LMI with SSTAs show smaller differences, compared to that between TC frequency and SSTAs, among the three pools. The areas with statistically significant positive correlations of TC LMI over the cool and warm pools with SSTAs are much larger than that in the moderate pool, where only the EEPO shows statistically significant results. These illustrate how the different characteristics of the TC frequencies and intensities over different SST background respond differently to climate change.

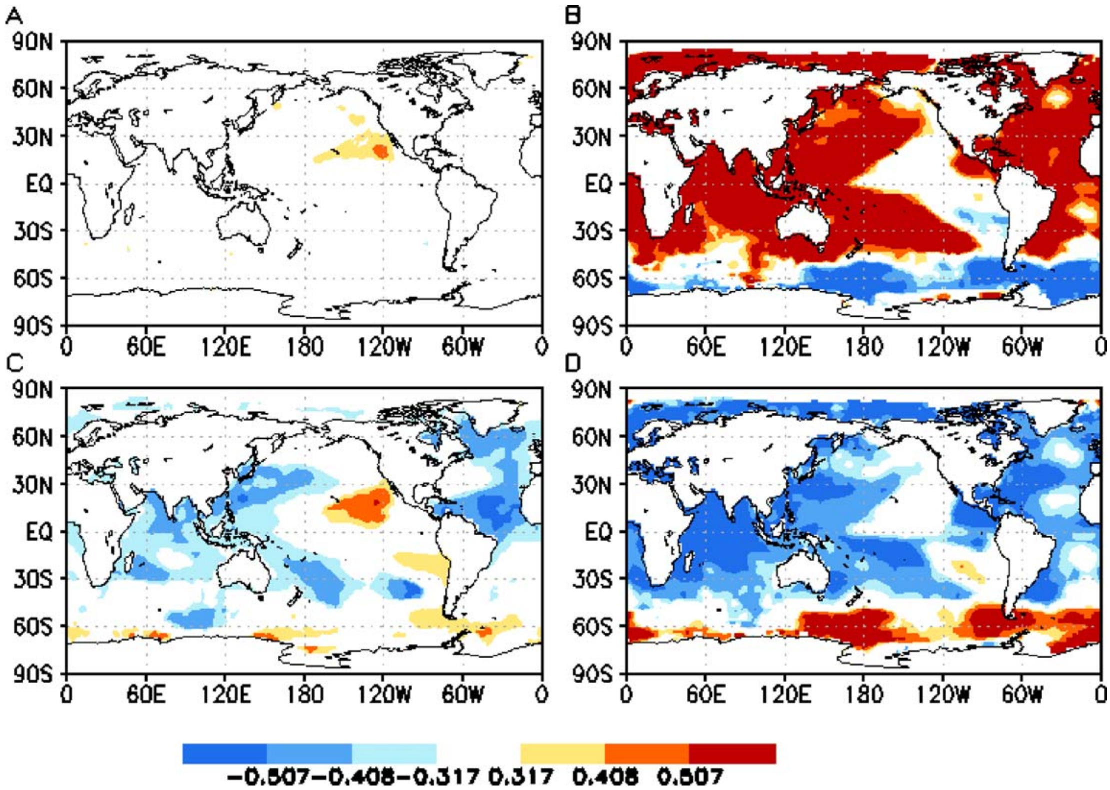

Figure 5. Correlation between annual mean SSTAs and the global TC storm counts over (A) the entire globe, (B) cool pool, (C) moderate pool and (D) warm pool during 1977–2016. The shaded areas indicate significant correlations of 0.317, 0.408, and 0.507, corresponding to the 90%, 95%, and 99% confidence levels respectively.

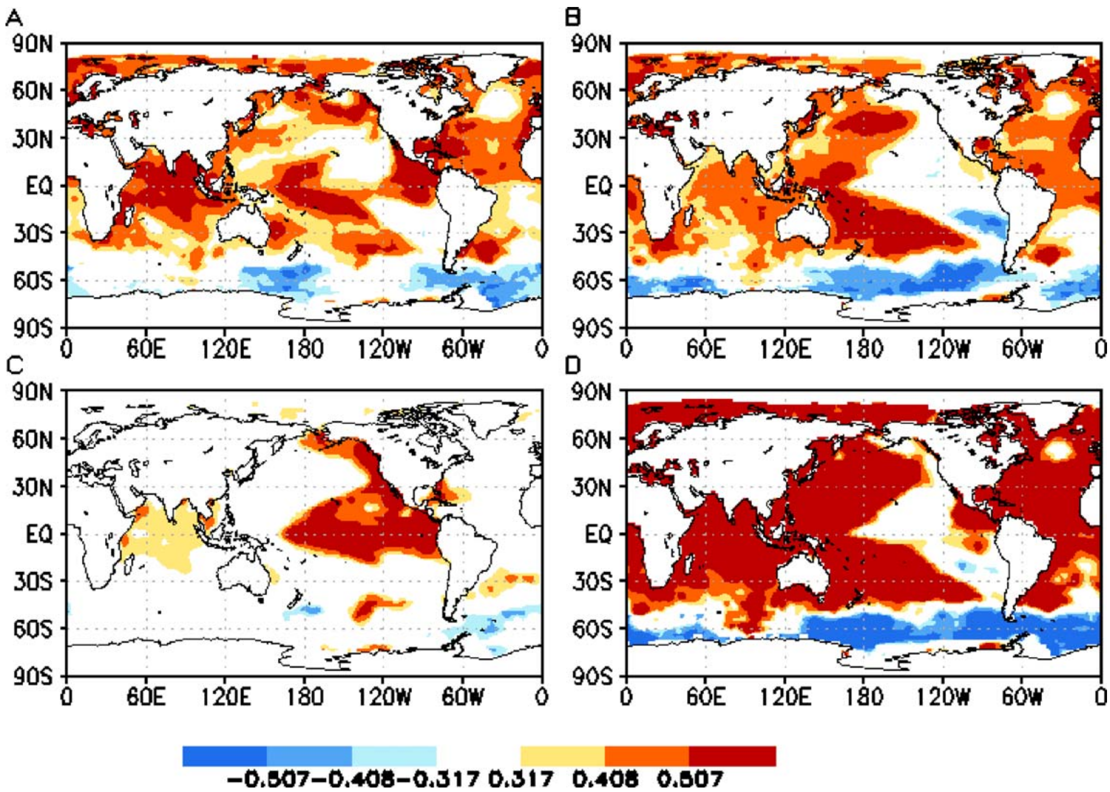

Figure 6. Same as figure 5 but for LMI.

Although previous studies of simulations and observations show uncertain changes of TC frequency under global warming [23], our result indicates that global warming has an opposite impact on the TC counts in the warm pool to that in the cool pool. We attribute the increasing trend of TC storms in the cool pool to the expansion of TC genesis areas over the cool pool, while the TC genesis area trend of the warm pool keeps steady. These results may also explain why storm frequency trends have been found to be so uncertain in previous research works, which did not consider the impact of environmental SST, and could imply that opposing trends may effectively 'cancel out' any notable trends in TC frequency.

Understanding changes in TC frequency and intensity in a warming world is important from both a science and societal standpoint. While TC is primarily an atmospheric phenomenon, warming SSTs have clear effects on TC frequency and intensity that should be taken into consideration to assist in reducing the uncertainty related to TC climatology and seasonal outlooks. In additional to environmental SST classification, we could also classify TCs into different categories according to their intensity when studying TC activity changes. Quantile regression of wind speed quantiles on time (year) or annual global SST could also be used for further study [33]. In this paper, we have established that employing this SST percentile-based classification approach has great potential to be a reliable indicator for explaining changes in TC frequency and intensity in a warming world.

Acknowledgments

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Data availability statement

The 1977–2016 best-track data that support the findings of this study are available at https://ncdc.noaa.gov/ibtracs/. The $2° \times 2°$ monthly SST data (ERSSTv5) are available at https://ncdc.noaa.gov/data-access/marineocean-data/extended-reconstructed-sea-surface-temperature-ersst-v5.

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