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Key Points:

- Tropical Pacific mean-state biases distort sea surface temperature (SST) trends and regional tropical cyclone (TC) activity, rendering them different from observations
- Flux adjustment reduces mean-state biases in CESM2, yielding more La Niña-like SST trends closer to observations over the historical period
- The effect of flux adjustment evolves, with future trends more El Niño-like and closer to the control run, indicating uncertain TC hazard

Supporting Information:

Supporting Information may be found in the online version of this article.

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Impacts of Sea Surface Temperature Warming Pattern Biases on Tropical Cyclone Activity and Hazard

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Abstract Most climate models simulate greater warming in the equatorial eastern Pacific than in the west under historical forcing, resulting in a reduced zonal sea surface temperature (SST) gradient and a weakened Walker circulation. This contrasts with observed trends and highlights a persistent model–observation discrepancy with far-reaching impacts on regional climate extremes. The authors' previous work showed that reducing mean-state biases in a coupled model yields SST trends more consistent with observations. Here, we downscale tropical cyclones (TCs) from these simulations and find that a strengthened zonal SST gradient is associated with increased TC frequency and hazards in the North Atlantic and suppresses activity in the South Pacific. In future projections, both biased and bias-corrected models simulate relative eastern Pacific warming, yet their TC responses differ regionally, with the bias-corrected model projecting greater TC activity and hazards over the North Atlantic.

Plain Language Summary How regional tropical cyclone (TC) activity will change in a warming climate remains uncertain, partly because climate models disagree on future sea surface temperature (SST) warming patterns. Observations show recent cooling in the tropical eastern Pacific, contrasting with the local maximum in warming simulated there by most climate models, a discrepancy linked to model mean-state biases. This study analyzes TC simulations downscaled from two configurations of CESM2: one that reduces tropical mean-state biases using flux adjustment and one that does not. We find that the bias-reduced simulations better reproduce historical SST trends, resulting in TC trends that are also somewhat better aligned with observations across many ocean basins. In the future, however, both model configurations project relative warming in the eastern Pacific, while their SST trend patterns diverge and become more spatially complex, leading to substantial differences in projected regional TC activity and hazards.

1. Introduction

Reliable regional projections of tropical cyclone (TC) activity are important for assessing future climate risks and informing adaptation strategies in coastal regions. Yet substantial uncertainties remain in future TC projections (e.g., Camargo et al., 2023; Knutson et al., 2020). These uncertainties reflect both imperfect representation of multiscale TC genesis processes (e.g., Núñez Ocasio & Dougherty, 2024; Núñez Ocasio et al., 2025; Roberts et al., 2020) and uncertainty in the large-scale environmental changes that modulate TC activity. In this study, we focus on the latter, particularly the patterns of sea surface temperature (SST) warming that strongly modulate large-scale atmospheric and oceanic conditions that control TC formation, tracks, and intensification (e.g., Murakami et al., 2020; Sobel et al., 2023; Wang et al., 2025; Xie et al., 2010).

A stark discrepancy exists between observed SST trend patterns and those simulated by state-of-the-art climate models. Observations show a cooling trend in the eastern equatorial Pacific over the recent decades, a pattern that can be described as broadly La Niña-like. Yet, most climate models simulate a local maximum in warming in this region, a pattern often described as El Niño-like, with even stronger warming projected in the future. Although the time scales and underlying dynamics of these patterns differ from those of interannual El Niño–Southern Oscillation (ENSO) events (e.g., Heede et al., 2020; Watanabe et al., 2024), the historical experience of ENSO, including associated TC activity variations across multiple basins, is so useful that we continue to describe these observed and simulated trends using the shorthand of El Niño-like or La Niña-like, notwithstanding the limitations of the analogies.

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The reasons behind the discrepancy between simulated and observed trends remain debated, but analyses of large-ensemble climate simulations show that internal variability alone cannot explain it (e.g., Seager et al., 2019, 2022; Wills et al., 2022). One explanation is that persistent tropical mean-state biases in climate models—such as the excessive cold tongue, misplaced Intertropical Convergence Zone (ITCZ), and thermocline biases—distort the models' response to external forcing (e.g., Cai et al., 2026; Dong et al., 2026; C. Y. Lee et al., 2022; S. Lee et al., 2022; Kim et al., 2022; Seager et al., 2019; Simpson et al., 2025). This hypothesis has been tested across model hierarchies using surface flux–corrected simulations (Seager et al., 2019; J.-Y. Zhuo et al., 2025), and research on the underlying mechanisms continues. In any case, however, it is important to understand how the mean-state biases and possible SST trend errors may affect our understanding of both present and projected future TC activity and other climate extremes (Heede et al., 2025; Lin et al., 2025; Sobel et al., 2023; Wang et al., 2025; Xie, 2020; Zhao & Knutson, 2024).

Here we examine how tropical mean-state biases influence the forced response of TC activity and hazard, with hazard quantified as the exceedance frequency distribution of TC maximum sustained winds. This study builds on our recent work (J.-Y. Zhuo et al., 2025), which developed a flux-adjusted version of the Community Earth System Model version 2 (CESM2-FA) to reduce mean-state biases and better constrain the simulated forced response of the tropical Pacific. We further combine these climate simulations with a TC downscaling model, the Columbia HAZard model (CHAZ) (C.-Y. Lee et al., 2018) to assess TC activity and hazard.

2. Data and Methods

2.1. CESM2 and Flux Adjustment

CESM2 (Danabasoglu et al., 2020) is used here at a horizontal resolution of $1.9^\circ \times 2.5^\circ$ for the atmosphere and nominal 1° for the ocean, following the configuration of J.-Y. Zhuo et al., 2025. Like many other Earth system models, CESM2 exhibits cold-tongue and double-ITCZ biases (Li & Xie, 2014; Zhang et al., 2023). These tropical mean-state biases arise from complex interactions among coupled processes whose individual contributions remain incompletely understood (Li & Xie, 2014; Tian & Dong, 2020) and are only modestly reduced at higher model resolution (Moreno-Chamarro et al., 2022). CESM2-FA, by contrast, applies climatological surface heat and momentum flux adjustments to reduce tropical SST and surface-wind biases (J.-Y. Zhuo et al., 2025). Flux adjustment has been widely used in seasonal prediction and climate modeling (e.g., Knutson & Manabe, 1995; Vecchi et al., 2014). Here, we use it as a diagnostic tool to isolate the influence of mean-state biases on the simulated climate response, rather than as a definitive solution, which would require internally consistent improvements to model physics or numerics.

We analyze 15-member ensemble simulations from both CESM2 and CESM2-FA, forced by historical forcing through 2014 and the high-emission SSP5-8.5 scenario from 2015 to 2049, following the coupled model inter-comparison project phase 6 (CMIP6) experimental design (Eyring et al., 2016). SSP5-8.5 is used to provide a strong greenhouse warming signal for isolating the effects of tropical mean-state biases, while we additionally analyze a five-member CESM2-FA ensemble under SSP3-7.0 to assess the scenario dependence of the projected responses. Further details of the flux adjustment setup and model validation are provided in J.-Y. Zhuo et al. (2025).

2.2. TC Downscaling Using CHAZ

We use the Columbia HAZard Model (CHAZ) (C.-Y. Lee et al., 2018) to downscale synthetic TCs from CESM2 and CESM2-FA, hereafter CESM2 + CHAZ and CESM2-FA + CHAZ. CHAZ simulates TC genesis, tracks, and intensity from large-scale environmental conditions. Genesis is determined using the tropical cyclone genesis index (TCGI; Section 2.3) (Camargo et al., 2014; Tippett et al., 2011), tracks follow a beta-advection model (Emanuel et al., 2008), and intensity is estimated from environmental predictors using statistical models that account for internal storm dynamics and land interaction (C.-Y. Lee et al., 2015, 2016).

For each CESM2 and CESM2-FA member, we generate 10 CHAZ track ensembles with 40 intensity realizations each. All 400 realizations are used for TC wind risk assessment, while only one intensity realization from each of the 10 track ensembles is used to compute TC genesis and track density. Here we present results based on the TCGI formulation using column integrated relative humidity (CRH) as the moisture variable. Uncertainty associated with using saturation deficit (SD) as the moisture variable (Camargo et al., 2014; C.-Y. Lee

et al., 2020) is discussed in Figure S11 in Supporting Information S1. CHAZ TC downscaling driven by ERA5 reanalysis (Hersbach et al., 2020) is also included to provide a historical reference for the downscaling framework.

2.3. Large-Scale Factors Affecting TC Activity

We also examine large-scale environmental factors that are closely related to TC activity, including the 200–850 hPa vertical wind shear (VWS), potential intensity (PI; Bister & Emanuel, 2002), column-integrated relative humidity (CRH; Bretherton et al., 2004), and clipped absolute vorticity at 850 hPa (AVort/ η). These fields are used to compute the TCGI:

$$\text{TCGI} = \exp(b + b_{\eta} \eta + b_{\text{CRH}} \text{CRH} + b_{\text{PI}} \text{PI} + b_{\text{VWS}} \text{VWS}) \quad (1)$$

The TCGI version used here is based on a statistical fit using the ERA5 environmental fields Hersbach et al. (2020) as described in Camargo et al., 2025. The regression coefficients are $b = -24.132$, $b_{\eta} = 2.512$, $b_{\text{CRH}} = 0.077$, $b_{\text{PI}} = 0.0622$, and $b_{\text{VWS}} = -0.1202$. Following Camargo et al. (2025), mean-state bias corrections are applied when calculating TCGI from CESM2 and CESM2-FA by comparing model-simulated environmental fields with ERA5 over the 1981 to 2010 period.

2.4. Observations

Observed SST data are taken from the HadISST data set (Rayner et al., 2003). TC observations are provided by the International Best Track Archive for Climate Stewardship version 4 (IBTrACS v04r01; Gahtan et al., 2024; Knapp et al., 2010). Here we use data curated by the National Hurricane Center for the North Atlantic, eastern North Pacific and central North Pacific, and data from the Joint Typhoon Warning Center for the rest of the world. We use 6-hourly storm positions (in longitude and latitude) and maximum wind speeds (in kt; 1 kt $\approx 0.51 \text{ m s}^{-1}$).

2.5. Metrics and Analysis

The equatorial Pacific zonal SST gradient is calculated as the SST difference between a western Pacific box (-140°E – 170°E , 5°S – 5°N) and an eastern Pacific box (170°W – 90°W , 5°S – 5°N), consistent with Seager et al. (2022) and J.-Y. Zhuo et al. (2025).

Only storms with a lifetime longer than 2 days and reaching at least tropical storm intensity ($>34 \text{ kt}$) are included. Unless otherwise noted, all TC analyses are performed during the peak TC season in each hemisphere, August to October (ASO) in the Northern Hemisphere and January to March (JFM) in the Southern Hemisphere, following previous studies (e.g., Camargo et al., 2025; C.-Y. Lee et al., 2025). TC genesis is defined as the first point reaching 34 kt. TC track density is calculated by counting 6-hourly TC positions within each $5^{\circ} \times 5^{\circ}$ grid cell and smoothed using a distance-weighted nine-point filter (Murakami et al., 2020). Basin-scale statistics are computed for seven ocean basins: the North Atlantic, eastern North Pacific, central North Pacific, western North Pacific, North Indian Ocean, South Indian Ocean, and South Pacific shown in Figure 1h.

TC hazard is evaluated from synthetic TCs within a 100 km radius of 18 cities in TC-prone regions. Return periods are estimated empirically from annual exceedance frequencies for different wind-speed thresholds, and we further examine changes in global 100- and 1,000-year return levels between the present and future climates. It should be noted that the absolute values of return curves are sensitive to the choice of search radius, and the return period for a given intensity within a radius will typically be shorter than that for a specific location, as a site may not experience the storm's maximum wind speed even if it passes nearby (C. Y. Lee et al., 2022; S. Lee et al., 2022). We use the metric primarily for evaluating relative climate-driven shifts rather than to provide precise absolute hazards (Section 3.4).

We analyze trends over 1979–2014, corresponding to the satellite era of reliable global TC observations (e.g., Klotzbach et al., 2022) and the CMIP6 historical forcing period, and over 2015–2049 under SSP5-8.5 (Flato et al., 2013). TC hazards are additionally evaluated over 2026–2035 to characterize the immediate-future forced response relevant to the insurance and disaster-management sectors. Statistical significance is assessed using two-sided (t) tests.

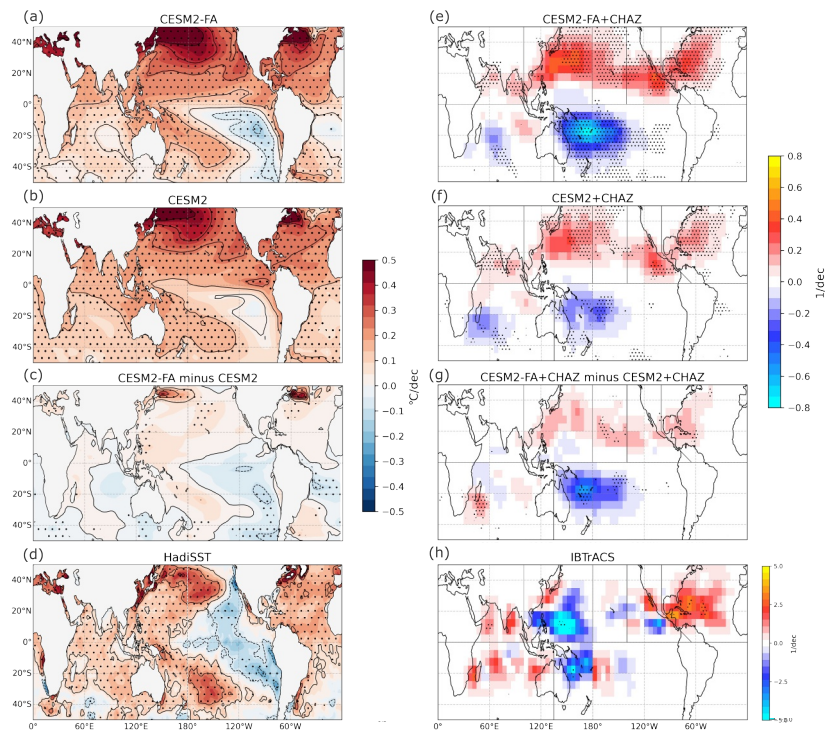


Figure 1. Historical trends (1979–2014) in sea surface temperature (SST) and tropical cyclone (TC) track density. Left panels show annual SST trends from CESM2-FA (a), CESM2 (b), the difference (CESM2-FA minus CESM2) (c), and HadISST observations (d). Right panels show corresponding seasonal TC track density trends (August–October in the Northern Hemisphere and January–March in the Southern Hemisphere) derived from CHAZ downscaling of CESM2-FA (e), CESM2 (f), their difference (g), and IBTrACS observations (h). Stippling denotes regions where trends are statistically significant at the 95% confidence level based on a two-sided *t*-test.

3. Results

3.1. Historical Trends of SST and TC Occurrence

Figure 1 shows the ensemble-mean SST trends over 1979–2014 and the corresponding TC track density trends. CESM2-FA produces a strengthened zonal SST gradient ($+0.06^{\circ}\text{C}$ per decade), with pronounced cooling in the equatorial eastern and southeastern Pacific (Figure 1a). In contrast, CESM2 simulates stronger warming in the equatorial cold tongue than in the western Pacific, resulting in a reduced zonal SST gradient (-0.03°C per decade; Figure 1b). The observed zonal SST gradient trend is $+0.20^{\circ}\text{C}$ per decade and lies within the spread of individual CESM2-FA members (-0.14 to $+0.28^{\circ}\text{C}$ per decade), but outside the CESM2 range (-0.31 to $+0.18^{\circ}\text{C}$ per decade; Figure S1 in Supporting Information S1), indicating that CESM2-FA better captures the observed zonal SST gradient. The SST trend difference (CESM2-FA minus CESM2; Figure 1c) forms a wedge-shaped La Niña-like pattern, resembling the observed tropical Pacific trend (Figure 1d), supporting previous findings that the observed equatorial eastern Pacific cooling contains a forced component underestimated in standard coupled climate simulations (Seager et al., 2019, 2022; Watanabe et al., 2024; Wills et al., 2022; J.-Y. Zhuo et al., 2025). Outside the equatorial Pacific, both the observed and simulated SST changes show substantial global warming, with particularly strong warming over the mid-latitudes of the western North Pacific (WNP), North Atlantic (NA), and southwest Pacific (Figures 1a–1d). One notable exception is the subtropical north-eastern Pacific, where both model configurations fail to reproduce the observed weak cooling. This discrepancy shows that flux adjustment does not eliminate all regional SST trend biases (J.-Y. Zhuo et al., 2025), with internal variability in the observations potentially contributing to the model-observation difference (Watanabe et al., 2024).

TC track density trends in CESM2-FA + CHAZ and CESM2 + CHAZ exhibit similar hemispheric asymmetries, with increased activity across most Northern Hemisphere basins and predominantly reduced activity across the Southern Hemisphere (Figures 1e–1f). Both simulations reproduce the observed increase over the NA and Bay of

Bengal, as well as the decrease east of Australia (Figures 1e and 1f). Relative to CESM2 + CHAZ, flux adjustment reshapes regional TC responses, enhancing activity over the NA, central North Pacific, and southwest Indian Ocean while suppressing activity over the South Pacific (Figure 1g). This corresponds to nearly twice the increase over the NA (+0.80 vs. +0.41 per decade) and more than twice the reduction over the South Pacific (−1.82 vs. −0.71 per decade; Table S1 in Supporting Information S1). Despite these pronounced regional changes, the difference in global TC frequency between the two simulations is not statistically significant (Table S1 in Supporting Information S1).

However, neither model configuration captures the pronounced decline over the WNP, instead producing only a weak reduction or no trend near the equator. Both also miss the reduced activity over parts of the eastern North Pacific and underestimate the observed increase over the South Indian Ocean (Figures 1e, 1f, and 1g). Over the WNP, CHAZ downscaling driven by ERA5 indicates an overall increasing trend in TC activity (Figure S2c in Supporting Information S1), consistent with the increasing TCGI and increasingly favorable large-scale conditions for TC genesis (Figures S2a and S2b in Supporting Information S1). The model-observation discrepancies of WNP TC may partly reflect basin-dependent relationships between large-scale climate variability and TC frequency. In the WNP, the observed relationship between ENSO and TC frequency is relatively weak on interannual timescales and also varies over time (e.g., Frank & Young, 2007; Sena et al., 2025). Recent ERA5-driven CHAZ simulations similarly show that relationships between TC frequency and major climate modes vary substantially among different basins (Han et al., 2025). Thus, downscaling models may not necessarily be expected to reproduce all aspects of observed WNP TC variability, even when driven by observed large-scale conditions. Nevertheless, our framework remains useful for isolating the TC response to large-scale environmental changes, particularly those driven by externally forced SST changes.

3.2. Historical Trends of Large-Scale Factors

The regional TC track density trends discussed in the previous section closely follow the corresponding changes in the large-scale environment, as evidenced by the strong spatial correspondence between TC track density trends (Figures 1e–1g) and TCGI trends (Figures 2a–2c). Relative to CESM2, reduced mean-state biases in CESM2-FA enhance TCGI over the NA and central North Pacific, while suppressing TCGI over the South Pacific (Figure 2c), consistent with the regional redistribution of TC activity shown in Figure 1g. The response over the WNP is more heterogeneous, with reduced TCGI over the equatorial and eastern WNP but enhanced TCGI across much of the subtropical northwestern WNP, consistent with the weak equatorial reduction and spurious subtropical increase in simulated TC activity discussed in Section 3.1. A meridional contrast is evident over the ENP, with reduced TCGI near the equator and enhanced TCGI in the subtropics.

Over the NA, increased potential intensity and reduced vertical wind shear create a more favorable environment for TC genesis in CESM2-FA (Figures 2f and 2i), with enhanced humidity and low-level vorticity further supporting TC formation in the main development region (Figures 2l and 2o). In contrast, the stronger reduction in South Pacific TC activity is primarily associated with enhanced vertical wind shear and reduced column-integrated relative humidity, which together suppress TC genesis (Figures 2i, 2j, and 2l). Over the WNP, increased potential intensity, weaker vertical wind shear, and enhanced column-integrated relative humidity together favor TC genesis, although these favorable changes are partly offset by reduced low-level absolute vorticity over the equatorial WNP (Figures 2f, 2i, 2l, and 2o). As a result, TCGI exhibits only a weak reduction over the equatorial WNP but increases markedly over the subtropical WNP (Figure 2c), consistent with the simulated TC response (Figure 1g).

Collectively, these large-scale environmental changes are more favorable for TC genesis in the Northern Hemisphere than in the Southern Hemisphere, explaining the simulated hemispheric asymmetry in TC responses. A quantitative decomposition of the contribution from each environmental variable to the total TCGI trend (Figure S3 in Supporting Information S1) further supports this interpretation, consistent with the CHAZ genesis scheme being explicitly formulated in terms of these environmental predictors.

3.3. Future Projections

Both CESM2-FA and CESM2 project maximum warming over the eastern equatorial and North Pacific and weaker warming over the South Pacific during 2015–2049 under SSP5-8.5 (Figures 3a and 3b). This pattern, characterized by enhanced EEP warming and delayed SEP warming, resembles the canonical response to

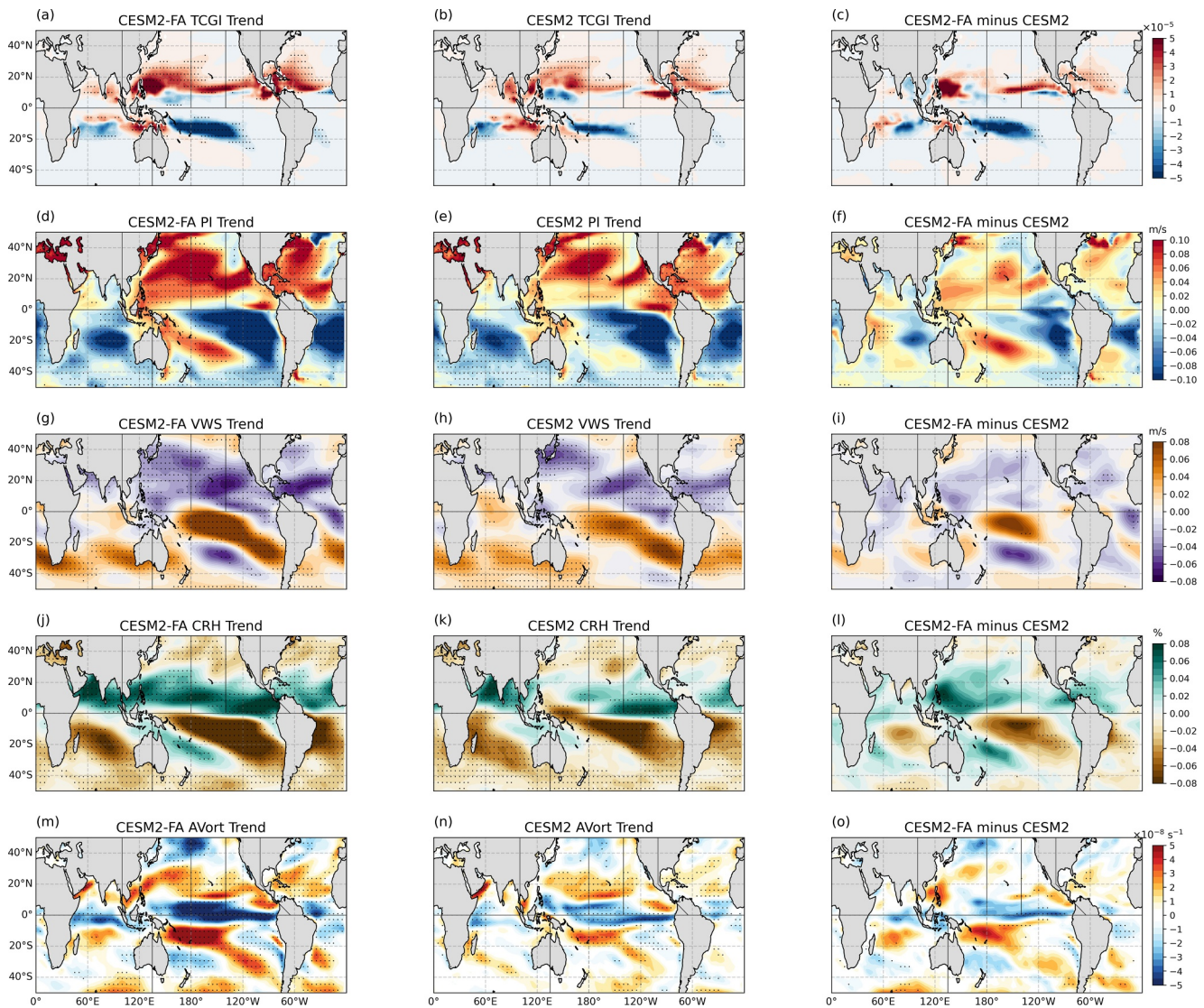


Figure 2. Historical trend (1979–2014) of tropical cyclone genesis index (a–c), potential intensity (d–f), vertical wind shear (g–i), column-integrated relative humidity (j–l) and low-level absolute vorticity (m–o) for CESM2-FA (left), CESM2 (middle) and their difference (right). Black dots mark ocean grid points where the trend is statistically significant at the 95% level and its magnitude exceeds 10% of the color-bar range; dots are drawn at every other grid point for clarity.

increasing CO_2 simulated by climate models (e.g., Vecchi & Soden, 2007; Watanabe et al., 2020; Xie et al., 2010), supporting the interpretation that the recent eastern Pacific cooling, although potentially forced, is nevertheless transient (e.g., J.-Y. Zhuo et al., 2025). Similar warming pattern is also reproduced in the five-member CESM2-FA SSP3-7.0 ensemble, albeit with a weaker amplitude (Figure S4 in Supporting Information S1), indicating that the projected SST evolution is robust across forcing scenarios, as also found for a broader range of scenarios by Lele et al. (2026).

Unlike the historical period (Figure 1c), the projected SST trend differences between CESM2-FA and CESM2 are neither La Niña-like nor El Niño-like (Figure 3c) and are substantially smaller in magnitude. Nevertheless, the resulting differences in the large-scale environment still produce pronounced regional differences in projected TC activity.

Relative to CESM2 + CHAZ, CESM2-FA + CHAZ projects substantially greater NA TC activity, with the increase shifting toward the subtropical western NA and away from parts of the tropical main development region (Figure 3f). Basin-wide NA TC occurrence is 129% higher in CESM2-FA + CHAZ over the projection period (Table S2 in Supporting Information S1). CESM2 + CHAZ projects a decrease in TC activity, consistent with

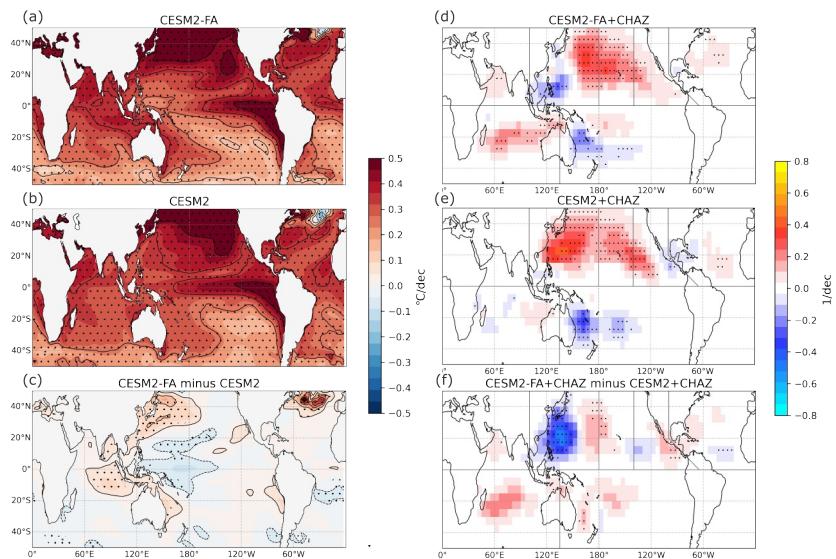


Figure 3. Near-future trends (2015–2049; SSP5-8.5) in sea surface temperature and tropical cyclone track density. Same as Figures 1a–1c and 1e–1g but for a different period.

previous studies showing that a more El Niño-like tropical Pacific warming pattern suppresses NA TC activity through changes in the large-scale environment (e.g., Fosu et al., 2024; Karnauskas et al., 2023; Sobel et al., 2023). The corresponding TCGI mirrors this pattern (Figure S6c in Supporting Information S1), with weaker increases in vertical wind shear, enhanced mid-level humidity, and more favorable potential intensity over the northwestern than southeastern main development region (Figures S6f, S6i, S6l, and S6o in Supporting Information S1).

The largest contrast is over the WNP, where CESM2-FA + CHAZ projects a zonal redistribution of TC activity relative to CESM2 + CHAZ, with reduced activity over the western part of the basin and enhanced activity farther east (Figure 3f). Consistent changes in TCGI (Figure S6c in Supporting Information S1) and the large-scale environment suggest that this zonal redistribution reflects differences in potential intensity, vertical wind shear, and low-level absolute vorticity (Figures S6c, S6f, S6i, and S6o in Supporting Information S1). In contrast, the pronounced South Pacific TC reduction in CESM2-FA relative to CESM2 during the historical period (Figure 1g) reverses sign in the future, with weakly enhanced TC activity replacing the historical reduction (Figure 3g), likely reflecting the transition from strong historical La Niña-like SST trend differences to much weaker differences that are neither La Niña-like nor El Niño-like. These projected regional TC responses are not specific to the high-emission scenario: the track density trends in the five-member CESM2-FA SSP5-7.0 ensemble resemble their SSP5-8.5 counterparts, albeit with weaker amplitude (Figure S5 in Supporting Information S1).

3.4. Implications for Regional TC Hazards

We evaluate TC hazards for 18 coastal cities in TC-prone regions during the immediate future (2026–2035), a period particularly relevant to risk management in the insurance and reinsurance sectors, and compare them with hazards during the historical baseline (1979–2014) and the broader 2015–2049 period examined in previous TC climate studies (e.g., Bloemendaal et al., 2022).

Reducing biases via flux adjustment substantially reorganizes the projected changes in TC landfall hazard across regions (Figure 4). Along the U.S. Atlantic coast, CESM2-FA consistently produces a stronger increase in landfall hazard than CESM2, from relatively frequent 10- and 20-year events to rare 100- and 200-year extremes. The corresponding absolute return-period estimates are shown in Figure S8 in Supporting Information S1. The contrast between two model configurations is particularly pronounced for Tampa and Miami and generally strengthens toward longer return periods. For example, at Miami, a historical 20-year event recurs approximately every 14 years by 2015–2049 in CESM2-FA, compared with every 17 years in CESM2; for a historical 200-year

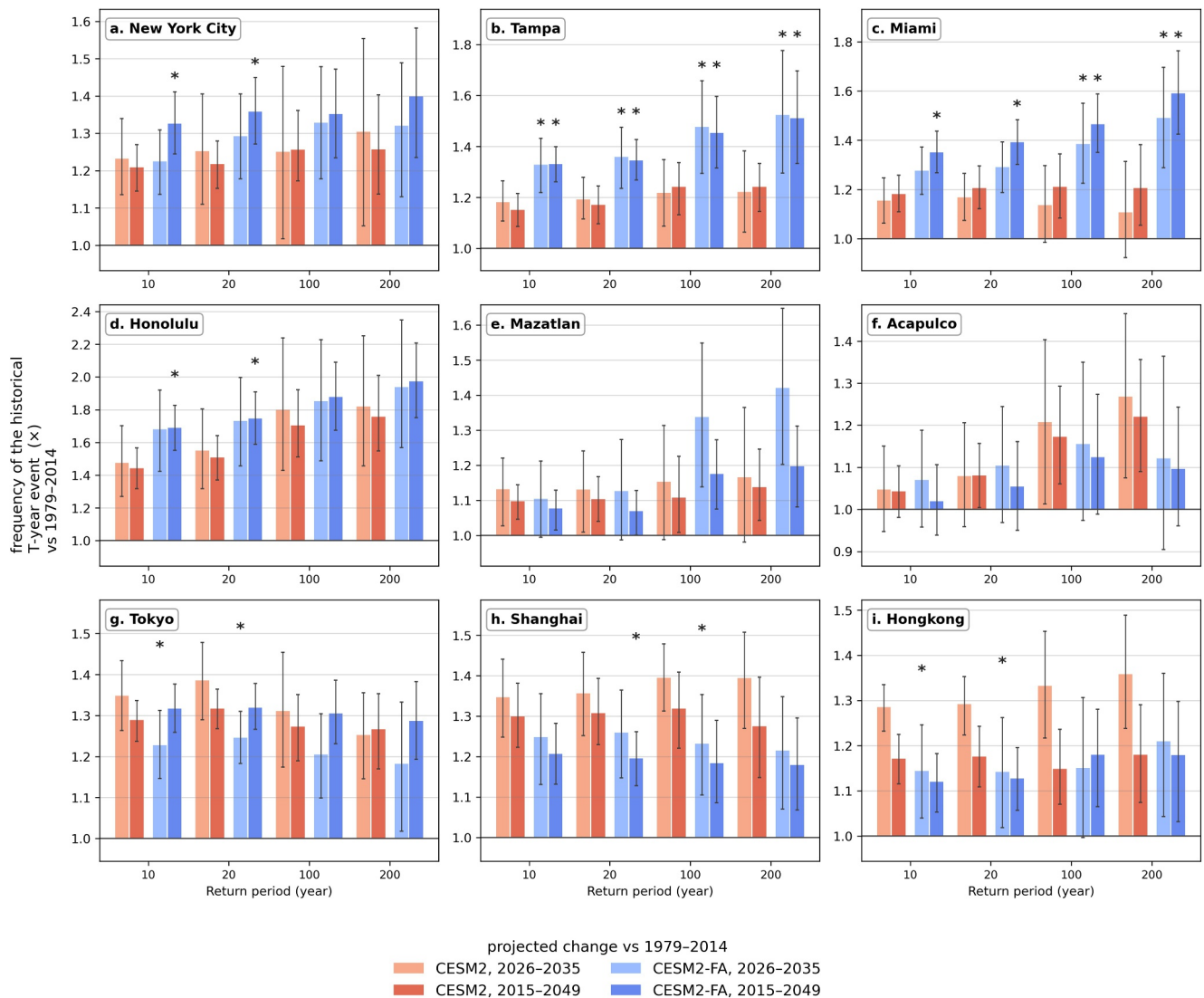


Figure 4. Projected changes in tropical cyclone landfall hazard at selected coastal cities. Bars show the dimensionless ratio T/T' , where T' is the projected return period of the same wind speed associated with a historical T -year event during 1979–2014. Red and blue indicate CSM2 and CSM2-FA, with light and dark shades for 2026–2035 and 2015–2049, respectively. Error bars show twice the ensemble standard deviation; asterisks indicate significant differences between CSM2 + CHAZ and CSM2-FA + CHAZ.

event, the corresponding return period shortens to approximately 125 years in CSM2-FA, compared with 165 years in CSM2. This is consistent with the enhanced TC occurrence projected across the Caribbean Sea, Gulf of Mexico, and along the U.S. East Coast (Figure S7 in Supporting Information S1). Notably, these regional contrasts are already evident over the immediate-future period (2026–2035) and are broadly consistent with those over 2015–2049, suggesting that SST warming-pattern biases are relevant to near-term TC risk assessment.

Projected changes are generally weaker in the eastern Pacific, with modest changes at Mazatlán and Acapulco. Over East Asia, CSM2-FA substantially reduces the projected hazard increase relative to CSM2, particularly for Shanghai and Hong Kong. Elsewhere, projected hazards generally increase over the North Indian Ocean, show relatively small changes over the southwest Indian Ocean, and decrease across the South Pacific, with CSM2-FA producing larger reductions than CSM2 at several locations (Figure S9 in Supporting Information S1).

Expanding from these specific city locations, the spatial patterns of low-probability events (e.g., 100- and 1,000-year return periods; Figure S10 in Supporting Information S1) confirm a hemispheric asymmetry, with increasing hazard across most of the Northern Hemisphere and a general decrease across the Southern Hemisphere.

Moreover, the differences between CESM2-FA and CESM2 (Figures S10c and S10f in Supporting Information S1) reinforce our findings that neglecting SST mean-state biases can lead to underestimation of TC hazard in the NA and misrepresentation of regional risk elsewhere. We also note that our 2026–2035 projections represent a continuous forced response starting from 1950, rather than a decadal prediction initialized from current observations. Thus, these results isolate the underlying forced component of immediate-term future TC risk, though they remain subject to residual internal variability not fully averaged out by a 15-member ensemble over a short 10-year period.

4. Conclusions and Discussion

In this study, we show that tropical mean-state biases can substantially distort historical and projected TC responses by altering SST warming patterns and the associated large-scale environment. Reducing tropical mean-state biases enables CESM2-FA to better reproduce the observed strengthening of the equatorial Pacific zonal SST gradient during 1979–2014 and yields historical TC responses more consistent with the observed increase in the NA and decrease in the South Pacific. The WNP remains an exception. The observed historical decline in TC activity is reproduced by neither model configuration and is also absent from ERA5-driven CHAZ simulations. This discrepancy suggests that processes beyond those represented by the resolved large-scale environment contribute to the observed trend.

For future projections, SST trend differences between CESM2-FA and CESM2 are smaller than during the historical period and are neither distinctly El Niño-like nor La Niña-like, yet they produce substantial differences in regional TC responses and hazards. Relative to CESM2, CESM2-FA projects greater TC hazard over the NA, including for New York, Tampa, and Miami, and reduced hazard over the South Pacific. These differences are evident in both the immediate future (2026–2035) and the broader 2015–2049 period, demonstrating that SST warming-pattern biases can materially affect near-term regional TC risk assessments.

Overall, our results highlight the importance of reducing tropical mean-state biases for improving regional TC projections and hazard assessments. A better dynamical understanding of how SST warming patterns influence regional TC responses, beyond simple ENSO analogies, will be important for reducing uncertainties in future projections. Future fully coupled convection-permitting simulations will provide an important benchmark for evaluating these mechanisms when convective processes are explicitly resolved.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

The scripts used to generate the figures are available at <https://doi.org/10.5281/zenodo.22772280> (J. Zhuo, 2026). IBTrACS data are available at <https://doi.org/10.25921/82ty-9e16> (Gahtan et al., 2024), and HadISST data are available at <https://www.metoffice.gov.uk/hadobs/hadisst/>.

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